A STRUCTURALIST ACCOUNT OF THE THEORY-CHANGE FROM NEWTONIAN TO EINSTEINIAN PHYSICS

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I confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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ABSTRACT

Some philosophers – such as Popper and Kuhn – have cited the theory-shift from Newtonian to Einsteinian physics as one of the great scientific *revolutions*. This thesis argues against this that the shift was 'evolutionary' and exhibits a high degree of continuity (or quasi-continuity). I will develop a view that selects the relationships between events – one specified by dynamical laws at issue – as the essential elements within these two physical theoretical frameworks. This view brings together the dynamical perspective of space-time (developed by Harvey Brown, Robert DiSalle and Nick Huggett) and structuralism (developed by Henri Poincaré and Pierre Duhem, and more recently resuscitated by John Worrall). The former view turns our attention away from the structure of space-time to the dynamical laws. While the second view will clarify to what extent the theory-change is evolutionary.

The thesis consists of five chapters. The first chapter discusses the failures of existing views on the theory-change. The second chapter develops my own positive view - building, as indicated, on the work of the two aforementioned perspectives. The third and fourth chapters consider detailed aspects of the particular theory-change from Newtonian to Einsteinian physics from the point of view. The final chapter discusses the strengths of my view in comparison to the existing accounts of the theory-change.

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Chapter 1

Formal, Conceptual and Ontological Aspects of the Theory-Change from Newtonian to Einsteinian Physics

1. Introduction

In a special edition of *Time* magazine published on December 31st 1999, Albert Einstein was selected as "the person of the century," reflecting the intellectual and technological significance of his achievements. Stephen Hawking there states that the theories of relativity brought about a "conceptual revolution of time, space, and reality," which enabled physicists to develop the empirical theories of modern cosmology. Einstein's achievement may be considered as a revolutionary one in that his theories replaced the Newtonian concepts of space and time, and thus made possible novel theories of matter, light and the overall structure of the universe.

The theory-change from Newtonian to Einsteinian physics has in fact been regarded as an archetypal example of a revolution in science by both scientists and philosophers. For example, the physicist Max Born identified the development of the theories of relativity as "the Einsteinian revolution" which opened "the beginning of a new era." (Born 1965, 2) And the philosopher of science Karl Popper wrote that "Einstein revolutionized physics." (Withrow 1967, 25) After the prediction made by general relativity of the deflection of light due to the sun's gravitational field was confirmed by observations, the London *Times* on November 7th 1919 famously ran the headline "Revolution in Science" with a sub-heading "Newtonian Ideas Overthrown." In view of the fact that Einsteinian physics is founded on his novel understanding of the concepts of space-time and of the equivalence of mass and energy, which are quite alien to the Newtonian frameworks, it seems difficult to deny the intuition behind the idea that this episode of theory-change was indeed revolutionary.

Einstein himself, however, rarely employed the term "revolution" in order to characterize his theories of relativity. (Cohen 1985) He instead warned that the term "revolution" mischaracterizes the way that the special and the general theories were developed. Their development is considered as one which "slowly leads to a deeper conception of the laws of nature" based on results of "the best brains of successive generations." (Klein 1975, 113) Although Einstein referred to the theory-change from Newton to Maxwell as a revolution in that "action at a distance is replaced by the field" (Einstein 1949, 35), he did not maintain that the theories of relativity were new fundamental theories. The special theory of relativity is claimed as "simply a systematic development of the electromagnetics of Maxwell and Lorentz". (Einstein 1954, 230) As for the general theory it was "the last step in the development of the program of field theory, … [and] it modified Newton's theory only slightly" (ibid., 260).

Two opposing points of view have characterized theory change in science as either evolutionary or revolutionary. The dispute between the two views is concerned with whether or not the development of scientific knowledge has an accumulative (or quasi-accumulative) nature, and is closely related to other epistemological issues, such as those of scientific realism and scientific rationality. The evolutionary view, supported by Duhem (1904/1954) and logical empiricists such as Hempel (1960), maintains that scientific change is an essentially continuous and cumulative progress. On the other hand, Kuhn (1962) explicitly articulated and defended a revolutionary view involving "paradigm changes." According to Kuhn, two different paradigms are incommensurable in their assertions about the world, aims, criteria of appraisal, conceptual frameworks, and even observational basis.

Advocates of both the evolutionary and the revolutionary views have employed the case of theory-change from Newtonian to Einsteinian physics in order to support their position. While Zahar (1973) and Friedman (1989) point out the commonality of mathematical formalisms in both theories as evidence of the accumulative nature of the theory-change, Kuhn considers the conceptual discontinuities concerning notions such as 'mass' and 'space-time' as evidence of the occurrence of a revolution brought about by Einsteinian physics.

This chapter will critically examine the above two views. It consists of criticism of four different approaches that attempt to decide in which aspects either continuity or discontinuity holds between Newtonian and Einsteinian theories. In the next section, Kuhn's view will be considered as a representative of revolutionary views. It will be argued here that Kuhn's revolutionary view is not supported by his argument that the concepts of mass and of space-time measurements of the two theories involved in the two theories are incommensurable. In the third section, two different attempts to show formal continuities between classical and relativistic physics will be considered: (1) the existence of a limiting relationship between the equations in Newtonian and Einsteinian physics (Zahar) and (2) the extension of covariance, which requires the equations expressing the laws to be satisfied in all inertial coordinate systems (Friedman). I will argue in this section that these two formal properties are insufficient to capture the essential elements of an acceptable evolutionary account of the development of the special and the general theories of relativity. In the fourth section, a case for the ontological continuity between the two theories based on a substantivalist interpretation of both Newtonian and relativistic space-times will be considered. In the fifth section, two cases for ontological discontinuity based on a substantival interpretation of Newtonian space-time and a relational interpretation of relativistic space-times will be examined. I will argue here that these interpretations of space-time have problems in that they miss the main objective of space-time theories, that is, the clarification of the relationships between the structure of space-time and the laws of motion. In the concluding section, I will argue that the lessons of this chapter are that the extent to which this theory-change was either continuous or discontinuous is best analysed from the structuralists' perspective, which can capture the real relationships between the structure of space-time and the laws of motion.

2. Kuhn's Scientific Revolution And Conceptual Changes in Einsteinian Physics

Thomas Kuhn famously argued in his *Structure of Scientific Revolutions* that there have been major discontinuous changes in the history of science. He explicitly cites the theory-change from Newtonian to Einsteinian physics as a case strongly supporting his claim. (Kuhn 1962)

The concept of paradigm in Kuhn's view plays a key role in characterizing the different stages of science. In the stable stage during which a specific scientific discipline matures, the discipline, which Kuhn calls a 'normal science,' "is predicated on the assumption that the scientific community knows what the world is like." (Kuhn 1962, 5) Scientists make great efforts to preserve this assumption, to the extent that "normal science often suppresses fundamental novelties because they are necessarily subversive of its basic commitments." (ibid.) Research within normal science is thus based on a 'paradigm,' which consists of the scientific community's metaphysics, conceptual frameworks, theories, methodology, and goals. A paradigm is essential to normal science, in that "no natural history can be interpreted in the absence of at least some implicit body of intertwined theoretical and methodological belief." (ibid., 16-7) Adopting a paradigm is "an attempt to force nature into the preformed and relatively inflexible [conceptual] box that the paradigm supplies." (ibid., 24) So, "[n]ormal-scientific research is directed to the articulation of those phenomena and theories that the paradigm already supplies." (ibid.)

However, with the advent of a crisis within the paradigm (if only in some vague sense) caused by the continuing failure to solve anomalies, the paradigm confronts challenges from competitors that question the fundamental assumptions underlying the earlier normal science: "[N]ature has somehow violated the paradigm-induced expectations that govern normal science. It then continues with a more or less extended exploration of the area of anomaly." (ibid. 52-3) And the "crisis may end with the emergence of a new candidate for paradigm and with the ensuing battle over its acceptance." (ibid. 84)

One of the competing paradigms, because of its success in solving the anomalies, attracts advocates who set the direction of their future research according to the new paradigm. "The transition from a paradigm in crisis to a new one from which a new tradition of normal science can emerge is far from a cumulative process ... Rather it is a reconstruction of field from new fundamentals, a reconstruction that changes some of the field's most elementary theoretical generalizations." (ibid. 84-5) A scientific revolution occurs when the new paradigm replaces the old one. One result is that different paradigms are "incommensurable" in their aims, conceptual frameworks, and even observational bases: "The normal-scientific tradition that emerges from a scientific revolution is not only incompatible but often actually incommensurable with that which has gone before." (ibid. 103) Kuhn's incommensurability thesis involves several radical claims – for example that even the empirical data for a given theory cannot be translated in a way that is neutral between competing paradigms:

> Scientists then often speak of the "scales falling from the eyes" or of the "lightning flash" that "inundates" a previously obscure puzzle, enabling its components to be seen in a new way that for the first time permits its solution. ... No ordinary sense of the term 'interpretation' fits these flashes of intuition through which a new paradigm is born. Though such intuitions depend upon the experience, both anomalous and congruent, gained with the old paradigm, they are not logically or piecemeal linked to particular items of that experience as an interpretation would be. Instead, they gather up large portions of that experience and transform them to the rather different bundle of experience that will therefore be linked piecemeal to the new paradigm but not to the old. (ibid., 122-3)

In order to support his revolutionary view, Kuhn suggests that there were two separate aspects of the theory-change from Newtonian to Einsteinian physics that support the incommensurability thesis. These are the conceptual change in the meaning of notion of "mass" (ibid., 102), and the absence of any neutral observational basis to evaluate the strengths of the two theories due to the "theory ladenness" of the space-time measurements in the two theories. (ibid., 149-150)

In the next section, I will argue that these two claims fail to support the incommensurability thesis.[1] As for the conceptual change in the meaning of the notion of mass, we will see that the concept of "relativistic mass," which Kuhn claims to be incommensurable with its classical counterpart, is not in fact a

[1] My arguments against Kuhn's cases for incommensurable thesis are developed from Cho(1994)'s brief accounts.

physically meaningful concept at all. And in the case of space-time measurements, I will show that although such measurements are in a sense theory-laden, a neutral observational basis between the two theories can nonetheless really be secured.

1) The Case of the Concept of Mass

According to Kuhn, although the terms employed in Newtonian physics such as mass are also employed in Einsteinian physics, the referents of these terms are not the same:

> [T]he physical referents of these Einsteinian concepts [mass] are by no means identical with those of the Newtonian concepts that bear the same name. ... Only at low relative velocities may the two be measured in the same way, and even then they must not be conceived to be the same. (Kuhn 1962, 102)

In the same spirit, Paul Feyerabend pointed out:

> [I]n classical, prerelativistic physics the concept of mass (and, for that matter, the concept of length and the concept of time duration) was absolute in the sense that the mass of a system was not influenced (except, perhaps, causally) by its motion in the coordinate system chosen. Within relativity, however, mass has become a relational concept whose specification is incomplete without indication of the coordinate system to which the spatio-temporal descriptions are all to be referred. ... what is measured in the classical case is an *intrinsic property* of the system under consideration; what is measured in the case of relativity is a *relation* between the system and certain characteristics of [the coordinate system] D'. (Feyerabend 1962, 80)

Although the term 'mass' appears in both theoretical frameworks, the Newtonian mass of a body is the same irrespective of its state of motion, whereas the Einsteinian mass varies depending on the motion of a body relative to the frame within which its mass is measured:

> [T]he total mass of a system is not a scalar quantity in relativity theory, so that its value depends on the reference frame with respect to which it is measured. For example a particle

whose mass is m, as measured in its own rest frame, appears to have a larger mass when measured in a second frame with respect to which it is moving. (Penrose 2004, 435)

In other words, the Newtonian mass is a scalar quantity m, which is invariant under any coordinate transformation, while the Einsteinian mass (expressed as $M = \gamma m$, where γ is the Lorentz factor, i.e. $1 / \sqrt{(1 - v^2/c^2)}$) is a variable quantity which increases with the velocity v of the body.

Feyerabend claims that the change in the concept of mass shows that there are enormous difficulties in relating the two successive scientific theories:

> It is also impossible to define the exact classical concepts in relativistic terms or to relate them with the help of an empirical generalization. ... It is therefore again necessary to abandon completely the classical concepual scheme once the theory of relativity has been introduced ... Our argument against meaning invariance is simple and clear. It proceeds from the fact that usually some of the principles involved in the determination of the meanings of older theories or points of view are inconsistent with the new, and better, theories. (Feyerabend 1962, 80-2)

The concepts of classical and relativistic mass essentially belong in "different and incommensurable frameworks." (ibid., 81) In his recent book on concepts of mass, Jammer describes the relationship between the concepts of invariant and relativistic masses as "ultimately the disparity between two competing views of the development of physical science." (Jammer 1999, 61) Kuhn also sees this conceptual change as a classic illustration of the incommensurability thesis: "the normal-scientific tradition that emerges from a scientific revolution is not only incompatible but often actually incommensurable with that which has gone before." (Kuhn 1962, 103)

This case, however, fails to provide legitimate evidence supporting the occurrence of a radical conceptual change. Einsteinian relativistic mass cannot in fact be considered as a physically significant concept that is the counterpart of the Newtonian mass. In fact the former is not a legitimate physical quantity that respects the principles of special relativity. Kuhn explicitly takes the 'relativistic mass' $M = \gamma m$, which increases with the velocity of the body. Yet this concept of mass does not properly fit within the framework of special relativity.

The special theory of relativity is essentially based on two fundamental postulates: (1) all physical laws take the same form in all inertial frames, and (2) the speed of light is always the constant c in all such frames. From these two hypotheses, Einstein derived the coordinate transformation which implements the principle of special relativity.[2] As a result, these two hypotheses yield predictions about the kinematical effects of time dilation, length contraction, and the addition of velocities. On the basis of this kinematics, a dynamical framework can be developed by positing the concepts of mass and momentum. In this context, as the above expression suggests, one can employ the *relativistic* concept of mass M_{rel} while maintaining the *classical* concept of velocity v_{cla} (dx/dt) in order to relativitize the concept of momentum, i.e. $p_{rel} = M_{rel}v_{cla}$. In other words, the Newtonian momentum $(p_{cla} = m_{cla}v_{cla})$ is modified into the relativisitic expression by adopting the

[2] Accordingly, one of essences of the special theory of relativity is that "all natural laws must be so conditioned that they are covariant with respect to Lorentz transformations." (Einstein 1940, p.329)

relativistic mass (rather than by changing labaratory time dt to proper time $d\tau$), i.e., $\gamma m dx/dt$. At this point, however, one is forced to adopt a primitive concept of improper 4-velocity, which is not Lorentz covariant. (Oas 2006, 4) "The improper velocity being a direct result of the imposition of RM [the relativistic mass] means that RM is at odds with the accepted kinematics of special relativity." (ibid.)

In a similar spirit, Wheeler and Taylor claim that:

> Any difference between [relativistic] formulae for momentum (for example, $mdx/d\tau$) and the corresponding Newtonian formula (mdx/dt) is therefore to be attributed to the difference between proper time and laboratory time, not to any difference in the value of m in the two descriptions of nature. (Wheeler and Taylor 1963, 108)

Given that the Lorentz factor $1/\sqrt{(1 - v^2/c^2)}$ measures the ratio between laboratory time and proper time, modifying the kinematical concept of velocity dt to $d\tau$ is more natural than modifying the concept of mass. So, in order to be consistent with the kinematics of special relativity, the Lorentz factor $1/\sqrt{(1 - v^2/c^2)}$ needs be associated with velocity, rather than with mass. This is expressed by Resnik as follows:

> Indeed, it should be noted that, whether we identify the factor $1/\sqrt{(1 - v^2/c^2)}$ with mass or with velocity, the origin of this factor in collision measurements is kinematical; that is, it is caused by the relativity of time measurement. (Resnik 1968, 199)

Because of this, Einstein himself considered the rest mass m as the only physically significant concept, and substituted the energy-momentum 4-vector for the relativistic mass. Thus he wrote:

> It is not good to introduce the concept of the mass $M = m / \sqrt{(1 - v^2/c^2)}$ of a body for which no clear definition can be given. It is better to introduce no other mass than 'the rest mass'

> m. Instead of introducing M, it is better to mention the expression for the momentum and energy of a body in motion.[3] (Einstein 1948, a letter to Lincoln Barnett)

In the special theory, just as space and time are incorporated within the single entity space-time whose components are $(t, \mathbf{x})$, so energy and momentum are united to form the energy-momentum 4-vector whose componets are $(E, -\boldsymbol{p})$. This quantity satisfies a conservation law, which, given the equivalence of energy and mass, incorporates the law of mass conservation, the law of energy conservation, and the law of momentum conservation. The squared magnitude of this four-vector represents the rest mass, $m^2 = E^2 - p^2$, which is invariant regardless of the choice of inertial frames. In this context, 'relativistic mass' is only the temporal component of the energy-momentum 4-vector of a given body. This single component is measured as being larger in motion than when the body concerned is at rest. However, all four components of the energy-momentum 4-vector are transformed in the proper way to maintain the vector's invariance under the change of the reference frame. So, although the single component varies, there is no sense in saying that the mass also varies. Along these lines, Wheeler and Taylor's answer to the question "is the mass of a moving object greater than the mass of the same object at rest?" is "no":

> The concept of 'relativistic mass' is subject to misunderstanding. That's why we don't use it. First, it applies the name mass – belonging to the magnitude of a four-vector – to a very different concept, the time component of a four-vector. Second, it makes increase of energy of an object with velocity or momentum appear to be connected with some change in internal structure of the object. In reality, the increase of energy with velocity originates not

[3] The relativistic mass, according to Adler, is employed only in the popular literatures, because it is intuitive and based upon simple mathematics. An example can be found in Hawking's *A Brief History of Time*: "Because of the equivalence of energy and mass, the energy which an object has due to its motion will add to its mass." (Hawking 1988, 20) And Feynman's *The Character of Physical Law* is another: "The energy associated with motion appears as an extra mass, so things get heavier when they move." (Feynman 1965, 76) But the concept does not appear in research articles and advanced textbooks written by the same authors.

> in the object but in the [kinematical] properties of space-time itself. (Taylor and Wheeler 1992, 250-1)

It seems that Kuhn's reading of the concept of mass is mistaken.

Defenders of Kuhn's thesis that radical change is involved in this shift could respond that although Kuhn may have misunderstood the way in which the concept of mass is radically transformed, adopting the concept of energy-momentum still shows that the concept of 'mass' experiences radical change. But, this response is not tenable. When the relativistic mass is replaced by energy-momentum 4-vector, it is the commonality between Newtonian and Einsteinian physics that becomes manifest – from the perspective of their group structure. The geometric properties of space-time consist of a topological Lie group[4], which involves the transformations of rotations, boosts and translation on $\mathbf{R}^4$. The concept of energy and momentum, within this framework, arise as the generators of transformations on the group of translations. Whilst this group in the relativistic case is the Lorentz group, the corresponding group in the non-relativistic case is the Galilean group. In both cases, the concept of energy, which is used as total relativistic mass, appears as the generator of time translations. In this context, Saunders views the relationships between the concepts of the rest mass in both physics as involving the group structure:

> The non-relativistic mass, in contrast, has a quite different interpretation ..., bound up with more detailed properties of the respective Lie algebras: in the case of the [inhomogeneous

[4] A Lie group is a topological group G whose group elements of some neighborhood $N_o\, G$ can be mapped homeomorphically on to an open, bounded subset of the real Euclidean space $\mathbf{E}_n$ for some n.

> Galilean group], to the 'neutral elements' of the algebra (it therefore defines the momentum and the energy in conjunction with the velocity); in the relativistic case to the Casimir invariants (a function of elements of the Lie algebra, not a separate element). In both cases these quantities have vanishing Lie bracket with every element of the Lie algebra; they are therefore conserved. One has a quite reasonable understanding of their inter-relationships as provided by the theory of group contractions. (Saunders 1993, 304)

So, by introducing the concepts of the energy-momentum 4-vector and the rest mass, the relationships between the concepts of mass can be captured. The relativistic mass, is neither a proper counterpart of the Newtonian mass nor a legitimate physical quantity that respects the principle of special relativity. Accordingly, Kuhn's attempt to use the concept of mass to support the occurrence of a radical conceptual change does not succeed.

2) The Case of Incommensurable Space-Time Measurements

While the above case for the revolutionary conceptual change in the notion of mass is not supported by space-time geometry, Kuhn's other case for the incommensurability thesis as applied to the Newton-Einstein shift is concerned with an alleged conceptual change in the notion of space-time itself. In the rest of this section, I will argue that this case also in fact fails to show that the development of Einsteinian physics was revolutionary.

According to Kuhn, given that the concept of space and time provides the foundation of both Newtonian and Einsteinian physics, the change of these concepts generates a revolution in the conceptual network. The transition from Newtonian to

Einsteinian physics can be characterized as a holistic one in the sense that it involves changes in a range of other interrelated concepts:

> To make the transition to Einstein's universe, the whole conceptual web whose strands are space, time, matter, force, and so on, had to be shifted and laid down again on nature whole. (Kuhn 1962, 149)

Within Newtonian physics, simultaneities and temporal intervals between any two events are all absolute in that they are the same for all inertial observers. In other words, two events that are simultaneous for an inertial observer are simultaneous for any other inertial observer regardless of her relative motion, and the same holds for temporal intervals. Spatial intervals between two simultaneous events are also absolute. Within Einsteinian physics, on the other hand, simultaneity, and both temporal and spatial intervals between any two events are all relative to the motions of inertial observers.

Kuhn maintains that these differences between the two theoretical frameworks show that the conceptual change involved was revolutionary. Advocates of the competing paradigms, according to Kuhn, experienced a "transition of vision," which meant that the two sets of scientists observed totally different worlds:

> 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. (ibid., 150)[5]

[5] This clearly separates Kuhn's revolutionary view from any evolutionary view. The latter must maintains that the realtivistic modifications of kinematic and dynamic concepts conserve or quasi-conserve essential observational and theoretical components of Newtonian physics. An evolutionary view, for example, claims the continuity of relativistic kinematic and dynamic concepts in the classical limit.

First of all, we need to ask what the occurence of this "transition of vision" exactly involves in this context. In the aforementioned first quotation, Kuhn suggests the occurrence of a change in the relationship between the fundamental conceptual elements, i.e. a structural change of the whole conceptual network. And the second quotation refers to a change of empirical substructures as a result of the conceptual change. So, given that measurements are essentially interwoven within different space-time concepts, they cannot provide a neutral basis from which to evaluate the relative empirical strengths of the two theories. Accordingly, the incommensurablity thesis involves the claim that no neutral observational basis exists due to theory ladenness.

Kuhn's conclusion is based on two premises, (1) the revolutionary conceptual change in notions of space and time, and (2) theory-ladenness of the measurements highlightened by those conceptual changes. From these two premises, Kuhn concludes that no neutral observational grounds exist for comparisons between the measurements in Newtonian and Einsteinian physics.

Two strategies might be employed to undermine Kuhn's argument. The first is to undermine one or both of the above premises. The second strategy is to argue that Kuhn's conclusion cannot be guaranteed even if we accept both premises. We will choose the second strategy. In this section, we will not attempt to undermine either the claim of the revolutionary development of the concept of space and time, or that of the theory-ladenness of the measurements based on the two different space-time theories. The strategy is instead to employ the very weapons of Kuhn's own argument. What will be argued is that *even if* we admit that radical conceptual changes occurred in the notions of space and time and we accept the theory-ladenness of the measurements at issue, there still exists a neutral observational basis from which to evaluate the relative evidential strengths of Newtonian and Einsteinian physics.

We need first to take a close look at the way Kuhn's premises can be understood within the context of this theory-change. As for theory-ladenness, the measurements of length are, as both sides agree, made with rigid rulers. It seems that all that the measurements with the rulers show is that if their two arms were aligned, their ends would coincide. How, then, can they be "theory-laden"?

Yet, it can in fact be argued that measurements with these instruments are dependent on a specific space-time theory, given that the length and interval of a rigid ruler and a clock are interpreted differently with respect to the two possible embedding theories. This is because the embedding theories are concerned with the spatio-temporal intervals between events themselves. Given that the length of two different ends of the rigid rods represents the relationships between two different spatio-temporal events, it could be differently interpreted with respect to different space-time theories. The length of a rigid ruler and the interval measured by a clock, according to Newtonian physics, are interpreted as invariant irrespective of their state of motion. On the other hand, within Einsteinian physics, the same instruments are posited as possibly experiencing length contractions due to their state of motion.

If, on the contrary, the measurements of spatio-temporal intervals employ instruments such as a light pulse and a clock, then theory-ladenness of spatial measurements occurs in the opposite way. Geroch shows how the measurement of spatio-temporal intervals is possible with light pulses and clocks. (Geroch 1981, 69-72) Light pulses can be employed to probe space-time because "light, once emitted, moves within the environment of space-time, independently of what the emitter was doing." (ibid., 72) And by employing mirrors, "one can arrange for the light to get back to us to tell us what space-time is like" (ibid.). Observers who carry a clock with them can evaluate the spatio-temporal intervals between the observer and a specific event by evaluating the time it takes for the light sent by them to be reflected back from the event. The clocks carried by moving observers are obviously neutral between Newtonian and Einsteinian theories. Within the latter framework, the temporal intervals of the clock are distorted only when an observer measures the clocks of the others which are in motion relative to the observer. In the case of measuring the observer's own clock, its measurement results will be identical regardless of whichever theory it is based on. Yet, the light pulses are laden with a specific space-time theory here. According to the special theory of relativity, the speed of the light pulses is constant regardless of the motion of an observer relative to the light source. Yet, in Newtonian physics, the speed of light pulse is posited to change depending on the observer's motion with respect to the light pulse. Given that the dimensions of the same instruments for the measurement of spatial intervals are differently interpreted in different theories, it seems that the instruments do not provide a neutral observational basis between the two theories.

Consider, for example, the Michelson-Morley experiment. This experiment was designed to measure the effect of the ether on the speed of light pulses. To detect this effect, the apparatus is equipped with an interferometer, which is posited as being at rest with respect to the earth moving through the ether. The idea of the experiment is to compare the speed of light pulses moving through the ether frame with the speed of light pulses perpendicular to the frame. By using half-silvered mirrors, light pulses are reflected to travel back and forth along two different directions, once along the direction of motion of earth and once at right angle to that motion. Although this experiment was originally designed to measure the speed of light with respect to the frame of ether, we can also employ this experiment in order to examine whether or not Lorentz contraction occurs. The occurrence of length differences for these two distinct round-trip journeys can be employed as an appraisal of Newtonian and relativity theories. In this experiment, the existence of a length contraction of the interferometer arms is a component that plays a crucial role in producing the length difference of the two round-trip journeys, which is the key to the appraisals of Newtonian and Einsteinian physics. When this experiment is prepared, an ordinary ruler is employed to determine the lengths of the interferometer arms. We also could think of the case that the experimental design employs light pulses and clock in order to determine the lengths of the interferometer arms. In both cases, when one assumes that the ruler (or light pulses and clock) can be employed to determine the lengths of the arms, one assumes the very theory to be appraised. (Laymon 1988, 250) The former case employing the ruler assumes that there does not exist Lorentz contraction effect, while the latter using light pulses assumes the opposite. Then, do the difference of the concept of space-time and the theory-ladenness of space-time measurement guarantee the incommensurability Kuhn suggested?

My answer is 'no.' Although we admit that a component of the experiment is theory-laden as mentioned, this experiment still produces a neutral observational basis for the appraisal of Newtonian and Einsteinian physics. Consider the lengths of round-trip journeys that are experienced by (1) the light pulses moving through the ether frame and (2) the light pulses moving perpendicular to the frame. In the original experimental setting, where c and v are the velocity of light and the earth in its orbit respectively and D is the distance of interferometer arm length, (1) is calculated as $2D/(1 + v^2/c^2)$, while (2) is $2D(1 + v^2/c^2)^{-1/2}$, which is $2D(1 + (v^2/2c^2))$ if terms higher than $(v/c)^2$ are neglected.[6] As Michelson and Morley rotated the

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[6] Let T = time light occupies to pass from a to c, and T_1 = time light occupies to

whole apparatus through 90°, the predicted displacement of the interference fringe becomes $2D(v^2/c^2)$. (Michelson and Morley 1887, 336)

In order to consider the possibility of the Lorentz contraction of the interferometer arms, we can consider a modified analysis of the result of the experiment, which assumes that the interferometer arm lengths can vary. (Silverstein 1914) In other words, the interferometer arm that is parallel to the motion through the ether frame experiences Lorentz contraction. According to Laymon, whichever theory we employ, the length of the two paths of the light travels in the two different directions, is calculated as the same, if terms higher than $(v/c)^2$ are neglected. (Laymon 1988) The existence or non-existence of contraction of the moving ruler by no means influences the anticipated effect of the difference of the lengths of the two paths. This result stems from the fact that the final outcome is a function of the sum of the lengths of the two interferometer arms, i.e., the lengths of arms initially parallel and the lengths of arms orthogonal to the direction of motion. Let the length of the former be D_h and the length of the latter be D_v. Given a 90° rotation of the interferometer, the anticipated path length change is $\beta^2(D_h + D_v)$ where β^2 is v^2/c^2, which is a function of the sum of the interferometer arm lengths. When we assume the hypothesis of Lorentz contraction to decide the length of the rulers, the corrected D_h, when an ordinary ruler yields a value of 11 meters for both D_h and D_v, D_h is

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pass from c to a_1. Then, T is calculated as $D/(c - v)$, and T_1 is calculated as $D/(c + v)$. And the whole time of the round-trip is $T + T_1 = 2D/(c^2 - v^2)$. So, the lengths of round-trip journeys i.e. (1) is $2D/(c^2 - v^2) = 2D/(1 + v^2/c^2)$, neglecting terms of fourth order. The length of the round-trip of other path is $2D(1 + v^2/c^2)^{-1/2}$, which is $2D(1 + (v^2/2c^2))$ if terms higher than $(v/c)^2$ is neglected.

calculated as $11(1 + v^2/c^2)^{-1/2}$. Ignoring higher order terms, D_h is obtained as $11(1 + v^2/2c^2)^{-1}$. Inserting this corrected value as an input value, the fringe shift becomes $2[11 + 11(1 + v^2/2c^2)^{-1}]\beta^2$. This then yields $2(11 + 11)\beta^2$ by expanding and ignoring terms of higher than second order. This is the same as the anticipated measurement in the case that no contraction of the ruler is assumed. So whether or not the length contraction is posited, the derived result of the fringe shift is the same. From this calculation, Laymon concludes:

> All of this means that while it is true that the actual length of the interferometer arms is a varying function of the very theories to be tested, when measuring that length the *computational* effect of assuming different theories from among the set to be tested is inconsequential. Hence, the phenomena (of fringe shift in rotating equal-arm interferometers) can be determined with an accuracy sufficient for testing the relevant theories *regardless* of which of the competing theories is chosen to specify the measurement procedures to be used to determine the experimental initial condition of length (Laymon 1988, 252-3).

We can see that, although a component of the measurement depends on a specific space-time theory, the experiments, whichever theories we employ, still provide a neutral observational basis for the appraisal of Newtonian and Einstein's physics. For the determination of the lengths of interferometer arms, despite being theory-laden, does not play a role in producing the anticipated effect of fringe shift.

It has been argued that Kuhn's incommensurability thesis is by no means supported by his own cases employing the concept of mass and space-time measurement in Newtonian and Einsteinian physics. Kuhn claims that the conceptual change in the notion of mass supports his incommensurability thesis. And also that this thesis is supported by the non-existence of a neutral observational basis for space-time measurements, stemming from the conceptual change in the notion of space-time.

However, as regards the first, it has been argued that the concept of "relativistic mass," which Kuhn claims to be incommensurable with its classical counterpart (classical mass), is not in fact a physically meaningful concept. And in the second case, it has been argued that although such space-time measurements are in a sense theory-laden, a neutral observational basis between Newtonian and Einsteinian physics can nonetheless really be secured. Accordingly, these two cases fail to support Kuhn's incommensurability thesis. Given that Kuhn's cases are used as crucial evidence for his claim that the shift from Newtonian to Einsteinian physics was revolutionary, my arguments provide reasons to doubt Kuhn's revolutionary account.[7] (Of course my main reason to Kuhn will be to develop and defend – later in this thesis – an 'evolutionary' view of this theory change which I argue is altogether superior to his revolutionary story.)

3. Evolutionary Views That Emphasize Formal Aspects of the Theory-Change

[7] Furthermore, we have seen that if one considers the group structure of various concepts of mass, the continuity between these concepts within this case of theory-change can be easily retrieved. And it will be argued in later section that the discontinuity of the concepts of space-time within the theory-change from Newtonian to Einsteinian physics, can be marginalized. And I will also argue here that the continuity within the laws of motion of the two theories can be considered as a more fundamental than the discontinuity in their structures of space-time. Taking all these into account, we can conclude that Kuhn's revolutionary account is by no means supported by his case from the theory-change from Newtonian to Einsteinian physics.

Kuhn's revolutionary view is, then, not supported by the case of theory-change from Newtonian to Einsteinian physics. It will next be argued that that change also fails to support the evolutionary views suggested by some contemporary philosophers. This section will consider evolutionary views that attempt to capture the continuity of theory-change from Newtonian to Einsteinian physics via the formal aspects of these theories. This view seems to reflect well the accounts in physics textbooks, in which the formal heuristics, such as 'the Newtonian limit' and 'the covariance principle,' connect Newtonian physics to Einsteinian physics. According to Rohrlich (1988), for example, a newer theory is related with a older one in a way that "[t]he mathematical framework of [the latter] is rigorously derived from that of [the former] (a derivation which involves limiting procedures)". (Rohrlich 1988, 303) Rohrlich emphasizes that physicists regards this formal aspect as the essential part of the relations between the two theories.

> Physicists, however, typically deduce *only the mathematical structure* of *S* from that of *T* and pay little attention to whether the concepts resulting from the physical interpretations of the symbols involved in those structures permit such a functional relation. They work largely intuitively. The mathematical structure or framework of the theory is considered to be primary, and the central terms (the meaning of certain central symbols) are later derived from the applications of that framework to actual situations. (ibid., my italics)

Batterman (1995) basically reiterates Rohrlich's view: "*only* the mathematical structures of the two theories can be related by this limiting derivational procedure" (Batterman 1995, 173), whereas "the interpretation and the ensuing ontologies [of the two theories] are in general not so related." (Rohrlich 1988, 303) This view maintains that the essential aspect of the continuity between the two theories occurs in the formal aspect of the mathematical equations of the two theories. We will see that this attitude can be found within various accounts which emphasize the continuity between Newtonian and Einsteinian physics, such as that of Hempel (1960), Zahar (1973) and Friedman (1983).

In this section, I will attempt to clarify what is in fact involved in this formal continuity. We will see that although it cannot be denied that the formal aspects provide important information concerning this theory-change, these formal properties are *not sufficient* to capture the essential elements of any evolutionary account of the development of special and general relativity from Newtonian mechanics. And this will be identified even in some of the aforementioned authors' writings. (Zahar 1973, 1989) There are four separate ways in which it has been claimed that formal relationships exist between the equations in Newtonian and in Einsteinian physics (i.e. "Newtonian limits" and "covariance principles" in special and general relativity). I will argue that none of these four ways succeeds.

1) The Correspondence Limit as A Formal Condition.

Logical positivists and their advocates emphasize the formal continuity that the correspondence relations exist between Newtonian and Einsteinian physics within the limit. Hempel writes his *Philosophy of Natural Science*:

> [The new] theory [in a scientific revolution] does not simply refute the earlier empirical generalizations in its field; rather, it shows that within a certain limited range defined by qualifying conditions, the generalizations hold true in fairly close approximation. (Hempel 1960, 76)

Despite his differences with the positivists on the generalization of theory-change, Zahar makes essentially the same claim (1973):

> [A] new relativistic law should yield the corresponding classical theory as a limiting case. In the most general case laws will involve the speed of light [c], the velocities $v_1, \ldots, v_n$ of a finite number of particles or processes ... If $R = 0$ and $K = 0$ are the relativistic and classical laws respectively, we require that:
>
> $R \rightarrow K$ as $(v_1/c, v_2/c, \ldots, v_n/c) \rightarrow (0, 0, \ldots, 0)$. (Zahar 1973, 244)

A successor theory is more comprehensive than the old one in that a limiting case of the former approximates the latter. The old theory is then, in this sense, a special case of the more comprehensive new theory. So, our case of theory-change seems to be an accumulative process.

According to Nickles too, the correspondence in the limit is the key aspect of "the reduction of the Einsteinian formula for momentum, $p = m_0 v / \sqrt{(1 - v^2/c^2)}$, where m_0 is the rest mass, to the classical formula $p = m_0 v$ in the limit as $v \rightarrow 0$." (Nickles 1973, 182) We can see the relationship from the expression of the Lorentz factor, i.e. $1 / \sqrt{(1 - v^2/c^2)}$, in the Lorentz transformation. As a Taylor series, the Lorentz factor can be expanded as $1 / \sqrt{(1 - v^2/c^2)} = 1 - 1/2\,(v/c)^2 - 1/8\,(v/c)^4 - 1/16\,(v/c)^6 - \ldots$. From this mathematical framework, we can consider the key expressions of the special theory of relativity as "Newtonian or classical quantities plus an expansion of corrections in powers of $(v/c)^2$." (Batterman 1995, 173) Consequently, Rohrlich claims that the mathematical framework of Newtonian mechanics is "rigorously derived" from that of the special theory of relativity in a "derivation which involves limiting procedures."[8] (Rohrlich 1988, 303)

Recall, however, that the mathematical formalisms themselves do not carry any physical meaning. The conceptual schemes which underlie the formalisms are surely necessary to comprehend the way these formalisms work within a specific physical theory.[9] A mathematical term such as the Lorentz factor is provided with empirical significance only within the theoretical framework of a specific theory. Lorentzian ether theory interprets the Lorentz factor as the effect of the contraction of matter moving through the ether, whereas special relativity interprets it as the modification of the spatio-temporal relations between events.

Furthermore, the limiting process imposes an empirical condition. The operation of neglecting higher powers of $(v/c)^2$ is based on the empirical consideration that the speed v of moving bodies is generally small with respect to the speed of light c. In this way, the limiting operation refers to the physical situation of a moving body. Hence, it seems that the limiting process also is not devoid of empirical content.

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[8] This relationships between the two theories are characterized as a formal one in that "the mathematical framework $M(T$ [the special theory]) implies $M(S$[Newtonian mechanics]) when the domain $D(T)$ is restricted to $D(S)$" (Rohrlich 1988, 303) where "D is given by the characteristic parameter [p] which provides the error estimate; if the error is negligable, one is within [$D(S)$]." (ibid., 305) This restriction then involves a limiting process: ($p \rightarrow 0$) $lim\ M(T) \rightarrow M(S)$.

[9] We can read this in Duhem: "If a physicist is given only an equation, he is not taught anything. To this equation must be joined rules by which the letters that the equation bears upon are made to correspond to the physical magnitudes they represent. And that which allows us to know these rules is the set of hypotheses and reasonings by which one has arrived at the equations in question. [This set of rules] is the theory that the equations summarize in a symbolic form: in physics, an equation, detached from the theory that leads to it, has no meaning." (Duhem 1902, 223)

At this point, defenders of the formal continuity can claim:

> The mathematical framework of [a older theory] is rigorously derived from that of [a newer theory] (a derivation which involves limiting procedures); but the interpretations and the ensuing ontologies [of two theories] are in general not so related. They involve qualitative differences and for this reason demand independent recognition. In this way, one comes close to Feyerabend's theoretical pluralism and at the same time one ensures a well-defined logical-mathematical linkage between [two theories]. (Rohrlich 1988, 303)

This view maintains that although we can admit that the mathematical structure involves more than the formal aspects, the essential aspect of the continuity between the two theories occurs within the formal aspect of the mathematical equations, whereas its conceptual aspects experience a radical shift.

But this view is not tenable. A central aim behind the limiting procedure is in fact to provide an empirical meaning for mathematical formalisms. Hence, the formal aspect is intricately interrelated with its empirical one. Before we examine this claim in the limiting process within the special theory, we first look at a similar case in the general thoery since the moral there is manifest. According to Renn and Sauer (1999), Einstein in fact useed the heuristics of the correspondence principle, i.e. the limiting procedure, to provide mathematical formalism with the empirical significance:[10]

[10] In this sense, Renn and Sauer characterize the heuristics of the correspondence as "the physical strategy," which starts from the well-known limiting case of the predecessor theory. "Along this strategy, Einstein sought to construct physically plausible generalizations whose specialization to the Newtonian limit was obvious." (ibid., 101) On the other hand, "a 'mathematical strategy' started from the requirement of the generalized relativity principle. The ground for pursuing this strategy had to be prepared by scanning the mathematical literature for suitable differential expressions with a well-known covariance group." (ibid.)

> Einstein ... required that the new theory would describe, under certain limiting conditions, the gravitational effects familiar from Newtonian physics. For this reason, he expected that the unknown gravitational field equation for the metric tensor would reduce to the Poisson equation for the scalar gravitational potential of the classical theory and that, under the same limiting conditions, the equation of motion of his new theory would yield Newton's second law with the force derived from this classical potential. ... We subsume these various demands under what we call Einstein's correspondence principle of general relativity. *The realization of this principle was a crucial condition for conveying physical meaning to the various mathematical constructs he elaborated since only in this way could they be brought into contact with the empirical knowledge imbedded in Newtonian gravitation theory.* (Renn and Sauer 1999, 99-100, my italics)

The empirical aspect involved in the correspondence principle can be shown through investigation of the so-called 'Newtonian limit' procedure within the general theory of relativity. Einstein's general theory is related to Newtonian gravitation theory by the formal procedure limiting the physical quantities to the empirical region where the effects specific to general relativity are small. According to the latter theory, the field equation is the Poisson equation $\nabla^2 \Phi = 4\pi G\rho$, that represents the distribution of a gravitational potential Φ due to the distribution of mass, when mass, the source of the potential, is distributed in continuous manner. And the equation of motion, which describes the trajectory of a test body influenced by gravitational field, can be written as $md^2x_i/dt^2 = -m\partial\Phi/\partial t$ (1). In contrast, the field equations in the general theory are Einstein's field equations $G_{ij} = R_{ij} - 1/2g_{ij}R = 8G\pi/c^4T_{ij}$, and the equation of motion is the geodesic equation $d^2x_i/d\tau^2 + \Gamma^i_{jk}(dx_j/d\tau)(dx_k/d\tau) = 0$ (2). In order to derive (1) from (2), we need the following physical hypotheses: *a*) the body moves at a speed that is negligible compared to the speed of light; *b*) the gravitational field that effects the body is very weak; *c*) the gravitational field is stationary, that is, the metric field is not changing with respect to time.

Under condition *a*), the equation of motion $d^2x_i/d\tau^2 + \Gamma^i{}_{jk}\,(dx_j/d\tau)(dx_k/d\tau) = 0$ (2) can be approximated to $d^2x_i/d\tau^2 + \Gamma^i{}_{jk}\,(dt/d\tau)^2 = 0$ (3), since $dt/d\tau$ is small compared to $dx/d\tau$. Under the condition *c*), the connection $\Gamma^i{}_{jk}$ can be rewritten as $\Gamma^i{}_{00} = -1/2\ g^{ij}\partial g_{00}/\partial x^i$ (i) because the derivative of g_{ij} with respect to t can be neglected. In addition, given the condition *b*), we can choose the coordinate where the metric g_{ij} is slightly different from the Minkowski metric η_{ij}, that is, $g_{ij} = \eta_{ij} + h_{ij}$. Since only η_{ij} contributes and h_{ij} can be neglected under the condition *b*), (i) becomes $\Gamma^i{}_{00} = -1/2\ \eta^{ij}\partial\eta_{00}/\partial x^i$ (ii). By inserting (ii) into (3), the equation of motion then become $d^2x_i/dt^2 = -1/2\ \nabla\ h_{00}$ (5).

At this point, (5) is "brought into contact with empirical knowledge imbedded in Newtonian gravitation theory." (ibid., 100) The comparison between (1) and (5) then gives $h_{00} = -\ 2\Phi + \mathrm{C}$, where C is an integration constant, and C = 0 in a boundary condition that both h_{00} and Φ approach 0 when r goes to infinity. In other words, (1) is approximated to (2) only when g_{00} is equal to $-\ (1 + 2\Phi)$. In this way, the unknown quantity g_{00} within the equation of general relativity obtains empirical meaning by referring to its classical counterpart, i.e. a variable specified by Newtonian gravity. So, in addition to the fact that each symbol has specific physical meaning[11], an apparently formal limiting procedure is intended as relating the

[11] It is apparent that the Newtonian limit procedure cannot be characterized as only a formal one. Instead we can see that various physical concepts and empirical conditions are also involved

symbols with empirical quantities which are well-confirmed by Newtonian mechanics. Along these lines, Renn sees more continuity between the two theories than Rohrlich identifies in the formal aspect:

> In fact, essential relations between fundamental concepts such as field and source largely persist, even though the concrete applications of these concepts may differ considerably, as in the case of a classical vs. relativistic field equation. *This structural stability turned the concepts and principles of classical and special relativistic physics into heuristic orientations when Einstein entered unknown terrain, for instance, when encountering a new expression generated by the elaboration of a mathematical formalism. None of these expressions in themselves constituted a new theory of gravitation.* Only by complementing them with additional information based on the experience accumulated, not only in classical and special relativistic physics, but also in the relevant branches of mathematics, could such expressions become candidates for a gravitational field equation embedded in a full-fledged theory of gravitation. (Renn 2005, 54, my italics)

The above account provides a clue to understanding the case of limiting procedures within the special theory. Just as the above procedures in the general theory provide mathematical formalism with empirical significance, so physics textbooks refer to the mathematical similarity between Newtonian mechanics and the special theory in order to show that mathematical terms, such as the Lorentz factor, are connected

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along with the mathematical formulae. First of all, the mathematical quantities and frameworks are used in order to represent physical quantities and models. In the above case, the mathematical quantities x and t represent kinematical concepts, i.e. the spatial and the temporal coordinates. Then the combination of the quantities constitutes the geodesic equation (2), which represents the equation of motion by means of the physical interpretation of the mathematical framework. Physical significance is given to the geodesic equation by interpreting the formula, that is, specifying which aspect of the world the formula represents. In this way, the mathematical formulae are employed in order to realize the physical concepts.

Secondly, the mathematical operations relate the mathematical frameworks to empirical conditions. In the above case, the limiting procedures that realize various physical hypotheses such as *a*), *b*), and *c*) provide the mathematical formulae with specific empirical conditions. The condition *a*) imposes an empirical condition justifies the neglect of the "relativistic effect" of the physical system, whereas the conditions *b*) and *c*) specify the empirical properties of the gravitational field which can be neglected in a non-relativistic system. Along these lines, the mathematical procedures implement empirical conditions by the physical hypotheses.

with empirical consequences that are well confirmed and already entailed by the predecessor theory.

The Einsteinian formula for momentum $p = m_0v / \sqrt{(1 - v^2/c^2)}$ is developed from the two principles of the special theory. And the fact that this formula converges to its counterpart within Newtonian mechanics secures indirect empirical support from the empirical confirmation of Newtonian mechanics. In this way, the formal aspect is intricately related with the conceptual aspect of a given theory. Accordingly, the formal aspect in the correspondence principle cannot completely capture the continuity between Newtonian and Einsteinian physics. Zahar captures the underlying reason as follows:

> It might be felt that there is nothing sacrosant about the correspondence principle. ... When scientists speak of past empirical successes, they have in mind *virtual* as well as *actually observed* facts. They think of smooth domains consisting both of presumed and of ascertained facts. They set out to account, not only for known isolated observations, but also for allegedly observed regularities. Such regularities are regarded as being approximately captured by existing laws. ... [I]t is still the case that the only way of getting at these *presumed* regularities is through continuity ... with past theories ... . (Zahar 1989, 20-21, original italics)

Accordingly:

> In all these cases we have to do with a syntactic-mathematical type of continuity which, coupled with the semantic stability of our observational language, entails continuity at the *empirical* level. (ibid., 19, italic my own)

2) The Covariance Principle as a Formal Condition

A more convincing case emphasizing the formal aspect of the continuity between Newtonian and Einsteinian physics seems to be the extension of the "covariance principle" involved in the theory-change. This principle has the formal feature that the equations expressing the laws of nature should be invariant under a given class of coordinate transformations. Friedman makes this clearly:

> Covariance ... is really *a property of formulations* of space-time theories rather than space-time theories themselves: it characterizes systems of differential equations ... representing the intrinsic laws of a space-time theory relative to some particular coordinatization in $\boldsymbol{R}^4$. (Friedman 1983, 213, my italics)

Along the same line, Zahar also claims:

> The new [Lorentz covariant] laws were mathematically derived from assumptions like the Relativity Principle which seem so *'formal' and innocuous as to be devoid of empirical content.* (Zahar 1973, 249, my italics)

Einstein in his landmark 1905 paper "On the Electrodynamics of Moving Bodies" viewed the extension of the covariance requirement as an essential heuristic: Maxwell's equations governing electro-magnetic phenomena are to be invariant in their form under a group of coordinate transformations specified by the principle of special relativity. Furthermore, Einstein considered the extension of the requirement of covariance to *all* coordinate systems (i.e. not just to the inertial frames) to be essential in the development of the general theory of relativity. It seems, then, that the extensions of the requirement of covariance are a central characteristic of the evolutionary development from Newtonian to Einsteinian physics:

> Einstein decided to treat *all* coordinate systems on a par and to impose a condition of *general* covariance on *all* physical laws. This condition, which is a *strengthening* of the requirement of Lorentz covariance (General Covariance of course implies Lorentz covariance), is an important element of continuity between the special and the general theories of Relativity. (Zahar 1973, 252)

The aim of this section is the same as one of the previous section – that is, to show that the formal aspect of covariance also falls short of giving an adequate characterization of the continuity involved in the theory-change. Janssen maintains that formal covariance by itself cannot distinguish Einstein's special relativity from Lorentzian ether theory. And in the case of general relativity, Friedman claims that despite the fact that the formal covariance of the general theory is same as that of its counterparts in Newtonian and the special theory, their physical significances are different. Hence, it is difficult to defend the view that the extension of the covariance requirement as simply a formal condition captures the essential aspects of the evolution from Newtonian to Einsteinian physics.

a. The Covariance Principle in Special Relativity: An emphasis on the formal property of covariance as the essential part of the development of the special and the general theory of relativity can be found in Einstein's writings:

> The content of the restricted relativity theory can accordingly be summarized in one sentence: all natural laws must be so conditioned that they are covariant with respect to Lorentz transformations. (Einstein 1940, p.329)

A specific principle of covariance requires the invariance of the laws of mechanics under coordinate transformations from one inertial coordinate system to another. In the case of Newtonian physics, the laws of mechanics hold with respect to a set of inertial coordinates, which are related through a group of Galilean transformations that implement the principle of Galilean relativity. But, Maxwell's equations are not Galileo-invariant. So, assuming that Maxwell's equations are correct, Einstein modified the coordinate transformations relating two inertial coordinate systems. With the introduction of the Lorentz transformations, the laws of electrodynamics take the same form with respect to all inertial coordinate systems, and hence the covariance of Maxwell's equations is established. In this way, Einstein's special theory re-establishes the principle of relativity in electrodynamics, and hence eliminates the preferred frame of reference, i.e. the absolute rest frame. In section two of "On the Electrodynamics of Moving Bodies," under the postulate that all physical laws take the same form under this coordinate transformation and the speed of light is always the constant *c*, Einstein derives the coordinate transformation implementing the principle of relativity of inertial motions. And sections six and nine of this paper show that the covariance of Maxwell's equations holds under the group of Lorentz transformations. It seems, then, that the extension of covariance to Maxwell's equations characterizes a sort of generalization from Newtonian mechanics to Einstein's special relativity.

But, it can be argued that the covariance principle has in fact empirical contents. We have seen in the last section that the procedure of requiring the 'Newtonian limit' is intended to relate mathematical quatities in relativistic theories with empirical quantities well-confirmed in Newtonian mechanics. In a similar manner, the apparently formal procedure of imposing covariance in fact starts from the corresponding laws in Newtonian mechanics. Accordingly, the covariance principle by no means involves only formal properties, since it provides a constraint over the entities involved in a physical law. We can see this in Zahar:

> Einstein based his heuristic on the requirement that all physical laws should be Lorentz-covariant; *i.e.* all theories should assume the same form, whether they are expressed in terms of x, y, z, t or in terms of x', y', z', t'. *But it would be practically impossible to discover new laws simply by looking out for all the equations which are covariant under the Lorentz transformation. A good method is to start from well-tested laws whose past success would anyway have to be explained by any new theory.* Thus the heuristic of Einstein's programme is based on two distinctive requirements: (1) a new law should be Lorentz-covariant and (2) it should yield some classical law as a limiting case. (Zahar 1989, 243, my italics)

Despite the aforementioned accounts of Friedman and Zahar emphasizing the formal aspect of covariance, it seems that both authors are well aware that the covariance principles in the development of the special and the general theory involves physical content. (We will see a paragraph where Friedman points out this in the next section.) Zahar writes:

> [O]n the face of it, the most distinctive requirement of Einstein's heuristic is empty ... . However, the requirement is trivialised only if one is allowed complete freedom in reformulating the law. If one is restricted to a given number of entities: $a_1, a_2, \dots, a_n$, then the covariant requirement, far from being empty, becomes a very stringent condition. ... *[I]n each particular case in which the heuristic is applied, the entities occurring in the covariant law are precisely those involved in the corresponding [and empirically well-confirmed] classical law.* (Zahar 1989, 110, my italics)

Based on Janssen's recent work on Lorentzian ether theory, there is an additional argument that the evolutionary process from Newtonian to Einsteinian physics cannot be completely captured by means of the formal aspect of covariance alone. In fact, the theory-change from Newtonian to Einsteinian physics is more than the formal extension of covariance requirement. This is because the formal aspect of covariance fails to capture the physical interpretation of Einstein's theory, given that it may have many different physical realizations. A supporting case is provided by Janssen, who points out that Lorentzian ether theory employs an identical mathematical structure which, however, has an interpretation quite different from that of Einstein's special relativity. (Janssen 1995, 2002b)

Lorentzian ether theory was proposed as an attempt to eliminate the inconsistency between the concept of a stationary ether and electrodynamics, both of which were then accepted physics. Electrodynamics predicts that light, as an electromagnetic wave, propagates at the constant speed of *c*. In the middle of the 19th century, it was widely assumed that light was propagated through a stationary medium known as the ether, with respect to which Maxwell's equations were assumed to hold. Given this assumption together with Newtonian kinematics, it can be inferred that the speed of light is not constant in a frame at rest with respect to the Earth. The Earth is moving with respect to the ether, and so the velocity of light with respect to the Earth is the vector sum of the velocity of the light with respect to the ether and the velocity of the Earth with respect to the ether. But the null results of a whole series of optical experiments attempting to detect the change of velocity of light seems to establish the constancy of the speed of light regardless of the motion of the light source.

Lorentzian ether theory attempted to resolve this inconsistency by assuming that the laws governing matter are Lorentz-covariant. Janssen characterizes this attempt by Lorentz as a combination of Newtonian mechanics and electrodynamics summarized in "the theorem of the corresponding states":

> [Lorentz] replaced the real space-time coordinates of an arbitrary inertial frame in Newtonian space-time by cleverly chosen fictive space-time coordinates that depend on the frame's velocity with respect to the ether. ... He likewise replaced the real electric and magnetic fields by fictive fields. In terms of these fictive fields as functions of the fictive space-time coordinates, Maxwell's equations hold in every frame in which the ether is either at rest or in uniform motion. ... This configuration of fictive fields translates into a configuration of real fields in the moving frame that is different from the configuration in the initial frame at rest in the ether. Lorentz referred to two such configurations of real fields as corresponding states, and to the mathematical result that if one is allowed the other also is as the *theorem of the corresponding states*. (Janssen 2002b, 424)

Lorentzian ether theory maintains a Newtonian view of *space-time*, but assumes that the laws governing *matter* are Lorentz-invariant. Furthermore, in order to eliminate *any* difference of interference patterns associated with the corresponding states (the so-called second-order effect), that might detect the Earth's motions with respect to the ether, Lorentzian ether theory interprets the theorem of the corresponding states as amounting to the contraction hypothesis:

> [A] matter configuration producing a certain field configuration in a frame at rest in the ether will, when the system is set in motion, change into the matter configuration producing the corresponding state of that field configuration in the frame moving with the system. (ibid., 425)

In other words, material bodies such as the interferometer arms employed in the Michelson-Morley experiment experience contractions by a factor of $\sqrt{(1 - v^2/c^2)}$ in the direction of their motion through the ether. As a consequence, this physical system modifies its shape and mass depending on the velocity of the system with respect to the ether. Lorentzian ether theory is thus able to explain by means of the contraction hypothesis why no effect of the ether can be detected.

According to Janssen, both Lorentzian ether theory and Einstein's special relativity employ an *identical* mathematical formalism despite their essentially different physical interpretations. (Janssen 2002) What the theorem of the corresponding states involves is essentially the Lorentz invariance of the laws governing matter. In other words, the fictive space-time coordinates and the fictive fields are introduced in order that Maxwell equations remain invariant under the group of Lorentz transformations. Hence, if we capture the essence of special relativity as a theory all of whose laws are Lorentz-invariant, we cannot distinguish Einstein's special relativity from Lorentzian ether theory.

These two theories are however importantly distinguished by their different interpretations of how the Lorentz invariance of laws is physically realized. Lorentz retained the kinematical properties of Newtonian space-time, and interpreted Lorentz invariance as stemming from the property of laws governing matter: the Lorentz-transformed quantities represent the modified configurations of matter in motion, which result in Lorentz invariance of the laws of nature. In other words, Lorentz viewed Maxwell's equations as holding with respect to the ether frame, and the configuration of the fictive fields as representing the modified configurations of matter in motion, which are different from its configuration at rest in the ether.

Einstein's interpretation, as Janssen sees it, is completely different in that it is founded on "a new concept of space-time." Lorentzian ether theory was supposed to reveal the motion of a body relative to the ether. Yet Einstein viewed the concept of the ether, which provides a preferred frame, as at odds with his belief that all inertial frames are equivalent. As a result, Einstein interpreted the very same formalism as a result of the kinematical properties of a new space-time, which stem from the principle of special relativity; the fictive fields in the theorem of the corresponding states are interpreted as the fields measured by inertially moving observers. In contrast with Lorentz's interpretation, Einstein interpreted Lorentz transformations as relating the space-time coordinates of one moving observer to those of another.[12] Accordingly, Lorentz-transformed quantities reflect different space-time coordinates measured by two observers in uniform relative motion. While Lorentzian ether theory is based on Newtonian space-time and Lorentz invariant laws governing matter, Einstein's special theory views both as founded on the kinematical properties of a new concept of space-time:

> From *a purely mathematical point of view*, Lorentz had thereby arrived at special relativity. To meet the demands of special relativity, all that needs to be done is to make sure that any proposed law is Lorentz invariant. Conceptually, however, Lorentz's theory is very different from Einstein's. In Einstein's theory, the Lorentz invariance of all physical laws reflects a new space-time structure. [On the other hand,] Lorentz retained Newton's conception of space and time, the structure of which is reflected in the invariance of the laws of Newtonian physics under what are now called Galilean transformations. (Janssen 2006, 5)

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[12] It seems that Einstein wrote in this spirit as follows: "the new feature of [the 1905 relativity theory] was the realization of the fact that the bearing of the Lorentz transformation transcended its connection with Maxwell equations and was connected with the nature of space-time in general." (Einstein 1955, a letter to C. Seeling)

Accordingly, from the perspective of the formal aspect of Lorentz invariance, Lorentzian ether theory cannot be distinguished from special relativity. However, Lorentzian ether theory and special relativity are essentially different theories. Accordingly, Einstein's special relativity amounts to more than just the theory that claims that all laws must satisfy Lorentz invariance. It follows that we cannot capture the essential feature of special relativity through the covariance principle alone. So, it can be concluded that the formal aspect of the covariance cannot completely substantiate any account of the development from Newtonian to Einsteinian physics as evolutionary.

b. The Covariance Principle in General Relativity: A similar moral can be drawn in the case of the general theory of relativity. By means of a formal principle of general covariance that requires the coordinate independence of the laws of physics, Einstein aimed to generalize the principle of relativity to apply to arbitrary coordinate systems including non-inertial flames. Einstein viewed the requirement of general covariance as a way to construct a theory realizing the generalized principle of relativity:

> The general laws of nature are to be expressed by equations which hold good for all systems of co-ordinates, that is, are covariant with respect to any substitutions whatever (generally co-variant).
>
> It is clear that a physical theory which satisfies this postulate will also be suitable for the general postulate of relativity. For the sum of all substitutions in any case includes those which correspond to all relative motions of three-dimensional systems of coordinates. (Einstein 1916, 117)

Under the influence of Mach's empricism, Einstein considered the concept of a preferred inertial frame (which enables us to define the concept of absolute motion) as epistemologically unsatisfactory, since such a frame could not be identified through any measurable observation. Accordingly, Einstein thought that a new theory of motion needed to be based on what was observable, i.e., relative motions. Given that both Newtonian mechanics and the special theory of relativity have this "epistemological defect" of admitting a set of preferred inertial frames, Einstein intended to develop a theory that did not refer to any preferred coordinate systems:

> Of all imaginable spaces R_1, R_2, etc., in any kind of motion relatively to one another, there is none which we may look upon as privileged *a priori* .... *The laws of physics must be of such a nature that they apply to systems of reference in any kind of motion.* Along this road we arrive at an extension of the postulate of relativity. (Einstein 1923, 113)

Just as the principle of special relativity eliminated the preferred inertial frames of electrodynamics, Einstein, by means of general covariance, intended to eliminate *any* preferred frame. Just as the relativity between inertial coordinate systems was achieved through the special theory, Einstein intended to generalize relativity to be applied to all arbitrary coordinate systems. In this way, acceleration could be viewed as being an artifact of the choice of the coordinate system. According to this account, it seems that the extension of covariance to non-inertial coordinates could be identified as the generalization of the principle of relativity to all frames of reference. The evolution from the special to the general theories can be characterized as the generalization of a relativity principle through extending covariance.

The above account of the development of general relativity, however, was not in fact fully realized as Einstein originally intended. Given that acceleration is still a physically significant concept in the general theory, general covariance by no means implements the generalized principle of relativity. While the concept of velocity is relativitized through the principles of relativity in Newtonian mechanics and special relativity, accelerating motions in the general theory remain as absolute motions. With reference to the local inertial frames i.e. a privileged subclass of frames, the concept of acceleration of a given body can be defined as the deviation from a geodesic trajectory of a free-falling body. None of the geodesic trajectories can be transformed into non-geodesic trajectories by means of coordinate change, and the distinction between the former and the latter is absolute with respect to coordinate change.[13]

Furthermore, although the formal role of covariance within the general theory of relativity is the same as the corresponding one within Newtonian mechanics and special relativity, the physical significance of covariance is interpreted as being distinct within the contexts of the different theories. The status of covariance in the general theory of relativity is complicated because the space-time it postulates is curved. To appreciate this, we need to separate the concept of an 'indistinguishability group' from a 'covariance group.' The latter characterizes the

[13] In this spirit, DiSalle views the principle of general covariance as based on the idea that "the privileged states of motion should not be mere artifacts of our coordinates, i.e. that they should be coordinate-independent." (DiSalle 2003)

range of coordinate systems where the equations representing physical laws of a given space-time theory hold. On the other hand, the former selects those "reference frames (states of motion) [that] are distinguishable (by a "mechanical experiment") relative to those laws." (Friedman 1983, 213) Hence, the latter is concerned with the formulation of a given theory, and the former is about the laws of that theory. Friedman claims that:

> "Sameness of form" (covariance) is much too weak to guarantee physical equivalence (indistinguishability) and therefore much too weak to express a relativity principle. The notions of "sameness of form" and covariance correspond to the notions of physical equivalence and relativity only in the context of flat space-time theories in which there exists a privileged class of inertial coordinate systems. ... But in non-flat space-time theories like general relativity these "nice" connections between indistinguishability and covariance break down. (Friedman 1983, 208)

While in Newtonian mechanics and special relativity, the covariance and the indistinguishability groups coincide, this is not the case in general relativity. The covariance group of the general theory is identical to the group of all coordinate transformations, whereas the indistinguishability group is the restricted group of transformations from one local inertial frame to another. The discrepancy between the two groups shows that the same mathematical requirement of covariance turns out to play different roles within the different theories. In the case of Newtonian mechanics and special relativity, where the flat space-time formalisms are available, their covariance implements the physical equivalence of inertial frames. Yet, in general relativity, without the existence of a privileged reference frame defined globally, covariance does not implement a relativity principle.

We have, then, considered four ways in which formal aspects of the relationships between Newtonian and Einstein physics by themselves do not supply physical interpretations that give information about the way the formalism represents the world. Accordingly, we cannot rule out the possibility that in spite of the continuity of mathematical formalisms, their conceptual interpretations could experience radical changes. The identical mathematical framework can have radically different interpretations. So, it seems that the mathematical continuity in theory-change as characterized so far is not inconsistent with conceptual discontinuity within the process.

4. Ontological Aspects of the Theory-Change of Space-Time Theories

A physical interpretation is, so I have argued, necessary to capture which physical aspect the mathematical formalism such as Lorentz covariance reflects. The accounts of Einstein and his commentators emphasize that the formalism is closely related to the structure of space-time. As noted in the previous section, Einstein pointed out that "the new feature of [the 1905 relativity theory] was the realization that the bearing of the Lorentz transformation ... was connected with the nature of space-time in general." (Einstein 1955) It was Herman Minkowski who first emphasized the importance of space-time within Einsteinian physics: "the Lorentzian contraction hypothesis is completely equivalent to the new conception of space and time." (Minkowski 1909) Among modern commentators, Satchel in his (1989) characterizes the essential feature of the development of special relativity as that of "the new kinematical foundation for all of physics inherent in Lorentz's ether theory." Thus, in order to comprehend the nature of the theory-change from Newtonian to Einsteinian physics, we need to shift our focus squarely to the conception of space-time, which underlies the mathematical formalisms of Newtonian and Einsteinian physics.

This section critically considers evolutionary and revolutionary views based on disputes over the ontological status of space-time.

The ontological status of space-time has been debated as a part of the "substance-relation controversy." The dispute is basically over the mode of existence of space-time.[14] *Substantivalism* is the view that space-time has an existence analogous to that of material substance. In contrast, *relationism* denies that space-time has an independent existence, and instead maintains that space-time is simply a set of relations between material bodies or physical events.[15]

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[14] The concept of space has always been at the foundation of theoretical frameworks seeking to comprehend the physical world, so that the mode of existence of space was discussed even before scientific theories of mechanics were developed. Plato in the *Timaeus* considered space a part of the physical world in that it 'exists always and cannot be destroyed' (Plato, 52b), while Aristotle seemed to oppose Plato's idea about the ontological status of space by insisting that place is not independent of matter (Aristotle, 208a 11-16). These metaphysical disputes, which appear repeatedly throughout the different contexts in the development of physical theories, can be understood as part of the debate between substantivalism and relationism.

[15] The substance-relation controversy can be traced in the work of Newton and Leibniz. According to Newton, space *exists* independently of material objects in the sense that place has its existence prior to its occupation by material objects: "we believe all those spaces to be spherical through which any sphere ever passes, ... even though a sensible trace of the sphere no longer remains there. We firmly believe that the space was spherical before the sphere occupied it." (Newton 1962, 133) Furthermore, space would still maintain its existence even if there were no

> The absolute-relational contrast represents a debate about the ontological status of space-time structure: whether theories ostensibly about space-time structure are merely theories about the spatio-temporal relations between physical objects, or whether they describe independently existing entities – space, time, or space-time – in which physical objects are located. (Friedman 1989, 62)

The nature of the theory-change from Newtonian to Einsteinian physics has often been discussed within this context. Substantivalism concerning both Newtonian and Einsteinian space-times entails that we can capture the continuity between them by means of the mode of existence of space-time as substance, which causes a given body to follow its trajectories according to laws of motion:

> [T]he metric field $g_{\mu\nu}$ of General Relativity is properly viewed as the modern representor of substantival spacetime. ... It determines the spacelike–timelike distinction, determines the affine connection or inertial structure of spacetime (i.e. defines which motions are accelerated and which are not), and determines distances between points along all paths connecting them. In all these ways, the metric is perfectly analogous to Newton's absolute space and time. (Hoefer 1998, 459)

On the contrary, the relationist interpretation of curved space-time in the general theory argues for the occurrence of an essential change of the mode of existence of

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material object in the physical world; "we can possibly imagine that there is nothing in space, yet we cannot think that space does not exist ..." (ibid., 137) Hence, given that space, as Newton pointed out, is *akin to* 'the nature of substance' rather than being exactly substantial like material objects, we may at least admit substantivalism as a claim that space is something *as real as matter.* The point is that although one cannot comprehend the specific mode of the existence of space, substantivalists still maintain the reality of space, i.e. existence itself, as a core of their agenda.

Leibniz can also be read as having his own different agenda concerning the reality of space. By criticizing Newton's idea of reality of space as a 'conceit of imagination', he claimed that "there is *no real space* out of material universe." (Alexander, 29) Instead, Leibniz provided an alternative understanding of the relational conception of space; space can be replaced as "something merely relative," which is "an order of the existence of things." For "space denotes in terms of *possibility*, and *an order of things* which exist at the same time, considered as existing together; *without inquiring into their manner of existing*." (ibid., 25) In modern terms, relationism asserts that there is no such thing as absolute reference frames and all that exists are relative reference frames defined with respect to material objects. Hence, we can read Leibniz not only as avoiding the need to be concerned with the mode of existence of space, but also as rejecting the reality of space itself.

space-time as compared to the classical theory. While space-time and matter in Newtonian mechanics and special relativity have independent existence, they do not have independent existence in the interpretation of space-time in general relativity, which "describes the world as a set of interacting fields including $g_{\mu\nu}$." (Rovelli 2001, 107)

In this section, it will be argued that these ontological interpretations concerning the mode of space-time fail to deliver an adequate account of the theory-change from Newtonian to Einsteinian physics.

1) Space-Time Substantivalism and An Evolutionary View of Theory Change

There are two different ways for substantivalists to attempt to underpin an evolutionary account of the theory-change. Firstly, space-time as the substantival entity "ether" might be alleged to provide the evolutionary element. (Einstein 1922) Secondly, the metric field $\boldsymbol{g}$ of the general theory might be alleged to be the successor of Newtonian space-time. (Hoefer 1996, 1998) This section will argue that the first alternative is an interpretation that has no physical foundation; while although the second one supports an evolutionary view, it does so only when the metric field $\boldsymbol{g}$ is viewed from the perspective of what space-time *does* (i.e., the codification of the behaviours of a body), rather than what space-time *is* (i.e., its mode of existence).

Although Einstein considered the ether as superfluous within the special theory, the existence of the ether became an issue when he attempted to capture the physical interpretation of the metric field ***g***. (Einstein 1922) In this context, the development of the concept of space-time is related to the mode of existence of the alleged substantial entity "ether":

> According to [the general theory] the metrical qualities of the continuum of space-time differ in the environment of different points of space-time, and are partly conditioned by the matter existing outside of the territory under consideration. This space-time variability of the reciprocal relations of the standards of space and time, or, perhaps, the recognition of the fact that "empty space" in its physical relation is neither homogeneous nor isotropic, compelling us to describe its state by ten functions (the gravitational potentials $g_{\mu\nu}$), has, I think, finally disposed of the view that space-time is physically empty. But therewith the conception of the ether has again acquired an intelligible content, although this content differs widely from that of the ether of the mechanical undulatory theory of light ... (Einstein 1922, 18)

Lorentz's ether theory assumes an ether pervading space, through which electrically charged particles move. The physical interactions between the ether and matter are governed by Lorentz's theory of electrons; the electrically charged particles generate excited states of the ether, corresponding to the electromagnetic fields. In comparison with mechanical theories that are interested in the mechanical properties of the ether, Lorentz's theory is based on the electromagnetic worldview, and all mechanical properties of the ether except its immobility are eliminated. Yet the electromagnetic ether can be interpreted as a substantival entity due to its interaction with matter.

Given that the ether is transparent to uncharged matter and is not influenced by the existence of matter, Lorentz's contemporaries identified the ether with empty space. In a similar spirit, Einstein stressed the roles of the ether in the development of relativity in "Ether and the Theory of Relativity." Here the evolution of both theories of relativity is described as the modification of the physical properties of the ether, which Einstein identified with the properties of space-time. First of all, Einstein viewed the ether as possessing the physical properties of Newton's absolute space. Accordingly, "Newton might no less well have called his absolute space 'Ether.'" (Einstein 1922, 17) Einstein indeed continued to discuss the development of the theories of relativity from the perspective of the change of the properties of the ether:

> [T]he special theory of relativity does not compel us to deny ether. We may assume the existence of an ether; only we must give up ascribing a definite state of motion to it, ... the ether of the general theory of relativity is a medium which is itself devoid of all mechanical and kinematical qualities, but helps to determine mechanical (and electromagnetic) events. ... the ether of the general theory of relativity is the outcome of the Lorentzian ether, through relativ[iz]ation. (ibid., 18-20)

The special theory of relativity is considered as removing "the last mechanical characteristic" of Lorentzian ether, "the ether velocity," without denying the existence of the ether itself. Given that in the general theory of relativity, Einstein attempted to relativitize all kinematical concepts, it seems, then, that the gradual modification of the concept of the substantival ether provides an evolutionary account of this theory-change.

Given that Lorentzian ether is identified with space-time, it is necessary to clarify in what sense the two entities are identified. In the history of the development of mechanics, two different properties of the ether have been identified with properties of absolute space. First, Lorentzean ether has been identified with absolute space since these entities have the property of absolute rest. According to Lorentz, absolute rest implies that the order of parts of the ether is unchanged with respect to its other parts:

> If for brevity's sake I say that the Aether is at rest, it is thereby meant only that one part of this medium is not displaced with respect to another and that all observable motions of the heavenly bodies are relative motions with respect to the Aether. (Lorentz 1895, 4, quoted from Rynasiewicz 1996)

The concept of absolute rest of the ether does not mean complete rest, which is vulnerable to the argument of infinite regress. As Rynasiewicz points out, "to speak of the absolute rest or motion of *X* would be to speak of *X*'s motion with respect to a *tertium quid Y*, and so on." (Rynasiewicz 1996, 289) In fact, this property is what Newton in *De Gravitatione* attributed to space. According to Newton, the order of the parts of space, which does not change, characterizes absolute space:

> It is only through their reciprocal order and position that the parts of ... space are understood to be the very ones that they truly are; and they do not have any other principle of individuation beside this order and position, which consequently cannot be altered. (Hall and Hall 1962, p.103, trans. by Torretti)

This property of the ether, that of being at absolute rest, can be considered as providing a privileged frame of reference, with respect to which the spatial distance between two events can be determined.

The second property that allegedly allows the ether to be identified with absolute space is as follows: absolute space can be identified with the ether because of its causal property of generating inertial structure. In other words, absolute space is a causally efficient entity – it causes material bodies to follow their trajectories in accordance with the laws of inertia and acceleration. From their reading of Einstein's works, Brown (2005) and Rynasiewicz (1996) claim that what Einstein had in mind when he claimed the identity of absolute space with the ether was the causal sense of absoluteness, rather than the existence of the privileged frame.

> The inertia-producing property of this ether [absolute space], in accordance with classical mechanics, is precisely *not* to be influenced, either by the configuration of matter, or by anything else. For this reason, one may call it 'absolute.' That something real has to be conceived as the cause for the preference of an inertial system over a non-inertial system is a fact that physicists have only come to understand in recent years. (Einstein 1924, Saunders and Brown eds. 1991, 15-16)

The causal property of the ether was characterized by Einstein as being causally absolute, i.e. as "having a physical effect, but not itself influenced by physical conditions." (Einstein 1921) And casual absoluteness is one of the elements that made Einstein modify the concept of space-time. For, "it is contrary to the mode of thinking in science to conceive a thing (the space-time continuum) … which acts itself, but which cannot be acted upon." (ibid., 55-6)

> Also, following the special theory of relativity, the ether was absolute, because its influence on inertia and light propagation was thought to be independent of physical influences of any kind. … The ether of the general theory of relativity … differs from that of classical mechanics or the special theory of relativity respectively, in so far as it is not 'absolute,' but is determined in its locally variable properties by ponderable matter. (Einstein 1924, Saunders and Brown eds.1991, 17-8)

It can be argued, then, that these causal properties of this inertia-producing entity illuminate "the gradual modifications of our idea of space resulting from the influence of the relativistic view point." (Einstein 1961, 161) This aspect seems to capture at least one important continuity in the theory-change from Newtonian to Einsteinian physics:

> The general theory of relativity formed the last step in the development of the program of the field-theory ... Space and time were thereby divested not of their reality but of their causal absoluteness – i.e., affecting but not affected – which Newton had been compelled to ascribe to them in order to formulate the laws then known ... [Thus] the elements of Newtonian theory passed over into the general theory of relativity. (idid., 254)

To the extent that the concept of ether experiences a modification of its central causal property in order to satisfy the action-reaction principle in the general theory, we can see the evolutionary development in the theory-change.

The above account of the conceptual development can also be further clarified from the viewpoint of the modern geometric formulation of space-time. Given that what was at issue concerning the physical properties of the ether is "the cause for the preference of an inertial system over a non-inertial system" [16], what Einstein referred to as the ether in classical dynamics was not the entire absolute space. Rather it is inertial structure within absolute space. In the modern geometric formulation of space-time theories, inertial structures are implemented by geometric entities, i.e., the four-dimensional affine connection in Newtonian space-time, and the connection and the conformal structure in Minkowskian space-time. The connections *determine*

[16] Einstein's expression that "the cause for the preference of an inertial system over a non-inertial system" implies that the ether generates a causal power to direct a given body to move in accordance to the laws of motion, such as the law of inertia and the law of acceleration.

the inertial trajectories of particles, and the conformal structure *determines* the propagation of light. So, it seems that the ether is viewed as substantial space, because both geometric entities can be seen as "inertia-producing entities."

Furthermore, the above causal account of space-time seems to reflect well the evolution of the general theory of relativity. The space-time metric field $\boldsymbol{g}$, which is interpreted as the ether, determines the connection ∇. A non-singular metric $\boldsymbol{g}$ uniquely determines the (torsion free) connection ∇, through the condition of metric compatibility $\nabla \boldsymbol{g} = 0$, which requires that the parallel transport of a vector should preserve its length. In other words, the metric compatibility condition, with the assumption of vanishing torsion, completely determines the inertial structure in the general theory. Accordingly, given that the inertial structure is determined by the metric field, which in turn is determined by material processes, it seems that the ether can be identified as substantial space-time, which realizes the action-reaction principle:

> I admit that the general theory of relativity is closer to the ether hypothesis than the special theory. This new theory, however, would not violate the principle of relativity, because the state of this $g_{\mu\nu}$ = ether would not be that of a rigid body in an independent state of motion, but every state of motion would be a function of position, determined through the material processes. (Einstein 1922, quoted from Rynasiewicz 1996, 295)

However, the problem with the above evolutionary view is that the causal element of space-time does not provide any physical foundation for the laws of motion. Despite the prevailing belief among the physics community of the time, the history of science seems to attest that the ether has not yet provided any physical mechanism whatsoever, which explicates the law of inertia. (Sklar 1972 and Hoefer 1998) Although it was widely believed that inertia could be explained by acceleration with respect to the ether, this turns out to be a merely "wishful thinking." (Sklar 1972, 289) Instead, the explanation of laws of motion is related to the kinematical properties of Newtonian space-time.

> How does the introduction of absolute space provide Newton with the wherewithal to explain the dynamical effects? Since the parts of absolute space endure through time, they provide a reference frame by which distance relations can be defined not only between bodies at a time but also between bodies at different times. ... [But] Newton's ability to account for inertial effects does not immediately depend on the postulation of space as a substance. Substantival absolute space serves only as a means of extending the domain of the distance relation to include pairs of nonsimultaneous events. (Maudlin 1993, 186-7)

In a similar vein, Brown claims that regarding absolute space as a substance is by no means essential in comprehending the workings of Newtonian physics:

> For Newton, the existence of absolute space and time has to do with providing a structure, necessarily distinct from ponderable bodies and their relations, with respect to which it is possible systemically to define the basic *kinematical* properties of the motion of such bodies. For Newton, space and time are not substances in the sense that they can act, but are real things nonetheless.[17] (Brown 2005, 142)

[17] The attempt to capture the substantiality of space is not completely supported by Newton's own characterization of the mode of existence of space. Substantival space is intended to provide a framework to capture the properties of space, but Newton claimed "it has its own manner of existence which fits neither substance nor accident." (Huggett, 110) It is argued that space is not substance in that it fails to pass the classical sense, since its existence depends on something else, which is God. And space is different from typical substances, such as mind and body, in that space is not active. At this point, we may at least admit that Newton thought of space as substance *metaphorically or analogically*, rather than literally, considering his remark that "[space] *approaches more nearly to* the nature of substance." (ibid., 111)

Along the same lines, DiSalle offers an argument that substantivalism fails to capture the way space-time explains the laws of motion.[18] The confusion underlying substantivalism, according to DiSalle, stems from the view that space-time is a substantial entity that causes a body to move in accordance with the laws of motion. He provides an analogy between space-time and Euclidean geometries to illustrate this point:

> To claim that space is Euclidean *only means* that measurements agree with the Euclidean metric; Euclidean geometry, if true, can't *causally explain* those measurements, because it only expresses the constraints to which those measurements will conform. (DiSalle 1995, 324)

And:

> Because the physical foundations of spatial geometry have been relatively clear, only a confused person would ask whether Euclidean geometry is really the cause of differences in length; that the differences can be measured, and that the measured results agree with the Euclidean metric, is all that anyone ever meant by the claim that space is Euclidean. ... [I]t is equally confused to ask whether spacetime is the cause of the distinctions between states of motion that its theory entails. (DiSalle 1992, 187)

In the case of Euclidean geometry, its geometric structure by no means causally explains its "laws" such as the Pythagorean theorem. Instead, the axioms of Euclidean geometry encode "the constraints to which those measurements will conform" (DiSalle 1995, 324). Accordingly, theories that assumes that physical space is Euclidean by no means imply that Euclidean space exists as a separate entity.

[18] It seems that the interpretation of absolute space as a causally efficient entity does not respect Newton's own intention: "[space is] not in the least mobile, *nor capable of inducing change of motion in bodies.*" (Newton 1962, 145) Newton certainly aimed to analyse the true motions by means of cause and effect, and made a distinction between absolute and relational motions with reference to absolute space. But it is not evident that an effect influencing bodies to follow inertial or non-inertial trajectories is actually caused by absolute space. What Newton mentioned is the fact that the true motion of bodies can be distinguished from relative ones by a certain effect, rather than that the effect of bodies is *caused* by a specific substantival entity: "the true and absolute circular motion of the water ... becomes known, and may be measured by this endeavour." It can be said then that the relationship between absolute space and the motions of body is one of supervenience, rather than one of cause and effect.

Instead, the success of Euclidean geometry stems from the fact that its laws codify physical measurements and processes. DiSalle then claims that the same thing can be said in the case of space-time theories:

> [T]he nature of spacetime is a question, not of whether a theoretical entity provides a causal explanation for appearances, but of whether the physical processes of measurement conform to geometric laws ... Spatial measurement has been *defined* by coordination with a basic physical process (motion of rigid bodies). (DiSalle 1995, 323-324)

No casual property of space-time then, according to DiSalle, elucidates the connection between the laws of motion and space-time. In the same vein, Brown points out that the causal property of space-time is superfluous[19], and even problematic in the general theory:

> In 1924, Einstein thought that the inertial property of matter ... requires explanation in terms of the action of a real entity on the particles. It is the space-time connection that plays this role: the affine geodesics form ruts or grooves in space-time that guide the free particles along their way. In GR, on the other hand, this view is at best redundant, at worst problematic ... For it follows from the form of Einstein's field equations that the covariant divergence of the stress-energy tensor field $T_{\mu\nu}$ vanishes, that object which incorporates the 'matter' degrees of freedom, vanishes. (Brown 2005, 141)

This line of thought can also be found in Hoefer's view, which holds that the continuity between Newtonian and Einsteinian space-time can be found within the metric field g of the general theory. When Hoefer claims that "the metric field $g_{\mu\nu}$ of General Relativity is properly viewed as the modern representor of substantival

[19] Along these lines, Brown and Pooley point out that the way that "all the free particles in the world behave in a mutually coordinated way" is a "*prima facie* mystery" in Newtonian mechanics (Brown and Pooley 2004, 4). They also claim that "to appeal to the action of a background space-time connection in which particles are immersed – to what Weyl called the guiding field – is arguably to enhance the mystery, not to remove it. For the particles do not have space-time feeler either." (ibid.)

spacetime" (Hoefer 1998, 459), it seems that he might advocate the traditional category of space-time substantivalism. Yet his argument shows that this is not in fact the case:

> [W]hy is it proper to view $g_{\mu\nu}$ as the representor of substantival spacetime? The metric's role is explicitly to give us the details of the structure of 4-D, curved spacetime. It determines the spacelike–timelike distinction, determines the affine connection or inertia structure of spacetime (i.e. defines which motions are accelerated and which are not), and determines distances between points along all paths connecting them. In all these ways, the metric is perfectly analogous to Newton's absolute space and time. (ibid.)

So, the metric $\boldsymbol{g}$ is by no means interpreted as "the representor of substantival space-time" because of the mode of existence of the entity. It is instead the commonality of function of the metric $\boldsymbol{g}$ which determines the space-timelike distinction and the affine connection of space-time. Hoefer admits that the general theory of relativity is "an awkward theory to comprehend using traditional [substantivalist] concepts of space-time." (Callendar and Hoefer 2002, 178)

Hoefer thus expresses his sympathy for DiSalle's view as "a realist about space (or space-time)'s structure, without making the mistake of inappropriate reification." (Callender and Hoefer 2002, 179) In fact, it is not difficult to find similarities between Hoefer's view and DiSalle's.

> Einstein believed in the reality of space-time, as ascribed in GTR by the metric field $\boldsymbol{g}$, because of its apparently ineliminable role in the *description* and *prediction* of metrical, inertial, and gravitational phenomena. (Hoefer 1996, 27, my italics)

> The metric ... serves to *define* absolute accleration and rotation, a function that Descartes's relationism could not allow any material thing, no matter how pervasive, to perform. (Hoefer 1998, 460, my italics)

> Absolute space ... is the theory that rest and motion can be distinguished; if we could *define* rest and motion physically so that they could be distinguished unambiguously, we would have a perfectly good reason to claim that physical events exhibit the structure of

> absolute space. We would not thereby be explaining that distinction, as Einstein thought. Instead we would only be using some physical distinction to define the difference between motion and rest. (DiSalle 1992, 187, my italics)

So, space-time exists not because of what it is, but because "space-time is [what] space-time does." (Hoefer 1996, 26)

From the above accounts, we can see that the affine connection, in opposition to Einstein's claim, is not in fact an inertia-generating entity in either Newtonian or Einsteinian physics. In other words, it is not a causally efficient entity whose geometric features causes material bodies to move in accordance with the laws of motion. Alternative accounts of the workings of space-time theory, which Brown and DiSalle suggest, will be left to the next chapter. In this context, it is enough to point out that it is not the mode of existence of space-time that explains the laws of motion. So, the causal assertions about space-time, in Kitcher's terms, are by no means "working parts," which "occur in problem solving-schemata." Rather they are *at best* "presuppositional posits" – "entities that apparently exist if the instances of the schemata are to be true." (Kitcher 1995, 149) Accordingly, we cannot expect that the causal properties of space-times provide an adequate evolutionary account of theory-change from Newtonian to Einsteinian physics.

2) Space-Time Relationism and A Revolutionary View of Theory Change

Another way in which a revolutionary account of this theory-change might be underwritten is by interpreting general relativity from the perspective of relationism. In this section, I argue that there are problems with this perspective too.[20]

Space-time relationists regarding the general theory, such as Smolin and Rovelli, draw our attention to an allegedly revolutionary change of the concept of space-time. While both Newtonian and Minkowskian space-times are considered as absolute in the sense that their existence is independent of the existence of matter, space-time in the general theory is interpreted as co-existing with matter. The ontological difference between the two space-times stems from two different theoretical perspectives. Rovelli summarizes the first perspective in a following way: space-time can be *identified* with the gravitational field since we can see the direct

[20] There is also a well-known failed argument for relationism, which argues that Einstein's general theory of relativity realizes Mach's principle that embodies relationists' agenda. It is now well-known that Einstein himself admitted that Mach's principle is not necessary and even inconsistent with general relativity. (Hoefer 1994) If Mach's principle were correct, in Newton bucket the effect of the shape of water surface would be identical whether the bucket or the shell is set rotating: the shape of water surface become concave in both cases. On the other hand, Newton's theory predicts that the rotating shell will have not any effect on the shape of the water surface. When Einstein attempted to determine the metric field of a rotating shell at its center, he calculated a shell which is rotating in Minkowski space-time. Although a tiny deviation from the metric field of Minkowski space-time is generated by the rotation of the shell, it was not enough to change the shape of water surface into concave one. (Janssen 2004)

Another problem occurs in a boundary condition. When Einstein calculated the metric field generated by the rotating shell around its center, he employed Minkowski space-time as a boundary condition of the situation. But at this point, he brought the assumption of absolute space-time back. For the boundary condition states that as the values of the metric field as we go to spatial infinity, space-time becomes flat. In this way, Mach's view is undermined by the fact that rotation is considered with respect to absolute space-time rather than other matter. (Sklar 1976).

We can also see the problem of Mach's principle from the fact that there exist non-flat solutions of EFE even when the energy momentum tensor is zero; that is, when there is no matter in the universe. (Earman 1986) What I am concerned with in this section is the attempts of more recent physicists as Rovelli and Smolin, who interpret the general theory as a relational theory.

influence of the latter on the former in physical equations. "Newton's background spacetime was *nothing but* the gravitational field! The stage is promoted to one of the actors.[21] ... [A]ny measurement of length, area or volume is, in reality, a measurement of features of the gravitational field." (Rovelli 2001, 107) Furthermore, the gravitational field has the same theoretical role as the

[21] This claim stems from the interpretation of the principle of equivalence. This is well reflected within Einstein's thought experiment concerning a freely falling person in an elevator, who cannot decide whether she is uniformly accelerating downward, or she is experiencing a gravitational field. The equivalence principle states that acceleration in Minkowski space-time is equivalent to experiencing the gravitational field, such that "in a sufficiently small area, inertia and gravitational forces cancel to any accuracy in a freefalling reference frame." (Rovelli 2004, 60) At this point, Rovelli provides two alternative interpretations of the principle:

> 1. as the discovery that the gravitational field is nothing but a local distortion of space-time geometry; or
>
> 2. as the discovery that *spacetime geometry is nothing but a manifestation of a particular physical field*, the gravitational field. (Rovelli 1997, 194, my italics)

Rovelli prefers the latter interpretation. So it seems that he considers the principle as implying space-time structure can be reduced to the property of gravitational interaction:

"Physical reality is now described as a complex interacting ensemble of entities (fields), the location of which is only meaningful with respect to one another. *The relation among dynamical entities of being contiguous ... is the foundation of the spacetime structure.* Among these various entities, there is one, gravitational field, which interacts with every other one and thus determines the relative motion of the individual components of every object we want to use as rod and clock. Because of that, it admits a metrical interpretation." (Rovelli 1997, 194, my italics)

However, we need to keep in mind that the above account is based on Rovelli's idiosyncratic reading of the equivalence principle, which replaces the traditional reading of the principle with a view to motivating his own approach of the quantum theory of gravity. Even Rovelli's first interpretation of the equivalence principle (the gravitational field is nothing but a local distortion of space-time geometry) is different from Einstein's equivalence principle. Rovelli's reading of the equivalence principle involves the reduction of space-time to the property of gravitational interaction. Yet, Einstein's own version of the principle does not necessarily imply that the former is reduced to the latter or the other way around. (Norton 1985, Janssen 2001) Einstein's own principle of equivalence relativitizes inertia (a space-time property), and gravity, rather than reducing one into the other. Einstein claimed that just as special relativity implies that the electric and the magnetic fields are special aspects of one entity called the electromagnetic field, so general relativity implies that the inertial structure of space-time and the gravitational field are both special aspects of the inertio-gravitational field.

electromagnetic field; "the gravitational field is represented by a field on spacetime, $g_{\mu\nu}$, just like the electromagnetic field A_{μ}. They are both *concrete entities*: a strong electromagnetic wave can hit you and knock you down; and so can a strong gravitational wave." (ibid.) In other words, space-time is relational in that general relativity "describes the world as a set of interacting fields including $g_{\mu\nu}$, and possibly other objects, and motion can be defined only by positions and displacements of these dynamical objects relative to each other." (ibid.)

The second perspective, through which the revolutionary feature within the theory-change is claimed, is the background-independent formulation of the general theory; if space-time in general relativity has no prior geometry, then this seems to make a radical difference from Newtonian space-time, whose geometry is absolute in that its spatio-temporal structure has fixed as being Euclidean[22]:

> The background arena in GTR is just *M* [the 4-dimensional differentiable manifold], which can have any of a huge variety of topologies, and whose only "absolute" features are 4-dimensionality and continuity. The rest of the spatio-temporal properties, geometric and inertial and temporal, are all encoded by ***g***, which is not fixed or prior but rather variable under the EFE. This looks extraordinarily promising from a relationist viewpoint: absolute space has finally been banished! (Callendar and Hoefer 2002, 174-5)

[22] The most often mentioned revolutionary feature in the general theory in contrast to its predecessors is its background-independence.

> [W]e motivated our discussion of manifolds by introducing the Einstein Equivalence Principle, or EEP: "In small enough regions of spacetime, the laws of physics reduce to those of special relativity; it is impossible to detect the existence of a gravitational field by means of local experiments." The EEP arises from the idea that gravity is universal: it affects all particles (and indeed all forms of energy-momentum) in the 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 conventional force.* (Carroll 2004, 151, my italics)

This section will criticize the above two relationist views, which claim to show that the theory-change from Newtonian to Einsteinian concept of space-time was a 'revolutionary' one.

(1) *Does the gravitational field (space-time) play the same theoretical role as the matter field like the electromagnetic field?*: Rovelli interprets the space-time metric as having an identical ontological status to that of matter fields. This is questionable because it neglects the unique role of the gravitational field. In this context, what is at issue is the commonality between the mode of existence of gravitational waves and matter. Rovelli interprets the commonality as one of ontological identity:

> A strong burst of gravitational waves could come from the sky and knock down the rock of Gibraltar, precisely as a strong burst of electromagnetic radiation could. Why is the first "matter" and the second "space"? Why should we regard the first burst as ontologically different from the second? (Rovelli 1997, 193)

It seems that gravitational waves and the matter field have ontological commonality in that they carry both energy and momentum, which are conserved through time. Given that the gravitational field represented by $g_{\mu\nu}$ is carrying gravitational energy-momentum just like the electromagnetic field $A_{\mu\nu}$ does, both fields are interpreted as concrete entities.

Although this view is widely held among current theoretical physicists, the potential destruction of the rock of Gibraltar by electromagnetic and gravitational radiation can be given different theoretical accounts. (Pooley 2002) The electromagnetic force maintains the rigidity of the rock by accelerating the pieces that constitute the rock away from their natural motion towards the common centre:

> When the rock is hit by a strong burst of electromagnetic radiation, the natural motions of the parts of the rock do not (significantly) change. Rather the parts of the rock are *differently* accelerated by forces that overcome the contracting forces between the parts of the rock. When the rock is hit by gravitational radiation, however, no additional accelerative forces are applied. Rather the natural motions are no longer towards the rock's centre but are radically divergent. So divergent, in fact, that the electromagnetic binding forces of the rock are no longer sufficient to accelerate the parts of the rock away from their natural trajectories. (ibid.)

While the electromagnetic *force* accelerates the pieces of the rock in different directions, the explanation employing the gravitational wave depends only on natural motions that follow the geodesic trajectories of the pieces of the rock.

Another difference between the electromagnetic and the gravitational cases can be identified in the mathematical formalism of the gravitational energy-momentum and the non-gravitational energy-momentum. The latter quantity is a tensor, while the former is not. Any physically meaningful quantities are supposed to be tensors that are invariant under the change of coordinate systems, with respect to which the physics of the system is described. In other words, physical quantities should be invariant irrespective of the choice of coordinate systems. Yet the gravitational energy-momentum does not pass this test since it is a pseudo-tensor, which is variable (and may even vanish) dependent on the choice of coordinate system.

A response to this difficulty might be that gravitational energy-momentum can be well defined in the case of local matter distributions in asymptotically flat space-time. In this case, the metric field can be decomposed into the Minkowski metric $\eta_{\mu\nu}$ and the metric perturbation $h_{\mu\nu}$, i.e., $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$. Given that the latter is written as a spin two field, the perturbation $h_{\mu\nu}$ is interpreted as the gravitational field that carries well defined energy-momentum. (Norton 2000)

> There is [a] circumstance in which the total energy of gravitational system such as a galaxy can be defined, even if there is considerable internal change in the galaxy. That arises when we presume that the galaxy sits within a spacetime that becomes asymptotically flat as we travel to spatial infinity. That is, if we are far enough away from the galaxy in all directions of space, we find ourselves in spacetime that comes arbitrarily close to the Minkowski spacetime of special relativity. In such a spacetime, we are able to define the energy of a system. We can use those abilities to define the energy of a distant galaxy, since we can treat that distant galaxy in largely the same way we would a distant object in special relativity. (Norton 2000, chapter 3)

Yet, this response cannot save Rovelli's interpretation. For given his account that "spacetime geometry is *nothing but* a manifestation of a particular physical field, the gravitational field" (Rovelli 1997, 194), Rovelli interprets the entire metric as 'material,' rather than only the local metric. (Pooley 2002)

Einstein also distinguishes the metric from the other matter fields due to their different theoretical roles. (Einstein 1923, Hoefer 1998) On the one hand, the matter fields exist *in* space and time. On the other hand, the metric is itself space-time. So, while the former, for example the electromagnetic field, can be removed from space-time, space-time does not exist if the metric field is eliminated. Hoefer cites a passage of Einstein's that make this point:

> [I]f we consider the gravitational field and the electromagnetic field from the standpoint of the ether hypothesis, we find a remarkable difference between the two. There can be no space nor any part of space without gravitational potentials [the $g_{\mu\nu}$]; for these confer upon space its metrical qualities, without which it cannot be imagined at all. The existence of the gravitational field is inseparably bound up with the existence of space. On the other hand a

> part of space may very well be imagined without an electromagnetic field ... (Einstein 1923, 21-3, quoted from Hoefer 1998, 459)

We cannot then justifiably base any claim of the ontological commonality between the metric and the electromagnetic field solely on the basis of the fact that both theoretical entities employ the field.

(2) *Does the background-independent formulation of space-time within the general theory show that the change from Newtonian theory to it was 'revolutionary'?*: Although Rovelli's claim is problematic, it seems that the background-independent formulation of space-time in general relativity provides a view that still provides a revolutionary account of theory-change from Newtonian to Einsteinian physics. Within Newtonian mechanics (and the special theory), space-time is absolute in that its spatio-temporal structure satisfying the laws of Euclidean geometry is fixed independently of the distribution of matter. In this framework, it is possible to determine the inertial trajectory of a given body with the construction of a preferred inertial frame that singles out an inertial observer who is unaffected by any force field. Inertial trajectories can be defined as straight lines with respect to the flat background geometry of space-time, whereas accelerated ones are defined as curved lines. Yet, this is not possible in the general theory. For the equivalence principle obliterates any preferred inertial frame, since the principle maintains that all bodies might experience acceleration due to the gravitational field. Accordingly, in the general theory, one cannot determine a background free from all force fields, with

respect to which inertial trajectories can be identified. In this sense, the general theory is characterized as a background-independent theory.

The background-independent formalism of space-time within the general theory of relativity, however, needs not be viewed as a revolutionary development with respect to its predecessors. For we can trace the continuity of the concepts of space-time between the general theory and its predecessors in three related ways. Firstly, the background-independent formalism of space-time is not implemented only in the general theory. Its predecessors, such as the Newtonian theory of gravity, can also accommodate their local space-time formalisms that are background-independent. Within the Newtonian theory of gravity, the non-inertial motion of a given body is described as a trajectory deviating from a geodesic, whose curvature measures the total force relative to its mass. Here immutable space-time plays a role of background with respect to which the straight or non-straight trajectories are determined. Furthermore, the background space-time is posited independently of its dynamical structure, i.e. the gravitational potential, and the mass-density function. However, by considering Einstein's principle of equivalence, one can also construct a background-independent formulation of the Newtonian theory of gravity. The result is "the Newton-Cartan theory of gravity," which avoids the conventional decomposition into the flat space-time background and the gravitational potential. By absorbing the gravitational potential into the space-time connection, the flat background loses its meaning. As a result, the inertial and non-inertial motions within this framework are defined with respect to curved space-time, which is in turn dependent on the gravitational potential and mass density function.

Defenders of a revolutionary view might still claim that background-independence is essential in the general theory, while it is merely contingent in its predecessors. However, although it can be admitted that unlike its predecessors, the general theory is essentially background-independent, the continuity with its predecessor theories cannot be neglected. For the space-time of the general theory is also based on the metric field $\boldsymbol{g}$, which is *locally* Minkowskian. Accordingly, the motions in the general theory are not completely relative in the sense that motion is defined with respect to the metric $\boldsymbol{g}$, which is the successor of absolute space.

A revolutionary view could follow if the background-independence within the general theory were viewed as being concerned with the causal connections between space-time and the dynamical fields. Yet, as pointed out in the previous sections, this view is groundless. Whether or not the metric $\boldsymbol{g}$ is background-independent, its function in determining the spacelike-timelike distinction and the affine connection of space-time remains the same in the course of the theory-change. So, it is not by any means clear that the background-independence within the general theory provides a valid reason for thinking of the theory-change as 'revolutionary.'[23]

[23] At this point, it is enough to raise a reasonable doubt against a revolutionary view based on the background independece of the general theory. More detailed discussions will come in the chap. 4.

5. Concluding Remark: Lessons from This Chapter

We have seen, then, that Kuhn's revolutionary view is by no means supported by his own case for the incommensurability of the concept of mass and the space-time measurements based on Newtonian and Einsteinian physics. As Toulmin pointed out, although the conceptual changes in the development of new theories did indeed occur, Kuhn's interpretation seems to be exaggerated (Toulmin 1970, 45). Hence, Toulmin maintains that the historical processes of theory changes are not punctuated with such dramatic events as Kuhn suggests.[24] They are instead the results of "a sequence of greater and lesser conceptual modifications differing from one another in degree." (ibid.) This evolutionary account is also consistent with Einstein's own characterization of the development of the special and the general theories as 'a systemic development of electrodynamics' and 'a slight modification of Newtonian theory'.[25]

[24] Kuhn also attempted to moderate his holistic picture of theory change in order to avoid the criticism that even totally incommensurable theories can be compared: "Most of the terms common to the two theories function the same way in both; their meanings, whatever those may be, are preserved ... Only for a small subgroup of (usually interdefined) terms and for sentences containing them do problems of translatability arise. The claim that two theories are incommensurable is more modest than many of its critics have supposed." (Kuhn 1983, 670-1)

Kuhn calls this modest position 'local incommensurability,' which provides the common ground of the comparison throughout theory change: "The terms that preserve their meanings across a theory change provide sufficient basis for the dicussion of difference and for comparisons relevant to theory choice." (ibid., 671) In spite of offering this moderate position, Kuhn does not provide any specific case supporting his claim.

[25] In a similar spirit, Bell states, "I would emphasize the continuity with earlier ideas. Usually it is the discontinuity which is stressed, the radical break with more primitive notions of space and time. Often the result is to destroy completely the confidence of the student in perfectly sound and useful concepts already acquired." (Bell 1987, p.67)

However, the evolutionary views introduced in this chapter are also not free from deficiency. Two evolutionary views, formal and ontological, fall short of fully clarifying the aspects in which the theory-change can be characterized as being accumulative or quasi-accumulative. The mathematical formulae constituting Newtonian and Einsteinian physics do not carry physical interpretations that make sense of the way the formalism works, whereas the ontological interpretations of space-times overlook the main aim of space-time theories – that of clarifying the relationship between space-time and the laws of motion.[26] Hence, the essential problem of the two evolutionary views is that these views cannot clarify how the laws of motion are physically realized and are connected with the concept of space-

[26] The problems facing these two evolutionary views can be viewed from the semantic perspective of theory. Given that one theory can be considered from three different aspects i.e. formal, semantic, and ontological, it is important to comprehend their connections. So we need to approach our case of theory change by considering the relationships among these three distinct but related elements: (1) mathematical and formal structures constituted by meaningless symbols, (2) theoretical models whose mathematical structure acquires its physical meaning within a theoretical framework, (3) ontological schemes that elucidate the mode of existence of the elements which constitute the model.

What is deficient in formal and ontological schemes is the relationship between space-time and the laws of motion. And with respect to mathematical formalisms, it is necessary to retrieve information about the way the laws of motion are implemented. Given that these three elements, while influencing each other, have their own independent status and function within space-time theories, we need to assemble these missing elements to comprehend theory change from Newtonian to Einsteinian physics.

This approach can also be clarified if we distinguish various levels of the interpretations of a given space-time theory. An interpretation can be carried out not only (1) to clarify the *true nature* of space-times, but also (2) to elucidate the *structure of certain classes of models* satisfying a given mathematical structure of space-time. The latter is concerned with the relational structure of models that satisfy the mathematical structure of space-time, whereas the former is about the mode of existence of space-time. In our context, the problem of ontological interpretations can be described as the discrepancy of these two different levels of interpretation. In other words, the mode of existence of space-time becomes irrelevant to the contexts of space-time theory that shows the connection between the laws of motion and space-time geometry.

time. To sum up, the problems of views that emphasizes mathematical formalisms stem from their disregard of what the formalisms are about. On the other hand, ontological interpretations of space-time fail to capture what these formalisms are about. That is, these interpretations do not succeed in clarifying the relationships between the laws of motion and space-time.

In this context, it is worthwhile to note where the problems of the aforementioned ontological discussions lead us. As pointed out in the last section, the discussion about substantivalism is concerned with the function of the geometrical structure of space-time, rather than with the mode of existence of space-time. Also notice that the background-independent formulation of space-time in the general theory is concerned more with the geometric structure that enables us to define metrical and affine concepts, rather than with the issue of whether or not space-time has causal powers to produce dynamical effects. Along these lines, recent modified relationists, who emphasize geometrical relations rather than ontological features, claim that there is a structural commonality between substantivalism and relationsim. Paul Teller (1991), who suggests a "liberalized relationism," claims:

> [R]elationalists can express themselves with the same language as substantivalists by describing space-time relations in terms of an arbitrarily established coordinate system. ... [T]he liberalized relationists' appeal to the common theoretical vocabulary is committed to the same inertial structure to which substantivalists feel committed. But since the coordinate systems are now taken to describe actual and possible relations to actually existing objects, instead of objectively existing space-time points, we are free from concluding that the structure in question must be structure of something substantial. (Teller 1991 380-1)

Gordon Belot also takes a similar view focusing on the geometry of space-time:

> [C]ontemporary substantivalists and relationalists [can] agree about the structure of geometry of spacetime but disagree about the way in which geometry is instantiated. The substantivalist will think of it as describing the structure of the set of spatiotemporal relations between spacetime points, … . The relationalist will think of the geometry of spacetime as describing the network of geometric possibilities for spatiotemporal relations between material events. (Belot 1999, 46)

Interpreted this way, the substance-relation controversy shifts its focus from traditional ontological accounts that emphasize the mechanical origin of the metric ***g*** to ones that emphasize the geometric relations provided by the metric. In a similar spirit, Hoefer summarizes the above modified relationism from the structural perspective of space-time, rather than from the perspective of its ontological underpinning. These relationists see the metric field ***g*** (i.e. space-time) as providing "the structure of actual and possible spatio-temporal relations between material things," rather than "a Machian reduction of metrical structure to material relations (Callender and Hoefer 2000)." Accordingly,

> ***g*** is not a thing or substance. Where matter is present, it is crucial to the definition of local standards of acceleration and non-acceleration; *the EFE record just this relationship.* In many ways, the desires of traditional relationists (esp. Leibniz, Huygens, Mach) are – arguably – met by GTR when interpreted this way (ibid.)

We have seen that when Hoefer characterizes the metric ***g*** as "a representor of substantival space-time," his claim is also concerned with the geometric features of space-time (which determines the space-timelike distinction and the affine connection of space-time). In a similar spirit, modified relationism is concerned with which spatio-temporal relations between events are codified within the metric ***g*** that is specified by Einstein's field equations, rather than with the mode of the existence of space-time.

This direction is explicitly captured under the heading of structural space-time realism, which attempts to "capture the best assumptions up to now separately associated with substantivalism and relationism, that is, those assumptions ... [that] substantivalists and relativists must share (Dorato 2000, 1612). According to Dorato:

> [Structural space-time realism] sides with the relationists in defending the relational nature of spacetime structure, but joins the substantivalists in arguing that spacetime exists, at least in part, independently of particular physical objects and events, the degree of "independence" being given by the extent to which geometrical laws exist "over and above" physical events exemplifying them (ibid., 1605).

This view essentially claims that the relational features of spacetime structure are the essential elements of space-time theories in both Newtonian and Einsteinian physics. Accordingly, space-time structuralism attempts to capture what the formalism has essentially latched on. This view claims that it deals with the essential elements of the two physics, and accordingly, if true, can provide crucial information in order to appreciate in which aspect, if any, the theory-change was evolutionary. The next chapter will consider this possibility by examining the strengths and weaknesses of Dorato's space-time structuralism.

Chapter 2

Space-Time Structuralism from the Dynamical Perspective of Space-Time Theories

1. Introduction

The main lesson of the previous chapter is that in order to analyse our case of theory-change properly, it is necessary to clarify the relations between space-time and the laws of motion. This chapter attempts to develop a version of space-time structuralism that accomplishes this aim. It will provide a framework that will be employed to elucidate the sense in which there is indeed a continuity between Newtonian and Einsteinian physics in subsequent chapters.

I begin by analysing the strengths and shortcomings of Dorato's version of space-time structuralism. Dorato's account attempts to capture and combine the best features of both space-time substantivalism and relationism. One premise that Dorato sees as common to the two views concerning the mode of existence of space-time is the one that states that it is the nature of space-time that explains dynamical laws. However, we have seen in the last chapter that this idea about explanation is one of the major problems of substantivalism and relationism, as it fails to capture adequately the relationship between space-time structure and dynamical laws. Given that Dorato's strategy of developing his version of space-time structuralism retains this explanatory scheme, it still is afflicted by the major problem that faces the ontological perspectives. Addressing this problem will lead us eventually to a new approach to understanding the way that space-time is related to dynamical laws.

A modified version of space-time structuralism will be suggested based on the dynamical perspective of space-time developed by Harvey Brown, Robert DiSalle, and Nick Huggett. In contrast with the ontological perspective that develops the foundations of dynamical laws on the basis of the nature of space-time, the dynamical perspective bases the physical foundation of space-time on dynamical laws. By overturning the traditional understanding of the structure of space-time theories, the dynamical perspective provides a much clearer connection between space-time geometry and dynamical laws. The main aim of this chapter is to develop a new version of space-time structuralism by considering the weaknesses of Dorato's version of space-time structuralism and the strengths of the dynamical perspective of space-time. We will see that the dynamical perspective of space-time and space-time structuralism can be natural allies, because both perspectives are sceptical of the "deep-down" ontology and the formalism-alone geometric perspectives. Accordingly, these two intuitions can be integrated in order to develop a new version of space-time structuralism. We will see that as a result, space-time structuralism can be modified into a view claiming that the structural properties of dynamical laws, which specify the relations of regularity between events, constitute the essential elements in Newtonian and Einsteinian physics.

The following section introduces structural realism suggested by Pierre Duhem and Henri Poincaré, and recently resuscitated by John Worrall, which provides a core intuition behind Dorato's space-time structuralism. The third and fourth sections move to a summary and a critique of Dorato's version of space-time structuralism. The fifth section then develops a modified version of space-time structuralism by considering the weaknesses of Dorato's view and the strengths of the dynamical perspective of space-time. The sixth section examines Newtonian dynamics as a supporting case for my modified version of space-time structuralism.

2. Scientific Change According to Structural Realism

The aim of this chapter is to develop an account that captures the relationship between postulated space-time structures and the dynamical laws, which constitute the essential parts of Newtonian and of Einsteinian physics. Dorato's version of space-time structuralism, which is the application of structural realism elaborated by Duhem, Poincaré and Worrall to the context of space-time theories, claims to provide just such an account. Dorato asserts that the spatio-temporal relations, which exist over and above physical events, integrate the best assumptions of the two competing ontological interpretations of space-time, i.e. substantivalism and relationism. This idea originates from the structuralist idea that the relations involved in mathematical structures play an essential role in the workings of a given theory.[1] Before we discuss Dorato's version of space-time structuralism, this section will consider a central argument and motivation for structural realism.

1) Duhem: As a result of his historical studies of mechanics, the physicist and philosopher Pierre Duhem suggested an evolutionary view of theory-change in science. In the preface of his *Origin of Statics* (1905), Duhem acknowledged that his historical studies had led him to a view that the development of physical theories is an evolutionary process, rather than a revolutionary one: "the alleged intellectual revolutions have most often been only evolutions which have been slow and prepared over history." (1905, *I*: p. iv) Moreover, "the sciences of mechanics and of physics have developed by an uninterrupted sequence of scarcely perceptible improvements of the doctrine taught in the medieval schools." Duhem's evolutionary thesis is also clearly stated in the conclusion of his *Evolution of*

[1] The emphasis on structure in a given theory is also prevalent in constructing theories outside of physics. For example, structuralism in political science is one of standard positions in understanding the behaviours of states. According to Waltz (1979), the structure of a system (the structure of the relationships between individual states is what Waltz is interested in) leaves aside, or abstracts from the characteristics of the elements constituting the system, and their attributes, and their interactions. They are left out, since

> [W]e can distinguish between variables at the level of the units and variables at the level of the system. ... To define a structure requires ignoring how units relate to one another (how they react) and concentrating on how they stand in relation to one another (how they arranged or positioned). Interactions, as I have insisted, take place at the level of units. How units stand in relation to one another, the way they are arranged or positioned, is not a property of the units. The arrangement of units is a property of the system. (Waltz 1979, 79-80)

Accordingly, it is necessary to discern structure existing between the concrete reality of events "only by virtue of having first established structure by abstraction from 'concrete reality.'" (ibid.) Given that structure is abstraction, it cannot be defined by enumerating material characteristics of the system: "it must instead be defined by the arrangement of the system's parts and by the principle of that arrangement." (ibid.) By developing a specific concept of structure, it is possible to establish "theoretically useful concepts to replace the vague and varying systemic notion that are customarily employed – notion such as environment, situation." (ibid.)

Mechanics: "The development of mechanics is, therefore, properly speaking, an evolution; each of the stages of this evolution is the natural corollary of the stages that have preceded it; it is the chief part of stages which will follow it." (Duhem 1908, 188) For Duhem, an essential condition of scientific progress is the "respect for tradition."

Although Duhem considers the development of a theory as constituting a "one step at a time" progress, this view does not apply to every part of a given theory. Continuity in the development of a physical theory, according to Duhem, occurs only in the representative parts of a theory, which "classify experimental laws." On the other hand, the explanatory parts of a theory, which aim to capture "the reality underlying the phenomena," are often replaced during the course of scientific change. This dichotomy is clearly related to Duhem's sceptical attitude towards metaphysics. He maintained that the aim of science is not to establish "judgements about the nature of things," but rather to specify "consequences conforming to experimental laws." The explanatory parts of a theory, Duhem claims, are parasitic on the representative parts which do the real work in a theory:

> It is not to this explanatory part that theory owes its power and fertility; far from it. Everything good in the theory, by virtue of which it appears as a natural classification and confers on it the power to anticipate experience, is found in the representative part. (Duhem 1914, 31)

Duhem's characterization of a 'natural classification' provides a clear account of structuralism. According to Duhem, a natural classification is analogous to a classification in zoology or botany: "those ideal connections established by his reason among abstract conceptions [in classification in biology] correspond to real relations among the associated [biological] creatures brought together and embodied in his abstractions." (ibid., 25) In a similar way, within a successful physical theory, "the relations it establishes among the data of observation correspond to relations among things" (ibid., 27). In this spirit, Psillos claims that "the Duhemian distinction between the representative and the explanatory parts of a theory may be seen as co-existensive with Worrall's structure and content distinction." (Psillos 1999, 309 n. 3)

> Duhem understands 'natural classifications' as revealing real relations among *unobservable entities*. But it can be argued that Duhem's realism reaches up only to the structural level, so to speak. A natural classification is such that it gets right the *relations* among unobservable entities, but not necessarily the unobservable entities themselves. This line of thought can be developed into *a prima facie* sustainable realist position, that of so-called *structural realism*. (Psillos 1999, 38, original italics)

In the course of scientific change, natural classifications representing relations between observable or unobservable entities undergo an evolutionary development. In contrast, the explanatory parts, which are intended to capture the reality underlying the phenomena, have experienced the occurrence of "constant breaking of explanations which arises to be quelled."

An illustrative example is provided by Duhem's critique of Maxwell's attempt to develop a mechanical understanding for his electromagnetic theory. The founders of electromagnetic theory, such as Coulomb, Poisson, and Ampère, according to

Duhem, emphasized empirical laws in constructing their theories.[2] Maxwell, on the contrary, looked for a mechanical model that was founded on an elastic ether that consists of layers of small particles. The motions of these mechanical elements generate electric currents and vortices which represents magnetic fields. According to Duhem, such explanations are "not built for the satisfying of reason but for the pleasure of the imagination." (Duhem 1954, 81) Such attempted explanatory parts of Maxwell's theory, Duhem claimed, are "irreconcilable with traditional doctrines" (Duhem 1902, 11). On the other hand, Duhem claimed that "what is essential in Maxwell's theory is Maxwell's equations" (ibid., 221-2), which "symbolize physical magnitudes which must be either measurable experimentally or formed from other measurable magnitudes" (ibid., 223). In the development of electromagnetic theory, these equations that represent the relationships between the electric and the magnetic fields are true and continuous elements, which are bequeathed from the work of Coulomb, Poisson, and Ampère.[3]

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[2] The emphasis of empirical laws in the development of electromagnetic theories can be found in Duhem's writing:

> [W]hen his experiment have allow him to formulate new laws that the theory had not foreseen, he must first try with the greatest care to represent these laws, to the required degree of approximation, ... as consequences of admitted hypothesis. Only after ... received hypothesis cannot flow from the established laws, is he authorized to enrich physics with a new magnitude, to complicate it with a new hypothesis. (Duhem 1902, 7, quoted from Ariew and Barker 1986)

[3] The explanatory parts of a theory, such as the ether model, are not based on 'properly observed phenomenon'. The explanatory parts, which aim to capture the nature of the world are likely to be subordinate to metaphysics. In contrast, experiments have allowed physicists to formulate the representative parts that aim to classify experimental laws. From this, we can notice that the representative-explanatory distinction is founded on whether or not a specific part of a given theory is empirically based. And this insight can be extended in our understanding of theory change, given that the fate in theory change differs in the representative and explanatory parts.

2) Poincaré and Worrall: The same line of thought can be found in Poincaré. Following a Kantian line, Poincaré claimed that unobservable entities and mechanisms are comparable to Kant's things-in-themselves, which we cannot fully capture. Yet, he believed that the success of science indicates that we can legitimately claim to have knowledge of the relations between things-in-themselves. "Still things themselves are not what [science] can reach as the naive dogmatists think, but only relations between things. Outside of these relations there is no knowable reality." (Poincaré 1902, 25) Poincaré's view is therefore an epistemic one – concerning what kind of knowledge of the world is possible, rather than concerning reality itself: "The true relations between these objects are the only reality we can obtain." (Poincaré 1905, 161) According to Poincaré, these relationships between unobservable entities and mechanisms are captured by the mathematical equations of empirically successful theories. In contrast, having knowledge of unobservable entities and mechanisms is beyond our capability:

> [T]hese equations express relations, and if the equations remain true, it is because the relations preserve their reality. They teach us, now as then, that there is such and such a relation between this thing and some other thing ... But these appellations were only images substituted for the objects which Nature will eternally hide from us. (Poincaré 1902, 174)

A motivation behind Poincaré's structural realism is that of providing an appropriate account of theory-change. According to Poincaré, although abandoned theoretical

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Based on its empirical grounds, we can distinguish the continuous parts in theory change from non-continuous one. The retention of a specific part basically depends on whether or not its empirical grounds are sound.

entities of once successful scientific theories might seem to show "the bankruptcy of science," this is based on a misunderstanding of the aim or the role of scientific theories:

> The man of the world is struck to see how ephemeral scientific theories are. After some years of prosperity, he sees them successively abandoned; he sees ruins accumulated on ruins; he predicts that the theories in vogue today will in a short time succumb in their turn, and he concludes that they are absolutely in vain. ... [However] his scepticism is superficial; he does not understand either the aim or the role of scientific theories. (Poincaré 1902, 173)

This sceptical attitude is superficial, because the relations between unobservable entities and mechanisms survive (or perhaps 'quasi-survive') in the course of theory-change. Although theoretical entities and mechanisms of past successful theories have later been rejected, the history of science shows that the relations between theoretical entities are maintained in the succeeding theories. And the relations, from the vantage point of those later theories, can be seen to have contributed to the success of the earlier one:

> [W]hat thus succumb are the theories properly so called, those which pretend to teach us what things are. But there is in them something which usually survives. If one of them taught us a true relation, this relation is definitely acquired, and it will be found again under a new guise in the other theories which will successively come to reign in place of the old. (Poincaré 1905, 182)

An example cited by Poincaré is the development of theories concerning optical phenomena from Fresnel's elastic ether theory to Maxwell's electromagnetic field theory. In this development, the mechanical ether constituting the former is replaced by a completely different entity in the latter – namely a electromagnetic field. In spite of this difference, there are strong similarities in their mathematical structure.

Worrall, who recently revived Poincaré's structural realism, points out that "Fresnel's equations [for the relative intensities of light reflected and refracted in partial reflection] are taken over completely intact into the superseding [Maxwell's] theory – reappearing there newly interpreted but, as mathematical equations, entirely unchanged." (Worrall 1996, 160) Just as Duhem considered that "what is essential in Maxwell's theory is Maxwell's equations," structural realism as advocated by Poincaré and Worrall claims that the mathematical structure of Fresnel's and Maxwell's theories, rather than their entities and mechanism, are the essential part of those theories.

A central motivation of Worrall's employment of Poincaré's idea is to cope with a recent argument against the evolutionary and accumulative development of science. Worrall attempts to embrace two apparently conflicting arguments concerning scientific realism: the 'no miracle argument' and the 'pessimistic induction.' (Worrall 1989) The former suggests that the success of science (especially its success in predicting new types of phenomena) would be a miracle if its successful theories were not (at least approximately) true. The strategy of the argument is basically to regard the success of scientific practice as evidence of the reality of theoretical claims. According to Laudan, the pessimistic induction, on the contrary, provides a stumbling block for realism, since even the most successful theories in the past have been discarded because they turned out be false theories – it therefore seems reasonable to infer that current theories too will later turn out to be false.

In order to support his claim, Laudan offers a list of theories that were "once successful and well confirmed, but which contained central terms which (we now believe) were non-referring." (Laudan 1981, 33) These counter-examples against the no miracle argument include the crystalline sphere of ancient and medieval astronomy, the phlogiston theory of chemistry, the caloric theory of heat, the vibratory theory of heat, the theory of circular inertia, and the electromagnetic and optical ether theories. Given these counter-examples, Laudan claims that

> Because [most past theories] have been based on what we now believe to be fundamentally mistaken theoretical models and structures, the realists cannot possibly hope to explain the empirical success such theories enjoyed in terms of the truth-likeness of their constituent theoretical claims. (Laudan 1984, 91-2)

Psillos reconstructs the pessimistic induction as follows.

> (1) Assume that the success of a theory is a reliable test for its truth.
> (2) So most current scientific theories are true.
> (3) Then most past scientific theories are false, since they differ from current theories in significant ways.
> (4) Many of these false past theories were successful.
> (5) So the success of a theory is not a reliable test for its truth. (Psillos 2001, 373)

Premises (1) and (2) are the realist's claims that Laudan aims to undermine. And premise (3) is based on the claim that earlier theories involve theoretical terms that are now regarded as non-referential: "Past theories are deemed not to be truthlike because the entities they posited are no longer believed to exist and/or because the laws and mechanisms they postulated are not part of our current theoretical description of world." (Psillos 1996, S307) Laudan's list provides historical evidence that supports premise (4). The history of science – (3) and (4) – then leads us to a *reductio ad absurdum* of (1). From the pessimistic induction from the history of science that is full of the past successful but false theories, Laudan argues the weak connection between truth and explanatory success.

Structural realism attempts to have the best of both arguments: "the only hopeful way of *both* underwriting the no miracles argument *and* accepting an accurate account of the extent of theory change in science." (Worrall 1989, 117) This view claims that, although the contents of a given theory are discarded, its underlying mathematical structures are invariant (or structurally invariant) in the course of theory change: "There was a continuity or accumulation in the shift, but the continuity is one of *form* or *structure*, not of content." (ibid.) If these well-supported mathematical structures are maintained under theory change, then it is highly probable that they represent the true underlying structures of nature, which are the elements contributing to the success of theories. [4]

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[4] A set of similar strategies entitled the "*divide et impera*" strategy have been suggested in order to undermine Laudan's argument by Kitcher (1995), Hardin and Rosenberg (1982) and Psillos (1999). According to this line of thought, one can learn a different lesson from Laudan's lists, which does not necessitate Laudan's conclusion. What we can learn from the pessimistic meta-induction, according to Psillos, is that realists need the 'right kind' of the explanatory connection between success and truth of theories.

This strategy is employed in Kitcher's distinction between 'working posits' and 'presuppositional posits' (Kitcher 1995). The former is "the putative referents of terms that occur in problem solving schemata" while the latter is "those entities that apparently exist if the instances of the schemata are to be true." (ibid., 149) This distinction is based basically on the fact whether a theoretical term is referring or non-referring. Kitcher identifies the referring parts as being responsible for the success of theories. In contrast, the non-referent ones, which can be eliminable, have a fate to be discarded.

For example, Fresnel's theory of diffraction, which explains the propagation of light as vibrations through the ether, appears false from the vantage point of Maxwell's theory of optics, in which the medium is the electromagnetic field rather than the ether (ibid. p.120). In accord, it seems, with the pessimistic induction, the ether in Fresnel's theory, in spite of its success in explaining optical phenomena, is a non-entity that was rejected in favour of the electromagnetic field. (Laudan 1981, p.231) Yet Worrall claims that there exists a better way to make sense of the success of Fresnel's ether theory in spite of the non-existence of central entity it postulates:

> [T]here is easy explanation of the success of Fresnel's elastic-ether theory of light ... Fresnel clearly misidentified the *nature* of light, but his theory nonetheless accurately described not just light's observable effects but also its *structure*. There is no elastic-solid ether of the kind Fresnel's theory ... involved; but there is an electromagnetic field. The field is not underpinned by a mechanical ether and in no clear sense "approximates" it. Similarly there are "no light waves" in Fresnel's sense, since there were supposed to consist of motions of material ether-particles. Nonetheless disturbances in Maxwell's field do obey *formally* similar (in fact, and unusually, mathematically identical) laws to some of those obeyed by the "materially" entirely different elastic disturbances in a mechanical medium. (Worrall 1994, 340)

Hardin and Rosenberg claim that although we can admit that central theoretical entities in the past theories do not refer to the intended objects, we can still talk about approximate truth due to the commonality of its same causal or explanatory role between past and present theories.

But these two suggestions fail to provide a clear cut criterion capturing the continuity in the course of theory change. As for Kitcher's suggestion, Psillos asserts that the identification of a 'presuppositional part' is based on a retroactive consideration: "This suggestion is retroactive and open to the charge that it is ad hoc: the eliminable posits are those that get abandoned." (Psillos 1999,112) This is the same for a 'working posit' which contributes the success of a given theory: "with the benefit of hindsight, one can rather easily work it out so that the theoretical constituents that supposedly contributed to the success of past theories turn out to be those which were, as it happens, retained in subsequent theories." (ibid.)

Hardin and Rosenberg's strategy is criticized to provide too liberal criterion in order to distinguish the essential contents of theories. Laudan criticizes their criterion as being too tolerant to be a rigorous one. If realists accepted Hardin and Rosenberg's criterion, they would be in an undesirable position as realists, in which they would have to admit the referential success of Aristotle's 'natural place' or Descarte's 'vortex.' (Laudan 1984, p.161)

Although Fresnel's and Maxwell's theories are based on significantly different ontological underpinnings, the two theories exhibit structural continuity because of the commonality of their mathematical equations:

> Both Fresnel's and Maxwell's theories make the passage of light consist of wave forms transmitted from place to place, forms obeying the same mathematics. Hence, although the periodic changes which the two theories postulate are ontologically of radically different sorts – in one material particles change position, in the other field strengths change – there is nonetheless a structural, mathematical continuity between the two theories. (ibid.)

Structural realism thus claims that mathematical structure is the invariant (or in more representative cases "quasi-invariant") element that makes theories successful, while the supposed nature of entities is only conjectural and may well later be radically revised. In this way, structural realism attempts to dissolve the conflict between the no miracle argument and the pessimistic induction.

3. Dorato's Spacetime Structuralism

In suggesting his version of space-time structuralism, Dorato follows a similar approach to Worrall's. Just as structural realism attempts to resolve the conflict between the no miracle argument and the pessimistic induction, Dorato attempts to resolve the controversy between substantivalism and relationism by synthesizing the two views:

> As I see it, such a position (structural space-time realism) allows us to capture the best assumptions up to now *separately* associated with substantivalism and relationism, that is, those assumptions that, at least within the general theory of relativity, substantivalists and relativists *must share*. (Dorato 2000, 1612, my italics)

As shown in the last chapter, the ontological status of space-time has been debated as a part of the substance-relation controversy. Dorato sees the dispute between the two parties as being basically concerned with the mode of existence of space-time. Substantivalism maintains the view that space-time has an existence independent of matter. Relationism denies that space-time has an independent existence, and instead claims that space-time is a set of relations of material bodies or physical events.[5] To resolve this debate, Dorato's space-time structuralism emphasizes the commonality of mathematical relations in spite of their different ontological interpretations.[6]

This view is basically an application of structural realism to the context of the interpretation of space-time. Just as different theories of light suggested by Fresnel and Maxwell share mathematical structure, Dorato claims that although

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[5] A physical event, on my account, is a thing that happens. Following Quine (1960), I do not ontologically distinguish physical events from material bodies in that they are the same genus of "material inhabitant of space-time." In fact, material bodies are main actors in events, and physical events without material bodies are difficult to think of. Yet, what distinguishes these two concepts is that an event has not extension in either space or time. A physical event is an idealized concept referring to the occurrence in the infinitesimal place and time, while physical bodies persist by having different parts at different times. This idealization is necessary for physical events to be represented as a set of points in space-time. Substantivalists consider a physical events occurring at substantial space-time points. On the other hand, relationists by no means admit existing space-time points in order to capture the occurrence of events.

[6] The emphasis of geometry in space-time theories can be read in the work of main participants of substance-relation controversies. In the first paragraph of Scholium, Newton states that his definitions of time, space, place and motion are intended to remove common people's prejudice by distinguishing 'absolute', 'true', and 'mathematical' concepts from 'relative', 'apparent', and 'common' ones. (Newton 1729, 6) Descartes, a classic relationist, also maintains that motions of bodies should be analysed by geometry; "As for me, I conceive of [motion] none except which is easier to conceive of than the line of mathematics: the motion by which bodies pass from one place to another." (Descartes 1979, 63)

substantivalism and relationism involve different views of the mode of existence of space-time, the underlying reality is captured by spatio-temporal relations represented by the common mathematical structure. In other words, space-time structuralism views the spatio-temporal relations between events as the essential elements of space-time theories:

> [W]e need a third option, which I refer to as "structural spacetime realism." Such a *tertium quid* sides with the relationists in defending the relational nature of the spacetime structure, but joins the substantivalists in arguing that spacetime exists,[7] at least in part, independently of particular physical objects and events, the degree of "independence" being given by the extent to which geometrical laws exist "over and above" physical events exemplifying them. (ibid., 1605)

One of the main motivations for space-time structuralism is that of reflecting the ambiguity of the mode of existence of the metric field **g**, which represents space-time in general relativity. Yet we can also find an analogous attempt regarding a similar problem within Newtonian space-time. In an attempt to moderate the

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[7] Leibnizean relationism can be interpreted as endorsing the reality of space although it rejects the reality of absolute space. By criticizing Newton's idea of reality of space as a 'conceit of imagination', Leibniz claimed that "there is *no real space* out of material universe" (Alexander 1956, 29). However, Earman (1989) and DiSalle (1994) claim that Leibniz's relational theory does not reject the physically objective reality of space-time. Earman, by a quotation of Leibniz's assertion that "whatever exists is either simultaneous with other experiences or prior or posterior," maintains that Leibniz also agreed about the absolute simultaneity. In the same spirit, DiSalle points out that

> [Leibniz's] relational theory of motion therefore presupposes absolute simultaneity and Euclidean Geometry on space at each moment of time. ... The spacetime structure that Leibniz thus takes for granted is only that required by prerelativistic kinematics, without the added affine structure required in order to speak of dynamical quantities like 'absolute rotation' and 'absolute acceleration'. ... Leibniz, like Newton, attributes physically objective characteristics to space and time that do not depend on time (DiSalle 1994, 266-67).

In this way, Leibniz's relationism can be interpreted as conceding *the reality of certain geometric structures*; that is, the reality of a temporal geometric structure supporting absolute simultaneity and spatial geometric structure embracing Euclidean geometry on each simultaneous time.

differences between substantivalism and relationism, Maudlin (1993) and Teller (1991) suggested a modified version of relationism regarding Newtonian space-time, the purpose of which is analogous to that of Dorato's space-time structuralism (i.e. "capture the best assumptions up to now separately associated with substantivalism and relationism"). Just as Leibniz claims that space is "order or relation; and nothing at all without bodies but the possibility of placing them" (Alexander 1956, 26), the modified relationism is grounded on the constraints over the possibility of placing material bodies. Yet, what is unique about the view is the adoption of all the spatio-temporal structures that substantivalism embraces. Teller calls it "liberalized relationism":

> [R]elationalists can express themselves with the same language as substantivalists by describing space-time relations in terms of an arbitrarily established coordinate system. ... [T]he liberalized relationists' appeal to the common theoretical vocabulary is committed to the same inertial structure to which substantivalists feel committed. But since the coordinate systems are now taken to describe actual and possible relations to actually existing objects, instead of objectively existing space-time points, we are free from concluding that the structure in question must be [the] structure of something substantial. (Teller 1991, 380-1)

Adopting the richer set of spatio-temporal relations, which are instantiated by material bodies, relationism can accommodate any spatio-temporal structure (such as affine structure) explicating the dynamical behaviours of material bodies. This intuition can also be found in Maudlin:

> The most direct way for a relationist to overcome Newton's argument is simple: Accept his ontology of *relations* while rejecting substantival absolute space as its supporting framework. Such a *Newtonian relationist* could still maintain that all spatiotemporal facts are facts about the relations between material bodies or, speaking four-dimensionally, material events. But for the Newtonian relationist those relations include a distance relation between noncontemporaneous events.

> The Newtonian relationist inherits almost all the power to make ontological distinctions that the Newtonian substantivalist has. For example, the Newtonian relationist can accommodate absolute motion and rest. (Maudlin 1993, 187)

The dynamical laws of Newtonian physics require geometrical structures, such as manifolds of events, time metric, and spatial metric between any two events. According to Dorato's version of space-time structuralism, the working part[8] of the theory is the invariant spatio-temporal relations between any two events e_1 and e_2 which, in case of Newtonian physics, includes (1) whether e_1 and e_2 are simultaneous events; (2) what is the temporal interval between e_1 and e_2; (3) what is the spatial interval between e_1 and e_2, whether they are simultaneous or not; (4) whether two events are located at the same place.

The above version of relationism then seems to accommodate the best assumptions of both space-time substantivalism and relationism. It underwrites the spatio-temporal structure of substantivalism, which is implemented by the actual and possible spatio-temporal relations between material bodies or events. Accordingly, this view can respond to the criticism that relationism does not have enough structures to explain the dynamical behaviours of bodies, i.e., affine structure.[9] In

[8] My expression of "working parts" is referring to theoretical elements contributing the empirical success of a given theory. This expression should not be confused with Kitcher's one "working posits," which refers to "the putative referents of terms that occur in problem solving schemata." (Kitcher 1995, 149)

[9] Barry Dainton in his *Time and Space* (2001: 197-198) provides a possible way that affine structure can be defined within the world that consists of two rotating bodies from neo-Newtonian relationists' perspective. By defining the concepts of intrinsic direction and instantaneous intrinsic world-line curvature, Dainton claims that "[a] neo-Newtonian relationist has the resources to accommodate all the dynamically relevant feature to be found in both relational and substantival Newtonian worlds. Of course, there is no need for the [neo-Newtonian] relationist to

this way, the spatio-temporal relations can in fact be considered as the essential elements in explaining the laws of motion. So modified relationism can assert that what is essential in explicating the dynamical behaviours of a given body are the spatio-temporal relations instantiated by material bodies or events, which do not, however, supervene on substantial space.

Although the story becomes more complex in the context of the general theory of relativity, Dorato's space-time structuralism developed in the context of that theory has basically the same motivation. In the context of Newtonian mechanics and special relativity, substantivalism presupposes an unambiguous distinction between "matter" and "space," or "content" and "container." Yet, it has been argued that this distinction within the general theory is arbitrary, because the metric field ***g*** can be viewed either as empty space or matter (Rynasiewicz 1996). The metric field ***g*** in the general theory, on the one hand, can be interpreted as absolute space since the length, the inertial structure, and spacelike-timelike distinction of spacetime are all determined by ***g***. On the other hand, ***g*** can also be interpreted as the matter field responsible for the gravitational interaction. Rynasiewicz points out this conceptual ambiguity by tracking down the conceptual continuity from Descartes' subtle matter and the ether to ***g***:

> In so far as Newton's absolute space can be seen in retrospect as a field, first *qua* grounds of the inertial ether of classical mechanics, and subsequently *qua* the ether of electrodynamics, his substantivalism is vindicated in general relativity. But by the same token, insofar as the heritage of the field concept can be traced back continuously from

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recognize every embedding of a given system into full Newtonian substantival space as physically distinct." (ibid., 198).

Leibniz to the mechanical luminiferous ether, and in turn to the effluvia and subtle forms of matter of the preceding centuries, so is the relationism of these earlier figures. How one projects the 'space-matter' distinction familiar to the original disputants onto a framework they would not have recognized is a matter of whim. (Rynasiewicz 1996, 299)

Given the conceptual continuity that is traced backward from Einstein to either Newton or Descartes, the metric field ***g*** could be considered as the successor of either Newton's absolute space or Descartes' subtle matter. Similarly, Dorato claims:

[T]he metric field, by carrying energy and momentum, and by being capable of both "acting" and "being acted upon," should be regarded, on the one hand, as *material.* On the other, by providing a distinction between the spatial and the temporal directions of all the other material fields, it performs the typical individuating functions of *classical space and time* regarded as *principia individuationis*, and is therefore *not* a matter field like any others. (Dorato 2000, 1611, original italics)

In order to dissolve this ontological ambiguity of the metric field ***g***, Dorato suggests space-time structuralism in order to moderate the substance-relation debates in the context of the general theory of relativity. Space-time structuralism is developed as a 'third way' between substantivalism and relationism:

Structural spacetime realism is a synthesis between these two traditional positions in exactly the same sense in which the metric field is *both* matter *and* spacetime, since it defends at the same time the *relational* character of space and time (by defending a structural-role identity for spacetime points), while claiming that geometrical structure used to represent them is "really," mind-independently exemplified by the physical world. (ibid. 1612)

Basically, Dorato's space-time structuralism adopts a similar strategy of liberalized relationism. This view underwrites all spatio-temporal structures adopted by substantivalism, but considers them as actual and possible relations instantiated by the fields. While substantivalism holds that the fields occupy space-time points, relationism sees space-time points as being instantiated by the fields:

> According to the [plenist] substantivalist the world is at base a manifold of spacetime points which support fields, in which the fields inhere. According to the plenist relationist the world is a field or set of fields (and perhaps particles) which instantiate spatio-temporal relations, in which the relations inhere. (Maudlin 1993, 201)

Space-time structuralism basically adopts the latter view. Thus the metric field ***g***, i.e. space-time in the general theory, is interpreted as representing the actual and possible spatio-temporal relations between material things. Callender and Hoefer (2002) summarizes this as follows:

> ***g*** [space-time] is not a thing or substance. Where matter is present, it is crucial to the definition of local standards of acceleration and non-acceleration; *the EFE [Einstein Field Equations] record just this relationship.* In many ways, the desires of traditional relationists (esp. Leibniz, Huygens, Mach) are – arguably – met by GTR when interpreted this way. (Callender and Hoefer 2002, 178, my italics)

Space-time structuralism maintains that the mode of existence of space-time in the special and the general theories can be characterized from the ontological perspective as consisting of "a bundle of universals or a web of relations." (Dorato 2001, 1615) According to this view, space-time is essentially characterized as the spatio-temporal relations such as "later than," "simultaneous with," "to the future of," "being spacelike separated from," and "being a certain invariant spatio-temporal distance from" etc. (ibid.)

In the case of the special theory of relativity, the spatio-temporal relations are codified in a Lorentzian metric. This involves the non-existence of absolute simultaneity relations between two events, but the spatio-temporal relations between two events are completely encoded within the invariant geometric intervals between events, i.e., in Cartesian coordinates $ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2$. In the case of the general theory, the metric field $\boldsymbol{g}$ codifies the spatio-temporal structures $ds^2 = g_{ij}\, dx^i\, dx^j$ ($i, j = 1,2,3,$ and 4) which are inter-related with the distribution of matter-energy through the constraints specified by Einstein's field equations. The parts of the field maintain spatio-temporal relations to one another while having properties that satisfy Einstein's field equations. In this way, space-time structuralism interprets space-time structure as having a relational existence, without viewing it as a substantival entity.

So far, we have seen that Dorato's suggestion of space-time structuralism is along the similar line with liberalized relationism. On the other hand, Slowik highlights the other side of space-time structuralism, which originates from the metric substantivalism suggested as a response to the Einstein-Earman-Norton Hole argument. (Slowik 2006, 2007)

The Hole argument attacks substantivalists regarding the general theory. The general theory of relativity is characterized as a model constituted by $< M, g, T >$; where M is a four dimensional Riemannian manifold representing a set of events, g is the metric tensor that specifies the spatio-temporal relations between events, and T is the stress energy tensor representing the distribution of matter. Earman and Norton (1987) view the manifold of space-time points as representing space-time:

> The advent of general relativity has made most compelling the identification of the bare manifold with spacetime. For in that theory geometric structures, such as the metric tensor, are clearly physical fields in spacetime. The metric tensor now incorporates the gravitational field and thus, like other physical fields, carries energy and momentum, ... Consider, for example, a gravitational wave propagating through space. ... If we do not classify such energy bearing structures as the wave as contained within spacetime, then we do not see how we can consistently divide between container [space-time] and contained [matter]. (Earman and Norton 1987, 519)

The claim then is that there is a problem with the view that the metric field represents space-time. Given that the metric field carries energy and momentum that can be interchanged with any other form of energy (for instance with mechanical energy), Earman and Norton maintain that the difference of the mode of existence between space-time and the metric field is manifest. We are then left with no alternative but to interpret the manifold of space-time points as representing space-time.

Earman and Norton then argue that manifold substantivalism which interprets the manifold of events as independently existing substantival entities leads to an unacceptable form of indeterminism. Given the general covariance of the Einstein's field equations, which requires that the equations hold in any coordinate systems, if a model $< M, g, T >$ is a physically acceptable one, $< M, d^*g, d^*T >$ is also a physically acceptable one, where d is a diffeomorphism relating all points of M with different value of g and T. If the mapping is interpreted in an active sense that generates a physically different state, $< M, g, T >$ and $< M, d^*g, d^*T >$ can be considered to be genuinely different physical affairs.[10] Since, given that these two models have different distributions of the metric and matter fields over the same space-time points M, they represent two different physical systems.

The Hole argument alleges a radical form of indeterminism. Suppose $< M, g, T >$ and $< M, d^*g, d^*T >$ are related by the identity mapping before certain time t, but by a non-identity mapping after t. These two different developments after t cannot be physically distinguishable, since both models satisfy the same laws of the theory. In order to highlight the problem, Earman and Norton assign different mappings inside and outside of a hole in a local space-time region. These mappings change the assignment of space-time points inside the hole region with the metric and matter fields, whilst leaving the assignment of the points outside the hole with the metric and matter field unchanged. As a consequence,

> [T]he physical theory of relativistic cosmology is unable to pick between the two cases. This is manifested as an indeterminism of the theory. We can specify the distribution of metric and matter fields throughout the manifold of events, excepting within the region designated as The Hole. Then the theory is unable to tell us how the fields will develop into The Hall. Both the original and the transformed distribution are legitimate extensions of the metric and matter fields outside The Hole into The Hole, since each satisfies all the laws of the theory of relativistic cosmology. The theory has no resources which allow us to insist that only one is admissible. (Norton 1999)

[10] There exist two different interpretations concerning the coordinate transformations. In the Cartesian coordinates system, a coordinate transformation maps the old point whose coordinate is $(\mathbf{x}, t)$ to the new point whose coordinate in the same system is $(\mathbf{x}', t')$. A passive interpretation is concerned with the way the physical situation is described in that the transformation maps a specific point $(\mathbf{x}, t)$ in one reference frame to the same point labeled $(\mathbf{x}', t')$ in the different reference frame. On the other hand, when the transformation is interpreted in an active sense, it generates a physically different state while the physical state is described in terms of the same coordinate system.

Various criticisms have been suggested to undermine the argument. But here I want to concentrate on Hoefer's metrical substantivalism, as being the most relevant to space-time structuralism. Slowik (2005) reads Hoefer's view as showing that "the evolution of [ideas about] space-time demonstrates how conflicting spacetime commitment may … incorporate the same necessary structures." (Slowik 2005, 151) Hoefer criticizes the hole argument by targeting Earman and Norton's premise that the substantial points of space-time are represented by a manifold of events M among three elements of the model $< M, g, T >$. Then, the mapping d relates different values of g, T with a manifold of events, which brings about an unacceptable form of indeterminism. This specific interpretation of space-time consists of an essential premise for the Hole argument to work. At this point, Hoefer points out that this understanding of space-time yields the wrong conclusion. According to Hoefer, what represents space-time is in fact the metric, rather than a manifold of events. Whilst Earman and Norton identify the metric field with a physical field in a sense that it can carry both energy and momentum, Hoefer emphasizes their difference:

> [T]o talk of the metric field as though it were a *physical* field – something of a cousin to the electromagnetic field, say – is awkward and unnatural. … Whereas the classical concept of a [matter] field is that of something *in* space and time, whose properties vary with location in a space and time that could just as well exist without the field, the metric is not *in* spacetime, and spacetime cannot be imagined to exist if it were 'removed.' (Hoefer 1998, 459, original italics)

In addition to denying the identify of the metric field with matter, Hoefer provides a reason why the metric field should be viewed as space-time:

> Why is it proper to view $g_{\mu\nu}$ as the representor of substantival space-time? The metric's role is exactly to give us the details of the structure of 4-D, curved spacetime. It determines the

spacelike-timelike distinction, determines the affine connection or inertial structure of spacetime (i.e. defines which motions are accelerated and which are not), and determines distances between points along all paths connecting them. In all these ways, the metric is perfectly analogous to Newton's absolute space and time. (ibid.)

Hoefer finds the origins of this view in the writings of Einstein:

> If we imagine the gravitational field, i.e. the functions g_{ik}, to be removed, there does not remain a space ... but absolutely nothing ... There is no such thing as an empty space, i.e. a space without field. Space-time does not claim existence on its own, but only as a structural quality of the field. (Einstein 1920, 155)

If the metric field is identified with space-time, the Hole argument does not hold. Whilst the argument is based on a premise that the physically permitted models < *M, g, T* > and < *M, d*g, d*T* > have two different distributions of metric and matter fields over the same space-time points, this is not the case in Hoefer's metric substantivalism. If space-time is to be identified with the metric field, we cannot say that the same space-time points have different metric fields. That is, given that the metric field fixes the identity of space-time points of *M*, the mapping of *d*g* does not result in the same points of *M* possessing different *g* and *T* values. Instead, *d*g* represents the same space-time points. (Stachel 1993) So without empirically equivalent alternatives that are generated by the mapping *d*, the failure of determinism is avoided.

Slowik (2006) points out that although Hoefer's view is suggested as a version of substantivalism, it is very close to relationism in the sense that it is based on the relational property of the metric field ***g*** in characterizing space-time. The essence of relationism lies in its identifications of a set of empirically equivalent alternative models with a single state-of-affairs. Belot and Earman describe the advocates of the view identifying diffeomorphically related models as the 'sophisticated' substantivalists, who "are helping themselves to a position most naturally associated with relationism". (Belot 2000, 588-9) Given this commonality of emphasis on the metric within substantivalism and relationism, Slowik advocates space-time structuralism:

> SR [structural realism] can also be helpful in explicating our evolving understanding of the importance of structure in spacetime theories considered historically. ... Likewise, the striking resemblance of many post-hole argument substantivalists and current [modified] relationist hypotheses can be seen as a further manifestation of this structuralist evolutionary tendency. As the analysis of spacetime theories progresses (the insufficiency of [traditional] relationism [in explicating inertial motions], the hole argument, etc.), the structures put forward by the competing ontologies draw ever more closer, and may have reached a point where there is no longer any significant difference. It is this capacity of SR to reduce the seemingly irresolvable ontological conflicts, and focus on the crucial role of structure, that marks its true advantage in the spacetime debates. (Slowik 2006, 150-151)

4. A Critique of Dorato's Structural Space-time Realism

The space-time structuralism developed by Dorato and Slowik seems to capture, then, the important elements of the workings of space-time theories. It identifies "a common structure" i.e. the relational properties of the metric field $\boldsymbol{g}$, shared by "sophisticated substantivalism" and "liberal relationism." But the emphasis on "a common structure" shared by the two competing views, is, surely, at best a weak explanation of the success of space-time theories. Dorato and Slowik follow a strategy similar as Poincaré and Worrall's emphasis on the common structure shared by Fresnel and Maxwell's theories. Yet the intention of structural realism is ultimately to find the essential elements contributing to the success of those theories, rather than simply finding any common structure. That is, what structural realism aims to capture are the "working parts" of theories. We have seen this in Duhem's account that the parts to which "theory owes its power and fertility" are the relations between observable or unobservable entities. And Poincaré and Worrall's structural realism explains the empirical success of a theory in terms of its structure. In this sense, the structures shared by Fresnel and Maxwell's theories are not only common structures, but also working parts that make these theories successful.

Accordingly, within the context of space-time structuralism, we need to ask whether or not the common structure shared by substantivalism and relationism (the relational properties of space-time) is the theoretical part that makes the success of space-time theories possible. This section will argue that the relational properties of space-time are not enough to capture the essential parts of space-time theories, i.e. the spatio-temporal relations between events are not the elements that make Newtonian and Einsteinian physics empirically successful. In fact, *dynamical laws* are by no means explained by the relational properties of space-time shared by substantivalism and relationism.

As Dorato's version of space-time structuralism captures the best assumptions from both substantivalism and relationism, the view retains a premise common to both ontological positions. This is that the dynamical effects of a given body are to be explained by the geometries of space-time, which represents the spatio-temporal relations. Within the general theory of relativity, Dorato considers that the law of inertia, e.g., is explained by the geometric structure of space-time:

> [T]he question of the independent existence of spatiotemporal structure calls into play the status of natural laws and their existence as being partially non-supervenient upon physical state of affairs and events. (Dorato 2000, 1614)

And:

> [A] structural spacetime *realist* must admit that geometrical laws [of space-time] exist independently of our minds, to the extent that such laws partially constitute the structure (or relations) that phenomena exemplify.[11] The laws I am referring to are relational constraints making it the case that, say, "free particles travel on geodesics of the spacetime." (ibid., 1617)

According to Dorato, the independent existence of spatio-temporal structure also explains trajectories in the case of gravitating motions. He also does not exclude the possibility that the relational properties of space-time have a causal power that explains the trajectory of the motion of a body in that the curvature of space-time deflects the orbits of massive bodies:

> By using the spatiotemporal structure as an explanatory tool, and declaring it to be a mind-independent *property* of certain physical systems, structural realists about spacetime may rely on the fact that *properties* (spatiotemporal ones included) *simply are*, in any respectable metaphysical theories, *the causal powers of the entities having them*. ... What causes the deflection of the orbit of the massive body is the gravitational field, a thoroughly physical field, *via* its geometrical, causally active relational properties. (ibid., 1616)

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[11] The independent existence of space-time geometry that represents a specific entity, whether it is based on substance or relation, has been a major intuition behind the reality of space-time. Alexander in his preface of *Leibniz-Clark correspondence* states that "one might interpret the Scholium as saying that space-time are *ideal entities* which it is helpful to consider in theory, ... identifying the set of frames of reference with respect to which the laws of dynamics would take the simplest forms (Alexander 1984)." Toulmin also sees the mode of existence of space as a geometric entity in that

> [O]ne need no more assert that Newton was committed by his theory of dynamics to the objective existence of a cosmic substratum called 'absolute space' than one need to say that a geometer ... is committed to the quasi-material existence of an invisible network of geometrical entities ... (quoted from Stein 1967)

According to Brown (2005), the above scheme, which Dorato's version of space-time structuralism follows, represents a widespread opinion among the philosophers of space-time (held by, e.g., Friedman 1983, Nerlich 1976, Balashov and Janssen 2003). Brown cites Nerlich as an example:

> [W]ithout the affine structure there is nothing to determine how the [free] particle trajectory should lie. It has no antennae to tell it where other objects are, even if there were other objects. ... It *is because space-time has a certain shape that world lines lie as they do.* (Nerlich 1976, 264, original italics)

According to such accounts, the geometric feature of the spatio-temporal structure explicates the behaviours of material bodies moving in accordance with the laws of motion. Brown and Pooley (2006) also interpret Balashov and Janssen's account of Lorentz contraction as following the same explanatory scheme that the geometrical structure of space-time makes sense of Lorentz invariance:

> [D]oes the Minkowskian nature of space-time explain why the forces holding a rod together are Lorentz invariant or the other way around? Our intuition is that the geometrical structure of space(-time) is the *explanans* here and the invariance of the forces the *explanandum*. To switch things around, our intuition tells us, is putting the cart before the horse (Balashov and Janssen 2003, 340-1).

And:

> [L]ength contraction is explained by showing that two observers who are in relative motion to one another and therefore use different sets of space-time axes disagree about which cross-sections of the 'world-tube' of a physical system give the length of the system. (ibid., 331)

The above accounts, along with Dorato's version of space-time structuralism, share the explanatory scheme that the geometric feature of space-time as an independent existence is what explains the dynamical laws of material bodies. Here, what is worth emphasizing is that its geometric feature stems from the mode of existence of space-time. It seems that although substantivalism and relationism suggest different modes of existence for space-time, they share the common explanatory scheme that space-time geometry is supposed to explain the dynamical effects of a given body. Liberalized relationism makes this clear:

> How does the introduction of absolute space provide Newton with the wherewithal to explain the dynamical effects? Since the parts of absolute space endure through time, they provide a reference frame by which distance relations can be defined not only between bodies at a time but also between bodies at different times. ... Newton's ability to account for inertial effects does not immediately depend on the postulation of space as a substance. Substantival absolute space serves only as a means of extending the domain of the distance relation to include pairs of nonsimultaneous events... [On the other hand] a [liberalized] relationist could still maintain that all spatiotemporal facts are facts about the relations between material bodies or, speaking four-dimensionally, material events. But for the [liberalized] relationist those relations include a distance relation between noncontemporaneous events. (Maudlin 1993, 186-7)

In this way, liberalized relationism sees the geometry of space-time as providing an explanation for the dynamical effects of a given body. Hence, given that both traditional substantivalism and relationism follow this scheme of explanation, it is no surprise that Dorato's version of space-time structuralism, which attempts to capture the common aspect of these two views, follows this line.

However, from the perspective of liberalized relationism, it in fact seems doubtful that the geometric nature of space-time provides an explanation of the dynamical effects of a body. In the previous chapter, we have seen that the mode of existence of space-time by no means cause the dynamical effects of a body. According to Maudlin's account, what the spatio-temporal relations do, instead, is to "provide a reference frame by which distance relations can be defined not only between bodies at a time but also between bodes at different times." (ibid.)[12] By means of these spatio-temporal relations between simultaneous and non-simultaneous events, it is possible to *define* a reference frame relative to which the laws of motion have their simplest forms. In other words, with respect to the reference frame, a given body not subject to external forces follows rectilinear and uniform trajectories, whereas if subjected to external forces, a body accelerates in proportion to, and the direction of, the exerting force. Accordingly, what the spatio-temporal relations between events provide is kinematical properties by which we can build concepts constituting dynamical laws, rather than space-time providing an explanation of dynamical laws.

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[12] It seems that this lack of kinematical property capturing the dynamical effects of a body is what is at stake in Newton vs. Descartes in *De Gravitatione*. Newton criticized Descartes' physics, since the analyses of space and motion based on a relationist's perspective cannot capture dynamical effects. In *Principles of Philosophy*, Descartes claimed that "the terms 'place' and 'space', then do not signify anything different from the body which is said to be in a place; they merely refer to ... position relative to other bodies" (Descartes 1967, II. 13).

Newton at this point attempts to show that Descartes' relational space does not have the appropriate kinematical structures to make sense of inertial trajectories of moving bodies. In *De Gravitatione*, Newton argued the absurdity of Descartes' position; "a moving body has no determinate velocity and no definite line in which it moves" (Hall & Hall 1962, 129). The main line of reasoning comes from pointing out weak kinematical properties of Descartes' relational theory of space. The place of a given body can be said to be both changing and not changing depending on different reference bodies. In this sense, 'places' do not exist in nature: "there is no basis from which we can at present pick out a place which was in the past, or say that such a place is any longer discoverable in nature ... (since) there are no bodies in the world whose relative positions remain unchanged with the passage of time" (ibid., 130). This is the problem of Cartesian kinematics:

> [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. (ibid., 130)

In other words, what Newton wanted to prove is that Descartes' relational space does not have the appropriate kinematical structure to define the positions (consequently the velocities) of bodies over time.

We can also find an argument that space-time geometry by no means explains dynamical laws in Teller's account concerning the relationships between space-time and the law of inertia. In the context of neo-Newtonian space-time, Teller criticizes the traditional view that considers space-time as explaining the law of inertia. Newtonian space-time needs to be modified since it does not satisfy the principle of Galilean relativity.[13] According to the principle, the dynamical laws cannot be distinguished when they refer to any uniformly moving frame. Accordingly, the identification of spatial points over time and the distance relations between non-simultaneous events is not dynamically meaningful.[14] Neo-Newtonian space-time

[13] Newtonian space-time consists of three plus one dimensional affine manifolds, in which the affine structure, by identifying individual points of space at different times, enables us to define straight lines that represent inertial motions of bodies. The construction of space-time structures begins with geometric objects, a collection of points representing a set of events, i.e. a topologically R^4 differentiable manifold *M* without any additional structure. A class of simultaneous relations between events are then introduced by the partitioning *M* into a family of hypersurface, which represents the simultaneous planes. In order to define the spatial distance between two simultaneous events and the temporal distance between two non-simultaneous events, the spatial and temporal metrics satisfying the laws of Euclidean geometry are introduced. In addition, the identification of individual points on non-simultaneous spaces provides Newtonian space-time with a structure of 'occurring-at-same-place' at different times. This rigging of points across different simultaneous spaces enables us to specify straight lines representing the inertial trajectories of bodies. And the identification of the second time derivative of separation from these straight lines with forces affecting them corresponds to Newton's second law of motion. In this way, the trans-temporal identity of individual points of space provides a foundation that supports the absolute motions of a body, such as uniform and accelerated motions. For, absolute motion is defined as "the translation of a body from one absolute place into another." (Newton 1726, 17)

[14] In Newtonian space-time, the identification of spatial points over time and the distance relations between non-simultaneous events enables us to select privileged trajectories. But a problem is that this posit accepts a *theoretically superfluous structure* of absolute position and velocity. This contradicts with the Galilean relativity principle, the most cherished principle in classical mechanics. In his Corollary V to the laws of motion, Newton himself, recognizing this problem of positing a redundant element in space, presented the belief in the relativity of motion; "When bodies are enclosed in a given space, their motions in relation to one another are the same

can then be constructed by eliminating these concepts from Newtonian space-time while leaving all other structures unchanged.[15] Without the identification of spatial points over time and the distance relations between non-simultaneous events, neo-Newtonian space-time needs a geometric-structure i.e., "connection" that identifies straight trajectories corresponding to inertial motions of a given body. Notice that the inertial effects of a body specify straight trajectories, rather than the other way around:

> Which trajectories are the ones to be called straight? That is, Which represent unaccelerated [inertial] motion? Or again, Which, if followed by an object, would describe the object as unaccelerated? There is nothing in the collection of bare space-time points and their "next to" relations to answer this question. ... Why should one balk at the introduction of the connection – the description of the pattern of straight and curved trajectories – simply as a theoretical construct needed for giving a good theory of the subject matter? The problem is that so far we have not given any non-trivial theoretical interrelations. We have not yet been given any handle on saying which trajectories to count as curved except the one which works by saying which trajectories, when followed by an object, exhibit inertial effects. (Teller 1991, 373-4)

Teller's view then is that space-time geometry does not underpin the law of inertia. Instead, the law of inertia underpins space-time geometry.

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whether that space is at rest or whether it is moving uniformly straight forward without any circular motion" (Newton 1729, 423). This suggests that a class of equivalent inertial trajectories of a moving body underdetermine at which point of space the body is located.

[15] As a modification of Newtonian space-time, Neo-Newtonian space-time restricts the spatial relation between events. Newtonian space provides a kinematical basis to decide whether or not any two events are at the same place, and how much spatial interval two events, simultaneous or not, are separated. To be consistent with the Galilean relativity principle, Neo-Newtonian space-time modifies its kinematical properties. The two events can be said to happen at the same location only after a specific Galilean coordinate, which allows the Galilean boosts, has been chosen. Neo-Newtonian space-time can then be represented as a stack of Euclidean planes, of which the affine structure is isomorphic to the one of Newtonian space-time. Accordingly, the invariant distance between two points is well defined only if the two events occur simultaneously. In this framework, the trans-temporal identity of parts of space has no physical significance any longer.

In the context of the general theory of relativity, the reversal of the direction of explanation within space-time theory is also manifest. In his recent *Physical Relativity* (2005), Brown emphasizes that the geodesic principle in the general theory, which corresponds with the law of inertia, can be derived from the dynamical content of general relativity, rather than from its space-time geometry. More specifically, the geodesic motion of a test particle can be derived from a form of Einstein's field equations, which is a vanishing of the covariant divergence of the stress-energy tensor associated with the body.

Accordingly, an alternative understanding of the workings of space-time theories is suggested, entitled "the dynamical perspective of space-time" (Brown 2005, and DiSalle 2006). According to this view, it is dynamical laws, rather than the mode of existence of space-time, that provide the foundation of space-time geometry.[16] The advocates of this view criticize the traditional understanding of the relation between space-times and dynamical laws. Brown views the influence of the structure of space-time on dynamical laws as "mysterious." The traditional view sees space-time geometry as providing an explanation of "brute facts" that all physical bodies in the universe satisfy the law of motion. Yet, Brown claims that without an understanding

[16] According to Poincaré, "from among all possible groups, we must choose one that will be the standard, so to speak, to which we shall refer natural phenomena" (Poincaré 1905, 70). Newton in the preface of *Principia* emphasized the coordination between geometry and mechanics: "the description of straight lines and circle, which is foundation of *geometry*, appertains to *mechanics*" (Newton 1729, 1). Although space-time geometry stems from our intuition of spatio-temporal relations between events, its aim is to provide a theory which makes sense of the laws of motion.

of how "the coupling between the particles and the postulated geometrical space-time structure" works, the traditional view is not yet a legitimate one:

> [F]orce-free particles have no antennae, that they are unaware of the existence of other particles. That *is* the *prima facie* mystery of inertia in pre-GR theories: how do all the free particles in the world know how to behave in a mutually coordinated way such that their motion appears extremely simple from the point of view of a family of privileged frames? But to appeal to the action of a background space-time connection in which the particles are immersed – to what Weyl called the "guiding field" – is arguably to enhance the mystery, not to remove it. For the particles do not have space-time feelers either. In what sense is the postulation of the 4-connection doing more explanatory work than Moliere's famous dormitive virtue in opium? (Brown and Pooley 2006, 72)

DiSalle also argues that the traditional explanatory scheme fails to account for the workings of space-time.[17] The problem of the traditional view, according to DiSalle, originates from the misunderstanding of space-time as an existent that causes a body to move in accordance with the laws of motion. An analogy contrasting Euclidean geometry and space-time geometry elucidates this point:

> In the case of Euclidean geometry, the laws of nature ... supported the view that we could objectively determine differences in length because they presented no problem for the underlying physical hypotheses about the comparison of rigid bodies. Because the physical foundations of spatial geometry have been relatively clear, only a confused person would ask whether Euclidean geometry is really the cause of differences in length; that the differences can be measured, and that the measured results agree with the Euclidean metric, is all that anyone ever meant by the claim that space is Euclidean. ... [I]t is equally confused to ask whether spacetime is the cause of the distinctions between states of motion that its theory entails. In both cases, the distinctions are postulated through the definitions, not explained, and the appropriate critical question to ask about them is whether the laws of nature allow us to make these distinctions empirically. (DiSalle 1992, 187)

[17] DiSalle (1988) finds the historical roots of the dynamical perspective of space-time from Lange and Thomson' accounts of inertial frame, which is a set of frames of reference with respect to which the laws of motion, such as the law of inertia and acceleration, takes the simplest form. And this line of thought can also be found in Stein (1967): "what matters for Newton's dynamics is that his theory – which includes, of course, the distinction between inertial frames and others – should have a physical application." In other words, what space-time does is to distinguish the inertial frames in which the laws of motion satisfy. In this way, the laws of motion determine space-time, not the other way around.

The success of Euclidean geometry does not come from the fact that its geometric features causally explain spatial measurements, but from the fact that the laws of Euclidean geometry encode "the constraints to which those measurements will conform" (DiSalle 1995, 324). In other words, the measurements of physical space are systematically encoded by means of the definitions of geometry constituting its laws such as the Pythagorean theorem. Accordingly, it is untenable to say that Euclidean space can be viewed as an existing entity. Instead, the success of Euclidean geometry stems from the fact that its laws codify physical measurements and processes. The same thing can be said in the case of space-time theories. The traditional explanatory scheme claiming that the mode of its existence explicates the laws of motion, in Brown's expression, is 'putting the cart before the horse.'

Instead, the secret of the success of space-time theory is the fact that the definitions in terms of space-time geometry are appropriately coordinated with the laws of motion. For example, DiSalle takes Newton's account that "the true and absolute circular motion … may be measured by this endeavour" (Newton 1729, 21) as showing the relationship between dynamical effects and absolute motions.[18]

[18] This relationship between dynamical effects and absolute motions can be found in Newton's famous thought experiment with the bucket and the globe. This experiment is performed with a bucket of water that is suspended by a long cord. The bucket is turned in one direction until the cord is tightly twisted, and the cord is left to untwist in the opposite direction. As the bucket rotates while the cord untwists, the surface of the water in the initial stage is flat, as before the bucket began to move. After a short while, the water recedes from the axis of circular motion because of the friction of the rotating bucket. Forming itself into a concave shape, the water at this moment climbs up the sides of the bucket. Newton claims that the phenomena cannot be systemically explained by relational theory. For when the relational motion of water with respect to the bucket is maximum (as the water rests and the bucket spins), there is no dynamical effect

According to this account, an absolute rotation of a given body is not responsible for the dynamical effect (a force) exerted on the body, but instead the dynamical effect provides a measure of absolute motion:

> I emphasize the role of dynamical laws in order to make it clear that, in asserting that Newton was proposing definitions required by his theory, ... the distinction [between rotation and non-rotation] can be made is an empirical claim that rests on the validity of Newtonian mechanics. ... [T]he fundamental question of Newtonian Scholium was not ... whether absolute space and time really exist. Instead, the question was how the geometrical distinctions implicit in the structure of absolute space could be coordinated with the dynamical distinctions implicit in the accepted laws of dynamics. (DiSalle 1995, 330)

In a similar spirit, Brown and Pooley claim that space-time geometry encodes the essential feature of the motions of a given body:

> For Newton, the existence of absolute space and time has to do with providing a structure, necessarily distinct from ponderable bodies and their relations, with respect to which it is possible systemically to define the basic *kinematical* properties of the motion of such bodies. ... [W]hat is at issue is the arrow of explanation. In our view it is simply more

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on the water. And the ascent of the water is greatest while there is no relational motion of the water with respect to the bucket (as the water and the bucket are spinning together at the same speed).

The point is that the kinematics in relational theory is not consistent with its dynamical effects. In this context, Newton emphasizes kinematics of absolute circular motion with respect to absolute space, which is consistent with dynamical effects: "the ascent of the water shows its endeavour to recede from the axis of motion; and true and absolute circular motion of the water, which is here directly contrary to the relative, becomes known, and may by measured by this endeavour" (Newton 1729, 21).

Another thought experiment, Newton's globe, demonstrates this point more clearly. Newton considered two globes joined together by a cord, which revolve around the common center of gravity in an empty universe. This idealized situation is considered in order to prevent a relationists' possible response by eliminating any bodies to which we can refer to their motions. Even in this case, "we might, from the tension of the cord, discover the endeavour of the globes to recede from the axis of their motion, and from thence we might compute the quantity of their circular motion" (ibid., 22). In other words, the true rotation of a body is not only relative to the contiguous body, but also relative to any bodies in the empty universe. From this two thought experiments, Newton tried to show that the relationists' kinematics is not appropriate because it is inconsistent with dynamical effects: "Therefore this endeavour does not depend on any translation of the water in respect of ambient bodies, nor can true circular motion be defined by such translation" (ibid., 21).

> economical to consider the 4-connection as a codification of certain key aspects of the behaviour of particles and fields. (Brown and Pooley 2006, 73)

When Brown and Pooley consider space-time geometry as codifying certain key aspect of motions of bodies, they refer to the fact that "all the [force-]free particles in the world know how to behave in a mutually coordinated way such that their motion appears extremely simple from the point of view of a family of privileged frames." (ibid.) That is, it refers to dynamical laws, such as the law of inertia and the law of acceleration. Accordingly, the 'connection' identifying straight trajectories of a given body is posited in order to encode its inertial and non-inertial trajectories.

In this way, the dynamical perspective of space-time suggested by Brown and DiSalle considers space-time geometry as being founded on its dynamical laws, not the other way around as traditionally viewed:

> [T]o propose a spacetime theory, at least in the manner of Newton and Einstein, is not to try to explain the observable (the behaviours of a body) by the unobservable (space-time geometry). Rather, it is to define a particular observable process as fundamental, and to use it as the basis for a geometrical picture that makes other observable processes physically intelligible. (DiSalle 1992, 187)

Accordingly, the arrow of explanation in Brown and DiSalle's view is the opposite of the traditional explanatory scheme of space-time.

Although both Brown and DiSalle emphasize dynamical laws as the foundation of space-time geometry, their views differ concerning the substance-relation debate and what constitutes dynamical laws. For the former aspect, Brown, it seems, does not reject the possibility of both substantivalism and relationism within the dynamical perspective of space-time[19]:

> [E]ven when one's ontology *includes* substantival space-time structure, the symmetries of the laws governing material systems are still crucial in such structures gaining operational chronogeometric significance. (Brown and Pooley 2006, 86)

On the other hand, DiSalle explicitly claims that the controversies are misleading attempts to understanding the workings of space-time theories:

> [T]he important question about a spacetime theory is not about how it squares with the ontological categories of substance and relation, but about the correspondence of the theory's fundamental definitions with law-like aspects of our experience. (DiSalle 1992, 188)

These two advocates of the dynamical perspective of space-time also differ over what constitutes the dynamical laws, which underpin the structure of space-time. Brown views the structure of space-time as stemming from the dynamics constrained by the micro-structures of matter ("the laws governing material systems"). On the other hand, DiSalle views dynamical laws as phenomenological laws constraining spatio-temporal measurements ("law-like aspects of our experience"). Although Brown and DiSalle have a different view concerning what constitutes this basic physical process, the common denominator is their emphasis

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[19] Given a clear intuition under the concept of space as void places, it is difficult to get rid of substantivalism, which Newton called "the primary places of things." (Newton 1729) In *de Gravitatione*, Newton characterized the parts of space from our "exceptionally clear idea of extension," by means of "*abstracting the dispositions and properties of a body* so that there remains only the uniform and unlimited stretching out of space in length, breadth and depth ... space can be distinguished into parts whose common limits we usually call surfaces" (Newton 1962, p.132). And even Newton admits the intuition underlying space-time relationism: "It is *only through their reciprocal order and position* that the parts of duration and space are understood to be very ones that they truly are; and they do not have any other principle of individuation beside this order and position, which consequently cannot be altered." (ibid., p.103) But the point of dynamical perspective is that the characteristics of space-time are only available by means of dynamical information. So it seems that these two perspectives are not necessarily incompatible.

on dynamical laws which underpin space-time geometry. The structure of space-time has its foundation in dynamical laws:

> [I]t is appropriate to appeal to the Euclidean symmetries of the forces at work to explain the same behaviour [of particles and fields]. And we simply deny that the Euclidean nature of space can ever be cited as a genuine explanation of these symmetries; *this* would be to put the cart before the horse. (Brown and Pooley 2006, 85)

Again:

> [T]he existence of spacetime is not some additional inference from those [dynamical] laws – any more than the existence of Euclidean space would be a further inference from the claim that spatial measurements are in accord with Euclid's postulates. That is, evidence that supports dynamical laws is not a kind of indirect evidence for the existence of the associated spacetime structure … [T]o believe that spacetime is real is precisely to believe that the physical laws that define its geometrical distinctions are real aspects of the physical world. (DiSalle 1992, 188)

It seems clear that the dynamical perspective on space-time has the advantage of explicating the relationship between space-time geometry and the laws of motion. Given that this view considers that space-time geometry stems from the laws of motion, there is no mystery about a claim that the behaviours of a given body exhibit the geometric structure of space-time. In the last chapter and this section, we have seen that the traditional explanatory scheme has a difficulty in clarifying the relationship between these two main elements of space-time theories. Although space-time geometry is traditionally viewed as providing the foundation of the laws of motion, what is not clear is the connection between these two structures.

> Talk of Lorentz covariance "reflecting the structure of space-time posited by the theory" and of "tracing the invariance to a common origin [of the invariance of space-time]" needs to be fleshed out if we are to be given a genuine explanation here … Unless this question is answered, space-time's Minkowskian structure cannot be taken to explain the Lorentz covariance of the dynamical laws. (Brown and Pooley 2006, 84)

Yet, by placing the foundation of space-time geometry within dynamical laws, the workings of space-time theories can be easily explained.

From the dynamical perspective of space-time theories, we can figure out what Dorato's space-time structuralism misses in understanding the workings of space-time theories. Given that the dynamical laws play a foundational role in space-time theories, neglecting their importance in constructing space-time structuralism will provide incomplete accounts of the development of space-time theories. Although Dorato does not completely neglect the dynamical contents of space-time theories, his account basically emphasizes spatio-temporal structure. By following the traditional explanatory scheme, Dorato's version of structural space-time realism falls short of capturing the physical foundation of space-time theories. In the last section, it was pointed out that the mathematical structures and the ontological scheme of both Newtonian and Einsteinian physics fall short of capturing the workings of these theories. This problem remains in Dorato's account of space-time structuralism.

5. A Modified Version of Space-Time Structuralism

A more plausible version of space-time structuralism than Dorato's needs to clarify the relationships between spatio-temporal relations (which Dorato emphasizes) and the dynamical contents of a theory (which the dynamical perspective emphasizes while Dorato largely neglects). Brown views space-time geometry as codifying "certain key aspects of the behaviour of particles and fields," while DiSalle expresses this relationship as follows:

> [P]articular physical processes, governed by established physical laws, can be represented by aspects of geometrical structure in the universe. And this claim provides the only physically meaningful sense in which the universe can be said to *have* a geometrical structure. More precisely, a claim ... that the structure determined by a particular set of physical laws is the structure of a particular four-dimensional space, expresses the only physically meaningful sense in which the universe can be said to have a space-time structure. (DiSalle 1995, 333)

The issue here is *how* space-time geometry codifies the laws of motion. My claim is that the structural constraints between events, which specify the relationships between events, exhibit the space-time geometry. These structural constraints between events are characterized along the line of structural realism in the sense that structural constraints between events involve the dispositional properties represented as the geometric relation between events without specifying micro-physical foundations underlying the relationships between events as "Nature will eternally hide from us." (Poincaré 1905, 161)

This modified version of space-time structuralism can be elucidated by comparing it with Huggett's relational account of space-time. Huggett's view also tries to clarify the relationship between laws of motion and space-time concepts by means of the relations of the regularity between events:

> *A specification of the totality of relations, masses, and charges of bodies at a time I will call the 'relational state,' or more loosely the 'relations.'* Although it involves facts about non-spatiotemporal properties, it deserves that title because it excludes any non-relational ... spatiotemporal properties; I take it that an honest relationist can endorse relational states as unproblematic relational objects.[20] (Huggett 2006, 47, my italics)

[20] A similar account can be found in Friedman (1983), who characterizes the trajectories of the particles as relational entities: "Suppose we are given the trajectories of the particles whose

Huggett views spatio-temporal properties as stemming from the laws of motion, which are supervenient on the relational regularities between events. According to him, the relational regularities are characterized along Humean lines: "when we attribute lawfulness to a statement we attribute *no more* to it than being a theorem of the 'strongest' (that is, most informative) and 'simplest' axiomatization of the totality of events in the history of the world, past, present and future."[21] (ibid., 43)

Given the relations of regularities between events specified by the laws of inertia or of acceleration, an inertial frame of reference can be constructed by designating a certain rest reference body (such as a fixed star) as the origin of coordinates whose orthogonal axes measures the distance from the reference body: "a frame is 'adopted' to some reference body if it is at rest at the origin of the frame, the axes are orthogonal and distances along the axes equal to the distances from the body." (ibid., 46) We can see, then, that inertial frames are supervenient on the relations of regularities between events. Although the above accounts assume the existence of a

world-lines *T* attempts to specify in its laws of motion (including, perhaps, the trajectories of light rays) and the matter fields or source variables (mass density, charge density, and so on) giving rise to the interactions described by *T*. These entities are relatively observable, and they are precisely the entities that the traditional relationist is willing to admit." (Friedman 1983, 152)

[21] Huggett's characterization of laws is based on the Mill-Ramsey-Lewis best system (MRL) approach. According to this view, the laws of nature are "a theorem (or axiom) in each of the true deductive systems that achieves a best combination of simplicity and strength." Ramsey also claims that the uniformities of laws of nature are "consequences of those propositions which we should take as axioms if we knew everything and organised it as simply as possible in a deductive system." The laws of motion seem to come as the best – simplest, most informative, and the true – summary of information about the phenomena of motions.

moving body in order to characterize inertial frames, Huggett generalizes this perspective to the case where no inertially moving body exists:

> Consider then the class of all frames related by arbitrary continuous spatially rigid transformations of the co-ordinates of adopted frames; this class contains frames in arbitrary states of motion with respect to any reference body, including all the inertial frames. (Huggett 2006, 46)

In contrast to the traditional account of the concepts of inertial frames and of acceleration as spatio-temporal properties, Huggett maintains that these concepts are founded on the regularity relations between events comprising the "relational history":

> [S]ince these laws supervene on the relational history and since they pick out the inertial frames, I claim that the inertial frames (and hence absolute accelerations) supervene on the history of relations: inertial frames are the frames in which the laws that supervene on the history of relations hold; absolute acceleration is acceleration in the frames in which the laws that supervene on the history of relations hold. Thus nothing but relations are needed to give an account of the absolute quantities, and hence dynamical state, of Newtonian mechanics. (ibid., 48)

Taking off from this, my version of space-time structuralism considers the relations of regularity between events as the essential elements that explain the success of Newtonian physics. But, there is a major difference between my view and Huggett's. Although I agree of course that inertial frames are determined by the law of inertia, it is difficult to accept that these laws of motion are *nothing but* "theorem[s] of the strongest and simplest axiomatization of the totality of events in this history." (ibid., 43) Heggett follows Mill-Ramsey-Lewis (MRL)'s approach in holding that laws only summarize our observations. Therefore, his view faces the same problem as

MRL's own approach – the inability to distinguish accidental generalizations from genuine laws. According to Dorato:

> Is this [summarizing observations, which best combine simplicity and strength] the only reason that accidental generalizations would be excluded from axiomatic systems? I do not believe so, because the concept of strength is unfailingly dependent on our cognitive purposes.[22] The selectivity that we are attempting to clarify is in fact not only tied to the "compressibility of information" permitted by a scientific law, ... but also to the fundamental, although too often overlooked assertion that *the truths to which we aspire, whether in science or in daily life, must be interesting.* (Dorato 2005, 91)

Hence, it seems that regularities between events – merely based on epistemic foundation – are too weak to characterize the law of inertia.

This weakness can be seen more clearly if we consider Newton's own account of the law of inertia, which is easily seen to be inconsistent with Huggett's account. According to Newton, the law of inertia attributes "the power of resisting by which every body ... perseveres in its state either of resisting or of moving uniformly straight forward." (Newton 1726, 404) Here, the law of inertia postulates a tendency or an observable disposition of inertia – a disposition that resists acceleration inertial mass and arises from a body's inertial mass. Although the mechanism of inertia is not further analysable in terms of the body's atomic structure, its dispositional property can be clarified. According to Dainton:

> What do inertial effects consist of? Typically, they consist of internal stresses between the component parts of a body. Objects follow inertial paths unless acted on by a force (which is created by gravity, magnetism, or an expenditure of energy). When objects are forced off their inertial path, this is typically achieved by applying force to one part of the object only, which sets up tensions *within* the object: that is, some parts of the object start exerting

[22] Given that both standards to be genuine laws, simplicity and strength, characterize "the axiomatization of the totality of events" essentially relative to our knowledge, rather than to the real physical world, it seems that Huggett's approach depends essentially on epistemic foundation.

> forces on other parts. In the rotating globes case, the tension is registered in the cord, which exerts a force on the globes (whose inertial motions are tangential to their circular motion). (Dainton 2001, 191-2)

This dispositional property is what distinguishes genuine laws of nature from accidental generalizations. As Bigelow, Ellis and Lierse (1992) put it:

> We claim that among the essential properties of a property there is the propensity or disposition of anything having it to show a certain kind of behaviour in a particular context. What science studies and codifies are the manifestations of these dispositions. (Bigelow, Ellis and Lierse 1992, 378)

This claim that genuine laws involve dispositional properties, then, overcomes problems that defeat MRL approach. And given that the law of inertia involves this dispositional property, which is over and above regularities between events, I reject Humean approach to dynamical laws advocated by Huggett.

I should emphasize that just as Huggett sees that the regularity relations between events as characterized by a "relational history," these dispositional properties are also characterized by "the relational structure of the world of experience and of science." (Dorato 2005, 111) Because of Newton's weak principle of equivalence – "the accelerative gravity, or the force that produces gravity is the same in all bodies universally." (Newton 1729), the micro-structure of the inertia of a given body is irrelevant in the context of law of inertia. Yet, the relational histories of events specified by the law of inertia, as Newton implied, stem from the dispositional property of inertia, which makes succeeding events occur. The law of inertia stems from this property manifested by geometric relations between events:

Suppose we are given the trajectories of the particles whose world-lines *T* attempts to specify in its laws of motion (including, perhaps, the trajectories of light rays) and the matter fields or source variables (mass density, charge density, and so on) giving rise to the interactions described by *T*. These entities are relatively observable, and they are precisely the entities that the traditional relationist is willing to admit. (Friedman 1983, 152)

So, I suggest that this relational history of events, which is manifested by a dispositional property involved within the laws of motion, captures the essence of dynamical laws. I call this the structural constraints between events.

The manifestation of dispositions codified by scientific laws essentially involves a relationship between different properties, in accordance with the fact that the kind of knowledge permitted by science is essentially relational and structural. This affirmation is justified not only inasmuch as the meaning of theoretical terms is implicitly defined by the context of the theory in which they appear, but also because ... the mathematical language we use to refer to theoretical entities furnishes essential information on the network of relationships that these entities exemplifies. (Dorato 2005, 115, my italics)

Along these lines, my modified space-time structuralism claims that what dynamical laws involve are the relational and structural constraints between events, rather than the relation of regularity between events. By viewing these structural constraints between events[23] as the essential elements of the laws of motion, a modified space-time structuralism is produced that is along the lines of structural realism, rather than one that like Huggett's emphasizes epistemic constraints over events. Hence,

[23] The notion of "events in space-time" in my modified space-time structuralism requires clarification. On my account, as pointed out in note 5 in this chapter, events are things occurring in the infinitesimal place and time. My account shares with substantivalism and relationism – a view of an event as an idealized concept being pointlike rather than having any spatio-temporal extension. But the account differs from those given by traditional substantivalism and relationism. From the perspective of substantivalism, events are occurring at given space-time points. And the spatio-temporal relations between events, according to Earman (1989:12), are "relations among substratum of ... spacetime points that underlie events." On the other hand, for relationism, the relations between events are direct without depending on space-time points that underlies events. Yet, these traditional views by no means consider these relations between events as being constrained by dynamical laws. In my view, laws play an essential role in that events stands in spatio-temporal relations in accordance with dynamical laws.

the difference between Huggett's and my view can be found in the difference that what involves dynamical laws. Huggett views dynamical laws as involving the relations of regularity, while I consider the laws as involving the structural constrains between events. The relations of regularity mean that the relations between events are specified by means of empirical regularity of Humean line. On the other hand, the structural constraint between events involves the dispositional properties represented as the geometric relation between events without specifying underlying micro-physical foundations.

Another example supporting my account, rather than Huggett's, can be found in the dynamical perspective of space-time. Brown maintains that the laws of motion stem from the dynamical properties of the micro-physical structure of matter configurations. In the case of general theory, the inertial trajectory of a body can be derived from the conservation principle, i.e. the vanishing of covariant divergence of the stress energy tensor field $T_{\mu\nu}$. Given that the conservation principle does not apply only to particular kinds of physical events but to all kinds of physical events occurring in the universe, the principle is universal in the sense that "the antecedent or referent class is a broad ontological category." (Bigelow, Ellis, and Lierse 1992, 385) In this way, Brown's account can also be interpreted as being odds with Humean approach of dynamical laws endorsed by Huggett. Given that the relational history specified by inertial motion within the general theory are derived by an universal principle, it seems to be difficult to advocate Humean approach of dynamical laws. Instead, the law of inertia in the general theory can be viewed as the structural constraint between events, which stems from the micro-physical structures of material bodies. In other words, the law of inertia provides a dispositional property of movement of a body, which is represented as the geometric relations between events without specifying underlying micro-physical foundations.

Given that the laws of inertia by no means refer to the material constitution of a body in a motion, what underlies the relations of regularity between events is debatable. There have been attempts to explain the law of inertia by means of quantum field theories and string theories. However, these attempts remain theoretical speculations without empirical support. Some critiques such as Smolin (2006) and Woit (2006) claim that these attempts are comparable to "epicycle on epicycle." Given this lack of empirical support, it is not unreasonable to doubt that these super-microscopic theories can be regarded as legitimate empirical science. Although it cannot be denied that inertia supervenes on a specific microscopic structure, it seems that what we can know are the relationships between events, which are specified by the laws of motion. Furthermore, given the fact that inertia is universal, i.e. does not depend on the material constitution of particles, the law of inertia needs no microscopic structure that plays a role in explaining the behaviour of a given body. In the case of classical theories, the advocates of the dynamical perspective, on the contrary, views that the structural constraint provided by the laws of motion is the essential part of space-time theories – the part which makes its empirical success possible:

> Like all physical geometry, spacetime theory explains phenomena of motion just to the extent that it exhibits the structural constraints to which the phenomena conform. (DiSalle 1995, 332)
>
> [A] claim such as Minkowski's (1908), that the structure determined by a particular set of physical laws is the structure of a particular four-dimensional space, expresses the only physically meaningful sense in which the universe can be said to have a space-time structure. (ibid.)

In the same spirit, Brown and Pooley claim:

> [I]t will be instructive to acknowledge that in many contexts, perhaps in most contexts, one should not appeal to the *details* of the dynamics governing the microstructure of bodies exemplifying relativistic effects when one is giving a constructive explanation[24] of them. *Granted that there are stable bodies*, it is sufficient for those bodies to undergo Lorentz contraction that the laws (whatever they are) that govern the behaviour of their microphysical constituents are Lorentz covariant. (Brown and Pooley 2006, 82)

This structural characterization of the laws of motion can also be found in Eugene Wigner, who wrote that "the laws of nature provide a structure and coherence to the set of events." (Wigner 1967, 17) And also:

> It is good to emphasize at this point the fact that the laws of nature, that is, the correlations between events, are the entities to which the symmetry laws apply, not the events themselves. Naturally, the events vary from place to place. However, if one observes the positions of a thrown rock at three different times, one will find a relation between those positions, and this relation will be the same at all points of the Earth. (ibid., 19)

[24] "A constructive explanation" is based on a "constructive theory," which Einstein characterized as an attempt to build up "a picture of the more complex phenomena out of materials of the more simple scheme." (Einstein 1919) The kinetic theory of gases that seeks to reduce thermal process to movements of molecules is a typical example. The aim of constructive theories is to achieve the underlying physical reality by understanding a group of natural process. In contrast, principle theories start from some general empirical regularities, which are elevated to the status of postulates. Special relativity and thermodynamics are typical examples. The elements which form their basis are not posited to show natural processes. Such a theory aims to explain phenomena by showing that they necessarily occur in accordance with the postulate. Since principle theories are concerned with a certain level of generalization of phenomena, their elements themselves do not necessarily correspond to underlying physical reality. Yet, it has been pointed out that this distinction is matter of degree, rather than absolute.

This characteristic of the laws of motion has been exhibited by Weinert as captured by under the structuralist view of laws[25]:

> We have spoken of laws of nature and laws of science without invoking classes of objects. Laws have merely been characterized in terms of structural features of physical systems. But material objects move within physical systems and are subject to their laws. We can redescribe what has been said about laws of nature from the perspective of individual objects. From the perspective of an object within the framework of a physical system (being accelerated from rest to a velocity v, ...), a law of nature can be seen as imposing structural constraints on the physical behaviour it is permitted to display. (Weinert 1993, 168)

For example, the law of inertia relates one event to another by specifying the geometric relationship between non-simultaneous events: "[E]very body continues in its state of rest, or of uniform motion in a right line,[26] unless it is compelled to change that state by force impressed upon it." (Newton 1729, 17) A given body's state of motion develops to other such states in accordance with the law. In other words, the law of inertia describes the evolution of physical systems by specifying

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[25] Weinert's structuralist account of the nature of laws is proposed to take a third way between the "Necessitarian view" and the "Regularity view." The former claims that the laws are supported by the relations among intrinsic properties of individual physical objects. In contrast, the latter maintains that laws of nature are contingent regularities, which come from inferences from a set of data. A major problem of the Necessitarian view is that law statements do not refer to essential properties, natural processes and existing objects. And in case of Regularity view, as pointed out, only contingent regularities are not sufficient to capture the nature of laws of science. To take a middle ground between these two troubled views, Weinert suggests a structural view of the laws of nature which claims that the laws of nature are based on structural properties which show the networks of interdependence of many properties and relations, which appear in a given scientific theory. In other words, the lawlike statements express structural information of a given physical system which is formulated as theoretical structure. (Weinert 1993)

[26] Within the modern geometric framework, Newton's inertial motions are represented by geodesics. A geodesic is defined as a body's curve that continues to parallel to itself. Accordingly, within this framework, the law of inertia states that a body unaffected by any external forces moves in a way that the tangent vectors to its trajectory remains parallel to itself. The thesis of my dissertation is that this structural constraint, which is expressed as the geodesic equation of motion plays an essential part that captures the continuity in the theory-change from Newtonian to Einsteinian physics (both the special and the general theory).

the relationship between the states of a given body's motion over time, which originates from the dispositional property of inertia, as pointed out earlier. Yet, the law of inertia by no means involves underlying mechanism whatsoever which explains *why* a given body follows a straight trajectory.

The law of acceleration also dictates the relationship between the states of a given body's motion over time, which Wigner described as "the correlations between events." (Wigner 1967, 19) The law of acceleration is concerned with the change of motion subject to forces exerted on a given body, such that its acceleration is proportional to and in the direction of "the motive force impressed." Although the law of acceleration involves a set of forces exerted on a given body and its mass, it does not involve any specific detailed mechanism whatsoever explaining why the body follows a curved trajectory. The law of acceleration specifies, instead, just the relationship between events.[27]

These characteristics of the laws of motion could be employed to support either Huggett's or my view. Yet, along with his characterization of the laws of inertia and acceleration, Newton considered the law governing gravity as *more than* "a theorem of the strongest and simplest axiomatization of the totality of events." He instead held that while the causal influence of gravity really exists, it is enough to explain

[27] An accelerating motion of a body, within the geometric framework, is represented as a curve that is not geodesics. The curvature of its trajectory measures the magnitude of the acceleration of the body, and the total force acting on the body. In this way, the relationships between events codify all information encoded in the laws of motion.

the behaviours of bodies through the laws of motion specifying the relations between events without referring to any underlying mechanism:

> I have not as yet been able to deduce from phenomena the reason for these properties of gravity, and I do not feign hypothesis. ... *It is enough that gravity really exists and acts according to the laws that we have set forth and is sufficient to explain all the motions of the heavenly bodies and of our sea.* (Newton 1726, 943, my italics)

Another dynamical principle[28], the principle of relativity, which plays a crucial role in the development from Newtonian to Einsteinian physics, can be characterized in a similar manner. According to Wigner, the principle of relativity provides a constraint over the correlations between events in that it provides a further structure over the laws of motion: "the correlations between events, are the entities to which symmetry laws apply, not the events themselves." (Wigner 1967, 19) This principle states that the dynamical laws obeyed by a given body cannot distinguish whether they are with respect to a rest or any uniformly moving frames. In other words, the physics of a body at rest and one moving uniformly is exactly the same. In this way, the principle of relativity provides additional constraints over dynamical laws, such as the law of inertia and acceleration, by identifying apparently distinct states of motion (the state of rest and uniform motion). This structural characterization is manifest in Einstein:

[28] Two ways of providing dynamic information are differentiated in this thesis: (1) dynamic laws and (2) dynamic principles. These two notions are different in two different ways. The first involves the way they are expressed, rather than their contents. Dynamic laws, such as Newton's three laws of motion, are written quantitatively – so easily translated into mathematical equations, while dynamic principles, such as the principle of relativity, and equivalence, are written qualitatively. The second way in which they are different is that, while a dynamic law imposes a structural constraint on events, a dynamic principle, on the other, provides a further meta-level constraint over laws. Of course since the laws in turn constrain events, dynamic principles also constrain events – but unlike dynamic laws they do so indirectly via those laws.

> The principle of relativity, or, more exactly, the principle of relativity together with the principle of the constancy of velocity of light, is not to be conceived as a "complete system", in fact, not as a system at all, but merely as a heuristic principle which, when considered by itself, contains only statements about rigid bodies, clocks, and light signals. It is only by requiring relations between otherwise seemingly unrelated laws that the theory of relativity provides additional statements. (Einstein 1907, quoted from Brown and Pooley 2006, 74)

In the above account, Einstein also characterized the principle of the constancy of speed of light as a structural one. The principle of the constancy of speed of light imposes a constraint over the dynamics of a given body. According to Norton, the principle of the constancy of speed of light specifies "a special velocity at each event." (Norton 2000) In this way, the dynamical principles provide the constraints over the relationships between events.

My view is, then, quite different from Dorato's version of space-time structuralism in that it states that the structure of space-time stems from dynamical laws. It is also different from Huggett's view in that dynamical laws encapsulate the structural constraints over events. Although I am sympathetic to Brown's view which emphasizes the micro-foundation of dynamical laws, my view admits only the structural characteristics of the dynamical principles which involve the relations between events without referring to their underlying mechanism. By providing a set of constraints over geometric trajectories of a moving body, dynamical principles specify the correlation between events. Thus, my view agrees with that of d'Espanat:

> A general agreement seems nowadays to exist among physicists that the aim of their scientific investigations is to discover structural relationships between individual "happenings." (d'Espanat 1971, 372)

A modified version of space-time structuralism views the structure of space-time as being founded on these structural properties of dynamical laws. So far, two structures of space-time theory are specified. Firstly, space-time concepts encode the invariant spatio-temporal relations between events, which Dorato emphasized in his version of space-time structuralism. In other words, space-time concepts involve objective spatio-temporal relations between events. Secondly, the laws of motion exhibit relations of regularity between events. Spatio-temporal relations between events are associated with the regularities between events, which are captured by dynamical laws. A modified space-time structuralism claims that the former stems from the latter.

6. The Case for a Modified Space-time Structuralism in Newtonian Space-Time

It can be argued that the structure of Newtonian dynamics can be fully captured within a modified version of space-time structuralism. Newtonian dynamics is founded basically on the concepts of motion and force. In the preface to the *Principia*, Newton stated that "rational mechanics is the science, expressed in exact propositions and demonstrations, of the motions that result from any forces whatever and of the forces that are required for any motions whatever." (Newton 1726, 382) Accordingly, the basic problem of rational mechanics is to "discover the force of nature from the phenomena of motions and then to demonstrate the other phenomena from these forces." (ibid.) The concept of force is, in other words, characterized in relation to the concept of motion. Newton introduced two kinds of force, inherent and impressed force, in the Definition 3 and 4, and we can clearly see that the concepts refer to motion:

> **Definition 3**: Inherent force of matter is the power of resisting by which every body, so far as it is able, perseveres in its state either of resting or of moving uniformly straight forward. (ibid., 404)

> **Definition 4**: Impressed force is the action exerted on a body to change its state either of resting or of moving uniformly straight forward. (ibid., 405)

These concepts of force are introduced without providing any clue about their nature or inner mechanism. This is understandable given that in the Definitions Newton provided general frameworks underlying his programme without specifying which force, such as gravity or magnetic force, he dealt with. Yet this attitude continues even when Newton dealt with the particular force of gravity. In the concluding section, the General Scholium, we encounter Newton's famous slogan against contriving fictions of the properties of force, i.e. "Hypotheses non fingo":

> Thus far I have explained the phenomena of the heavens and of our sea by the force of gravity, ... I have not as yet been able to deduce from phenomena the reason for these properties of gravity, and I do not feign hypotheses. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. ... And it is enough that gravity really exists and acts according to the laws that we have set forth and is sufficient to explain all the motions of the heavenly bodies and of our sea. (ibid., 943)

Instead, the concepts of the two forces, as pointed out in the aforementioned Definitions, are characterized with reference to the concept of motion, that is, to change of place. And the definitions become the basis for the first and the second laws of motion, which in turn provide the relationship between the force and change in the quantity of motion:

> **Law 1**: Every body perseveres in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by force impressed. (ibid., 416)
>
> **Law 2**: A change in motion is proportional to the motive force impressed and takes place along the straight line in which that force is impressed. (ibid.)

Within these laws of motion, it is essential to distinguish (uniform rectilinear) inertial motions from non-inertial ones, i.e. accelerated motions. The former occurs in the absence of any external impressed force, whilst the latter occurs due to the action of an external force. Newton saw that any motion occurs because of combinations of these two forces. In other words, any motion can be decomposed into an inertial element, which occurs due to the inherent force, and a non-inertial element, which occurs due to the impressed force: "Projectiles persevere in their motions, except insofar as they are retarded by the resistance of the air and are impelled downward by the force of gravity." (ibid., 416) In this way, the laws of motion, without referring to the properties or mechanism of inherent or impressed force, describe the relations of regularity between non-simultaneous events.[29] The

[29] Modified space-time structuralism could be criticized based on Newton's well known attempt of providing a Cartesian style of explanation of gravity in terms of pressure gradients in some plenum. However, recall that in spite of his attempt, this mechanism is irrelevant in Newtonian mechanics, and its working parts are structurally characterized laws of motion.

distinction between inertial and non-inertial motion is effected by means of the geometric relations between events, i.e. whether they form either uniform rectilinear or curved trajectories, which Wigner called "the correlations between events."

Kinematical properties are then required in order to quantify motion. In other words, the state of motion can be specified through kinematical properties, such as locations, and spatio-temporal intervals, which have a Euclidean structure.[30] Quantitative studies of motion are thus based on the kinematical properties which constitute space-time structure.

We can see, then, that the concept of space-time is founded on dynamical information. This has been pointed out by modern commentators, such as Lange (1884) and Thomson (1885), and recently resuscitated by Torretti (1983) and DiSalle (1995). These commentators have emphasized that legitimate kinematical properties, can be captured only by reference to the laws of motion:

> Newtonian time, like Newtonian space, is accessible only with the assistance of Newton's dynamical principles. (Torretti 1983, 12)

And:

[30] The conceptions of kinematics are constructed by means of geometry, since places and motions are defined with points and lines. And geometry plays a crucial role within Newtonian dynamics due to the weak principle of equivalence. The principle maintains that the trajectories of freely falling bodies are the same regardless of its internal constitution, i.e. whether the physical or chemical composition of bodies are aluminium or gold. Newton in his *Principia* explicitly endorsed the weak principle of equivalence: "the accelerative gravity, or the force that produce gravity is the same in all bodies universally." (Newton 1729) The "weak" is included in the principle in order to distinguish it from other versions of principle of equivalence, such as strong principle of equivalence or Einstein's principle of equivalence.

> [T]he fundamental question of Newton's Scholium was not whether space and time are absolute, or whether absolute space and time really exist. Instead, the question was how geometrical distinctions implicit in the structure of absolute space could be coordinated with the dynamical distinctions implicit in the accepted laws of dynamics. (DiSalle 1995, 330)

The close connection between dynamics and kinematics has also been mentioned by contemporary physicists such as Penrose, where Aristotelian physics is referred to as Newtonian physics without considering Galilean relativity:

> [L]et us ... try to see what kind of spacetime structure would have been appropriate for the dynamical framework of Aristotle and his contemporaries. In Aristotelian physics, there is a notion of Euclidean 3-space $\mathbf{E}^3$ to represent physical space, and the points of this space retain their identity from one moment to the next. *This is because the state of rest is dynamically preferred, in the Aristotelian scheme, [over] all other states of motion. We take the attitude that a particular spatial point, at one moment of time, is the same spatial point, at a later moment of time, if a particle situated at that point remains at rest from one moment to the next.* (Penrose 2004, 383, my italics)

The above dynamical perspective can also capture the way that absolute time is posited within Newtonian mechanics. One of the important characteristics of Newton's absolute time, according to Newton, stems from the objective fact that we can decide the "order of succession" of 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; and they do not have any other principle of individuation beside this order and position, which consequently cannot be altered.[31] (Newton 1962, p.103, trans. by Torretti, my italics)

[31] The characterization of space-time from the orders and positions of events can be contrasted with substantival account of space-time: "spatiotemporal relations among such events and processes are parasitic on the spatiotemporal relations inherent in the substratum of space-time points and regions" (Earman 1989, 11). But it seems that Earman's characterization of the meaning of absoluteness does not come from the reading of the Scholium. Earman's paragraph by paragraph commentaries provided before his summarization of the senses of absoluteness never refer to Newton's phrase which can be read as a claim that space-time is a substance.

In characterizing the parts of space and the moments of time, Newton opposed individuating properties above and beyond orders and positions of physical events. Newton again made this clear in *Principia*: "all things are placed in time as to order of succession; and in space as to order of situation." (Newton 1729, 19) Another important characteristic of absolute time is uniformity of temporal duration: absolute time "in itself and from its own nature flows equably without regard to anything external".[32] (ibid., 17) These characteristics of absolute time are only accessible through dynamical information since the law of inertia plays an essential role in determining the structure of absolute time. This is because a physical process keeping Newtonian time is identified as a straight uniform motion of a given body, which traverses equal distances in equal times. The uniform flow of time is required to maintain the law of inertia, because straight uniform trajectories can be turned into curved ones by selecting non-uniform time intervals. We can see here that the concept of absolute time, which sets the standard of swiftness and slowness of motions stems from a dynamical law that relates the events over time:

> The critical question is not whether Newton successfully proves that "[the existence of] time is absolute" – for this was never his purpose – but whether his definition of absolute time is a good one. And in the context of the *Principia*, this amounts to asking, does this definition have objective physical content? That is, can we define equal intervals of elapsed time without recourse to some arbitrary standard? Is there a good physical definition of what it means for time intervals to be equal, even if no actual clock measures such interval

[32] The phrase "time *flows* equably" might be interpreted as accepting the existence of medium or substratum underlying the process of time. But Newton made it clear that the flow of time does not presuppose certain medium or substratum, within which the flows take place. And the structure of time does not depend on the motion of any mechanical clock or standard of regular rotating bodies. The phrase "time flows equably," without the ontological underpinning, is then understood as the structure of time, that is, the passage of equal intervals of time. So, the characteristic of absolute time is the structure of uniformity of the temporal duration, rather than a specific mode of existence of time.

exactly? The answer is "yes": this is precisely the definition of time implied by Newton's laws of motion, which postulate an objective distinction between inertial motions, which cross equal distances in equal times, and motions that are accelerated by an impressive force. In short, an ideal clock that keeps absolute time is simply an inertial clock. (DiSalle 2002, 39)

Furthermore, the concept of simultaneity, i.e., the existence of globally defined temporal intervals between any events is related to dynamical information: "we do not ascribe various durations to the different parts of space, but say that all endure together. The moment of duration is the same at Rome and at London, on Earth and on the stars, and throughout all the heavens[33]." (Newton 1962, 137) Brown views this property of time as stemming from a dynamical law in a sense that this feature is related to positing a force acting at a distance like gravity:

In the rarified Newtonian world of *free* particles moving in Euclidean 3-space, there is no privileged notion of simultaneity, even when viewed with respect to the frame at rest relative to Newton's hypothetical absolute space.

It follows that Newtonian simultaneity is a by-product of the introduction of forces into the theory. Indeed, Newton spread time through space in inertial frames in such a way that actions-at-a-distance like gravity are instantaneous and do not travel backwards in time in some direction. (Brown 2005, 20)

Thus the kinematical properties (Newtonian space and time) are required in order to encode the relations of regularity between events, i.e. inertial and non-inertial motions, which are specified by dynamical laws.

[33] Absolute simultaneity between two events involves that there exist objective facts regarding whether or not two events occur at the same moment. The structure of absolute simultaneity enables us to partition every event into simultaneous classes. Accordingly, absolute time is characterized as absolute simultaneity and the unique temporal metric between events. From these two characteristics, the temporal intervals between any two events e_1 and e_2, whether simultaneous or not, are well defined. If a Cartesian coordinate system is used to represent Newtonian space-time, the coordinates of x, y, z, and t is generally identified as three spatial positions and a temporal moment.

Up to now, it has been argued that the essential aspect of both Newtonian dynamics is the inertial trajectories of a given body, which relate events over time. And this dynamical information determines which structure of space-time is appropriate to make sense of dynamical schemes at issue. While the state of rest within Newtonian dynamics requires a kinematical property of spatial points enduring over time, an equivalent class of inertial motions within neo-Newtonian (Galilean) dynamics requires an equivalence class of spatial points. Newton characterized absolute space as a set of locations, which are "similar and immovable"[34]: "Absolute space, in its own nature, without relation to anything external, remains always similar and immovable." (Newton 1729, 17) This phrase can be interpreted as providing a kinematical property of absolute rest:

> [T]here is a unique, correct way to make the identification so that for any two events e_1 and e_2, even ones lying in different instantaneous spaces, it is meaningful to ask, Do e_1 and e_2 occur at the same spatial location? (Earman 1986, 10)

By identifying the locations of events as time passes, a body's being truly at rest is a well-defined concept in Newtonian space-time. Because of the concept of true rest of events, spatial distances between any two events, whether or not the events occurs at the same time, are also well defined. In this kinematical framework,

[34] The phrase "similar and immovable" can be interpreted as endorsing the conception of absolute space as substance. But as following quotation shows, Earman interprets the phrase "similar and immovable" as a structural claim. Earman in this context considers absolute space as "a theoretical entity," which provides the explanation of phenomena of a given body's motions (ibid.). In other words, the "similar and immovable" feature of absolute space is treated as a kinematical property which enables us to define absolute rest and spatial length between two events. At this point, Dorato's version of space-time structuralism would views the kinematical property as stemming from the structure of space-time. On the contrary, the dynamical perspective of space-time considers the kinematical property as claiming that "there is a real difference between motion and rest in the same absolute place over time." (DiSalle 2002)

absolute motion can be defined as "the translation of a body from one absolute place to another." (Newton 1729, 11)

However, this kinematical property is not supported by the dynamical information captured by the principle of Galilean relativity, one of the most cherished principles in classical mechanics. In his Corollary V to the laws of motion, Newton himself, recognizing a problem in positing the kinematical property of absolute rest, showed his belief in the relativity of motion: "The motions of bodies included in a given space [i.e., inertial frame] are the same among themselves, *whether that space is at rest or whether it is moving uniformly straight forward* without any circular motion." (Newton 1729, 29) This suggests that a class of equivalent inertial trajectories of a moving body underdetermine at which point of space the body is located. At this point, we can clearly see the inconsistency between kinematics positing distinguishable individual points of space and the Galilean relativity principle of motion, which identifies individual points of space. Given that this tension is based on his rejection of certain privileged trajectories in the structure of space, it is doubtful that trans-temporal identity of individual points of space is what Newton actually intended in his overall framework. Contemporary commentators such as Slowik and Penrose point out that given his lack of sophisticated mathematical machinery, Newton had no choice but to employ kinematical properties, which are not supported by the dynamical laws at issue:

> [S]ince Newton was intent on allocating the requisite geometrical structure to delineate inertial motion, and since "absolute spatial position" represented the best *available means*

of reaching goal, Newton would appear to have had no other choice but to violate the empirical import of Galilean relativity through the installation of this absolute structure. When Newton was faced with the dilemma of accepting either a theory too weak to render inertial motion coherent or one too strong to rationalize Galilean relativity, he chose the latter – concluding that too much is better than incoherent! (Slowik 2000, 38)

Along these lines, we can also see that the geometry of space-time is specified by the transformational rules between a set of dynamically equivalent inertial frames. It was noted earlier that a set of inertial frames is determined by dynamical laws, which exhibits the regularity relations between events. Transformational rules hold between these coordinates. And these transformational rules reveal the geometry of space-time through their symmetry properties.[35] In Cartesian coordinate systems, the spatial symmetries of Newtonian space-time can be written as $\mathbf{x} \rightarrow \mathbf{x}' = \mathbf{R}\mathbf{x} + vt + C_1$, where $\mathbf{x}$ consists of x, y, z components, $\mathbf{R}$ is a constant rotation matrix in SO(3) and C_1 are real numbers. Temporal structure can also be characterized through the symmetry under a group of temporal translations, which actually represents Newton's characterization of time: "absolute, true, and mathematical time, of itself, and from its own nature, flows *equably* without relation to anything external."

[35] The characteristic groups enable us to sort out the essential elements of spatio-temporal relations that characterize space-time. The dynamical perspective considers the movements of an idealized rigid body as underlying the group. The invariance of the laws of motion under a group of spatial translations of the body characterizes the structure of space. In the same way, the invariance of the laws of motion under a group of spatio-temporal transformations characterize the structure of space-time. Since space-time geometry is decided by the invariants of groups of transformations, the geometry of space-time can be characterized by its symmetries. A specific symmetry, within group theoretic formulation, is defined as invariance under a specified group of transformations. In the coordinate system formalism of space-time, the transformation between coordinate systems that represents reference frames form a group. Note that the coordinate systems are determined by the motion of a given body, that satisfies the laws of motion. And the symmetries of space-time is determined by the invariant geometric structures independent of choosing any specific reference frame.

(Newton 1729, 17) This uniformity can be written as $t = t + C_2$, where t and C_2 are real numbers. These spatial and temporal symmetries display the geometry of space-time. The spatial and temporal intervals between two events remain invariant under the aforementioned coordinate transformations, and the symmetries allow mappings of space-time onto itself preserving absolute simultaneity and affine connection. In this way, space-time geometry encodes the invariance of laws.

6. Conclusion

In the previous section, we have seen that the relationships of regularity between events underpin inertial frames and space-time geometry. By emphasizing that the working parts of space-time theories are the structural properties of dynamical laws, a modified space-time structuralism has the advantage of clarifying the way that dynamical laws are associated with spatio-temporal relationships. In other words, space-time geometry is founded on the structural properties of dynamical laws, which exhibit the regularity relations between events.

Dorato's version of space-time structuralism stresses that spatio-temporal relations between events consist of one essential part of space-time theories. According to the dynamical perspective of space-time, the spatio-temporal relations between events stem from the dynamical laws representing inertial or non-inertial trajectories of a given body. A modified space-time structuralism incorporates the strengths of space-time structuralism and of the dynamical perspective of space-time, such that it views the structural properties of dynamical laws as the essential elements of space-time theories.

Given the strengths and the weaknesses of Dorato's space-time structuralism, this chapter attempted to develop a modified version of space-time structuralism. Dorato's account captures a common element shared by substantivalism and relationism, that is, the relational property of space-time. On the other hand, the weakness is that by maintaining a central assumption of the traditional explanatory scheme of space-time, Dorato's version of space-time structuralism is insufficient to capture the working part of space-time theories i.e. the dynamical laws of space-time theories, as we have learnt from the dynamical perspective of space-time. A modified version of space-time structuralism attempted to integrate the strengths of space-time structuralism and the dynamical perspective of space-time. What is necessary for a plausible version of space-time structuralism is to comprehend the interrelationships between spatio-temporal relations, which Dorato emphasizes, and the dynamical contents of a theory, which the dynamical perspective emphasizes. In order to propose a modified version of space-time structuralism, which incorporates the lessons of the dynamical perspective, it was necessary to clarify the interrelationship between spatio-temporal relations and dynamical laws. My version of space-time structuralism emphasizes the relations of regularity between events, which underpin inertial frames and space-time geometry. In this way, a modified space-time structuralism has the advantage of clarifying the way that dynamical laws are associated with spatio-temporal relationships. Given that the essential parts of space-time theories are the structural properties of dynamical laws, i.e. the regularity relation between events, this provides the correct perspective from which to view the theory-change from Newtonian to Einsteinian physic. In the following chapters, we will see that the modified space-time structuralism supports an evolutionary view of this development, rather than a 'revolutionary' one.

Chapter 3

The Structuralist Account of the Development of the Special Theory of Relativity

1. Introduction

This chapter aims to provide a structuralist account of the theory-change from Newtonian mechanics to Einstein's special relativity – one based on the space-time structuralism developed in the previous chapter. The thesis is that the evolutionary development exhibited in this case can be brought into uniquely sharp relief when viewed from my modified space-time structuralism.

As pointed out in the first chapter, it is not at all straightforward to see the continuity in the theory-change given that there are significant differences between Newtonian and Minkowski space-times.[1] However, by viewing their inertial structure[2] as the

[1] In the case of Newtonian space-time, the invariant spatio-temporal relations between any two events e_1 and e_2 can be selected as follows; (1) whether e_1 and e_2 are in a simultaneity class; (2) what the temporal interval is between e_1 and e_2; (3) what the spatial interval is between e_1 and e_2; (4) whether two events are located at the same place. Given the principle of Galilean relativity, these spatio-temporal relations need to be modified to those in neo-Newtonian space-time by abandoning (4) and modifying (3) to (3') what is the invariant spatial interval between two simultaneous events e_1 and e_2. However, in the special theory of relativity, (1), (2), and (3') become variable spatio-temporal relations dependent on the observers' motions. But it does not at all mean that there are no exists any invariant spatio-temporal relations between events in the special theory. In this framework, the spatio-temporal distance between any two events is invariant, while this is variant within the earlier theory. Given that the spatio-temporal relations are determined from the structure of space-time and what is the intrinsic spatio-temporal relation between events in one theory is not intrinsic in the succeeding theory, it is easier to find the discontinuity in the course of the theory-change.

essential part of these two theories, we are now in a better position to comprehend the common structure shared by these two theories.[3] An earlier account along these lines was developed by Brading and Landry (2005), who argue that the inertial structures of Newtonian and Minkowskian space-times can be viewed as "shared structure between models of the theory," showing "the relationship between predecessor and successor theories":

> [S]hared structure between models of the theory can be used to tell us about the continuity of structure across theory change. ... [W]e compare the inertial structure of Galilean spacetime to that of Minkowski spacetime. Both Newtonian and Special Relativistic mechanics satisfy the principle of relativity, and this implies that for each theory the coordinate transformations between inertial frames must form a group. In the first case we have the Galilean group, and, in the second, the inhomogeneous Lorentz group; both the Galilean and Lorentz groups of transformations being permutations of R^4. The relationship of shared structure between Newtonian mechanics and Special Relativity obtains when specific limiting conditions are imposed within Special Relativity. Under these conditions, the Lorentz transformations reduce to the Galilean transformations and so the two theories share the same group-structure. (Brading and Landry 2005, 17)

This emphasis on the group structure of the coordinate transformations between inertial frames dates back to Felix Klein's Erlangen programme, which focuses on

[2] Inertial structure is mathematically represented by the affine structure consisting of manifolds of points and the connection. The task of this chapter is to interpret this mathematical structure.

[3] By emphasizing inertial structures that are four-dimensional concepts, we can also see the commonality in the dimensionality between Newtonian space-time and Minkowski space-time. If we view the structures of space and time as theoretical entities represented by 3 + 1 and 4 dimmensional manifolds, it seems that discontinuity is more essential. While classical space and time are seen as separate entities that are represented by 3-dimensional space and 1-dimmensional time, relativistic space-time is viewed as a single entity *space-time* represented by a 4-dimensional manifold. Then, Minkowski's statement that "space by itself, and time by itself, are doomed to fade away into mere shadows, and *only a kind of union of the two will preserve an independent reality*" (Minkowski 1908, 75) can be read as providing an *ontological significance* of a single four dimensional manifold, which is clearly distinct from its classical counterpart. Yet, this ontological difference turns out to be insignificant given that an inertial structure is a four-dimensional affine space. Only space-time has a enough structure to capture the inertial structure of Newtonian dynamics, i.e. symmetries under the Galilean transformations that relate an equivalence class of inertial frames.

the formal properties of a continuous group in characterizing geometrical structure. According to the Erlanger programme, group theory can be employed to determine the essential structure of the geometry in that the genuine characteristics of the geometry are the invariant quantities under a group of specific transformations:

> There are spatial transformations which leave the geometric properties of spatial structures completely unchanged. ... We designate the intention of all these transformations as the *principal group* of spatial alterations; *geometric properties are not altered by transformations of the principal group.* Also conversely one can say: *geometric properties are characterized by their invariability under transformations of the principal group.* (Klein 1872, 463)

In the coordinate system formalism of space-time models, the transformations between coordinate systems representing inertial coordinates form a group, and the symmetries of that group distinguish the invariant geometric structures, independently of the choice of any specific reference frame. From this perspective, Brading and Landry maintain that a commonality of inertial structures can be identified in both Newtonian to Einsteinian physics. Hence we can say that this element is preserved in the theory-change.

This is a major step in the right direction. Yet, as pointed out in the first chapter, the mathematical group structure is not enough to capture fully an evolutionary development underlying this theory-change. One must ask also about the physical foundation of the group. We must take into account not only the formal aspects common to the two theories, but also how the evolving formalisms are given physical significance within them. It is possible for the shared group, which is exhibited by the relations between the reference frames, to have quite different interpretations within the context of different theories. Even if one insists on the shared formal structure being tied to observable phenomena in the same way, two quite different interpretations remain open in this particular case. One possibility is to view the group structure as stemming from space-time structure, which exists independently of particular physical objects and events. The other possibility is to consider the group structure as being based on dynamical laws concerning physical events.

This chapter will endorse the latter perspective. The basic structure of this chapter is to examine whether the two fundamental postulates within the special theory of the special theory stem from space-time structure or dynamical laws. The second section will introduce accounts that attempt to capture the two postulates through the former, which is elaborated by Janssen and Norton. The third section provides criticisms of their view, and instead argues that the problems of the space-time view (that considers the two postulates as stemming from the structure of space-time) can be remedied within modified space-time structuralism (that views the two postulates as expressing the relationships between events, which are specified by dynamical equations of electrodynamics). The fourth section will argue that the theory-change from Newtonian mechanics to the special theory of relativity can be viewed as essentially continuous if the two postulates are compared with their counterparts within Newtonian mechanics from the perspective of modified space-time structuralism.

2. Accounts of the Theory-Change Emphasizing the Structure of Space-Time

In the context of the theory-change from Newtonian mechanics to Einstein's special theory of relativity, we find a view close to Dorato's in the writings of Janssen (1995, 2002a, 2002b, 2004). He holds that in the case of Minkowski space-time, the common cause for the behaviours of physical events stems from the "causally efficacious structure" of space-time. This concept of "causally efficacious structure" is developed by using Salmon's notion of causal explanation that is characterized by "causal interactions" and "causal processes," which involve the exchange of conserved quantities such as energy, or momentum.[4]

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[4] In Salmon's early characterization of causal processes, a causal process is a process capable of transmitting marks. (Salmon 1984) What transmission of a mark consists in is that the mark occurs "at" each successive point at each successive instant. Salmon's idea of mark transmission is devised to distinguish pseudo-processes from the genuine ones, because pseudo-processes are lack of ability of transmitting marks. And another component of his explanation is a causal interaction that occurs when one causal process intersects another and produces a modification of its structure.

However, Kitcher (1989) points out that, because of the dependence of counterfactuals, Salmon's characterization of causal processes cannot correctly capture a causal structure itself. The definition of mark transmission is based on counterfactual, because whether mark transmission occurs depends on how it would behave if unmarked. Since the truth values of counterfactuals, on which the definition of Salmon's causal processes depends, is not available by empirical tests, causal structure is not empirically accessible on the Salmon's theory.

Given this criticism, Salmon gives up his early causal mechanical model that depends on mark transmission, and develops a new conserved quantity theory. Salmon seriously considers the problem of counterfactual and elaborates the definition of causal processes that is free of counterfactual contents.

Salmon's conserved quantity theory analyses causal interactions and causal processes, both of which are now defined by conserved quantities such as energy, or momentum. For example,

> Minkowski space-time certainly explains length contraction, but it hardly qualifies as a causally efficacious substance. This objection can be avoided by broadening Salmon's concept of causation ... The *COI* [common origin inference] in this case is to a structure rather than a substance. (Janssen 2002a, 501)

According to Janssen, the essential part in the development of the special theory of relativity can be captured in the structure of space-time. This is best reflected in a single sentence in Stachel's "Einstein on the theory of relativity" prepared for the editorial notes to Einstein's seminal paper "On the Electrodynamics of Moving Bodies":

> Einstein was the first physicist to formulate clearly the kinematical foundation for all of physics inherent in Lorentz's electron theory. (Stachel et al. 1989, 253)

Janssen comments:

> If I were allowed one single sentence to describe the breakthrough Einstein achieved with special relativity, this would be the one. No doubt about it. This one sentence, I claim, sets the agenda for the rational reconstruction of the history of special relativity. (Janssen 1995)

Janssen considers this "kinematical foundation" as stemming from the structure of space-time, as is elaborated by Minkowski. Janssen views the existence of space-time structure as the "common cause" of the Lorentz invariance of Maxwell's equations and of other laws governing physical interactions.

> [F]rom a modern point of view, the central innovation of Einstein's 1905 paper is the reinterpretation of Lorentz invariance, a well-known feature of the formalism of Lorentz's theory, as reflecting a new space-time structure. ... [T]he strongest argument for this reinterpretation is that *it traces the Lorentz invariance of Maxwell's equations and the Lorentz invariance of other physical laws to a common cause, namely this new space-time structure*. (Janssen 2002b, 430, my emphasis)

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when the cue ball collides with the other ball, they causally interact with each other in a way that they exchange energy. On the other hand, white coloured chalk on the cue ball does not satisfy the condition to be a conserved quantity that transmits between the two balls, since the path of chalk is not a world line involving exchange of a conserved quantity.

Janssen earlier (1995) endorsed the contemporary philosophy of space-time, which characterizes space-time as "a differentiable manifold dressed up with a metric field and maybe other geometric object fields encoding its metric and affine properties." Although Einstein was silent about the elementary material substance underlying the special theory, Minkowski space-time, according to Janssen, does this job:

> Special relativity, unlike the electromagnetic program, does not make any claims about the constitution of matter. The theory only imposes the constraint that all physical laws be Lorentz invariant. The reason Einstein did not want to commit himself to anything more specific was that he recognized that physics was in for another major overhaul, this one coming from quantum phenomena. ... *With the introduction of Minkowski space-time, however, it becames a constructive theory. Minkowski space-time is the structure responsible for all the effects derivable from special relativity alone.* Special relativity, from this point of view, replaced Newtonian space and time by Minkowski space-time and does not make any claims about the contents of the new space-time other than that their spatio-temporal behaviour had better accord with Minkowski's new rules. (Janssen 2002a, 505-6, my emphasis)

Janssen claims that the structure of space-time – its postulated metric – provides an elementary constructive foundation for the special theory, and the structure of space-time can be viewed as more primitive than the behaviour of any given body. Hence, the space-time theory based on the Minkowski metric is a "constructive theory." What Minkowski's spacetime does for the special theory of relativity is what Boltzman's statistical mechanics does for thermodynamics.

Janssen's view can be considered as sharing an intuition with Dorato's in that both emphasize the structure of space-time: "Special relativity ... does not make any claims about the contents of the new space-time other than that their spatio-temporal behaviour had better accord with Minkowski's new rules." And given Janssen's view that Minkowski space-time is a constructive element providing "a picture of the more complex phenomena out of materials of the more simple scheme," (Einstein 1919) he also endorses the independent existence of space-time structure.

Another clear explanation of this position can be identified within Norton's writings, which basically endorse Janssen's view that the dynamical effects are due to the structure of space-time: "Einstein shows us that forces of all types must transform alike because they inhabit the same space and time." (Norton 2004) Norton in fact claims that the hypothesis of the constancy of the speed of light along with the principle of relativity can be viewed as stemming from the properties of space-time itself:

> *This constancy [of the speed of light] is somehow built into the essence of space and time according to the theory; spaces and times repeatedly contort themselves in order to preserve its constancy for all inertial frames of reference.* We must of course recover from the novice error that there is something special about light that brings all this about. In principle, light – electromagnetic radiation – has nothing to do with it. Special relativity would say the same things about space and time in a completely dark universe. *The real result is that there is a special speed built into the structure of space and time* and, in seeking to go as fast as it can, light happens to travel at that speed. (Norton 2000, my emphasis)

Although it is possible that Norton's claims about spaces and times "contort[ing] themselves" are meant metaphorically, he surely holds the view that the constancy of the speed of light is a property of space-time in a straightforward literal sense.

This line of thought regarding the principle of relativity was also identified within Norton's writings by Brown (1993, 251):

[The principle of relativity in the special theory] does not arise as a fundamental postulate of special relativity, but as *an important theorem dependent on the symmetries of the Minkowski metric* [as space-time structure]. (Norton 1989, my emphasis)

More specifically, a model of space-time of the special theory of relativity consists of a dynamically allowed triple $< M, g_{ab}, T_{ab} >$, where M is a four dimensional space-time manifold representing a set of events, g_{ab} is the Minkowski metric (which specifies the spatio-temporal relations between events) and T_{ab} is a dynamic tensor field (representing the distribution of matter). Norton then defines the principle of relativity in special relativity as follows:

Principle of Relativity (Special Relativity): If $< M, g_{ab}, T_{ab} >$ is a model of a special relativistic theory and F and F' are any two inertial frames, then the theory satisfies the principle of relativity only if there exists a member L of the symmetry group of the Minkowski metric g_{ab} such that

(a) L maps F onto F' and
(b) $< M, g_{ab}, L^*T_{ab} >$ is also a model of [the special relativistic theory]. (Norton 1989, 1251–2).

Brown (1993, 250-1) interprets Norton as claiming that only the first condition follows from the complete equivalence of all inertial frames, which represents the symmetry of space-time associated with the principle of relativity:

Norton in fact recognises that condition (b) does not strictly follow from the nature of the symmetry automorphism L. His point is that insofar as PR is a 'theorem' it is encapsulated in condition (a) ... which "reminds us that the Minkowski space-time itself designates no inertial frame as preferred" – the metrical structure is preserved under change of frame. Condition (b) then *independently*

> ... stipulates that the [laws governing] additional structures defined on space-time, such as Maxwell fields or mechanical fluids, likewise do not distinguish any inertial frame as preferred. (Norton 1989, 1252)

As pointed out earlier, Brown (1993, 251) asserts that Janssen and Norton's views involve a particular ontological attitude – one which views space-time geometry as being "ontologically prior to the 'additional [dynamical] structures,' like fields, defined on the manifold." Norton can thus be interpreted as viewing the principle of relativity as a property of the structure of space-time, which is independent of the dynamical laws governing material contents. Accordingly, "the shared structure" specified by the principle of relativity, pointed out by Brading and Landry, is concerned with that of the space-times of Newtonian mechanics and the special theory of relativity.

Janssen (2002a, 2004) and Norton (2005) also provide accounts of the development of the special theory of relativity as a modification of the space-time structure responsible for the dynamical laws of electrodynamics and optics. Their accounts, of course, emphasize on the concept of space-time.

Janssen (2002a, 2004) claims that Einstein's well-known account of the asymmetries in the electro-magnetic interaction between a magnet and a wire leads ultimately to a view concerning the concept of space-time. Einstein, as is well known, showed his unease about the quite different theoretical accounts supplied by classical physics of (a) the case with a wire at rest in the ether while a magnet approaches and (b) the case with a magnet at rest in the ether while a wire approaches.[5] Einstein claimed:

[5] A reason that made Einstein give up the concept of the immobile ether came from a consideration of the electrodynamic interaction between a magnet and a wire. Einstein referred to the following two cases in order to show a failure of Lorentz's ether theory in detecting the state of rest: (a) the case with a wire at rest in the ether while a magnet approaches and (b) the case with a magnet at rest in the ether while a wire approaches. Although it seems that these two cases are symmetric because their relative velocities and registered currents in the wire are identical,

> The existence of the electric field was therefore a relative one, dependent on the coordinate system used, and only the electric and magnetic field taken together could be ascribed some kind of objective reality. This phenomenon of electromagnetic induction forced me to postulate the [...] relativity principle. (Einstein 1919, Stachel et al., Vol. 7, 264-5)

In other words, there exists only a magnetic component in the electromagnetic field in case (b), whereas both electric and magnetic components in the electromagnetic field contribute in case (a). Although they have different theoretical explanations, Einstein saw that these two cases are completely interchangeable because these two cases are different only with respect to reference frames moving with different velocities. (So, according to the principle of relativity, the dynamical laws describing the two cases are identical.) Einstein employed this argument to show the failure of Lorentzian ether theory to detect the state of rest. According to Janssen (2004), this account amounts to a claim concerning space-time structure:

> Maxwell's theory is compatible with the relativity principle if it can be shown that *the observer measuring the Lorentz-transformed electric and magnetic fields **E'** and **B'** also measures the Lorentz-transformed space and time coordinates (**x'**, t')* (Janssen 2004, my italics).

While in his (2002) he writes:

> Special relativity not only merges the electric and the magnetic field into one electromagnetic field, *it also merges space and time into space-time, and energy and momentum into energy-momentum. ...* [T]he new theory posits one structure to account for phenomena that were attributed to various structures in the old one (Janssen 2002a, 505, my italics).

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theoretical explanations for the two cases, according to Lorentzian ether theory, are quite different. Faraday's law explains case (a): the approaching magnet induces the electric field, which causes electrons in the wire to move. As for case (b), on the other hand, the explanation is that while electrons in the wire move through the magnetic field, a Lorentz force, which is generated from the magnetic field, causes electrons move throughout the wire. Einstein felt it puzzling to explain the two obviously symmetric phenomena so differently. Although the two explanations produced by Lorentz's theory based on the ether are different, the "asymmetries do not appear to be inherent in the phenomena." (Einstein et al., 1954, 37)

Norton (1992, 183) also emphasizes the essential role of the concept of space-time in Einstein's account establishing the principle of relativity in electrodynamics. Einstein in his (1905) stated that this was motivated from the asymmetries in the Lorentzian ether theory's description of electro-magnetic interaction and the failure of a set of optical experiments that attempted to detect the motion of the earth relative to the immobile ether ("one truly immobile space"):[6]

> Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relative to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest. They suggest rather that, as has already been shown to the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good [in all inertial spaces]. We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate ... The introduction of a "luminiferous ether" will prove to be superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties .... (Einstein 1905)

The last sentence (along with the aforementioned interpretation of the prinicple of relativity), since it is concerned essentially with a kinematical property based on the structure of space-time, seems to imply that the development of Einstein's special theory is indeed about the structure of space-time:

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[6] In the early 20th century, then current two overarching theoretical frameworks, i.e. Newtonian dynamics and Maxwell's Electrodynamics, seemed to have a problem of inconsistency. Whilst Electrodynamics predicted that light, as an electromagnetic wave, propagated at the speed of *c*, this seemed impossible according to Newtonian kinematics. At that time, it was widely assumed that light was propagated through an immobile medium known as the ether, with respect to which Maxwell's equations were assumed to hold. Given this assumption and Newtonian kinematics, it can be inferred that the speed of light cannot be constant in a frame at rest with respect to the Earth. Since the Earth is moving with respect to the ether, the velocity of light with respect to the Earth is the vector sum of the velocity of the light with respect to the ether and the velocity of the Earth with respect to the ether. In this context, it seems that Norton (1992) reads the concept of space-time as essential in Einstein's account that the negative results of a series of optical experiments, which tried to detect the change of velocity of light, led him to think of the concept of the luminiferous ether identified the "one truly immobile space," as "an idle metaphysical conception."

> With these words, Einstein introduced the principle of relativity to this theory. The principle asserts, in effect, that the laws of mechanics, electrodynamics and optics are to hold equally well in all inertial spaces. (Einstein picks out the inertial spaces indirectly as those "for which the equations of mechanics hold good.") Newton's quest for the one truly immobile space among them is to be abandoned. (Norton 1992, 183)

The above emphasis on the structure of space-time seems to be consistent with Einstein's elimination of the apparent inconsistency between the principle of relativity and the constancy of the speed of light. Because the speed of light is taken to be a constant *c* with respect to all observers, it seems that a state of absolute rest exists, with respect to which the speed of light is constant. However, this conflicts with the principle of relativity, which rules out a state of absolute rest. Einstein resolved this apparent inconsistency by giving up the concept of absolute time, while maintaining the principle of relativity. From reflection on the concept of simultaneity, Einstein argued that the principle of relativity and the constancy of the speed of light are compatible if one abandons the absolute concept of simultaneity between spatially distant events. Instead, observers in relative motion disagree on which spatially distant events are simultaneous:

> [B]efore relativity theory, simultaneity was taken to be a two place relation between events. Events *A* and *B* could be simultaneous *simpliciter*; after relativity theory, it was recognized that events *A* and *B* can be simultaneous only with respect to an observer or frame of reference. (Norton 2005, 16)

Accordingly, "use of the older concept had required the tacit presumption that judgements of simultaneity are independent of observer or frame of reference." (ibid.) While within Newtonian space-time the temporal relationships between two events are invariant regardless of the choice of observers, within Minkowski space-time the temporal relationships between two events are different dependent on the choice of observers. In contrast, what is invariant within Minkowski space-time is the combination of the spatial and temporal intervals between events, so that an invariant space-time is consistent with the constancy of the speed of light and the principle of relativity. In this way, the spatio-temporal structures of Newtonian physics are modified to the ones of Einstein's special theory:

> Since judgements of simultaneity arise through kinematics, Einstein now needed to ascertain *how our traditional notions of space and time must be modified to accommodate this new result of the relativity of simultaneity. That accommodation is the working out of the special theory of relativity, a new theory of space and time.* (Norton 2005, 14)

The theory-change from Newtonian to Einsteinian physics, from this point of view, can be described as essentially involving a modification of the posited structure of space-time: "one truly immobile space" is replaced by spaces and times that "repeatedly contort themselves in order to preserve [the constancy of the speed of light] for all inertial frames of reference." (Norton 2001)

3. Criticisms of Janssen and Norton's Space-Time View

Janssen and Norton's view can be summarized as follows:

(1) The structure of Minkowski space-time is a causally efficient one that is "responsible for all the effects derivable from special relativity." (Janssen 2002a, 54)

(2) The light postulate and the principle of special relativity are the intrinsic properties of space-time. According to Norton, the speed of light is "a special speed built into the structure of space and time" (Norton 2000), and the principle of special relativity arises "as an important theorem dependent on the symmetry of the Minkowski metric." (Norton 1989)

(3) The common group representing the inertial structures within Newtonian mechanics and the special theory of relativity, which Brading and Landry point out, stems from the structure of space-time.

(4) The development of Minkowski space-time can, therefore, be characterized as a modification of the structure of Newtonian space-time to retain the principle of relativity, while accommodating the hypothesis of the constancy of the speed of light.

I will argue in this section that, in fact,

(1') Minkowski space-time does not provide a *causal* explanation of the phenomena derivable from the special theory of relativity.

(2') Instead, the special theory offers a *structural* explanation that specifies "structural constraints [involved in the equations that express the dynamical laws of electrodynamics] that events are held to satisfy." (Bub 1974, 143) The light postulate and the principle of special relativity encode structural information concerning the relationships between events, which are specified by the dynamical laws of electrodynamics, rather than by the intrinsic properties of space-time. Accordingly, the kinematical properties that are derived from these two postulates also capture the structural relationships between events.

(3') The group structure common to Newtonian mechanics and the special theory of relativity is based on dynamical behaviours of material bodies: the group in the former case stems from the movements of body, the group in the latter stems from the behaviours of bodies and light pulses.

(4') It will be argued in the next section that rather than Janssen and Norton's conclusion **(4),** we should infer that an accurate account of the theory-change from Newtonian mechanics to the special theory of relativity must emphasize the essential continuity in their dynamical principles, such as the principle of inertia and the principle of relativity.

Janssen's claim **(1)**, that Minkowski space-time provides causal explanations of the phenomena derivable from the special theory, fails because it omits essential constituents of causal explanation. According to Salmon's account, a legitimate causal explanation should provide 'causal interactions' and 'causal processes.' But, remember that Minkowski's account of space-time does not involve any causal interactions and causal processes.

This shortcoming is further underlined by a recent development of the concept of mechanism. According to McChamer, Darden and Craver (2000, 2-3),

> [M]echanisms are sought to explain how a phenomenon comes about or how some significant process works. Specifically:
>
> > Mechanisms are entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions.
>
> ... Mechanisms are composed of both *entities* (with their properties) and *activities*. Activities are the producers of change. Entities are the things that engage in activities. ... Entities often must be appropriately located, structured, and oriented, and the activities in which they engage must have a temporal order, rate, and duration. ... Mechanisms are regular in that they work always or for the most part in the same way under the same conditions. The regularity is exhibited in the typical way that the mechanism runs from beginning to end ... Complete descriptions of mechanisms exhibit productive continuity without gaps from the set up to termination conditions. Productive continuities are what make the connections between stages intelligible.

Given that Janssen follows Salmon's line of causal explanation, one way to support his view is to clarify the mechanism of space-time structure generating the behaviours of bodies. Yet, it is certainly not true that the explanation of phenomena provided by space-time theories satisfy the above standard of 'mechanism.' Although space-time can be considered as somehow being an entity, what are its "activities" that produce the motions of a given body? And what are the "productive continuities" involved in space-time? Until these are clarified, space-time theories cannot be viewed as providing a mechanism that produces the behaviours of a given body.

Brown and Pooley (2006) criticize Janssen's claims along similar lines:

> [A]s matter of logic alone, if one postulates space-time structure as a self-standing, autonomous element in one's theory, it need have no constraining role on the form of the laws governing the rest of content of the theory's models. *So how is its influence on these laws supposed to work?* Unless this question is answered, space-time's Minkowskian structure cannot be taken to explain the Lorentz covariance of the dynamical laws. (Brown and Pooley 2006, 84, my italics)

According to Brown and Pooley, Janssen's common origin inference also fails to clarify why the structure of space-time should be the cause of the Lorentz invariance of Maxwell's equations or the Lorentz invariance of any other physical law:

> One might … go so far as to agree that all particular instances of paradigmatically relativistic kinematic behaviour are traceable to a common origin: the Lorentz covariance of the laws of physics. But Janssen wants us to go further. He wants us to then ask after the common origin of this universal Lorentz covariance. It is his claim that this can be traced to the space-time structure posited by Minkowski that is never clarified. (ibid., 85)

From the above perspectives, Brown and Pooley can be understood as making a claim that Janssen's view is not tenable because he fails to clarify the "causal processes and interactions" (in Salmon's term) or "mechanism" (in Darden, Machamer and Craver's term) originated from space-time, which generates "all particular instances of paradigmatically relativistic kinematical behaviour."

DiSalle's argument introduced in the last section can also be applied to show that Minkowski space-time supplies no causal explanation:

> To claim that space is Euclidean *only means* that measurements agree with the Euclidean metric; Euclidean geometry, if true, can't *causally explain* those measurements, because it only expresses the constraints to which those measurements will conform. (DiSalle 1995, 324)

As Janssen himself (2002a, 429) points out, "there are important parallels between the geometry of Minkowski space-time and the standard Euclidean geometry of ordinary space":

> The choice of a particular inertial frame in Minkowski space-time is similar to the choice of a particular set of orthogonal axes to serve as a Cartesian coordinate system in Euclidean space. Using the space-time coordinates of such inertial frames, one can compute lengths and distances in Minkowski space-time with a formula similar to the Pythagorean theorem used when computing lengths and distances in terms of Cartesian coordinates in Euclidean space. A Lorentz transformation to get from one inertial frame in Minkowski space-time to another is similar to the rotation of a set of orthogonal axes in Euclidean space to get from one Cartesian coordinate system to another. The freedom to pick any inertial frame in Minkowski space-time is reflected in the invariance under Lorentz transformations of all laws governing physical systems in Minkowski space-time just as the freedom to pick any Cartesian coordinate system in Euclidean space is reflected in the invariance under spatial rotations of all laws governing physical systems in Euclidean space. (ibid.)

According to Einstein:

> [Minkowski] also showed that the Lorentz-transformation (apart from a different algebraic sign due to the special character of time) is nothing but a rotation of the coordinate system in the four-dimensional space. (Einstein 1969, 59)

Substituting Minkowski geometry for Euclidean geometry, DiSalle's criticism also applies to the special theory. Just as the structure of Euclidean geometry does not causally explain its laws, such as the Pythagorean theorem, the structure of Minkowski geometry does not cause the phenomena derivable from the special theory of relativity.

It seems that the above argument is consistent with Einstein's own account in his *Autobiographical notes*, where the role of the geometry of Minkowski space-time was viewed simply as a convenient mathematical formalism which codifies the dynamical laws of the special theory:

> Minkowski's important contribution to the theory [the geometry of Minkowski space-time] lies in the following: Before Minkowski's investigation it was necessary to carry out a Lorentz-transformation on a law in order to test its invariance under such transformations; he, on the other hand, succeeded in introducing a formalism such that *the mathematical form of the law itself guarantees its invariance under Lorentz-transformations.* (ibid., my italics)

In other words, the laws expressing electrodynamics are codified within the invariance of Minkowski geometry.

So much for my criticism of step (1) of Janssen's and Norton's argument. I will now turn to the second step. Modern commentators on the special theory suggest that, contrary to Janssen's and Norton's (2), what Einstein's special relativity provides is a *structural* explanation. We can see the two characteristics of a structural explanation in Hughes (1987) and DiSalle (2006).

The first characteristic is captured by Hughes (1987), who basically claims that structural explanations provide structural constraints that events are held to satisfy. He takes the light postulate in the special theory as an example showing that it provides a structural constraint on the relationships between events by dictating the maximum velocity that each event can reach:

> [A] much better answer would involve sketching the models of space-time which special relativity provides and showing that in these models, *for a certain pair of events, not only is their spatial separation x proportional to their temporal separation t, but the quantity x/t is invariant across admissible (that is, inertial) coordinate systems; further, for all such pairs, x/t always has the same value.* This answer makes no appeal to causality; rather it points out structural features of the models that special relativity provides. It is, in fact, an example of a structural explanation. (Hughes 1989, 256-7)

The second characteristic of a structural explanation is that the above structural constraints between events stems from laws of electrodynamics, which are captured by Maxwell equations, rather than from their underlying entities and mechanisms. In other words, the structure of Minkowski space-time stems from the laws of electrodynamics:

> Minkowski space-time is *not* presented as a deeper sort of reality underlying the phenomena described by Einstein, explaining them as, say, the kinetic theory of gases explains the phenomena described by the ideal gas law. A more careful assertion would be one that acknowledged, at least, that a very different kind of explanation is at work. Minkowski space-time has been described as providing a "structural explanation" (see Hughes 1987): the phenomena are to be explained by the fact that the world is a model of a certain structure. But then in this way, the explanation would have to be that the world conforms to Einstein's relativity principle because it is a model of Minkowski space-time. Then the seeming explanatory character is misleading. ... In order to explain the physical meaning of the Minkowski structure, we could do little more than make the same assertion in reverse: *the world has that structure because the laws of electromagnetic propagation are the fundamental invariants.* (DiSalle 2006, 115-6, my italics)

Hence, structural explanations, in our context, can be characterized as ones that provide structural constraints between events, which are specified by equations that express the laws of electrodynamics. These two characteristics of structural explanations can be identified within the fundamental postulates of the special theory of relativity.

The first characteristic is obvious in the light postulate. Instead of capturing its underlying mechanism, the light postulate describes the structure constraining events, specifying "a special velocity at each event" (Norton 2000), which is encoded in Maxwell's equations. As pointed out earlier, this structure constraining events is captured by Hughes as follows: "for a certain pair of events, not only is their spatial separation x proportional to their temporal separation t, but the quantity x/t is invariant across admissible (that is, inertial) coordinate systems; further, for all such pairs, x/t always has the same value." (Hughes 1989, 256)

The second characteristic in a structural explanation can also be found in the light postulate; the light postulate stems from Maxwell equations, rather than its underlying mechanism. Einstein (1907) states that the light postulate came from Maxwell-Lorentz theory:

> It is by no means natural to expect that the hypothesis stated above, which we call the principle of the constancy of the velocity of light, should be actually satisfied in nature, yet – at least for a coordinate system of a certain state of motion – it is made likely by the confirmations which Lorentz's theory, that is based on the assumption of an absolutely resting ether, have obtained by experiment. (Einstein 1907)

However, Einstein was sceptical of mechanism underlying Maxwell equations in that "Maxwell's equations did not permit the derivations of the equilibrium of the electricity which constitutes a particle"[7]:

> [T]he bearing of the Lorentz transformation transcended its connection with Maxwell's equations ... Maxwell's theory did not account for the micro-structure of radiation and could therefore have no general validity. (Einstein 1955, a letter to Carl Seelig)

The then current version of Maxwell's theory that implied the constancy of light speed was underpinned by the Lorentzian ether. This provided the medium of propagation of electromagnetic waves including, of course, light pulses. The

[7] Given Planck's work on black-body radiation implying energy-quantization of light, Einstein expressed doubts about whether the classical mechanics is valid at the micro-level: "All my attempts ... to adapt the theoretical foundations of physics to [Plank's work] failed completely. It was as if the ground had been pulled out from under one['s feet], with no firm foundation to be seen anywhere, upon which one could be built." (ibid., 45)

Lorentzian ether, at the early stages of its development, was viewed as providing a medium possessing mechanical properties, through which light is supposed to propagate. In contrast, at the later stages of its development, the ether was attributed no mechanical properties, but instead simply regarded as the 'seat' of the electromagnetic field. (Earman 1989, 51, Brown 1993, 229) Einstein also pointed out that the ether became superfluous in the development of the special theory. Yet, despite the rejection of the mechanism of the ether as a theoretical entity, the legitimacy of Maxwell's equations was unquestioned because of their empirical success:

> If mechanics was to be maintained as the foundation of physics, Maxwell's equations had to be interpreted mechanically. This was zealously but fruitlessly attempted, while *the equations were proving themselves fruitful in mounting degrees.* (Einstein 1969, 25, my italics)

In the same spirit, Brown points out:

> [I]n the Lorentz theory of the electron, developed from 1890 onwards, the ether lost its mechanical status; it was a new kind of imponderable matter, no*thing* more than the seat of the electromagnetic field … . *Thus Lorentz could provide no obvious explanation for light-speed constancy in the ether rest frame, other than the fact that it was a consequence of his fundamental field equations.* (Brown 1993, p.229-230, my italics)

So these accounts can be viewed as further support for structural realism. As Duhem stated, "what is essential in Maxwell's theory is Maxwell's equations" (Duhem 1954, 221-2). These "symbolize physical magnitudes which must be either measurable experimentally or formed from other measurable magnitudes." (ibid., 223)

The second characteristic of a structural explanation is also manifest in the principle of relativity. In other words, the principle of relativity is a structural property of the laws of electrodynamics.

> [N]ot only the phenomena of mechanics but also those of electrodynamics have no properties that correspond to the concept of absolute rest. Rather, *the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good* ... [which postulate] will hereafter be called "principle of relativity" (Einstein 1905, my italics)

Accordingly, the Lorentz transformations codifies the laws of electrodynamics.

> General laws of nature are co-variant with respect to Lorentz transformations.
>
> *This is a definite mathematical condition that the theory of relativity demands of a natural law*, and in virtue of this, the theory becomes a valuable heuristic aid in the search for general laws of nature. (Einstein 1917, my italics)

The principle of relativity is also considered as providing constraints on the relationships between events, which are represented by rigid bodies, clocks, and light signals:

> Like all electrodynamics, [the special theory of relativity] to be developed here is based on the kinematics of a rigid body, since *the assertions of any such theory have to do with the relations among rigid bodies (coordinate systems), clocks, and electromagnetic processes.* (Einstein 1905, my italics)

In other words, it provides "*structural constraints [specified by electrodynamics] that events are held to satisfy*" (Bub 1974, 143) without referring to their underlying hypothetical material constitutions.

This characteristic of the principle of relativity is also captured by Wigner (1967): "the correlations between events, are the entities to which symmetry laws apply[8]." (Wigner 1967, 19) The principle of special relativity states that the dynamical laws of a given body in a rest frame are the same as when they are referred to any uniformly moving frame. In other words, the physics of a body at rest or in uniform motion is exactly the same. In this way, the principle of relativity provides a symmetry relation between a set of events, which identifies apparently distinct states of motion of a body (the state of rest and uniform motion).

More importantly, the aforementioned characteristics of a structural explanation can be found in Einstein's own methodological remarks about his special theory. According to Einstein (1919), the special theory based on the two fundamental hypotheses, i.e. the light postulate and the principle of special relativity, is a "principle theory" which provides "general characteristics of natural processes" by means of "mathematically formulated criteria which *the separate processes or the theoretical representation of them have to satisfy*." (Einstein 1919, 228) A "principle theory" is to be contrasted with a "constructive theory." And the latter "attempt[s] to build up a picture of the more complex phenomena out of the

[8] In the same vein, Einstein (1907) mentioned the structural characteristic of the principle of relativity:

> The principle of relativity, or, more exactly, the principle of relativity together with the principle of the constancy of velocity of light, is *not to be conceived as a "complete system", in fact, not as a system at all, but merely as a heuristic principle which, when considered by itself, contains only statements about rigid bodies, clocks, and light signals.* It is only by requiring relations between otherwise seemingly unrelated laws that the theory of relativity provides additional statements. (Einstein 1907, my italics)

materials of a relatively simple formal scheme from which they start out." (ibid.)

According to Flores (2000), Einstein's own distinction between the two types of theories is in fact a threefold one:

> First, Einstein distinguishes principle and constructive theories by *what* these theories postulate as their starting points. One can regard this as an *ontological* distinction: constructive theories postulate the existence of 'entities' (with specific properties) while principle theories postulate general physical principles that govern the behaviour of matter. Second, principle and constructive theories are distinguished by how we come to know their starting points. This is an *epistemological* distinction. The 'principles' or 'postulates' of a principle theory are empirically discovered. ... On the other hand, the starting points of a constructive theory are 'free creations of the human mind,' as Einstein might say, and thus are not empirically discovered. Finally, principle and constructive theories also differ because they play distinct conceptual roles in scientific theorizing. Principle theories establish *constraints* that the theoretical descriptions of phenomena offered by constructive theories must satisfy. (Flores 2000)

Given these three distinctions, we can see that these two different types of theories are based on the aforementioned two different types of explanations, i.e., causal and structural explanations. First of all, the postulated "entities" introduced in a constructive theory fit well with Duhem's characterization of the explanatory parts, which is based on "judgements about the nature of things," aim to provide "the reality underlying the phenomena." (Duhem 1914) In particular, constructive theories aim to provide a causal mechanism, which "opens up the black boxes of nature to reveal their inner workings." (Salmon 1989, 182) Furthermore, just as Duhem held that explanatory parts are not empirically based, so Einstein held that the entities introduced by a constructive theory are not empirically discovered but are instead results of "free creations of human mind." Second, empirically based principles or postulates fit well with Poincare and Worrall's "structure revealing the relations among things [or events]." Just as the latter are based on the "experimental laws," which provide "structural constraints that [separate] events are held to satisfy" the former "establishes constraints that the theoretical descriptions of phenomena offered by constructive theories must satisfy." Principle theories can, therefore, be considered as providing structural explanations.

Einstein returned to this methodological issue in his *Autobiographical Notes* (1969):

> *By and by I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. The longer and the more despairingly I tried, the more I came to conviction that only the discovery of a universal formal principle could lead us to assured results.* The example I saw before me was thermodynamics. The general principle was there given in the theorem: the laws of nature are such that it is impossible to construct a *perpetuum mobile* (of the first and second kind). (Einstein 1969, 53, my italics)

Just as the laws of thermodynamics provide structural constraints over thermal phenomena such as the impossibility of the construction of a *perpetuum mobile*, the two postulates provide a set of structural constraints over the relationships between events. And these two postulates are the fundamental principles capturing the behaviours of electromagnetic moving bodies.

> These two postulates suffice for the attainment of a simple and consistent electrodynamics of moving bodies based on Maxwell's theory for bodies at rest. (Einstein 1905)

In the special theory, kinematical properties are derived from these two hypotheses. In other words, these kinematical properties describe structural constraints that are satisfied by both fundamental hypotheses capturing the relationships between events. For example, the derivation of length contraction can be viewed in this way:

> What has, in effect, been shown [in the derivation of length contraction] is that if the speed of light as measured with respect to [inertially moving] frame *F'* is to be found to be the same value as when measured with respect to the 'resting frame' *F*, then rods and clocks at rest in *F'* had better contract and dilate (with respect to frame *F*) in the coordinated way that is encoded in the k-Lorentz transformations. ... What has been shown is that rods and clocks

> must behave in quite particular ways in order for the two postulates to be true together. (Brown and Pooley 2006, 76)

In this way, kinematical properties within special relativity capture the structural relationships between events. In order to make sense of the invariance of the speed of light and of the principle of relativity, the relationships between events, which are measured by rods and clocks, need to be modified in a systematic way codified in the Lorentz transformation. Accordingly, special relativity provides structural explanations because the two fundamental hypotheses, i.e. the light postulate and the principle of special relativity, provide "structural constraints that [separate] events are held to satisfy."

Notice, then, the difference between Janssen's view – a view that might be called as 'space-time structuralism', and my modified space-time structuralism. As pointed out in the previous section, Janssen's view is close to Dorato's space-time structuralism in the context of the special theory. Janssen in particular views space-time as a "causally efficient structure," which explains the Lorentz invariance of Maxwell's equations and other physical laws: "[w]ith the introduction of Minkowski space-time, ... [special relativity] becomes a constructive theory. Minkowski space-time is the structure responsible for all the effects derivable from special relativity alone." (Janssen 2002a, 506) Norton (1989) writes along similar lines that the light postulate represents "a special speed built into the structure of space and time," and the principle of special relativity arises as "important theorem dependent on the symmetries of the Minkowski metric." So according to Janssen's structuralism, space-time is the structure that plays essential and *causal* role in the special theory. By contrast, in my modified view, the light postulate and the principle of special relativity are fundamental postulates which encode the relationships between events, – relationships specified by the dynamical equations of mechanics and electromagnetism. The structure of space-time provides only a geometric way of exhibiting these relationships between events, and is not considered as a causally efficient entity.

I turn now to critique of step **(3)** of Janssen's and Norton's argument, and my argument for a revised premise **(3')**. My main point here is that once the dynamical relationships between events are placed at centre stage, the common group structures shared by Newtonian mechanics and the special theory can be viewed as stemming from the relationships between events, rather than from space-time structure.

Brown (1993) sees the essential role of dynamical information within the two theories as implicit in Earman's account of the symmetry principles:

> Earman ... is careful to distinguish between the 'space-time symmetries' (related to the symmetry group) of a given manifold and the 'dynamical symmetries' (which appear to incorporate the boosts) of a given dynamical theory defined on that manifold. I take it that, until dynamical objects and their laws are 'introduced' into a given space-time, Earman's view must be that coordinate transformations representing real boosts are simply not defined. (Brown 1993, 249)

Earman seems to provide a physical foundation for the relevant space-time symmetry, which is different from the accounts provided by Janssen and Norton. In his *World Enough and Space-Time* (1989), Earman distinguishes the space-time symmetries of *T* (a classical theory of motion), which characterize its space-time structures, from the dynamical symmetries of *T* encapsulating the equivalence of the states of motion. (Earman 1989, 45-6) In the light of this distinction, Earman (1989) formulates the following two symmetry principles:

> **SP1** Any dynamical symmetry of *T* is a space-time symmetry of *T*.
> **SP2** Any space-time symmetry of *T* is a dynamical symmetry of *T*. (Earman 1989, 46)

Yet, it seems that what Earman says here is that the space-time and the dynamical symmetries are interrelated *with neither having priority*.

> Behind both principles lies the realization that the laws of motion cannot be written on thin air alone but require the support of various space-time structures. The symmetry principles then provide standards for judging when the laws and the space-time structure are appropriate to one another. (ibid.)

Earman's account in his (1989) is rather close to the space-time view. Aside from his position in the substance-relation debate, Earman characterizes space-time substantivalism as a claim that substantival space-time explains the behaviours of a body. (ibid., 10) Given his own interpretation of Newton's Scholium, it seems that Earman holds a position close to the space-time interpretation concerning space-time substantivalism:

> Space-time is endowed with various structures that are intrinsic to it. ... Space-time is a substance in that it forms a substratum that *underlies* physical events and processes, and spatiotemporal relations among such events and processes are parasitic on the spatiotemporal relations inherent in the substratum of space-time points and regions. (Earman 1989, 11, my italics)

And if the space-time symmetry in a dynamical system is viewed as a map of space-time structure onto itself that *underlies* dynamically possible systems of world lines into dynamically possible system of world lines, the space-time interpretation is not so farfetched reading of Earman's account. So, it seems that Brown reads what he wants to see from Earman's accounts of the symmetry principle.

However, I still think that Brown's view on the dynamical perspective of space-time holds. A better line of reasoning can be found in the accounts of those who applied group theory to Newtonian mechanics and special relativity. In the case of Newtonian mechanics, the geometry of space, according to Poincaré, arises from abstraction from the movements of an idealized rigid body: "[The geometry of space] would be only the study of the movements of solid bodies; but its object is certain ideal solids, absolutely invariable, which are but a greatly simplified and very remote image of them." (Poincaré 1905, 70) This means that our idea of space stems from our perception of bodily behaviour such as moving up to, away from, and around the objects that occupy space, rather than the other way around. An idealized rigid body can move freely without change of dimensions, and by abstraction we can characterize spatial relations, such as the lengths between points. Poincaré emphasized the role of the group in studying geometry:

> [T]here exist in nature some remarkable bodies which are called solids, and experience tells us that the different possible movements of these bodies are related to one another in much the same way as the different operations of the chosen group. (Poincaré 1887, 290)

Consider transformations of the locations of an idealized rigid body, which are represented by the mappings that take the body from a location *a* to a location *b* by any path, whether straight or not. In this situation, the transformations of the body's locations from *a* to *b* satisfy a group in that (1) the transformations have their inverses since the body can move freely from *b* to *a*; (2) inverse mappings of the transformations yield the identity mapping; (3) the transformation of the body's locations from *a* to *b* is the sum of composite mappings of a series of small transformations. In this way, spatial relations arise from the group structure of the movements of a rigid body: "what we call [spatial] geometry is nothing but the study of formal properties of a certain continuous group; so that we may say space is a group." (Poincaré 1898, 41)

Minkowski (1908) similarly employed the concept of a group to comprehend Einstein's special theory of relativity. According to Miller, Minkowski considered Einstein's "principle of relativity" as stating that the covariance specifies "definite relationships between real observed quantities of moving bodies." (Miller 1981, 240) In Minkowski's seminal lecture "Space and Time" (1908), this empiricist thesis is reiterated: "The views of space and time which I wish lay before you have *sprung from the soil of experimental physics*, and therein lies their strength." (Minkowski 1908, 75) The symmetry groups of Newtonian mechanics and Einstein's special theory are characterized as the invariance under two different groups of coordinate transformation. The former is the group of Galilean transformations (G_∞), while the latter is the group of Lorentz transformations (G_c). The special theory is characterized by G_c because of the constancy of the speed of light. Here, these groups are related to the behaviour of rigid bodies and of light pulses:

> [T]he impulse and true motive for assuming the group G_c came from the fact that the differential equation for the propagation of light in empty space [Maxwell equation] possesses that group G_c. On the other hand, the concept of rigid bodies has meaning only in mechanics satisfying the group G_∞. (Minkowski 1908, 81)

The kinematical consequence, such as Lorentz contraction, for example, stems from the motions of bodies:

> [The Lorentz contraction hypothesis] sounds extremely fantastical, for the contraction is not to be looked upon as a consequence of resistance in the ether, or anything of that kind, but simply as a gift from above, – as an accompanying circumstance of the circumstance of motion. (ibid.)

In the special theory, "the circumstance of motion" is essentially characterized by the behaviours of a body whose speed is close to that of light. Accordingly, the common group structure of Newtonian mechanics and the special theory is founded on the relationships between events; in the former case, the movements of body provides the relationships between events, and in the latter case, the behaviours of bodies and light pulses provides the relationships between events.

4. The Evolutionary Development from Newtonian to Einsteinian Physics

The previous section has refocused our attention from the structure of space-time within the special theory to the relationships between events, which are specified by dynamical principles of the special theory. This section aims to clarify the continuity (or quasi-continuity) between Newtonian dynamics and the special theory by emphasizing the relationships between events – namely those specified by the dynamical principles of these two theories of physics.

In the last chapter, I noted that the core of Newtonian dynamics is Newton's laws of motion along with the principle of Galilean relativity. The dynamical laws, such as the laws of inertia and acceleration, constrain the relationships between events, i.e. the trajectories of inertial and accelerated motions. These laws specify how the initial state of a given body's motion develops into other states. That is, these laws of motion describe the evolution of physical systems by specifying the relation of regularity between the states of a given body's motion over time. The other essential part of Newtonian dynamics is the principle of relativity, which asserts that the dynamical laws of a given body cannot be distinguished when they are referred to any uniformly moving frame.[9] In this way, the principle of Galilean relativity provides additional constraints on the behaviours of a body in that it identifies apparently distinct states of motion. These structural constraints on events determine a set of privileged frames (inertial frames), i.e. the structure of space-time. The structure of space-time, an inertial frame, is determined by a set of parallel straight

[9] The principle of relativity is not just a projection from relativity theory. But the principle is in fact essential part of Newtonian mechanics. In his Corollary V to the laws of motion in the *Principia*, Newton again expressed 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." (Newton 1729, 423) And we can also see the principle of relativity in *De Motu*: "the whole space of the planetary heavens either rests (as is commonly believed) or moves uniformly in a straight line, and hence the communal center of gravity of the planets are the same … ." (Newton 1962, 301)

lines representing the behaviour of inertial motions, and this behaviour is specified by the law of inertia.

In this section, we will see that within Einstein's special theory of relativity, these two essential elements continue to play the same essential role just as they did in Newtonian dynamics. Specifically, concerning the two fundamental postulates of the special theory: (1) The principle of special relativity is a result of a modification of the principle of Galilean relativity; (2) the dynamically privileged motions in the special theory also play essential roles, just as in Newtonian physics, while the consideration of the electrodynamics of moving bodies calls for a modification of these relationships between events.

Just as within Newtonian dynamics, the dynamically privileged inertial system, as Lange (1885) showed, is determined by the behaviours of three free particles, the dynamically privileged system in the special theory is determined by the behaviours of light pulses. (Torretti 1983, 55) In other words, the behaviour of light plays the role of selecting the privileged states of motion. Given that the light postulate plays a similar role to that of the law of inertia, the commonality between Newtonian dynamics and the special theory cannot be neglected. Before examining the role of the light postulate in the special theory of relativity, we will now consider another dynamical constraint between events, that is, the principle of special relativity.

According to Einstein, the principle of special relativity is a result of the application of the principle of relativity to the theory describing optical and electro-magnetic phenomena. Newtonian laws of motion describe regularity relations between events without considering the above dynamical law of electrodynamics. Einstein's special theory of relativity then aims to modify the relationships between events so that they satisfy the laws of electrodynamics: "the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good." (Einstein 1905)

Brown (1993) maintains that the principle of relativity in the special theory is indeed analogous to Newton's principle of Galilean relativity:

> Galileo's ship experiment did not explicitly mention optical or electro-magnetic effects. But it would be foolhardy to conclude that they constituted for him a probable counterexample to the inertial relativity principle, given the role it played in his defence of Copernicanism. (Brown 1993, 232)

And one cannot argue that Brown reads too much into Newton. Consider Newton's own account provided by Brown as follows:

> In the case of Newton, the point can be put forcibly. Nothing in his semi-corpuscular theory of light indicated a possible violation of relativity in optics, and as regards magnetism, Newton explicitly referred to it in the *Principia* as just one of the several possible central ('centripetal') forces in nature which come under the sway of his laws of motion (Newton 1934). Magnetism was in principle as much part of Newtonian *mechanics* as gravity was, and although it had not the same dependence on distance, there is every reason to think that it was likewise to be read as velocity-independent. (Newton's less frequent references in the *Principia* to the then even more obscure phenomenon of electrical activity do nothing to alter this overall picture.) (ibid.)

Yet, the principle of relativity needs to be modified in the context of electro-dynamical phenomena, since these seem to imply that there exists a privileged inertial frame that makes the velocity of a light pulse constant:

> [T]he situation that led to setting up the theory of special relativity [is as follows.] ... Mechanically all inertial systems are equivalent. In accordance with experience, this equivalence also extends to optics and electrodynamics. However, it did not appear that this equivalence could be attained in the theory of the latter. I soon reached the conviction that this had its basis in a deep incompleteness of the [classical] theoretical system. (Einstein's letter to Erika Oppenheimer on 13 Sep 1932, quoted from Stachel, 2004, 110)

This inconsistency between the principle of relativity and the light postulate was resolved by Einstein's conclusion that the principle of relativity as classically understood needs to be modified by changing the concept of simultaneity between events. The light postulate specifies the way time is diffused, and so Einstein argued that for the speed of light to be invariant, observers in relative motion might have different simultaneity relationships to spatially distant events. In order to make sense of the light postulate, it turns out that the principle of relativity involves transformations between inertial frames, which do not preserve relationships of simultaneity. Without this modification, the two fundamental principles that constitute the special theory – the light postulate and the principle of relativity – are inconsistent.

Norton seems again to claim that this particular modification is ultimately about the structure of space-time:

> Since judgements of simultaneity arise throughout kinematics, Einstein now needed to ascertain how our traditional notions of space and time must be modified to accommodate this new result of the relativity of simultaneity. That accommodation is the working out of the special theory of relativity, a new theory of space and time. The new theory solves

> Einstein's original problem of conforming Maxwell's electrodynamics to the principle of relativity ... (Norton 2005, 14)

Yet, as was argued in the previous section, if Norton's view is that the structure of space-time founds the kinematical properties, then it gets the relationships between space-time and dynamical principles upside down. For what has been shown is that in order to be faithful to the two fundamental principles that capture the relationships between events, spatio-temporal structure needs to be deformed according to the rule of the Lorentz transformation. In this way, the structural constraints expressed by the two fundamental principles, which stem from laws of electrodynamics, are encoded within the structure of space-time, not the other way around.

The structural constraints in the principle of special relativity can thus be viewed as a modification of its counterpart of its predecessor, i.e. Newtonian dynamics. Furthermore, given that the light postulate plays the role of characterizing inertial motions for light pulses, the commonality between Newtonian dynamics and the special theory becomes manifest. Torretti in his *Relativity and Geometry* (1983) claims that the light postulate (LP) corresponds to the principle of inertia (IP) for light quanta:

> [T]he LP [the light postulate] may be regarded as the Principle of Inertia applicable to light quanta. (For greater clarity, one ought perhaps to replace ... Einstein's expression "a light ray moves," which anyway sounds peculiar, by "a light point moves.") We must not lose sight of the striking analogy between Lange's treatment of the classical Principle of Inertia (IP), that governs – also in Special Relativity – the free motion of material particles, and the manner how Einstein introduces the LP. (Torretti 1983, 55)

The principle of inertia suggested by Ludwig Lange (1885) considers the motions of free particles, which are rectilinear and travel equal distances in equal times, as determining an inertial system.[10] He analysed Newton's law of inertia as consisting of spatial and temporal parts. The former is characterized by the rectilinear shape it assigns to the trajectory of a freely moving body, whereas the latter is characterized by constant speed of the body that moves along such a trajectory. To make sense of these two parts, he defines an inertial system in which the trajectory of a freely moving body is rectilinear and the speed of the body, which provides the scale of time, is constant. Lange called each of these two elements inertial. The principle of inertia, then, consists of two definitions and two theorems as follows:

> **Definition 1.** A rigid frame F is said to be *inertial* if three freely moving particles[11] projected non-collinearly from a given point in F describe straight lines in [relative space] S_F.

[10] Lange's attempt is to provide empirical meaning to the inertial law. What is the inertial motion of a body referring? The statement that the law refers to absolute space is more than an empirical one since absolute space cannot be observed. To resolve this question, Lange (1885), along with Thomson (1884), defines inertial frame by means of the motions of free particles.

[11] Lange required the motion of three free particles in order to determine inertial frame. Given that the curved trajectory G_1 of a given particle P_1 can be considered as moving in a straight line by constructing a moving coordinate system, it is impossible to define an inertial frame by employing only one moving particle. It is also impossible for any two or three moving particles P_1, P_2 (P_3) to have a coordinate system in which both of the trajectories become straight, since these moving particles could have a coordinate system in which all of the trajectories become straight. "Three arbitrary moving points can be represented as moving on three straight lines, for the triangle formed by the points at any moment corresponds to a some triangle whose vertices lie on three (concurrent and coplanar) straight lines." (DiSalle 1988, 91)

Although the above three particles that move in straight lines are not enough to determine inertial frame, an additional constraint completes the task. The constraint is to rule out the collinearity of the three points, and the parallelism of the trajectories of the three points. The former case enables a fourth curve to be transformed to a straight line by rotating the coordinate system around the line where the three points are placed. And the latter case enables the entire system to be shifted back and forth in the common direction of the three lines. The motions of the three free points

Theorem 1. Every freely moving particle describes a straight line in an inertial frame.

Definition 2. A time scale t is said to be *inertial* if a single particle moving freely in an inertial frame F travels equal distances in S_F in equal times as measured by t.

Theorem 2. Every freely moving particle travels equal distances (in the relative space of an inertial frame) in equal times (measured by an inertial time scale). (Torretti 1983, 17)

Thus Lange claimed that an inertial system needs to be constructed in order to make sense of the principle of inertia: "The law of inertia involves the assumption that an inertial system can be constructed: that is, a system in which all paths of points left to themselves are rectilinear and increase in proportion of time." (Lange 1885, 273) The above two definitions show that this inertial system is defined by considering the behaviours of three freely moving particles.

According to Torretti (1983; 51), when Einstein referred in his (1905) to the "stationary" frame, i.e. "a coordinate system in which the equations of Newtonian mechanics hold good," the frame is best described as Lange's arbitrary inertial frame. This is supported by Einstein's later statement (1916; 772) that "a Galilean system of reference" is one with respect to which "a mass, sufficiently distant from other masses, moves with uniform motion." Torretti, taking Einstein (1911) into consideration[12], also suggests that in addition to Lange's first definition of an inertial system, "[t]he rectilinear propagation of light *in vacuo* provides ... an

satisfying the constraints, determine the inertial frames. Accordingly, any fourth free point can be viewed as traveling in a rectilinear way. (ibid.)

[12] According to Torretti, Einstein (1911) assumed that "[i]f an inertial and a non-inertial frame move past each other with uniform acceleration, a light-lay emitted through empty space in a direction normal to the mutual acceleration of the frames, describes a straight line in the inertial frame, a curved line in the other." (Torretti1983, 51)

additional criterion for the identification of inertial frames, which ... does not presuppose a definition of time." (ibid.) In other words, these two conditions correspond to the spatial part of Lange's definition of inertial system. Hence, the spatial part of Einstein's stationary system can be defined as:

> **Definition 1'.** Three free particles projected non-collinearly from a point in F describe straight lines in S_F.
>
> **Definition 1' (Supplement).** A light pulse transmitted through empty space in any direction from a point in F describes a straight line in S_F. (ibid.)

Yet, in order to describe the motion of any body, a temporal part is also necessary:

> If we want to describe the *motion* of a particle, we give the value of its coordinates as functions of time. However, we must keep in mind that a mathematical description of this kind only has physical meaning if we are already clear as to what we understand here by "time." (Einstein 1905)

Lange's view of time entails that, given that the inertial motion of a body, as pointed out in the last chapter, provides the measure of Newtonian time, Newtonian time can be measured only in the place where an inertial motion of the body occurs. In other words, Newtonian time is accessible only based on dynamical information exemplified in certain natural processes. Einstein seriously considered this local nature of time, as did Poincaré.

> It might seem that all difficulties involved in the definition of "time" could be overcome by my substituting "position of the small hand of my watch" for "time." *Such a definition is indeed sufficient if a time is to be defined exclusively for the place at which the watch is located; but the definition is no longer satisfactory when series of events occurring at different locations have to be linked temporally*, or – what amounts to the same thing – when events occurring at places remote from the clock have to be evaluated temporally. (Einstein 1905, my italics)

"Einstein time" is then suggested in order to define a time coordinate for an inertial system. In opposition to Newton time, which "diffuses *indivisibly* throughout all space," (Hall and Hall 1962, 104), Einstein time is supposed to diffuse throughout all space, which can be measured by reflected photons.

> *The [common time for the locations A and B] can now be determined by establishing by definition that the "time" required for light to travel from A to B is equal to the "time" it requires to travel B to A.* For, suppose a ray of light leaves from A for B at "A-time" t_A, is reflected from B toward A at "B-time" t_B and arrives back at A at "A-time" t'_A. The two clocks are synchronous by definition if
>
> $$t_B - t_A = t'_A - t_B$$
>
> (Einstein 1905, my italics)

Hence, from the above equation, the time at B can be determined as $t_B = 1/2(t'_A + t_A)$. Given that the location B is arbitrary, the reflected photons can be employed to define a function of the time coordinate over all inertial frames:

> By means of certain (imagined) physical experiments, we have established what is to be understood by *synchronous clocks at rest relative to each other and located at different places*, and thereby obviously arrived at definitions of "synchronous" and "time." (ibid., my italics)

A function of the time coordinate is defined on inertial frames "in such way that at each instant the light-front lies on a sphere with its centre at the source and its radius proportional to the time elapsed since the light was emitted." (Torretti 1983, 55) Accordingly, Lange's definition of the temporal part of inertial system is modified by means of the behaviour of a light-pulse, which propagates in every direction from a point at rest in a Lange's inertial frame.

> **Definition 2'.** A light pulse transmitted through empty space in any direction from a source at rest in F traverses equal distances in equal times. (Torretti 1983, 54)

Hence, one can identify a clear analogy between the principle of inertia and the light postulate. Just as Lange's definition of inertial frame becomes meaningful by providing an inertial system in which the principle of inertia is satisfied, Einstein employs the behaviour of the light pulse in order to make sense of the required system of reference in which the light postulate is satisfied.

> Lange saw that the IP [the principle of inertia] is meaningless unless we define at least one frame in which it holds good. Lange defines such a frame by considering the behaviour of three free particles in motion. ... The IP is the factual statement that every other free particle moves in the frame thus defined in the same way as those three, that is, in a straight line, with constant speed. ... [The definition 2'] concerns the behaviour of a single light-pulse, propagating in every direction from a point at rest in a Lange's inertial frame. Time is to be defined on the frame in such way that at each instant the light-front lies on a sphere with its centre at the source and its radius proportional to the time elapsed since the light was emitted. Having thus defined the requisite system of reference, Einstein is able to formulate the LP [the light postulate]. It is the factual statement that every other light-pulse propagates *in the said frame* in the same way as the former, regardless of the state of motion of its source ... (Torretti 1983, 55)

In this way, Torretti claims that "[I]n this the LP [the light postulate] does not differ essentially from the IP [principle of inertia]." (ibid.)

How then does the theory-change from Newtonian theory to special relativity look when considered in this light? My claim is that although there are undoubtedly discontinuities between the space-time structures posited by Newtonian dynamics and by special relativity, the commonality is much more important than the discontinuities. It is because their dynamical principles relating events – (1) the principle of inertia and the light postulate; (2) the principles of Galilean relativity and special relativity – carry out identical work. These principles specify the dynamically-preferred motions, and determine the structures of space-times.[13] In the last section, I have argued that the structural constraints between events, which are specified by the equations of electrodynamics, play essential roles in the special theory. And this section clarifies the commonality between the structural constraints within Newtonian dynamics and special relativity. This is captured by the law of inertia, which is expressed by geodesic equations in these two theories. Although this equation in the special theory gains additional physical significance including the phenomena of electrodynamics, its essential status, as is pointed out in this section, does not change during our case of theory-change. Modified space-time structuralism emphasizes this commonality of this relationship between events. These relationships are specified by dynamics, and are more deep-rooted than the spatio-temporal relationships between events. Hence, it follows that the element of

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[13] The essential role of the behaviours of light pulses in determining the structure of space-time can also be identified in Einstein's following account.

> … [W]e imagine the two ends (A and B) of the rod equipped with clocks that are synchronous with the clocks of the rest system, …
>
> We further imagine that each clock has an observer commoving with it, and that these observers apply to the two clocks the criterion for the synchronous rate of two clocks formulated in section 1. Let a ray of light start out from A at time t_A; it is reflected from B at time t_B, and arrives back at A at time t'_A. Taking into account the principle of the constancy of the velocity of light, we find that
>
> $$t_B - t_A = r_{AB}/V - v$$
>
> and
>
> $$t'_A - t_B = r_{AB}/V + v$$
>
> where r_{AB} denotes the length of the moving rod, measured in the rest system. Observers co-moving with the rod would thus find that the two clocks do not run synchronously, while observers in the system at rest would declare them to be running synchronously.
>
> Thus we see that we cannot ascribe *absolute* meaning to the concept of simultaneity; instead, two events that are simultaneous when observed from some particular coordinate system can no longer be considered simultaneous when observed from a system that is moving relative to that system. (Einstein 1905)

continuity in this theory-change was definitely more deep-rooted and more important than the one of discontinuity.

5. Conclusion

In chapter two, we saw that the working parts of space-time are the relationships between events specified by the laws of motion. In this chapter, I have argued that this perspective can clarify the extent to which the shift from Newtonian dynamics to special relativity was a continuous (or "quasi-continuous") one. If the spatio-temporal relationships between events are considered as the essential parts of the two theories, then the discontinuity between these two theories seems more salient than what is continuous. This is because the structure ascribed to space-time by the later theory has properties that the structure assigned by earlier theory definitely does not have.

However, by looking at the shared group representing their inertial structures, we can see the essential continuity between these two theories. With the dynamical perspective of space-time, dynamical information is brought to centre stage in comprehending our case of theory-change. And modified space-time structuralism clarifies the continuity (or "quasi-continuity") in the theory-change. In other words, if we consider the aspect of the two theories to concern the relationships between events specified by dynamical principles, then we can see and indeed highlight the important element of continuity in the theory-change. Inertial trajectories play an essential role in Newtonian dynamics that does not, however, take the laws of electrodynamics into consideration. Accordingly, the concept of inertial trajectories needs to be modified within the special theory by considering the dynamical constraint provided by the equations of electrodynamics. By considering the constant speed of light, the extent to which the principle of inertia is applied is extended to involve the behaviours of light quanta. And this is in fact what underlies the conceptual change in the suppositions about space-time. In this way, the theory-change is seen as evolutionary: the laws of the predecessor theory capturing the relationships between events are modified by the new theory into more general laws by considering the dynamical elements neglected by the predecessor.

Two pleasing results further endorse this view. First, modified space-time structuralism can avoid the criticism that afflicts the unmodified version of space-time structuralism, namely that emphasizing the concepts of space-time is *post hoc*. Given that space-time concepts become essential after the development of the special theory, it might seem that emphasizing space-time concepts are arbitrary. However, if the concepts of space-time can be viewed as encoding the laws of motion, which is considered as the working part of the overall theory, this criticism is avoided. If it is accepted that dynamical laws play a central role both in Newtonian dynamics and in the special theory, then the story of an evolutionary change cannot be charged with being 'whiggish' or *post hoc*.

Second, no one really denies that there is a strong element of continuity (as their very names suggest) between the special and the general theories of 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 in the two theories. On the one hand, Minkowski space-time is developed within 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." (Norton 1999, 130) 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:

> In the Riemann tradition, one considered a space and a group of transformations. But the geometric entities investigated are no longer the invariants of the transformations, for in that case there are essentially none. Instead one is interested in the invariants of a quadratic differential form, the fundamental or metrical form, that is adjoined to the space. As a result, the groups associated with geometries in the two traditions have very different significance. (Norton 1993, 42)

Hence, trying to understand the continuities between the special theory and the general theory of relativity (or the Newtonian theory and Einsteinian theory of gravitation) by means of common group structure by no means provides a complete picture. Yet, by emphasizing the dynamical contents in both theories, one can avoid this problem. The task of the next chapter will be to demonstrate this.

Chapter 4

The Structuralist Account of the Development of the General Theory of Relativity

1. Introduction

This chapter considers the theory-change from the special theory to the general theory of relativity from the perspective of modified space-time structuralism. In the first chapter, I considered the weaknesses of various different accounts of the ontological continuities and discontinuities in the theory-change. In this chapter, I will reconsider these weaknesses from the perspective of modified space-time structuralism. This chapter is structured as follows. In the next section, I will argue (1) that modified space-time structuralism can identify the essential part of the general theory, and (2) that when viewed within this structuralist's framework, the theory-change from the special theory to the general theory of relativity is essentially continuous (or "quasi-continuous"). And in the last section, I will consider a response from the supporter of a revolutionary view.

2. The Essential Role of Inertial Motions within General Relativity (GR)

(1) Evolutionary and Revolutionary Views on GR Reconsidered

Apparently evolutionary and revolutionary features of the general theory of relativity were discussed in the first chapter:

(1) Space-time identified as the substantival entity "ether," which causes the motion of bodies according to the laws of motion, is alleged to provide an evolutionary element in the theory-change from the special to the general theory.

(2) The general theory is viewed as revolutionary given that the space-time metric has an identical ontological status to that of matter fields such as the electro-magnetic field.

(3) The background-independent formulation of the general theory shows that the theory-change from the special theory to the general theory of relativity is essentially revolutionary.

In this section, we will see that the weaknesses of these claims about the general theory can be remedied from the perspective of my modified space-time structuralism. By criticizing claims (1) and (2), which emphasize the causal roles of general relativistic space-time, we will see that the essential part of the general theory, just like its predecessors, is the specification of the inertial motions of bodies (specified by the geodesic equations of motion). And this basic framework based on inertial trajectories that specify the relationships between events obtains additional physical significance by incorporating dynamical information about gravitational interactions, i.e. Einstein's principle of equivalence, which provides a further constraint over the relationships between events. In this sense, we can say that the development from the special to the general theory is essentially continuous. We will see that this is in fact what underlies the aforementioned formal continuity within the theory-change. As for claim (3), we will see in the next section that the background-independent formulation of the general theory in fact endorses an evolutionary view, rather than a revolutionary view, when looked at from the perspective of modified space-time structuralism.

The evolutionary claim (1), as was pointed out earlier, was in fact endorsed by Einstein himself:

> The inertia-producing property of this ether [absolute space], in accordance with classical mechanics, is precisely *not* to be influenced, either by the configuration of matter, or by anything else. For this reason, one may call it 'absolute.' That something real has to be conceived as the cause for the preference of an inertial system over a non-inertial system is a fact that physicists have only come to understand in recent years. ... Also, following the special theory of relativity, the ether was absolute, because its influence on inertia and light propagation was thought to be independent of physical influences of any kind. ... The ether of the general theory of relativity ... differs from that of classical mechanics or the special theory of relativity respectively, in so far as it is not 'absolute,' but is determined in its locally variable properties by ponderable matter. (Einstein 1924)

The structure of space-time in general relativity is represented as a four dimensional differential manifold *M*, which is equipped with a semi-Riemannian metric tensor $\boldsymbol{g}$ of signature (1,3). And the distribution of material things is encoded in its stress energy tensor $\boldsymbol{T}$. The dynamics is specified by Einstein field equation (*EFE*) $G_{ij} = R_{ij} - 1/2g_{ij}R = 8G\pi/c^4T_{ij}$, which associates the curvature of space-time (the function of $\boldsymbol{g}$ and its first derivatives) with $\boldsymbol{T}$. What is notable about this equation is that the metric tensor $\boldsymbol{g}$ occurs not only in the left hand side of *EFE* which decides the spatio-temporal structure, but also in the right hand side of *EFE* which encodes the matter distribution. And this correlation between the two metric tensors in *EFE* shows the way that space-time directs the motion of material bodies, while the mass-energy distribution in turn influences spatio-temporal structure.

This theoretical posit of the general theory of relativity is considered as providing a causal explanation showing how "space acts on matter, telling it how to move. In turn, matter reacts back on space, telling it how to curve." (Misner et al. 1973, 5) More importantly, Einstein in *the Meaning of Relativity* (1922) expressed that the general theory was motivated by this causal view:

> *[A]bsolutum* means not only 'physically real,' but also 'independent in its physical properties, having a physical effect, but not itself influenced by physical condition. ... [I]t is contrary to the mode of thinking in science to conceive a thing (the space-time continuum) which acts itself, but which cannot be acted upon. (Einstein 1922, 55-6)

Dorato also follows this line of thought:

> By using the spatiotemporal structure as an explanatory tool, and declaring it to be a mind-independent *property* of certain physical systems, structural realists about spacetime may rely on the fact that *properties* (spatiotemporal ones included) *simply are*, in any respectable metaphysical theories, *the causal powers of the entities having them.* ... What causes the deflection of the orbit of the massive body is the gravitational field, a thoroughly physical field, *via* its geometrical, causally active relational properties. (Dorato 2000, 1616, my italics)

However, as pointed out in the first chapter, these causal accounts of space-time, according to Brown, are not only superfluous, but even problematic within the context of the general theory:

> From his earliest inklings of a theory of gravity based on the principle of equivalence and the curvature of space-time, until 1927, Einstein assumed that all test bodies would follow the grooves or ruts of space-time defined by curves that are straight, or equivalently that are of extremal length. *We have seen that during this period Einstein assigned a causal role to space-time structure in precisely this sense: to nudge the particles along such privileged ruts. This kind of action of space-time on matter was taken to primitive; fortunately it turned out to be unnecessary. Appeal to the form of the field equations was enough to deliver the principle of geodesic motion.* ... In particular, [C. Misner, K. Thorne, and J. Wheeler] explain how the geodesic behaviour of test bodies can be derived from the vanishing of the covariant divergence of the stress-energy tensor associated with the body. (Brown 2005, 141, my italics)

The geodesic principle within the general theory, which corresponds with the law of inertia, can be derived from the dynamical content of general relativity, rather than from its space-time geometry.

In fact, we can see that the above explanation, i.e. the derivation of the geodesic equation, is a structural one in the two sense elaborated in the previous chapter. First, the geodesic equation of motion can be derived from a *structural constraint over events*, i.e. the conservation of energy-momentum in a world tube around the world line of a particle. This constraint requires that "the energy-momentum emerging out of [the upper boundary of the world tube] has to equal the energy-momentum entering [the bottom boundary of the world tube]". (Misner et al. 1973, 473) This can be said to be structural given that the requirement is the consequence of a geometric consideration of the 'Bianchi identity,' which is intuitively expressed as the boundary of a boundary is zero[1]" (ibid, 365-7):

> The one central point is a law of conservation (conservation of charge; conservation of momentum-energy).
>
> The other central point is "automatic fulfillment" of this conservation law.
>
> "Automatic conservation" requires that source not be an agent free to vary arbitrarily from place to place and instant and instant.
>
> Source needs a tie to something that, while having degrees of freedom of its own, will cut down the otherwise arbitrary degrees of freedom of the source sufficiently to guarantee that the source automatically fulfills the conservation law. Give the name "field" to this something.
>
> *Define this field and "wire it up" to the source in such a way that the conservation of the source shall be an automatic consequence of the "zero boundary of a boundary."* (ibid., 366, original italics)

In case of the general theory, this automatically conserved quantity is the Einstein tensor $\boldsymbol{G}$. Just like the conservation of the source ($\boldsymbol{d}^*\boldsymbol{J} = 0$) within electrodynamics is a consequence of the Bianchi identity satisfied by the dual of the Maxwell field

[1] In case of a 3-dimensional space-time region, the Bianchi identity captures a geometric intuition that the 1-dimensional boundary of the 2-dimensional boundary of the 3-dimensional region is zero. And in case of a 4-dimensional space-time region, the identity represents a geometric intuition that the 3-dimensional boundary of the 3-dimensional boundary of the 4-dimensional region is zero. (ibid., 356-7)

tensor $*F$, the conservation of the energy-momentum tensor ($d*T = 0$) within the general theory is a consequence of the Bianchi identity satisfied by Einstein tensor G. The physical significance of this structural constraint is simply to prohibit any events in this region from being neither created nor destroyed:

> Conservation demands no creation or destruction of source inside the four-dimensional [space-time region]. Equivalently, integral of "*creation events*" (integral of $d*J$ for electric charge; integral of $d*T$ for energy-momentum) over this four-dimensional region is required to be zero. (ibid., my italics)

Furthermore, the procedure of the derivation of geodesic equation does not involve the complexities about the internal structure of a particle.

> Is there not an inner contradiction in trying to apply to a "particle" (implying idealization to a point) a field equation that deals with the continuum? Answer: There *is* a contradiction in dealing with a point. Therefore do not deal with a point. *Do not deal with internal structure at all. Analyze the motion by looking at the geometry outside the object. That geometry provides all the handle one needs to follow motion. …* Surrounding "the Schwarzschild zone of influence" of the object, mark out a "buffer zone" that extends out to the region where the "background geometry" begins to depart substantially from flatness. Idealize the geometry in the buffer zone as that of an unchanging source merging asymtotically ("boundary β of buffer zone") into flat space. It suffices to recall the properties of the spacetime geometry far outside an unchanging (i.e., nonradiating) source … to draw the key conclusion: relative to this flat spacetime and regardless of its internal structure, the object remains at rest, or continues to move in a straight line at uniform velocity. (conservation of total 4-momentum) In other words, it obeys the geodesic equation of motion. (ibid., my italics)

The complexities of a particle's internal structure require a consideration of the coupling of the curvature of space-time to the particle's internal structure such as angular momentum, mass quadruple momentum, and higher moments. These elements of internal structure couple with the curvature of background space, and by no means allow the buffer zone where its metric approaches Minkowskian. Yet, by considering a test particle, "geometry provides all the handle one needs to follow motion" in that the buffer zone reduces in size to zero while the metric of the buffer zone approaches Minkowskian. Along with this consideration, the structural constraint of events within the world tube (i.e. the conservation of energy-momentum) then entails the required relationships between events, that is, the geodesic equation of motion.[2]

The second aspect characterizing the above derivation as a structural one is that this geodesic equation of motion is derived from Einstein's field equation as the conservation of energy-momentum is essentially incorporated within Einstein's field equation. This becomes manifest when the general theory is compared with electrodynamics:

> [I]n no theory but Einstein's is this principle incorporated as an identity. Only [in the general theory] does the conservation of energy-momentum appear as a fully automatic consequence of the inner working of the machinery of the world. ... Out of Einstein's theory one can derive the equation of motion of a particle. Out of Maxwell's one cannot. ... The Maxwell's field equations are so constructed that they automatically fulfil and demand the conservation of charge; but not everything has charge. The Einstein field equation is so constructed that it automatically fulfils and demands the conservation of momentum-energy; and everything does have energy. ... Why ... is the derivation of the geodesic equation of motion of an object said to be based on "Einstein's geometrodynamic field equation" rather than on "the principle of conservation of 4-momentum? Because geometry responds by its curvature to mass-energy in every form. Most of all, because geometry tells about mass-energy inside, free of all concern about issues of internal structure. (Misner et. al. 1973, 475)

In fact, the law of the energy-momentum conservation is a consequence of the Bianchi identity satisfied by Einstein tensor *along with* Einstein field equations in a

[2] Misner, Thorne, and Wheeler (ibid. 476) contrast this derivation of the geodesic equation of motion with the one of Lorentz's equation of motion from the conservation of energy-momentum, which requires to deal with a particle's interaction with a field and with its own electromagnetic field. In other words, "no advantage was taken of geometry outside as indicator of motion inside; (2) a detailed bookkeeping was envisaged of the localization in space of the electromagnetic energy; and (3) this bookkeeping brought up the issue of the internal structure of the particle, which could not be satisfactorily resolved."

sense that the (contracted) Bianchi identify $G^{ij}{}_{;j} = 0$ guarantees that Einstein field equations contain the law of energy-momentum conservation. (This is analogous to Maxwell equations, which contain the charge conservation with the help of the Bianchi identity satisfied by the dual of Maxwell tensor) Accordingly, the conservation law stems from dynamical information that "all matter and fields are wired into the geometry of space-time." (ibid., 409) So, the geodesic equation of motion, which specifies the relationships between events, stems from the dynamics of the general theory of relativity, rather than from its space-time structure, as modified space-time structuralism claims.

So much for my criticism of the step (1). I turn now to the step (2) of the causal account of the general theory of relativity. The geodesic equations of motion in fact play an essential role in comprehending gravitational waves, which appear to provide causal account of the general theory. As pointed out in the first chapter, Rovelli (1997, 2001) emphasizes this causal role of gravity:

> [T]he gravitational field is represented by a field on spacetime, $g_{\mu\nu}$, just like the electromagnetic field A_μ. They are both *concrete entities*: a strong electromagnetic wave can hit you and knock you down; and so can a strong gravitational wave. (Rovelli 2001, 107)

And:

> A strong burst of gravitational waves could come from the sky and knock down the rock of Gibraltar, precisely as a strong burst of electromagnetic radiation could. Why is the first "matter" and the second "space"? Why should we regard the first burst as ontologically different from the second? (Rovelli 1997, 193)

Gravitational waves are basically small fluctuations of the metric $g_{\mu\nu}$, which are described as 'ripples' of space-time. When the gravitational field in empty space is very weak, the metric is split into the Minkowski metric $\eta_{\mu\nu}$ and the metric perturbation $h_{\mu\nu}$, i.e., $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$. By neglecting terms in $h_{\mu\nu}$-squared and higher powers, 'linearized field equations' can be derived from Einstein's field equations. The result is a set of linear second-order partial differential equations for $h_{\mu\nu}$. And with the choice of Lorentz gauge, which corresponds to the choice of coordinates, these equations can be transformed so as to be similar in form to Maxwell's equations, which predict electromagnetic waves. This linearized theory of gravitation, just like its electromagnetic counterparts, has a solution that predicts gravitational waves travelling with the speed of light. Accordingly, gravitational waves seem to pass through space just like electromagnetic waves.

However, we have seen in the first chapter that this mathematical analogy between gravitational and non-gravitational waves breaks down, when one considers the difference between the gravitational energy-momentum and the non-gravitational energy-momentum. The latter quantity is a tensor, while the former is not. Although physically meaningful quantities should be tensors, the gravitational energy-momentum does not pass this test. It is instead a *pseudo*-tensor, which is variable (and may even vanish) dependent on the choice of coordinate system:

> [I]ts non-tensorial nature means that there is no well-defined, intrinsic 'amount of stuff' present at any given point. In particular, unlike a genuine tensor, [a pseudo-tensor] can be made to vanish at any given moment by a suitable coordinate transformation. *[This] therefore cannot really be telling us about the local interchange of energy-momentum between gravity and matter.* (Hoefer 2000, 193, my italics)

And Norton (2000) expresses the same view:

In so far as I can understand this response, it really just tells us that a pseudo-tensor should be given *no physical interpretation*. It should merely be used as a mathematical intermediary in computing the gravitational energy and momentum of extended systems. (Norton 2000, ch. 3, my italics)

Can this problem be avoided by considering the gravitational energy-momentum of some extended system? Norton's answer is "no":

The difficulty with this problem is that the gravitational energy and momentum of extended systems fare only marginally better. ... Following the classical model, one would expect that we could take the energy and momentum densities of [gravitational and non-gravitational energy-momenta] and sum them up over the space occupied by, for example, a galaxy of stars to find the galaxy's total energy and momentum. *In general, this cannot be done. One cannot define meaningfully the total energy and momentum of some extended system, where the total energy and momentum is to include both gravitational and non-gravitational contributions. At best, these total quantities can be defined in special [unrealistic] cases.*[3] (ibid., my italics)

Hence, just as in the special theory, Salmon's notions of "causal interactions" and "causal processes," which are based on the exchange of conserved quantities, do not fit in the general theory either.

Instead, the physical significance of gravitational waves is captured in terms of the inertial motions of the general theory:

When the rock is hit by a strong burst of electromagnetic radiation, the natural motions of the parts of the rock do not (significantly) change. Rather the parts of the rock are *differently* accelerated by forces that overcome the contracting forces between the parts of

[3] Norton explicates why it is difficult to define the total energy and momentum of certain extended system as follows:

The summation of the information in [gravitational and non-gravitational energy-momentums] to recover a total energy can be done if there is a rest frame in which the geometry of the spacetime is independent of time. That would rise if we had a completely isolate galaxy not of stars but of passive lumps of matter held apart by sticks such that the whole system just sat there completely motionless. *Real systems are not so nicely behaved.* Stars radiate and thereby change their mass; stars in galaxies move about relativie to each other; gravitational waves impinge upon the galaxy form the outside. All this affects the geometry of spacetime and precludes the summation. (Norton 2000, my italics)

> the rock. *When the rock is hit by gravitational radiation, however, no additional accelerative forces are applied. Rather the natural motions are no longer towards the rock's centre but are radically divergent.* So divergent, in fact, that the electromagnetic binding forces of the rock are no longer sufficient to accelerate the parts of the rock away from their natural trajectories. (Pooley 2002, my italics)

The distortion by a gravitational wave is in fact captured by considering its effect on the *motions* of bodies that the wave passes. Here the equation of geodesic deviation, which describes the relative motions of two or more bodies, describes that a set of particles, which follows their own geodesics, is deformed by the tidal acceleration generated by the gravitational wave. In other words, this equation describes the oscillations in the separation between neighbouring inertailly moving particles, which are described as the oscillating curvature tensor of a gravitational wave.

We can see that the essential role of the specification of the inertial motions of bodies in the above account properly fits within the framework of the general theory of relativity, if we look at how current standard textbooks (such as Misner et al. 1973, Wald 1984, and d'Inverno 1992) motivate Einstein's field equations (*EFE*). Here, the physics of the curvature tensor $\boldsymbol{R}$ on the left hand side of *EFE* is motivated from a Newtonian equation that expresses the relative acceleration of neighbouring test particles – so called "the tidal acceleration of two nearby particles." And its corresponding general relativistic expression, i.e. the equation of geodesic deviation, then provides the expression of the curvature tensor $\boldsymbol{R}$.[4]

> An important clue [in deriving *EFE*] is provided by the comparison of the description of tidal force in Newtonian gravity and general relativity. In the Newtonian theory, the

[4] The right hand of *EFE* stems from the correspondence between the mass density of matter ρ within Poisson's equation ($\nabla^2\Phi = 4\pi\rho$) and a stress-energy tensor T_{ab}: $T_{ab}v^a v^b \leftrightarrow \rho$.

gravitational field may be represented by a potential, Φ, and the tidal acceleration of two nearby particles is given by $-(\boldsymbol{x}\nabla)\nabla\Phi$, where $\boldsymbol{x}$ is the separation vector of the particles. On the other hand, in general relativity, from [the geodesic deviation equation] the tidal acceleration of two particles is given by $-R_{cbd}{}^{a}v^{c}x^{b}v^{d}$, where v^{a} is the 4-velocity of the particles and x^{a} is the deviation vector. This suggests that we make the correspondence, $R_{cbd}{}^{a}v^{c}v^{d} \leftrightarrow \partial_{b}\partial^{a}\Phi$. (Wald 1984, 71-2)

Hence, the geometrical structure of space-time, i.e. the curvature tensor in fact encodes the relationships between events, which are specified by the equations of geodesic motion and geodesic deviation. Geroch's analogy also makes this point well:

[W]e might imagine the earth inhabited by small, very flat, two-dimensional ants, which crawl about the surface .... We ask, Would such ants be able to determine whether or not the surface of the earth is curved? In order to answer this question, we might begin with a more general question: *What is the sum total of all the information (of a geometrical character) that these ants could accumulate about the surface of the earth?* They could certainly locate various points on the surface of the earth, and they could certainly measure distances between pairs of points (by crawling between points) – and that is about it. ... *The ants have access only to points on the earth and distances between nearby points; we have access only to events in space-time and intervals between nearby points. The ants, from the information they have, can detect curvature* ... This analogy suggests, then, that, using only geometrical constructions involving the events in space-time and the intervals, we may introduce a quantity which may be thought of as the "curvature of space-time geometry" itself. (Geroch 1978, 166-9, my italics)

So, within the general theory of relativity, the inertial motions of bodies play the key role. Brown in his *Physical Relativity* clearly expressed this point:

[The fact that geodesic motion is a theorem and not a postulate] sheds light on the meaning of inertia (in the sense of inertial motion) and gravity.

Gravity traditionally has had two faces. It explains why things fall down and it explains why the fall is not uniform across space and time. Take the latter aspect first. Two objects are in free fall in my office: the head of my student who has just nodded off in a tutorial, and the copy of Misner, Thorne and Wheeler's *Gravitation* that I am throwing at him. ... [T]he two objects do not quite move along parallel lines – they are each heading after all towards the centre of the Earth. This of course has to do in GR with geodesic deviation, with the so-called 'tidal' effects of space-time curvature. It is tempting to think that in GR this is all we mean, or should mean, by gravity. *For when we come to explaining why the objects are falling in the first place, the answer seems almost banal. It is because the frame defined by my office is accelerating in relation to the local inertial frames, and in relation to the latter frames the objects, being force-free, are simply moving inertially. The glory of*

> *this explanation is that it accounts for the universality of free fall – that all bodies, independent of their constitution, fall at the same rate.* ... [W]hen 'force-free' test bodies undergo geodesic flow in GR, whether there is geodesic deviation or not, such motion is ultimately due to the way the Einstein field $g_{\mu\nu}$ couples to matter, as determined by the field equations. (Brown 2005, 142-3, my italics)

(2) Inertial Motions in the Development of the General Theory of Relativity

In this section, we will see that the trajectories of inertially moving bodies in fact play an essential role in the *development* of the general theory. Yet, given additional dynamical information about gravitational interactions, the characterization of which trajectories are inertial needs to be modified. A dynamical principle involved here is the equivalence principle. The special theory stems from electrodynamics, but neglects gravity. Introducing consideration of the gravitational 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 general theory, this connection is incoporated into a dynamical principle, which results in a new concept of inertial motion. The principle stems from the fact that a given body should satisfy the same laws of motion whether this motion is considered with respect to a rest frame or to a frame uniformly accelerated by a homogeneous gravitational field:

> [O]ne can ask oneself whether an observer, uniformly accelerated relative to K in the region considered, must understand his condition as accelerated, or whether there remains a point of view for him, in accord with the (approximately) known laws of nature, by which he can interpret his condition as "rest." Expressed more presiely: do the laws of nature, known to a certain approximation, allow us to consider a reference system K' as at rest, if it is

accelerated uniformly with respect to *K*? Or somewhat more generally: Can the principle of relativity be extended also to reference systems, which are (uniformly) accelerated relative to one another? The answer runs: As far as we really know the laws of nature, nothing stops us from considering the system *K*' as at rest. If we assume the presence of a gravitational field (homogeneous in the first approximation) relative to *K*'; for all bodies fall with the same acceleration independent of their physical nature in a homogeneous gravitational field as well as with respect to our system *K*'. The assumption that one may treat *K*' as at rest in all strictness without any laws of nature not being fulfilled with respect to *K*', I call the "principle of equivalence." (Einstein 1916)

So, the true strength of the gravitational field cannot be identified simply by observing the motions in a frame of reference. The inertial or accelerating motions of a given body, which are assumed to be considered with respect to a rest (or a uniformly moving) frame, could be relativitized to any uniformly accelerating reference frames that involve a uniform gravitational field:

> This assumption of exact physical equivalence makes it impossible for us to speak of the absolute accelerations of the system of reference, just as the special theory of relativity forbids us to talk of the absolute velocity of a system. (DiSalle 2002)

In this way, the equivalence principle exhibits the close connection that exists between inertia and gravity. In the above passage, Einstein viewed the principle as extending the principle of relativity, which relativitizes the absolute acceleration of a system. Yet, it has been pointed out that this role of the principle of equivalence is misleading.[5] (Friedman 1983, Earman 1974, Janssen 2004) This is because the

[5] Einstein (1907) initially thought that the principle of equivalence enabled him to generalize the relativity between uniform and accelerated motions. By transforming the space-time coordinate of an accelerated observer, it seemed that her acceleration could be relativitized. An accelerated observer can maintain that she is at rest by stating that the gravitational field for her is different from the gravitational field of the inertial observer. This is the core of Einstein's thought experiment of a free falling person in an elevator. But according to Janssen (2004), this view of the principle is not tenable: "Two observers in uniform motion are physically equivalent. [In contrast], two observers in non-uniform relative motion obviously not." Sitting at one's desk in the patent office does not feel the same as feeling from the roof of the building, even though the man falling from the roof can, if he were so inclined, claim that he is at rest and that the

distinction between accelerating and non-accelerating motion is manifest in the general theory: the latter is represented by a geodesic and the former is represented by a non-geodesic. What Einstein in fact intended with this principle turned out to be the dual role of the metric tensor representing inertia and gravity (Norton 1985, Janssen 2004).[6] According to Einstein:

> The inertio-gravitational field, represented by the metric tensor field, describes the metrical properties of space, inertial behaviour of bodies in space, and the effects of gravity. (Einstein 1918)

Norton and Janssen reiterate this point:

> Einstein's principle of equivalence asserted that the properties of space that manifest themselves in inertial effects are really the properties of a field structure *in* space: moreover this same structure also governs gravitational effects. ... The structure responsible for inertial and gravitational effects is the metric tensor. (Norton 1985, 40-1)

And:

> 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 [a given] inertio-gravitational effect breaks down into an inertial component and a gravitational component is not unique but

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dishevelled patent clerk whose eyes he meets on the way down is accelerating upward in a space with no gravitational field at all." (Janssen 2004, 10)

[6] Norton (1985) introduces failed attempts to comprehend Einstein's principle of equivalence.

Pauli (1921) considered the principle as a claim that by transforming to an appropriate space-time coordinate system, an arbitrary gravitational field could be transformed away in an infinitely small region of space-time: "[F]or every infinitely small world region ..., there always exist coordinate system $K_0(X_1,X_2,X_3,X_4)$ in which gravitation has no influence either on the motion of particles or any other physical processes." (Pauli 1921, p.145)

Yet this view is not tenable, since the presence of a gravitational field corresponds with non-vanishing curvature of the space-time, which is the intrinsic property of geometry. Consider a case that tidal force acts on a free falling droplet. The aim of the above equivalence principle is to eliminate the tidal force. But it is impossible to do this. The tidal bulges on a freely falling droplet remains as the droplet becomes arbitrarily small, ignoring such effect as surface tension (Ohanian 1976). Given that the gravitational field is described by an invariant quantity, it remains the same under any coordinate transformations. In this spirit, Synge states that "[i]n Einstein's theory, either there is a gravitational field or there is none, according as the Riemann tensor does not or does vanish. This is absolute property; it has nothing to do with any observer's world line (Synge 1960, ix)."

> depends on the state of motion of the observer making the [judgement], 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. (Janssen 2004, 9)

Just as the special theory of relativity assumes that the electric and the magnetic fields are special aspects of one entity called the electromagnetic field, so the general theory of relativity takes it that the inertial structure of space-time and the gravitational field are both special aspects of the inertio-gravitational field. The principle of equivalence 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 gravity, the motion of a gravitationally accelerating body can be decomposed into two separate elements; (1) its inertial motion and (2) the acceleration due to gravity. The former is a "natural tendency to move uniformly in a straight line" and the latter is a motion due to the gravitational field. Within Einstein's general theory of relativity, the principle of equivalence (the relativity between inertia and gravity) states that the decomposition of motion into inertial and gravitating components is not unique:

> The focus of Einstein's concern is the necessity in special relativity and classical mechanics of presuming an immutable division of relative spaces and frames of reference into the privileged inertial and the noninertial. The principle of equivalence enabled him to eliminate the immutability of this division, by reinterpreting the nature of the inertial effects which distinguish the privileged inertial spaces and frames from all others. (Norton 1985, 21)

This results in a new concept of an inertial motion, which is 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. (Penrose 2004, 393-4).

Why is a free-falling trajectory chosen as the privileged inertial one among the infinite alternative combinations of inertial and gravitational motions, which are all allowed by the principle of equivalence? According to DiSalle, one could choose any decomposition into an inertial motion and a gravitational motion in constructing a theory of gravity:

> We can choose *any* coordinate system and identify its straight lines as geodesic worldlines; then we can construct the gravitational field as is required in order to make up the difference between these geodesics and the actual motions. (DiSalle 1995, 332, my italics)

However, Einstein did not choose an arbitrary coordinate system and identify its straight lines as corresponding to inertial motion, but determined a free-falling trajectory of a system as the privileged one. What is the justification of this? DiSalle points out that along with the equivalence principle, the requirement of general covariance selects gravitational free fall as the privileged state of motion:

> Combined with the equivalence principle ... [the principle of general covariance] implies that a central Newtonian idea – that gravity is a force causing deviations from uniform rectilinear motion – is based on an arbitrary choice of coordinates. For a trajectory that satisfies all empirical criteria for being inertial in a particular frame of reference – e.g. the

> trajectory of the center of mass in our example – may be freely falling relative to some other trajectory that satisfies the same criteria. By contrast, a freely-falling trajectory is a freely falling trajectory in any coordinate system; it is only the decomposition of it into its inertial and gravitational parts that will be different in different coordinate systems. (DiSalle 2002)

Thus, because other decompositions violate the principle of general covariance, one should consider the unique decomposition into an inertial motion and a gravitational motion. As DiSalle points out, the requirement of general covariance is then by no means an argument against a privileged state of motion. On the contrary, it is an argument that the privileged states of motion should not be a mere artifact of our choice of coordinate system (ibid.). Accordingly, gravitational free-fall, in the framework of the general theory of relativity, is a privileged state of motion.

(3) Modified Space-time Structuralism Looks At the Theory-Change

Modified space-time structuralism thus captures the continuity (or quasi-continuity) in the theory-change from the special to the general theory. In the last chapter, we have seen that the inertial principle, which stems from the light postulate, plays essential role within the special theory. And the special theory modifies inertial trajectories through the principles of the special relativity and the light postulate. In a similar manner, inertial motions play the essential role in the general theory, and the principles of equivalence, a dynamical principle of the general theory of relativity, once more modify the concept of inertial motion. Although these inertial motions, which specify the relationships between events, gain additional physical significance through the additional constraint involving the principle of inertia applied to light pulse in the special theory and the principle of inertia considering the equivalence principle in the general theory of relativity, these inertial motions are all represented by the same mathematical structure, that is, geodesics. A geodesic is defined as a body's curve that continues to parallel to itself. So, the inertial motion of a body involves a local constraint between events, i.e. the tangent vector to the trajectory of the body remains parallel to itself. This structural constraint, which is expressed as the geodesic equation of motion, plays an essential part that captures the continuity in the theory-change from the special theory to the general theory of relativity.

Another way to see this structural continuity in the theory-change can be identified in the "comma-goes-to-semicolon" rule, which is the mathematical expression of the equivalence principle. The principle stems from a theoretical posit that the gravitational interaction is universal, and thus the trajectory of a freely falling body in a gravitational field does not depend on the internal structure of the body. In the special theory, one can determine the inertial trajectory of a given body with respect to a preferred inertial frame, which singles out an inertial observer who is unaffected by any force field. The straight trajectory of a body with respect to Minkowski space-time is defined as the inertial one. In contrast, given that the equivalence principle obliterates any preferred inertial frame, all bodies might experience acceleration due to the gravitational field. Instead, with reference to a local inertial frame, the trajectories of free-falling bodies are selected as a privileged one. This essential role of local inertial motions within the general theory is clearly captured by Misner, Thorne, and Wheeler.

> Don't try to describe motion relative to faraway objects. *Physics is simple only when analyzed locally.* And locally the world line that a satellite follows [in spacetime, around the Earth] is already as straight as any world line can be. Forget all this talk about 'deflection' and 'force of gravitation.' I'm inside a spaceship. Or I'm floating outside and near it. Do I feel any 'force of gravitation'? Not at all. Does the spaceship 'feel' such a force? No. Then why talk about it? Recognize that the spaceship and I traverse a region of spacetime free of all force. Acknowledge that the motion through that region is already ideally straight. (Misner et al. 1973, 4-5)

The theory-change from the special theory to the general theory of relativity can be captured in a single sentence representing the principle of equivalence – namely, that "physics is simple only when analysed locally."

> Whenever one is and whenever one probes, one finds that then and there one can introduce a local inertial frame in which all test particles move along straight lines. Moreover, this local inertial frame is also locally Lorentz: in it the velocity of light has its standard value, and light rays, like world lines of test particles, are straight. But physics is more, and the analysis of physics demands more than an account solely of the motions of test particles and light rays. What happens to Maxwell's equations, the laws of hydrodynamics, the principles of atomic structure, and all the rest of physics under the influence of "powerful gravitational fields"?
>
> The answer is simple: in any and every local Lorentz frame, anywhere and anytime in the universe, all the (nongravitational) laws of physics must take on their familiar special-relativistic forms. ... This is Einstein's principle of equivalence in its strongest form ... The principle of equivalence has great power. *With it one can generalize all the special relativistic laws of physics to curved spacetime.* (Misner et al. 1973, 385-6, my italics)

Then, we can see the structural continuity in the theory-change from the special to the general theory of relativity within the so-called "comma-goes-to-semicolon" rule, which is "guaranteed by, and in fact is a mere rewording of, the equivalence principle." (ibid., 387) This rule states that the transformation from laws in special relativistic space-time to ones in curved space-time merely requires that the partial derivatives of special relativistic laws, i.e. flat space-time gradients, are replaced by covariant derivatives, i.e. curved space-time gradients.[7] Here, there are strong similarities within their mathematical structures although the latter obtains new physical significance by incorporating gravitational interactions:

> Compare the abstract geometrical law ... in curved spacetime with the corresponding law ... in flat spacetime. They are identical! ... *The laws of physics, written in abstract geometric form, differ in no way whatsoever between curved spacetime and flat spacetime*; this is guaranteed by, and in fact is a mere rewording of, the equivalence principle.
> Compare the component version of the law ... as written in an arbitrary frame in curved spacetime ... ,with the component version in a global Lorentz frame of flat spacetime ... . They differ in only one way: the comma (partial derivative; flat-spacetime gradient) is replaced by a semicolon (covariant derivative; curved-spacetime gradient). This procedure for rewriting the equations has universal application. *The laws of physics, written in component form, change on passage from flat spacetime to curved spacetime by a mere replacement of all commas by semicolon* (no change at all physically or geometrically; change due only to switch in reference frame from Lorentz to non-Lorentz!). This statement, like the nonchanging of abstract geometric laws, is nothing but a rephrased version of the equivalence principle. (ibid., 386-7)

This structural similarity captures the essential continuity in the theory-change from the special theory to the general theory. Consider the generalization of the trajectory of freely-falling bodies with respect to flat space-time to one with respect to curved space-time.[8] Freely-falling bodies move in straight lines with respect to flat Minkowski space-time. And this is mathematically represented as the vanishing of the second derivative of the parameterised paths $x^{\mu}(\lambda)$: $d^2x^{\mu}/d\lambda^2 = 0$. Yet, although $dx^{\mu}/d\lambda$ are the components of a well-defined vector, i.e. tensor, $d^2x^{\mu}/d\lambda^2$ are not. Accordingly we adopt the chain rule as follows: $d^2x^{\mu}/d\lambda^2 = (dx^{\nu}/d\lambda)\partial^{\nu}(dx^{\mu}/d\lambda)$. Then, by "comma-goes-to-semicolon" rule the partial derivative is replaced by a covariant

[7] A simple recipe for generalizing laws of physics to the curved spacetime context, known as the minimal coupling principle. In its baldest form, this recipe may be stated as follow. 1. Take a law of physics, valid in inertial coordinates in flat spacetime. 2. Write it in a coordinate-invariant (tensorial) form. 3. Assert that the resulting law remains true in curved spacetime. (Carroll 2004, 152)
[8] I follow Carroll (2003) for this example.

one: $(dx^{\nu}/d\lambda)\partial_{\nu}(dx^{\mu}/d\lambda) \rightarrow (dx^{\nu}/d\lambda)\nabla_{\nu}(dx^{\mu}/d\lambda) = d^2x^{\mu}/d\lambda^2 + \Gamma^{\mu}{}_{\rho\sigma}(dx^{\rho}/d\lambda)(dx^{\sigma}/d\lambda)$. So we can see that in the general thoery, the trajectory of free-falling bodies satisfies the geodesic equation: $d^2x^{\mu}/d\lambda^2 + \Gamma^{\mu}{}_{\rho\sigma}(dx^{\rho}/d\lambda)(dx^{\sigma}/d\lambda) = 0$.

From the perspective of modified space-time structuralism, the equivalence principle modifies the relationships of events in that it identifies apparently different states of motions. And it specifies the trajectories of free-falling bodies under gravitational interaction. So, my modified version of space-time structuralism can provide an evolutionary account of the theory-change from Newtonian to Einsteinian physics. By emphasizing the essential role of the relations of regularity between events, which specially specify the inertial trajectories of bodies, we can see the commonality in our case of theory-change. The inertial trajectories of bodies are all specified by the relations of regularity between events, which are represented by the principle of inertia in Newtonian mechanics, the light postulate in the special theory, and the equivalence principle in the general theory. By considering physical interactions that are not taken into account within predecessor theories, the shared mathematical structures, i.e. geodesics obtain additional physical meaning in the course of the theory-change.

Furthermore, from the above perspective, we can understand why continuity is more essential than discontinuity within the theory-change from the special to the general theory. Within both the special and the general theories, the dynamical laws determine the structure of space-time in that these behaviours of bodies codify the spatio-temporal relations between events. Within the special theory, these spatio-temporal relationships between events are represented by the Minkowski geometry, which relates the inertial frames defined by the trajectories of bodies and light pluses. In contrast, within the general theory, 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, Thorne, and Wheeler:

> [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 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.* (Misner et al 1973, 33)

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, Thorne, and Wheeler (1973, 5) 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.' (ibid.)

And Ellis and Williams (2000) capture this essential role of inertial motions within the context of the theory-change.

> As in the case of particle world-lines, the relative separation of neighbouring light rays can be used to detect space-time curvature, ... *In the space-time context, Euclid's axiom that parallel straight lines never meet is replaced by an equation (the equation of geodesic deviation) determining how the distance between neighbouring geodesics varies as a result of space-time curvature.* In the case of light rays, these effects are directly observable by measuring apparent angular diameters of distant objects. (Ellis and Williams 2000, 213, my italics)

Accordingly, 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.

Thus, if we look at the theory-change from the Newtonian theory of gravity to the Einsteinian theory of gravity from the perspective emphasizing the dynamical laws rather than space-time, the essential continuity between the two theories is easily identified. Although their different space-time structures exhibit a discontinuity, the general theory of relativity still maintains the essential framework of Newtonian mechanics and of special relativity: the relationships between events specified by the dynamical laws play essential role and determine the spatio-temporal structure. Given that the relationships between events, which are specified by the dynamical laws, are more essential than the structure of space-time, I endorse the evolutionary view in this case of theory-change i.e., the general feature of the theory-change is "essential continuity with modification," just as Einstein himself implied.

The defenders of a revolutionary view might claim that my thesis of continuity between Newtonian dynamics, the special and the general theory of 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.[9]

Another response from advocates for a revolutionary view could come from the fact that in contrast to inertial motion in Newtonian dynamics and the special theory, the same notion in the general theory of relativity is not universal. It is because bodies with internal angular momentum do not follow geodesics in the absence of external forces:

> The object possesses an angular momentum, mass quadruple moments. And higher multipole moments. They interact with the tide-producing accelerations (Riemann

[9] When Brown (2005: 141) emphasizes this characteristic in the general theory, it does not show that the notion of inertial motions in the general theory is fundamentally different from the one in its predecessors. Rather his main point is the important role of dynamics in overall theoretical structure of the general theory. However, this role of dynamics, as discussed in the chapter 2, is as important within Newtonian dynamics and the special theory as within the general theory.

> curvature) of the background geometry. Depending on the orientation in space of these moments, interactions drive the object off its geodesic course in one direction or another. ... No object of finite mass moving under the influence of a complex background will admit a buffer zone where the geometry approached Minkowskian values with arbitrary precision. Therefore it is incorrect to say that such an object follows a geodesic world line. (Misner et al. 1973, 476-9)

Within the general theory, a massive particle, which involves internal structure such as an angular momentum, mass quadruple momentum, do not follow geodesics because of its interaction with a background geometry. It seems to be an undeniable conceptual change in our case of the theory-change.

Yet, this response is not tenable either. This is because inertial motion within Newtonian dynamics and the special theory can be defined under approximated and *ceteris paribus* conditions. The former involves a test particle with zero mass, and the latter involves there is no external force, which abstracts the complexities of phenomena that real world involves. If the internal structure of a massive bodies and its interaction with a background are considered, the inertial motions within Newtonian and the special theory does not follow geodesics either. So, just as the inertial motion in the general theory can be defined by means of abstraction eliminating internal angular momentum from body, the inertial motion in its predecessor can be defined by means of abstraction eliminating any external forces. The notions of inertial motion within all these three theories involve these approximations. Hence, it seems difficult to claim the occurrence of the radical change in the notion of inertial motions based on its approximation within the general theory.

2. Can We Still Say That Curved Space-time Revolutionizes Physics?

The defenders of a revolutionary account of the theory-change from Newtonian to Einsteinian physics might also respond that radical change is involved in a difference between the concepts of space-times in the special theory and the general theory of relativity, that is, flat space-time in the former vs. curved space-time in the latter. Actually, this is the most frequently mentioned revolutionary feature in the general theory in contrast to its predecessors.

> [W]e motivated our discussion of manifolds by introducing the Einstein Equivalence Principle, or EEP: "In small enough regions of spacetime, the laws of physics reduce to those of special relativity; it is impossible to detect the existence of a gravitational field by means of local experiments." The EEP arises from the idea that gravity is universal; it affects all particles (and indeed all forms of energy-momentum) in the 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*. (Carroll 2003, 151, my italics)

Within the general theory, the gravitational interaction emerges from the curvature of space-time. In contrast, its predecessors adopt the gravitational field posited independently from the rigid structure of space-time. This seems to suggest that the general theory of relativity can be viewed as revolutionary in terms of different understanding of the relationships between the dynamical field and space-time structure (i.e., between matter and space-time). This section criticizes this revolutionary claim from the perspective of modified space-time structuralism.

In order to do this task, we will consider the relationship between the Newtonian theory of gravitation (a theory based on flat space-time) and the Newton-Cartan theory of gravitation (a theory based on curved space-time). These two alleged rival theories are chosen in our context because the relationship between these two theories maintains the identical structure to the two theories in our case of the theory-change in terms of the difference between the concepts of space-times.[10] Then, our thesis of this section is: "Can the structure of space-time within the Newton-Cartan theory of gravitation can be viewed as being revolutionary – a genuinely incompatible rival – in comparison to the one within the Newtonian theory of gravitation?" If the argument for a revolutionary view succeeds here, there is a good reason to view that Einstein's theory of gravitation, i.e., the general theory of relativity, revolutionizes the special theory of relativity.

But I will argue that if we emphasize dynamical laws, we can in fact see the conceptual change from flat to curved space-time as a gradual modification. We will see here that curved space-time is the result of the elimination of superfluous space-time structure, which is not supported by dynamical laws. Before we argue the case as regards the classical theories of gravitation, we examine a similar case of

[10] This case employing neo-Newtonian space-time and Newton-Cartan theory of gravitation is a rational reconstruction of history in a sense that these two theories in fact post-date, respectively, the transitions from Newtonian physics to the special theory relativity, and from the special theory to the general theory of relativity. Despite the fact that they are post hoc inventions and hence played no role in history of science, I am considering these cases because they maintain exact identical structure in comparing the structure of space-time.

Newtonian and neo-Newtonian (Galilean) space-times since its moral is easier to draw.

(1) 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.[11] (van Fraassen 1980, 44-50) This claim is based on an interpretation of Newton's *Principia* (1726). In the Scholium, Newton 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

[11] A general form of the empirical equivalence thesis maintains that for any theory *T* which entails observational evidence *E*, there exists another rival theory *T'* such that *T'* also entails *E* and therefore is empirically equivalent to *T*. As a consequence, *T* and *T'* warrant the same degree of belief. Accordingly, one reaches the sceptical conclusion that *E* cannot provide a reason for believing one theory rather than the other.

This empirical equivalence thesis makes a very strong claim in that it is concerned with every possible theory rather than with particular cases. In a section of the *Scientific Image*, van Fraassen provides a guide for building an empirically equivalent rival in general cases: from any given theory *T*, we can create the rival *T'*, which claims that the empirical consequences of *T* is true, but that *T* itself is false. (van Fraassen 1980, ch.3) By construction, *T* and *T'* are empirically equivalent but logically incompatible theories.

However, the above van Fraassen's construction has been criticized on the ground that it might be "excluded from serious scientific discourse for failing to satisfy an a priori constraint on the proper form for a scientific theory." (Kukla 2000, 22) Yet, he also provides a specific case based on Newtonian space-time, which this section is concerned with.

Newtonian mechanics. Van Fraassen assumes that Newton takes Absolute Space to exist in a literal sense (ibid., 45):

> The 'apparent motions' form relational structures defined by measuring relative distance, time intervals, and angles of separation. For brevity, let us call these relational structures *appearances*. ... When Newton claims empirical adequacy for his theory, he is claiming that his theory has some model such that *all actual appearances are identifiable with (isomorphic to) motions* in that model. ... Newton's theory does a great deal more than this. It is part of his theory that there is such a thing as Absolute Space, that absolute motion is motion relative to Absolute Space, that absolute acceleration causes certain stresses and thereby deformations in the appearances, and so on. (ibid., 45-6)

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 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," by means of

> abstracting the dispositions and properties of a body so that there remains only the uniform and unlimited stretching out of space in length, breadth and depth. … . In all directions, space can be distinguished into parts whose common limits we usually call surfaces; … . [W]e can possibly imagine that there is nothing in space, yet we cannot think that space does not exist … (Newton 1962, 132-7)

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:

> It is from their essence or nature that [the parts of absolute space] are places; and that the primary places of things should be movable, is absurd. These are therefore the absolute places; and translations out of those places, are the only absolute motions. (Newton 1729)

Leibniz also considered Newton as asserting the reality of absolute space: "[Newtonians] maintain, therefore, that space is *a real absolute being.*" (Alexander 25)[12]

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. (Newton 1962, 130)

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 … ." (Newton 1962, 301)

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[12] This reading of Newton's account is associated with the debate between substantivalism and relationism about space. According to van Fraassen, "it is part of his (Newton's) theory that *there is such a thing* as Absolute Space…" (van Fraassen 1980, 45). In this spirit, Rynasiewicz characterizes the substance-relation controversy as a choice "whether we should be realists in some suitably *robust sense* about space and time (space-time), or whether no such *entities* exist over and above the objects and events of the material world." (Rynasiewicz, 1996, 279)

Slowik suggests that Newton recognized the requirement to "equip space and time with the *necessary* structure to discern inertial motion," (Slowik 2002, 38) 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. (ibid.) Newtonian space-time provides *superfluous* structures, i.e. absolute position and velocity to capture absolute motions such as acceleration.

> [S]ince Newton was intent on allocating the requisite geometrical structure to delineate inertial motion, and since "absolute spatial position" represented the best *available means* of reaching this goal, Newton would appear to have had no other choice but to violate the empirical import of Galilean relativity through the installation of this absolute structure. When Newton was faced with the dilemma of accepting either a theory too weak to render inertial motion coherent or one too strong to rationalize Galilean relativity, he chose the latter – concluding that too much is better than incoherent! (ibid.)[13]

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

[13] Penrose (2004: 387) expresses the similar view as Slowik's, and suggests that this unavailable mathematics in Newton's time is actually a *fibre bundle* within modern differentiable geometry.

> Clearly we should take Galileo seriously. There is no meaning to be attached to the notion that any particular point in space a minute from now is to be judged as the same point in space as the one that I have chose. ... It may seems alarming that our very notion of physical space seems to be something that evaporates completely as one moment passes, and reappears as a completely different space as the next moment arrives! But here the mathematics [introduced earlier] comes to our rescue ... . *Galilean spacetime* is not a product space $\mathbf{E}^1 \times \mathbf{E}^3$, it is a *fibre bundle* with base space $\mathbf{E}^1$. In a fibre bundle, there is no pointwise identification between one fibre and the next; nevertheless the fibres fit together to form a connected whole.

another are the same *whether that space is at rest or whether it is moving uniformly straight forward* without any circular motion." (Newton 1729, 423) 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 Newtonian 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, as shown in the previous chapter, be formulated without absolute position and velocity since 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. (Earman 1986, 45-55) 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 dynamical perspective of space-time, it is easy to see that the empirically equivalent space-time models he points to are not in fact genuine rivals. The dynamical perspective views the structure of space-time as stemming from dynamical laws which specify the relationships between events. Hence, the superfluous structure of space-time, which is posited over and above dynamical laws, cannot be considered as doing real work within Newtonian dynamics. Van Fraassen constructs an infinite number of empirically equivalent theories by 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 considered as genuine rival theories.

Van Fraassen's 'problem' stems from the claim that the structure of space-time exists "over and above" the dynamical laws that specifies the motions of material bodies. Empirically equivalent rival space-time models become an issue only if the structure of space-time is incorrectly viewed as an essential working part of the theory, which is independent from dynamical laws. Accordingly, van Fraassen's argument is effective only to one who – mistakenly – views space-time as an independently existing entity or structure.

(2) 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. (Earman 1993, 31)

In more detail, the Newtonian theory of gravity can be formulated as a theory with a gravitational field that propagates through a background flat neo-Newtonian space-time. However, another formulation is available – the so-called Newton-Cartan theory of gravity. In this theory, the gravitational field is absorbed into the structure of space-time (the connection with non-zero curvature). There is a clear and important dissimilarity in the relation between the posited space-time structure and the dynamical structures of these two theories. While space-time in the Newtonian theory of gravity is independent of its dynamical structure, the space-time structure of the Newton-Cartan theory involves a connection that depends on the matter distribution. These two theories then appear to be genuine empirically equivalent rivals: they are constructed so as to be empirically equivalent and they seem to be genuine rivals in that positing gravitational interaction as a fundamental force is significantly different from treating it as a curvature of space-time.

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 propagating as a fundamental force. The gravitational field is expressed as the negative gradient of the gravitational potential: $\mathbf{G} = -\ \mathrm{grad}(\mathbf{\Phi})$. And Poisson's equation, $\partial^2\mathbf{\Phi}/\partial x^2 + \partial^2\mathbf{\Phi}/\partial y^2 + \partial^2\mathbf{\Phi}/\partial z^2 = 4\pi\rho$, relates the gravitational potential $\mathbf{\Phi}$ to the mass density function ρ. The equation of motion can be written as $md^2x_i/dt^2 = -\ m\partial\mathbf{\Phi}/\partial t$, 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, the curvature of which measures the total force per unit mass. A notable characteristic of these space-time structures is their immutability in the sense 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 propagation of the gravitational field through 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 space-time curvature, 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 $\mathbf{\Phi}$ set in an inertial frame $[x_i]$ (of which the equation of motion is $md^2x_i/dt^2 = -m\partial\mathbf{\Phi}/\partial x$), we can set a new gravitational potential $\mathbf{\Psi} = \mathbf{\Phi} + x_j\, d^2b_j/dt^2$, 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 $[x_i]$. As a result, a new equation of motion can be written as $md^2y_i/dt^2 = -m\partial\Psi/\partial y = 0$, 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 be 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 word, 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. (Malament 2007, 266)

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 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." (Newton 1726, 943) 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." (Hall and Hall, 103) 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 similar trick 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.[14] 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 a 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 of what is "superfluous" within the former theory is not made by the latter theory since Newton explicitly recognized

[14] One could ask why should anyone believe the equivalence principle when we are concerned with pre-Einstein physics. Yet, this is what essentially distinguishes the Newton-Cartan theory of gravity from the Newtonian theory of gravity. The issue here is whether or not the the former's employment of the equivalence principle provides a genuine rival of the latter.

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. (Newton 1726, 423, my italics)

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... (Newton 1729, 558, my italics)

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 adopts the dynamical perspective since the dynamical structures are indistinguishable. (Bain 2004)

A defender of a revolutionary view in this case might still argue that this analogy between van Fraassen's argument and that of Earman is by no means complete. In van Fraassen's argument, the inertial trajectories of a given body, which are specified by its laws of motion, do not support the distinction between two rivals *TN*(0) and *TN*(v). The inertial trajectories within Earman's two rival theories are, however, different. On the one hand, the Newtonian theory of gravity employs the motion of bodies subject to a zero total external force as being inertial motion. On the other hand, the Newton-Cartan theory of gravity considers the motion exerted by a zero total external non-gravitational force as an inertial motion. So, the analogy between the two cases is not exact.

But this response is not tenable. In van Fraassen's case, two rivals *TN*(0) and *TN*(v) cannot be distinguished because the laws of motion that the two theories satisfy are the same. In contrast, the Newtonian theory of gravity and the Newton-Cartan theory of gravity cannot be considered as genuine rivals despite the fact that their laws of motion are different. Although the laws of motion are expressed in different forms, the inertial trajectories relating events, which are specified by the laws, are dynamically indistinguishable. The difference is simply in the way the laws of motion are described. This was clearly recognized by Penrose:

> [T]his does not actually represent a change in Newton's theory [of gravity], but merely provides a different description of it. ... Roughly speaking, in [Newton-]Cartan's scheme, it is the inertial motions in this Einsteinian, rather than the Newtonian sense, that provide the 'straight' world lines of space-time. Otherwise, the geometry is like the Galilean [space-time] ... [In the Newton-Cartan theory of gravity,] the Newtonian gravitational field is completely encoded into its structure. (Penrose 2004, 394)

So, if we consider the relationship between flat and curved space-time formulations from the point of view of modified space-time structuralism, the latter is seen as a *modification*, in that the curved space-time formulation eliminates the structure of space-time that is not supported by its underlying dynamical laws. Just as neo-Newtonian space-time is a result of a gradual modification from Newtonian space-time, the curved space-time formulation is a result of a gradual modification of flat space-time formulation. According to Friedman:

> [T]here is a close analogy between the move from [the Newtonian theory of gravity] to [the Newton-Cartan theory of gravity] and our earlier move from the kinematics of [Newtonian space-time] to the kinematics of [neo-Newtonian space-time]. Both cases start with a theory that invokes indeterminate entities. In the kinematics of [Newtonian space-time] the absolute space V is indeterminate .... In [the Newtonian theory of gravity] the gravitational potential Φ (together with the flat connection D^o) is indeterminate. [I]n both cases we move to a new theory that eliminates the indeterminate entities in question by taking formerly definable objects as primitive. In the kinematics of [Newtonian space-time] the flat connection D^o is definable in terms of dt, h, and V; in [neo-Newtonian space-time] we take D^o as primitive and drop V. In [the Newtonian theory of gravity] the nonflat connection D is definable in terms of D^o and Φ; in [the Newton-Cartan theory of gravity] we take D as primitive and drop D^o and Φ. (Friedman 1983, 121)

In comparison to the former case which eliminates absolute velocity, the latter case does not get rid of absolute acceleration relative to D^o. The Newton-Cartan theory of gravity replaces it with new notion of absolute acceleration. Yet, both cases have the same structure, in that theories with superfluous space-time structures are replaced by theories without them. So, if one can accept that the development from Newtonian to neo-Newtonian space-time is an evolutionary process, one should again accept the development of flat to curved space-time as the same.

Yet, if these conceptual changes are considered from the perspective of space-time alone, our evolutionary view seems to be weak. According to Friedman (1983):

> [A] more reasonable criterion of ontological commitment [of geometrical objects] requires only that a theory is commintted to objects that are *explicitly definable* from its primitive or basic objects. The objects not only exist mathematically; they are distinguished by the formulas of the theory. On this criterion, the formulation of [the Newton-Cartan theoty of gravity] is no longer committed to the flat connection and gravitational potential of [the Newtonian theory of gravity]. In fact, ... the formulation of [the Newton-Cartan theory of gravity] does not even imply the existence of a unique gravitational potential and flat connection. On a more reasonable criterion of ontological commitment the two theories are not equivlaent, for they are not committed to the same objects. (ibid., 122, note 15)

However, as modified space-time structuralism suggests, postulating the inertial principle that free-falling particles follow the geodesic trajectories of space-time does not imply the existence of an unobservable entity, the "affine structure." Instead, what is essential about this principle is the relationships between events, which are specified by the dynamical principle.

The modification of kinematics in accordance with dynamical principles is an evolutionary process. This is because that a modification, according to modified space-time structuralism, is concerned with a change in the decomposition into inertial and gravitatiting motions, rather than a change of ontological commitment.

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 gravitionally accelerating body can be decomposed into its inertial component and its gravitational one. Given that within 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 the additional consideration of gravitational interaction. Given that these relationships between events are modified by considering an additional force field on top of its predecessor's characterization of the relationships between events, the theory-change from flat to curved space-time formulation is an essentially evolutionary process.

Chapter 5

Conclusion

This thesis argued for an evolutionary account of the theory-change from Newtonian to Einsteinian physics. Two opposing points of view can be found in the literature, which characterize the theory-change as either evolutionary (for example, Hempel and Friedman) or revolutionary (for example, Popper, Kuhn and Feyerabend). These views attempt to support their positions by referring to the formal, conceptual and ontological aspects of both Newtonian and Einsteinian physics. We have seen that these two views by no means provide appropriate accounts of this particular theory-change. And I tried to provide a new version of the evolutionary view – one that responds to the weaknesses and builds on the strengths of already existing views.

The weaknesses of the existing evolutionary views provide important clues for my own account of the shift from Newtonian to Einsteinian physics. Although the formal aspect yields important information concerning the continuity (or quasi-continuity) of the theory-change, it is deficient – the formal mathematics requires a physical interpretation that is essential to the theories involved and captures the theories' essential aspect contributed to their empirical success. The ontological accounts of space-time are expected to remedy the shortcomings of the formal accounts of the theory-change.

However, in order to provide an acceptable account of the theory-change, one needs to solve a major problem pointed out by critics such as Brown, DiSalle, and Huggett (who can be categorized as supporting the dynamical perspective of space-time). These critics have criticized these ontological accounts for mischaracterizing the relationships between space-time and the laws of motion, which constitute the two pillars of Newtonian and Einsteinian physics.

Another central motivation of my thesis is structuralism as advocated by Duhem, Poincaré, and recently resuscitated by Worrall. This view provides a perspective to maintain the strengths and remedy the shorcomings of the formal and ontological accounts of the theory-change from Newtonian to Einsteinian physcis.

I have argued that the dynamical perspective of space-time and structuralism can be natural allies because they oppose both 'formalism-alone' accounts and 'deep-down' ontological accounts of scientific theories. Along these lines, I have attempted to develop the modified space-time structuralism by realizing the weaknesses of Dorato's version of space-time structuralism and incorporating the strengths of the dynamical perspective of space-time.

Dorato provided an initial attempt to specify what is the essential structure in Newtonian and Einsteinian physics. He considers the spatio-temporal relations between events as the essential structure that explains the behaviours of bodies. However, we cannot expect this view to provide an acceptable account of the theory-change. For Dorato's view is based on the dubious assumption that the spatio-temporal relations between events underpin the laws of motion. We can see this problem from the lesson suggested by the dynamical perspective of space-time, which provides a much more straightforward account of the relationships between space-time and the laws of motion; the laws of motion underpin space-time, not the other way around.

As a result, my version of space-time structuralism views the relations of regularity between events as essential parts of Newtonian and Einsteinian physics. A similar view is suggested by Huggett's regularity account of space-time, which considers the laws of motion as involving *nothing but* "a theorem of the strongest and simplest axiomatization of the totality of events in this history." However, my view is different from Huggett's in that mine sees dynamical laws as encapsulating the structural constraints over events. And my view is also different from Brown's view which emphasizes the micro-foundation of dynamical laws. Unlike Brown's, my view stresses the structural characteristics of the dynamical principles which involve the relations between events and does refer to any underlying mechanism.

Within this framework, the continuity between Newtonian and Einsteinian physics can be brought to centre-stage. My version of space-time structuralism suggests that the continuity in the theory-change can be clarified if we recognize that the essential part of that theories i.e., the relations of regularity between events specified by dynamical principles, are the dynamically-privileged trajectories of material bodies. These dynamical principles in the special and the general theory are the light postulate and the equivalence principle, which pick out the dynamically-privileged relations between events, i.e. the inertial trajectories of a given body. Although the relativistic dynamical principles of electrodynamics i.e., the constancy of the speed of light and the principle of relativity, modify the relations of regularity between events as compared to Newtonian theory, their role in picking out dynamically privileged trajectories continues to operate within the special theory of relativity. And the additional dynamical information about gravitational interaction involved in the principle of equivalence modifies the concept of inertial trajectories in the general theory. Yet, inertial motions specifying the dynamically-privileged trajectories also play the essential role within the general theory, just as in Newtonian mechanics and in the special theory. This aspect highlights the most important way in which the two theories are related to each other. Hence, we can see that a modified space-time structuralism gives the clearest and most defensible argument for the view that the shift from Newtonian to Einsteinian physics was an evolutionary one.

In summary, in addition to clarifying the continuity between Newtonian and Einsteinian physics, my view improves the existing accounts of the theory-change in following aspects:

(1) In comparison to previous evolutionary accounts that emphasize the formal aspect of the theory-change, my view captures the essential elements underlying the formal aspects, which contribute to the empirical success of both theories.

(2) In comparison to previous evolutionary accounts that emphasize the influence of the ontological aspect of space-time and in fact fail to clarify the relationships between space-time and the laws of motion (these are two essential elements in Newtonian and Einsteinian physics), my view straghtforwardly captures these relationships without difficulty.

(3) My view has the advantage over Dorato's version of space-time structuralism in that it better explicates the relationships between the laws of motion and space-time geometry and the continuity between Newtonian and Einsteinian physics.

(4) While a modern geometric view emphasizing space-time geometry faces a problem in explicating the continuity between the special and the general theory of relativity because two theories adopt quite different approaches of geometry (Klein's and Riemann's approaches), my view is free from this problem because the laws of motion are emphasized rather than space-time geometry.

(5) My view avoids a criticism legitimately aimed at a modern space-time view –that the space-time view is *post hoc* (or whiggish) in its account of the theory-change from Newtonian to Einsteinian physics. In contrast, emphasis on the laws of motion, involved in my view, can be clearly identified in the founders of Newtonian and Einsteinian physics, i.e. Newton and Einstein themselves.

(6) My view can easily avoid the criticism based on the empirical equivalence arguments claiming that there exist logically distinct but empirically equivalent rivals, such as flat and curved space-time theories. By emphasizing dynamical laws, the modified space-time structuralism can explain why the alleged empirically equvalent rivals are not in fact genuine rivals.

(7) Finally, my view, in comparison to Brown's, faces no demand to provide an account of the micro-foundation of the relations of regularity between events. This is because my view emphasizes that the structural information involved in the laws of motion is what makes both Newtonian and Eisnteinian physics emprical successful.

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