Universiteit Utrecht

Thesis

History and Philosophy of Science

On the interpretation of special relativity: Brown versus Janssen

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Abstract

Since the appearance of 'Physical Relativity' of Harvey R. Brown a discussion has developed in the literature about the theory of special relativity of Einstein. There exist two possible approaches to special relativity: the principle and constructive approach. Both approaches predict the same; both finish with the familiar Lorentz transformations. Therefore they are empirically indistinguishable. Janssen represents the antagonists. Janssen and Brown emphasize that the approaches are not explanatory equivalent. They claim that their approach is explanatory superior. Other philosophers have shed their light on this disagreement. This thesis will discuss the debate between Janssen and Brown and the reactions to this. I will conclude that this disagreement is based on the confusion that for phenomena there exists only one best explanation. Instead, explanations are pragmatic. The context of the question determines the most appropiate explanation.

Contents

1 Introduction

In this thesis I will elaborate on the disagreement between Harvey Brown and Michel Janssen about the approach to special relativity. They both defend a different interpretation of special relativity. This debate finds its origin in a paper of Albert Einstein more than 100 years ago. This paper is written in the miracle year of Einstein. This publication is part of four innovative papers that occurred within one year. In his controversial work 'On the Electrodynamics of Moving Bodies' Einstein introduced in 1905 what we now call the theory of special relativity [Einstein, 1905]. The theory was innovative because it contradicts the old concepts of space and time. As we will see, it totally changed the old idea of simultaneity.

1.1 Special relativity

The theory of special relativity sheds new light on the properties of space and time. Einstein employed two seemingly contradictory principles, the light and relativity principle. In order to reconcile those postulates he concluded that we need to define a new sense of simultaneity. Whether two events are simultaneous depends on the frame of reference. If two observers are located in two different frames of reference, they will disagree about simultaneous events.

The combination of those two principles in one theory induces two empirical consequences: time dilation and length contraction. Time dilation is the effect that occurs when two observers in different inertial systems moving with uniform motion disagree about the time that has elapsed between two specified events. The clocks of the observers will get out of step and therefore their perception of time differs. Length contraction of a rod is the length reduction as seen from an observer moving with uniform motion relative to the rod. Time dilation and length contraction are both mathematically described by the Lorentz transformations. These formulas demonstrate the relation between the coordinates of two different inertial systems moving with uniform motion relative to each other[1].

$$x' = \gamma(x - vt) \tag{1}$$

$$y' = y \tag{2}$$

$$z' = z \tag{3}$$

$$t' = \gamma(t - \frac{v}{c^2}x) \tag{4}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v}{c}^2}} \tag{5}$$

[1] The notation Einstein used differs from the modern version

We take a huge step in time and arrive in 1976. In this year a new interesting paper appears with John S. Bell as the author. He addresses the incompletely didactic accessibility of special relativity. The noteworthy paper is called "How to teach special relativity" [Bell, 1987]. He found the same Lorentz transformation only with a different strategy. Bell states that

> The difference of style is that instead of inferring the experience of moving observers from known and conjectured laws of physics, Einstein starts from the *hypothesis* that the laws will look the same to all observers in uniform motion [Bell, 1987, 77].

Instead, Bell focused on the internal behavior of rods and clocks. He was interested in the behavior of atoms and molecules that make up a rod. Einstein's starting points were two principles, Bell's starting points are elementary particles and its interactive laws. The two principles are on the background in the formulation of Bell. He used a moving charge and calculated the corresponding field. He arrived at the same result as Einstein, the Lorentz equations. The main point of Bell is that his strategy will add something to the *understanding* of students about special relativity.

Literature has increased since the publication of 'Physical Relativity' of Brown [Brown, 2005]. Brown continues with the ideas of Bell. Focus should be on the microlevel of special relativity. This improves the explanatory power of special relativity. As we will see, Janssen represents the counterpart. He emphasizes that elementary particles necessarily satisfy the structure of nature. Atoms and molecules obey the principles of nature, because they have no choice. Janssen and Brown represent the two interpretations of special relativity. Both think that their interpretation has more explanatory power and is therefore superior to the other interpretation. As such, Janssen sees special relativity as a kinematic theory. Brown believes in the dynamical character of special relativity.

2 Historical overview

Sometimes, physical theories have strong philosophical implications. The introduction of a new theory can change the philosophical trend. Special relativity is such an example. The philosophical ideas about spacetime were highly influenced by special relativity. The philosophical movements substantivalism and relationism are affected by the notion of spacetime. These philosophical issues continue in the discussion of Janssen and Brown.

2.1 Substantivalism versus relationism

Philosophy of science is filled with the ongoing debate between substantivalism and relationism. Substantivalism claims that space and time are absolute, independent objects (substances). Relationism states that space and time are only the result of the ordering of objects. From a philosophical point of view, this distinction of substantivalism and relationism is a dichotomy. A spacetime theory belongs necessarily to substantivalism or relationism.

This debate started with the correspondence between Gottfried Leibniz and Samuel Clarke; the Leibniz-Clarke correspondence [Erlichson, 1967]. Clarke is the spokesman of Isaac Newton. Leibniz criticized the substantivalistic view of Newton and Clarke in 1915. Leibniz developed philosophical arguments against the presence of absolute space and velocity based on the principle of sufficient reason and the identity of indiscernibles. In reply Clarke (and Newton) came up with the famous bucket argument. The surface of water in a bucket (not spinning) is flat. But as the bucket starts to spin, the shape of the surface becomes concave. The water continues spinning in concave shape even when the bucket stops spinning. So we have two situations with a concave surface: a spinning and non spinning bucket. The origin of the concave shape cannot be explained by the spinning of the bucket. That property is not similar in both situations. Instead, the concave shape can only exist relative to some absolute rest system. Unfortunately, this correspondence lasted only two years, until the death of Clarke.

With the interference of Ernst Mach an important philosopher enters the discussion. He is a relationist and rejects an absolute reference system. According to him, the bucket experiment does not prove the existence of an absolute reference system and he offers an alternative view. The concave shape is not relative to an absolute reference system but in relation to the collection of mass in the universe. Motion occurs with respect to the fixed stars, so in an empty universe there would be no curvature of the surface of the water spinning in the bucket. With these arguments the discussion continues in special relativity and general relativity. This thesis only deals with the theory of special relativity.

We will see that substantivalism also plays an important role in the disagreement between Janssen and Brown. It is a question where Janssen and Brown are engaged with. In the first papers of Janssen about special relativity he claims that length contraction and time dilation are *causally* constrained by Minkowski spacetime. Brown refers to the substantivalist view to indicate that causal interactions need a substance. Janssen denies, just as Brown, that Minkowski spacetime is a substance. Janssen reformulates his statement. Minkowski spacetime is the common-origin (no causal interaction) of length contraction and time dilation. Minkowski spacetime is now a structure, rather than a substance.

2.2 The Aether

The philosophical debate of substantivalism and relationism is applicable to the transition from Lorentz's Aether theory to Einstein's special relativity. At the end of the 19th century scientific theory predicted an absolute rest system: the aether [Brown, 2005]. This absolute medium was considered to be independent and observable. And light propagates with respect to this medium. Physicist were convinced that such a rest system would be measurable. The relative motion of the Earth through this medium is reason for the possibility to measure this medium.

Maxwell was a scientist who believed in the existence of an aether. He is famous for his Maxwell equations that are still used today. They describe the interactions between electric and magnetic fields and charges and currents. Furthermore, he discovered that light is an electromagnetic wave. In order for light to propagate it needs to travel relative to something. This something Maxwell called the luminiferous aether. The aether is the absolute rest system in which the Maxwell equations are valid. His theory was a fine piece of work and got much support.

Multiple experiments were done in order to determine the existence of the aether. No experiment could detect the aether, but there were reasons to doubt the quality and the sensitivity of the experiments. In 1887 a very sensitive experiment was performed by Albert A. Michelson and Edward R. Morley: the Michelson-Morley experiment. It showed that to second-order the aether wind was undetectable. The null result was surprising and a motive to adjust the existing aether theories. Hendrik A. Lorentz worked also in the discipline of electromagnetism. He remained confident that the aether existed based on the intuition of substantivalism. Lorentz preserved the aether in his new theory by invoking the Lorentz transformations[2]. Lorentz's theory was a reconciliation of the aether and the null-result of the experiments. Apparent length contraction is the reason why the aether is undetectable. Length and time vary in non-aether inertial systems. But still, the aether inertial system contained the proper length and time coordinates.

However, not every physicist followed this line of reasoning. Oliver Heaviside considered the electrical interaction between a charge and the aether. He calculated that a charge in motion relative to the aether loses its spherical distribution. Instead the surface of the equipotential forms an ellipsoid. George F. FitzGerald responded in a letter to Heaviside with the following explanation:

> We know that electric forces are affected by the motion of the electrified bodies relative to the ether, and it seems a not improbable supposition that the molecular forces are affected by

[2] Einstein found the same formulas and named them after Lorentz.

> the motion, and that the size of a body alters consequently [FitzGerald, 1889].

This analysis stayed practically unnoticed until 1967.

Einstein rejected the aether completely in his 'On the Electrodynamics of Moving Bodies' [Einstein, 1905]. In his theory there was no place for the aether, because Einstein observed no preferred inertial system. As a consequence he decided not to implement the medium. Einstein's results were the same Lorentz transformations and in the beginning both theories were considered to be alike. On the contrary, the interpretation Einstein gave to the Lorentz transformations is different from that of Lorentz. According to Einstein, moving bodies do in fact contract. It is undetectable because the measuring rods and clocks deform in the exact same way.

Other scientists mistakenly considered Lorentz's and Einstein's theory as one and the same physical theory. For full appreciation Einstein had to wait for the contribution of Hermann Minkowski. This mathematician represented spacetime in the now called Minkowski diagram. This mathematical presentation emphasized the beauty of special relativity and the difference between the physical implications of the Lorentz transformations. Now it is time to look at the content of special relativity and the representation of Minkowski.

3 The implications of special relativity

3.1 Time dilation

Let's have a look at what the theory of special relativity entails. Consider a simple clock that consists of two mirrors and a light beam bouncing between the fixed mirrors. The time between two reflections is fixed when one is in the clock's inertial system. The blue line in figure 1 represents this clock. The situation changes when one is moving relative to the clock. This is valid, since the relativity principle states that every reference system is possible. Remember that for both observers the light beam is still propagating with the same velocity (the light principle). In this case, the light beam covers more distance. This is illustrated with the purple line in figure 1. These two clocks elucidate the concept of time dilation. Because the velocity of light remains constant, and the distance is longer, the time light needs to cover that distance is longer. We can calculate the increase of time by the right triangle that is shown in figure 2. The Pythagorean theorem gives the relation between the distances of the right triangle.

$$(c\Delta t')^2 = (v\Delta t')^2 + (c\Delta t)^2 \tag{6}$$

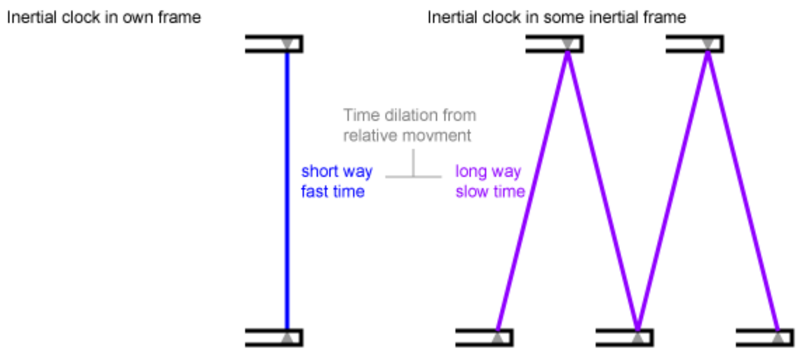

Figure 1: A bouncing light signal between two mirrors

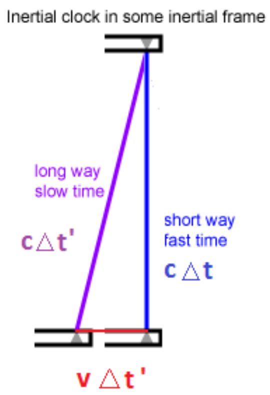

Figure 2: The right triangle for the light signals of a clocks

This can be solved to get an expression for $\Delta t'$.

$$\Delta t' = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}\Delta t = \gamma \Delta t \tag{7}$$

3.2 Length contraction

Now, we move on to length contraction. Consider a rocket that moves from event A to event B with velocity v. The distance between event A and B in the stationary frame is l. The distance is l' between A and B in the moving frame of the rocket. We can sum to equations for both the stationary and the moving frame.

$$v = \frac{l}{\Delta t} \tag{8}$$

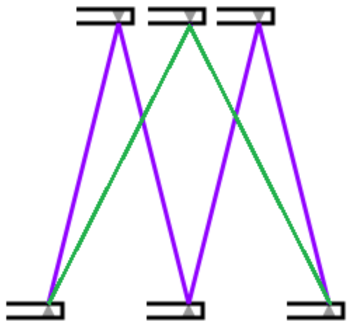

Figure 3: Two moving clocks with different velocities

$$v = \frac{l'}{\Delta t'} \tag{9}$$

In both equations is v equal. We can conclude that

$$\frac{l}{\Delta t} = \frac{l'}{\Delta t'} \tag{10}$$

We just calculated the relation between t and t' so it is a small step to the relation between l and l'.

$$l = \frac{l'}{\sqrt{1 - \frac{v}{c}^2}} \tag{11}$$

3.3 Spacetime interval

With these clocks we can also show the conservation of spacetime intervals. We add another clock that is shown by the green line in figure 3. Let's have for the purple clock the (x', t') coordinates and for the green clock the (x'', t'') coordinates. We can define a right triangle just as in figure 2. Now we have two equations.

$$(c\Delta t)^2 = (v\Delta t')^2 - (c\Delta t')^2 \tag{12}$$

and

$$(c\Delta t)^2 = (v\Delta t'')^2 - (c\Delta t'')^2 \tag{13}$$

We see that both clocks agree on the length of one line, $c\Delta t$. Length contraction only occurs in the direction of motion so $c\Delta t$ remains the same. We can set up the following equation.

$$(v\Delta t')^2 - (c\Delta t')^2 = (v\Delta t'')^2 - (c\Delta t'')^2 \tag{14}$$

This is known as the conservation of spacetime intervals, in this case in one dimension. This can be generalized for y and z since the situation is symmetric for the other axes. Equation 15 shows the more general notation.

$$\Delta s^2 = c^2\Delta t^2 - \Delta x^2 - \Delta y^2 - \Delta z^2 \tag{15}$$

3.4 Lorentz transformations

We can derive the Lorentz transformations from the spacetime interval formula in one dimension as an example for more dimensions. We have

$$(ct)^2 - x^2 = (ct')^2 - x'^2 \tag{16}$$

We assume that space is homogeneous such that every observer sees the same and therefore the transformations have to be linear.

$$x' = Ax + Bct \tag{17}$$

$$ct' = Cx + Dct \tag{18}$$

We substitute these equations into equation 16 and we get

$$(ct)^2 - x^2 = [(Cx)^2 + (Dct)^2 + 2CDcxt] - [(Ax)^2 + (Bct)^2 + 2ABcxt] \tag{19}$$

This results in criteria for A, B, C and D. The restrictions are

$$A^2 - C^2 = 1,\ D^2 - B^2 = 1\ and\ AB = CD \tag{20}$$

The first two restrictions follow the identity of hyperbolic geometry

$$cosh^2\phi - sinh^2\phi = 1 \tag{21}$$

So we know that

$$A = D = cosh\phi\ and\ C = B = -sinh\phi \tag{22}$$

such that x and t increase. We can fill in the values for A, B, C and D. We get

$$x' = cosh\phi x - sinh\phi ct \tag{23}$$

$$ct' = -sinh\phi x + cosh\phi ct \tag{24}$$

We know that for the primed frame $x' = 0$ we have the unprimed coordinate $x = vt$. We get the formula

$$0 = cosh\phi vt - sinh\phi ct \Rightarrow tanh\phi = \frac{v}{c} = \beta \tag{25}$$

With the hyperbolic identities we get the values of $cosh\phi$ and $sinh\phi$.

$$cosh\phi = \gamma,\ sinh\phi = \beta\gamma \tag{26}$$

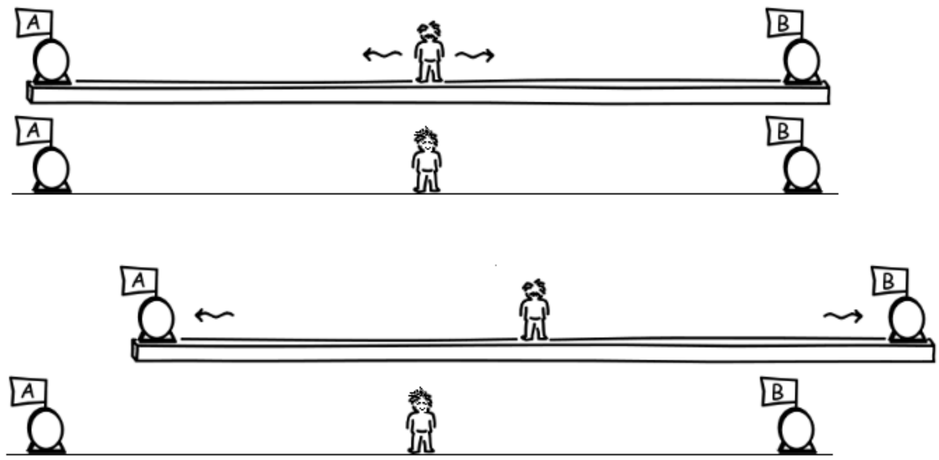

Figure 4: Poincaré and Einstein moving relatively with uniform motion, Einstein's perspective

Finally, we get the Lorentz transformations for one dimension.

$$x' = \gamma x - \frac{\gamma v}{c} ct \Rightarrow x' = \gamma(x - vt) \tag{27}$$

$$ct' = -\frac{\gamma v}{c} x + \gamma ct \Rightarrow t' = \gamma(t - \frac{vx}{c^2}) \tag{28}$$

This line of reasoning is symmetric for coordinates y and z so we can get an expression for all dimensions.

3.5 Simultaneity

These consequences might seem peculiar. That is because we are used to idea of absolute simultaneity, when in fact, special relativity shows the relativity of simultaneity. Simultaneous events in one reference system are not simultaneous any more in a relatively moving frame. Consider Henri Poincaré and Einstein between two light sensors A and B as shown in figure 4. Both have their own two light sensors. At $t = t' = 0$ Poincaré and Einstein are at exactly the same point in space. At this moment Einstein sends a light signal to his sensors A and B. He is moving relative to Poincaré and his light sensors in the positive direction of x. Because of the light principle, Einstein will observe that the light signal hits his light sensors at exactly the same moment, simultaneously. For Poincaré these events are not simulteneous. He will see that Einstein's light sensor A is hit first, and then light

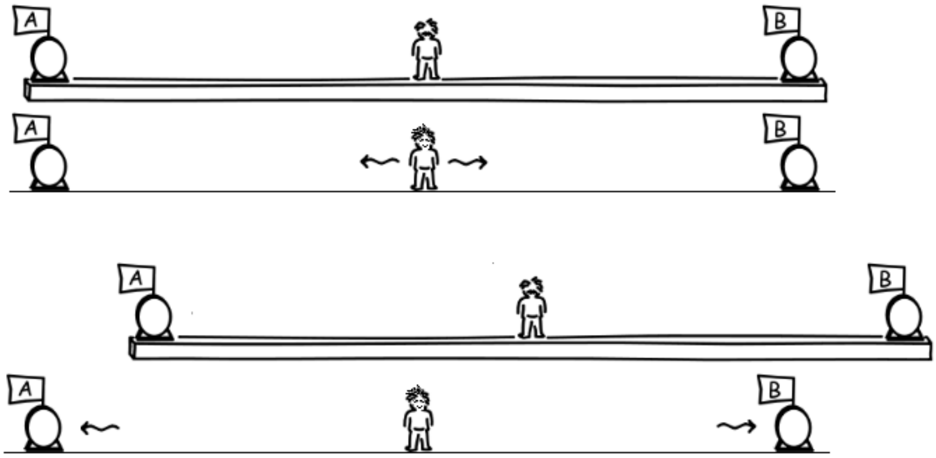

Figure 5: Poincaré and Einstein moving relatively with uniform motion, Poincaré's perspective

sensor B. Figure 5 shows the perspective of Poincaré. For him the light signal propagates also with the value of c. As Einstein is moving further away, the light signal will hit Poincaré's light sensors at exactly the same time. Einstein will say that the events of Poincaré's light sensors are not simultaneous. So, simultaneity depends in what inertial system you are.

3.6 Lorentz invariance

Special relativity is a Lorentz invariant theory. Lorentz invariant quantities do not depend on the inertial frame. Every observer will agree on the value of these quantities. For special relativity the spacetime interval in section 3.3 is such a Lorentz invariant quantity. The expression for a spacetime interval is valid for all reference frames.

The properties distance and time depend on the reference frame. These properties are Lorentz covariant. They change under the Lorentz transformations. Simultaneity is defined by the Lorentz covariant property time and therefore depends on its reference frame.

Lorentz invariance can be applied to more theories than special relativity. In fact, a violation of Lorentz invariance is never observed in any theory. All current physical theories obey Lorentz invariance. Consequently, the scientific community is strongly committed to this symmetry.

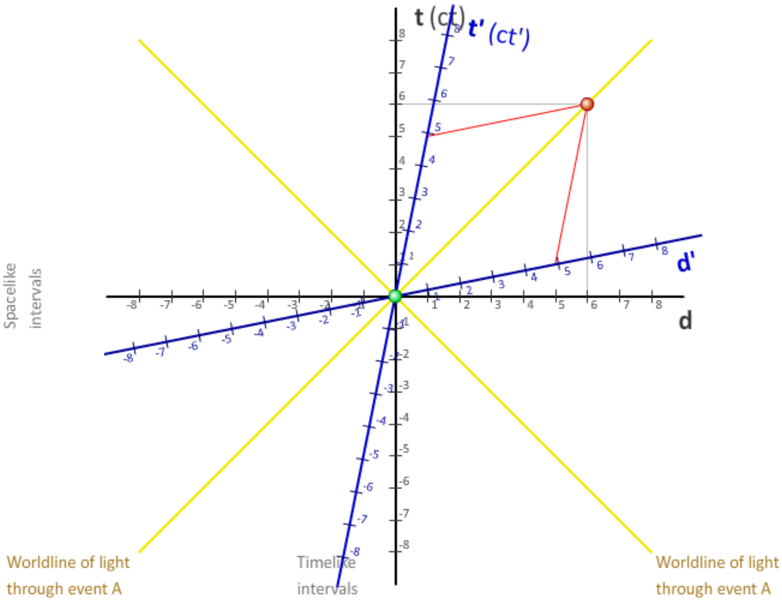

Figure 6: One dimensional Minkowski spacetime for (x, t) and (x', t') coordinates

3.7 Minkowski spacetime

As mentioned before, the appreciation of Einstein's work grew after the publication of Minkowski. His mathematical redefinition of spacetime improved the credibility of spacetime. The Minkowski diagram shows the coordinates of different inertial system in one diagram. Figure 6 shows an event with different (x, t) and (x', t') coordinates. It represents how two observers in two different inertial system do not agree about the time and space coordinates. The x'-axis and the t'-axis are squeezed towards each other. Simultaneous events in Minkowski diagram can be drawn by parallel lines of the t'-axis.

With the notion of spacetime intervals we can define three different types. We know that for one dimension

$$\Delta s^2 = \Delta x^2 - c^2 \Delta t^2 \tag{29}$$

There are three possibilities for the value of Δs^2.

$$\Delta s^2 < 0 \tag{30}$$

$$\Delta s^2 = 0 \tag{31}$$

$$\Delta s^2 > 0 \tag{32}$$

Equation 30 is for time-like intervals. In figure 6 this is illustrated by the light cones separated by the yellow lines. The upper light cone is the future, the lower light cone represents the past. Equation 31 reflects light-like intervals. This is represented by the yellow lines. A light ray would travel on these yellow lines. The last equation 32 stands for space-like intervals. These are the left and right cones confined by the yellow lines.

4 Principle approach

Janssen's interpretation shows a lot of similarities with the 'principle approach' of Einstein. To a great extent, he follows the original work of Einstein. When we know how Einstein presented his special relativity, we will understand the approach of Janssen better. Essential for the paper of Einstein are two principles, the light and the relativity principle. With these principles Einstein derived the Lorentz transformations. We are especially interested in the principles, not in the exact derivation.

4.1 Einstein's distinction

The approach Einstein employed in his special relativity is to be considered the 'principle approach'. He was requested to explain his theories (including theory of general relativity) himself in a letter he wrote for the *London Times*. The letter was published on November 28 in 1919 and it provided Einstein the opportunity to explain the relativity theories to the lay public. To achieve this goal he discerns two kinds of theories. The aforementioned 'principle approach' and the 'constructive approach'. Both methods lead to the same empirical results but via a different route. Einstein defines constructive theories as follows:

> They attempt to build up a picture of the more complex phenomena out of the materials of a relatively simple formal scheme from which they start out [Einstein, 1919, 228].

The constructive approach is comparable to a bottom-up explanation. The starting point of the constructive approach are thus the materials the phenomena consist of. The bottom-up explanation also starts at the elementary level of the phenomena. Atoms and molecules are the elementary constituents. Both approaches are comparable as they start at the smallest possible scale. Opposite to the constructive approach is the principle approach.

> The elements which form their basis and starting-point are not hypothetically constructed but empirically discovered ones, general characteristics of natural processes, principles that give rise to mathematically formulated criteria which the separate processes or the theoretical representations of them have to satisfy [Einstein, 1919, 228].

The principle approach thus defines mathematically formulated criteria. These criteria are derived from experience and postulated as principles. If for some reason a mistake is discovered within a theory containing one or more principles, the first properties scientists will check are the experimental devices or the calculations. Doubt on the principles will be last. The principles are the starting points and operate at the highest level of a theory or the top. As for the top-down approach, the starting points are also at the top-level. The principle and the top-down approach have a lot of similarities.

This distinction can be characterised as a difference in the direction of explanation. Constructive theories explain from bottom to the top. Principle theories explain from the top and downwards to the bottom. This distinction does not assign any value to the veracity of a theory. On the basis of this distinction we cannot decide which theory is better. According to Einstein both manners have their advantages.

> The advantages of the constructive theory are completeness, adaptability, and clearness, those of the principle theory are logical perfection and security of the foundations [**?**, 2].

Both have explanatory value, but in a slightly different way.

4.2 Thermodynamics versus the kinetic theory

Einstein was not only applying his distinction to his own theory, but had another theory in the back of his mind. He referred to the analogy with thermodynamics. The laws of thermodynamics form the basis of the theory at the top-level, creating a top-down explanation, or equally a principle approach. The axioms are considered true because violation has never been observed. Nevertheless, the veracity cannot be proven. The constructive approach in this case is the kinetic theory of gases. This is the bottom-up version of the description of gases. The elements represent the bottom-level of the theory. It treats gases consisting of a large number of molecules all moving randomly in a box. This microscopic viewpoint can explain macroscopic properties as pressure, temperature and volume. Einstein does not give any more examples of the two approaches in the same field of science. Special relativity and thermodynamics versus the kinetic theory of gases are the two common instances. Einstein claims that in general most theories are constructive, only a few are principle theories. This thesis will focus on special relativity in particular.

4.3 Lorentz's distinction of theories

Einstein was not the first to distinguish theories by the way they explain. The distinction of Einstein finds great similarities with the distinction already drawn by Lorentz in 1900 [Frisch, 2005]. Lorentz divided theories in two categories: principle- and mechanisms-theories. The first begins by postulating general principle or general laws. The latter starts by postulating mechanisms of the appearances. Mechanism theories provide us 'with flawed, yet lively representations of the connections between and the nature of things' [Frisch, 2005, 179] The examples given by Lorentz for the principle theory are energy conservation and the evolution towards equilibrium of a system out of equilibrium (the first and second law of thermodynamics). The molecular kinetic theory of gases, Kelvin's vortex theory and Hertz's mechanics of concealed motions are instances of mechanisms-theories. Later we will discuss the differences between the distinctions of Einstein and Lorentz in section 7.4.

4.4 Relativity Principle

Now we continue with the two principles in the paper of Einstein. The two principles are the relativity principle and the light principle. These principles offer the starting points for the principle approach for the explanation of special relativity. I will discuss the relativity principle first, and next the light principle.

The relativity principle as a postulate has its background in the rejection of absolute rest. In his paper [Einstein, 1905] Einstein gave the example of electrodynamical interaction between a conductor and a magnet. It does not matter in practice whether one moves the conductor towards the magnet or the other way around. Both movements lead to the same electrodynamical interaction and the two examples appear as one and the same phenomenon. Mathematically, in the time of Einstein, the calculations for both instances proceeded in a totally different way but ended in exactly the same mathematical expressions. Einstein believed that nature is not able to distinguish between the two cases. They are exactly the same. The relativity principle takes care that these two phenomena are treated as one single phenomenon. The relativity principle rejects the existence of an absolute rest, or any preferred inertial system. The failed experiments of Michelson and Morley to measure the aether was for Einstein another reason to reject absolute rest. There were several arguments against the aether and none that indicate a preferred inertial system. For Einstein it was clear that an aether was superfluous.

> [N]ot only the phenomena of mechanics but also those of electrodyamics have no properties that correspond to the concept of absolute rest [Einstein, 1905, 124].

So the laws do not depend on the coordinate system in which they are described. His formulation of the postulate is as follows

> If two coordinate systems are in uniform parallel translational motion relative to each other, the laws according to which the

> states of a physical system change do not depend on which of the two systems these changes are related to [Einstein, 1905, 128].

Einstein was not the first physicist to speak about the relativity principle. Galileo and Newton preceded him in this field among other physicists and philosophers. Galileo wrote in the 17th century that observation of motion among bodies with the same velocity is not possible. He performed (thought) experiments that show the principle of relativity. No relative motion can be observed when objects are falling from a moving ship. This situation cannot be distinguished from the situation that a body is falling from a ship that is at rest. Thus, the same laws apply to both events.

Newton extended the concept of the principle of relativity with three laws of motion. The behavior of bodies in a certain space is the same whether that space is at rest or moves uniformly in a straight line. Differently formulated, the laws of motion of Newton are invariant under Galilean transformations. These laws are thus also valid in any Galilean transformed coordinate system.

4.5 Light Principle

The second principle Einstein employs is the light principle. It claims the constancy of the speed of light for every observer. Einstein's formulation is as follows

> Every light ray moves in the "rest"[3] coordinate system with a fixed velocity V, independently of whether this ray of light is emitted by a body at rest or in motion. [Einstein, 1905, 128].

This claim does not only hold for the 'rest' coordinate system, but also for any other coordinate system. When we combine this with the light principle we get the stronger claim that the speed of light is invariant for inertial frames.

The confidence of Einstein was fed by the electrodynamics of Maxwell. Maxwell concluded that light was an electrodynamical phenomenon and that the speed of light depended on the electrodynamical constants μ_0 and ϵ_0. The speed of light in a vacuum was determined to be $\frac{1}{\sqrt{\mu_0\epsilon_0}}$. Though the electrodynamical theory of Maxwell proved its success with empirical adequacy, the speed of light was too great to measure accurately. So Einstein had no direct empirical support for his light postulate in 1905. Nowadays we can measure the speed of light with high precision.

Similar to the relativity principle, the idea of the constant speed of light already existed. So both principles already existed independent of each other. The revolutionary aspect of Einstein's paper is the combination of

[3]Notice that "rest" coordinate system could mean any reference system, since Einstein makes no distinction between frames.

the two principles in one single theory. Einstein admitted that at first sight they seem incompatible. A closer look reveals that they are compatible if one is able to endorse a new notion of simultaneity. This new definition of simultaneity is a necessary step towards special relativity.

4.6 Simultaneity

The two principles, when combined, immediately require a new definition of simultaneity. This new formulation considers the effects of (non-)moving observers. As we have seen before, simultaneity is not fixed. It depends on the reference frame of the observer.

An implicit condition for light is that it propagates isotropically. This is necessary for the argumentation of simultaneity. Einstein assumed that the propagation of light is independent of direction and location. The time for light to travel from point A to B is equal to the time it takes to travel from B to A. This property cannot by proven. However, it is not a far-fetched assumption.

With this condition we discuss an example of Einstein from section 'On the relativity of lengths and time' of his article [Einstein, 1905, 129]. It clarifies that simultaneity depends on the observers. Imagine a rod with two clocks attached to the ends A and B. The clocks are synchronous in the rest system. This is can easily be done by emitting a light signal exactly in the middle of the two clocks. Light propagates isotropically and therefore the clocks are hit after exactly the same time span. The two clocks indicate the time of the rest system. We now look at the time for an observer moving with velocity v. A ray of light is emitted at side A at time t_A; reflected at side B at time t_B, and it reaches side A again at time t'_A. The time for the moving observer differs. The time span between the events has slightly changed.

$$t_B - t_A = \frac{r_{AB}}{V - v} \tag{33}$$

and

$$t'_A - t_B = \frac{r_{AB}}{V + v} \tag{34}$$

where r_{AB} is the length of the moving rod, measured in the rest system and V is the speed of light. Thus, moving observers do not agree on time measurements of observers which are at rest relative to the clocks.

5 Constructive approach

Opposite to the principle theory of Einstein, constructive approaches start at the bottom-level and build up an entire theory. Several philosophers contributed to this approach and came with similar versions of a dynamical theory of special relativity. The ones I will discuss are by Lorentz, Bell and Brown.

5.1 Lorentz

Lorentz had been working on the electron theory from 1892 to 1904 [Goldberg, 1969]. During these years his theory developed towards the final version of 1904. This publication was called 'Electromagnetic Phenomena in a System Moving with any Velocity Less than that of Light'. Until around 1911 the special theory of relativity was called the 'Lorentz-Einstein theory'. Their theories were considered equivalent because they were empirically indistinguishable. This opinion was not held by Lorentz, he never accepted the theory of special relativity of Einstein. He maintained that the aether was the rest frame. Next will be an elaboration on the development of the electron theory of Lorentz.

5.1.1 Electron theory

Lorentz's electron theory was based on Newton's laws of motion and Maxwell's equations. Newtonian mechanics provided the structure of spacetime and the behavior of matter. The contribution of Maxwell were the laws for electric and magnetic fields to describe the structure of the aether. In contrast to Maxwell, Lorentz distinguished two kinds of fundamental entities: aether and matter. Interaction is possible through the existence of electrons in two ways. First, the electromagnetic fields of a given charge and current distribution are specified by the **E** and **M** equations[4]. Second, through the Lorentz force, the force that acts on electrons caused by an electromagnetic field. Charge and fields determine each other by this force. '[T]he ether affects the motion of electric charges; and charge and current configurations act as sources of electromagnetic fields propagating in the ether' [Frisch, 2005, 662].

In the first version of electron theory a problem concerning invariance arose. Newtonian mechanics is invariant under Galilean transformations, i.e. if Newton's laws hold in a certain reference frame, then they hold in any other reference frame in relative uniform motion to the first reference frame. The difficulties appear for the Maxwell equations. They are not invariant under Galilean transformation. The electromagnetic equations are only valid for the rest system, the aether. As said before, the Michelson-Morley experiment in 1887 did not measure this aether. Empirical data suggested that the Maxwell equations should be Galilean invariant. Somehow the electromagnetic equations must also hold for moving observers to

[4] Lorentz's equations only involve two microscopic fields instead of the four of Maxwell's equations.

a second order[5]. Lorentz adjusted his theory to the null-result with the introduction of the concept of corresponding states. 'If the Maxwell equations allow a certain configuration of charges and fields in a system at rest (in the privileged ether frame) then they allow the same configuration in an inertial frame moving through the ether, where the fields now are 'fictitious' fields in terms of 'fictitious' coordinates, which are related to the real fields and coordinates through what amount to the Lorentz transformations' [Frisch, 2005, 665]. These Lorentz transformations are the same transformations as those used by Einstein. The philosophical background and physical meaning differs greatly. 'To Lorentz, the contraction of length was primary; it was a real effect, explainable in terms of the interactions of molecules. To Einstein, the length contraction was an artefact of measurement, a result of the fact that observers in different frames of reference would disagree on how the measurements were made' [Goldberg, 1969, 990]. For time dilation they also had a different interpretation. Lorentz ascribed the term 'local time' to the time of any reference system besides the aether. The purpose of the new time coordinates created by the time transformation was only mathematical. Local time had no real meaning. For Einstein, time-intervals in different reference systems are equivalent. He introduced the concept of relativity of simultaneity. The time clocks indicate depends on the reference system of the observer.

Lorentz's aim was to model a theory such that it can explain the phenomena. Indeed, Lorentz's theory had an undetectable length contraction and time dilation. And of course, an unmeasurable aether. Measuring instruments contract in the same ratio as the objects to be measured. 'Local time' was a mathematical trick and Lorentz never believed that clocks slow down. Perception of 'local time' was therefore impossible.

Above is an instance of a bottom-up description. Lorentz considered his work to contain only fundamental assumptions and no special hypotheses [Goldberg, 1969]. The assumptions cover the microscopic world. Examples of such assumptions are a stationary aether, a round electron when stationary, a uniformly distributed charge etc. Nevertheless, the theory of the electron is able to provide an explanation for electromagnetic phenomena by the reduction of macroscopic behavior into microscopic properties. Lorentz even hoped to explain a wider range of phenomena as chemical interactions or the properties of metals.

5.2 Bell

The constructive approach remained in the shadow of the principle approach for some decades. According to J.S. Bell this is unjustified. He shed light

[5]Lorentz developed first and second order adjustments. We will go directly towards second order modifications.

Figure 7: Spaceship paradox

on the importance of the constructive approach in 'How to teach special relativity' [Bell, 1987].

5.2.1 Spaceship paradox

Representative for Bell's argument is the example of the spaceships, also known as the 'spaceship paradox' illustrated in figure 7. Imagine three spaceships A, B and C where B and C are at equal distance from A. A signals B and C to accelerate identically. For spaceship A the distance between spaceship B and C is fixed as they have the same velocity at every moment. Before the start of the experiment a thin thread is placed between spaceships B and C. According to Lorentz contraction the thread will break as spaceships B and C will create a force which the thread cannot bear.

Calculations show that indeed the thread will break at a certain high velocity. Bell emphasizes that the interpretation of Einstein is misleading since in his approach the Lorentz contraction only seems to be kinematical, when in fact the Lorentz contraction is physical. Bell states that

> It is my impression that those with a more classical education, knowing something of the reasoning of Larmor, Lorentz, and Poincaré, as well as that of Einstein, have stronger and sounder instincts [Bell, 1987, 80].

The traditional approach of Joseph Larmor, Lorentz and Poincaré emphasize the elements (molecules, atoms) at the bottom-level involved in the Lorentz contraction. Bell presented an approach similar to that of Lorentz. The next section will continue with this point.

5.2.2 Contraction of electrical field moving source

Bell calculated the field of a moving point charge and showed that the field is squeezed in the direction of motion. He started with the field components

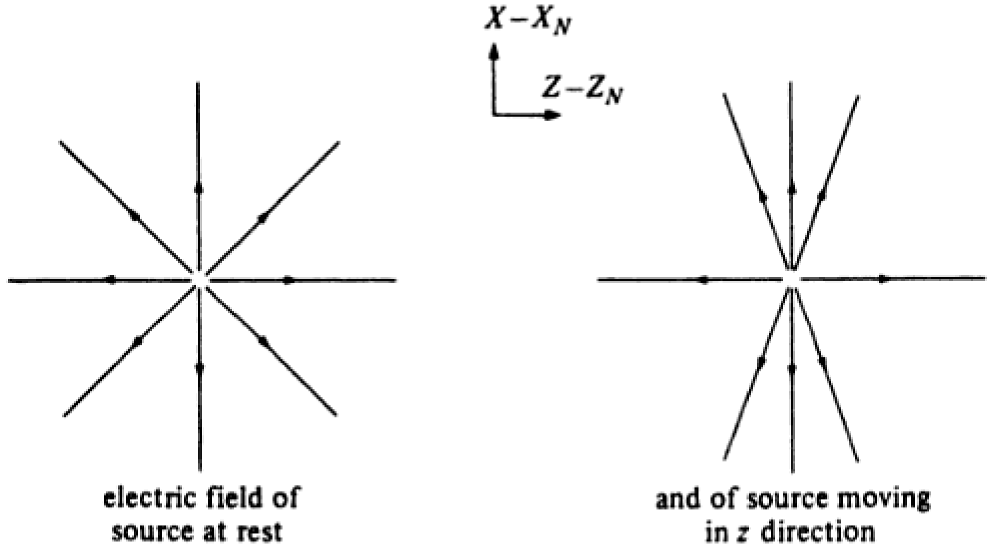

Figure 8: Contraction electrical field moving charge

for a charge Ze moving with constant velocity V along the z-axis.

$$E_z = Zez'(x^2 + y^2 + z'^2)^{-\frac{3}{2}} \tag{35}$$

$$E_x = Zex(x^2 + y^2 + z'^2)^{-\frac{3}{2}}(1 - \frac{V^2}{c^2})^{-\frac{1}{2}} \tag{36}$$

$$E_y = Zey(x^2 + y^2 + z'^2)^{-\frac{3}{2}}(1 - \frac{V^2}{c^2})^{-\frac{1}{2}} \tag{37}$$

$$B_x = -\frac{V}{c}E_y \tag{38}$$

$$B_y = +\frac{V}{c}E_x \tag{39}$$

where

$$z' = (z - z_N(t))(1 - \frac{V^2}{c^2})^{-\frac{1}{2}} \tag{40}$$

and $z_N(t)$ is the position of the charge at time t. When $V = 0$ these equations are just the familiar Coulomb equations, spherically symmetrical. When $V \neq 0$ the spherical symmetry breaks. The magnetic field is absent in the direction of motion and the electrical field is squeezed in the direction of motion. For higher V or $\frac{V^2}{c^2}$ the asymmetry is stronger. This can be seen in figure 8. Naturally, this kind of distortion will alter the equilibrium of fast moving material consisting of small particles (electrons etc). Microscopic electrical forces in this process will alter the shape of a moving body.

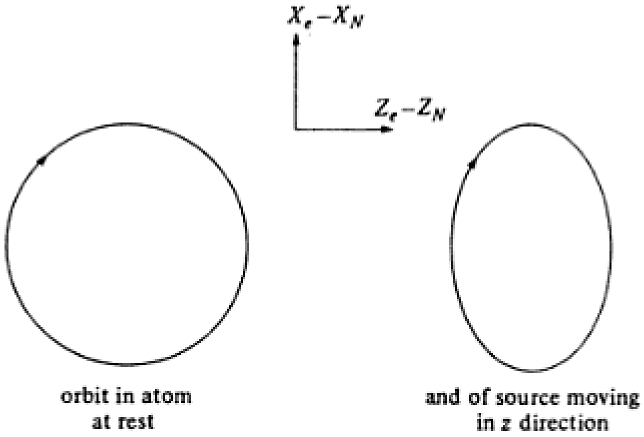

Figure 9: Contraction of the orbit of an electron around a nucleus

For now we were dealing with a single moving charge Ze. Bell continued his analysis with a single atom, an electron orbiting a heavy nucleus. To simplify the mathematical expressions, the effects of the field of the electron are neglected. The question is what happens to the orbit of the electron when the atom is set in motion. The expression of the field of the moving nucleus is known and the equations of motion can be solved to calculate the displacement of the electron from the nucleus[6]. The calculations are too difficult to do algebraically and a computer programme is necessary to solve the equations. The solutions given by the computer show that the orbit of the electron at rest is circular, but deforms in the direction of motion when the motion becomes uniform. This is illustrated in figure 9. The orbit changes into an ellipse and this contraction is given by the fraction

$$\sqrt{1 - \frac{V^2}{c^2}} \tag{41}$$

where V is the velocity of the nucleus during the orbit. The orbit is extended by time dilation with a factor of

$$\frac{1}{\sqrt{1 - \frac{V^2}{c^2}}} \tag{42}$$

Bell then demonstrated that the Lorentz equations arise from a transformation. There exists a system of primed variables for the uniformly moving atom that is identical to the stationary atom relative to the original variables.

[6]The derivation itself will not be presented here since it is not the main point.

Again, we have a theory with the Lorentz transformations as the primary goal. Bell's approach is clearly constructive. Its starting points are atoms and molecules. Bell pointed out that his method has similarities with the approach of Lorentz.

> It is found that if physical laws are Lorentz invariant, such moving observers will be unable to detect their motion. As a result it is not possible experimentally to determine which, if either, of two uniformly moving systems, is really at rest, and which moving [Bell, 1987, 77].

Equally, in the case of the philosophy of Einstein, this distinction is not possible. Bell adds that the facts of physics do not allow us to prefer one theory above the other. It all comes down to a difference in philosophy. Moreover, it is not necessary to accept the philosophy of Lorentz to accept the Lorentzian pedagogy.

5.3 Brown

In 2005 Brown published his book 'Physical Relativity, Space-time Structure from a Dynamical Perspective' [Brown, 2005]. It is an interconnection between history, philosophy and physics on the issues concerning special and a little less general relativity.

Brown argued that the constructive approach to be superior to the one of Einstein. The traditional view is that the structure of spacetime (Minkowskian spacetime) imposes the Lorentz-invariance of the laws. Brown states that this explanation has the arrow in the wrong direction. The structure of spacetime does not answer the question as to *why* rods contract and clocks dilate[7]. A satisfactory answer of *why* length contraction and time dilation occur, lies within the constructive approach.

According to Brown, it is a fact that laws are Lorentz-invariant. The answer to why the behavior of rods and clocks is consistent with the spacetime structure, must be found in the dynamics of the microscopic structure of the rods and clocks. The priority goes to dynamical laws instead of the spacetime structure. Relativistic phenomena demand dynamical explanation [Brown, 2004].

After the publication of this book a discussion arose in philosophy about the nature of explanatory power of both approaches. The question is then, is one of the two explanation superior? One of the commentators is Janssen. He claims the opposite, the principle approach of special relativity is superior. Next chapter will elaborate on the discussion between Brown and Janssen.

[7]This discussion is about the explanans and the explanandum. What are the phenomena that ask for explanation and what is the structure/mechanism that provides the explanation?

6 Debate Brown and Janssen

The focus of the next sections will be on the disagreement between Brown and Janssen. Janssen is professor in the history of science studying mainly the relativity theory (special and general) and quantum theory. He entered the debate in response to the works of Brown. Brown and Janssen both contributed to the literature with several articles or books and these contributions play a central role in the discussion on the theory of special relativity. Other philosophers mainly react to the dispute between Janssen and Brown. This will be discussed in chapter 7. The disagreement centres around several aspects within the interpretation of special relativity. We first start with the terms kinematics and dynamics. Later we will continue with the taxonomy of approaches of physical theories. We end with the discussion about the arrow of explanation and the ontology of spacetime.

6.1 Kinematics versus dynamics

Kinematics and dynamics are part of the discussion. Those terms come into play when dealing about the causal background of time dilation and length contraction. The search for an explanation of those physical phenomena causes a discussion about the possible underlying processes and principles. Disagreement about the nature of kinematics and dynamics lies at heart of the interpretation of special relativity theory. Let's have a look at the variety of definitions of kinematics and dynamics.

6.1.1 Brown

The definition Brown applies is the following: 'What is kinematics? In the present context it is the universal behavior of rods and clocks in motion, as determined by the inertial coordinate transformations' [Brown, 2005, 4]. Brown continues that rods and clocks are 'moving atomic configurations' and this combined with the definition leads to a false dichotomy. Rods and clocks are macroscopic objects, nevertheless, they are held together by microforces such as electromagnetic forces. So Brown claims that both kinematics and dynamics of for example a rod are not independent from each other. To strengthen his point, he cites a quote from Wolfgang Pauli in 1921:

> The contraction of a measuring rod is not an elementary but a very complicated process. It would not take place except for the covariance with respect to the Lorentz group of the basic equations of electron theory, as well as those laws, as yet unknown to us, which determine the cohesion of the electron itself [Brown, 2005, 4].

So length contractions of a rod works on every scale. On the scale of the rod itself and on the scale of electrons that constitute the rod. This makes the distinction between kinematics and dynamics unfundamental. An additional point is that we cannot give a complete description of the physical processes at the level of the electron. The development of the quantum theory might give the appropriate explanation. That is the essential point that Brown makes in his book 'Physical Relativity'. 'The special theory of relativity is incomplete without the assumption that the quantum theory of *each* of the fundamental non-gravitational interactions - and not just electrodynamics - is Lorentz-covariant' [Brown, 2005, 5].

Quantum theory is essential for the behavior of elementary particles. This was already noticed by William Swann [Swann, 1941]. He states that a complete theory should contain the details of elementary physics. '*It thus appears that a relativistically invariant quantum theory, or something closely analogous to it, is a necessary supplement to the general principle of invariance of equations if we are to provide for the Fitzgerald-Lorentz contraction* [...]' [Swann, 1941, 201].

Quantum theory can operate as the link between the Lorentz transformations and the relativity principle. The Lorentz covariance of Maxwellian electrodynamics has no direct link with the applicability of the relativity principle within electrodynamics, unless the Lorentz transformations encode the behavior of rods and clocks in such a way that they are not just a formal change of variables. And this relies on the best knowledge about the micro-constitution of stable macroscopic objects. Quantum theory can offer a detailed description at the most fundamental level of processes which necessarily be Lorentz covariant.

Clearly, Brown ultimately wants quantum theory to describe the underlying mechanisms. Despite the deficient definitions, Brown prefers the dynamical approach.

6.1.2 Janssen

In contrast to Brown, Janssen applies another (slightly different) definition: 'What it means for a phenomenon to be kinematical, in the sense in which I want to use this term, is that it is just an instance of some generic feature of the world, in this case instances of default spatio-temporal behavior [of all physical systems]' [Janssen, 2009, 27]. He continues:

> Unless one challenges the classification of the phenomenon as kinematical in this sense - and the *universality* of the relevant feature will militate strongly against that - there is *nothing* more to learn from that particular phenomenon, neither about the specific system in which it occurs nore about the generic feature it instantiates [Janssen, 2009, 27].

In [Janssen, 2009] Janssen offers three examples of physical experiments that show his point. 'It shows that various phenomena that were given a dynamical explanation in Lorentz's ether theory are actually kinematical' [Janssen, 2009, 1]. Furthermore, Janssen distinguished two kinds of kinematics: 'A phenomenon is kinematical in the broad sense if it is independent *of the specifics of the dynamics*. It is kinematical in the narrow sense if it *is an example of standard spatio-temporal behavior*'[Janssen, 2009, 28]. A phenomenon that is kinematical in the narrow sense, is automatically kinematical in the broad sense.

Janssen claims that kinematics is superior to dynamics. According to Janssen superiority comes from the fact that 'Minkowski space-time provides the source of explanation for various previously unexplained phenomena, where the dynamical theory fails to forge a link between different types of Lorentz-invariant laws' [Van Camp, 2011a, 1101]. The explanatory power comes from Minkowski spacetime. This structure offers the superior kinematical explanations.

Kinematics and dynamics have no consistent definitions to employ in the discussion. These terms have a prominent role in the discussion of special relativity, although Brown and Janssen have no idea where to draw the line between kinematics and dynamics.

6.1.3 How do rods and clocks measure spacetime?

We measure spacetime properties with rods and clocks. Nobody denies this fact, but disagreement is about the measurement itself. How are rods and clocks able to measure spacetime? What is the reason that rods and clocks can measure spacetime and what can the kinematical or dynamical view provide? Clearly, Brown and Janssen have a different view on the underlying processes or constraints of how rods and clocks measure distance and time.

Brown discusses an analogy with historical waywisers to explain how rods and clocks measure spacetime. Waywisers were used to measure the distance along a road. The amount of rotations of the wheel correspond to the distance travelled. Obviously, the friction between the waywisers and the road causes the wheel to spin. But how does this work in the context of spacetime and rods and clocks? How do free-particles know in which spacetime they live and how to behave in a coordinated way? According to Brown, there are no such things as ruts or grooves in space-time that direct the free-particles[8]. Particles have no antennae or space-time feelers to sense any geometrical structure. Brown ascertains that it is better 'to consider absolute space-time structure as a codification of certain key aspects of the behavior of particles (and/or fields)' [Brown, 2005, 25]. Such a geometrical structure is confirmed empirically, but it does not explain the behavior of rods and clocks, it is only a definition. In the dynamical approach rods

[8]Although this was a popular idea in the late twentieth century.

contract and clocks dilate because of how they are made up, not because of the nature of its spatio-temporal environment. The dynamics inside the rods and clocks determine its behavior. Therefore ultimately it is necessary to look at the quantum theory for the underlying processes. These physical processes, determined by physical laws, appear to be part of geometrical structures through some kind of codification.

Janssen has a different view on the measurement of space-time. 'Rods and clocks measure times and distances because they exhibit the default spatio-temporal behavior of all physical systems.' As he explains: '[M]inkowski space-time *encodes the default spatio-temporal behavior of all physical systems in a world in accordance with the laws of special relativity.* [...] Special relativity imposes the *kinematical constraint* that all dynamical laws must be Lorentz invariant' [Janssen, 2009, 28]. He clarifies his statement with an analogy of paintings and the property shape. The shape of many paintings is rectangular. This property cannot be explained by looking at the painting itself. For practical reasons the frames are made rectangular to be able to fix the canvas tight around the frame. This shape transcends the individual paintings, but still the painting is carrying the property shape. The same idea holds for Lorentz invariant properties of rods and clocks. The reason that rods contract cannot be found in rods themselves. And the cause of time dilation cannot be traced back to the clock itself. The search for the underlying reason for such properties should not be focussed on individual objects (paintings or individual laws). The reason behind length contraction and time dilation lies outside the objects.

The disagreement centres around the preference for a kinematical or dynamical explanation for the behavior of rods and clocks. Brown argues that the dynamical approach is more fundamental because of its explanatory power. Dynamical understanding is necessary for a successful theory. Janssen claims that the principle approach is preferable compared to the constructive approach because of its kinematic structure, the geometry of Minkowski spacetime. 'I have argued that the main objection against Lorentz's theory is that it seeks to provide dynamical explanations for a class of phenomena, namely all manifestations of Lorentz invariance, that special relativity revealed to be kinematical' [Janssen, 2009, 27].

6.2 Taxonomy of physical theories

Another aspect which is associated with kinematics and dynamics is the connection with constructive and principle theories. Principle theories have postulates as its starting points. They operate at the top-level of the theory. Just as well, kinematics describes bodies and system of bodies from the top-level. The constitution of the bodies are not taking into consideration. Dynamics studies the underlying forces that effect motion. The starting point is the bottom-level. The constructive approach also starts with the constitution. The phenomena remain the same, irrespective of description by kinematics/principle theories or dynamics/constructive theories. The taxonomy of physical theories is part of the disagreement of Janssen and Brown. Janssen favors principle theories and Brown prefers constructive theories.

Brown (and Oliver Pooley) maintain that the principle approach of Einstein does not provide any explanatory power [Brown, 2004]. According to Brown, the principles do not have any power over physical bodies. The way they would impose this power is peculiar. The two postulates would then constrain the behavior of rods and clocks as follows. A combination of the two postulates results in the invariance of the speed of light. The value of the speed of light in one resting frame F must equal the value in another resting frame F'. The rods and clocks better contract and dilate to obey these constraints. Further, according to the relativity principle the rods and clocks have to contract and dilate in a particular way, they have to obey the Lorentz transformations. Brown and Pooley conclude that '[..] rods and clocks must behave in quite particular ways in order for the two postulates to be true together' [Brown, 2004, 7]. This does not at all explain the behavior of rods and clocks. The two postulates appear to be true because of the behavior of rods and clocks. Instead, this explanatory power is achieved by the constructive approach. They go further by claiming that in general principle theories provide explanations that are deficient. They say that Einstein already made such a comment on his own distinction, principle theories were inferior in their *explanatory power*.

Janssen is convinced that special relativity in the form of 1905 is not deficient in explanatory power. He emphasizes that Einstein first tried to provide a constructive version of special relativity. He did not succeed and convinced himself that only universal principles could lead to a reliable result with the example of thermodynamics in the back of his mind. The fact that the postulates would survive the quantum revolution made Einstein confident that the theory would persist. The postulates are supported by empirical evidence. The fact that Einstein never cited any empirical evidence does not imply its weakness. The principle approach by Einstein holds explanatory power because '[O]ne explains the phenomena by showing that they necessarily occur in a world in accordance with the postulates' [Balashov, 2003, 331]. Yuri Balashov and Janssen admit that the reality behind the phenomena remains unknown. A constructive theory can operate as a model to explain the phenomena. 'One explains the phenomena by showing that the theory provides a model that gives an empirically adequate description of the salient features of reality' [Balashov, 2003, 331].

Both Brown and Janssen agree that the distinction should not be taken too strictly. Brown admits that the distinction is not a categorical one. A principle theory can still contain constructive elements and therefore the definition is not strict in practice. Janssen stresses that constructive and principle theories can complement each other and should not be considered as rivals.

Both will not admit that the two approaches, principle and constructive, have equal explanatory power. Janssen places his kinematical explanation in the context of the principle approach of Einstein. He is convinced that this is explanatory better than Brown's explanation. The same holds for Brown, he thinks that explanations should fit the form of constructive theories. They are explanatory superior. The arguments of Brown and Janssen contain elements of both the kinematics and dynamics and the principle and constructive theories distinction. The disagreement remains indecisive partly because of the lack of clear dichotomies. The arguments are a mixture of the faulty distinctions.

6.3 The arrow of explanation

Besides the discussion about the terminology about kinematics and dynamics and the approaches, there remains a dispute between the arrow of explanation. It focuses on the link between the phenomena and the underlying theory (mechanism or structure). The relation can be drawn in two directions. Janssen argues that the space-time symmetries are the *explanans* and that the Lorentz invariance of the various laws is the *explanandum*. For Brown it is the other way around.

Balashov and Janssen declare their kind of explanation as before: 'length 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' [Balashov, 2003, 331]. Brown asserts that this does not count as an explanation. Instead, it forms an explanation or definition of the explanandum. The assumption being used is that rods and clocks that measure the cross-sections of the 'world-tube' obey Minkowski geometry. This geometrical constraint induces the ability to measure differences in 'world-tubes'. In these kinds of explanations the geometrical features are constituted as principles just as well as the principles Einstein started with. They present a mathematical description of the macroscopic behavior. According to Brown the right question would be: why do physical objects satisfy the constraints of Minkowski geometry? Brown demands: 'What is to be explained is how it is possible that this single rod comes to be assigned two different lengths when measured with respect to two inertial frames' [Brown, 2004, 9]. The geometry gives no causal explanation. 'The real issue is not whether physical geometry is easy to get your hands on, but rather whether, when it is absolute and immune to perturbation as in Newtonian and Minkowski space-time, it offers a causal explanation of anything' [Brown, 2005, 26].

Janssen disagrees and maintains that Minkowski space-time explains the

Lorentz invariance. Balashov and Janssen use an example of the nose of Cyrano in three-dimensional space [Balashov, 2003, 340]. At night Roxanne spots Cyrano from her balcony and she sees his nose attached to his face. In the darkness she can only observe the nose as a silhouette and as Cyrano removes from the balcony, his nose appears smaller and smaller. At the end the nose has vanished from her sight. This situation is considered to be normal behavior of three-dimensional Euclidean space and no explanation is needed. Astonishment would be appropriate if the nose would have appeared equal size when Cyrano was running off. Balashov and Janssen acknowledge that in order to keep the nose intact the forces holding it together must necessarily be invariant under spatial rotation. But the question is the arrow of explanation. Is the fact that his nose appears smaller explained by the nature of Euclidean space or the forces that keeps the nose together? Likewise for special relativity, does Minkowski space-time or do the underlying forces provide an explanation. Balashov's and Janssen's *intuition* is that the geometrical structure of space-time is the explanans and the invariance of the forces the explanandum.

The arrow of explanation is the essential difference between Janssen and Brown. This is the core of their dispute. The real issue here is that they both cling to a different type of explanation.

6.4 The ontology of spacetime

The ontology of space-time offers restrictions towards Minkowski spacetime. It is important to know what kind of ontology Janssen and Brown give to Minkowski space-time. Is it a substance or not? This is an interesting question because substantivalism entails philosophical consequences.

A substantivalistic view about space-time in special relativity would conflict with the action-reaction principle according to Einstein and Leibniz. The principle says that substances do not only act, but are also acted upon. It seems odd to have an object that is able to act itself, but cannot be acted upon, because influence occurs always in two directions. With the development of general relativity the violation of the action-reaction principle was solved. The spacetime influences the behavior of mass and mass tells spacetime how to curve. The spacetime of special relativity only tells mass how to behave. Mass does not influence the properties of spacetime.

Brown argues that we do need to agree with Einstein and Leibniz as long as we contain that space-time is not a substance in special relativity. 'The view that the *space-time manifold* is a substratum or bedrock, whose point elements physical fields are properties of, is just the twentieth century version of the ether hypothesis' [Brown, 2005, 67]. This way, the criticism of Einstein on his special relativity is refuted by Brown. He places the spacetime of general relativity on the same footing. Brown and Pooley [Brown, 2004] assert that for general relativity the space-time manifold is also a non-entity.

The spacetime Janssen has in mind is also not a substance. If one would demand causal efficacy then we have to admit that spacetime is a substance. But Janssen does not claim causal efficacy, he only states that Minkowski space-time explains Lorentz invariance. So both Janssen and Brown do not see spacetime of special relativity as a substance. Janssen claims that special relativity as a physical theory does not tell as anything about the ontology of space-time. 'Special relativity is completely agnostic about what inhabits or [...] *carries* Minkowski space-time. All the theory has to say about systems inhabiting/carrying Minkowski space-time is that their spatio-temporal behavior must be in accordance with the rules it encodes' [Janssen, 2009, 28]. Janssen claims that 'Minkowski space-time explains by identifying *the kinematical nature* (rather than the cause) of the relevant phenomena.' [Janssen, 2009, 28].

6.5 *COI*-argument Janssen

So Janssen and Brown disagree on several aspects. The main issue is the arrow of explanation. Janssen sees in Minkowksi spacetime the solution of their dispute. He argues that the key for his view is that the spacetime structure is a 'common origin' [Janssen, 2002]. Minkowski spacetime offers a structure that is felt by all phenomena living in this spacetime. This structure constrains the dynamical laws to be Lorentz invariant. Without this common origin, Janssen claims, the fact that all dynamical laws are Lorentz invariant is a striking coincidence. Let's have a look at what exactly a common origin entails.

Again, Janssen and Brown are diametrically opposed to each other. In short, Janssen claims that

> The symmetries of Minkowski space-time explain the symmetries of the dynamical laws.

and Brown claims the exact opposite that

> The symmetries of the dynamical laws explain the symmetries of space-time.

Brown rejects the idea of a common origin and states that this Minkowski space-time has no explanatory power at all. 'What is required if the so-called space-time interpretation is to win out over the dynamical interpretation (and Craig's neo-Lorentzian interpretation) is that it offers a genuine explanation of Lorentz covariance' [Brown, 2004, 13]. The Minkowski space-time posited by Janssen is an non-entity with no explanatory power. '[I]f one postulates spacetime 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' [Brown, 2004, 14].

The next step is to examine the strength of the common origin inference or *COI*-argument. Let's see why Janssen thinks the *COI*-argument can settle the discussion. He elaborates on his *COI* in his lengthy article *COI* Stories: Explanation and Evidence in the History of Science [Janssen, 2002]. This article encompasses recommendations why we should be more open to *COIs*. It is filled with historical examples that show *COIs* are woven strongly into scientific practice. According to Janssen, *COIs* play an important role on the level of scientific reasoning. Common origins provide solid structures or mechanisms that give valuable explanations. This then provides an *explanation* for these coincidences, which is counted as *evidence* for that explanation.

To reinforce the notion of *COI* Janssen's paper is filled with exemplary historical cases. We have selected the historical case of Darwin and his natural selection. In the 19th century, Darwin introduced a scientific argumentation for the theory of evolution by natural selection. He realized he had to support his theory by a powerful argumentation that would be able to overcome the possible resistance and criticism. The foundation of the theory was essential for Darwin, since his ideas were revolutionary. Darwin joined a five-year expedition to explore the coastline of South-America. During this voyage of the Beagle, Darwin spotted many exotic species not known in his home country. Especially at the Galápagos Islands in the Pacific Ocean Darwin found some interesting species. The finches on these islands have many similarities with the familiar finches, but they slightly differed from the well-known finches from his homeland. The difference that Darwin was interested in was the shape of the beak. The beaks of the finches on these islands were different in shape, even different species of finches at these islands had different shapes. Darwin concluded that the finches have a beak that functions well under its circumstances. This striking coincidence can be taken back to a common origin: beaks are well adapted to its niches[9]. Similarly, if one would dissect the flipper of a seal and the wing of a bat, the configuration of the bones is the same. This coincidence can be explained by the common-origin of the same bone structure. Now we have two separate *COIs*, one that involves facts of adaptation and one that involves similarities in homology. Those two *COIs* can be combined to one *MCOI* (meta-*COI*). The *MCOI* entails that organisms are subject to natural selection. Survival of the fittest induces the properties of adaption and homology. This particular model of *COI* is complex. There are two separate *COIs* to illustrate the independence of adaptation and homology. Together they make up the *MCOI*. Otherwise, the input of the *MCOIs* would be dependent on the output of the *MCOI*. We see first the striking coincidence of adaptation and homology, but these are consequences of the overarching natural selection of organisms.

[9] A niche is a certain combination of conditions that will attract specialized animals.

More general, the preference for one hypothesis is induced by a common-origin explanation. This can be anything between a totally developed theory and an immature concept. Explanation in this context is related to the idea of explanation from Wesley Salmon's 'ontic conception of explanation'. It provides a framework for *COIs*: 'The ontic conception sees explanations as exhibitions of the ways in which what is to be explained fits into natural patterns or regularities. This view ... usually takes the patterns and regularities to be causal' [Janssen, 2002, p 467]. According to Janssen this characterization is correct for his common-origin explanation. Except that it is too narrow. Salmon focuses on substances with causal efficacy, but Janssen displaces the focus to structures or mechanisms as they are much more common in scientific practice. Minkowski spacetime is such a structure without any clear causal efficacy.

COIs show a lot of similarities with *IBE* (Inference to the Best Explanation). Both show the need to search for a best explanation and to reject the alternatives. For a complete picture, we discuss this broader type of explanation. In a field of science, usually, there is a pool of possible theories that explain the phenomena. The question is then, how are we able to select one of them as the most reliable theory? Gilbert Harman came with the notion of Inference to the Best Explanation in 1965. It is one of many theories that try to describe scientific reasoning. This is what Harman conceives as *IBE* [Harman, 1965, 89].

> In making this inference one infers, from the fact that a certain hypothesis would explain the evidence, to the truth of that hypothesis. In general, there will be several hypotheses which might explain the evidence, so one must be able to reject all such alternative hypotheses before one is warranted in making the inference. Thus one infers, from the premise that a given hypothesis would provide a "better" explanation for the evidence than would any other hypothesis, to the conclusion that the given hypothesis is true.

The "best" explanation provides the most reliable common-origin. Symmetry, harmony and simplicity are the key words. Common-origins tend to pursue those virtues by collecting the most coincidences possible. In the context of *IBEs* this provides the criterion to select the hypothesis with the best common-origin and ignore the alternative hypotheses. Harman's faith in the best hypothesis is so strong that he will conclude that the hypothesis is true. Janssen will not go that far. He states that *COIs* do not authorize one to judge over the ontological status of the inferred common origin. 'One cannot draw conclusions about the ontological status of theoretical entities simply from the fact that the existence of these entities is being inferred to via a *COI* or a *CCI*' [Janssen, 2002, 468][10]. Consequently, the ontological

[10] *CCI* stands for Common Cause Inference

status in general remains undecided. *COIs* will not help with the question of scientific realism.

A common-origin is a special case of an *IBE*. One should discern alternative hypotheses from the "best" hypothesis on the criterion that the best hypothesis includes the best common-origin, i.e. the one that traces the most coincidences to one single origin. According to Janssen this common-origin functions as evidence for that hypothesis. Thus, the explanatory power of *COIs* functions as evidence for its explanation. That *COIs* count as evidence is a bonus. Janssen illustrates the relevance of evidence and explanatory power with an example of people waiting for a late bus [Janssen, 2002, 459].

1. There are many people waiting at the bus stop *because* the bus is late.

2. The bus is late *because* there are many people waiting at the bus stop.

Both sentences contain the word 'because' but they play a different role in each sentence. Sentence (1) offers an explanation *why* there are many people waiting at the bus stop. The role of 'because' is therefore explanatory. The fact that there are many people waiting at the bus stop is irrelevant. In sentence (2) the role of 'because' is evidentiary. The second part of the sentence provides evidence for the fact that the bus is late. We still do not know why the bus is late. It could be bad weather conditions or the driver got lost with directions. According to Janssen these examples show that evidence and explanation are related. The explanation in sentence (1) plays a central role in sentence (2). The evidentiary relationship is being fed by the explanation given in sentence (1). The relation between explanatory power and evidence is generally missed by others. In modern philosophy the tendency is to question the evidentiary role of explanatory power. As a consequence, the reliability of *IBEs* with subspecies *COIs* is at stake. Janssen emphasizes that this gap between philosophy of science and scientific practice is remarkable. The history of science shows that many explanations are considered to be evidence for its theory.

That explanatory power counts as evidence has a consequence for the interpretation of explanatory power, it contains epistemic value. In philosophy of science, there are others who disagree. For example, Bas Van Fraassen sees evidence and explanation as two separate things. 'Evidence is provided to justify claims *that* something is the case. Explanations are provided to answer questions *why* something is the case' [Janssen, 2002, 459]. According to Van Fraassen, these questions 'depend so strongly on who is asking and in what context, that the answers only have value in that context and for those sharing the interests and presuppositions of the person raising the question' [Janssen, 2002, 459]. Explanatory power has therefore no epistemic but only pragmatic value. Janssen justifies that this hierarchy of labelling empirical adequacy with epistemic value and explanatory power with pragmatic value does not reflect scientific practice.

Janssen promises important tasks for *COIs*. Besides that they are helpful for theory choice, they solve the problem of underdetermination and moreover can replace Kuhn's scientific revolutions. Janssen claims that *COIs* can reduce the problem of underdetermination known from Pierre Duhem and Willard Van Orman Quine. The problem of underdetermination is that evidence can give multiple theories as a possible solution. Even though some theories would seem more logical, other possibilities cannot be ruled out because it matches the evidence. According to Janssen, the essence of the problem of underdetermination is that the only criterion is empirical adequacy. Once we insert explanatory power as another criterion the problem disappears. We can pick the theory with the greatest empirical adequacy and explanatory power as the best option and forget about all the alternatives.

Besides the solution for underdetermination, *COIs* provide the force behind theory change. Thomas S. Kuhn analysed important changes in the history of science and concluded that scientific revolutions contain a structure that repeats itself in time. Scientific revolutions change the paradigm of the scientific community. For example, the scientific community lives in the paradigm that the Earth is the centre of the Universe. This paradigm will become shaky when empirical anomalies are discovered that contradict the prevalent theory. When the scientific community is convinced that the empirical anomalies are not just wrong measurements or miscalculations, the foundations of the prevalent theory will start to shake. The retrograde movement of planets was a mysterious anomaly in the geocentric model. Additionally one had to insert epicycles to explain the loops that planets make. The heliocentric model could explain these loops as apparent movements, because of the relative motion of the Earth around the Sun. Both theories explain the observations in a different way. And that is exactly why scientific revolutions occur. The geocentric and heliocentric are incompatible theories. It is impossible to believe in the validity of both theories at the same time. Forced by the incompatibility it is necessary to choose. Since the heliocentric model is better in explaining the empirical anomalies, the scientific community will turn to another paradigm through a scientific revolution, the heliocentric paradigm.

Janssen acknowledges the existence of scientific revolutions, but for different reasons than Kuhn. Explanatory deficiencies are the force behind theory change. The cycles and epicycles of Claudius Ptolemy to explain the retrograde movement were too complex. They were inserted after the observations of loops and they appear as coincidences for no good reason. Nicolas Copernicus simplified Ptomely's model by stating that both the mechanism of the Earth and the other planets are the same. The common-origin in Copernicus's model is the Sun at the center of the Universe. The coincidental epicycles were gone. One mechanism for all planets is better than two mechanism for the Earth and the other planets. The explanatory deficiency is fixed by the interference of a common-origin. Janssen claims that if we look at the history of science, we see that common-origins are the solutions to explanatory deficiencies. Janssen claims that *COIs* are strong enough to overcome objections. Objections were raised that it counteracts the Catholic doctrine and that the predicted stellar parallax could not be measured. Still, Copernicus' model was strong enough to overcome those objections. The credibility of the model remained intact.

Despite the advantage of the removal of the epicycles, Copernicus' model was far from perfect. It still contained shortcomings because the planets move in cycles with the Sun at the centre. Copernicus's model is not a terminal, it is a stepping stone that opened the door for future theories. Kepler provided another stepping stone by stating that planets move in elliptical orbits with the Sun in one of the loci. Janssen calls this path of stepping stones 'forward-engagement'. Every stepping stone has a new piece of physics to add with the formulation of a more sophisticated common-origin than the precursor.

Another point Janssen wants to make is that *COIs* are non-local elements. They are not bounded to locales, periods or disciplines. Historians tend to look only at local elements and are passive to recognize structures that transcend local practice. Janssen provides an analysis of *COIs* as overarching elements in scientific methodology. In his lengthy article he gives several examples of common origins in the history of science. These examples include scientific reasoning from Newton, Darwin, Copernicus, Kepler and Einstein. Janssen claims that this historical approach prevents an a priori philosophical expectation that *COIs* are omnipresent. The scientists all benefited from the *COIs* for exploring their ideas and develop a high level op scientific reasoning to present their theory. *COIs* are ubiquitous and Janssen emphasizes that they all explain a set of coincidences.

Clearly, Janssen sees a great future for *COIs*. *COIs* provide a lot of interesting advantages that cover not only theory choice, but also enters the world of underdetermination and Kuhn's theory change. Though, the real issue has not been discussed yet. As mentioned before, Brown wants to know the underlying mechanism. Janssen is aware of the fact that he is not capable of giving the underlying force behind *COI*. He can only say *COIs* are part of scientific reasoning and the patterns emerge in different disciplines, periods and locales. Brown's point is that without such an underlying force, the Minkowski spacetime is a non-entity. He is not convinced by the article of Janssen. Brown emphasizes that Minkowski spacetime would only be meaningful if it is clear how it constrains matter and laws. How can there be communication between a non-existent Minkowski spacetime and its inhabitants? Spacetime structure is defined by the behavior of physical laws. Brown cites Robert DiSalle to illustrate his point [Brown, 2005, 25].

> When we say that a free particle follows, while a particle experiencing a force deviates from, a geodesic of spacetime, we are not explaining the cause of the difference between two states or explaining 'relative to what' such a difference holds. Instead, we are giving the physical definition of a spacetime geodesic. To say that spacetime has the affine structure thus defined is not to postulate some hidden entity to explain the appearances, but rather to say that empirical facts support a system of physical laws that incorporates such a definition.

Janssen knows the criticism of Brown and at the end of the paper Janssen deals with the question about the constraining role of Minkowski spacetime. Is the explanation of *COIs* sufficient enough to count as a full explanation? Janssen confirms '[T]his is the key question, what is the force behind *COIs*?' [Janssen, 2002, 513]. He confesses that a sound justification of the success of *COIs* is impossible. Instead, he wonders what the best possible justification could be. According to Janssen, *COIs* as part of inductive inference is best explained by Darwin. Darwin sees them as extensions of everyday reasoning. 'This requires us to assume that whatever conditions for *COIs* high success rate in our neck of the woods also hold in the strange new worlds explored by science' [Janssen, 2002, 513-514]. This is a risky enterprise with pitfalls under way. We have no guarantee that the conditions of the *COIs* hold in the parts of science we have never been before. But this is the best we can do.

Janssen divides science in two contexts to illustrate the necessity of justification. The two contexts of science are: context of persuasion and context of pursuit. Justification is only necessary when it comes to tracing the truth. Justification for the reliance of *COIs* is necessary to justify whether *COIs* present nature. 'To appreciate the role and the force of *COIs*, it is important to recognize that theories serve (at least) two different purposes in scientific practice. They provide representations of selected features of reality and they provide instruments for investigating such features' [Janssen, 2002, 465]. So theories with *COIs* have two functions. First, theories inspired by *COIs* operate as representations by providing classifications in particular branches of science. They order a set of phenomena by classifying types of phenomena into classes of *COIs*. Secondly, the theory should also guide the proponents in providing an arrangement of evidence that strengthens the position of the theory. The context of pursuit does not require any philosophical justification. In the context of persuasion justification is necessary. The best justification Janssen can give in this context is the justification given by Darwin mentioned above.

Does this paper bring Janssen and Brown any closer to a solution of their dispute? No, Brown is not content with the arguments given by Janssen. Brown still has no answer to his question how Minkowski spacetime interacts with matter and laws. To see how this debate evolves, we look at other philosophers that mingled into the discussion.

7 Reactions to the debate of Janssen and Brown

The debate between Janssen and Brown has been noticed by several other philosophers. After the publications of Janssen and Brown many comments on the debate have been written. I will discuss contributions of commentators which I find valuable. Contributions are divers in the aspect they enlighten. Some philosophers pick a side, others point out that there is actually no difference in the perspectives of Janssen and Brown. First we discuss philosophers that favor one of the two approaches in sections 7.1 and 7.2. We continue with philosophers who attempt to nuance the discussion in sections 7.3 to 7.6.

7.1 Defending constructive approach / attacking principle approach

Besides Brown and Pooley there not many proponents of the constructive approach. Mathias Frisch is one of the few philosophers that favors Brown's view. Further, I would like to discuss the contribution of David Miller. His paper has two sides. One, he offers a constructive approach with a model consisting of four point charges. Calculations of this model result in the familiar Lorentz transformations. On the other hand, he does not favor the constructive[11] approach. He claims that the approach depends on the situation. We start with the opinion of Frisch and then discuss the constructive approach presented by Miller.

Frisch agrees in the discussion about the arrow of explanantion with Brown. To quote Frisch: 'my point is merely that the realization that all our dynamical laws are Lorentz-invariant does not automatically generate a demand for a further explanation of that principle, as Janssen suggests' [Frisch, 2005, 182]. The *COI* is not a necessary explanation. The 'brute fact' of Lorentz invariance of all dynamical laws does not require an explanation. But this does not mean it is impossible. The question is, is Minkowski spacetime an adequate explanation and the answer of Frisch is no. Frisch agrees with the arguments of Brown. Invocation of the entity Minkowski spacetime does not provide an explanation as long as the interaction of rods and clocks with spacetime structure is undefined and unclear.

Miller provides a new version of a constructive approach for length contraction [Miller, 2009]. He emphasizes that Bell's analysis demands two improvements. First, Bell's model needs to be transparent. The solution given by Bell is a numerical solution. An algebraic solution could show the

[11] Miller only speaks of the dynamical and perspectival approach.

completeness of the analysis. Second, in the analysis Bell uses the relativistic expression for Newton's second law at the start. Also this is inaccurate, since these expressions have to be the solutions of the analysis and not the input.

Miller's goal is to provide a more accessible example of a constructive approach than the one given by Bell. Miller wants a model to be simple for the sake of calculations and he wants it to be in equilibrium to have physical meaning. Calculations of an unstable configuration have no physical implications. Miller offers such a model with the analysis of two negative and two positive point charges. To guarantee stability he places two point charges at the ends of a transparent and frictionless tube. This is necessary for only one dimension. Calculations of the electric and the magnetic fields yield the familiar Lorentz transformations[12].

The main advantage of this approach is 'that the length contraction of an object that changes speed is derived within a single frame and does not involve the comparison of the synchronization of clocks in two different inertial frames. This eliminates the notion that the length contraction occurs when a physical object changes frames somehow involves the relativity of simultaneity' [Miller, 2009, p4].

The paper by Miller is the only recent paper we could find that contributes to the constructive approach. Miller's paper is an improvement compared to Bell's approach. It certainly provides understanding at the bottom-level of special relativity. It shows that the constructive approach is still under construction. The future might bring a more complete constructive approach that is even simpler. Despite this, Miller is not an advocate of the constructive approach. In section 7.3 we will see that Miller does not select constructive or principle theories, because the choice depends on the physical picture. Frisch is clearly in favor of Brown, though he does not bring any new arguments into the discussion.

7.2 Defending principle approach / attacking constructive approach

The literature contains more philosophers who disagree with the constructive approach. The most active philosopher is John D. Norton. He wrote a critical paper on the constructive approach. His analysis attempts to invalidate the efforts of Brown. The endeavors of Graham Nerlich and Wesley Van Camp will also be discussed. Nerlich is mainly dissatisfied with the level of the article of Bell. Van Camp sheds new light on this dispute by invoking a new argument in favor of the principle theory. He rejects the original arguments of Janssen.

Norton wrote an article that attacks the constructive approach in 'Why

[12] We are not interested in the exact calculations.

constructive relativity fails' [Norton, 2008]. This article is meant to 'explore whether the sort of constructivism Brown advocates is a viable alternative to the standard view' [Norton, 2008, 882]. The object of study is only special relativity. Norton states that if constructivism is able to offer something new, it must contradict the 'realist' view of space-time. The 'realist' view of Minkowski spacetime consists of three claims:

- The four-dimensional spacetime is coordinatized by (x, y, z, t)
- The spatiotemporal interval s is a 'straight' line determined by spacetime and independent of matter
- Rods and clocks measure the spacetime since the laws of physics are adapted to the independent geometry of spacetime.

Norton attempts to show that in order for constructivism to be successful it must accept the 'realist' conception partly. Norton claims that 'The construction project must tacitly assume an already existing spacetime endowed with topological properties, so that it can introduce spatiotemporal coincidences, and a unique set of standard coordinates' [Norton, 2008, p824]. The intention of constructivism is to derive Minkowski spacetime from elementary particles, not to adopt Minkowski spacetime already from the start. In constructivism Minkowski spacetime is constructed from matter properties. The phenomena of length contraction and time dilation are consequences of the properties of matter. The microstructure of matter provides the forces responsible for Lorentz contraction. Norton claims that the strongest form of constructivism is as follows:

> *Construction of Minkowski spacetime.* It is possible to recover the geometry of Minkowski spacetime from Lorentz covariant matter theories devoid of spatiotemporal presumptions [Norton, 2008, 825].

For the construction of a matter theory certain parameters are presumed at the start of the construction. Those coordinates refer to events in spacetime. But, there is no justification for the adoption of coordinates at the start of the enterprise. They should reveal themselves at the end of the project. So 'to presume spacetime coincidences is to presume spatiotemporal notions that were explicitly disavowed' [Norton, 2008, p828]. This strong version of constructivism therefore fails according to Norton. One cannot arrive at the four dimensional spacetime of the realist's conception of spacetime without presuming it at the start.

Brown defends his selection process. His set of coordinates is derived from the behavior of free particles in inertial motion and the expected behavior of rods and clocks. The consequence is that all matter theories will end up with the same expressions, since all matter theories are Lorentz invariant.

‘When we express each matter theory in Lorentz covariant form, it must turn out that the standard set of coordinate systems (x, y, z, t) invoked in each formulation are the same set across the matter theories’ [Norton, 2008, 829]. Norton emphasizes that nothing assures us that the coordinates from one matter theory correspond to the coordinates from another matter theory. That the coordinates coincide is what Brown calls a ‘brute fact’. Norton states that this miracle is equal to the supposition of a standard coordinate system.

Norton continues with the relation between matter and spacetime. Constructivists are obliged to state that spacetime is determined by matter. Norton claims that the opposite is true. ‘Very familiar results strongly suggest - but do not prove - that the spatial distances and times elapsed are properties of the spacetime and the matter of a Lorentz covariant matter theory is merely an instrument used to measure them’ [Norton, 2008, 830]. This arrow of influence is hard to neglect for constructivists. Analogous to the argument of common origin inference, Norton uses this argument to state that spatial distances and time elapsed are properties of Minkowski spacetime. ‘When all matter theories return spatiotemporal measurements all of which conform to a Minkowski spacetime geometry, that is strong evidence that they have a single, common origin, the Minkowski spacetime that they are measuring’ [Norton, 2008, p831]. Space and time are properties of Minkowski spacetime and matter (material clocks and rods) measures these properties as asserted in the realist’s conception of spacetime.

It is possible for a constructivist to deny this kind of reality, but only at some cost. This cost consists of the commitment to operationalism[13]. To see why, Norton introduces a thought experiment. Consider a spacetime that is empty of matter or contains a static matter distribution. In this situation nothing changes when we move between different events A and B. These events A and B are non-coincident and timelike-separated. The question is how time is perceived by constructivists and by spacetime realists. According to the realist’s view time has elapsed between points A and B. The constructivist has no available rods and clocks to measure time, since mass is unavailable or constantly distributed. Consequently, the constructivist can not measure change in time. They believe that time properties are the result of matter properties.

The only escape is that a constructivist must deny the elapsed time between events A and B. Then these thought experiments make no sense at all for a constructivist. Norton introduces another thought experiment to show us the peculiar consequences. Consider two non-interacting identical clocks in Minkowski spacetime relative at rest. We assume that the clocks tick at the same rate. One way to determine the equality of the rate is to emit light signals from the first clocks at times 1, 2, 3, ... and have them

[13]Quantities have no value unless they are actually measured.

arrived at the other clock at times 50, 51, 52, ... In this example there are no light signals to check the agreement of the time rate. However, a realist believes the time rates of both clocks are triggered by the time that is included in the clocks itself. For the constructivist '[t]he assertion must be that it makes no sense to speak of times elapsed unless a clock or the change in some material process actually measures the times elapsed. This is the extreme form of operationalism mentioned' [Norton, 2008, p833]. When a constructivist decides to reject this operationalism, he immediately endorses the idea that times elapsed and spatial distances are properties of spacetime.

Another attack on the constructive approach was made by Nerlich [Nerlich, 2010]. It focuses completely on the article written by Bell and forms a criticism of his constructivism. Nerlich is mainly critical of the level of the article. Its structure is chaotic and contradictory. The constructivism presented is incomplete. Some terms need more explanation. For example: the contraction that Bell applies is a function of velocity. But velocity is not well defined in the paper of Bell. The concept of motion is shaky. Bell does not mention a substratum in which light can propagate or any other definition of motion. As a result, we do not know what is moving and what not. Moreover, motion is undefined. A 'velocity' for Bell is a vector without any physical meaning and therefore incomplete. It follows from mathematical equations but does not originate from physics. Nerlich points out that Bell leaves a lot of questions unanswered. Many physical details are not clearly defined by Bell and therefore this constructivism is not useful.

Van Camp is inclined to favor the special theory of relativity but for different reasons than Janssen. 'I do want to argue, along with Janssen, that special relativity is explanatory more fundamental than Lorentzian dynamics. However, the reason behind this has been missed by both Janssen and Brown' [Van Camp, 2011a, 1104]. According to Van Camp, the fundamental explanatory function deserves more attention. Van Camp asks why should we follow Janssen in his conviction that a kinematic explanation is superior? Just as the kinematic approach, a dynamic or constructive theory can provide a common-origin explanation. Kinematic explanations are not necessary for common-origins. So, the kinematic structure (geometry of Minkowski spacetime) is not essential for common-origins and the choice between the kinematic of dynamic approach remains on the same footing. The arguments of Janssen and Brown are repeated and the discussion strays.

Van Camp comes with a new insight to distinguish the principle theory from the constructive theory. Van Camp refers to DiSalle. DiSalle analysed the development of space and time theories from Galileo to Einstein. Van Camp concludes that 'These are theories that serve as preconditions for the possibility of scientific knowledge by establishing a consistent conceptual framework that defines the meaning of empirical investigations under it' [Van Camp, 2011a, p1104]. In the case of special relativity, Einstein offers 'a clear and meaningful definition of time, space, and motion, including dynamical descriptions' [Van Camp, 2011a, 1105]. The novel definition of simultaneity is the key to this success. This new definition is powerful because it 'acknowledges the constitutive role of the velocity of light and uses it to impose a structural framework wherein physical explanations can be made'[Van Camp, 2011a, 1105]. An explanation of these postulates is meaningles, that would induce circular reasoning. Van Camp claims that this necessity comes from the fact that spacetime theories operate at a high level. They clear the way for other physical theories that function in this spacetime. So special relativity offers the conceptual framework for constructive theories to be meaningful.

We have discussed the criticism of Norton, Nerlich and Van Camp on the constructive approach. We will see that the constructive approach has progressed with the work of Miller. He introduces a new version of constructive special relativity. Therefore Nerlich's criticism is weakened. Further, the contribution of Van Camp can be better explained in the more general context of explanation. What are explanations supposed to do? We will discuss later whether conceptual frameworks provide understanding.

Norton's criticism is the most sophisticated comment and this requires more attention. Is a constructivist justified to employ a coordinate system to label rods and clocks even though a complete spacetime is not posited yet? I think he is justified because the coordinates reflect the behavior of material objects. The coordinate system is a mathematical tool and it does not necessarily imply the existence of Minkowski spacetime. During this description it turns out that all material objects behave according to certain rules. The coincidence that all material objects behave according to the same coordinates does not imply a spacetime structure. The coordinates primarily describe the behavior of the material objects. Brown is justified to describe material objects with a coordinate system as a mathematical tool. Thus, Norton's comments are not threatening the explanatory power of Brown's constructive approach. This aspect is not decisive for theory choice between Janssen and Brown.

7.3 Reactions to the distinction between kinematics and dynamics

The distinction drawn between dynamics and kinematics is taken into consideration by several philosophers. Part of the disagreement between Janssen and Brown lies in the definition of kinematics and dynamics. The main comment on this distinction is that it is hard to draw. The two concepts are vague and new definitions are given by other philosophers. The most meaningful responses are listed below.

Frisch states that the disagreement about kinematics and dynamics is not a genuine disagreement [Frisch, 2011]. Discussion about how to draw the line between kinematics and dynamics is not a discussion about substance.

Although Janssen and Brown apply different definitions, they are still compatible. The different definitions of kinematics and dynamics do not provide a conflict. 'Brown insist[s] that the default behavior of objects captured in the theory of relativity follows from a universal constraint on the dynamics, but that is compatible with the claim that the phenomena in question are instances of some generic feature of the world - that is, with the claim that the phenomena are kinematical in Janssen's sense' [Frisch, 2011, p181]. The issue between Janssen and Brown comes down to a disagreement about terminology. The disagreement lies in 'the explanatory relations between the dynamical constraint and its geometrical representations' [Frisch, 2011, p181].

Already in 1991 Dennis Dieks gave his opinion about the application of kinematics and dynamics [Dieks, 1991]. 'There can therefore be no doubt about the physical reality of the contraction of moving bodies; the contraction can certainly be treated by means of dynamics. At the same time in relativistic kinematics rods and clocks in an arbitrary inertial frame can legitimately serve to supply coordinates; there is no preferred frame. As a result, kinematical and dynamical considerations go hand in hand' [Dieks, 1991, p5]. Dieks explains himself with a rotating rigid disk, the well-known Ehrenfest paradox. Paul Ehrenfest described in 1907 a rotating rigid cylinder of radius R and height H. This cylinder starts rotating around its axis and it will reach a state of uniform rotation. R is the radius for a resting observer. The rigidity of the cylinder demands two things. The periphery of the cylinder is contracted compared to the rest situation and the radius of the cylinder is not contracted compared to the rest situation. This difference will cause stresses to appear in the cylinder. From this perspective, motion has certainly a real physical effect on bodies. But on the other hand, the principle of relativity gives another perspective, a kinematical perspective. Every inertial frame can serve as a resting frame with a resting unit rod. There is no conflict between the kinematical and dynamical perspective. They are just two different situations of looking at the situation and they apply to the same phenomena without bringing up any inconsistency.

Matthew Gorski [Gorski, 2010] introduces new definitions for kinematics and dynamics. He distinguishes specific dynamics, general dynamics and kinematics. 'The *kinematics* is the coordinate transformations and generic relationships between spatio-temporal quantities. [...] The *general dynamics* states the relationship between a force of any kind and position or one of its derivatives. [...] The *specific dynamics* states the laws for a particular kind of force ' [Gorski, 2010, p5-6]. Next, Gorski defines how a phenomenon should be categorized. 'A phenomenon is broadly kinematical if it is explained by the kinematics or the general dynamics. A phenomenon is narrowly kinematical if it is explained by the kinematics or the space-time symmetries of the general dynamics. A phenomenon is dynamical otherwise' [Gorski, 2010, p6]. This motivation for these new definitions is to please Brown. 'The interesting feature of my way of drawing the distinction is that it is also acceptable to Brown, even though he says that there is a "true *lack* of a clear distinction between kinematic and dynamic effects (in particular in the context of length contraction and time dilation)" ' [Gorski, 2010, 6].

Alberto A. Martínez does not agree with the distinction made by Brown. Originally the terms were created by Ampère with the meaning: 'Kinematics was the science that aimed to study motions of bodies in our environment as they appear to observation and regardless of the forces that might produce them.' [Martínez, 2007, 212]. Physicists took the position that physics should be about observables instead of abstract notions of invisible characteristics. The first task should be to describe the phenomena by how they appear without mentioning underlying processes. This definition should not be confused with denial of underlying forces. The origin of the behavior of for example rods and clocks is acknowledged but not taken into consideration. So we are able to describe trajectories of moving bodies without referring to their mass and internal forces that keeps them together. The issue is epistemological. We should not bother ourselves with underlying processes we do not know anything about. This does not imply that kinematics is more fundamental.

Hitherto, philosophers argued that the distinction between kinematics and dynamics does not contain any inconsistency. Miller introduces a new aspect of the kinematic/dynamic distinction. He distinguishes two different processes, namely active and passive transformations. He points out that the situation of a moving observer perceiving a rod at rest and the situation that a observer at rest perceives a moving rod are different. So it matters whether the observer or the rod is going to another inertial frame. Instead of the familiar kinematic and dynamic distinction, Miller uses the words active and passive transformation or perspectival or dynamical effects as labels for this distinction. A passive/perspectival transformation corresponds to a transformation of the coordinate system (observer) to a different inertial frame. An active/dynamical transformation corresponds to a transformation of the physical objects to another inertial frame. These processes are physically different. When a rod in equilibrium changes frame, 'there are physical changes in it which can be calculated from a consideration fo the forces which keep it in equilibrium and it is those changes which lead to the satisfaction of the Lorentz transformation conditions. In the other hand, when an observer is changes frames, the rod will remain its physical state. Furthermore, Miller distinguishes 'connected' and 'unconnected' lengths. A connected length is 'the length of a physical object in equilibrium' [Miller, 2009, 637]. This is the opposite of unconnected length, which is 'the distance between two objects that are independent of each other' [Miller, 2009, 637]. This is important because connected and unconnected lengths behave differently for active and passive transformations. For a perspectival change of frames the ratio of both connected and unconnected lengths alters with the factor γ. But this is not the case for a dynamical change of reference. In this situation only the connected length changes with a factor of γ. The change of the unconnected length depends on the rate of acceleration of the objects between inertial frames. Connected and unconnected length respond differently to boosts. The result can be summarized in a table.

Ratio of length when	Connected length	Unconnected lengths
Observer changes frames	γ	γ
Objects change frames	γ	Variable

Miller concludes that what is the best interpretation depends on the situation. '[T]he changes in a connected object (object in equilibrium under internal forces) when it is transferred between inertial frames involves dynamical effects. In contrast, the different observations of a single connected object by different inertial observers are a perspectival, not a dynamical, effect' [Miller, 2009, 638].

I agree with Frisch, Dieks and Martínez that the distinction is not fundamental. The example of Dieks shows why this distinction is not well-founded. A phenomenon (e.g. the rotating rigid cylinder) can be explained by dynamics as well as kinematics. They form two different perspectives consisting of the same elements. The choice between the perspectives is pragmatic. The origin of the distinction is historical as explained by Martínez. In this sense, kinematics is a subset of dynamics and the distinction is clearly not a dichotomy. In practice this distinction is useful to describe the dispute of Janssen and Brown. But we should keep in mind that it is hard to draw the line between kinematics and dynamics. As a consequence, the dispute becomes vague. Even with the extension of Gorski it remains difficult to draw the line between specific and general dynamics and kinematics.

Miller's paper is valuable for the discussion between Janssen and Brown. There is a physical difference between a resting and a moving rod. But this only applies for non-equilibrium situations. A moving rod will eventually attain equilibrium again (if possible). So the issue between Janssen and Brown remains in the case the rod is in equilibrium again.

7.4 Reactions to the distinction between constructive and principle approach

Another point of discussion between Janssen and Brown is the preference for the constructive or the principle approach. Although it is related to the aforementioned kinematics and dynamics distinction, the comments in this section are different from kind than the comments in the previous section. Therefore we handle this topic separately. The contribution of two philosophers will be treated below, Mathias Frisch and Francisco Flores. They both have an interesting reaction to the original distinction of Einstein.

Frisch [Frisch, 2011] concludes that part of the discussion lies in the distinction between constructive and principle theories. The distinction made by Einstein functions as the framework of the dispute for Brown. Brown claims that constructive theories provide explanation and more importantly, principle theories fail to explain. Constructive theories are explanatory superior compared to principle theories. This distinction is a direct copy of Einstein's distinction, but it is not the complete picture. According to Frisch a framework of different theories can be improved. He suggests to distinguish two kinds of principle theories based on the analogous distinction made by Lorentz. Lorentz's idea of principle and constructive theories were slightly different than Einstein's, see section 4.3. According to Lorentz, general principles can work on all levels of science. He considered constructive theories to be mechanism theories. This led Frisch to the following distinction [Frisch, 2011, 179]

- (i) mechanism or constructive theories, such as the kinetic theory of gases;
- (ii) purely phenomenological principles, such as the second law of thermodynamics
- (iii) general principles or constraints on all (or at least multiple) levels, such as the principle of energy conservation

This distinction gives a more complete overview of the possible frameworks of a theory according to Frisch. In Einstein's distinction the category of general physical principles is left out. Frisch states that this is an important category because 'general constraints [..] guide theory construction and theory choice and [...] we take every physical theory, or perhaps every theory within a certain domain, to satisfy it' [Frisch, 2011, 179]. Frisch claims that the debate should take place in this more clear tripartite classification.

Furthermore, Frisch emphasizes that Lorentz maintained that both kinds of theories have explanatory value. The choice of theory is context dependent. Lorentz believed that 'there are multiple ways by which we try to understand natural phenomena [...] Individual characteristics and inclinations determine the choice for each scientist' [Frisch, 2011, p179]. Frisch agrees and adds for the threefold distinction: 'To explain a phenomenon [...] is to embed the phenomenon into a pattern of functional dependencies - in Jim Woodward's terminology it is to answer "what-if-things-had been-different-questions" - and phenomenological principles can provide us with answers to such questions just as general principles or constructive theories can' [Frisch, 2011, p179]. His opinion concurs with that of Lorentz. 'Explanation is a highly context-dependent notion and that there may be contexts in which a phenomenological account can provide the best explanation, just as there are others in which a constructive account is called for or where an appeal to a general principle provides the simplest and best explanation' [Frisch, 2011, p179-180].

Flores offers a total different viewpoint in his 'Einstein's theory of theories and types of theoretical explanation' [Flores, 1999] before the book of Brown appears. Flores names three categories of difference between principle and constructive theories drawn by Einstein (i) ontological, (ii) epistemological and (iii) functional. The aim of Flores is to shift the emphasis of the difference from Einstein's traditional ontology towards a more functional distinction.

First we take a look at what the ontological difference between theories consists of. 'Constructive theories postulate the existence of "entities" (with specific properties) while principle theories postulate general physical principles that govern the behaviour of matter' [Flores, 1999, p125]. Constructive theories are concerned with entities and principle theories are concerned with physical principles.

We continue with the second difference in theories, epistemology. It concerns the question: how are the starting points of each theory discovered? According to Einstein, the starting points of principle theories are empirically discovered, opposite to starting points of constructive theories that are not empirically discovered. For principle theories 'the scientist has to worm these general principles out of nature by perceiving in comprehensive complexes of empirical facts certain general features which permit of precise formulation' [Flores, 1999, p125]. These conjectures can be idealized and raised to the status of postulates. The starting points of constructive theories are hypothetical constituents and both the existence of these elements and their properties can be created freely. It is that for successful theories the constructed elements correspond to microphysical objects. So, theories can have empirically discovered or hypothetical constituents as starting points.

The third difference Einstein's distinction contains is function. The principles of principle theories function as criteria the physical processes have to satisfy. If an error is found, we will try to find the error in the description and we will not doubt the mathematical criteria. According to Flores, Einstein believes that functional distinction is derived from the ontological distinction. Einstein thinks that the ontological distinction is the most important distinction and this led to the classification of principle and constructive theories. Flores demonstrates that the functional difference is the most important one and that the functional distinction framework vs. interaction forms a better distinction for theories. The ontological based distinction of constructive and principle theories should be omitted.

Flores argues why the functional distinction is better than the ontological distinction of Einstein. He explains that the universal gravitation of Newton does not fit the ontological distinction, but instead fits the functional distinction. Therefore the functional distinction is better. The universal gravitation of Newton does not fit into the ontological distinction: constructive and principle theories. The fact that it is hard to classify in Einstein's distinction shows that the functional distinction between framework and interaction is more robust. Flores argues why the universal gravitation (UG) cannot be the 'starting point' of either a principle or a constructive theory. UG does not correspond to a principle theory because it is derived from the three laws of motion. It is a consequence, not the axiom. So then, if it does not survive on its own, can it be *part* of a principle theory? According to Flores the answer is no. The derivation of the UG cannot be done without referring to phenomena. So it is not even part of a principle theory. Otherwise, the force of gravity should form the 'starting point' of a constructive theory. Although it seems as if the force is the building block of the universal gravitation, the analogy is not strong enough. '[...] notice that the collective behaviour of gravitational forces cannot *explain* the law of UG in the way that the collective behaviour of molecules explains the ideal gas law. This is because each "component" gravitational force can only be determined by the very law itself' [Flores, 1999, p129]. So for the case of UG the ontological focus is untenable.

Flores focuses on the functional dimension of Einstein's distinction and employs these terms: framework and interaction theory. Framework theories provide the scaffolding for other theories to build on. 'The main elements of these "upper-level" theories are general physical principles (typically expressed as "laws") and definitions of physical terms which are expected to be applicable in the analysis of any physical system' [Flores, 1999, p129]. Interaction theories '[...] describe specific physical processes *within* the constrains imposed by the principles (or one of the consequences) of a framework theory' [Flores, 1999, p129]. With these new definitions we can state that the relation is: 'all principle theories are framework theories and vice versa; all constructive theories are interaction theories but not vice versa' [Flores, 1999, p129].

Frisch is correct to point out that explanation is context dependent. The main lesson is that the context determines which explanation fits best. Constructive *and* principle theories have explanatory potential. It is impossible to say in advance which explanation is better. Flores' point is more subtle. He shifts the ontological emphasis towards a functional difference. We will see in section 7.6 that Flores takes this improved distinction to be complementary. I do not see why a subtle change of function is necessary for the role of explanation. The context dependence is already valid for the original ontological distinction by Einstein.

7.5 Reactions to the arrow of explanation

The next disagreement is the view on the arrow of explanation. Janssen states that Minkowski spacetime provides a common origin explanation of Lorentz covariance. Brown states the opposite. The Lorentz covariance of the dynamical laws provides the explanation for the existence of Minkowski spacetime. Frisch and Gorski provide the most interesting reactions to this issue and their reactions are discussed below.

Frisch considers this to be a genuine disagreement. The main difference is that Janssen offers a common origin explanation and states that without such an origin the Lorentz covariance of all dynamical laws seems a cosmic coincidence. Frisch finds two claims in this argument for the arrow of explanation. 'First, Janssen claims that without further explanation the fact that all dynamical laws are Lorentz-invariant would appear to be a gigantic coincidence and, hence, this fact is in desperate need of an explanation. Second, he claims that Minkowski spacetime can in fact provide the needed explanation' [Frisch, 2011]. Frisch elucidates both claims.

Frisch gives two examples which include a degree of 'coincidence'. First he gives the example of the Coulomb force. The force between two charged objects turns out to be $1/r^2$ case after case. Our common sense will tell us that this is probably not a coincidence at all. We believe that Coulomb force is the common physical law behind all these phenomena. On the contrary, in a game of dice we would consider it to be a coincidence that time after time the die would appear as a six. We will find it unlikely and would not construct a law that could predict future die rolls. So not every coincidence cries out for an explanation. 'If we have reasons to believe that a phenomenon can be explained by appealing to physical laws, then this in *itself* is a reason enough to think of the phenomenon as not being coincidental' [Frisch, 2011, p182]. Frisch argues 'that once we are able to explain a common feature of different phenomena in terms of the physical laws governing these phenomena, we are *not required* to offer a further explanation' [Frisch, 2011, 182]. So the principle of Lorentz invariance does not require any further explanation. Though, it is still possible to offer an additional explanation as Janssen proposes. According to Frisch, the common origin argument given by Janssen is superfluous. The two claims are rejected by Frisch.

Gorski wrote an article concerning the arrow of explanation in special relativity [Gorski, 2010]. He discusses the importance of spatiotemporal symmetries in the debate between Janssen and Brown. According to Gorski part of the disagreement lies in the different interpretation of those symmetries. Gorski defines the difference of the arrow of explanation between Brown and Janssen as follows [Gorski, 2010, p2]:

- **B.** The symmetries of the dynamical laws explain the symmetries of space-time.

- **J.** The symmetries of space-time explain the symmetries of the dynamical laws.

The concept of spacetime Janssen and Brown possess, plays the crucial role according to Gorski. Gorski points out that Janssen's concept of spacetime is about laws. The claim that all laws are Lorentz invariant is a very special law: a meta-law. It is considered to be so fundamental that it transcends other laws. 'In a space-time theory understood as postulating meta-laws, the symmetries of spacetime explain the symmetries of the specific and general dynamical laws by making them "inevitable, unavoidable-necessary" [Gorski, 2010, p13]. Brown is arguing for:

> **B2.** The symmetries of the specific dynamics, the fact that those dynamics admit stable rod and clock solutions (inter alia), and the fact those solutions describe the actual world, explain the symmetries of space-time.

For Brown the laws are not the bearers of spatio-temporal properties or symmetries. 'So, just because a law exhibits a certain symmetry, we cannot automatically identify it as a spatio-temporal one' [Gorski, 2010, p15]. Space-time should not only be about laws. It should also include some characteristics of the matter distributions. 'For Brown, to make a claim about space-time is to say something about the behavior of matter or matter fields. Thus, to explain a property of space-time is just to explain why matter behaves in a certain way' [Gorski, 2010, p16]. The symmetries of spacetime therefore play the crucial role in the arrow of explanation.

The analysis of Frisch fits into my own analysis in chapter 8. I agree that explanations are not required infinitely. Somewhere we should consider if an extra explanation is meaningful and stop asking for more explanations. Gorksi is right about the concept of spacetime Janssen and Brown possess. But this is not the core of their dispute. Janssen and Brown disagree about the role of explanation, and therefore they have a different idea about the content of spacetime.

7.6 Reactions to the role of explanation in special relativity

The point missing in the discussion of Brown and Janssen up to now is the more general role of explanation. Principle and constructive theories go together with certain types of explanation. Therefore preferences for a kind of explanation determines preference for principle or constructive theories. Janssen and Brown disagree on the criteria of an explanation and consequently on the choice between principle and constructive theories. This section consists of philosophers (Flores, Dieks and Van Camp) who place the discussion into a more general discussion about the role of explanation.

Flores discusses the role of theoretical explanation in 1999 [Flores, 1999]. His distinction between framework and interaction theories is a stepping stone towards the role of explanation. Flores refers to Salmon and Kitcher about the two possible explanations: bottom-up explanations (BUE) and top-down explanations (TDE). Salmon's idea of explanatory power is that 'we explain a law when we uncover the underlying causal mechanisms that bring it about' [Flores, 1999, p130]. On the other hand we have Kitcher with a different view. He states that 'we explain a law by deriving it from more general laws using the argument patterns that best unify our (current) state of knowledge' [Flores, 1999, p130]. Salmon's conclusion is that we should not treat them as conflicting views but rather as two complementary views of distinct types of explanation. According to Flores this is exactly the difference between the interaction and framework theories. BUEs and TDEs are in a way the symptoms of the interaction and framework distinction. 'Only laws that belong to an interaction theory, and particularly those that belong to constructive theories, receive BUEs. Laws that belong to framework theories, on the other hand, always receive TDEs' [Flores, 1999, p130]. So, we conclude that with this distinction we can understand why certain theories are assigned BUEs or TDEs.

Dieks published an article about the role of explanation in physics in 2009 [Dieks, 2009]. This article is specified to bottom-up and top-down explanations. The comparison between top-down explanations and bottom-up explanations shows little difference.

The top-down version Dieks is especially interested in is the addition made by Minkowski. He turned Einstein's theory into a more mathematical formulation. The main difference between the formulation of Einstein and Minkowski is that the latter can do without an interpretation of rods and clocks. Minkowski uses arbitrarily chosen variables with no physical meaning. Now we can consider one point to be a 'world-point' with arbitrary coordinates. The development of one 'world-point' forms a 'world-line'. All together they constitute the world. The laws of physics are the relations between the 'world-lines'. In the bottom-up approach the rods and clocks are treated as objects that consists of molecules and atoms. The behavior of the objects is determined by the physical laws that drive the constituents and their interactions. Dieks compares those two approaches and concludes that there is no real difference.

To explain his point, Dieks gives an example of length contraction. From the bottom-up view 'it must be the case that the microscopic processes that are responsible for the macroscopic features of the body are governed by Lorentz invariant laws' [Dieks, 2009, p11]. This is independent of the constitution of that particular object. There is an equilibrium configuration that determines the length of the object. An object with the same composition in another frame will have the exact same equilibrium state. The relations between those states are the Lorentz transformations. So the Lorentz contraction expresses the relation between the equilibrium states of the two frames. From a different viewpoint we can see that the relativity principle is part of the argument of the result of length contraction. When we ignore the microscopic constituents we return to the principle approach of Einstein. Both Einstein and Lorentz use the same theoretical ingredients but in a different order. 'Lorentz started from the microscopic building blocks of bodies, analysed their equilibrium positions and went on to prove that if there is one such equilibrium in a resting body, there must be corresponding equilibria in moving bodies such that the resulting macroscopic lengths of these moving bodies relate to the rest length via the Lorentz contraction. In this proof he had to assume that all laws change in the same way in the transition from rest to motion as the laws of electrodynamics — which is equivalent to assuming that all laws are Lorentz invariant' [Dieks, 2009, p11]. The distinction between top-down and bottom-up is not different in theoretical machinery. Dieks has as main conclusion that *'[t]here is no uniquely best way of explaining the relativistic effects'* [Dieks, 2009, p13]. The difference between explanations is pragmatic. 'Explanation and understanding are relative to questions we ask and interests we have' [Dieks, 2009, p13].

Van Camp [Van Camp, 2011b] also contributed to the principle/constructive distinction. However the aim is to search for the possibilities for a principle approach for quantum mechanics. Van Camp sees Flores' distinction as a correct starting point. The functional role of theories require more attention. However Van Camp has two additional points to the work of Flores. Flores argues that explanation is derived from the functional role. According to Van Camp this should be the other way around. The functional role is determined by the explanatory goals. Furthermore, when this is the case, the explanatory goals cannot simply be separated into two types of explanation. The distinction is incomplete. As mentioned before, principle theories are able to provide something more than only unification. They can offer a conceptual framework where other theories can operate in. So the functional difference raised by Flores can be seen as explanatory pluralism. And logically this leads to theoretical pluralism since the functional role is derived from the explanatory goal.

I agree that explanation is the force behind types of theories. Our aim is to understand the phenomena, and this aim determines which type of theory suits best. There is no one way of explaining phenomena. Explanations are pragmatic and the context assigns the best theory.

8 My analysis of the two interpretations

I have discussed two different interpretations of special relativity. Janssen's interpretation encompasses that Minkowski spacetime is the common origin of the fact that all laws are Lorentz invariant. In contrast to Brown, he states that Minkowski spacetime is explained by the symmetries of the dynamical laws. The incidental fact of Lorentz invariance of all dynamical laws does not require further explanation.

The empirical consequences of both interpretations are equivalent. They both predict exactly the same length contraction and time dilation. So, an experimental set-up will never be able to distinguish between the interpretations. In philosophy of science this is known as contrastive underdetermination. It means that for any body of evidence which confirms a theory, there might be one or more alternative theories that are confirmed by that same body of evidence. We do not have to know them at present. Those alternative theories could be introduced long after the initial confirmed theory.

This contrastive underdetermination should not be confused with holist underdetermination. The idea of holism is that systems constructed of smaller parts should be viewed as a whole. The properties of the system cannot be completely understood by looking at the constituents. Holistic underdetermination contains the same idea. When we test a hypothesis in isolation and get a negative result, we do not know whether to reject the result of the experiment or to get rid of one or more of the constituents. This kind of underdetermination is not included in the scope of this thesis. If we want to differentiate between both interpretations, we have to look at non-empirical properties. Fortunately, both approaches have several non-empirical differences which can help us with theory choice. We do not have other options to settle the question. Let's look at some of those differences.

A recurrent difference between Brown and Janssen is that Brown consequently employs the term dynamics and on the other hand, Janssen employs the term kinematics unceasingly. Can we declare our preference for one of those to assist in theory choice? My answer is no. Kinematics and dynamics do no form two incompatible notions. Kinematics does not deny the presence of the underlying forces. And vice versa, dynamics allows perspectival effects. Sciencists should be concerned with their employability. Phenomena will be described necessarily kinematically when there is a lack of dynamical knowledge. But this leap to kinematics does not deny the existence of underlying processes unknown to the scientists. Future research can reveal the option that allows scientists to speculate about the dynamics of the phenomena. Kinematical and dynamical phenomena are compatible and therefore the terms are lousy criteria to provide a guidance for theory choice. Kinematics and dynamics do not conflict with each other. They coexist perfectly well. They both describe the phenomena in a different perspective. These terms form lousy criteria for guidance for theory choice.

Accordingly, the distinction between principle and constructive theories is not a sufficient distinction to conduct theory choice. The same story of the distinction between kinematics and dynamics applies to the distinction of principle and constructive theories. Both theories are not incompatible. Constructive theories could include symmetries and principles that are not directly constructed into the theory but are interwoven with theoretical elements. For example, Brown assumes the Lorentz invariance of all dynamical laws. This has similarities with the assumption of the relativity principle. Principle and constructive theories contain the same elements, but in a different arrangement.

Do these inadequate distinctions help in the case of special relativity and do they offer a good model for theory choice in general? The question is now twofold. For the first question, can we rely on non-empirical distinctions and consequently see whether Janssen's or Brown's approach is preferable? These non-empirical issues listed above will not settle the question. The difference between kinematics and dynamics and likewise between principle and constructive theories cannot be applied strictly to special relativity. It is not clear on which criteria the differences are based and therefore the distinction is not fundamental. It is not possible to conclude in advance that one type, constructive/dynamical or principle/kinematical, is a better theory. We see that in the application to special relativity both distinctions do not form dichotomies.

For the second question, do these distinctions help in the case of theory choice in general? Principle and constructive theories do tell something about how theories explain. They give insight in the diversity of possible explanations. Some successful theories are principle theories and other prevailing theories are constructive theories. How successful theories are does not depend on which type of theory it is.

The cases of thermodynamics and the kinetic theory of gases represent different kind of explanations. 'Thus the kinetic theory of gases seeks to reduce mechanical, thermal, and diffusional processes to movements of molecules - i.e., to build them up out of the hypothesis of molecular motion' [**?**, 1]. On the other hand, we have thermodynamics. 'Thus the science of thermodynamics seeks by analytical means to deduce necessary conditions, which separate events have to satisfy, from the universally experienced fact that perpetual motion is impossible' [**?**, 1-2]. This case is similar to special relativity, it is not possible to decide which explanation is better on the basis of such distinctions. Special relativity and thermodynamics versus kinetic theory of gases are perfect examples of the combination of both distinctions. The distinction consequently appears sound and complete. The collection of theories goes further than just these two exemplary theories. Explanations show a lot of diversity. The distinctions do not cover this diversity in explanatory power. An example is the Universal Gravitation discussed by Flores. This theory cannot be categorized because it does not fit Einstein's distinction, but it fits his own distinction.

Overall, the overlap in the distinction tells us that we are not dealing with dichotomies but with overlapping groups of two specific types of explanation. Generally, the distinction between principle and constructive theories (and the related distinction kinematics and dynamics) is not capable of declaring a special role to one of them. Theory choice grounded on the basis of this distinction remains undecided.

8.1 Argument of *COI*

In the debate between Janssen and Brown for the arrow of explanation, Janssen has proposed a new argument, called the *COI*-argument. The article is discussed in great detail above. The main conclusion is that the argument of COI is decisive in the case of special relativity and for theory choice in general. As Janssen explains, the symmetries of the dynamical laws appear to be contingent. The addition of Minkowski spacetime as a common-origin provides an explanation of the coincidence of the Lorentz invariance of all dynamical laws. The coincidences are reduced to one structure: Minkowski spacetime. According to Janssen, this explanation is superior to Brown's explanation. Janssen claims that generally, theories with less coincidences and stronger common-origins are explanatory better than theories that lack these properties.

Janssen's argument of *COI* comes down to the strength of simplicity. The theory with the least amount of assumptions among other competing theories should be selected as the best theory. This is stated by the principle called Occam's Razor. Alternative hypotheses may be correct, but they are inferior due to increase of complexity. One should prefer simplicity until simplicity is at the expense of explanatory power. Based on this principle, it is natural to select theories containing *COI* arguments. Let's examine the implication of this *COI* argument.

The main contribution of the *COI* argument for special relativity is that it takes away the accidental existence of the Lorentz invariance of all physical laws. Minkowski spacetime is the overarching structure that constrains the physical laws to be Lorentz invariant. One could argue that a *COI* does not at all take away any contingency. On the side of Brown, he thinks that the common-origin (in the shape of Minkowski spacetime) does not offer an extra dimension to the explanation of special relativity. It is a pseudoargument for the existence of Minkowski space-time. Janssen and Brown both agree that all dynamical laws are Lorentz invariant. Brown accepts that as a brute fact. Janssen has the urge to explain this contingent fact through the means of overarching Minkowski spacetime. This structure imposes the Lorentz invariance. For Brown it is necessary to be more explicit how this influence is achieved by Minkowski spacetime. How do the laws know in which spacetime they live and therefore how to behave? How does matter know how spacetime is curved and thus how to behave? The point of Brown is that without a causal-mechanical picture the common-origin argument (or a unification argument) has no explanatory value in the case of special relativity. Minkowski spacetime is a pseudostructure. Our brains have the need to organize information in such a way that it looks beautiful. The structure that Minkowski spacetime reveals in a Minkowski spacetime diagram looks beautiful to the eye, but it does not necessarily have to refer to an existing spacetime structure.

Janssen maintains that his interpretations reduce the coincidences better than Brown's do. He argues that because of this reduction of coincidences his approach is superior. He admits that he is not able to give an comprehensive account of the interaction between Minkowski spacetime and the dynamical laws and matter. This does not apply to all the examples of *COIs* given in his paper. Remarkable is that the lack of causal efficacy for the *COI* argument only appears in the case of special relativity. Janssen lists a number of *COIs* that are analogous to Minkowski space-time. The examples consist of evolution theory of Darwin and different models of the solar system (Ptolemy, Tycho Brahe, Copernicus, Johannes Kepler and Poincaré). My point is that these examples clearly have a different character. These common-origins would be immediately acceptable for Brown, because the underlying causal mechanisms are available. We know the structure of our DNA and how it is inherited. These mechanisms lie at the heart of evolution theory. The gravitational forces that underlie the dynamics assist the validity of the *COI* that explains the solar system. But this is not the case for Minkowski spacetime. The question is, is Brown justified to require a causal-mechanical explanation of Janssen's Minkowski spacetime? I will argue that it is not necessary for Janssen to give any causal-mechanical background. A causal-mechanical explanation is not needed for a *COI*. The essence is the *COI*, a causal supplement is not mandatory.

8.2 Types of explanations

The *COI* argument of Janssen is not novel. This kind of explanation is already known by a different name. The person associated with this type of explanation is Philip Kitcher. He wrote an article about unification as explanation in 1981 [Kitcher, 1981]. Unification unites several different phenomena and reduces them to one account. This idea reflects our intuition. Naturally, our idea of good explanations is that they are able to connect apparently unrelated phenomena. Kitcher defines the strength of this kind of explanation as follows: 'Science advances our understanding of nature by showing us how to derive descriptions of many phenomena, using the same pattern of derivation again and again, and in demonstrating this, it teaches us how to reduce the number of facts we have to accept as ultimate' [Kitcher, 1989, 423].

For a complete picture of explanation, it is helpful to list the most prominent theories of explanation. With this we are more capable to analyse the arguments of Janssen and Brown. In philosophy of science there are roughly four models of explanation [Pitt, 1988]. First, the deductive-nomological model, second, the statistical relevance, third, the causal mechanical model and fourth, the unificationist account of explanation. Let's look at all the theories of explanation before we go any further.

First is the deductive-nomological model (*DN* model) with Carl Hempel as the innovator of this model. The *DN* model consists of the familiar explanandum and the explanans. The explanandum is a sentence which includes the phenomena that need to be explained and the explanans is a sentence with the purpose to account for the phenomena. The explanans is the explanation of the explanandum and therefore it has to obey some logical and empirical requirements. 'The sentences constituting the explanans must be true' [Pitt, 1988, 11] is the empirical condition. Hempel lists three logical conditions: 'the explanandum must be a logical consequence of the explanans. [..] The explanans must contain general laws. [...] The explanans must have empirical content' [Pitt, 1988, 11] The first two requirements form the deductive criteria of the argument. The premises of the explanans must deductively lead to the conclusion of the explanandum. The third requirement is the nomological part of the arguments. The general law must contribute to the explanandum, that without it the explanandum is not valid any more.

Second is the statistical relevance (*SR*). *SR* focuses on conditional dependence. It is assumed in this model that statistical relevant properties have explanatory power. It is easy to illustrate this with an example. Consider the combination of the probability to get a heart attack and the habit of smoking three cigarettes a day. Research will conclude that P(*heart attack*| smoking three cigarettes a day) $\neq$ P(*heart attack* | smoking no cigarettes at all). Then, smoking cigarettes on a regularly basis is statistically relevant for getting a heart attack. Another property can be total irrelevant. P(*heart attack*| wearing a blue sweater) = P(*heart attack* | wearing a green sweater). The fact that somebody wears a blue or green sweater cannot explain the occurrence of a heart attack.

Third is the causal-mechanical explanation. Salmon's characterization of statistical explanations is replaced by the causal-mechanical account. He discusses the importance of cause-effect relations for scientific explanation [Salmon, 1984]. This relation is what Salmon calls a physical process. This is presented by a line in a spacetime diagram. A cross section of two or more lines is called an event. This is a point in a spacetime diagram. Physical processes have the ability to transfer information from one point in spacetime to another. An example of a physical process would be a ball moving from your foot into the goal. An event would be the ball hitting the car next to the football field. The moment that they collide is a point in spacetime.

Last is the unificationist explanation mainly developed by Kitcher in [Kitcher, 1981] and [Kitcher, 1989]. Using historical examples he concludes that argument patterns play a central role in explanatory unification. His task was to find the concept of these argument patterns. Kitcher employs the notion of the logician's approach to define the argument patterns in scientific reasoning. The argument pattern consists of many elements. First there is the schematic sentence. '[A]n expression obtained by replacing some, but not necessarily all, the non-logical expressions occurring in a sentence with dummy letters' [Pitt, 1988, 173]. Second, we have a set of filling instructions for a schematic sentence. The filling instructions will tell us how dummy letters can be employed to replace the original content. Third, there is a schematic argument that consists of several schematic sentences. Fourth, the argument needs a classification. It is necessary to classify the premises and the inferences and check the origin of these inferences. With these rules we can formulate a general argument pattern.

These four are the best known theories and extensively debated in philosophy of science. There is no consensus on the best type of explanation. Disagreement dominates the discussion because every type of explanation encompasses a suitable example. So, when we look at the most successful theories, they do not belong to one type of explanation. Successful theories exist in all kinds of ways, not of one typical origin.

For me this shows why Janssen and Brown cannot claim the superiority of their explanation. The type of explanation does not determine the quality of an explanation. Instead, we should look at explanations at individual cases. The properties (positive and negative) vary for each explanation. So, Janssen and Brown cannot claim the superiority of their own interpretation on the basis of the types of explanations listed above.

8.3 Theoretical virtues for theory choice

So why do some explanations receive our preference? We should judge on the basis of individual cases. We could make a list of criteria that we think a good theory should include. Then two aspects provide the quality of a theory. The more criteria are met, the better the theory appears. If a theory includes a bigger list of criteria, then we would prefer this theory. The other factor is that some criteria are primary and some have less priority. If a theory has a few but still important criteria then we would prefer this theory. In philosophy of science criteria are called theoretical virtues. Examples[14] are unifying power, predictive power, explanatory power, consistency, simplicity, coherence, fertility, accuracy, elegance and beauty. Mutually they are connected. Simplicity can influence the ability for predictive power and explanatory power depends on accuracy. How these theoretical virtues should be applied remains unclear. But we know that they all contribute to the quality of an explanation.

The role of the theoretical virtues deserves more attention. How should we interpret those virtues? One could defend that they have epistemic value. But this is not the case. We should not consider these criteria as proof. An example is the heliocentric model of Copernicus. The advantage

[14] This list is not necessarily complete.

of this model compared to its predecessor is more explanatory power with the unificational Sun at the center of the Universe. Meanwhile, this theory is outdated. Currently, the prevailing theory for the Solar system is general relativity. With hindsight we can state that the unificational Sun at the center is no evidence for Copernicus' model.

The non-empirical criteria function as a guide for theory choice. Increase in accuracy or a high degree of coherence does not prove the validity of a theory. It merely represents our level of understanding. Theoretical virtues are pragmatic. They are useful in their application for theory choice.

Let's turn to special relativity again. Non-empirical virtues make the difference for Janssen and Brown, because both interpretations are empirically equal. Janssen is attached to unification. He thinks that this gives the required explanatory power that is decisive for theory choice. Brown thinks that without causal-mechanical background unification has no explanatory power. Janssen's most important criteria is unifying power. He concludes that this property makes his explanation a good explanation. Brown is attached to explanatory power (causal-mechanical) as an important property of a good explanation.

8.4 Origin of difference in theoretical virtues

Why do Janssen and Brown disagree about the role of unification and explanatory power?Personality influences the order of importance. An adventurous scientist would tend to take more risks and consider novel theories more easily than a conservative scientist. So personal characteristics do matter, but only up to a certain level. The major influence is the circumstances. Explanations are answers to why-questions. Why do rods contract? Why do clocks dilate? What does Minkowski spacetime look like? The exact form of why-question is not fixed. Consider the example of Adam and the apple taken from Van Fraassen [Van Fraassen, 1980, 127]. The Bible tells the story about Adam and the forbidden fruits in Paradise. We are able to ask why-questions about this story. Namely the following

1. Why was it Adam who ate the apple?
2. Why was it the apple Adam ate?
3. Why did Adam *eat* the apple?

The why-questions have the same intention. They ask why something is the case. But the emphasis within the question is slightly different. An answer of question 1 could be, because Eve does not find apples tasteful. This answer would not be satisfactory for question 2. So it matters how the question is formulated. I agree that explanations have pragmatic value. The same reasoning holds for special relativity. Explanations depend on the question that is asked. Some questions aim for unification, some for a causal-mechanical account. The variety of explanation elucidates that there can be several possible explanation for why-questions related to special relativity.

For the case of special relativity, Janssen and Brown ask different question. The why-questions subtly fix the context. Janssen is curious how two observers can disagree about the length of physical objects given the fact that rods are stable objects over time and in rest in some inertial system. A unificational explanation is sufficient for this kind of question. The two observers perceive different spacetime axes and therefore perceive different cross-sections of spacetime that represent the length of the object. Brown asks why those rods have different lengths given the fact that two observers perceive different cross-sections of spacetime. This demands a causal-mechanical explanation of the properties of the rod. Janssen's explanation has the kinematical characteristics he prefers. Brown's explanation includes dynamical processes inside the rod. The context determines the why-question.

Although it lacks causal-mechanical elements, Janssen's explanation offers a conceptual look at the structure of spacetime. Minkowski diagrams (irrespective of its ontological status) are powerful tools to visualize time dilation, length contraction and simultaneity. In one glance we can see the consequences of special relativity. So even without causal-mechanical elements it offers a clear image of the theory. Whether this explanation is satisfactory depends on the context. It could be the case that the why-question is not concerned with the underlying physical forces but asks for a conceptual explanation. Then a unificationary explanation would suffice.

The explanation following the question possesses the theoretical virtues. This explanation takes place within the framework of a theory. For example, why do we observe retrograde movement of planets in our Solar system? The answer is that the Sun is the center of our Solar system (heliocentric model) and the retrograde movement is only a side-effect of the Earth's perspective. The unificational position of the Sun explains the perspectival consequences of the Earth. It does not refer to the constituents of the Earth and the Sun. So we would interpret this explanation as kinematical.

One could also ask why Mars and the Earth are moving around the Sun in the same direction. This would require an explanation about the evolution of our Solar system. The causal-mechanical laws of the components explain the birth of Mars and the Earth. We would interpret this explanation as dynamical.

Likewise for the discussion about the best explanation, it is useless to argue about the best question. One is free to put forward any question. Each question is equally valid, as long as it is suitable within the relevant context. Thus, Janssen and Brown are both in the position to formulate questions about relativity. The questions highlight different aspects of special relativity and therefore bring up different theoretical virtues.

8.5 Status of (arrow of) explanation

This pragmatic view of explanation asks for the scientific status of explanation. What do all these types of explanations provide? The aim of science is to grasp the natural phenomena. With the help of explanations we understand the world around us better. Our understanding of the world is the key to the success of science. The acquired skills in science enable us to discover tools to influence nature. And the success of science shows that we are capable of manipulating nature for our purposes. Much progress has been made to make life on Earth more convenient. Technological and medical innovations contribute to our comfort.

The success of science proves that explanations are at least meaningful. Therefore we have to establish that explanations play an important role in science. But this meaningful status does not imply that explanations that have great explanatory power are therefore true. This conclusion is a bridge too far. Explanations do not necessarily describe reality. The history of science is filled with theories with great explanatory power that turned out to be incorrect. Understanding required corrections to old explanations and the old explanation was replaced by an improved explanatory theory. Though at the time the scientific community committed to the deficient explanation. Current explanatory theories will probably be replaced by an improved alternative explanatory theory. This process will continue. So explanations are not fixed through time. Our understanding will change accordingly. We cannot rely on one of our explanatory theories and claim that it will last forever. We do not know what will happen in the future. Therefore we can not look at explanation as ontologically valid. The aim of explanation is primarily understanding.

Generally, one can have a phenomenon combined with different explanations. They all can have explanatory value in their own context. It is possible that these different explanations all contain different arrows of explanation. Mutually the arrows might clash, but they are constructed for our understanding and do not necessarily describe reality. One can pick any arrow of explanation if it contributes to the understanding of the world. For example, one could explain the world history with the price of cereal. Big events (world wars, important political changes, economical crisis) can be linked with the changes in the cereal market. The arrow that is suggested is that history can be explained by the cereal market. This arrow can be refuted as realistic, but it still gives insight that economics and politics are influenced by such factors as food supplies.

In the case of special relativity we have discussed two prominent explanatory theories. They provide understanding via different methods. Janssen explains by the notion of Minkowski spacetime. Brown gives a causal-mechanical explanation. The arrow of explanation is opposite in both cases. The clash is acceptable when one sees that explanations provide understanding but do not have ontological implications. A good explanation provides great understanding.

9 Conclusion

Recently, special relativity has got renewed attention in the literature. The publication of Brown 'Physical Relativity' in 2005 has given rise to this discussion. He emphasizes that a proper explanation of special relativity includes that the symmetries of the dynamical laws explain the symmetries of spacetime. This is in contrast to the general conception of special relativity. Janssen holds on to this conception and claims the opposite, the symmetries of spacetime explain the symmetries of the dynamical laws.

Janssen and Brown are key figures in the interpretation of special relativity. They both cling to their own approach. This discussion has not gone by unnoticed. Many philosophers responded and argued for the possible foundation of the issue. Some commentators confirmed the ideas of Janssen or Brown. They agree with Janssen or Brown and endorse one type of explanation. Others took a more neutral position. There is no disagreement, since their explanations do no contradict.

I join the philosophers who state that the disagreement between Janssen and Brown is based on the misconception that for phenomena there exists one best explanation. Rather, the context determines the explanation. The type of explanation, causal-mechanical or statistical relevance, depends on the context. Understanding can be achieved through many ways. Phenomena should be studied case by case. Related phenomena do not necessarily ask for the same type of explanation.

Besides types of explanation, we differentiate between theoretical virtues. These virtues (simplicity, explanatory power, empirical adequacy, etc) are the properties we demand from explanations. The order of importance is not fixed. The combination of virtues is a idiosyncratic process up to a certain level. This accounts for why Janssen and Brown have different preferences. Janssen favors unification as a theoretical virtue. He thinks that understanding is achieved when we have an account that has minimal assumptions. Phenomena are traced back to a unifying structure or concept. On the other hand, Brown thinks that explanatory power is the strongest when the causal-mechanical background has revealed itself. The value of the theoretical virtues also depends on the context. In the case of special relativity, a unifying explanation can be of great understanding. Minkowski spacetime may have no causal mechanical input, but it can provide understanding through the conceptual visualization of the structure of spacetime. At the same time, there are explanation that require a more causal-mechanical picture of the behavior of the rod living in Minkowski spacetime. Then the molecules and atoms inside the rod form the main elements of an explanation.

The solution does not lie in the middle. We do not need to compromise between the two explanation. The solution is that both explanation are good, dependent on the context. It is inappropriate to ask which explanation is better.

So, Janssen and Brown have no substantial disagreement. Both interpretations are not incompatible. They contribute to our understanding of special relativity. Moreover, they agree about the status of Minkowski spacetime. "I claim that Minkowski space-time explains Lorentz invariance. For this to be a causal explanation, Minkowski space-time would have to be a substance with causal efficacy. Like Brown, I reject this view [...]. As I hope to make clear, Minkowski space-time explains by identifying the *kinematical nature* (rather than the cause) of the relevant phenomena" [Janssen, 2009, 28]. Janssen and Brown reject causal efficacy as part of special relativity. Interaction between Minkowski spacetime and the dynamical laws has no causal character.

The only difference lies in the role of Minkowski spacetime. According to Brown Minkowski space-time is 'no more than a codification of the behaviour of rods and clocks' [Janssen, 2009, 28]. Janssen has a similar definition but the in the opposite direction. 'Minkowski space-time *encodes the default spatio-temporal behavior of all physical systems in a world in accordance with the laws of special relativity*' [Janssen, 2009, 28]. Both interpretations of the role of Minkowski spacetime are possible arrows. Whether they are appropriate depends on the context. Sometimes it is meaningful to emphasize the constraining role of Minkowski spacetime. On the other hand, there are contexts that demand a central role for particles and molecules.

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