Bottom-Up versus Top-Down: The Plurality of Explanation and Understanding in Physics

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1. Introduction

Physics is the paradigmatic example of a successful science. One of its great successes is that it possesses an impressive track record of giving explanations of natural phenomena, by which these phenomena are made understandable. This much is generally granted, but things become less clear when one asks what these physical explanations exactly consist in. Philosophers of science have proposed a variety of analyses of explanation (nomological-deductive, causal, unification, to mention but a few), and it is not immediately obvious which of these proposals best captures physical practice.

The position defended in this article is that there is no unique answer to this question; that the question is even ill-posed. Explanations and ways of achieving understanding are contextual in physics, no less than in other disciplines. As a consequence there exists no uniquely best explanatory scheme. Instead, there is a plurality of possible physical explanations and ways of understanding physical processes, and it depends on the type of question that is asked and on the aim and interests of the scientist that poses the question which one is the most appropriate. In other words, what is the best explanation and the best strategy for achieving understanding depends on contextual, pragmatic, factors. In the following I shall illustrate this general point by focussing on a specific instance of the plurality that is involved: bottom-up versus top-down approaches in fundamental physics. Let me start with some words about the historical context in which this distinction was first explicitly introduced --- this will, quite fittingly, help to make clear what its role and status are.

Shortly after the First World War, in 1919, Albert Einstein unexpectedly rose to world-wide public fame. In 1916 the final version of his General Theory of Relativity had appeared, which had secured his reputation in the academic world. Even during the war years preparations had started in English university circles to test one of the most significant predictions of this new theory, namely the bending of light by massive bodies. It is true that also Newton’s theory of gravitation predicts such an effect, if light is conceived as a stream of particles attracted by gravity, but the numerical value of the deflection predicted by Einstein was significantly different. In the case of star light bent by the sun General Relativity yields a deflection about twice as big as the Newtonian value, which suggests the possibility of a crucial experiment. So it happened that in 1919 two sun eclipse expeditions were sent off from England in order to measure the actual magnitude of the light deflection. The outcomes were presented at a special joint meeting of the Royal Astronomical Society and the Royal Society of London on 6 November of the same year, where the majority of those present considered the results to favour Einstein’s theory most, although there was no unanimity. The next day, 7 November 1919, however, the London Times carried an extensive article about the meeting, with the headline “REVOLUTION IN SCIENCE. NEW THEORY

OF THE UNIVERSE." This marked the beginning of Einstein's role as a public hero and genius. The editors of the London Times invited Einstein to write a popular piece about his new theory, a request he gladly agreed to, and on 28 November appeared his now-famous article *My Theory* (Einstein, 1919; Einstein, 1954, 227).

Besides for its role as one of the milestones in the public perception of Einstein, this 1919 article has become known for the methodological considerations with which Einstein prefaced his explanation of relativity theory. Here, Einstein made a distinction between two ways of constructing theories and giving explanations in physics, one 'bottom-up' and one 'top-down'. As he put it (Einstein, 1954, 228):

"We can distinguish between various kinds of theories in physics. Most of them are constructive. 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. 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. When we say that we have succeeded in understanding a group of natural processes, we invariably mean that a constructive theory has been found which covers the processes in question.

Along with this most important class of theories there exists a second, which I will call 'principle-theories.' These employ the analytic, not the synthetic, method. 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. 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.

The advantages of the constructive theory are completeness, adaptability, and clearness, those of the principle theory are logical perfection and security of the foundations.

The theory of relativity belongs to the latter class. In order to grasp its nature, one needs first of all to become acquainted with the principles on which it is based."

Thus, constructive theories and explanations start from the basic constituents and elementary processes that build up a phenomenon, like when we explain the pressure exerted by a gas from the collisions of the gas molecules against the walls of the container. By contrast, a 'principle-theory' begins with postulating some general principle, suggested by experience. Properties of individual processes are subsequently deduced from the requirement that these processes should behave in accordance with what the general principle stipulates.

Einstein's introduction of this methodological dichotomy evidently served an immediate purpose: he was facing the important task of explaining his own theory of relativity, which he indeed had presented and developed starting from general principles. The latter is true both for the special theory of relativity, published in 1905, and the general theory, published in 1916. In particular the special theory, on which I shall focus here, closely follows the axiomatic-deductive model. It starts with two clearly stated principles (Lorentz et al., 1923, 37-38): 1. *the relativity principle* (the physical laws have the same form in all inertial frames of reference) and 2. *the light principle* (the speed of light is independent of the velocity of the emitting source). As it turns out, these two simple and general starting points suffice for the prediction of many concrete physical phenomena, like time dilation and length contraction. A striking and important point is, as we shall shortly see, that these predictions are possible without going into any detail about how the clocks and rods exhibiting the dilations and contractions are built up from atoms and molecules, and without any specific information about how these elementary constituents interact. Everything follows from very general considerations: the type of explanation is top-down.

In his 1919 London Times article Einstein is not very outspoken about the relation between the two types of physical explanation that he had distinguished: he cites advantages on both sides. If anything, he seems to favour the constructive approach, given his statement that "when we say that we have succeeded in understanding a group of natural processes, we invariably mean that a constructive theory has been found which covers the processes in question." But given the context, namely the purpose of making the theory of relativity understood and acceptable to a general audience, and given that Einstein himself had developed his theory from general principles, it is only natural that the constructive approach is mentioned in the beginning of the 1919 London Times article but soon fades into the background.

The theory of relativity soon acquired enormous fame and came to be considered as the paradigm of modern physical thinking, on a par with or even surpassing Newton's achievements. Given this course of events, it is understandable that both in circles of physicists and of philosophers of science the idea has not infrequently taken root that at least as far as relativity theory is concerned top-down, principle, explanations possess a privileged status. Indeed, it is not difficult to find claims in the literature that bottom-up explanations of typically relativistic effects like time dilation and length contraction are inappropriate or even impossible (see section 3 for a sample of such claims).

Against this, I shall argue that quite generally *both* types of account --- bottom-up and top-down --- are viable. The typically relativistic dilations and contractions can surely be understood in a constructive, bottom-up, fashion. This does not deny that the top-down derivations that have become standard in the literature also possess explanatory value and lead one to understand why these effects must exist according to relativity theory. The choice between these different explanatory strategies has a pragmatic character and depends on contextual factors. There is no clear-cut and general difference between the two types of explanation with regard to their power to generate understanding, because the notion of understanding is contextual in the same way explanation is.

As already mentioned, for concreteness I shall focus on the choice between bottom-up and top-down explanations in special relativity. However, I think it will become clear from the general line of argument that with respect to these possible explanatory options there is no important relevant difference between relativity theory and other physical theories. Moreover, bottom-up and top-down explanations are just two examples from a wider gamma of possible explanation forms (cf. de Regt, 2006). Quite generally, physics is pluralistic as far as explanations and ways of obtaining understanding are concerned.

2. Special Relativity as a Theory of Principle

In the very first sentence of his "On the Electrodynamics of Moving Bodies", the 1905 paper in which he first formulates the special theory of relativity, Einstein (1905, 891; Stachel et al., 1989, 276; Lorentz et al. 1923, 37) sets the tone for both his own article and for most of the work on relativity that was to follow later: he draws attention to the fact that the hitherto usual theoretical treatments of electrodynamic phenomena contain distinctions and asymmetries that are absent from these phenomena themselves. This high-level abstraction observation, about possible 'excess baggage' in the form of theories, then motivates Einstein's first postulate, the principle of relativity. As still formulated in the introduction of the paper, this principle tells us that the laws of electrodynamics and optics, like the laws of mechanics, hold good in their same standard form in all inertial frames of reference --- a little bit later on in the article it becomes clear, however, that this is taken to be valid for *all* laws, even for yet to be discovered non-electrodynamical and non-mechanical ones. To this postulate Einstein immediately adds a second one that stipulates that light is always propagated in empty space with a definite velocity c, independent of the state of motion of the emitting body. As Einstein promises us, still in the same introductory remarks, these two postulates will suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies.

Here we see the principle-theory approach in full swing: the starting point is the formulation of very general requirements, suggested by empirical data (that no difference between inertial frames can be detected as far as the form of applicable theoretical principles is concerned, and that the velocity of light is always the same, had been suggested by several 19th-century experiments performed precisely with the purpose of finding empirical counterparts to the theoretical asymmetries mentioned by Einstein in the first sentence of his article --- it was the failure of these experiments that provided positive empirical input for Einstein's postulates). Einstein's two starting-points are very general in character, even to the point that one wonders how they could lead to such concrete and specific predictions as changes in the lengths of moving rods and retardations in the pace of moving clocks. But Einstein is able to honour his promise and indeed deduces these effects from his axioms.

This remarkable feat is achieved by Einstein through his insistence that lengths and times are not merely abstract concepts, but correspond to what is indicated by concrete measuring instruments, rigid rods and clocks. At the end of the introductory section of his 1905 paper Einstein famously declared: "The theory to be developed is based … on the kinematics of the rigid body, since the assertions of any such theory have to do with the relationships between rigid bodies (systems of co-ordinates), clocks, and electromagnetic processes". Thus, coordinates are identified with notches in rigid material axes, distance is what is measured by rigid measuring rods, and time corresponds to what is indicated by the hands of synchronized clocks. It certainly appears at first sight that a strong operationalist flavour emanates from these statements, a theme that was soon picked up by logical positivists and operationalists (see Reichenbach, 1949, and Bridgman, 1949) --- although it is not so clear whether Einstein himself was here committed to an outspoken philosophical position (Dieks, 2008). For our theme it is only important, however, to note that the two general postulates are supplemented by Einstein with this concrete interpretation of spatial and temporal concepts in terms of rods and clocks; and that this makes a connection possible with concrete physical phenomena. The latter becomes evident when we realize that the relativity postulate now says that phenomena measured in one inertial system (also referred to as inertial *frame*, a system of Cartesian axes in inertial motion) with the help of rods and clocks resting in that system, can have an exact counterpart in any other inertial system, in which phenomena are measured with rods and clocks co-moving with that other system. The regularities found in the phenomena as judged from within all these different frames must be the same. Likewise, the light postulate comes to stipulate that in any inertial system the velocity of light assumes the value c if the distance covered is measured with rods resting in the frame and time is determined with clocks resting in it. These requirements can only be fulfilled if rods and clocks behave in a way that is different from what is assumed in pre-relativistic physics. According to Newton's theory good (in the sense of not deformed) measuring rods do not change their length when they are given a velocity, and good clocks similarly keep ticking at the same pace. But it is easy to see that this behaviour cannot be in accordance with Einstein's two postulates. Indeed, according to Newtonian theory the speed of light must be c-v if measured with rods and clocks that rest in a frame which itself is moving with speed v in the same direction as the light (assuming that the speed of light is c in the original frame, with respect to which the new system with its rods and clocks moves); and this would be in conflict with the light postulate.

As Einstein goes on to show in his article, the requirement that the two relativistic postulates be always exactly fulfilled uniquely fixes what has to happen to moving rods and clocks: the rods have to shrink, undergo Lorentz contraction; and the clocks must slow down, be affected by time dilation. This is precisely the 'principle-theories' procedure described by Einstein in his 1919 London Times article: the postulates "give rise to mathematically formulated criteria which the separate processes or the theoretical representations of them have to satisfy." Whatever the physical and chemical constitution of the rods and the clocks: if the two postulates of special relativity are to be fulfilled moving rods have to be shorter and moving clocks have to go slower.

3. The Physical Reality of the Relativistic Effects and the Status of Rods and Clocks

The axiomatic-deductive way in which the theory of relativity was introduced, together with the very general nature of the axioms, have from the start given rise to questions about the nature of the relativistic effects. Even if it is clear that the existence of contractions and dilations can be logically derived from the postulates, does this also mean that they represent physically real phenomena, real material changes in the rods and clocks? It has repeatedly been suggested that this is not the case: that the changes have to do more with the theoretical *description* given to the rods and clocks, or with the conditions of observation, than with things happening in the bodies themselves; that in this sense the effects are more apparent than real. Indeed, no connection with bottom-up accounts in terms of molecules, and forces between them, is provided so that a "mechanical" understanding of the effects is lacking in the derivation from the postulates. Some authors have been misled by this, even to the extent of claiming that the relativistic effects are more psychological than physical in character. Among early examples are the famous American physicists Lewis and Tolman, who wrote in 1909 that in Einstein's theory "the distortion of a moving body is not a physical change in the body itself, but is a scientific fiction"; the changes in the units of space and time are "in a certain sense psychological". This they contrasted with older proposals by H.A. Lorentz according to which there is "a real distortion of the body" caused by deforming forces (Lewis and Tolman, 1909). In the same vein Laub (1910) commented on Lorentz's theory that in it "observed changes in a moving body are of an objective nature", implying that in Einstein's theory the situation was different. Similarly, Von Ignatowski (1910) wrote: "measurements on a moving body yield only an apparent value". And the mathematician Varičak (1911) commented that the relativistic "contraction is, so to speak, only a psychological and not a physical fact".

These allegations did not remain unchallenged. Already in 1909 Ehrenfest intervened with a thought experiment that showed how the relativistic contractions can give rise to undoubtedly physical effects, like the explosion of a solid body. Ehrenfest's paper (1909) invites us to consider a solid material cylinder that is set into rotating motion around its axis. As a result of the rotation, strains will arise in the material: the elements of the

> cylinder will tend to undergo relativistic contraction into the direction of their rotational motion but will remain undeformed in the directions perpendicular to their rotational velocity. For the cylinder as a whole this leads to conflicting tendencies that may result in the destruction of the cylinder if the velocity of rotation becomes great enough. There can therefore be no doubt that causal processes, having to do with the forces between the atoms and molecules, are involved in the contractions and dilations.
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> Also Einstein himself participated in the discussion with a reply to Varičak's paper (Einstein, 1911). Opposing the idea that the Lorentz contraction is subjective or an artefact of conventions of measurement, he described a method for determining quite objectively that moving ideal rods are shorter, even without the use of synchronized clocks. Moreover, in a letter of 1919 to the philosopher Petzoldt Einstein commented on Ehrenfests's thought experiment (Stachel, 1980, 7): “It is well to remark that a rigid circular disk at rest must break up if it is set into rotation, on account of the Lorentz contraction of the tangential fibers and the non-contraction of the radial ones. Similarly, a rigid disk in rotation (produced by casting) must explode as a consequence of the inverse changes in length, if one attempts to put it at rest.” In a preserved draft of a letter from 1951 (Stachel, 1980, 8), Einstein likewise pointed out that to obtain a rotating rigid disk without relativistic strains and tensions, one would have to first melt a disk at rest, then put the molten disk into rotation and finally solidify it while rotating.
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> Clearly then, the principle-theory approach should not lure us into the mistaken belief that no bottom-up, causal stories about the relativistic effects are possible. In fact, at several points in his career Einstein in retrospect gave vent to related reservations about his original introduction of special relativity. An early example is in his lecture *Geometry and Experience* (Einstein, 1954, 232; *Geometrie und Erfahrung*, Einstein, 1921), delivered not long after the just-mentioned discussions about the physical reality of the contraction effects. In *Geometry and Experience* Einstein states (1954, 236): “The idea of the measuring rod and the idea of the clock in the theory of relativity do not find their exact correspondence in the real world. It is also clear that the solid body and the clock do not in the conceptual edifice of physics play the part of irreducible elements, but that of composite structures, which must not play any independent part in theoretical physics.” This is very relevant to our topic: as we have seen, Einstein’s original derivation of the contraction and dilation effects proceeded through the identification of distances and periods with the indications given by ideal rods and clocks, without mentioning anything about the causal processes going on in the interior of these devices. Nothing at all was said about their atomic or molecular constitution and about the forces that keep them together, and as we have seen this could easily create the false impression that no ordinary causal processes are involved at all in the contractions and dilations. But in the quoted passage Einstein emphasizes that rods and clocks are ordinary bodies with a microscopic structure and therefore determined in their macroscopic features by what occurs at the microscopic level.

In the same 1921 lecture Einstein continues (1934, 237): “It is my conviction that in the present stage of development of theoretical physics these concepts (i.e., rods and clocks; my addition) must still be employed as independent concepts; for we are still far from possessing such certain knowledge of the theoretical principles of atomic structure as to be able to construct solid bodies and clocks theoretically from elementary concepts.” Note how the last part of this quote resonates with Einstein’s description of the constructive method in his 1919 newspaper article! It is pretty clear that Einstein never thought that general principles about rods and clocks should *replace* considerations about atomic constitution and causal processes. The axiomatic approach was introduced as an alternative that was particularly appropriate given the context of the situation Einstein was facing. This situation is that we are accustomed to using rods and clocks for making space and time coordinates physically concrete, but are not able to directly describe these devices in terms of their atomic and molecular constitution; this makes it expedient to introduce them as independent concepts. Moreover, we are interested in questions of a very general character, not pertaining to particular bodies or particular causal processes. The axiomatic approach is able to explain why the contractions and dilations must be there in a quite general way, whatever the details of the underlying causal processes.

Einstein himself later characterised the top-down approach as a practical decision, made for the time being. As soon as a direct causal characterisation via fundamental physical theory becomes available, Einstein tells us, this treatment will have to replace the axioms-about-rods-and-clocks account. We find this statement at various places in Einstein's writings. Thus, at the end of his career he writes in his Autobiographical Notes (Schilpp, 1949, 59): "One is struck by the fact that the theory introduces two kinds of physical things, i.e., (1) measuring rods and clocks, (2) all other things, e.g., the electromagnetic field, the material point, etc. This, in a certain sense, is inconsistent; strictly speaking measuring rods and clocks would have to be represented as solutions of the basic equations (as objects consisting of moving atomic configurations), not, as it were, as theoretically self-sufficient entities." He then immediately goes on to explain that the appeal to measuring rods and clocks should be seen as a make-shift procedure for the time being, as long as no complete fundamental bottom-up treatment of rods and clocks is available, "with the obligation, however, of eliminating it at a later stage of the theory."

In fact, Einstein seems overcautious here. He could have resorted to Hermann Minkowski's work: in his famous 1908 address Minkowski already showed how special relativity can be built up in terms of fundamental physical laws alone, without any appeal to rods and clocks as independent entities.

4. The Principle-Approach Perfected: Minkowski

On 21 September 1908 Hermann Minkowski (1909; Lorentz et al., 1923, 73) delivered his lecture *Raum und Zeit*[1]. The lecture has become famous, and the sentence from the introductory statement, "Henceforth space by itself and time by itself are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality," has acquired proverbial status. Still, there are aspects to Minkowski's ideas that so far have not received the attention they deserve (Dieks, 2008). I here shall focus on how Minkowski is able to avoid an appeal to rods and clocks in his presentation of special relativity.

The impression created by Minkowski's just-quoted 'winged words', namely that spacetime is an entity existing independently of matter, should be treated with caution. Reading Minkowski's paper rather suggests that his position was sympathetic to Leibnizean relationism, and that he here was close to Einstein's sympathies --- although both authors were not explicit about their philosophy of space and time, writing as they did on problems in

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[1] Many of the ideas can already be found in a lecture Minkowski gave a year earlier (Minkowski, 1915).

physics rather than philosophy. How Minkowski viewed the ontological status of spacetime becomes clear if we look at his discussion of how we can lay down spacetime coordinates. Unlike Einstein, Minkowski did not engage in a discussion of rods and clocks in order to define such coordinates; he suggested a very different procedure. This alternative procedure has not been the subject of serious study in the philosophy of physics literature --- rather surprisingly, for Minkowski's proposal implements a way of constructing the edifice of special relativity in which only general features of fundamental physical laws play a role, without the need of invoking macroscopic measuring instruments. In a nutshell, Minkowski's suggestion is to do without any pre-given interpretation of coordinates in terms of distances and clock settings, and to start with a theoretical account of elementary physical phenomena in terms of completely arbitrarily chosen variables. The form of the regularities formulated this way will most likely be extremely complicated, but by going to new independent variables, that is, by performing mathematical coordinate transformations, one may simplify. As the final result of this process of successive simplifications a preferred set of *spacetime* coordinates will be found as that "system of reference *x, y, z, t,* space and time, by means of which these phenomena then present themselves in agreement with definite laws" (Lorentz et al., 1923, 79). As can be expected, the 'definite laws' Minkowski explicitly refers to are Maxwell's equations of electrodynamics in their standard form. But later in his article he assumes that *all* fundamental laws of nature, including those yet to be discovered and responsible for the stability of matter, should exhibit the same symmetry properties as the equations of electrodynamics. This boils down to executing Einstein's programme of doing away with rods and clocks; in spite of the absence of complete knowledge of all laws and in spite of a lack of detailed insight into how macroscopic measuring devices should be described by fundamental theory --- as Minkowski's elegant mathematical treatment shows, such knowledge is not necessary to fulfil, albeit in abstract form, Einstein's desideratum.

More in detail, Minkowski starts by introducing coordinates *x, y, z, t* as arbitrary address labels of 'world-points'; the manifold of *all* world-points is 'the world'. These world-points are not meant as abstract geometrical entities: Minkowski makes it immediately clear that the coordinates should be seen as attributes of physical, even 'observable' ('*wahrnehmbare*') things. As he puts it: "Not to leave a yawning void anywhere, we will imagine that everywhere and everywhen there is something perceptible. To avoid saying 'matter' or 'electricity' I will use for this something the word 'substance'" (Lorentz et al., 1923, 76). The use of the term 'observable' here may seem strange: Minkowski can hardly be supposed to require that miniscule portions of his substance, whatever its nature, should be accessible to the unaided senses. But we should bear in mind that this is a science paper, not an exercise in philosophy --- let alone an application of logical positivist ideas *avant la lettre*. Physicists are wont to use the term 'observable' as a way to denote properly *physical* things, with which it is possible to enter into causal interaction. Minkowski's '*wahrnehmbar*' should be interpreted accordingly, as simply denoting 'physical' or 'material'.

After this introduction of substantial points, Minkowski focuses on the career of one such point, for which he coins the term 'worldline'. He continues (Lorentz et al., 1923, 76): "The whole universe is seen to resolve itself into such worldlines, and I would like to state immediately that in my opinion physical laws might find their most perfect expression as reciprocal relations between these worldlines." Minkowski's idea that the laws of physics represent relations between physical worldlines plays a central role in his subsequent argument. Starting from the laws of physics, which thus express relations between worldlines and consequently regularities in the behaviour of material systems, Minkowski starts his spacetime analysis: as already explained, the usual inertial coordinates x, y, z, t are determined as those coordinates in terms of which the laws take on their standard forms.

Thus, we have found a way to present special relativity that does not depend on the existence of rigid rods and clocks. The theory is now given a more abstract rendering, in which only the existence of fundamental physical laws is assumed. Einstein's relativity postulate now becomes the requirement that the form of these laws be invariant under a certain group of transformations (the Lorentz transformations). The operations in this group can be interpreted as transitions from one inertial frame of reference to another --- the spirit of the invariance requirement is therefore not different from that of Einstein's original relativity postulate. With Minkowski's approach, however, special relativity attains a more fundamental form than in Einstein's own presentation, because we no longer need rods, clocks and materially realized inertial systems; in Minkowski's presentation special relativity deserves the predicate 'principle theory' more than ever. The overarching Principle now states the invariance of all laws of nature under Lorentz transformations, and Einstein's derivations can be repeated with greater generality in this new context. Again, the typically relativistic effects can be derived without going into the specific details of the material processes that are involved --- the invariance properties of the laws suffice for reaching the desired conclusions. However, now that everything derives from the fundamental laws that govern the behaviour of the elementary building blocks of physical objects and processes, the possibility of thinking about bottom-up, causal accounts of these relativistic phenomena also starts to force itself upon us, and the question of the relation between bottom-up and top-down becomes more urgent.

5. Special Relativity as a Constructive Theory

In section 3 we have already laid down the groundwork for the argument of the present section: the typically relativistic effects like length contraction and time dilation can give rise to phenomena that one at least is inclined to describe in terms of microscopic causal processes. In the case of the rotating and eventually exploding cylinder, for example, it is natural to ask about the forces that are responsible, the amounts of energy that are involved, and so on. Likewise, one may wonder about the detailed mechanisms that make rods shrink when a velocity is imparted to them. Also in this latter case effects may arise like the breaking of objects, which seem to cry out for causal explanation. A notorious example is furnished by John Bell's (1976; 1987, 67) 'two rockets problem' in which two rockets undergo equal accelerations, in such a way that their mutual distance remains the same. A rope connecting the rockets will tend to Lorentz contract during the process, because it acquires a velocity. As a consequence, the rope will become tighter and may eventually even break when the velocity becomes high enough.

As Bell recounts, he experienced that many physicists are amazed when confronted with this outcome of the thought experiment (not unlike the physicists we quoted in section 3). Bell attributes their confusion to the top-down manner in which the theory of relativity is usually taught, and pleads for a different approach in which the focus is shifted from top-down to bottom-up, constructive and causal, accounts of relativistic phenomena. We will comment on the relation between these two approaches in the next section; here, we merely want to emphasize that such a constructive approach is indeed possible.

In section 3 we saw that Einstein himself already warned against the idea that macroscopic bodies like rods and clocks are not susceptible to bottom-up analysis: these bodies evidently consist of atoms and molecules, so that their behaviour should be determined by the laws that govern these sub-microscopic constituents and their interactions. It was mentioned in passing in section 3 that before the advent of relativity theory H.A. Lorentz had already developed a theoretical scheme by means of which he tried to explain that moving bodies contract (even before special relativity, the contraction idea had gained currency as a way of accommodating the famous ‘null experiments’, like the Michelson-Morley experiment). Lorentz’s approach (e.g., Lorentz, 1904; Lorentz et al., 1923, 11) focused on the forces that hold macroscopic bodies, like measuring rods, together. These forces change when the bodies are set in motion, and this has the effect of changing the mutual distances between the atoms and molecules. Lorentz was able to prove that this leads to the right macroscopic contraction in the direction of motion (the same contraction we encounter in relativity theory) if it is assumed that under motion all possible forces change in the same way as the electromagnetic ones. This latter assumption anticipates Minkowski’s requirement that all laws should be invariant under Lorentz transformations, but still, the type of explanation here is clearly causal and bottom-up. The account works by determining the equilibrium positions of the atoms and molecules in the interatomic and intermolecular force fields, and by finding out how these equilibria are altered when the forces change due to motion.

Exactly the same explanations can be given in relativity theory. If we know what the fundamental building blocks of matter are, and know how the forces between them vary when a system is set into motion, it becomes possible in principle to calculate how the macroscopic features of these bodies will change when they start moving. Actually, it seems pretty obvious that bottom-up explanations of this type are possible for everything that happens according to relativity theory.

6. The Relation between Bottom-Up and Top-Down

Minkowski’s approach makes it easy to confront and compare our two explanatory strategies. In Minkowski’s presentation of special relativity the basic ingredients are matter and fundamental laws governing matter, and although Minkowski’s own approach is rather top-down, these ingredients also set the stage for a Lorentz-like bottom-up account in terms of atoms, molecules and the forces between them. Minkowski’s scheme further contains the general principle that all laws are invariant under Lorentz transformations. The way Minkowski introduces his scheme, starting from concrete phenomena, investigating their regularities and thus arriving at laws, and finally inquiring about the invariance properties of these laws, might create the impression that this principle cannot be an independent component of the theory: once the laws have been found, whether or not they are Lorentz invariant is a matter of inspection and does not need independent stipulation. However, the idea obviously is that it is part of relativity theory to suppose that also new laws that may be found as a result of future research will possess these same invariance properties. Interpreted in this way the principle can be considered an independent part of relativity theory, on whose authority we are entitled to assume certain general properties of all physical processes, even those processes whose specific features we do not yet know. Now, for the logic of the relation between top-down and bottom-up it is a central point that these general features, shared by all physical laws, are sufficient to show that all accounts, either bottom-up or top-down, will lead to the same essential aspects of the typically relativistic effects like length contraction and time dilation.

The way this works may be sketched as follows. Take the example of length contraction. Suppose we have a macroscopic body at rest in some inertial frame of reference. Whatever its microscopic constitution and whatever the forces that hold it together, 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. There will exist some kind of equilibrium configuration (from a macroscopic viewpoint) of the atoms and molecules, and this configuration determines the length of the body. From the Lorentz invariance of the laws responsible for the equilibrium we now deduce that a body with the same composition but resting in another inertial frame, therefore one that moves with velocity v with respect to our original frame, possesses a corresponding equilibrium state. This second equilibrium state has a description in terms of the internal Cartesian coordinates of the second inertial frame that is exactly the same as the description given of the first equilibrium in terms of the coordinates of the first frame. But we know the relations between the coordinates of the two frames: these are given by the Lorentz transformations. This implies that the equilibrium length of the second, moving, body is related to the length of the first body by the Lorentz contraction. For example, if the first body exactly fills the space between the coordinates $x = 0$ and $x = 1$, so that it has length 1, its moving mirror image will exactly fit between $x' = 0$ and $x' = 1$, in which the primed coordinates belong to the moving frame. The Lorentz transformation formulas now tell us that this coordinate difference 1 between the primed coordinates corresponds to a coordinate difference $\sqrt{(1 - {v^2}/{c^2})}$ between the unprimed coordinates (assuming that the velocity v is in the x direction). So as judged from the first frame the length of the moving body is less than 1: it has the Lorentz contracted value.

As will be clear from this sketch, the relativity principle does all the work in securing that the right contraction and dilation factors will result. The microscopic details can be left out: by omitting the references to sub-microscopic constituents and forces, and only mentioning the macroscopic body itself, we would recover Einstein's original approach, the archetypical top-down type of account of a relativistic effect. Still, the just-sketched derivation itself is essentially identical to the one proposed by Lorentz. 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. So it turns out that both Lorentz's constructive approach and Einstein's/Minkowski's principle approach use exactly the same theoretical ingredients! To some extent, this puts the distinction between top-down and bottom-up into perspective: there is no difference in the relevant theoretical machinery.

Is there any remaining difference, then, between the two approaches? There certainly is, but the relation between the two ways of explaining relativistic effects is not one of mutual exclusion or of right versus wrong (cf. de Regt, 2006). Both derivations use the same physical theory, and both are clearly equally valid as far as logical deduction is concerned. The difference between the two arguments is in the emphasis on one premise instead of another, and in where the deduction starts. These differences correspond to differences in exactly *what* one wishes to know, and *from which point of view*; in other words, the difference is pragmatic: it relates to our desires and interests and not with an objective context-independent superiority of one approach over the other.

Indeed, suppose we are considering a problem like that of Ehrenfest's paradox or Bell's rockets, and ask ourselves at which point during the acceleration process, and where, something will break. Or, more generally, think of the question of whether and when a rod that is set in motion by an accelerating force will shrink. These are questions about the dynamics of the contraction process, and in this context of dynamical questions a dynamical bottom-up approach is obviously the right one. For example, to know whether an accelerated rod will become Lorentz-contracted we have to investigate whether it will be able to reach a state of internal equilibrium, and this depends on the interplay of internal and external forces and on thermodynamic considerations. Knowledge of these relevant causal factors will make it possible to determine the details of the deformation process; moreover, the resulting causal bottom-up picture provides us with a clear insight into what happens and in this way generates *understanding*. It was especially the latter point that motivated John Bell (1976) to call for a drastic revision of the way relativity is taught: namely, to abandon the usual top-down approach initiated by Einstein and to revert to a Lorentz-like procedure in which one starts with atoms and forces. Bell thought that this bottom-up method was the way *par excellence* to obtain understanding of the relativistic effects (actually, Einstein's own 1919 remarks about the constructive method go into the same direction). However, we have already seen that the top-down approach uses exactly the same theoretical elements, although with different emphasis. This by itself already casts doubt on the notion that no explanation and understanding could be achieved by the top-down method. Indeed, the more than hundred years of history of special relativity have abundantly demonstrated that in certain contexts physicists accept the original Einstein-like derivations of the relativistic effects as real explanations and ways of acquiring genuine insight and understanding. The contexts in question are different from the dynamical ones we mentioned a moment ago: they pertain to the comparison of different inertial frames of reference, and bodies resting in them, without asking anything about what happens when a body is *transferred* from a state of rest in one frame to a state of rest in another. So the comparison is between bodies of which it is given that they are moving uniformly with respect to each other in completely similar internal states --- a 'stationary' situation, to be contrasted with the earlier mentioned 'dynamic' cases in which accelerations played a role. In the stationary case it is illuminating, as we have already seen in some detail, to concentrate on the general invariance properties of the laws of physics. Lorentz invariance explains why rods that are each other's exact counterparts in different frames possess lengths that are related via a Lorentz transformation. The picture that arises here has a simplicity and compactness that makes things understandable (see de Regt and Dieks, 2005, for more on the relevance for understanding of the intuitive accessibility of such theoretical pictures). The Lorentz contraction is here represented as the natural relation between moving bodies, and as reflecting general spacetime symmetries. This is what has become accepted as the 'orthodox' understanding of relativistic effects, against which Bell fulminated but which physical practice has demonstrated to be perfectly defensible in itself.

7. Conclusion

Since its introduction, the special theory of relativity has usually been regarded as a typical principle theory, in which the direction of explanation is top-down. In accordance with this, it is not uncommon to find statements in the literature to the effect that attempts at bottom-up, causal, explanations are out of place in relativity. However, there have certainly been many physicists, among whom the old masters Einstein, Minkowski, Ehrenfest and their likes who never fell prey to this misunderstanding. The possibility of bottom-up strategies in relativity, which we have stressed in this paper, is therefore not something new; but it is still worth stressing in view of the continuing dominance of the top-down approach both in the teaching of relativity and in philosophical accounts of the theory. John Bell (1976) was right in resisting this dominant attitude by drawing attention to the possibility of bottom-up accounts. From our point of view, however, “he struck a spark but threw no light”: he overshot the mark by suggesting that the bottom-up approach is *the* understanding-providing one.

The issue has been receiving growing attention in the recent philosophy of physics literature, especially after the publication of Harvey Brown’s (2005) book *Physical Relativity*, which defends a position very similar to that of Bell. In the wake of Bell’s and Brown’s publications a serious dispute has arisen among philosophers of physics about the correct way of explaining relativistic effects. On the one hand there are those who defend the orthodox viewpoint: these argue that it is the top-down approach that is appropriate, since only it fully captures and reflects the general spacetime structure of the world according to special relativity (see, e.g., Janssen, 1995, 2002; Balashov and Janssen, 2003). On the other hand there are those who maintain that this top-down approach ignores the physical mechanisms that are at work (e.g., Brown and Pooley, 2001, 2006; Brown, 2005), and therefore is unable to provide us with genuine explanations and understanding.

What I have argued here is that this dispute derives from a misconception. *There is no uniquely best way of explaining the relativistic effects*. The differences between the explanations are differences in *the use we make* of one and the same theoretical scheme. They relate to decisions about where to put the emphasis and where to begin and end the analysis; and these decisions in turn are conditioned by what we are interested in. In other words, the difference is one of *pragmatics*. Explanation and understanding are relative to questions we ask and interests we have. Explanation and understanding, not only in relativity theory but also in theoretical physics and even in theoretical science in general, are inherently pluralistic.

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