Chapter 7

Experience and Representation in Modern Physics: The Reshaping of Space

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> The essential in what I strove for during
> my long life centers on the question:
> What can be methodically concluded for
> physics from the fact of a universal law of
> light propagation and from the equivalence
> of inertial and gravitational mass?
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> *Albert Einstein*[1]

7.1 Introduction

It is common knowledge that the two theories of relativity have fundamentally changed our notions of space and time. Spacetime, a union of space and time, is now conceived as a four-dimensional manifold equipped with a Lorentzian metric, in general relativity it has furthermore become dynamic. That the two theories should have such a sweeping impact on the concepts of space and time is no matter of course. After all, they started out as theories dealing with specific physical phenomena, such as electromagnetism and gravitation, phenomena which were conceived to occur *in* space and time, so that it was not obvious that their description should bring about changes in these concepts. Quantum theory, on the other hand, did not by itself change our notions of space and time, at least not yet in the form of an established theory. All surprising aspects of the quantum world have eventually been attributed to new and strange properties of matter and radiation, not of space and time. At the outset, one might have speculated that the non-local features of quantum systems required a modification of space and time concepts,[2] but up to now, quantum theory has turned out to be quite conservative as regards spacetime structures.

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[1] "Alles Wesentliche was ich im Laufe eines langen Lebens erstrebt habe, gruppiert sich um die Frage[:] Was kann für die Physik methodisch geschlossen werden aus der Thatsache eines universellen Gesetzes der Lichtausbreitung und aus der Gleichheit der trägen und schweren Masse?" This is Albert Einstein's response to an inquiry of the *Technische Rundschau*, Bern, 31 January 1955; Albert Einstein Archives 1–199. We are grateful to Diana Buchwald, editor in chief of the *Collected Papers of Albert Einstein*, for pointing our attention to this quotation and for providing the translation.

[2] Thus, Max Born speculated in 1919 "that the way out of all quantum difficulties has to be sought starting from fundamental considerations: one must not transfer the concepts of space and time as a four-dimensional continuum from the macroscopic world of experience to the atomistic world, the latter obviously demands another kind of manifold of numbers as an adequate image." (Max Born to Wolfgang Pauli, 23 December 1919; the German original has: "daß der Ausweg von allen Quantenschwierigkeiten von ganz prinzipiellen Punkten aus gesucht werden muß: man darf die Begriffe des Raumes und der Zeit als eines 4-dimensionalen Kontinuums nicht von der

The historical examples of the relativity and quantum revolutions raise the general questions:

- Which experiences led to the establishment of new space and time concepts in the history of modern physics?
- Why did these specific experiences have this consequence and why at this particular historical moment?

From the standpoint of a strict conventionalism, these questions should make no sense. In spite of the fact that historically only specific theories did shape space and time, conventionalism argues that it is a mere matter of convenience, whether we decide to change our concepts of space and time or rather the concepts of the things and events filling them.[3] But is it really only a matter of convenience that we do not pursue relativity theory in Newtonian space and time and quantum theory with classical matter and radiation in a novel quantum spacetime?

The conventionalist's viewpoint neglects the fact that the concepts of space, time, and matter have their origin in pre-scientific structures of thinking and, no matter how advanced they may have become, derive part of their operational meaning from this origin.[4] By contrast, the conventionalist viewpoint presupposes that they may be decoupled from their origin without losing meaning.

Conventionalist arguments also often brush over the question of the historical availability of the postulated alternative formulations. As a matter of fact it is usually not easy to come up with theoretical constructions that describe physical phenomena as either being tied up with the space-time framework or as taking place within it. While it is difficult to prove the non-existence of one of the conceivable alternative constructions, historically there is always only a limited but evolving repertoire of possibilities. And even where such alternative space-time formulations of a specific physical theory are available, the novel space-time structures involved will not in general be transferrable to phenomena outside of the domain of the theory. This would not be compatible with the expectation that all of physics takes place within one and the same arena of space and time.

Why do certain experiences have an effect on the structure of space and time rather than simply modifying the physics of things in space and time, while others do not? The above discussion shows that it is not possible to dismiss such questions on conventionalist grounds. From the perspective of an historical epistemology, we formulate three criteria that together constitute the necessary conditions for representations of physical experience to have an impact on the space-time structure of physics.

Experiences may have an impact on concepts of space and time, if

- *Constructibility*: the available means for their representation allow for a consistent description of space and time structures distinct from the pre-existing ones;
- *Operationability*: the novel space-time structures incorporate prior knowledge on space and time, be it former theoretical or pre-theoretical knowledge, from which the new theoretical constructs can derive a spatio-temporal meaning;

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makroskopischen Erfahrungswelt auf die atomistische Welt übertragen, diese verlangt offenbar eine andere Art von Zahlenmannigfaltigkeit als adäquates Bild." Pauli 1979, 10).

[3] For a detailed account on conventionalism, and its geometrical version in particular, see Ben-Menahem 2006.

[4] This also appears to be the point of Einstein's insistence on the importance of rods and clocks as "independent concepts" (Einstein 2001, 213) in relativity theory; see Einstein 1921.

- *Universality*: the novel space-time structures are applicable to all domains of physical knowledge.

These criteria may be illustrated by a simple example familiar from discussions of conventionalism.[5] Imagine a universe in which local measurements have led to the conclusion that space is Euclidean. Now introduce an ‘expansion field’ extended through all of space. It describes for each point in spacetime a local expansion of bodies at that point. An illustration of such an expansion field would be a reduced notion of temperature affecting all bodies in the same way. Length and shape of rigid rods (as well as of all other bodies) indeed depend on the temperature of their immediate environment. Suppose that the ‘temperature’ field varies on large scales across space. If rods are used by the people of astro-geometers to establish the large-scale geometry of space, the result may well be that it is non-Euclidean. Is this now an artifact of the temperature field or should this be interpreted as the discovery of a new space structure? The new space concept satisfies the operationability criterion because space measurements are performed in the usual way, just on larger scales. If the mathematical tool of a generalized metric is available, it then becomes possible to conceptualize the measurements with the expandable rods in terms of a Riemannian space, so that the criterion of constructibility is also fulfilled. This shows the historical contingency introduced by the constructibility criterion – indeed the present thought experiment did emerge only in the wake of the introduction of non-Euclidean geometries. But the requirement of universality may become problematic. Real physical temperature does not affect all bodies in the same way, unlike our hypothetic expansion field. Also, there may be other legitimate forms of space measurement, e.g. using light signals. Only if several independent types of space measurements give convergent results, does it become plausible to accept these new experiences as establishing a new space concept.

Experiences to which these criteria are applied have to be conceived of as always being ‘pre-processed’, i.e., processed prior to entering a new spacetime framework or other theoretical discourses. The essence of pre-processing is to assimilate any kind of input to pre-existing internal or external knowledge representations. The question of whether experiences give rise to new spacetime structures thus translates into the question of whether such pre-existing knowledge representations can be transformed or re-interpreted as such spacetime structures.

In the case of the expandable rods, the pre-existing knowledge representation to which results of measurements are assimilated is that of Euclidean space. The failure of this assimilation causes puzzlement and does not automatically lead to the establishment of a new spacetime structure. As we have argued, such establishment requires the above criteria to be fulfilled. Given that the pre-existing spacetime structure fulfills the universality criterion as a default, the most natural reaction to such a failure is to search for a problem in the specific measurement procedure. This procedure has not just spacetime aspects but also involves other physical properties such as the rigidity of the rods and their behavior under temperature changes, which might play a role for the failure. Only if it turns out that all conceivable measurement rods universally display the troubling behavior, does a change of spacetime structure become a plausible option. However, as soon as it turns out that spatial distances can also be measured by means of light, and that such measurements confirm the original Euclidean predictions, the notion of an alternative spacetime structure will be quickly dis-

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[5] See Poincaré 1952, 65–68; see also Feynman, Leighton, and Sands 1989, 42/1–42/5.

carded. One might, of course, imagine a universe in which the index of refraction is related to temperature in such a manner that the measurements based on light will always produce the same results as those based on rigid rods. Only in this case the new measurements display a universality that might hint at that of a new spacetime structure, which at this point might become more plausible than the assumption of a correlation of index of refraction and temperature. There is, however, no guarantee that this new structure can actually be constructed. Indeed, for understanding historical processes, the most important criterion is that of constructibility. In principle there are two cases. Either an appropriate representation allowing the assimilation of the new experiences is already available, because it has been independently developed, or such representation has to be constructed by accommodating the existing structures to the new experiences in conflict with them. Our astro-geometers may thus either rely on the hitherto neglected mathematical knowledge and realize that the world at large scales is in fact Riemannian, or they eventually manage to develop non-Euclidean geometry as the large-scale geometry of their world.

A side remark may be in order. The above criteria may be applicable to conceptual developments more generally, even when less fundamental concepts are at stake than those of space and time. This is obvious for the criterion of constructibility. In more general cases the criterion of operationability may be reformulated in terms of the interpretability of novel constructs in terms of prior related concepts. The criterion of universality may be reformulated accordingly as a question of the domain of applicability of the new concept.

In the following section, we will briefly sketch aspects of the historical development of the relation between the concepts of space and time, up to classical physics, whose space concept is based on the exclusion of gravitation (section 7.2). We will then describe the impact of the growing corpus of experiential knowledge on optical and electromagnetic phenomena on the classical concepts of space and time (section 7.3). Next we discuss the re-introduction of gravitation into space-time-concepts, as it was brought about by general relativity (section 7.4). We will then discuss quantum theory as the case of a theory that had no comparable impact on the concepts of space and time (section 7.5). Finally, we shall come back to the questions raised at the beginning of this chapter concerning the experiences leading to new space and time concepts, and address them on the basis of the cases discussed.

7.2 The relation between space and time before relativity

One of the most striking novel features of relativity theory is the emergence of the concept of spacetime connecting space and time into one entity. Within relativity, time and space can only be separated depending on the state of motion of a particular observer. This particular relation between space and time can only be articulated within a specific theoretical framework. More generally speaking, however, space and time are connected in many ways within other layers of knowledge. In particular, as cognitive structures space and time have their origin in the experience of motion and change. In sensorimotor experience, spatial, temporal, material, and causal aspects are not differentiated from the beginning.[6] Yet, separate mental models of space, time, object, and cause may develop in accommodating to this experience.

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[6] See, e.g., the discussion in Piaget 1959.

The specific characteristic of these models will depend on historically specific experiences and the possibilities to establish relations among them, for instance in societies that develop elaborate metrologies. In the course of history, experiential spaces have expanded considerably, including the development of instrument-based measurement operations. Only when spatial and temporal experiences and their linguistic representations become the subject of explicit reflections, general concepts of space and time can be constructed that are no longer confined to specific experiential domains, as is, e.g., the case in Aristotle's natural philosophy. At the same time, it must be possible to relate these general concepts somehow to the existing experiences, thus rendering these general concept operationable to some extent. This does not imply that these general concepts are connected to instrument-based measurement operations, as they underlie, e.g., Euclidean geometry. While the emergence of instrument-based measurement operations is a common phenomenon in complex societies such as the early civilizations of Mesopotamia, Egypt, and China, the independent emergence of explicit reflections on linguistic representations of spatial experiences have been a rather rare phenomenon.[7]

In all theoretical traditions prior to relativity theory, however, space and time largely occur as separate concepts. This is all the more astonishing as the individual concepts of space and time vary significantly among different theoretical traditions. This separation is therefore probably inherited from intuitive thinking. In particular, the elementary identification of stable entities such as objects and places implies a distinction from the aspect of change, the latter eventually giving rise to the concept of time. Temporal change, moreover, covers a much wider experiential field of which spatial change, i.e. motion, is only one particular case.

This does not preclude, however, close connections between spatial and temporal aspects within thinking, in theoretical as well as in practical and specifically in metrological contexts. The way in which elementary spatial and temporal experiences are processed depends on the available means of representations, first and foremost language. Such symbolic representations may vary among cultures but nevertheless typically display or generate a number of structural parallels between spatial and temporal categories. One instance of such parallels is the use of spatial linguistic markers in representing time which may leave its mark in theoretical reflections on space and time. Another instance is the use spatial properties in the metrology of time. This symbolic connection between space is not yet present in intuitive concepts of time which merely presuppose the correlation of different processes. Clocks make use of this in a practical way by selecting a process to which other processes can then be related, thus establishing a symbolic representation of the passage of time that can be shared. An immediate representation of points in time and of time intervals by spatial magnitudes is then established by the fact that for most clocks the process in question is a change of spatial position. Theoretical reflections may either start from such practical experiences or from the linguistic representations and the parallels of spatial and temporal experiences embodied by them.

As soon as spatial concepts and magnitudes are represented by the means of geometry, they could also be used for representing other magnitudes including (as is evident from the above) time. This possibility is for instance implicit in Euclid's concept of magnitude. Another matter is a combined geometric representation of space and time. A first extensive

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[7] See Schemmel 2016; see also Chapter 1.

use of geometric techniques for representing non-spatial magnitudes is found in the work of Nicole Oresme from the fourteenth century. It occurred in the context of the scholastic elaboration of Aristotle's theory of change. Oresme developed diagrams that depicted the variation of a quality, such as heat, whiteness, or grace, over an extension, which could represent either temporal or spatial dimensions. The extension is typically represented by a line. The intensity of the quality in each point of the extension is represented by a vertical line of a given length. The extensive use, exploration, and ensuing transformation of such diagrams in the study of motion eventually led to a fundamental re-interpretation, in early modern times, of this geometrical technique in terms of a space-time-diagram for motion.[8]

While motion is naturally described in terms of space and time, it is also intimately connected to the notion of causation. However, the borderline between a descriptive (space-time) kinematics and an explanatory (causal) dynamics is subject to fundamental historical change. The main reason is that the causes of motion may themselves be connected to the structure of space and time. An extremely influential theoretical model of space and motion is Aristotelian natural philosophy, which originated in Greek antiquity and was the prevalent philosophical framework in Europe well into early modern times.

Aristotelian space is anisotropic, because it privileges directions, e.g., towards or away from the center of the universe. Space (or place, more precisely) participates in the causation of motion, since all bodies strive to reach their natural place. Motions towards natural places happen by themselves and are classified as natural motions, whereas motions caused by extrinsic forces are classified as violent motions. The eternal motions of celestial bodies are a class of their own and are supposed to proceed along circles.

Extensive exploration of this explanatory model – focused on planetary motion on the one hand and mechanical motion on the other – highlighted its problematic aspects and led to its transformation. The establishment of a new model of planetary motion given by the Copernican system constituted a major challenge, because the neat distinction between celestial and terrestrial physics in the Aristotelian model became questionable. This undermined the Aristotelian concept of spherically structured space, favoring a homogeneous and isotropic conception of space. The establishment of insights such as the parabolic shape of the projectile trajectory similarly constituted a challenge, because the neat distinction between natural and violent motion made it difficult to explain how this shape comes about. Instead it turned out to be more plausible to explain this on the basis of a uniform inertial motion and an accelerated motion of fall caused by a force.

The adaptation of the Aristotelian explanatory scheme to these challenges eventually led to the establishment of Newtonian mechanics and its explanation of celestial and terrestrial motions. Newtonian space is homogeneous and isotropic. Uniform motions (i.e., motions in a straight line with constant speed) are not in need of a causal explanation. Only accelerated motions need a causal explanation. The cause is either a force independent of the structure of space, or the inertial force caused by space in reaction to such an independent force.

In Newtonian physics, space offers an absolute frame of reference, which cannot be detected, since rest and uniform motion with respect to it are physically equivalent. This non-observability of the absolute standard of rest led to a reformulation introducing a privileged class of reference systems, called inertial systems. While in Aristotelian and Newtonian

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[8] Schemmel 2014.

physics, motion was defined with respect to space, it is now the inertial structure of space that is derived from the motion of a particular type of bodies, namely ‘free particles’. The space of classical mechanics is highly counter-intuitive, because space no longer offers landmarks with respect to which all motion can be described, and only allows for the identification of accelerated but not of uniform motions. The introduction of the inertial system concept was only possible after classical mechanics had been consolidated to an extent that such abstractions could be made, which, while being counter-intuitive, were uniquely suited to the formal structure of the theory.

What are the implications of Newtonian physics for the relation between space and time? Newtonian physics relates space and time by distinguishing one particular kind of motion: uniform motion in a straight line. The content of Newton’s first law, the law of inertia, can be expressed by stating that free particles move uniformly along straight lines.[9] From this perspective, a unified description of space and time as spacetime becomes first reasonable, because uniform motion in a straight line can be described by straight lines in four-dimensional spacetime. No spacetime metric and not even an affine connection is required for this. A projective structure is sufficient.[10]

Uniform motion in a straight line is distinguished in Newtonian physics by not being in need of a causal explanation. Only deviations from the straight lines in four-dimensional projective space are in need of a causal explanation, namely by forces. This suggests a separation between space and time on one hand and physical processes in space and time on the other: spacetime with its inertial structure serves as an unchanging stage for physical processes that require causal explanation. Newtonian physics thus separates inertia and gravitation: inertia is part of the space-time structure and gravitation is part of the material structure of the universe. The resulting projective structure of Newtonian spacetime is universal and trivial. If gravitation is itself considered part of the spacetime framework, this framework becomes non-trivial, namely locally variable and dynamic. Obviously, to integrate gravitation with the description of inertial motion, one is in need of the principle of equivalence. A weak form of this principle is already an ingredient of Newtonian physics, although not a fundamental one. We shall later come back to the question of why Newton and his contemporaries did not formulate a strong principle of equivalence. Here we only note that the non-trivial geodesics resulting from it may have spoken for a four-dimensional formulation of physics. But still there would have been no four-metric in Newtonian spacetime. Historically, the four-metric entered mechanics through the back door of optics and electrodynamics. This will be discussed in the following section.

7.3 The impact of electromagnetism on the classical concepts of space and time

Since the notion of space of classical mechanics had been developed on the basis of mechanical experiences only, new perspectives on space emerged when experience from other

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[9] See Pfister 2004 for a particularly lucid exposition of this formulation of Newton’s first law, including definitions of ‘free particle’ and ‘straight line’.

[10] See Pfister 2004, 56–58. Historically, the idea of space having a Euclidean measure and time flowing uniformly, which Newton explicitly adhered to, predated the formulation of the law of inertia. Note, however, that this does not imply the existence of a spacetime metric, which does indeed not exist for Newtonian spacetime. (Ehlers 1973 and later Earman 1989 designate a spacetime with Euclidean space-measure and a time-measure by the term ‘Leibnizian’ spacetime.)

branches of physics, in particular optics, was taken into account.[11] A wave theory of light suggested an ether, which might serve as a new standard of motion and even as a standard of rest if it has no internal motion. As such the concept of a stationary ether presents a modification of the concept of space of classical mechanics defined by the relativity of inertial motions. Indeed, historically, the further elaboration of ether-based physics led to substantial modifications of the concept of space, not by introducing a standard of rest, however, but rather by reasserting the principle of relativity for all of physics.

Initially, the absence of internal motion in the ether was strongly suggested by the phenomenon of stellar aberration, because it was possible to consistently define relative motion (of a source and an observer) as the difference between two absolute motions with respect to the ether. The rest frame defined by the ether played a more overt role in the derivation of the ray-optical law of refraction (Snell's law), because, in general, the derivation of ray optics from wave optics holds only in the rest frame of the ether. It could thus seem even plausible that the laws of refraction might be used to establish absolute motion. In particular, the direction of light that determined the magnitude of the angle of refraction was expected to be the direction of light with respect to the ether at absolute rest. However, it turned out that the experimentally observed refraction could be reproduced by naively inserting into Snell's law the direction of light actually observed in the rest frame of the medium. This fact had of course been essential for the phenomenological formulation of Snell's law. From the perspective of an ether theory, it was in need of an explanation. Such an explanation was provided by Augustin Fresnel who assumed that the medium slightly drags along the ether (in dependence on its refractive index), thereby effectively compensating any explicit effect of absolute motion relative to the ether.

The Michelson-Morley experiment was designed to probe the motion of the Earth with regard to the ether. To this end, the travel times of light rays in different directions with regard to the motion of the Earth were compared by the means of observing phase differences of light revealed by displacements of interference patterns. The non-observability of such phase differences allowed for the conclusion that the velocity of the Earth with respect to the ether must be less than one fourth of the Earth's orbital velocity, implying nearly complete dragging of the ether by the Earth, in contrast to the small dragging effect proposed by Fresnel and strongly supported by Hippolyte Fizeau's experiment measuring the index of refraction in moving media.

When optics became part of Maxwell's electrodynamic theory, realizing that light was an electromagnetic wave-phenomenon, these problems were transposed into a new context: that of an electrodynamics of moving bodies. Early attempts at formulating such a theory by Hertz and Heaviside assumed that the ether was fully dragged along inside matter, and could thus explain why the motion of the Earth did not have to be taken into account in the explanation of any terrestrial electric or magnetic phenomena. They were unable, however, to explain Fizeau's experiment or, for that matter, deliver a satisfactory theory of optics as a branch of electrodynamics. Whereas a slightly dragged-along ether seemed to be the most simple explanation for the unobservability of the motion of the Earth with regard to the ether in optics – with the exception of the Michelson-Morley experiment –, a totally dragged-along ether seemed the simple-most assumption to explain the unobservability of the motion of the Earth in the realm of electric and magnetic phenomena. The reason behind

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[11] This section is partly based on a close rereading of Janssen and Stachel 2004 and personal discussion with Michel Janssen.

these different perspectives is the fact that the ‘optics of moving media’ was a field in which rich experiences were available, leading to such sophisticated assumptions as the Fresnel coefficient and partial dragging, whereas the electrodynamics of moving bodies was merely a formal extension of electrodynamics at rest, which was most easily achieved by simply assuming that the equations of an electrodynamics in motion were the same as those at rest, realized by the assumption of a totally dragged-along ether. Through the Michelson-Morley experiment, however, this merely formal hypothesis gained physical plausibility, clashing as it does with the optical evidence in favor of an essentially stationary ether.

With a further elaboration of electromagnetic theory it became possible to explain effects that had formerly been explained mechanically, such as ether dragging, by electromagnetic interactions. The simplest possible assumption in the sense of avoiding the introduction of convoluted hypothesis about the ether’s motions was to postulate that it was at rest, an assumption key to Lorentz’s elaboration of Maxwell’s theory in the 1890s. On this basis it became the main challenge to explain all effects that had earlier been explained by some form of ether dragging.

Lorentz could account for the Fresnel coefficient by introducing an atomistic model of matter allowing him to account for refraction and other optical phenomena on the basis of an interaction between incoming radiation, the motion of the charged atomistic constituents of matter, and the secondary radiation produced by it.[12] This secondary radiation interfered with the primary radiation to produce the macroscopic refracted ray. In summary, the partial dragging of the ether could be replaced by local interactions of the *radiation* carried by the immobile ether with the microscopic constituents of bodies otherwise freely moving through the ether. The calculations leading up to this result were rather involved, because the Maxwell equations were assumed to hold only in the rest frame of the ether. This amounts indeed to a remarkable paradox of Lorentz’s world view. While Maxwell’s equations had originally been established by terrestrial experiments on an Earth that rapidly traverses the ether, the assumption of a stationary ether obliged him to assume that their validity in a terrestrial frame was actually little more than a mere coincidence.

However, Lorentz could simplify the calculations when he observed symmetries between the equations for dielectric matter at rest in the ether and for dielectric matter in motion.[13] Indeed, the two sets of equations coincided to order v/c if in the equations for moving matter one introduced both a new set of electromagnetic field variables (mixing electric and magnetic field variables) and a new time variable. These new variables carried no explanatory weight but just served to simplify otherwise complicated expressions. In experiments dealing with intensities of electromagnetic radiation, however, one could treat these new variables as if they described the same physical quantities as the old ones. Indeed, there had been derivations of the Fresnel coefficient in a purely wave optical context, which had relied solely on the introduction of a new time variable equivalent to the Lorentzian auxiliary time. In these earlier derivations, however, the introduction of a new time variable had to be included as an explicit assumption rather than being derived from the invariance properties of dynamical equations. While the introduction of a new time variable might appear to be more immediate along purely optical arguments, its appearance in an electrodynamic context was more seamless as it did not require an explicit interpretation of the new variable.

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[12] Lorentz 1892.

[13] Lorentz 1895.

Taking account of the null results of the Michelson-Morley experiment turned out to present a challenge for Lorentz's approach, because it represents an experiment that, in principle, could have detected the motion with respect to the stationary ether to second order in v/c. While Lorentz's theory suggested an effective equivalence of stationary and fully dragged ether to first order, it also ascribed real physical existence to the stationary ether, whose state of rest should be revealed in second order experiments. Whereas for first order effects the explanation could rely on electrodynamic mechanisms, now an additional hypothesis had to be introduced, whose meaning in terms of electromagnetic interactions was less evident, namely the hypothesis that bodies are contracted in the direction of their motion through the ether.[14]

The last two paragraphs may appear unnecessarily technical in the context of an account of the emergence of the relativistic concepts of space and time, but they reveal an essential mechanism at work in this process. With his auxiliary time and his contraction hypothesis, Lorentz had effectively constructed a formal framework for new time and space variables. However, Lorentz's techniques were neither derived nor presented in this manner, rather appearing as natural outgrowths of, or at least plausible assumptions within, a complex and phenomenologically rich dynamical theory, which in turn stabilized and at the same time constrained these innovations. Given the foreign character of these new spacetime variables, such a stabilization was indeed an important condition for integrating them into the larger body of physical knowledge that could not be achieved with equal ease by merely postulating them. Similarly, the constraints imposed by the underlying dynamical theory provided the new variables with a persuasive uniqueness not achievable by mere speculation.

This secured the constructibility of the new space and time variables. The price for this achievement was, however, that also the physical interpretation of the new variables was highly constrained by the framework in which they were embedded, concealing the possibility of implementing them as new concepts of space and time with their own operational meaning and a universal domain of reference.

Returning to the questions raised in the introduction, it may be asked what qualified the new space and time variables to serve as defining a new space-time framework. Lorentz had established the first of our three criteria, viz. constructibility. He had pushed the means of classical electrodynamics to the point of allowing for a consistent and complete description of space and time structures distinct from the pre-existing ones. But these new theoretical constructs were still devoid of any spatio-temporal meaning, because their relation to prior knowledge of space and time was only established indirectly through the complex framework of electrodynamics. The establishment of a more direct relation required a rethinking of space and time measurement that lay outside the scope of Lorentzian electrodynamics.

From a broader perspective on the conceptual foundations of physics such a rethinking was natural and, more importantly, possible, because the constructibility of new space and time variables had already been established. The ultimate success of such rethinking depended, however, on further conditions. It had to be checked whether such newly constructed space and time concepts could be related to prior knowledge of space and time and whether they fulfilled the criterion of universality. From such a broader perspective, both Poincaré and Einstein identified Lorentz's auxiliary time variable as giving the time in a moving system as actually measured. Einstein furthermore succinctly captured the core of

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[14] Lorentz 1895.

the prior knowledge of space and time in terms of generic measurement procedures, showing how this procedure could be made compatible with the identification of Lorentzian space and time variables as giving the actually measured quantities, and argued for the universality of the resulting framework. One of the key arguments was the compatibility of the new transformation laws with all results from classical physics in the limiting case of velocities small compared to the speed of light. The universality of the framework has since been corroborated by all available physical evidence, with only gravity necessitating a further modification of this framework.

While special relativity as formulated by Einstein brought about new notions of space *and* time, it was only Minkowski's reformulation in terms of a four-dimensional formalism that unified the two into a single structure, spacetime. This single structure consists in a four-dimensional geometry with a pseudo-Euclidean metric. Its mathematical features immediately reflect the laws of special-relativistic physics, thereby reducing the elaborately constructed Lorentz transformations to mere rotations within this geometry. One far-reaching implication of this framework is a new understanding of energy-momentum conservation in terms of four-dimensional quantities. Another implication is the emergence of concepts that are distinctly spatiotemporal in character, such as the concept of proper time, which integrates spatial aspects (path dependency) and temporal aspects (transience) into an inseparable whole.

7.4 The re-inclusion of gravitation into the concepts of space and time.

As we have seen, in Newtonian physics, gravitation was excluded from discussions of the structure of space and time because it was considered to be a force among others *within* space and time. *Prima facie* it was to be expected that this would not change in special relativity. In Newtonian physics, the exclusion of gravitation was the premise for the postulation of homogeneous space and time endowed with an inertial structure, allowing in turn the re-introduction of gravitation, now as a force. The universality of gravitation could be accounted for by means of the additional assumption that gravitational mass is proportional to inertial mass. The universality of gravitation was thus attributed to a mere coincidence. Special relativity introduced, as we have seen, a completely new conception of spacetime. It was therefore entirely open whether the complex reconciliation of gravitation and spacetime structure could be reproduced under these conditions. Although gravitation was the most familiar of all physical forces, in this situation it was not dissimilar to a newly discovered phenomenon. Knowledge about this phenomenon was stored in the Newtonian theory of gravitation. The question was therefore which aspects of this theory were to survive in the new framework because they reflected indispensable empirical knowledge, and which had to be discarded because they just corresponded to features of a conceptual system that had to be overcome. Since these aspects were closely entangled, an answer to this question could only be found by exploring various alternatives.

These alternatives had distinct implications for the understanding of space and time. It was, for instance proposed by Poincaré and Minkowski to replace Newton's force law by a retarded action-at-a-distance law complying with the principle that no physical interaction propagates faster than light.[15] But while such a law would not require any further modifi-

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[15] Poincaré 1906 and the Appendix of Minkowski 1908. English translations and discussions of both texts are found in Renn 2007a, Vol. 3.

cation of the special-relativistic understanding of space and time, it does raise fundamental questions about energy and momentum conservation. On the other hand, given the role of electromagnetism for special relativity it was plausible to build a new theory of gravitation according to this model of field theory. The first to try out such a theory was Max Abraham, but without success, since it turned out that his theory not only transgressed the bounds of the special-relativistic framework but was actually inconsistent.[16]

In order to remain within this framework, further-going modifications of classical concepts such as that of mass were required, as was realized by Gunnar Nordström and Einstein. Nordström attempted to construct a truly special-relativistic field theory of gravitation using a scalar source term, but soon encountered difficulties arising from the fact that in special relativity energy-momentum is represented by a second-rank tensor.[17] These difficulties forced him to modify his theory in such a way that it effectively left the special-relativistic spacetime framework, because coordinate differences no longer correspond directly to measured differences, their relation being determined by a dynamic factor. Therefore, the spacetime concepts of special relativity lose their operationability, a fact that may call into doubt the validity of these concepts. At the same time, the theory showed the constructibility of an alternative spacetime concept, based on the reinterpretation of the operationally defined distance measurements as providing the relevant spacetime framework. Given that this development emerged from a theory of gravity, the universal character of gravity automatically carries over to the new spacetime concepts, so that all our three criteria for the establishment of a new spacetime framework are fulfilled.

The problematic criterion in this case turns out to be the constructibility. First, the realizability of reinterpreting measured differences as the geometrically relevant distances hinges on the availability of a mathematical formalism in which coordinate differences and physical distances are conceptually divorced and can be systematically related to each other. And even given the realization that such a framework was available in the non-Euclidean geometry of Gauss and Riemann, this mathematical apparatus was rather complex given the comparatively simple deviations from pseudo-Euclidean geometry in the Nordström theory. This complexity and conceptual overhead might therefore have seemed too high a price to pay for leaving the familiar ground of special relativity.[18]

With the attempts of Abraham and Nordström, the potential of electromagnetism as a model for a relativistic field theory of gravitation was, however, not exhausted, in particular as approaches using a scalar field were of reduced structural richness compared to the electromagnetic model. It was particularly plausible to look for a generalization of the gravitational field analogous to the generalization of the electrostatic to the electrodynamic field by the introduction of additional degrees of freedom, viz. those of the magnetic field. In the framework of special relativity, this latter generalization could be seen as a consequence of the relativity principle. In fact, for Einstein himself, the existence of two equivalent descriptions involving different splits of the electromagnetic field into its electric and magnetic

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[16] Abraham 1912b; Abraham 1912a. English translations of these texts and further references are found in Renn 2007a, Vol. 3; see, in particular, the discussion in Renn 2007b. See also Renn and Schemmel 2012.

[17] Nordström 1912; Nordström 1913a; Nordström 1913b. English translations of these texts are found in Renn 2007a, Vol. 3. For a discussion of Nordström's theories see, in particular, Norton 1992 (reprinted as Norton 2007).

[18] As late as 1917, Max von Laue used the conceptual unfamiliarity of general relativity to argue for Nordström's theory and its special-relativistic framework (Laue 1917).

components depending on the state of motion was an important hint used in the formulation of special relativity.

It was therefore plausible to turn this argument around and postulate the existence of a generalized gravitational field manifesting itself in different forms depending on the state of motion. In order to fill this scheme with actual physical content it was, however, required to find an adequate complement to the familiar static gravitational field. Such a complement was suggested by the somewhat artificial distinction between uniform and accelerated motion in Newtonian mechanics. By questioning this distinction one could introduce, at the same time, the idea of unifying gravitational and inertial effects and generalizing the principle of relativity to include accelerated motions. This unification was possible (strong equivalence principle) as the physical parameters determining the strength of both kinds of effects, gravitational and inertial mass, respectively, were proportional (weak equivalence principle).[19]

The distinction between inertial and non-inertial motion was prominently challenged by Ernst Mach who suggested an interaction between masses to account for the occurrence of inertial forces. Mach's critique thus provided the missing ingredient for Einstein's attempt to construct a dynamical theory of gravitation based on the idea of a generalized gravitational field. As a consequence, inertia played the role that magnetism played in the electromagnetic case, thereby providing an untapped experiential resource for the formulation of a new theory of gravitation. But since in Newtonian physics inertia was a structure of space and time, this specific implementation of the electromagnetic model implied possible consequences for spacetime. In particular, it quickly turned out that the equation of motion in the combined inertio-gravitational field had a geometrical interpretation, namely that of describing a geodesic in curved spacetime.

This means that one and the same mathematical structure, the metric field, serves to represent the inertio-gravitational field and the geometrical properties of spacetime. Accordingly, a field equation for this field, as it was part of the overall scheme associated with the electromagnetic model, assumed the meaning of an equation determining the dynamical spacetime geometry. The implications of this dynamics surpassed by far the horizon of expectations based on the experiences with prior field theory. As it turned out, it could no longer be forced into any of the available pictures about the relation between space and time on the one hand and matter on the other. Rather, these notions became entangled in new ways.

The question as to which experiences led to the establishment of new space and time concepts in general relativity can thus be answered by pointing to the process of integration of special relativity, Newtonian gravitation, and the inertial structure of classical mechanics as we have described it. But we have also raised the question of why these specific experiences had this consequence and why at this particular historical moment. It is here that we come back to our three criteria, constructibility, operationability, and universality. It is actually in this sequence that these criteria became relevant in the history of special relativity.

Remarkably, their sequence was different in the history of general relativity. Using his equivalence principle to refer concepts of space and time of special relativity to gravitational effects simulated by accelerated motion, Einstein could immediately transfer their

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[19] See, e.g., Norton 1989.

operational content to the theory under construction. That this transfer would also not strip them of their universal nature was clear from the domain they were being transferred to, i.e. the equally universal phenomena of gravitational and inertial forces. In contrast, e.g., to Nordström, Einstein's modeling of gravitation with the help of accelerated motion directly brought him to explore his theory in terms of new space and time concepts. This explains the inversion of the historical sequence in which the criteria became relevant. From the outset, Einstein searched for a new spacetime framework. To a certain extent he could explore this framework with the guidance of his equivalence principle by considering various cases of accelerated motion. All such cases should qualify as legitimate manifestations of the generalized gravitational field of the theory to be constructed. The accumulation of insights following this heuristics did, however, not amount to the construction of the desired theory.

Constructibility was afforded by the introduction of a new mathematical representation from differential geometry which allowed conceptualization of the intricate relation between measured quantities and coordinate differences, suggested by the heuristic generalization of the Minkowski line element. The specific means available to the historical actors, e.g. metric geometry as opposed to affine geometry, shaped the space of constructible formulations. The criterion of constructibility can, however, not be fulfilled by solely establishing a mathematical representation of the new spacetime concepts. First of all, as the new spacetime concept had be introduced as an element of a new theory of gravitation, a complete construction requires the establishment of an adequate field equation reproducing what is empirically known about gravity. Second, the construction must not invalidate what has already been heuristically achieved in the domain of operationability. This excludes, in particular, any restriction on the admissability of accelerated motion as being interpreted as a generalized gravitational field, following, e.g., from the field equation.

The new spacetime concept brought about by general relativity is characterized by the fact that it locally corresponds to the spacetime of special relativity and that its dynamics is that of the inertio-gravitational field. This is in stark contrast to theories in which there remain non-dynamical aspects of space and time beyond the local correspondence to special relativity, such as the survival of real inertial forces in Nordström's theory. The background independence of general relativity hinges on the complete inclusion of inertial effects into the dynamic field determining spacetime. As strong as this criterion is, it does not exclude variations of general relativity, e.g., by the introduction of a cosmological constant.

7.5 The role of space and time in quantum theory

In quantum mechanics space and time continue to play a role and are potentially affected by its conceptual framework. The concept of position in space is related in ordinary quantum mechanics to the position operator. As a consequence, the position and the momentum of a particle can no longer simultaneously be determined, even in principle, with absolute precision, as it is the case in classical physics. Nevertheless, neither the concept of position nor its operational definition in terms of classical measurements are affected by this limitation.

It is therefore no surprise that in quantum field theory space and time can be treated in full analogy to classical field theory as parameters of the field. In essence, therefore, quantum field theory makes use of the spacetime framework of special relativity. This framework is only challenged by quantum theoretical considerations when spacetime itself is conceived as a dynamical field, as happens in general relativity. Another major difference between classical and quantum field theory is that the latter provides a successful framework also for a field theoretical description of many-particle dynamics. Hence, while in classical field theory the space-time coordinates serve a double role as dynamical particle positions and arguments of continuous field functions, only the latter role remains important in quantum field theory.

Historically the field concept has raised problems in the framework of quantum theory. These problems have motivated alternative conceptualizations that may be examined as to their potential implications of the concepts of space and time. The most radical of these attempted to get rid of the field concept altogether, as in Wheelers heuristic research program “everything as electrons.” On the background of a conceptualization of space as the “positional quality of the world of material objects,”[20] this program might have led to a fundamental revision of the concepts of space and time by quantum theory. Wheeler’s thought involved the identification of all electrons and positrons as a single particle whose world line went back and forth in time, thus cutting our world sheet many times. From this perspective, the indistinguishability of identical particles can be interpreted as a non-trivial connection of distant points of space.

Indeed, if only trajectories of particles are considered to be real, one may even speak of an identification of points in space. Had such a program been successful, it might have brought about new concepts of space and time. Whether the historical lack of success of this program reflects a principal obstacle or is merely a result of the limited means available, this example illustrates the crucial role of the actual *constructibility* of new concepts of space and time. In short, it turned out to be historically impossible to rebuild quantum physics as a more satisfying theory of matter and radiation by reformulating it within a new space-time framework.

One might think of representing the history of physics as a sequence of ever more general concepts of space and time. It may, however, turn out to be misguided to expect that space and time will always maintain their fundamental status through all profound changes. Instead they may lose this status to other concepts which may lack the operational foundation in prior knowledge characteristic not only for space and time but also for other canonical fundamental concepts such as matter, motion, force, and causality. This process of marginalization of canonical fundamental concepts may again be illustrated by means of the history of quantum physics.

A purely formal marginalization of space already occurs in analytical mechanics, which offers the option of focusing on an abstract space constituted by possible states of a physical system (state space, phase space, configuration space). States are typically characterized not just by spatial parameters but also by their temporal derivatives. Therefore the properties of state space are different from those of ‘ordinary’ physical space. Nevertheless, in classical physics, ordinary physical space remains fundamental, while state spaces may be considered as auxiliary constructions, since physical states can always be projected onto ordinary physical space as a distribution of matter along with the initial conditions, without loss of information about the dynamics.

In quantum mechanics, when entanglement enters, this projection is no longer possible. For instance, the wave function of a two-particle system cannot be represented as a probability distribution over ordinary space due to correlations between position measurements

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[20] Albert Einstein in his foreword to Jammer 1954, xiv.

of the two particles. Therefore, in quantum mechanics ordinary space loses its ontological role since the state of the world can no longer be represented by a function over universal space and time coordinates.[21] Even when physical processes in quantum mechanics are interpreted as definite processes in space and time (path integral formulation), their interference does not take place in this spacetime, but only in configuration space. In this sense, ordinary spacetime is marginalized by the Hilbert space structure of quantum mechanics.

But Hilbert space cannot be conceived as a profoundly changed fundamental concept of physical space. It does, in particular, not replace the concept of space of classical or relativistic physics, but rather incorporates these concepts in a somewhat marginalized form. This would only change if it were possible to apply quantum physical considerations to the dynamics of spacetime itself. As long as there is no viable quantum theory of gravity and cosmology, the constructibility of the new spacetime concepts it might introduce is not given.

7.6 Conclusion

We have started our chapter with two questions. First, which experiences led to the establishment of new space and time concepts in the history of modern physics? And second, why did these specific experiences have such consequences and why at a particular historical moment? In the previous sections we have tried to answer the first question by reviewing the historical development of space and time concepts from the perspective of the experiences that have given rise to them. Clearly, however, an equally important component of the development were the conceptual and formal tools allowing the formulation of these concepts. What shaped the dynamics of their development? Before we come to propose answers to the second question, we would therefore like to make a few remarks on the general dynamics of conceptual frameworks.

Concepts of space change only in the context of entire theories. These are not elements of an abstract set of theories but always develop historically out of pre-existing knowledge systems. These systems comprise the available means for addressing the perceived problems and thereby define the space of possible solutions and further developments. The perceived problems possibly comprise new experiences, which have to be integrated with preprocessed experiences already incorporated in the knowledge system. The system character of knowledge has implications for the long-term development of the means of representation. These will only be elaborated and transmitted if they serve some function within a knowledge system, in particular as means for solving relevant problems. As a consequence, new means for articulating concepts of space and time will typically only emerge from the historical development of such larger systems, for instance comprehensive physical theories. Therefore, in addition to the three criteria mentioned in the introduction as conditions for the emergence of new concepts of space and time, i.e., constructibility, operationability, and universality, we actually have a fourth criterion, viability, requiring that a proposal for new space and time concepts is part of a theoretical framework that successfully addresses the relevant problems.

The criterion of constructibility is therefore not defined by the question of whether the necessary tools may have been in principle available to the historical actors, as if they were

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[21] Loss of projectibility is also given in statistical mechanics, of course, but does not imply a change in ontology and only reflects our state of knowledge.

part of a universal tool box, but if the historical development of some available knowledge system could possibly have brought them about. Constructibility, in short, is defined by previous historical processes of construction and thus highly path-dependent. The historical sequence of the construction of knowledge systems involves an iterative procedure of representation and reflection. Representation is here understood in the broad sense of a set of external, i.e., material, representations of a knowledge system, such as its description in terms of language, symbolic formalisms, or artifacts. Reflection is equally broadly understood as the set of thinking processes accompanying the implementation and exploration of such a knowledge system with the help of these representations that may lead to the construction of new knowledge structures, which may then be characterized as knowledge structures of higher-order.

Accordingly, means for solving problems within knowledge systems may be distinguished by their degree of reflexivity, indicating the specific sequence of representation and reflection that gave rise to them. In the case of Euclidean geometry, for instance, the figures that can be drawn with compass and rulers may be considered as first-order representations, while its linguistic formulation within a deductive structure constitutes a second-order representation.[22] The invention of non-Euclidean geometry presupposed a degree of reflexivity that allowed to consider such second-order representations and their possible alternatives in turn as an object of reflection that may constitute the meaning of geometry independently from its first-order representations. In summary, means of construction have their own history that may be more or less closely related to the history of the subject matter under consideration.

The match between mathematical formalisms and the physical world has often been discussed as a puzzling fact, because of the difficulty to explain the adequacy of the mental constructions of mathematics for the description of physical experiences. However, when those mental constructions are understood as the result of long chains of sequences of reflections and representations, which at each stage involve specific experiences, the mathematical formalisms themselves turn out to be saturated with experience. This is, of course, not necessarily the same kind of experience that is to be captured by some physical theory. It thus may seem that, along this line of thinking, the puzzle can be reduced to the question of how to integrate different domains of experiences. This integration is, however, made even more difficult by the fact that the experiences underlying a given formalism are only implicitly represented by it, since the formalism is usually the result of a long chain of reflections and representations.

The codification of experience in terms of knowledge structures is indeed one of the reasons for the characteristic *recursive blindness*[23] of abstract thinking with regard to its own experiential sources, a recursive blindness that also accounts for the seemingly a priori character associated with the concepts of space and time. Bringing together different domains of experience by matching physical experiences with mathematical formalisms, therefore, typically raises the question which aspects of a formalism represent experiences and which have to be considered either as merely formal aspects or as representing experiences in need of reinterpretation. For instance, in the case of the electrodynamics of moving bodies, the challenge was to integrate the experiences of electromagnetism codified in Maxwell's equations with the experiences of mechanics codified in the Galilean transformations. The necessary

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[22] See Damerow 1994, 268–270 and Schemmel 2016, 47–50.

[23] Renn and Hyman 2012, 493.

adaptation of the latter formalism raised the question of what aspects of it were related to an operational understanding of space and time measures and what aspects represented experiences in need of reinterpretation, such as that of simultaneity.

To sum up, it is not the case that the factor that systematically varies in the historical development of physical theories is primarily the ever larger extent of experience described by them, while the availability of adequate mathematical formalisms enters as a contingent factor or one that is governed by an entirely different logic. Rather, the development of formalisms itself involves the processing of experiences and is often closely related to the development of physical theories in the sense of our fourth criterion of viability. Therefore, from a larger perspective, there is a co-evolution of physical theories and the formalisms they employ to cover the experiences they strive to explain: while they may belong to separate intellectual or disciplinary traditions, they are typically still part of the shared knowledge available to society at large.

This co-evolution also accounts for the global dominance, despite the persistent emergence of locally viable alternative solutions, of a single stream of development in the sense of 'the winner takes all'. As in evolutionary theory, optimization is a local phenomenon always working with the available means, rather than within an abstract set of theories. In this process of optimization, any established solution (e.g. Newtonian classical mechanics) – 'established' both in an intellectual and institutional sense – is typically stabilized and extended by assimilating a maximal range of experiences, thereby gaining an advantage with respect to conceivable alternatives (e.g. Leibnizian mechanics) that are not granted a similar chance of being implemented.

It is this local dynamics that accounts for an overall development that, at the level of a history of ideas decoupled from their embodiment in the material means and concrete experiences, may seem to display a rather astonishing movement back and forth among fundamental notions of space. In particular, there is, as we have seen, the dissociation of space from gravity in Newtonian physics, by which Newtonian space becomes homogenous and isotropic, whereas in general relativity gravitation becomes a feature of spacetime. General relativity thus returns to the notion that space (or spacetime) guides motions under the influence of gravitation, a notion closer to Aristotelian physics than to Newtonian. One may therefore ask if there could not have been a more direct pathway connecting the Aristotelian notion of anisotropic space to that of Einstein. Here we have argued that the apparent swaying motion of this long-term development cannot be understood at the level of ideas of space alone. As we have also argued, such ideas only inherit their viability from the broader theories they are part of. As a matter of fact, in modern science it is the integration of an increasing corpus of experience by means of formalisms that defines progress. Therefore, on a global level, the historical development is actually much more constrained than a history of abstract ideas can account for.

This we can see more clearly, when we take into account that there is another fundamental reason for the streamlining of global developments, in addition to the winner-takes-all logic described above explaining the extrusion of alternatives. Alternatives themselves typically only emerge in the process of exploring the available means (e.g. as special relativity developed out of Lorentzian electrodynamics) and are the more viable, the richer their experiential basis, which in turn is largely provided by the established solution. The elaboration of alternatives to such a given solution (with the help of the means it provides) may either result in its abandonment (e.g. when special relativity emerged from searching alternatives to Lorentzian ether theory) or in its reconceptualization in new and different terms, for instance with the help of a new formalism (e.g. Minkowski's formalism being the result of a reconceptualization of special relativity). Such reformulations have a double function: they serve to assimilate already existing but not yet integrated experiences to a theory, thus rooting it even more deeply in experience (e.g. assimilating optics to electrodynamics by reformulating the laws of electromagnetism in terms of Maxwell's equations), and they may become the starting point for the integration of novel experiences and, possibly, the eventual overcoming of the established theory (e.g. when special relativity is reformulated in terms of Minkowski's formalism enabling the development of general relativity).

From this perspective, let us therefore once more review our account of the historical evolution of the concepts of space and time in physics with particular attention to the viability of alternative trajectories. For a long time, gravitation was a natural component of conceptions of space. What was later identified as the influence of gravitation is primarily motion taking place spontaneously and in a specific direction. This spontaneity and directedness was indeed an aspect of natural motion in Aristotelian physics, in which sublunar natural motion was directed towards the center of the Universe (which coincided with the center of the Earth) or away from it, while celestial motion was circular around the center.

Historically, alternatives to the geocentric world view were formulated in ancient Greece. The question thus arises whether the fact that a specific Earth-bound perspective was elaborated into a comprehensive system of knowledge should be deemed contingent. There may have been systematic reasons for the dominance of the geocentric world view, for instance the possibility to incorporate insights of terrestrial physics (such as the doctrine of the elements) and anthropocentric ideologies (such as Christian religion), but in view of the existence of alternatives, the dominance of geocentrism appears to be at least partially contingent. After all, the decision was based on a relatively small empirical basis, but once it was taken and an increasingly large corpus of knowledge was assimilated to it, the alternatives appeared ever less plausible.

On the other hand, the connectivity of the system developed over the centuries and the large amount of knowledge incorporated gave the addition of new insights a potentially large impact on the system as a whole. Thus, when astronomical developments eventually favored a view in which the Earth was no longer at the center of the universe, not only could the question arise whether the fall of bodies was just an Earth-bound phenomenon and not a manifestation of natural motion in a cosmological context, but the very concept of natural motions was called into question. Hence what had earlier been considered natural motions was in need of an alternative explanation. As is well known, Newton's solution was to postulate a universal force of gravitation that explained the formerly natural motion of free fall and the celestial motions. Thereby he integrated the great amount of experience pre-processed in terrestrial and celestial mechanics on the basis of new explanatory models, such as that of force as suggested by magnetism.

From terrestrial physics, and the analysis of projectile motion in particular, the idea of an inertial motion emerged, which was to become seminal for the new concept of space. Inertial motion demanded an absolute standard to judge motion, which was achieved by the concept of absolute space. Inverting the Aristotelian categorization of motions, inertial motion thus became the sublimated version of natural motion, while the motion of fall came to be interpreted as forced.

Why did the new concept of gravitation not become part of the new concept of space? Besides the question of the availability of the mathematical means of construction, a conceptualization of gravitation in terms of a four-dimensional spacetime would have rendered impossible the very formulation of Newtonian mechanics, in which gravitation served as the paradigmatic model of a force. Therefore its inclusion in a concept of spacetime was no viable option for Newton. One might well imagine that a few decades later, after Newtonian gravitation had served its historical role of integrating celestial motion and terrestrial mechanics, alternative formulations of gravitation in terms of spacetime structures would have become possible. In this context one may think of the representation of gravitation and inertia in terms of a projective or an affine structure on spacetime already within the context of Newtonian physics, as presented by Newton-Cartan theory.[24]

All such attempts fall short, however, of constructing dynamical field equations. It therefore does not seem to be coincidental that the invention of general relativity occurred soon after the formulation of Lorentzian electrodynamics, which provided the model for a field theory of gravitation and inertia. Nevertheless, the successful formulation of gravitation in terms of a dynamic spacetime within general relativity today faces a similar problem as the one it would have faced in Newton's times: it separates gravitation from the other forces. So far all attempts to geometrize the other forces have failed; as well as all attempts to integrate gravitation – despite its special status – into a quantum field theoretical framework.

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[24] For an introduction to that formulation, see Misner, Thorne, and Wheeler 1973, 289–303.

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