Physics Before and After Einstein
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Chapter 4

The Origins and Concepts of Special Relativity

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1. Einstein's 1905 Paper of Special Relativity

Albert Einstein published three epochal papers in 1905. The first, dated 17 March, is known as the theory of light quantum [21]. The second, dated May, is the theory of Brownian movement [25]. The last, dated June, is the special theory of relativity (referred to here as 'STR') [23]. It is this last paper that we will discuss in this chapter.

These three papers, therefore, were published within four months. What is more, he published on 30 April 1905, i.e. between the first and the second, his doctoral dissertation "A New Determination of Molecular Dimensions" [10]. The brevity of the period during which these four papers were published, suggests certain deep relationships among them. I will discuss this later, in Section 8, and begin here with a general overview of the STR paper.

As is well known, Einstein's paper on STR led to fundamental reformation in our conceptual framework of space and time. He wrote in 1905 to his close friend Conrad Habicht [13]:

> [The STR paper] is an electrodynamics of moving bodies, which employs a modification of the theory of space and time; the purely kinematic part of this paper will surely interest you.

As suggested above, this paper consists of two parts: "I. Kinematic Part" and "II. Electrodynamic Part". Besides them, he supplies at the start of the paper a short general introduction. In it, he first explains why he thinks it necessary to introduce the first postulate, i.e. the principle of special relativity (referred to as "the relativity postulate" below). Then he proceeds, without giving any reason, to the introduction of the second postulate, i.e. the principle of constancy of light velocity (referred to as "the light-velocity postulate" below).

He explains the relativity postulate as follows:

> Not only the phenomena of mechanics, but also those of electrodynamics have no properties that correspond to the concept of absolute rest. Rather, the same laws of electrodynamics and optics will be valid for all coordinate systems in which the equations of mechanics hold [i.e. the so-called "inertial systems"].

That is to say, the Galilean principle of relativity[1] known to be valid in classical mechanics should be extended to the electromagnetic and optical regions. The crucial point here is that, as is the case with the Galilean principle of relativity, the applicability of relativity postulate in STR is restricted to the inertial systems, which form a special class of coordinate systems having uniform mutual velocities.

Einstein supplies two reasons for introducing the relativity postulate. One is the asymmetry inherent in his contemporary Maxwell's electrodynamics, i.e. in the relative motion of a magnet and a conductor, an explanation of electric induction being quite different depending on which one of the two is in motion, while the observed phenomena depends only on the relative motion. The other is the failure of attempts to detect, in the electromagnetic and optical phenomena, an influence of the Earth's motion relative to the stationary ether at rest. The stationary ether had been stipulated to exist as a medium conveying electromagnetic or light waves by Hendrik A. Lorentz's theory of electrons, which was widely accepted then for the explanation of electromagnetic and optical phenomena.

On the other hand, Einstein does not supply any reason for the light-velocity postulate, which he states as follows:

> Another postulate, which is only seemingly incompatible with it [the relativity postulate], namely that light always propagates in empty space with a definite velocity c that is independent of the state of motion of the emitting body.

By stating "only seemingly incompatible with it", he seems to have meant the incompatibility of the light-velocity postulate with the classical additivity of velocities, which is a result of the Galilean transformation of coordinates.[2] As the latter transformation is based on the Galilean principle of relativity, the light-velocity postulate is in conflict with the relativity postulate in classical mechanics.

The "Kinematic Part" consists of five sections. Section 1 gives the "definition of simultaneity", where he first points out the close relationship between the judgments of time and of simultaneity as follows,

> [A]ll our judgments involving time are always judgments about *simultaneous events*. If, for example, I say that "the train arrives here at 7 o'clock," that means, more or less, "the pointing of the small hand of my watch to 7 and the arrival of the train are simultaneous events." [italics original]

He then proceeds to define simultaneity at different locations, A and B. Utilizing the light-velocity postulate, he stipulates that a "time" common to A and B can be established by the definition that the "time" required for light to travel from A to B ($= t_B - t_A$) is equal to the "time" it requires to travel from B to A ($= t'_A - t_B$). Thus, the two clocks placed at A and B are synchronous to each other, by definition, only if

$$t_B - t_A = t'_A - t_B.$$

[1] Galileo Galilei explained, in "The Second Day" of his book *Dialogue Concerning the Two Chief World Systems* published in 1632, the reason why the effects of the Earth's motion do not appear in the motion of bodies on the Earth. He suggested there the relativity principle named after him, which implies that the laws of motion are the same among the coordinate systems with uniform mutual velocities.

[2] To every choice of values x, y, z, t that determines the place and time of an event in the rest system K, there are corresponding values ξ, η, ζ, τ that fix this event to the system k (which has parallel spatial axes to those in K) moving with velocity v in the x-direction relative to the rest system. The Galilean transformation of coordinates states that the relation between these values are $\xi = x - vt$, $\eta = y$, $\varsigma = z$, $\tau = t$.

Times thus defined constitute "the time of the rest system," and permit the definition of "simultaneity at different locations" in this rest frame.

It is worth mentioning here that, with the rapid development of the railway network in Europe at that time, the synchronization of distant clocks had become urgent technological subjects in order to keep train services punctual. As a country famous for its clock-making industry, Switzerland was a centre for the unification of time. As a result, many applications for patents on this theme were arriving at the Patent Office at Bern, to which Einstein belonged [29].

In Section 2, he introduces, besides clocks, a measuring rod, and tries to utilize it to determine the length of a rigid rod in uniform translational motion (a) from the moving coordinate system and (b) from the rest system, as follows:

> (a) The observer moves together with the aforementioned measuring rod and the rigid rod to be measured, and measures the length of the rod by laying out the measuring rod in the same way as if the rod to be measured, the observer, and the measuring rod were all at rest.
>
> (b) Using clocks at rest and synchronous in the rest system as outlined in "Section 1," the observer determines at which points of the rest system the beginning and the end of the rod to be measured are located at some given time t. The distance between these two points, measured with the [measuring-]rod used before – but now at rest – is also a length that we can call the "length of the rod."

He states the invariance of the length of the rod in the case (a):

> According to the principle of relativity, the length determined by operation (a), which we call 'the length of the rod in the moving system,' must equal the length ℓ of the rod at rest.

On the other hand, he insists that the length of the rod changes in the case (b):

> [T]he length determined by operation (b), which we shall call 'the length of the moving rod in the rest system,' will be determined on the basis of our two principles, and we shall find that it differs from ℓ.

He then proceeds to examine more precisely the situation in (b) above, and to imagine that the two ends (A and B) of the moving rod (with velocity v) are equipped with clocks that are synchronous with the clocks of the rest system; hence, these two clocks are "synchronous in the rest system". A ray of light starting at time t_A on the clock at A adjusted to "the time of the rest system" is reflected from B at time t_B on the clock at B, which is similarly adjusted, and returns back to A at time t'_A. With r_{AB} designating the length of the moving rod found in operation (b), the ray of light travels, in the rest frame, between times t_A and t_B the distance $r_{AB}+v(t_B-t_A)$, and between t_B and t'_A the distance $r_{AB}-v(t'_A-t_B)$. Utilizing the light velocity c in the rest frame, he obtains

$$t_B - t_A = \frac{r_{AB}}{c-v}, \qquad t'_A - t_B = \frac{r_{AB}}{c+v}.$$

He then examines whether or not the observer moving with the rod finds that the synchronization criterion of "Section 1" applies to these clocks. From the viewpoint of this observer, this ray of light goes and returns for the same length ℓ of the rod, and, if the clocks were synchronous, would have required the same time-span each way. Hence, he states:

Observers co-moving with the rod would thus find that the two clocks do not run synchronously, while observers in the system at rest would declare them to be running synchronously.

The above statement also implies the so-called "relativity of simultaneity", i.e. the judgment of whether or not the two events occur simultaneously varies depending on the system of coordinates from which the two events are observed.

In Section 3, he derives the so-called "Lorentz transformation". For every choice of values x, y, z, t that determine the place and time of an event in the rest system K, there are corresponding values ξ, η, ζ, τ that fix this event to the system k (which has parallel spatial axes to those in K) moving with velocity v in the x-direction relative to the rest system. The problem to be solved is to find the system of equations (i.e. "transformation") connecting these two sets of quantities. He points out at the start, "It is clear that these equations must be linear because of the properties of homogeneity that we attribute to space and time." Utilizing this criterion, he derives the transformation by evaluating, from the rest system, the synchronization condition of the clocks in the moving system k, i.e. $\tau_1 - \tau_0 = \tau_2 - \tau_1$; and the light-velocity postulate applied for the propagation of rays of light emitted at $t = \tau = 0$, e.g. $x/t = \xi/\tau = c$, $y/t = \eta/\tau = c$ and $z/t = \zeta/\tau = c$. Thence, he arrives at the result,

$$\xi = \beta(x - vt), \qquad \eta = y, \qquad \varsigma = z,$$
$$\tau = \beta\left(t - \frac{v}{c^2}x\right), \quad \text{where } \beta = \frac{1}{\sqrt{1-(v/c)^2}}.$$

Although he does not name these equations, we call them the "Lorentz transformation", because about a year earlier Lorentz wrote down very similar transformation equations and stated that Maxwell equations remain unchanged under this transformation [35]. But, as will be explicated in Section 5 of this chapter, the equations Lorentz wrote contained some errors, and did not keep their form totally unchanged. Furthermore, unlike Einstein, Lorentz only stipulated them *a priori* without supplying any derivation.

Einstein then derives, in Section 4, several results from the above Lorentz transformation equations. First is the so-called "Lorentz contraction". He shows that, seen from the rest system, every rigid body at rest relative to the moving system (with velocity v) appears to be contracted in the direction of motion in the ratio $1 : \sqrt{1-(v/c)^2}$. Next, he shows that a clock placed at the origin of the moving system k, i.e. at $x = vt$ in the rest system K, delays each second by $1 - \sqrt{1-(v/c)^2}$ sec, or by about $(v/c)^2/2$ sec, relative to those clocks synchronous in the rest system.

Concerning this latter result, he points out:

If there are two synchronous clocks in A, and one of them is moved along a closed curve with constant velocity v until it has returned to A, which takes, say t sec, then this clock will lag, on its arrival at A, $t(v/c)^2$ 2 sec behind the clock that has not been moved.

This is the origin of the famous "twin paradox", the problem in which is that, seen from the viewpoint of the moved clock, it is the clock at rest at A that appears to be moved and, thus, that should appear to be delayed. This paradox was later resolved by the remark that, in order to move a clock along a closed curve to its starting point, an acceleration process is inescapable, and this constitutes the cause of the delay [14]. To avoid such confusion, Einstein gives just after the quoted part above an experimentally verifiable fact:

> From this we conclude that a balance-wheel clock that is located at Earth's equator must be very slightly slower than an absolutely identical clock that is located at one of the Earth's poles.

The last section of part 1 is entitled "Section 5. The Addition Theorem for Velocities." He evaluates there, from the rest system, the velocity U of a point moving with a constant velocity w in the ξ-direction on the moving system k (with velocity v in the x-direction with respect to the rest system). Utilizing the Lorentz transformation, he obtains

$$U = \frac{v + w}{1 + vw/c^2},$$

which substitutes the classical additivity of velocities (i.e. $U = v + w$), and eliminates the incompatibility of the two postulates stated before. He shows, from the above, that the light velocity c is the greatest possible velocity.

As for the "Electrodynamic Part", we restrict ourselves here to a brief survey. In Section 6, he derives the transformation law for electric and magnetic forces, by applying the relativity postulate and the Lorentz transformation to Maxwell's electromagnetic equations. One result from this is that the electromotive force arising upon motion in a magnetic field, i.e. the so-called "Lorentz force", is nothing but the electric force appearing in the moving system. In Section 7, he derives, by applying the results of Section 6 to the equations representing electromagnetic waves, the so-called Doppler's principle for light waves and the law of aberration of a ray of light, i.e. the transformation law for the frequency and direction of electromagnetic waves.

In Section 8, he considers the transformation from rest to a moving system, of the energy in a ray of light enclosed within a closed surface, and comments:

> It is noteworthy that the energy and the frequency of a light complex vary with the observer's state of motion according to the same law.

Although he avoids mentioning it, this result is in exact agreement with the energy value $h\nu$ of the light quantum, which he showed in the paper he wrote three months earlier.

Utilizing the equations thus obtained, he further considers the reflection of light by a perfect mirror. He calculates the difference in energy between the incident and the reflected light-rays, and identifies this difference as the work done by the radiation pressure on the mirror. Thus, he finally arrives at an expression for the pressure of radiation, to which we will return in Section 8 below.

2. The Origins of the Relativity Postulate

As stated in the preceding section, Einstein supplies in the introduction to his STR paper two reasons for introducing the relativity postulate. One is the asymmetry inherent in his contemporary Maxwell's electrodynamics; the other is the failure of attempts to detect motion of the Earth relative to the stationary ether.

As to this latter reason, Einstein explained it in his Kyoto Address delivered in 1922 during his visit to Japan as follows [1]:

> It is certain, however, that the idea [of the principle of relativity] was contained in the problems concerning the optics of moving bodies. Light propagates through the sea of the ether. The

> Earth also moves in this same ether. If seen from the Earth, ether flows against it. Nevertheless, I could not find the facts verifying this flow of ether in all physics literature.
>
> Therefore, I wanted somehow to verify this flow of ether against the Earth, namely, the movement of the Earth. When I posed this problem to my mind at that time, I never doubted the existence of the ether and the movement of the Earth. Thus, I wanted, by appropriately reflecting light from one source by mirrors, to send one light along the motion of the Earth and the other in the opposite direction. Anticipating that there should be some difference in the energy of these beams, I wanted to verify this by the difference of heat caused by them in terms of two thermocouples. This idea was just of the same sort as that of the Michelson's experiment, but I did not know this experiment very well then.
>
> While I had these ideas in mind as a student, I came to know the strange result of Michelson's experiment. Then, I came to realize intuitively that, if we admit this as a fact, it must be our mistake to think of the movement of the Earth against the ether. That was to say the first route that led me to what we now call the principle of special relativity. Since then I have come to believe that, though the Earth moves around the Sun, we cannot perceive this movement by way of optical experiments.

The above quotation may clarify the details of the second reason.

Michelson's experiment, mentioned above, means the light-interference experiment carried out by Albert A. Michelson and Edward W. Morley in 1887. They performed a very precise measurement in order to detect the Earth's motion against the ether. However, even though they changed the directions of the two beams of light with respect to the Earth's motion, no change in interference pattern was observed. Einstein seems to have come to know of this experiment due to Wihelm Wien's paper of 1898 [51], about which Einstein wrote to his fiancée on 28 September 1899 (when he was a student) [55]. Wien indicated in this paper ten attempts that all had negative results to detect the Earth's motion against the ether, where the Michelson–Morley experiment was included as the last of ten attempts.

Nevertheless, later in 1952, Einstein denied the direct influence of this experiment on his construction of STR. He said in a reply to a question when being interviewed by Robert Shankland [46]:

> I am not sure when I first heard of the Michelson experiment. I was not conscious that it had influenced me directly during the seven years that relativity had been my life. I guess I just took it for granted that it was true.

However, Shankland continues:

> Einstein said that in the years 1905–1909 he thought a great deal about Michelson's result, in his discussions with Lorentz and others in his thinking about general relativity. He then realized (so he told me) that he had also been conscious of Michelson's result before 1905 partly through his reading of the papers of Lorentz and more because he had simply assumed this result of Michelson to be true.

Therefore, the "ten attempts with negative results" listed in Wien's paper seem enough for Einstein in 1905. The reason he mentioned only Michelson's experiment in his Kyoto Address was that he regarded it the most important and famous of the ten at the time of the Address.

The relativity postulate had another root precedent to the two stated in the STR paper. P.A. Schilpp, the editor of *Albert Einstein: Philosopher–Scientist*, persuaded Einstein earnestly to contribute to his book an article, which explains how Einstein arrived at his various theories. As a result, Einstein's "Autobiographical Notes" (abbreviated below as

"Notes") appeared. He described in it a paradox, which he hit upon at the age of 16, in 1895, and which contained the germ of the relativity postulate.

He imagined himself pursuing a ray of light with light velocity c and seeing a spatially periodical electromagnetic field at rest. He stated [57]:

> From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same law as for an observer, who, relative to the Earth, was at rest. For how should the first observer know, i.e., be able to determine, that he is in a state of fast uniform motion?

According to my interpretation, the above statement is a consequence of Einstein's conjecture that, owing to the Galilean principle of relativity, there would be no way of determining whether one is in a state of fast uniform motion or not [2].

The above view is consistent with the description in Einstein's small essay on the state of the ether in a magnetic field, which he wrote to one of his uncles in the same year of 1895 [4]. In it, Einstein did not adopt Lorentz's view of the stationary ether, which he encountered much later in 1901 [54]. In fact, he discussed in this essay, "The motion of the ether produced by an electric current" and "the deformation produced by the motion of the ether" [22]. Therefore, as far as Einstein viewed the ether as a movable (i.e. draggable) mechanical entity, he had no reason to doubt the validity of the Galilean principle of relativity in this case, which was then known to be valid for mechanical phenomena.

I have pointed out one more possible origin of the relativity postulate, consistent with the above, buried in his doctoral dissertation mentioned in Section 1 [3]. There he solved the viscous hydrodynamic equation in the coordinate system of a suspended solute molecule. At this point he utilized the Galilean transformation of the hydrodynamic equation from the rest frame of the solvent to the moving coordinate of the solute. Although he published his dissertation in 1905, it is certain that he was familiar with this method from his student years of 1896–1900 [61]. Similarly, he treated in his STR paper the coordinate transformation of the electromagnetic equations from the rest to the moving frame. Moreover, in 1910 he utilized the latter result to solve the electromagnetic equation in the moving coordinate of a small mirror suspended in a cavity filled with black-body radiation [28].

Therefore, the first step leading to the relativity postulate seems to have been the application of the Galilean transformation in the continuous medium.

3. Revision of the Concept of Time

Einstein's Kyoto Address, mentioned in Section 2, tells almost the same story of the construction of STR as that given by Max Wertheimer [49] based on his conversation with Einstein in 1916. In both these accounts, Einstein began with the conviction that (a) Maxwell's equations are valid and that (b) Maxwell's equations – and all other laws of nature – must have the same form in all inertial systems, i.e. the relativity postulate.

Maxwell's equations lead to the deduction of the equation for electromagnetic waves and, thus, also light velocity. Therefore, the application of the relativity postulate to Maxwell's equations brings forth the constancy of light velocity, i.e. light velocity should be constant irrespective of the motion of the system of coordinates observing it. The latter proposition, however, seemed inconsistent with the classical additivity of velocities, which required that light velocity in vacuo c should depend on the velocity of the observer. Einstein tried to keep Maxwell's equations valid for all inertial systems while allowing c to vary, but in vain.

It was around this point that he became aware of the Michelson–Morley experiment [56], which implied the conclusion to which Einstein's thinking had already led him: that c is constant for all observers. Gradually, he focused on the question of the meaning of the measurement of a moving body and, finally, on the meaning of the judgment of simultaneity involved in such experiments. Thus, Einstein arrived at his operational definition of distant simultaneity, described in Section 1, in terms of simultaneity in the same place using the presumed constancy of light velocity.

Einstein's seemingly innocuous requirement that simultaneity be operationally defined led to the rejection of the concept of an absolute time valid in all coordinate systems. On this matter, his Kyoto Address testifies to the important role played by his friend Michele Besso [1, p. 14]:

> This invariance of light velocity conflicted with the law of the additivity of velocity well known in mechanics. Why on earth did these two contradict each other? I felt I had come up against a serious difficulty. Expecting to modify the Lorentz's way of thought somehow, I spent almost one year in useless thoughts. Then, I could not but think that this mystery would be too hard for me to solve.
>
> Nevertheless, a friend [Michele Besso] of mine in Bern relieved me by chance. It was a beautiful day. I visited him and began to talk to him like this.
>
> "I have a problem that I cannot solve for the life of me. Today, I've brought with me the battle to you."
>
> I discussed various things with him. Thereby, I felt inspired and was able to reach enlightenment. The next day, I revisited him and said to him,
>
> "Thanks a lot. I have completely interpreted my problem now."
>
> My interpretation was really about the concept of time. Namely, time could not be defined absolutely, but is in an inseparable relationship with the signal velocity. Thus, the previous extraordinary difficulty had been solved completely for the first time. Within five weeks of this realization, the principle of special relativity as we know it was established.

Besso is the person who had introduced Einstein to Ernst Mach's *The Science of Mechanics* (*Die Mechanik in Ihrer Entwicklung Historisch-Kritisch Dagestellt*) [37], and to whom Einstein acknowledged his debt for "many a valuable suggestion" in his 1905 STR paper.

4. Poincaré's Analysis of Space and Time

If the accomplishment of Einstein's STR were no more than what has been presented so far, the distance between Einstein's and other contemporary reflections and methods would not have been as great as is often claimed. In fact, it is well known that Einstein read around 1903, together with his friends in the "Olympia Academy" ("Akademie Olympia"), Poincaré's book *Science and Hypothesis* (*La Science et l' Hypothèse*), which had been published in 1902 [47]. As explained below, this book and Poincaré's paper of 1898 "Measure of Time" ("Mesure du Temps") cited therein, include such topics as the revision of the concept of time, the relativity postulate, the constancy of light velocity, and the unobservability of the Earth's motion against the ether.

In Chapter 6, "The Classical Mechanics", of that book, the following description is found concerning the concept of space and time [45]:

1. There is no absolute space, and we only conceive of relative motion; and yet in most cases mechanical facts are enunciated as if there were an absolute space to which they can be referred.
2. There is no absolute time. When we say that two periods are equal, the statement has not meaning, and can only acquire a meaning by a convention.
3. Not only have we no direct intuition of the equality of two periods, but we have not even direct intuition of the simultaneity of two events occurring in two different places. I have explained this in an article entitled "Measure of Time."
4. Finally, is not our Euclidean geometry in itself only a kind of convention of language? Mechanical facts might be enunciated with reference to a non-Euclidean space which would be less convenient but quite as legitimate as our ordinary space; the enunciation would be more complicated, but still would be possible.

As concerns the relativity postulate, Chapter 7, "Relative and Absolute Motion", refers to it as "the principle of relative motion" [43]:

> The movement of any system whatever ought to obey the same laws, whether it is referred to fixed axes or to the movable axes which are implied in uniform motion in a straight line. This is the principle of relative motion; it is imposed upon us for two reasons: the commonest experiment confirms it; the consideration of the contrary hypothesis is singularly repugnant to the mind.

The constancy of light velocity is referred to in his 1898 paper "Measure of Time" [42]:

> When an astronomer tells me that some stellar phenomenon, which his telescope reveals to him at this moment, happened nevertheless fifty years ago, I seek his meaning, and to that end I shall ask him how he knows it, that is, how he has measured the velocity of light.
>
> He has begun by *supposing* that light has a constant velocity, and in particular that its velocity is the same in all directions. That is a postulate without which no measurement of this velocity could be attempted. [italics original]

With regard to the effect of the motion of the Earth against the ether, Chapter 10, "The Theories of Modern Physics", states [41]:

> Suppose we discover that optical and electrical phenomena are influenced by the motion of the Earth. It would follow that those phenomena might reveal to us not only the relative motion of material bodies, but also what would seem to be their absolute motion. Again, it would be necessary to have an ether in order that these so-called absolute movements should not be their displacements with respect to empty space, but with respect to something concrete. Will this ever be accomplished? I do not think so, and I shall explain why.

Thus, just like Einstein, Poincaré also believed that one could not discover the motion of the Earth against the ether. What is more, Einstein read the above much earlier than 1905.

5. The Lorentz–Einstein Problem

What then did Lorentz think about it? His 1895 book, written in German, which Einstein had certainly read, as testified by his letter of December 1901 to his fiancée, and by his Kyoto Address, contains Lorentz's explanation of the Michelson–Morley experiment. According to it, although the effects proportional to v/c (v: velocity of the Earth against the ether) compensate for each other, those proportional to its square should be observable. However, this was not detected experimentally.

In order to explain this, Lorentz could only assume that the whole of the experimental apparatus was contracted in the direction of the Earth's movement (i.e. Lorentz contraction). He gave the reason why such a contraction should occur through his assumption on the inter-molecular forces, as follows [36]:

> Surprising as this hypothesis may appear at first sight, yet we shall have to admit that it is by no means far-fetched, as soon as we assume that molecular forces are also transmitted through the ether, like the electric and magnetic forces of which we are able at the present time to make this assertion definitely. [...] Now, since the form and dimensions of a solid body are ultimately conditioned by the intensity of molecular actions, there cannot fail to be a change of dimensions as well.

Poincaré criticized Lorentz's explanation as being "ad hoc" in Chapter 10 of his book subsequent to that quoted above [44]:

> I must explain why I do not believe, in spite of Lorentz, that more exact observations will ever make evident anything else but the relative displacements of material bodies. [...] He showed that the terms of the first order should cancel each other, but not the terms of the second order. Then more exact experiments were made, which were also negative; neither could this be the result of chance. An explanation was necessary, and was forthcoming; they always are; hypotheses are what we lack the least. [...] No; the same explanation must be found for the two cases, and everything tends to show that this explanation would serve equally well for the terms of the higher order, and that the mutual destruction of these terms will be rigorous and absolute.

The above is what Einstein knew about Lorentz–Poincaré's theory.

However, that was not the whole story. In response to Poincaré's criticism, in 1904 Lorentz constructed a more general theory entitled "Electromagnetic phenomena in a system moving with any velocity less than that of light", which was published in Holland and Einstein could not obtain. As stated in Section 1, it was in this paper that the Lorentz transformation was first introduced.

He starts with the assumption that Maxwell's equations only hold on the stationary ether. Then he introduces variables that are obtained by the Lorentz transformation from the true coordinates and time on the stationary ether. And he showed that, if one regards variables thus obtained as the coordinates and time on the moving bodies, Maxwell's equations on the moving bodies also retain the same form. He named the variable obtained by the Lorentz transformation from true time as "local time".

Moreover, Poincaré referred to this "local time" in his address delivered before the International Congress of Arts and Science in St Louis in 1904, saying that if we adjust our watches utilizing light signals, the watch on the moving body will show the "local time" [40]. After this address, Poincaré constructed, in his homonymous articles of 1905 and 1906, his own theory of electrons by introducing the relativity postulate ("le postulat de relativité") into Lorentz's theory [39].

At first sight, Lorentz–Poincaré's theory, as described above, seems to have informed Einstein's STR in advance. In fact, in 1953, the distinguished mathematician Sir Edmund T. Whittaker published a chapter "The Relativity Theory of Poincaré and Lorentz" in his

The History of Ether and Electricity, Vol. 2: Modern Theories 1900–1926 [50]. Einstein's contribution is only commented on in a section of the chapter.

Even before its publication, Max Born, a physicist friend both of Whittaker and of Einstein, tried to dissuade Whittaker from describing Einstein's work in that way, but in vain [60]. Born soon found an occasion (the fifteenth anniversary of the discovery of STR, held in Bern in 1955) to criticize Whittaker's account in public [5]:

1. Lorentz himself regarded Einstein as the discoverer of the principle of relativity, and was reluctant to abandon the ideas of absolute space and time to the end of his life.
2. The exciting feature of Einstein's STR is his audacity to challenge Newton's established philosophy, the traditional concepts of space and time.

The question of whether Lorentz–Poincaré's theory was STR or not is sometimes called the Lorentz–Einstein problem. In 1960, Japanese historian Tetu Hirosige developed Born's criticism through an analysis of Poincaré's works. He dealt with Poincaré's Sorbonne lecture of 1899, his address to the International Congress of Physics of 1900 at Paris, his book *Science and Hypothesis* of 1902, and his St Louis address of 1904. Hirosige stressed that [31]:

1. In contrast to Einstein, Poincaré lacked the concept of electromagnetic field as an independent and dynamical physical entity, as is shown by his indication of the crisis of the action–reaction principle in the interaction between matters and electromagnetic waves.
2. In spite of his indication that space and time need not be absolute, Poincaré did not attempt to reconsider the meaning of space and time in the theory of physics and to dispense with the concept of the ether.

At the same time, Gerald Holton criticized Whittaker from an historical point of view [32]:

1. Poincaré's 1904 address, which Whittaker cited, did not enunciate the new principle of relativity, but summarized the difficulties which contemporary physics opposed to six classical laws or principles, including the Galilean–Newtonian principle of relativity.
2. Lorentz's paper of 1903, which Whittaker cited as containing most of the basic results of Einstein's 1905 paper, was in fact published in 1904 in Holland, which Einstein could not obtain. Moreover, he did not need to know of it, because Einstein *derived* the transformation equations that Lorentz assumed *a priori*.
3. Lorentz's 1904 paper was not on STR, as we understand it since Einstein. There, Lorentz used nonrelativistic addition law for velocities ($\boldsymbol{v} = \boldsymbol{V} + \boldsymbol{u}$), and, contrary to what Whittaker wrote, Lorentz's transformation equations of 1904 is valid only to small values of v/c, due to Lorentz's miscalculation.

Later on, Holton's position was further developed by his former student Stanley Goldberg [30].

6. Introduction of the Light-Velocity Postulate

As we have seen, Poincaré revised Lorentz's theory of electrons based on the Maxwell equations to include the relativity postulate. As noted in Section 3, a combination of these two (Maxwell's equations and the relativity postulate) allowed the constancy of light velocity to be deduced. Therefore, they felt no need to put forth independently the light-velocity postulate.

The situation was much different for Einstein, who had expressed his doubts about the existence of the ether as early as 1899 in a letter to his fiancée, as follows [53]:

> I'm convinced more and more that the electrodynamics of moving bodies as it is presented today doesn't correspond to reality, and that it will be possible to present it in a simpler way. The introduction of the term "ether" into theories of electricity has led to the concept of a medium whose motion we can describe, without, I believe, being able to ascribe physical meaning to it. I think that electrical forces can be directly defined only for empty space [...]

The above quotation shows that Einstein already doubted then the existence of the ether and the validity of Maxwell's electrodynamics based on it. Therefore, we should regard Einstein's STR as a theory constructed upon these doubts from the start.

In fact, Einstein's letter of 1955, which Max Born quoted in his Bern lecture mentioned in Section 5, states [58]:

> The new feature of [STR] was the realization of the fact that the bearing of the Lorentz-transformations transcended their connection with Maxwell's equations and was concerned with the nature of space and time in general. A further new result was that the "Lorentz invariance" is a general condition for any physical theory. This was for me of particular importance because I had already previously found that Maxwell's theory did not account for the microstructure of radiation and could therefore have no general validity [...]

Born commented on the above, "The last sentence of this letter is of particular importance. For it shows that Einstein's paper of 1905 on relativity and on the light quantum were not disconnected."

The above account is also confirmed by Einstein's comment on Max Laue's book [34] on STR. Einstein wrote to Laue on 17 January 1952 [33]:

> When one looks over your collection of proofs of [STR], one becomes of the opinion that Maxwell's theory is unquestionable. But in 1905 I already knew for certain that Maxwell's theory leads to false fluctuations of radiation pressure and hence to an incorrect Brownian motion in a Planck cavity.

What is more, in his later paper of 1916 on the quantum theory of radiation [26], he calculated the fluctuation of radiation anew. In this recalculation, he utilized the transformation equations corresponding to the optical Doppler effect and to the stellar aberration, which he had deduced in Section 7 of his STR paper of 1905 from the Maxwell equations. Concerning these relations, he states [9]:

> One could object that [these] equations [...] are based upon Maxwell's theory of electromagnetic field, a theory that is incompatible with quantum theory. But, this objection touches the form more than the essence of the matter. Because, in whichever way the theory of electromagnetic processes may develop, it will certainly retain Doppler's principle and the law of aberration [...] According to the theory of relativity, the transformation law applies, for example, also to the energy density of a mass that moves with the (quasi) speed of light.

The above quotations testify that STR was constructed, or at least thought of, as a theory applicable beyond the realm of the applicability of Maxwell's theory.

In fact, as distinct from Lorentz's 1904 paper [35], which starts with Maxwell's and Lorentz-Force's equations, the Kinematical Part of Einstein's STR paper contains neither. Therefore, in spite of its title "On the Electrodynamics of Moving Bodies" ("Zur Electrodynamik bewegter Körper"), his STR paper does not premise Maxwell's electrodynamics.

However, in order to derive the Lorentz transformation equations, Einstein required the constancy of light velocity, which had already led him to the revision of the concept of time. Thus, in order to transcend Maxwell's electrodynamics, he had no choice but to elevate the constancy of light velocity deduced from the latter to the status of the light-velocity postulate [3, p. 21]. Thus, the essential difference between the theory of Lorentz–Poincaré and that of Einstein lies in the fact whether or not the light-velocity postulate is put forth independently of the relativity postulate. In other words, Lorentz–Poincaré's theory lacks the "Kinematical Part" essential for STR.

Einstein's STR was later utilized in the explanation of the Compton effect (i.e. scattering of a photon by an electron) by Arthur Compton [6], and in the introduction of the matter-wave by Louis de Broglie both in 1923 [7], while Lorentz–Poincaré's theory was not. Moreover, Einstein's STR gave rise to Paul Dirac's relativistic quantum theory of electrons in 1928 [8], whereas Lorentz's and Poincaré's electron theories were useless. In short, while Lorentz–Poincaré's theory remained the classical theory, Einstein's STR survived the quantum revolution.

7. Einstein's Autobiographical Error

Why did so many excellent researchers of the history of STR overlook the obvious fact that STR was constructed as a theory transcending Maxwell's electrodynamics? The reason might lie in a crucial error contained in "Notes" in the first and the second editions of *Albert Einstein: Philosopher–Scientist*, published in 1949 and 1951 respectively. The problem occurred in the following lines [19]:

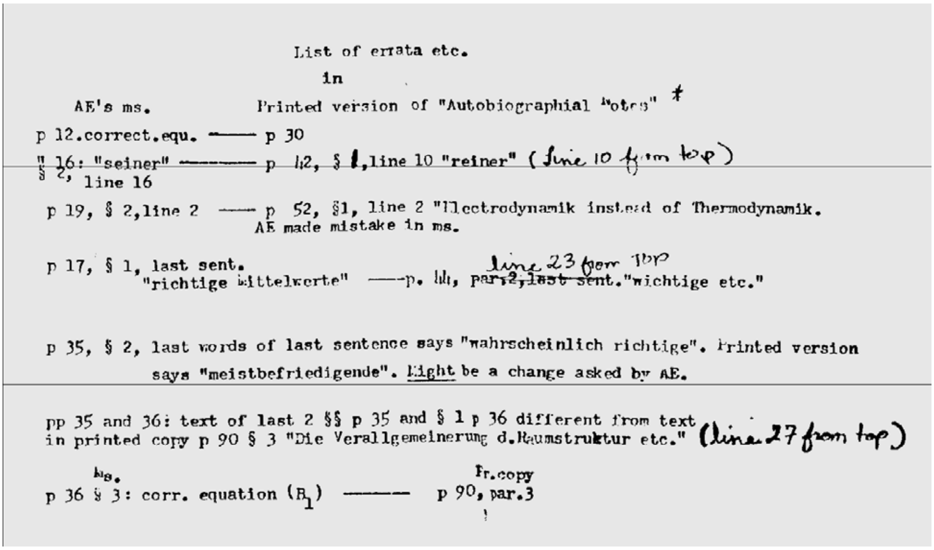
> Reflections of this type made it clear to me as long ago as shortly after 1900, i.e., shortly after Planck's trailblazing work, that neither mechanics nor *thermodynamics* (except in limiting cases) claim exact validity. By and by I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. [italics added]

Einstein intended to write "electrodynamics", not "thermodynamics." The above paragraph hides the fact that the correct version was published first in 1955, the year of Einstein's death, as the German edition in Stuttgart [12]. This edition identifies itself as "The only authorized transcription of the volume published in 1949 [*Einzig autorisierte Übertragung des 1949 erscheinenen Bandes*]." Einstein himself approved the correction. This error misled students of the history of STR to believe that Einstein regarded electrodynamics as holding good instead of thermodynamics.

I inquired of The Albert Einstein Archives at Jerusalem how the error and the correction took place. The answer from an archivist (Barbara Wolff) was as follows [2, p. 204]:

> When "Autobiographisches" was published in 1949, someone found several errors in the printed version (we do not know who) and Helen Dukas [Einstein's secretary] marked the corrections in Einstein's copy of the book. We not only recognize her handwriting, but also have a letter in which she explains that she corrected the errors in Einstein's copy of the book. [. . .] In addition, she typed a "list of errata" (undated, supposedly just after the 1949 edition). [. . .] One copy of the list was given to Peter Bergmann [Einstein's assistant] and we were convinced that the first additions to the list were his.

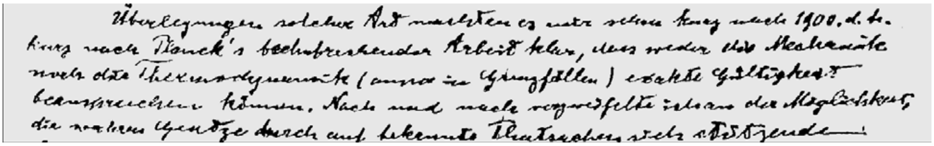
Dukas' errata list is reproduced in Figure 1; the relevant passages in the manuscript and the correction on the printed version are shown in Figures 2a and 2b.



List of errata etc.
in
AE's ms. Printed version of "Autobiographial Notes" *

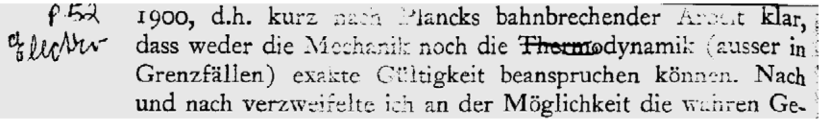
p 12.correct.equ. —— p 30
" 16: "seiner" —— p 42, § 1, line 10 "reiner" (line 10 from top)
§ 2, line 16
p 19, § 2, line 2 —— p 52, §1, line 2 "Electrodynamik instead of Thermodynamik.
AE made mistake in ms.
p 17, § 1, last sent.
"richtige Mittelwerte" ——p. 44, par. ~~2, last sent.~~ line 23 from top "wichtige etc."
p 35, § 2, last words of last sentence says "wahrscheinlich richtige". Printed version says "meistbefriedigende". Might be a change asked by AE.
pp 35 and 36: text of last 2 §§ p 35 and § 1 p 36 different from text in printed copy p 90 § 3 "Die Verallgemeinerung d.Raumstruktur etc." (line 27 from top)
Ms. Pr.copy
p 36 § 3: corr. equation (B_1) —— p 90, par.3

Figure 1. "List of errata" for Einstein's "Notes". The relevant mistake is on p. 19 of Einstein's manuscript and on p. 52 of the printed version of the first (1949) and the second (1951) editions, which was corrected in the German (1955) and the third (1969) editions. Two other important corrections are also stated: 'seiner' (his) on p. 16 of the manuscript was misread as 'reiner' (pure) on p. 42 of the printed version, which was also corrected. 'richtge' (exact) on p. 17 of the manuscript was misread as 'wichtige' (important) on p. 44 of the printed version, which was not corrected. Permission granted by the Albert Einstein Archives, The Jewish National & University Library, The Hebrew University of Jerusalem, Israel.



Überlegungen solcher Art machten es mir schon kurz nach 1900, d. h. kurz nach Planck's bahnbrechender Arbeit klar, dass weder die Mechanik noch die Thermodynamik (ausser in Grenzfällen) exakte Gültigkeit beanspruchen können. Nach und nach verzweifelte ich an der Möglichkeit die wahren Gesetze durch auf bekannte Thatsachen sich stützende

(a)



p 52 Electro

1900, d.h. kurz nach Plancks bahnbrechender Arbeit klar, dass weder die Mechanik noch die ~~Thermo~~dynamik (ausser in Grenzfällen) exakte Gültigkeit beanspruchen können. Nach und nach verzweifelte ich an der Möglichkeit die wahren Ge-

(b)

Figure 2. (a) Einstein's manuscript, (b) the correction on the printed version. The third line of (a) reads as 'Thermodynamik'. In (b), 'Thermo' is corrected to 'Electro', where the handwriting is Dukas's. Permission granted by the Albert Einstein Archives, The Jewish National & University Library, The Hebrew University of Jerusalem, Israel.

The necessity of the correction is evident from three other passages in the "Notes" [18]:

A theory is the more impressive the greater the simplicity of its premises is, the more different kinds of things it relates, and the more extended is its area of applicability. Therefore the deep impression which classical *thermodynamics* made upon me. It is the only physical theory of universal content concerning which I am convinced that, within the framework of

> the applicability of its basic concepts, *it will never be overthrown*. [italics added]
>
> This form of reasoning [in Planck's derivation of his radiation formula] does not make obvious the fact that it contradicts the mechanical and *electrodynamical* basis, upon which the derivation otherwise depends. Actually, however, the derivation presupposes implicitly that energy can be absorbed and emitted by the individual resonator only in "quanta" of $h\nu$, [...] in contradiction to the laws of mechanics and *electrodynamics*. [italics added]
>
> The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results. The example I saw before me was *thermodynamics*. [italics added]

The correction was essential in order to make the text consistent.

One of those stymied by Einstein's mistake was Arthur I. Miller. He wrote in his book of 1982 [38],

> Of this paper on Brownian motion, Einstein wrote (1907d) that its results convinced him of *the insufficiency of mechanics and of thermodynamics* to account for properties of all systems of matter in motion. Moreover, Einstein continued, this state of affairs should be enough to convince everyone of the necessity for making fundamental changes in the basis of theoretical physics. [italics added]

The italicized part recalls the wording of the mistake in "Notes". Indeed, the statement Miller quotes agrees with the error in "Notes", but not with Einstein's paper of 1907 [24]. In that paper, Einstein meant, it is only in the absence of "the molecular-kinetic theory of heat", i.e. his statistical thermodynamics to be discussed in the next section, that the "fundamental changes" would have been required.

Because of this misinterpretation, Miller obscures the nature of STR [38]:

> Nevertheless, as long as one was not studying the instantaneous state of a system, in regions of space small enough so that fluctuation phenomena must be taken into account, then "equations of mechanics and thermodynamics can be employed," and with this restriction in mind one could also make use of Maxwell's equations. This Einstein did in the third paper that he published in vol. 17 of the *Annalen*, the relativity paper.

The above passage shows that Miller regards STR as a theory strictly restricted within the realm of classical physics applicable only to the macroscopic domain. If one takes this position, however, one can explain neither the necessity of setting up the light-velocity postulate as an independent postulate nor the difference between the theories of Lorentz–Poincaré and Einstein.

8. The Relationship among the Four Papers of 1905

As emphasized by Born, Einstein's papers on STR and on the light quantum are closely related. Japanese physicist–philosopher Mitsuo Taketani, former student and colleague of Hideki Yukawa (Japanese first Nobel Prize laureate physicist), wrote in a book on the history of quantum mechanics published in 1948 [48]:

> Einstein rejected the ether due not only to the Michelson–Morley experiment, but also to the standpoint of the light-quantum theory. [...] Einstein pointed out in the former paper that the classical electromagnetism contradicts the light quantum theory. In other words, light was not considered as vibrations of the ether in that paper. Therefore, Einstein did not reject the ether at first in his paper of relativity theory, but in his paper of light quantum. Having rejected

positively the medium ether, it became necessary for him to set up a kinematics that does not rely upon the ether [hence the STR paper].

The above quotation reflects Taketani's three-stage theory for the development of scientific theories. According to it, Planck's radiation formula corresponds to the phenomenological stage, the light quantum theory to the substantial stage, and STR to the essential stage. This explains the relationship between the first and the last of the four papers written in 1905.

As stated in Section 1, the second of the four papers is his dissertation, "New Determination of Molecular Dimensions." In this paper, Einstein estimates the viscosity coefficient of a liquid solution by solving the viscous hydrodynamic equation in the coordinate system of the solute molecule. As stated in Section 2, this estimation has to do with one of the sources of the relativity postulate. He also estimates the diffusion coefficient of the solute molecules utilizing the expression for the osmotic pressure of a dilute solution. Combining these two expressions of viscosity and diffusion coefficient together with their experimental data available on tables, he could calculate the diameter of molecules and Avogadro's number. Although Einstein did not publish his dissertation until 1905, it is certain that he started to work on it earlier than 1903 [52]. In my view, this paper constitutes the common origin of his three epochal works of 1905. I will give my reason below.

Before 1905, he published three papers on statistical physics (referred to below as "the statistical trio"). The first, published in 1902, was his attempt to close the gap in Boltzmann's kinetic theory of heat [16]. By this, Einstein meant the lack of derivations of the law of thermal equilibrium and the second law of thermodynamics from the equations of mechanics and the probability calculus. On the other hand, the second and the third ones, published in 1903 and 1904, do not rely upon mechanics [11]. The system there treated is a generalized thermodynamical system expressed by state-variables (*Zustandsvariabeln*), and, therefore, as I pointed out elsewhere [3, p. 11], the theory presented in these papers should more properly be called 'statistical thermodynamics' rather than 'statistical mechanics'. Thus, leaving the realm of mechanics, Einstein could safely apply his theory to black-body radiation in the third of the statistical trio [59].

In this last part of the statistical trio, he showed that the obtained expression of energy fluctuation for material systems also applies to black-body radiation (i.e. thermal radiation at equilibrium with the emitting body kept at constant temperature). Therefore, it is conceivable that he examined the consequence of replacing osmotic pressure in his dissertation with radiation pressure. This may have been one of the routes by which he arrived at the theory of light quantum. In fact, the light-quantum theory paper argues the similarity of thermodynamic and probabilistic behaviours among monochromatic radiation, the ideal gas, and the dilute solution. This constitutes the relation between the first and the second of the four papers.

The general applicability of his statistical thermodynamics allows the application of his treatment of the diffusion of solute molecules in his dissertation to the diffusion of microscopically visible small particles. Therefore, if we replace the solute molecules in the dissertation with the microscopically visible small particles, the latter particles are expected to execute rapidly varying random motion just like molecules do. It might be in this way that he arrived at the theory of Brownian movement, which treats the diffusion process of small particles and the osmotic pressure exerted by them.

Einstein was stimulated by the success of the replacement of the equations for material systems with those of radiation in the last of the statistical trio and in the light quantum theory. Therefore, as stated in Section 2, he tried to consider the result of replacing the liquid solution in his dissertation with black-body radiation, and the hydrodynamic equation with electromagnetic field equations. This seems to have been one of the routes by which he arrived at STR. Thus, his dissertation seems the common source of Einstein's three epochal works of 1905.

A more definite relationship among the three epochal papers is exhibited in his "Notes". In it, Einstein describes a thought experiment,[3] which applies his theory of Brownian movement to a small mirror suspended in a cavity filled with black-body radiation [20]. As will be explained in Chapter 8, Einstein and quantum theory, of this book, in order to investigate more closely the structure of radiation, a precise expression of the radiation pressure and, therefore, the Maxwell's equations in the moving coordinate of the suspended mirror became necessary. Therefore, the urgent purpose of the construction of STR at that time seems the investigation into "the structure of radiation" and more generally into "the electromagnetic foundation of physics" [2, pp. 209–210].

9. Einstein's Route to General Relativity

In September 1905, as a sequel to the STR paper, Einstein published a paper entitled "Does the Inertia of a Body Depend upon Its Energy Content?" [15]. He derived in it the famous law of mass-energy equivalence,

$$E = mc^2.$$

His procedure of derivation was as follows. First, he identified the energy difference of a body measured from the rest and from the moving (with the velocity v) frames of reference as the kinetic energy $\frac{1}{2}mv^2$ of that body. Second, he considered the case that, measured from the rest frame, light with energy L is emitted from that body. Third, he calculated the energy of the emitted light measured from the moving frame, utilizing the transformation equation of light energy obtained in Section 8 of the STR paper. The resultant energy difference of the light energy measured from the two frames means the reduction in kinetic energy of that body after the emission of light. This reduction corresponds to that of its inertial mass by L/c^2 after the loss of its energy L.

In 1907, Johannes Stark, the editor of the *Jahrbuch der Radioaktivität und Elektronik*, asked Einstein to contribute a review on the recent development of STR to his journal. In writing this review, Einstein took the first step of his investigations into the gravitational field and into the general theory of relativity. On this process, Einstein said in the Kyoto Address:

> It was just then [preparing the "review"] that I realized that, despite the fact that all the rest of the laws of nature fitted into the discussion by the special theory of relativity, solely the law of universal gravitation did not. I felt deeply that I wanted somehow to find the reason why. But, I could not fulfill this purpose easily. Above all, what is most unsatisfactory to me was that, while the relationship between inertia and energy was given excellently by the special theory of relativity, that between this and weight, namely, between energy and the gravitational field,

[3] A thought-experiment is an imaginative experiment considered in order to make inferences theoretically.

> was left quite uncertain. I imagined that its explanation could not be accomplished in terms of the special theory of relativity.

As he admitted in the above, Einstein does not seem to have thought seriously about the problem of gravitation until that time. One of the reasons might be that, in the chemico-thermal tradition (to be explained in Chapter 8) to which Einstein belonged, gravitation was not a common topic compared with more practical problems such as thermal radiation, physical chemistry and electromagnetic theory. Therefore, 26-year-old patent officer Einstein concentrated on the latter problems in 1905. Moreover, in that tradition, neglecting the problem of gravitation was not regarded as a fault of the paper, and thus, scholars of this tradition accepted and welcomed Einstein's STR [2, pp. 210–214].

On the other hand, in the case of Poincaré, who belonged to the other more idealistic tradition (i.e. the particle-dynamical tradition), the negligence of gravitation was a serious fault. What is more, when he wrote his paper of 1905, Poincaré was already a 51-year-old established scholar, and thus not allowed to commit such a fault. Thus, in Poincaré's homonymous articles of 1905 and 1906, he was at pains to explain in mathematical detail how one might account for gravitation in his new dynamics.

In the introduction to his 1907 paper, Einstein wrote as follows [27]:

> The most important result of the fourth part is that concerning the inertial mass of energy. This result suggests the question whether energy also possesses *heavy* (gravitational) mass. A further question suggesting itself is whether the principle of relativity is limited to *nonaccelerated* moving systems. In order not to leave these questions totally undiscussed, I added to the present paper a fifth part that contains a novel consideration, based on the principle of relativity, on acceleration and gravitation. [italics original]

And his review ends with the remark [27, p. 311]:

> Thus the proposition derived in Section 11 that to an amount of energy E there corresponds a mass of magnitude E/c^2, holds not only for the *inertial* but also for the *gravitational* mass, if the assumption introduced in Section 17 is correct. [italics original]

The "assumption" stated above is the so-called principle of equivalence, i.e. the equivalence of the laws of nature between the accelerated system and the system at rest in certain homogeneous gravitational fields.

From the above quotations we can see, as I noted elsewhere [1, p. 10], that "the heavy mass of energy" was a more urgent problem for Einstein at that time than the limitation of relativity postulate to nonaccelerated moving systems. He explained the reason for this in his Gibson lecture, given at Glasgow in 1933, which also gives the reason why he did not attempt to treat the problem of gravitation within STR [17]:

> In the theory I advanced, the acceleration of a falling body was not independent of its horizontal velocity or the internal energy of a system. [. . .] This did not fit in with the old experimental fact that all bodies have the same acceleration in a gravitational field. This law, which may also be formulated as the law of the equality of inertial and gravitational mass, was now brought home to me in its all significance. [. . .] I now abandoned as inadequate the attempt to treat the problem of gravitation [. . .] within the framework of special theory of relativity.

Thus, he was led to the 'principle of equivalence' in the way he remembered in the Kyoto Address:

> I was sitting in a chair in the patent office at Berne. Suddenly at that time, an idea dawned on me.

"If a man falls freely, he should not feel his weight himself."

I felt startled at once. This simple thought left me with a deep impression indeed. It was this deep impression that drove me to the theory of gravitation. I went on thinking and thinking.

When a man falls, he has the acceleration. The judgments he makes must be those in the system of reference with acceleration.

Thus, I determined to extend the principle of relativity, so as to be applicable not only to the system of reference moving with uniform velocity, but also to that moving with acceleration. By doing so, I expected that the problem of gravitation could be solved at the same time. I expected so because we can interpret the reason why a person in a free fall does not feel his weight, as that there is, other than the gravitational field caused by the Earth, another gravitational field compensating it. In other words, in a system of reference moving with acceleration, it is required that there should appear a new gravitational field.

Yet, I could not solve the problem completely at once. It was after another eight years that I found out the true relationships.

As we have seen, there was an undoubted continuity of his research on both the special and the general theories of relativity.

Acknowledgements

I am grateful to the Albert Einstein Archives, Jewish National & University Library, Jerusalem, for furnishing me with materials and information.

References

The following abbreviations are used: *AEPS,* P. A. Schilpp ed., *Albert Einstein, Philosopher–Scientist*, 1st ed. (Evanston, 1949), 2nd ed. (New York, 1951), 3rd ed. (La Salle, 1969): *AJP, American Journal of Physics*; *Brownian*, R. Fürth ed., *Investigations on the Theory of Brownian Movement* (London 1926, reprint New York 1956); *CPEE, The Collected Papers of Albert Einstein*, English Translation, vol. 1– (Princeton, 1987–); *HSPS, Historical Studies in the Physical and Biological Sciences; LCP, H. A. Lorentz, Collected Papers* (9 vols., The Hague, 1934–1939); *Letters*, J. Renn & R. Schulmann eds., *Albert Einstein–Mileva Marić, Love Letters* (Princeton, 1992); *Miraculous*, J. Stachel ed., *Einstein's Miraculous Year*, Princeton, 1998; *Origins*, G. Holton, *Thematic Origins of Scientific Thought* (Cambridge MA; 1973); *PR, The Principle of Relativity* (London, 1923, reprint New York, 1952).

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[4] S. Abiko: "Reply to Darrigol," *HSPS*, 35 (2005), to be published.
[5] M. Born: "Physics and Relativity," A. Mercier & M. Kervaire eds., *Fünfzig Jahre Relativitätstheorie* (Basel, 1956), pp. 244–260 on p. 247 & p. 250; *Physics in My Generation*, 2nd ed. (New York NY: Springer, 1969), pp. 100–115 on p. 103 & p. 105.
[6] A.H. Compton: "A Quantum Theory of the Scattering of X-rays by Light Elements," *Phys. Rev.* 21 (1923), 483–502.
[7] L. de Broglie: "Waves and Quanta," *Nature* 112 (1923), 540.
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[9] A. Einstein: *op. cit.* ref. [**??**], on pp. 228–229.
[10] A. Einstein: "A New Determination of Molecular Dimensions," *Brownian*, pp. 36–62; *CPEE*, 2, Doc. 15, pp. 104–122; *Miraculous*, pp. 45–69.

[11] A. Einstein: “A Theory of the Foundations of Thermodynamics,” *CPEE*, 2, Doc. 4, pp. 48–67; “On the General Molecular Theory of Heat,” *CPEE*, 2, Doc. 5, pp. 68–77.

[12] A. Einstein: “Autobiographisches,” P.A. Schilpp ed., *Albert Einstein als Philosoph und Naturforscher* (Stuttgart: Kohlhammer, 1955), pp. 1–36 on p. 19. I am indebted to Professor Masakatsu Yamazaki of the Tokyo Institute of Technology for having notified me the existence of this German edition.

[13] A. Einstein: *CPEE*, 5, Doc. 27, pp. 19–20.

[14] A. Einstein: “Dialog about Objections to the Theory of Relativity,” *CPEE*, 7, Doc. 13, pp. 66–75; see also S. Abiko: “On the Origin of Asymmetric Aging in the Twin Problem: Comments on M. Harada’s and M. Sachs’ Views,” *Physics Essays*, 15 (2002), 172–175.

[15] A. Einstein: “Does the Inertia of a Body Depend upon its Energy?” *PR*, pp. 67–71; *CPEE*, 2, Doc. 24, pp. 172–174; *Miraculous*, pp. 161–164.

[16] A. Einstein: “Kinetic Theory of Thermal Equilibrium and of the Second Law of Thermodynamics,” *CPEE*, 2, Doc. 3, pp. 30–47.

[17] A. Einstein: “Notes on the Origin of the General Theory of Relativity,” Carl Seelig ed., *Ideas and Opinions* (New York, 1954 & 1982), pp. 285–290 on p. 287.

[18] A. Einstein: “Notes,” *AEPS*, pp. 32–33; pp. 44–45; pp. 52–53.

[19] A. Einstein: “Notes,” *AEPS*, pp. 50–53.

[20] A. Einstein: “Notes,” *AEPS*, 1, 50–51.

[21] A. Einstein: “On a Heuristic Point of View Concerning the Production and Transformation of Light,” *CPEE*, 2, Doc. 14, pp. 86–103; *Miraculous*, pp. 177–198.

[22] A. Einstein: “On an Investigation of the State of the Ether in a Magnetic Field,” *CPEE*, 1, Doc. 5, pp. 4–6 on p. 5.

[23] A. Einstein: “On the Electrodynamics of Moving Bodies,” *PR*, pp. 35–65; *CPEE*, 2, Doc. 23, pp. 140–171; *Miraculous*, pp. 123–160. The English translations of this paper quoted below are from *Miraculous*.

[24] A. Einstein: “On the Inertia of Energy Required by the Relativity Principle,” *CPEE*, 2, Doc. 45, pp. 238–251 on p. 239.

[25] A. Einstein: “On the Movement of Small Particles Suspended in Stationary Liquids Required by Molecular-Kinetic Theory of Heat,“ *Brownian*, pp. 1–18; *CPEE*, 2, Doc. 16, pp. 123–134; *Miraculous*, pp. 85–98.

[26] A. Einstein: “On the Quantum Theory of Radiation,” *CPEE*, 6, Doc. 38, pp. 220–233; see also S. Abiko: “Einstein’s Theories of the Fluctuation and the Thermal Radiation: the First Quantum Theory through Statistical Thermodynamics,” *Histria Scientiarum*, 10 (2000), 130–147, on 141–143.

[27] A. Einstein: “On the Relativity Principle and the Conclusion Drawn from It,” *CPEE*, 2, Doc. 47, pp. 252–311 on pp. 254–255. It should be noted here, that, in *CPEE*, 2, the last sentence quoted is mistranslated as “In order not to leave this question.” The German words “Um diese Fragen” in the original should be translated into plural, i.e. “these questions.” This mistake seems to be caused by the prevailing attitude, which disregard the importance of the first question.

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[33] Unpublished letter quoted in G. Holton: “Influences on Einstein’s Early Work,” *The American Scholar*, 37 (1967–1968), 59–79; *Origins*, 197–217 on 201–202.

[34] M. Laue: *Das Relativitätstheorie* (Vieweg, 1911).

[35] H.A. Lorentz: “Electromagnetic Phenomena in a System Moving with any Velocity Less than That of Light” (1904), *LCP*, 5, pp. 172–197; *PR*, pp. 9–34.

[36] H. A. Lorentz: “Michelson’s Interference Experiment,” *PR*, pp. 5–6.

[37] E. Mach: *Die Mechanik in Ihrer Entwicklung Historisch-Kritisch Dagestellt*, 1883; the Engl. trans. *The Science of Mechanics*, La Salle: Open Court, 1893. In “Notes,” Einstein wrote, “It was Ernst Mach who, in his *History of Mechanics*, shook this dogmatic faith [in mechanics as the final basis of all physics]; this book exercised a profound influence upon me in this regard while I was a student.”

[38] A.I. Miller: *Albert Einstein's Special Theory of Relativity* (Reading, 1981; reprint New York, 1998), p. 128.
[39] H. Poincaré: "Sur la dynamique de l'electron," *Comptes Rendus de l'Academie des Science*, 140 (1905), 1504–1508 & *Rendiconti del Circolo Mathematico di Palermo*, 21 (1906), 129–176.
[40] H. Poincaré: "The Principles of Mathematical Physics," *The Monist*, 15 (1905), 1–24 on 11.
[41] H. Poincaré: *Value*, p. 129.
[42] H. Poincaré: *Value*, p. 220.
[43] H. Poincaré: *Value*, p. 87.
[44] H. Poincaré: *Value*, pp. 129–130.
[45] H. Poincaré: *Value*, pp. 73–74.
[46] R. Shankland: "Conversations with Albert Einstein," *AJP*, 31 (1963), 47–57 on 55.
[47] M. Solovine: "Introduction," A. Einstein: *Letters to Solovine*, New York: Citadel, 1993, pp. 5–13 on p. 9.
[48] M. Taketani: *The Formation and the Logic of the Quantum Mechanics*, vol. 1 (Tokyo, 1948; reprint Tokyo, 1972), p. 62, in Japanese. My translation from Japanese.
[49] M. Wertheimer: *Productive Thinking*, enlarged ed. (New York, 1959), pp. 213–233. He was one of Einstein's colleagues at the University of Berlin and is renowned as the father of Gestalt psychology.
[50] E. Whittaker: *A History of Aether and Electricity, the Modern Theories 1900–1926* (London, 1953), pp. 27–77.
[51] W. Wien: "Ueber die Fragen, welche die translatorische Bewegung des Lichtäters betreffen," *Annalen der Physik und Chemie*, 65 (1898), no. 3, Beilage: i–xvii on xv–xvi.
[52] Letter from Einstein to Michele Besso, 17 March 1903, *CPEE*, 5, Doc. 7, pp. 11–12 on p. 11.
[53] *Letters*, pp. 10–11 (10 Aug. 1899).
[54] *Letters*, p. 72 (28 Dec. 1901), where he expresses his intention to read Lorentz's 1895 book written in German.
[55] *Letters*, p.15 (28 Sept. 1899).
[56] *Letters*, p. 15 (28 Sept. 1899), which cited Wien's 1898 paper referring to the Michelson–Morley experiment; *Letters*, p. 72 (28 Dec. 1901), which referred to Lorentz's 1895 book explaining the result of this experiment.
[57] "Notes," *AEPS*, 1, pp. 52–53. I have omitted, in the last sentence of the quoted part in Schilpp's translation, the word "otherwise" which has no German counterpart in Einstein's original text and seems a mistranslation.
[58] Quoted in Born (1956), *op. cit.* note 26 on pp. 248–249; Born (1969) on p. 104. This letter was first published on *Technische Rundschau* N. 20, Jg. 47, Bern, 6 Mai 1955.
[59] See Section 3 of Chap. 8 of this book.
[60] *The Born–Einstein Letters* (London, 1971), pp. 197–198.
[61] This method of calculation is on G. Kirchhoff (W. Wien ed.): *Vorlesungen über Mechanik* (Leiptzig, 1987), which Einstein cited in his dissertation. He also states, while he was a student at ETH, "The balance of time I used in the main in order to study at home the works of Kirchhoff, Helmholtz, Hertz, etc.," on "Notes," *AEPS*, 1, pp. 14–15.