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# Relativity Theory: Genesis and Completion

V. A. Petrov *,

[a] *A. A. Logunov Institute for High Energy Physics,*

*NRC "Kurchatov Institute",*

*Protvino, 142281 Russia*

**e-mail: Vladimir.Petrov@ihep.ru*

**Abstract**. This is a concise survey of the history of the relativity theory from the Galileo relativity principle to the general formulation of the theory of relativity by Ignatowski.

**Keywords:** relativity principle, space, time, inertial frame, space-time geometry.

## INTRODUCTION

When discussing the choice of topics with the Program Committee of this Workshop, it was proposed to include the history and philosophy of physics in the program. Why do we consider it important?

- First, over time, what we do in science now will become the past in future.
- Secondly, the ups and downs of the search for truth by scientists of the past are very instructive.
- Thirdly, almost always, the circumstances, often very dramatic, of the struggle for priority, are very interesting as they reveal personal features of the scientists of the past.

So, my report is one of a few contributions to the implementation of this proposal. We hope hope it will be interesting and accepted favorably. This will be a signal to continue this practice in the future, at the next meeting to be held at the Logunov IHEP.

## RELATITY PRINCIPLE FROM DAWN TO A NEW BLOOM

Below we give a short account of those physicists whose work significantly influenced the progress towards the creation of the theory of relativity.

- Galileo Galilei

As the "center of gravity" of our subject lies in the Relativity Principle let me start my story with the famous book "Dialogo sopra i due massimi sistemi del mondo" (1632) (see English translation in [1]) by Galileo Galilei where the principle was clearly formulated for the first time. A few quite vague and ambiguous ideas in this line can be found in ancient Greek philosophers. We do not dwell on that.

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This is how Galileo himself formulated the principle:

"*When you have observed all these things* (that is various events taking place inside the closed cabin of the ship: the fly of birds and insects, the fall of bodies, the trajectory of a thrown ball etc. My note, V.P.) *carefully (though there is no doubt that when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still."*

In books and textbooks, one can often come across the statement that Galileo, they say, formulated the principle of relativity "only for mechanical phenomena".

However, Galileo speaking about "these effects" clearly had in mind *any* physical phenomena.In no way he either limited the speed of his illustrating ship to be slow or excluded from his consideration some natural phenomena. Yes, such a statement of the principle does not look like the language of modern physics and may even seem naive and obsolete, but in essence it is completely accurate.

So, in what follows we, when using the term "relativity principle", will keep in mind "Galilei's principle of relativity" in its most universal sense.

At the same time, we resolutely reject the interpretation of Galileo's principle of relativity as a principle that affirms the invariance of Newton's laws, which narrows and therefore distorts its original formulation.

- René Descartes

The whole history of the difficult path to the theory of relativity is inextricably linked with the "ether". One of the first proponents of such a notion was René Descartes. In his writings, he consistently adhered to the Aristotelian thesis "*Natura abhorret vacuum*" and filled the Universe with an all-pervading certain substance, which later became finally known as "ether" (or "aether"). According to Descartes, the ether carried out all the interactions of bodies, as well as the phenomenon of light. Hence the expression "luminiferous ether"[2]. It was this substance that was at the center of attention of physicists during subsequent centuries, especially in the late 19th and early 20th centuries.

OK, now the space is not empty, cheers up to Aristotle. But what about the very "space"? Mathematically the notion is *bona fide* and not least thanks to Descartes, who "arithmetized" the empty space by inventing the method of coordinates whose role in the consequent development of physics, mathematics and technology cannot be overestimated.

- Isaak Newton

Leaving the ether aside for a moment, let us ask whether the physical existence of space itself is conceivable without regard to matter?

Isaac Newton summarized his thoughts on this subject in the following way [3]:

> "*Absolute space, in its own nature, without regard to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies: and which is vulgarly taken for immovable space ... Absolute motion is the translation of a body from one absolute place into another: and relative motion, the translation from one relative place into another*".

As one deals with motion of physical bodies another essence appears inevitably, the time. And again Newton, just as in the case of space, distinguishes two types of time:"*Absolute, true and*

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*mathematical time, of itself, and from its own nature flows equably without regard to anything external, and by another name is called duration: relative, apparent and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time ...*"

We see that Newton was not so adherent to the absolute. The next quotation from "Principia..."actually repeats the Galileo relativity principle:

" *When bodies are enclosed in a given space, their motions among themselves are the same whether the space is at rest, or whether it is moving uniformly straight forward without circular motion*."

Note that Newton did not include absolute space as an object of the principle of relativity, avoiding an obvious contradiction. However, absolute space was considered as an object, relative to which acceleration occurs.

What is important for us now is to note that Newton essentially relied on the Galilean principle of relativity, and associated with each (inertial) frame of reference its own time (in addition to the coordinates).

Let us note a very important circumstance. It was identification of the Galilei relativity principle with form-invariance of the second Newton law which launched the incorrect interpretation of the Galilean principle of relativity with invariance with respect to the transition from an (arbitrarily chosen) "resting" inertial frame to an inertial frame moving (along the axis *x*) uniformly and rectilinearly with a speed $v$ expressed by the following specific (supposedly "Galilean") transformations

$$x' = x - vt,\ y' = y,\ z' = z,\ t' = t \quad (1)$$

These transformations form a group (again incorrectly named "Galilei group") and leave intact the second Newton law

$$\boldsymbol{F} = m\ddot{\boldsymbol{r}}.$$

From this incorrect identification of the principle of relativity with the principle of invariance under transformations (1) a long history of unsuccessful attempts to measure the "velocity relative to absolute space" (filled with ether) began. Related feature is the absoluteness of time seen in (1) though Newton mentioned beyond his "absolute time"also "relative, apparent and common time". Only two centuries later immutability of the absolute time $t' = t$ was changed for another time which Newton would call "relative".We will see this below.

- Christiaan Huygens

Newton, with his famous "*hypotheses non fingo*" ("I do not invent hypotheses") and the theory of action at a distance, did not publicly express his concern about the emptiness of space (although such a concern existed).

In contrast, Christiaan Huygens, who was renown (among other outstanding achievements) for his formula for the time of oscillation of the simple pendulum, used Descartes' ethereal theory as the basis for his ingenious wave theory of light [4].

Before him, it had never occurred to anyone that light could be associated with some kind of vibrations (let us noted that Huygens considered the ether waves to be longitudinal and only later Fresnel proved that they should be transversal). For example, Newton, a contemporary of Huygens and even personally acquainted with him, adhered to the fact that light is a set of tiny moving corpuscles. However, two hundred years later, it turned out that he was not too far from the truth. The wave theory of light, as is known, "won victory" over the corpuscular theory, easily explaining the phenomena of interference and diffraction which was demonstrated by Young and Fresnel. But a real and brilliant incarnation was waiting for it ahead.

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- <u>James Clerk Maxwell</u>

On the long and difficult road to the theory of relativity the most significant was, perhaps, the problem of the "ether wind" which James Clerk Maxwell was very concerned about and to which he devoted his letter to D. P. Todd headlined "*On a Possible Mode of Detecting a Motion of the Solar System through the Luminiferous Ether*" and published posthumously [5].
From his unified theory of electric and magnetic fields he derived that an electromagnetic perturbation created in some point of space is to propagate over the ether with a finite speed and, in particular, to create luminous phenomena. One could estimate this speed as near 300 000km/sec.
As visible light was a kind of electromagnetic wave the idea arose to measure - with help of optical phenomena- the speed of the body in relation to the absolute space in which, as it was believed, the luminiferous ether rested.

- <u>Experimental searches for the "ether wind</u>".

As the light was thought to be waves in the ether so experimental searches for the "ether wind" naturally dealt mainly with optical phenomena.
We will limit ourselves to two examples, the first of which is little known, while the second has become a "classic of the genre" and an obligatory mention in any book on the theory of relativity.
Thus, the French physicist Éleuthère Élie Nicolas Mascart published in 1872 [6] his report about his optical measurements with the following summary:
" *The general conclusion of this memoir would be that translational movement of the earth has no appreciable influence on optical phenomena produced from a terrestrial source or solar light, that these phenomena do not give any means of measuring the absolute motion of a body, and that* ***relative movements are the only we can measure***."
Concerning the conceptual value of this result, Paul Langevin wrote [7]:
"*The very recent introduction of the principle of relativity in physics and mechanics already entails consequences of the first importance and* ***it is essential to remember that Mascart, after a considerable experimental effort, was the first to affirm its accuracy."***
15 years later, Albert A. Michelson and Edward W. Morley conducted their now legendary "experiment of Michelson-Morley".
The authors when summarizing their results in the article "*On the Relative Motion of the Earth and the Luminiferous Ether*" [8] limited themselves to a rather modest conclusion:
" *It appears from all that precedes, reasonably certain that if there be any relative motion between the earth and the luminiferous ether, it must be small*."
In fact, it can be said that, within the very good accuracy achieved by them at that time, they did not find any traces of the "ether wind".

- <u>Woldemar Voigt</u>: the first attempt on absolute time

Just the same year 1887 as of the Michelson - Morley experiment a noteworthy article appeared [9].
In the course of consideration of the invariance of the wave equation in moving reference systems a Göttingen professor Woldemar Voigt has found that corresponding transformations from a system at rest to a system moving with constant velocity $v$ included not only the change of coordinates ( see Eq.(1) "Galilei" transformations) but also the change of time! Here are Voigt's transformations ($c$ stands for the velocity of light):

$$x' = x - vt,\ y' = \sqrt{1-\frac{v^2}{c^2}}y, \qquad z' = \sqrt{1-\frac{v^2}{c^2}}z,\ \ t' = t - \frac{vx}{c^2}\,(2)$$

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Anyone who is at least a little familiar with the theory of relativity, seeing these equations, will surely exclaim: "The roots are not where they should be!" And, of course, he will be right. The correct expressions "with roots in the right place" would be later obtained by Larmor and Lorentz. If it occurred to Voigt to check the transitivity or reciprocity of this transformation, then he would certainly come to the correct result! But to say: "Voigt was wrong" and just go further would be unfair. Yes, the equations are not what is needed, but they contain a great truth: *time is not absolute, it depends on the reference system!*
We saw this in an indefinite form in Newton, but Voigt, for the first time in the history of physics, gave this fact a quantitative content. Even if not entirely true (although fair at low speeds) this in no way diminishes the conceptual significance of Voigt's find. Which, unfortunately, he himself could not fully appreciate. His finding on the "relative time" was rediscovered in 1992 by H. A. Lorentz.

- Almost on top of the mountain: Joseph Larmor and Hendrik Antoon Lorentz.

The correct transformations were obtained by 1900 independently by Larmor [10] and Lorentz [11] in the course of investigations of the electrodynamics of moving media. They searched for transformations of time and space coordinates which would leave the Maxwell equations form-invariant. Both managed to fulfill this task. Of course, their result is well known now to everyone, but we will not deprive ourselves of the pleasure of writing them again.

$$x' = \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}},\ y' = y, z' = z,\ t' = \frac{t - \frac{vx}{c^2}}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (3)$$

We used to call these transformations "Lorentz transformations" (with the light hand of Poincaré) but, certainly, it would be fairer to call them "Larmor-Lorentz transformations". Interestingly, Lorentz himself suggested using the term "relativistic transformations", but for some reason the name "Lorentz transformation" first used by Henri Poincaré, stuck.

- Jules Henri Poincaré

When moving to another frame of reference, not only space-time coordinates change. For example, energy and momentum, electric and magnetic fields, charge density and current vector. Lorentz struggled a lot to get these formulas, but he was only able to do it with the help of Henri Poincaré. The latter not only corrected some of Lorentz's mistakes, but gave a completely general view of the principle of relativity and its physical consequences. Many of these consequences, such as "time dilation" or "length contraction" that have attracted a lot of public attention, are a simple consequence of transformations (3). We give here the formulation of the principle of relativity, given by Poincaré in 1904 [12] (which can be regarded as a modernized Galileo principle) and "*according to which the laws of physical phenomena must be the same for a stationary observer as for one carried along in a uniform motion of translation, so that we have no means, and can have none, of determining whether or not we are being carried along in such a motion".*
Poincaré, unlike other participants in this race, actually applied the universality of the principle of relativity, including gravity in consideration. In fact, his 1905 papers [13] contain a complete set of formulas and equations (for example, relativistic mechanics), making the theory of relativity a ready working tool.

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- Hermann Minkowski

Among other things, in the work of Poincaré a new interpretation of the theory of relativity was given as a choice of 4-dimensional pseudo-Euclidean geometry, and the Lorentz transformations could be considered as "rotation by an imaginary angle". This point (combining space and time into a single 4-dimensional continuum) served a starting point for Hermann Minkowski who developed Poincaré's idea to a mathematically flawless tensor approach [13] to the theory of relativity, in which he introduced the concepts that we still use today: forward and backward light cones, space like and timelike 4-vectors and surfaces, stress tensors etc. Thus, the essence of the relativity theory could be expressed as a choice of underlying geometry as a 4D pseudo-Euclidean space-time ("Minkowski space").

- Albert Einstein

Finally, we need to add the most celebrated participant in solving the problems of "Electrodynamics of Moving Bodies" and, of course, we are talking about Albert Einstein. Unlike previous researchers, he set the task of deriving time and coordinate transformations by analyzing clock synchronization on the basis of two postulates, namely [14]. :
"1. *The laws by which the states of physical systems undergo change are not affected, whether these changes of state be referred to the one or the other of two systems of co-ordinates in uniform translatory motion.*
2. *Any ray of light moves in the "stationary" system of co-ordinates with the determined velocity c, whether the ray be emitted by a stationary or by a moving body*."
How did he manage to arrive at these postulates? Einstein begun his work on relativity at a not very good time (probably in the beginning of 1905): the basic formulas of the theory of relativity had already been obtained by others. At that time he was an examiner at the Patent Office in Bern, one of the most respected European intellectual property agencies, which regularly received all the latest information on science and technology, including all the most important scientific journals and reviews. There are many different opinions about why in his first publication he did not refer to any of the authors listed above. Given his access to the main publications of European physicists, it is hard to believe that he simply ignored their papers, especially those that dealt with his own scientific interests. He could, of course, consider these papers incorrect, erroneous. Then his criticism would only serve as a favorable background for his own results. But what was there to criticize?
Let me give you my personal version or rather "vision" of this story that I came up with after thinking a lot about his article [14].
Unlike Larmor and Lorentz, Einstein found his own way of deriving transformations between inertial frames. He applied the clock synchronization procedure with help of the light rays (used earlier by Poincaré [15]), taking it to compare the resting and moving frames. His props consisted of two ingredients: *the principle of relativity* (which he had known since 1903 after reading the book of Poincaré [16]) and *the postulate of constancy of the speed of light* in relation to the movement of the source, a fact inherent in any waves in a medium, in this case the medium was ether. Yes, he did successfully derive the Larmor - Lorentz transformations in this way! But with all the originality, it would be just a re-obtaining of the known result! It was too little for a young scientist who longed for real glory. One can imagine that at this moment Poincaré's words came to his mind: *"And our ether, does it really exist?"*. Yes, without ether, we can't say anything about the speed of light ... its constancy ... And what if ... And the main thought abruptly came: "Down with the ether, even Poincare himself doubts, but we can preserve its property of the constancy of the speed of light and let this be a new postulate!" Thus the phrase was born: "*the introduction of a "luminiferous ether" will prove to be superfluous…*".

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Now his work was not just a repetition of what others have done, but a completely new understanding of events: light without ether! No one has dared to do this yet. To “aethereers”, this might seem as absurd as the propagation of sound in the void…

Of course, this picture is just my fantasy, but it seems to me that there is reason for it. It is the rejection of the ether in the future that will serve as the basis for the long-term promotion of Einstein as the true and only creator of the theory of relativity.

## TWO RELATITY THEORIES?

Such a judgment is best illustrated by a quote from the speech by the famous mathematician Hermann Weyl [17]:

“*Foundation and creation of the theory of relativity are the work of a single person: Albert Einstein.”*

How could such a blatantly false conclusion be reached, one can only guess. But what is the "theory of relativity" after all? Since September 1905, two theories of relativity could be distinguished: the "ethereal" theory of Larmor, Lorentz and Poincaré and the "etherless" theory of Einstein. The only difference was that the first used the ether as a carrier of light while the second allowed light to propagate in the empty space (provided that its velocity is independent of the motion of the source) . The common element was the relativity principle. We emphasize that in both theories the speed of light was constant (albeit for different reasons).

As for all the formulas and equations, they were basically the same. The same were the predictions of the future, and the description of the measured phenomena. One should only agree with the conclusion [18]: “*It seems impossible to distinguish, by any experiment, Lorentz’s and Poincaré’s theory from Einstein’s special relativity.* ***The empirical content of those theories is identical****"*.

What then prevents us from putting Larmor, Lorentz and Poincaré at least next to Einstein? Why is it repeated in the many writings on the theory of relativity that these scientists "failed to take some last, decisive step" towards the creation of a theory that would allow them to become on a par with Einstein? The answer is simple: they continued to cling to the decrepit concept of ether, while Einstein took a grandiose and bold move: he discarded the ether, replacing it with empty space! Although at the cost of an additional postulate, ingeniously borrowed from the rejected "ethereal" theory.

If to read Poincaré one can clearly see that he was fully aware of the paradoxical properties that the ether had to have. From the relativity principle would follow this that the ether should have remained at rest in any inertial frame. Something crazy, isn’t it? Nonetheless he intuitively hesitated to say “good buy” to this strange substance. However, as we will see further, things appear to be not so crazy and Poincaré would be right, though he would never know it. .

At the moment let us take into account that the whole history of the creation of the theory of relativity, as it (with inevitable modifications) is presented in textbooks, is usually limited only to the names (crescendo) of Galilei, Newton, Lorentz and Einstein. Note that when mentioning Lorentz, it is necessarily added that he, poor fellow, “did not understand the essence of relativity”. Sometimes, however, it is said about Poincaré . In the sense that he "could not take the last, decisive step."

It seems to me that even the limited information about the process of creating the theory of relativity that I was able to bring to your attention will allow you to disagree with this tendentious judgment. And the historical process itself is beautifully illustrated by the following words by Poincaré [19]:

“*Science …is a collective creative work, and it cannot be anything else; it is like a monumental construction that has to be constructed for centuries, and where everybody must bring a stone to, and this stone can cost him a whole life.*

*Hence, it gives us a feeling of a necessary cooperation, solidarity of our labour with the labour of our contemporaries, our predecessors and our followers*.”

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This could be the end, but I would like to tell you about one more participant of the creation of the theory of relativity, although little known, but who for the first time gave the principle of relativity its unique and universal meaning.

## COMPLETION: IGNATOWSKI'S RELATIVITY

- Vladimir Ignatowski

28 December 1909, two events were opened in Moscow: the Ist All-Russian Congress on the fight against alcoholism and the XIIth Congress of Russian Naturalists and Physicians.The attention of the local press was attracted rather by the first of them: a greeting from Count L. Tolstoy was read there. However, if the newspapermen knew physics, they would certainly pay attention to the second event as well.
28 December the afternoon session of the XIIth Congress of Russian Naturalists and Physicians opened with a plenary talk by Vladimir Sergeyevitch Ignatowski, who had just received a PhD "summa cum laude" from the university of Giessen in Germany. The title of the talk was "Relativity Principle".
The very first introductory words of the speaker aroused surprise in some, and an ironic smile in others. He neither more nor less "swung" at the authority of the already famous Einstein.
"*When Einstein introduced the principle of relativity, he assumed at the same time that the speed of light $c$ was a universal constant, i.e. it retained the same value for all coordinate systems...Now I have asked myself the question of which relationships resp. transformation equations one arrives when one only puts the relativity principle at the forefront of the investigation* (My emphasis, V.P.) *and whether Lorentz's transformation equations are the only ones that satisfy the relativity principle*".

I don't want to bore you with a rather lengthy, although not very complicated, calculations by Ignatowski, which you can find in [20], [21] if you wish. I will give only the main result, namely, the general form of 4-dimensional transformations between inertial systems moving relative to each other in a straight line with a constant speed.
Let us an inertial frame $K'$moves relative to another inertial frame $K$ rectilinearly with the constant velocity $v$ along the $x$ axis. Then the relativity principle implies, as Ignatowski derived, that coordinates in these two frames are related as follows

$$x' = \frac{x-vt}{\sqrt{1-nv^2}},\ y' = y, z' = z,\ \ t' = \frac{t-nvx}{\sqrt{1-nv^2}} \ (4)$$

Here $n$ is a constant parameter with the dimension inverse to the square of the speed.
The principle of relativity itself fixes neither the magnitude nor the sign of this "world constant" as Ignatowski dubbed it.
Let us consider separately cases when $n = 0$ , $n > 0$ and when $n < 0$.
The case $n = 0$ leads us to the transformations (1) which we have seen and which were unreasonably called "Galilean". They were proved incompatible with electromagnetic phenomena, but are in use as a good approximation in the domain of nonrelativistic energies.
If $n > 0$ then we see from Eqs.(4)that no frame can move relative to another frame with a speed faster that $v_{max} = \frac{1}{\sqrt{n}}$.
If to identify $v_{max}$ with the speed of light then we recognize in equations (4) the familiar Larmor - Lorentz transformations (3). At first glance, there is nothing special about this, and Ignatowski simply rediscovered what had already been obtained by others, i.e. Lorentz transformations. However, it

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should be understood that the Ignatowski transformations do not contain the speed of light, but the universal maximum speed of any material object.
Coincidence of the speed of light with the universal maximum speed is a particular case and possible only due to the masslessness of the photon. If a photon had at least some, the most insignificant mass (the current upper bound is $10^{-22}$ eV/c$^2$ ), Einstein's entire second postulate loses all meaning, while Ignatowski's transformations would remain valid.
This, in its turn, means that massive material bodies can only move with a speed $v < v_{max}$ and only those with zero mass move with $v = v_{max}$ (and not less).
A remarkable fact in the derivation of these transformations is that Ignatowski - unlike *all* his predecessors - in no way uses electrodynamics (or any other specific physical phenomena), relying only on the general properties of space-time.
*This gives the principle of relativity a complete and true universality.*
However, we digressed from the remaining option, $n < 0.$ In this option we would encounter quite a strange world. First of all in this world speeds of bodies are not limited: they can have any value because no limiting speed arises. Instead, the energy cannot surpass a maximum value $E_{max} \leq \frac{m}{\sqrt{-n}}$.
Then the momentum is directed opposite to the speed : $\boldsymbol{p} = \frac{-mv}{\sqrt{1-nv^2}}$. Particles of zero mass are impossible. Finally, the very concept of "time" looks unnatural. The fact is that the symmetry group in this case is not the Lorentz group $O(3,1)$, but the group of 4-dimensional Euclidean rotations $O(4)$. All 4 axes are equivalent and the choice of one of them as "time" is not dictated by any physical considerations. Thus, such a bizarre world is unlikely to correspond to the one in which we exist, and the option $n < 0$ must be discarded as non-physical.
Thus, we come to the conclusion that *Einstein's second postulate is redundant*: it follows from the principle of relativity *if* to assume that the photon is massless. Also, light loses its privileged position: the conclusions of the theory of relativity would retain their value even if the photons were massive.
Of course, the fact that Einstein in his famous paper actually used not a separate postulate, but one of consequences from the principle of relativity (with some additional assumptions) does not make the Larmor - Lorentz transformations obtained by him incorrect. However, it should be recognized that Ignatowski's approach is the most general and logical.

## QUANTUM RESURRECTION OF THE ETHER

Another thing is the "killing of the ether". As already mentioned, this is what Einstein is given special credit for, giving him a clear superiority over the rest, who got lost among the outdated and old-fashioned mechanical models of the ether. However, attention! We take the work of Einstein of 1920 [22] and do not believe our eyes!
“ *There are weighty arguments to be adduced in favor of the ether hypothesis. To deny the ether is ultimately to assume that empty space has no physical qualities whatever, the fundamental facts of mechanics do not harmonize with this view”.*
After such a sensational confession Einstein informs about what does he understand under “ether”:
“ *According to the General Theory of Relativity, space is endowed with physical qualities; in this sense, therefore, there exists an ether. According to the General Theory of Relativity space without ether is unthinkable*.” Again a specific entity is invited : gravitation. Yet such an option leaves questions**.** First of all the classical (and GR is classical, non-quantum theory) ether should, if to hold to the relativity principle, remain at rest in any inertial frame. Quite a crazy picture, indeed.
Let us, however, take into account that all what we discussed earlier did not concern the quantum properties of the matter. For us now one basic feature of the quantum field theory matters: the vacuum state $|\,\Omega >$. The vacuum state is Poincaré invariant

$$U(a,\Lambda)|\,\Omega > = \,|\,\Omega >$$

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with $a$ a 4D translation and $\Lambda$ a proper Lorentz transformation, $U$ is some Poincaré group representation, $\{a, \Lambda\} \in \mathcal{P}_+^\uparrow$ . In particular, under translations we get

$$U(a, \mathrm{I})| \, \Omega > = e^{iP^\mu a_\mu}| \, \Omega > = \ | \, \Omega > ,$$

$P^\mu$ is the generator of translations or , in quantum token, the 4 momentum operator.
I.e.

$$P^\mu | \, \Omega > = \ 0$$

So, the quantum vacuum has zero momentum, i.e. *stays at rest in any inertial frame*. The property that the ether should have, but which cannot be achieved in the non-quantum world.
But maybe this is just a void? Nothing? Not at all. This is alike a medium because the observable field differs from the field in the void. E.g., we have for the electric field

$$E(r) = \int dr' \, \varepsilon(r - r') E_0(r')$$

where Fourier transform of $\varepsilon$ is

$$\hat{\varepsilon}\,(k) = \int dr e^{-ikr} \, \varepsilon(r) = \ 1 + \ \Pi(k)$$

and $\Pi(k)$ is the self-energy part of the electromagnetic field due to quantum fluctuations, say, into an electron-positron pair. So, the quantum vacuum is not void and possesses the properties of a complicated quantum state.
Thus, we can interpret the fact that Poincaré sometimes denied the ether, but then returned to it again, as his brilliant, albeit premature, intuition because quantum theory in his time was only taking its first timid steps, while the classical ether, as we have seen, is impossible.
We think it is aproppriate to conclude this part with Paul Dirac's citation [23]:
"*…the aetherless basis of physical theory may have reached the end of its capabilities and to see in the aether a new hope for the future."*

## CONCLUSION

Although I have had to make some omissions, I think I have been able to present a history of relativity that differs in some important respects from the conventional one. Those interested in more detailed information are advised to read the excellent book [24].

## CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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