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The Concept of Aether in Classical Electrodynamics and Einstein's Relativity

In physics, the notion of empty space can be traced to two altogether different areas of thought which belong to (as of yet) quite separate sub-domains. On one hand, we have quantum field theories and its virtual particles (implying that space is never devoid of particles – or fields) while on the other hand we have Einstein's general relativity and its 'aether' as a signifier of an intrinsic metric structure of spacetime. Even though conceptualizations of aether were essential for what both mentioned theories turned out to be, the quantum field theory approaches will not interest us here. We will deal with the history of theories of aether in classical (non-relativistic) physics and with the strange ways of the notion of aether in Einstein's relativity.

The need for the modern scientific incorporation of the notion of empty space emerged very early on – with Newton's formulation of the law of universal gravitation, which implies that gravitation propagates through empty space instantaneously with infinite velocity. Force exertion over empty space – the so-called direct action at a distance – was a source of philosophical and theological dispute right from the start. Newton himself was uneasy about the introduction of action at a distance over empty space. It was hard to conceive how one body could possibly influence another body without contact and over vast empty regions of space, such as those spanning the Solar system. "Can a body act where it is not?"[1] As Einstein pointed out, people were used to conceiving everyday forces as consequences of contact between two bodies[2]. Since gravitational action at a distance seemed so radically different from contact forces of everyday life, physicists have set out to unify what they believed were only two different manifestations of the same physical phenomenon of force. Doing so, they could either reformulate *contact forces* as an incidence of action at a distance, or *vice versa* reformulate *action at a distance* as an incidence of a contact force. This

1 J. Larmor, *Aether and Matter*, Cambridge University Press, Cambridge 1900, p. 24.

2 A. Einstein, "Äther und Relativitätstheorie", in *Collected papers of Albert Einstein*, Vol. 7, Doc. 38, Princeton University Press 1920b, p. 309

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latter treatment contains the hypothesis of the existence of aether: it implies that direct action at a distance only seemingly takes place directly over empty space, whereas the latter is not empty but filled with some sort of all-pervading substance, *the aether*, which is – either through its state of motion or through its elastic deformations – the true mediator of force between distant bodies[3].

As scientists discovered that light experiences diffraction, reflection and refraction (Grimaldi and Huygens), it became probable that light could have the nature of a wave. There were still some unsolved issues regarding this fact – straight paths of light rays, for example, seemed to substantiate the corpuscular theory of light (supported by Newton, among others) – but nevertheless the aether theory gained a lot of momentum[4]. As Reichenbach had put it: "If light has the nature of a wave and is, consequently, not a substance, but a phenomenon of motion in a medium – what then is that medium itself?"[5] Two choices seemed possible: the aether could be either fluid or solid (elastic). This issue was settled in 1816 by Fresnel and Arago: they showed that it was impossible to produce interference using two perpendicularly polarized light rays. This meant that light was a transverse wave. (Meaning that wave oscillations are transverse to the direction of energy transfer. The famous Mexican wave during a football match is an example of a transverse wave: the spectators stand up and sit down while the wave travels sideways.)

This was a fact of utmost importance. Since fluids can mediate *surface* transverse waves but not *bulk* transverse waves (as is the case with light) there was only one option left: the aether had to be a solid (elastic) substance[6]. This resulted in a large number of different solid aether models, each of them explaining a particular feature or phenomenon of light[7]. There existed no unified aether theory that could provide a theoretical framework for a consistent theory of light. It was, however, clear that there was a fundamental conceptual difference between classical mechanics and optics: the space of mechanics was empty,

3 Einstein, *ibid.*, pp. 309–10.

4 *Ibid.*

5 H. Reichenbach, *From Copernicus to Einstein*, trans. Ralph Winn, Philosophical Library, New York, p. 38.

6 M. Born, J. Ehlers, M. Pössel, *Die Relativitätstheorie Einsteins*, 7th Edition, Springer, Berlin 2003, p. 92.

7 See also E. T. Whittaker, *A History of the Theories of Aether and Electricity, From the Age of Descartes to the Close of the Nineteenth Century*, Hodges, Figgis & Co., Ltd., Dublin 1910.

while the space of optics had been filled with aether. Light needed a medium to propagate and scientists were trying to resolve what its properties should be.

In the following decades of the 19th century groundbreaking research of Michael Faraday, James Clerk Maxwell and Heinrich Hertz led to the conclusion that light was nothing but electromagnetic radiation[8]. This implied that electricity, magnetism and optics were one and the same science. Maxwell developed a beautiful mathematical theory that tied together optics, electricity and magnetism. At the time, light, heat, electricity and magnetism were each thought to have their own respective aether. Due to Maxwell's work the aether of light merged with electric and magnetic ethers into one and the same substance[9]. This was a great simplification. As to the nature of this substance Maxwell was a firm believer in a mechanical aether[10], but he – or anyone else for that matter – wasn't able to formulate a Newtonian theory of mechanical aether that would explain all observed features of the electromagnetic field[11].

In Newtonian mechanics (that was thought to hold true for light and electromagnetism in general), the main mechanical principle, the Galilean principle of relativity, states that all uniformly moving reference frames are equivalent for the formulation of physical laws – and can be viewed as frames at rest. The first hypothesis about the kinematic state of the aether was therefore the simplest one: the light aether in outer space, far away from all material bodies, is at rest in an inertial (unaccelerated) system[12] : the aether was assigned a velocity vector, but its acceleration was set to zero. The aether velocity was proposed to be spatially uniform and one should somehow be able to measure it. Most relevant experiments prior to the emergence of Einstein's relativistic physics were therefore focused on establishing to what extent the aether was carried along with the Earth, if at all, as the Earth moved through space. There were seemingly only two possible options for the outcome of these experiments: George Gabriel Stokes proposed the aether at the surface of the Earth is completely dragged along by Earth, as if it were a viscous fluid: this implies that the relative velocity

8 J. C. Maxwell, *Treatise on Electricity and Magnetism*, Vol. 2, Dover Publications, 1954, p. 383., see also M. Born *op. cit.*, p. 163.

9 Maxwell, *ibid.*

10 *Ibid.*, Born, *op. cit.*, p. 164, Einstein, *op. cit.*, p. 310.

11 Einstein, *ibid.*

12 Born, *ibid.*

of aether to Earth's surface, "the aether wind velocity", is zero. Augustine Fresnel, on the other hand, proposed the aether outside refractive media is at rest (while inside moving refractive media it is partially dragged along in an elastic manner[13]): this would cause an "aether wind" with speeds of the order of Earth's orbital velocity 30 km/s at the Earth's surface.

Several ingenious experiments were built to decide between the two options, but their results seemed contradictory: stellar aberration, *i. e.* displacement of positions of fixed stars due to Earth's motion through space, was a well-known phenomenon discovered by James Bradley in 1727 (not to be confused with stellar parallax). It implied there is no aether drag[14]. This seemed to negate Stokes's and confirm Fresnel's hypothesis. The aether was not dragged by the Earth at all. Fizeau's experiment, set up in 1851, measured the speed of light in a moving liquid[15]. The result again seemed to confirm Fresnel's hypothesis: the speed of light in a moving liquid (with refractive index close to 1.0) was essentially the same as in the vacuum. Both experiments indicated that the aether wind at the surface of the Earth should be detectable. But Michelson's experiment, performed in 1881, established with unprecedented precision that there was no detectable evidence of the relative motion between the aether and the Earth in any direction. The speed of light was always measured to have the same constant value, regardless of the direction of Earth's motion through space. It was confirmed with high precision that light has the same speed in all reference frames. This fact is known as the law of constancy of the speed of light. In other words, no aether wind was detected – the aether seemed to be completely dragged along by the Earth. This negated Fresnel's and confirmed Stokes's hypothesis.

The null result of the Michelson experiment was extremely puzzling – it was in contradiction with the most fundamental mechanical principle: the Galilean or classical principle of relativity. This state of affairs indicated a serious conflict between classical mechanics and electrodynamics. Since classical mechanics was an established discipline, it seemed clear that Maxwell equations had to be

13 Pais, A., *Subtle is the Lord, The Science and the Life of Albert Einstein*, Oxford University Press, Oxford 2008, p. 118.

14 Born, *op. cit.*, p. 112. Einstein, *op. cit.*, pp. 245–7.

15 Einstein, *op. cit.*, p. 246.

wrong, electrodynamics had to be wrong[16]. But all the experiments were proving it wasn't. At this point the Dutch theorist Hendrik Antoon Lorentz entered the discussion. He struggled hard to reconcile contradicting results of otherwise impeccable experiments. He developed a new theory of aether and electromagnetism with several distinctive features: the aether did not interact with matter in any way whatsoever, it was merely a substratum of the electromagnetic fields arising from charged microscopic particles. It was completely stationary and completely rigid. Its role was to mediate electromagnetic fields which cause electromagnetic forces between charged bodies[17].

Using his stationary aether theory Lorentz managed to reconcile seemingly contradicting outcomes of Fizeau and Michelson experiments[18]. But this wasn't possible without an additional *ad hoc* postulate – the now famous *Lorentz contraction* (proposed by Lorentz in 1892, independently by Fitzgerald in 1889, and derived from basic principles by Einstein in 1905). The postulate claims that the bodies contract in the direction of motion through stationary aether. Lorentz demonstrated that if *all* the bodies moving relative to the aether contracted by a certain amount in the direction of the movement, then all effects of aether wind would be compensated. He was also trying to explain the contraction *dynamically* – by an influence the aether has on molecular forces that determine the shape of each body of matter.

This state of affairs was somewhat surprising: after several centuries of growingly elaborate aether theories, the most developed aether theory seemed like a substantial regression. Lorentzian aether was completely stationary, perfectly rigid and could not be detected by an experiment. Physics seemed to have traveled a full circle: Lorentzian aether had all the features of the classical Newto-

16 R. Feynman, Six *not-so-easy Pieces. Einstein's Relativity, Symmetry, and Space-time*, Basic Books, New York 2011, p. 53.

17 Born, *op. cit.*, p. 178.

18 H. A. Lorentz, "The Relative Motion of the Earth and the Aether", trans. Wikisource from De relatieve beweging van de aarde en den aether, Amsterdam 1892, p. 74. Accessed online on 12. 1. 2013 at: http://en.wikisource.org/wiki/The_Relative_Motion_of_the_Earth_and_the_Aether. H. A. Lorentz, "Michelson's Interference Experiment", trans. from "Versuch Einer Theorie der elektrischen und optischen Erscheinungen in bewegten Körpern", Leiden, 1895, in *The Principle of Relativity*, Dover Publications 1923.

nian absolute space. As Max Born put it: the aether theory has led in its highest development to the sublation [*die Aufhebung*] of its fundamental concept[19].

Elimination of Aether. The Special Theory of Relativity

Albert Einstein was the one to resolve the deadlock: he proved that the contradiction between the principle of relativity and the law of constancy of speed of light was only apparent. He managed to incorporate both as two cornerstones of a new physical theory: the special theory of relativity. The validity of the principle of relativity was, to Einstein, beyond doubt: the laws of not only mechanics but also of electrodynamics must and can retain the same form in all inertial reference frames. The law of constancy of speed of light was also correct: the speed of light is indeed the same in all uniformly moving reference frames. It was an experimental and also a theoretical fact. So what was wrong?

Mathematical aspect of the problem was as follows: classical transformation law, the Galilean transformation, is not universally valid. This has never been problematic from the point of view of classical mechanics. Scientists have been using Newtonian mechanics for centuries and it provided overwhelmingly satisfactory descriptions for essentially all known mechanical phenomena. Problems occurred only after they had tried to interpret the Galilean transformation as a universal principle and applied it to electrodynamics. To bring this fact to light, Einstein was led primarily by his firm belief in the principle of relativity and less by the outcome of Michelson's experiment. The conclusion was nevertheless the same: if the speed of light is the same in all moving reference frames, this means that light does not prefer a single reference frame. In other words, light does not prefer the *aether* frame – any other claim would, according to Einstein, introduce a perfectly unfounded asymmetry[20]. But if light prefers no specific reference frame – Michelson proved it experimentally and Einstein explained it theoretically – then one further step seemed just as obvious as it was necessary: there is no aether frame and there is no aether. The sole mechanical property that Lorentzian aether still obtained was its immovability, its frame – and Einstein was the one to dismiss it as fallacious[21]. The electromagnetic fields

19 Born, *op. cit.*, p. 192.

20 A. Einstein, "Äther und Relativitätstheorie", in *Collected papers of Albert Einstein*, Vol. 7, Doc. 38, Princeton University Press 1920b, p. 313.

21 *Ibid.*

were no longer to be interpreted as physical states of some medium, but rather as independent physical entities like atoms of ponderable matter.

Special theory of relativity has thus dismissed an absolute reference frame along with the existence of classical aether to be able to achieve something much more meaningful: to remove an apparent contradiction between electrodynamics and mechanics, and unite both within a common framework. This unification would have been impossible without a new transformation law to replace the Galilean transformation. Although this new transformation law had already been discovered by Lorentz, Einstein was the first to derive it from the first principles. It is nevertheless called the Lorentz transformation. It was already shown by Lorentz that Maxwell-Lorentz equations retain their form if one uses Lorentz transformation law to pass between different inertial systems – the equations are said to be *Lorentz covariant*. Newton's laws however were not Lorentz covariant: the form of these equations changed if one used Lorentz transformations to pass between different inertial systems. Maxwell-Lorentz electrodynamics therefore needed no modifications, but it was necessary to modify Newton's laws to suit the principle of relativity and to obtain their Lorentz covariant formulation (this was done by Max Planck in 1906). Special theory of relativity further demonstrated that Lorentz contraction, Lorentz's ad-hoc hypothesis to save his theory[22], *does indeed occur*. The contraction is a direct consequence of Einstein's theory – but it is not caused *dynamically* by the aether exerting force on the molecules of matter, as Lorentz thought. It occurs *kinematically,* as a consequence of the fact that the measuring apparatus is *moving* relative to the object measured.

In 1907, Einstein was commissioned to write a review paper on relativity for the *Jahrbuch der Radioaktivität und Elektronik*. This paper[23] is nowadays regarded as one of the major milestones on the path from special to general relativity. At that time, most likely in November 1907, Einstein got the famous insight he later referred to as "the happiest thought of his life". He was the first to realize that the following simple observation has profound consequences: "…*for an observer falling freely from the roof of a house there exists* – at least in his immediate surroundings – *no gravitational field*. Indeed, if the observer drops some bodies then these remain relative to him in a state of rest or of uniform motion,

22 *Ibid.*

23 A. Einstein, "On the Relativity Principle and the Conclusions drawn from it", in *Collected papers of Albert Einstein*, Vol. 2, Doc. 47, pp. 252–311.

independent of their particular chemical or physical nature […]. The observer therefore has the right to interpret his state as 'at rest'."[24] (Einstein's italics). Einstein's argument was as follows. Since all freely falling bodies in gravitational field accelerate at the same rate (in other words, since inertial mass of a body is equal to its gravitational mass), any freely falling (accelerated) observer has every right to judge that he is in an inertial system (i.e. in zero gravity). Therefore, Einstein realized in 1907, the special theory of relativity needs to be generalized to systems containing gravitational fields – there exist no physical grounds for privileging "the usual" inertial systems: free-falling systems in gravitational fields are fully equivalent to inertial systems. This principle later became known as *the equivalence principle* and it represents one of the conceptual cornerstones of general relativity.

Einstein developed a crucial and beautiful insight into what this equivalence means in his famous rocket-ship example[25]: imagine you're in a spaceship with no windows resting on the Earth's surface. Everything in the spaceship is at rest. If you drop a ball, it's going to fall on the floor with the acceleration due to gravity. A pencil will drop at the same rate. Every other body will drop at the same rate. You will claim, judging from these two experiments, you are in a gravitational field. Now imagine you are in the very same spaceship way out in empty space far away from all the other masses, practically in zero gravity. Now the ship turns on its engines and starts accelerating "vertically" with the Earth's gravitational acceleration. You are in zero gravity, using your spaceship engines to accelerate the ship. Everything in the spaceship is at rest. If you drop a ball, it's going to fall on the floor with the acceleration of gravity. A pencil will drop at the same rate. Every other body will drop at the same rate. Now compare it to the situation when the spaceship is safely resting on the surface of the Earth: everything is exactly the same (Feynman: 130). You will again claim, judging from these experiments, you are in a gravitational field. In other words, *there is no physical experiment that can distinguish whether a system is being at rest in a gravitational field or whether it is accelerating in zero gravity*. Dynamically

[24] A. Einstein, "Grundgedanken und Methoden der Relativitätstheorie, in ihrer Entwicklung dargestellt", in *Collected papers of Albert Einstein*, Vol. 7, Doc. 31, Princeton University Press 1920a, p. 265.

[25] A. Einstein, *Über die Spezielle und die allgemeine Relativitätstheorie*, Verlag Friedr. Vieweg & Sohn, Braunschweig 1917, p. 45. See also Feynman, *op. cit.*, p. 129.

both cases are fully equivalent[26]. Properties of motion in an accelerated system are the same as those in an unaccelerated system with the presence of gravity[27]. Gravity has only *relative* existence – it is merely an effect of the coordinate system we use to formulate natural laws. *This* is why any general theory of relativity must necessary lead to a theory of *gravitation:* one can produce effects indistinguishable from gravity by merely jumping to an accelerated coordinate system[28].

Einstein did not publish anything new on relativity until 1911. Pais attributes this fact, among other things, to Einstein's intense work on quantum theory[29]. Another significant contribution to relativistic physics was, however, published in 1908 by Hermann Minkowski, a mathematician at the University of Göttingen. In a nutshell, Minkowski reformulated Einstein's new kinematics into a 4-dimensional geometry (three spatial and one temporal dimension) with several highly advantageous properties[30]. To name just one: he was able to show that the 4-dimensional distance between any two spacetime events is a Lorentz invariant – it does not change as we pass between different inertial systems. Minkowski's formalism was an enormous formal simplification of the relativity theory. Roger Penrose stated that special relativity was not a self-contained theory until Minkowski rewrote it into its modern geometric form[31].

Einstein was at first reluctant to accept Minkowski's work as he was sceptical about all the abstract mathematics Minkowski was using. This reluctance was rooted in Einstein's admiration of positivistic philosophy of Ernst Mach, a famous physicist and one of the leading figures of the Vienna circle. But Einstein's doubts did not last long. By 1912 (at the latest), he came to fully appreciate the power of geometrization of relativistic physics. This epistemological shift was

26 See also M. Jammer, *Concepts of Mass in Contemporary Physics and Philosophy*, Princeton University Press, Princeton 2000.

27 L. D. Landau, E. Lifshitz, *The Classical Theory of Fields*, trans. M. Hamermesh, Butterworth-Heineman, Amsterdam 1987, p. 243.

28 A. Einstein, "Die Grundlage der allgemeinen Relativitätstheorie", in *Collected papers of Albert Einstein,* Vol. 6, Doc. 30, Princeton University Press 1916b, p. 288.

29 Pais, *op. cit*., p. 188.

30 H. Minkowski, "Space and Time", A Translation of the Adress delivert at 80th Assembly of German Natural Scientists and Physicians, at Cologne, 21 September 1908, in *The Principle of Relativity*, Dover Publications 1923, pp. 73–91.

31 R. Penrose, *The Road to Reality, A Complete Guide to the Laws of the Universe*, Vintage Books, London 2005, p. 406.

most likely initiated by the following *Gedankenexperiment* which led Einstein to realize that the Euclidean geometry is invalid in accelerated systems. Imagine you're located in an accelerated system, for example, on a rapidly spinning wheel of a merry-go-round. You now take a ruler and measure the radius *r* of the wheel. Then using the same ruler you measure the circumference of the wheel. You would expect from the Euclidean geometry the ratio of circumference to radius to be 2π. If the wheel had not been rotating, this would indeed have been the case – but in the presence of rotation it is not. Due to Lorentz contraction, the ruler contracts in the direction of motion (in tangential but *not* in radial direction) so the circumference is actually *larger* than 2πr. The Euclidean formula is incorrect. This means, Einstein continues, that Euclidean geometry is not valid in accelerated systems. Or to put it in an equivalent manner: *the Euclidean geometry is not valid in gravitational fields*. Gravity changes the geometry of spacetime[32].

Resurrection. Relativistic Aether of General Relativity (1916-1924)

It was not yet clear *how* gravity changes the geometry of spacetime but it became obvious to Einstein that the geometric approach was unavoidable. The formalism of Minkowski was an absolutely necessary step on the path to the generalization of the relativity theory. Furthermore, the content of Einstein's project was now more precisely constrained: he had to find a general non-Euclidean geometry that allowed most general coordinate transformations that still retain the invariance of 4-dimensional distances between infinitely close events (local Lorentz covariance). One of many problems lay in the fact that in rotating frames Lorentz contractions differ for different points of spacetime within the *same* coordinate frame, depending on the point distance from the axis of rotation. Points along the radius of the spinning wheel have different velocities and therefore different Lorentz contractions. One could therefore no longer employ *one* ruler and *one* clock for the entire coordinate system[33]. A separate pair of rulers and clocks would be needed for each point along the radius. In other words, space and time – in any ordinary sense of the word– became physically insignificant parameters. Coordinate systems, in which space and time would be well defined, turned out to be an exceedingly limited subclass of all pos-

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32 Einstein 1917, *op. cit.*, §23.

33 A. Einstein, "Die Grundlage der allgemeinen Relativitätstheorie", in *Collected papers of Albert Einstein*, Vol. 6, Doc. 30, Princeton University Press 1916b, p. 290.

sible coordinate systems. Einstein thus had to reformulate the laws of physics without referring to lengths and time intervals as measured *in any specific coordinate system of any specific geometry*. This seemed an impossible task at first. As he put it himself, describing physical laws without reference to a specific geometry seemed similar to describing our thoughts without words[34]. The equations had to retain the same form in all possible curved generalized coordinates. After years of hard work and some help from his friends – most notably Marcel Grossmann and Michele Besso – he succeeded. The final version of field equations of general relativity was published on November 25th 1915. One week earlier, he submitted a paper to the Prussian Academy of Sciences in which he correctly derived the anomalous perihelion precession of Mercury's orbit. This was a historic result, unexplainable within Newtonian dynamics. But the paper from November 18th contains another discovery: the first correct calculation of the gravitational bending of light. A light ray passing by the Sun should deflect by 1.7 arc seconds.

The first effect had been known for decades, while the second one was a theoretical prediction of general relativity. It was experimentally confirmed in 1919 and had very interesting consequences for Einstein's attitude towards the notion of aether. Since gravity bends light and shifts planet orbits, and since gravity is a manifestation of curved geometry of spacetime, it was no longer possible to describe spacetime as physically neutral, as a void lacking all physical features[35]. Field equations of general relativity were non-linear: gravitational field and matter (which is the source of this field) play equivalent roles. The gravitational field determines the distribution of matter, which determines the gravitational field, which determines the distribution of matter etc. This loop indicates a nonlinearity, which ultimately paved the way for a shift in Einstein's position on the aether, but as noted by Kostro, Einstein was too engaged in getting rid of the old aether to introduce a new one immediately after the first consistent formulation of general relativity[36]. General relativity was perceived as quite controversial, and Einstein spent a lot of energy defending it in the next years. Only in 1918,

[34] A. Einstein, "How I Created the Theory of Relativity", the Address at Kyoto University 1922, trans. Yoshimasa A. Ono, in *Physics Today*, American Institute of Physics, August 1982.

[35] L. Kostro, *Einstein and the Aether*, Aperion, Montreal 2000, pp. 47–8.

[36] Kostro, *op. cit.*, p. 74.

in one of the replies to the German anti-Semitic scientist Phillip Lenard, did he finally clarify his position on the existence of aether[37]:

> There is no such privileged state of motion, as has been taught to us by the special theory of relativity, and that is why there is no Aether in the old sense. The general theory of relativity also does not know a privileged state of motion in a point, that one could vaguely interpret as velocity of an Aether. However, while according to the special theory of relativity a part of space without matter and without electromagnetic field seems to be characterized as absolutely empty, e. g. not characterized by any physical quantities, empty space in this sense has according to the general theory of relativity physical qualities which are mathematically characterized by the components of the gravitational potential, that determine the metrical behavior of this part of space as well as its gravitational field. One can quite well construe this circumstance in such a way that one speaks of an Aether, whose state of being is different from point to point. Only one must take care not to attribute to this *Aether* properties similar to properties of matter (for example every point a certain velocity).

In January 1920, he was even more specific[38]. He writes that in 1905 he was of the opinion that one is "no longer allowed to speak about the aether in physics. This opinion, however, was too radical"[39]. It *was* still permissible "to introduce a medium filling all space and to assume that the electromagnetic fields (and matter as well) were its states. But, it is not permitted to attribute to this medium a state of motion at each point, by analogy with ponderable matter. This aether may not be conceived as consisting of particles that can be individually tracked in time."[40]

He again emphasized that in general relativity gravitational potentials express physical properties of empty space (i.e. regions of space without matter and electromagnetic field). "Thus, once again "empty" space appears as endowed with physical properties, i.e., no longer as physically empty, as seemed to be

37 Interestingly enough the whole Nazi anti-Semitic campaign against Einstein culminated around the question of the aether. We refer to Kostro's book for further details (Kostro, *op. cit.*, p. 79.).

38 A. Einstein, "Grundgedanken und Methoden der Relativitätstheorie, in ihrer Entwicklung dargestellt", in *Collected papers of Albert Einstein,* Vol. 7, Doc. 31, Princeton University Press 1920a, p. 278.

39 Einstein 1920, *Ibid.*

40 *Ibid.*

the case according to special relativity. One can thus say that the aether is resurrected in the general theory of relativity, though in a more sublimated form. The aether of the general theory of relativity differs from the one of earlier optics by the fact that it is not matter in the sense of mechanics. Not even the concept of motion can be applied to it." In the new theory, geometry can no longer be separated from "true" physical facts, thus the concepts of "spacetime" and "aether" merge together. "Since the properties of space appear as determined by matter, according to the new theory, space is no longer a precondition for matter; the theory of space (geometry) and of time can no longer be presupposed prior to actual physics and expounded independently of mechanics and gravitation."[41]

As he became extraordinary professor at the University of Leiden, he wrote to Lorentz that he would lecture about aether in the theory of relativity. His inaugural lecture[42] was written before April 1920, but delivered in October 1920. He emphasized one more time that general relativity had once and for all banned the notion of empty space[43]. There is no empty space because there is no space without gravitational field, and therefore no space without curvature, no space without structure. Space without metric properties is unthinkable in general relativity. Herein lies also the main difference between gravitational field and electromagnetic field: no part of space can ever be without gravitational field while we can well produce regions of space without electromagnetic field. "The existence of gravitational field is directly connected to the existence of space."[44]

Conclusion

The aether of general relativity was thus reintroduced as a scientific concept by the same physicist who dismissed it more than a decade earlier. Let us summarize the course of events. The notion of aether was legitimized by the immovability and unresponsiveness of the Newtonian absolute space. Its further materializations were developed through progress in optics and electrodynamics. The problem culminated in the late 19th century as a series of inconsistencies in the explanations of physical experimental results. These implied that the basic

41 *Ibid*.

42 A. Einstein, "Äther und Relativitätstheorie", in *Collected papers of Albert Einstein*, Vol. 7, Document 38, Princeton University Press 1920b, pp. 305–323.

43 Einstein, *op. cit*., p. 317.

44 *Ibid*., p. 319.

principles of classical mechanics and electrodynamics were contradictory. The only way to reconcile these results with the existence of aether was to introduce a very sophisticated theory of stationary and non-interacting aether with all the features of Newton's absolute space. The contradictions were finally removed by Einstein's special relativity. This theory banned the notion of aether from contemporary physics. As Einstein was working on the generalization of special relativity, it became clear that space and matter might not be as independent as widely believed. In their final form the field equations of general relativity indicate, as John Wheeler famously put it, that matter tells space how to curve, and space, simultaneously, tells matter how to move. Empty space was found to be a dynamic medium – a new aether. A generalization of Special relativity, which forbade the notion of aether, ultimately led Einstein to its reintroduction.

In his inaugural lecture, Einstein continues with a remark that was to remain in the focus of his work for the rest of his life. As we understand today, he writes, the elementary particles are essentially nothing but condensations of the electromagnetic field. Contemporary physical explanations of the world rely on the existence of two quite different fundamental entities: gravitational field and electromagnetic field. In other words, Einstein writes, *space* (gravitational field) and *matter* (electromagnetic field). It would be a great step forward to succeed in unifying these two fields. The opposition between aether and matter would, again, be overcome, and physics would become a logically closed system of thought[45].

This unification of gravity and electromagnetism was something Einstein struggled for for the rest of his life. He never succeeded in making any real progress because, according to Pais (and others), he never accepted quantum theory (a theory he also laid foundations for) in its present form. But his imperative of unification of all interactions in one common physical framework has survived. One hundred years later Einstein's dream of a unified theory still represents a single most difficult and most important problem of modern physics. Physicists nevertheless made huge progress in the past century using relativistic versions of quantum mechanics, called quantum field theories. One such theory, called the Standard Model of fields and particles, has merged electromagnetic, weak and strong interactions in a single theoretical framework. Gravity, however, still remains well outside the scope of this unification. For now.

45 Einstein, *op. cit.*, pp. 319–320.

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