Relativity Today

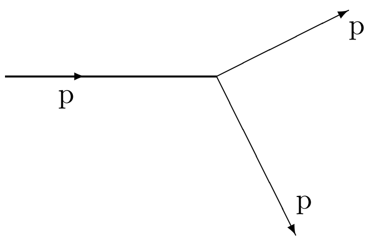
- **In the public mind, relativity remains an esoteric and mysterious theory, «that only ten scientists in the world can understand». Yet it is regularly verified by the countless experiments conducted on high-energy particles and taught daily to tens of thousands of beginning students.**
- **In the framework of classical physics, «special» relativity, the true geometry of space-time, governs today's quantum theories. It underlies all attempts to understand the sub-nuclear world.**
- **General relativity, another aspect of Einstein's work, was a solitary creation. It plays a major role in explaining many recent astrophysical observations. It is an integral part of our global understanding of the physical universe.**

Einstein did not invent relativity. Besides, there are several. And these theories, very poorly named, are interested in the absolute much more than in the relative. As for «general relativity», if it was indeed Einstein who founded it, it is precisely not general... We can continue like this and take the opposite view, in an almost systematic way, of the catalog of common ideas on the origin and meaning of relativity. This is because these received ideas have been so for more than half a century: they have had plenty of time to wear out.

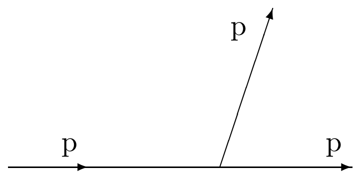
The metaphysical or ideological and even epistemological debates about relativity are today obsolete: the criticisms of Bergson as well as those of Jdanov are forgotten... Nevertheless, a confusion remains that is all the greater because it is implicit.

If similar misunderstandings surround almost all the achievements of modern physics, they are particularly serious in the case of relativity, which deals with two of the most fundamental categories of thought: space and time. Any challenge to the common understanding of these notions is necessarily felt as a painful attack. It is true that Einstein forced us to considerably modify our ideas about space and time; however, the «us» in the preceding sentence properly designates only physicists, forced to abandon the classical conception that dated back to Galileo and Newton. As for laypeople, the irony of history is that they reacted just as violently to the Einsteinian vision, even though the Newtonian conception itself was far from being assimilated. In everyday life and even in the field of usual technology, recourse to the theoretical concepts of classical physics is rarely necessary. Thus, the common conception of space and time, essentially empirical, is today still largely Aristotelian – and rightly so! – including among physicists.

Seeing Relativity:



p incident at 450 MeV



p incident at 32 GeV

It is not so easy to directly visualize a situation where classical, Newtonian mechanics is patently invalidated. Although the Einsteinian relativity is confirmed today, it is generally in an indirect way. Here, however, is a case where its necessity is immediately visible. When a projectile hits a stationary object of the same mass and transfers part of its energy, the Newtonian form of the laws of conservation of energy and momentum leads to predicting that the bodies, after their collision, move away on trajectories forming a right angle between them. This is indeed what is observed when photographing the collision of two protons (one initially at rest) at low energy (450 MeV). Einsteinian mechanics, on the other hand, modifies this prediction and predicts an acute angle, differing all the more from the right angle as the energy of the incident particle is higher. The experiment (at 32 GeV) confirms the theory.

The Einsteinian scandal is thus only the delayed effect of the Galileo-Newtonian shock. Many (pseudo) paradoxes of Einsteinian theory already have equivalents in classical theory; as for the more specific ones among them, the past decades have stripped them of a large part of their mystery in the eyes of contemporary physicists. Let us therefore try to shed light on some aspects of relativity as it presents itself in current physics.

The Principle of Relativity Saved by Abandoning the Galilean Theory

If Einstein did not invent the theory of relativity, he brought to light *one* theory of relativity, which came to replace the one that was until then «obvious», dating back to Galileo and Newton. Indeed, one must distinguish the very idea of relativity, the *principle of relativity*, from the various theories that can express it. This principle affirms, in simple terms, that there exist equivalent points of view on the physical universe. By «points of view», I mean here what physicists explicitly call a «reference frame»: a reference system to which the various physical quantities are related. These quantities are indeed *relative*; the position of a body can only be defined in relation to another, the speed of a moving object likewise: neither the position nor the speed of a traveler walking in the corridor of a moving train is the same depending on whether it is related to the end of the last car or to that of the station platform. It is therefore necessary, a priori, when writing a physical law, that is, a relation between physical quantities, to clearly specify the reference frame used, whether it is, for example, the last car, or the platform – or a car of any other train. This is where the principle of relativity comes in, to express the existence of *equivalent* reference frames, that is, reference frames where the phenomena of physics have the same appearance and the laws of physics the same form. The physical quantities themselves certainly differ from one of these reference frames to another: only the relations in which they enter are the same. Thus, if two quantities are, in a certain reference frame, proportional, namely $A = kB$, A and B being the values of these quantities and k a constant, one will have in an equivalent reference frame, the same proportionality relation, $A' = kB'$, even though the values A' and B' in the second reference frame a priori differ from the values A and B in the first. Of course, two arbitrary reference frames are generally not equivalent. If they are animated, one relative to the other, by arbitrary motions, the laws of physics will take various forms there. Thus, the phenomena and laws of mechanics in a rotating carousel differ from their expression at rest by the appearance of the famous «centrifugal force»: in the stopped carousel, a ball placed on the floor remains motionless, but if it rotates, it takes a movement outward that makes the rotational motion perceptible to the carousel passengers even in the absence of any other observation. The importance of the principle of relativity comes precisely from its affirmation that, among the vast infinity of possible reference frames, there are certain ones that are equivalent, for example, reference frames simply shifted in space: the laws of physics certainly have the same expression in a French laboratory and an American laboratory. Less trivial is the equivalence discovered by Galileo, in a famous page where he emphasizes the identity of description of physical phenomena in the hold of a boat when it moves at constant speed, in magnitude and direction, in other words, in uniform motion. It is this difference in motion – uniform! – that constitutes the very heart of the principle of relativity, entailing ipso facto the abolition of any idea of absolute motion.

«The Galilean Transformation».
The train travels at constant speed (v) and the rear of the last car passes the end of the platform at the instant taken (by convention) as origin. After a time t, the train has covered a distance vt, which it suffices to subtract from the position x of a traveler relative to the end of the platform to obtain his position x' relative to the rear of the train: $x' = x - vt$. This «obvious» reasoning is invalidated when one notices that there is no logical reason to assume that the length standards of the moving train coincide with those of the station, so that a coefficient of «spatio-temporal parallax» can very well be introduced, $x' = \gamma(v)[x - vt]$, leading to the Lorentz transformation.

With Galileo, long before Einstein, the theorization of space and time already departs from everyday experience. This is even clearer for an immediate consequence of the principle of relativity, fundamental enough to often receive the name of principle: that of inertia. It affirms that a moving object on which no force is exerted moves uniformly – and not that it comes to rest as ordinary experience would suggest. Indeed, a body at rest in a reference frame (the train) is from the point of view of an equivalent reference frame (the station) in uniform motion, so that these two states of motion must correspond to the same physical characterization: the absence of forces.

It remains to give a concrete expression of the principle, that is, a theory of relativity that specifies how the values – in principle different – of the same physical quantity are linked in two equivalent reference frames. These «transformation formulas», which express the passage from one reference frame to another, then allow verifying that the form of physical laws remains unchanged during this passage. The most fundamental of these formulas, if not the most important in practice, concern space and time. In other words, one must know how to express the spatio-temporal coordinates of an event, that is, to locate its place and instant, in two reference frames in uniform relative motion. Until 1905, the so-called «Galilean» formulas were taken for granted, obvious, according to which the position x' of a certain event relative to the reference frame R' (the tail of the train) was obtained by subtracting from its position x relative to the reference frame R (the end of the platform) the distance traveled at speed v during the time t elapsed since the train passed. As for this elapsed time, it was taken for granted that it was the same in both reference frames. These formulas:

$$x' = x - vt$$
$$t' = t$$

are of such triviality that no one, or almost no one, thought to write them – until their erroneous nature was perceived! This theory only expressed certain aspects, taken for evident, of classical mechanics. It was the development, in the 19th century, of electromagnetism that would trigger the conflict. Indeed, the electromagnetic theory synthesized by Maxwell around 1870 violated Galilean relativity; Maxwell's theory thus predicted that the speed of light was invariant, which is obviously absurd from the Galilean point of view where the speed of a moving object always depends on the reference frame used.

Paradox or Parallax? Length Contraction and Time Dilation:

Among the most shocking consequences of Einsteinian theory are the «length contraction» and «time dilation»: a moving object would have its dimensions increased (in the direction of motion) and its temporal evolution rhythm slowed down. Much ink has been spilled discussing the objectivity of these phenomena: is a moving ruler «really» shorter than when it is at rest? Does a particle live «really» longer when moving than at rest? The experiment certainly confirms the theoretical prediction: muons from cosmic rays have time to reach the ground by crossing the atmosphere before disintegrating. They thus travel several tens of kilometers at a speed obviously less than that of light, namely 300,000 km/s. Their journey thus lasts about ten-thousandths of a second while their lifetime at rest is about one millionth of a second. But how to interpret these phenomena?

It is in fact quite simply effects of perspective, or more precisely, of parallax, in space-time, quite analogous to usual spatial effects. When one wishes to measure the length of an object by comparing it to a graduated ruler, it goes without saying that one locates the ends of the object on the reference ruler placed parallel to the length one wants to measure. If for some reason this parallelism is impossible, the obliquity of the ruler relative to the measured object will cause the sighting to locate, by projection (perpendicular to its own direction) on the ruler, an apparent length greater. This «length dilation» is the parallax effect, due to the fact that the location is done on a reference ruler whose spatial direction differs from that of the object. Nevertheless, the object does have an intrinsic length which is obtained by placing the ruler parallel to its own direction or, failing that, by correcting the reading by the appropriate angular factor.

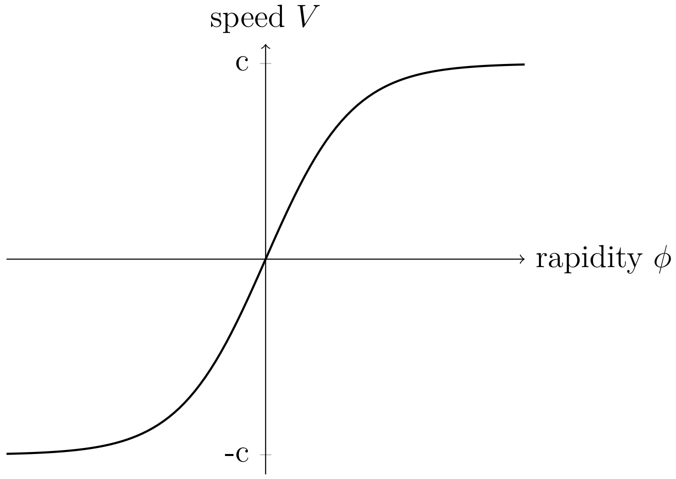
Let us use the graphical representation of space-time where an event is located on a plane by its temporal and spatial coordinates (we keep here only one spatial direction for the convenience of illustration). The axes then materialize the reference frame used, and a change of reference frame translates into a change of axes. It is the role of the transformation formulas to specify the relative arrangement (orientation and graduation) of the axes corresponding to two equivalent reference frames. In the case of two spatial dimensions (Euclidean), two equivalent reference frames differ by their orientation and are deduced from each other by a simple rotation. In the spatio-temporal case (Einsteinian), the so-called Lorentz transformation is less familiar.
An object of length L_0 in its own reference frame will, in another reference frame, be located differently and will be assigned a shorter length L. But, as in the spatial case, this is a parallax effect: it is only if the spatio-temporal axes of the object coincide with those of the ruler used that one can claim to measure the proper length of the object. Time dilation is explained in an analogous way. These effects are therefore perfectly «real», while concerning only «appearances».

However, one could still get away with assuming that material bodies, by their electromagnetic constitution, underwent during their displacements in the «ether», strange contractions: it is this modification, undergone by the measuring instruments which, exactly compensating the variation in the speed of light, would explain its apparent constancy. At the end of the 19th century, physics was thus oriented towards a detailed study of the electromagnetic properties of matter which would have served as a basis for understanding the apparent, and paradoxical, properties of space and time. The great historical merit of Einstein is to have reversed this approach. He proposed, rather than solving the problem posed by the divergence of electromagnetism and Galilean relativity, to eliminate it by renouncing the latter. The *principle* of relativity could be saved, provided the theory was modified. Adopting the transformation formulas

$$x' = \frac{x - vt}{\sqrt{1 - v^2/c^2}}$$

$$t' = \frac{t - vx/c^2}{\sqrt{1 - v^2/c^2}}$$

the electromagnetic theory became perfectly relativistic, that is, invariant under change of reference frame. Einstein was not the first to write these formulas, moreover today called «Lorentz formulas», but, before him, they were interpreted only in a phenomenological sense, requiring a deeper explanation from the constitution of matter. Einstein on the contrary, while introducing them by an essentially operationalist analysis (how to synchronize clocks using light signals, etc.), gave them a fundamental position. Contemporary physics is deeply indebted to this innovation. The principled character conferred by Einstein to the theory of relativity has only strengthened. If historically, (Einsteinian) relativity derives from electromagnetic theory, the conceptual chain is, from the current epistemological point of view, reversed, and one can regret that this reversal has not yet been universally adopted on the pedagogical level.



Do Not Confuse Speed and Rapidity:

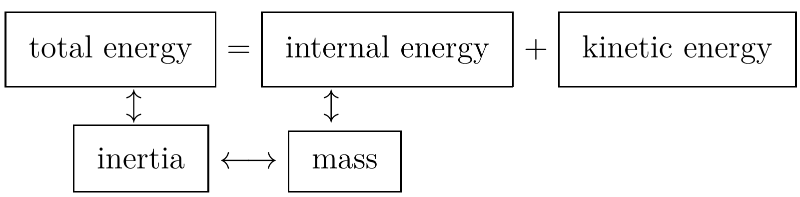
The notion of speed is, in Einsteinian theory of relativity, a frequent source of confusions and pseudo-paradoxes. The troubling existence of a limit speed c (that of light) indeed requires a bizarre composition law, where speeds do not add in a simple way as in Galilean theory. Instead of the expression $v' = v + V$ for the speed v' of a moving object in a reference frame R' in uniform motion at speed V relative to the reference frame R where the speed is v, we have here $v' = \frac{v+V}{1+vV/c^2}$ (so that if $v = c$, we indeed have $v' = c$ too). Most conceptual difficulties disappear if one introduces the notion of *rapidity*. The rapidity φ of a moving object of speed v is defined by the expression $v = c \tanh \varphi$, relation represented by the figure above. It is easy to see that rapidity takes any numerical values, without further limitation. Above all, it obeys a simple additive composition law: $\varphi' = \varphi + \phi$, where φ' and φ are the rapidities of the moving object relative to the two reference frames R' and R, and ϕ the relative rapidity of these two reference frames. We also see that for speeds low compared to that of light, speed and rapidity, up to the numerical factor c, coincide: $v \simeq c\varphi$ for $v \ll c$. Therefore, the Galilean concept of speed gathers properties that, in the general, Einsteinian case, belong to two different – though related – quantities: the rate of temporal variation of distance on one hand, the additive parameter of motion on the other. In other words, where there is one Galilean speed, there are two Einsteinian ones: the first which by implicit abuse of language we have continued to call «speed»; the second, which has been baptized «rapidity». Both must be introduced and their simultaneous consideration alone can provide an adequate generalization of the concept of speed. Today, the notion of rapidity is commonly used by physicists. Its almost general introduction (though recently) in teaching eliminates many pedagogical difficulties.

A very similar situation exists in elementary geometry applied to topography, when one wants to characterize the inclination of a slope. One says, for example, that the slope of a road is 5% if the elevation difference is 5 m for a distance of 100 m. These slopes, as long as they are small, add up, in the sense that a direction presenting a slope of 3% relative to a hill of slope 5% (for example, the line of sight of a theodolite) has a slope of 8% relative to the horizontal. It is clear, however, that for large slopes this additivity no longer holds. One must then introduce a parameter θ, related to the slope t by the relation $t = \tan\theta$. This parameter θ is none other than the angle which, by essence, is additive. A direction presenting an angle of Θ relative to the flank of a hill making itself with the horizontal an angle of θ deviates from the horizontal by an angle $\theta' = \theta + \Theta$. The corresponding slopes, on the other hand, are linked by the exact relation $t' = \frac{t+T}{1-tT}$ (whose resemblance to the Einsteinian relation of composition of speeds underlies a deep mathematical analogy). For small angles, the tangent and the angle are almost confused and the distinction is useless, like that of speed and rapidity in the Galilean case.

A «Super-Law» of Physics.

For three-quarters of a century, we have had to recognize the existence, alongside electromagnetic interactions, of other interactions that govern fundamental particles on a very small scale. These interactions, called «strong» and «weak», constitute the essential field of study in particle physics. Now, if they prove to be most complex, one of their uncontested characteristics so far is to obey Einsteinian theory of relativity. The latter is thus verified daily by the thousands of experiments conducted on high-energy particles. In this particular field of physics, relativity, far from being an esoteric theory with elusive effects, forms the very framework for the conception and analysis of experiments. It is truly materialized by the operation of gigantic particle accelerators. On the theoretical level, it underlies all attempts to understand the subnuclear world. Born in the framework of classical physics, it now reigns just as constrainingly over quantum theories. Describing universal general properties of space and time, the arena where physical phenomena unfold, relativity constitutes today, following Wigner's word, a «super-law» of physics: relativistic invariance is a necessary condition of validity for any new theory.

Mass, Inertia, Energy:



$\updownarrow$ identification in Einsteinian theory
$\longleftrightarrow$ identification in Galilean theory

Many popularizing or didactic statements of Einsteinian relativity insist on the variability of mass with speed. One must be careful here with abuses of language. In Newtonian mechanics, governed by Galilean relativity, the notion of mass has a double content. It denotes on one hand the quantity of matter intrinsically contained in a physical object, and on the other hand its coefficient of inertia, measure of the difficulty in modifying the object's state of motion. These two quantities are universally proportional, and, with a suitable choice of units, can be identified. In Einsteinian relativity on the contrary, these two notions decouple. Nowadays, the name mass is reserved for the first, which, by essence, characterizes the object independently of its motion; mass is therefore an invariant quantity. Inertia, on the other hand, is here proportional to energy and indeed increases with speed; it even grows indefinitely when the speed approaches the limit speed, which entails the impossibility of actually reaching the latter.
As for the (too) famous formula $E_0 = mc^2$, it must today be understood as identifying, up to the factor c^2, the mass of an object, in the intrinsic sense above, with its *internal* energy, itself an invariant property (hence the index 0). The total energy consists of this internal energy and the kinetic energy, due to motion; the internal energy is also the «rest» energy, when the kinetic energy is zero.
There is therefore a great difference between Galilean relativity and Einsteinian relativity. For the first, mass and inertia are identical, constant and independent of energy. For the second, mass and inertia differ, mass identifies with internal energy, inertia with total energy. In Einsteinian theory, only (total) energy is conserved. We see the subtlety of the relations between the two theories – the first nevertheless being an approximation of the second – and all the risks of misunderstanding that the necessary abuses of language entail by which one uses the same denomination («mass», «energy») for concepts certainly analogous, but not homologous.

The theory of relativity is therefore a true geometry of space-time, which governs the physicist's work with as much force as ordinary spatial geometry governs that of the architect. Shortly after the Einsteinian breakthrough (1905), Minkowski then Weyl gave relativity a mathematical formulation responding to the modern conception of geometry: the study in a certain space of its invariant properties under a certain *group* of transformations. The group structure, undoubtedly one of the most important in mathematics, finds here a vast field of application. Usual spatial geometry is linked to the Euclidean group (translations and rotations); relativity corresponds to the «Lorentz group», generated by Lorentz transformations (in addition to spatial rotations). In this conception, the emphasis is on *invariant* properties. It is they indeed that express the intrinsic, absolute aspects of the space studied. Thus in ordinary geometry, the distance between two points is a Euclidean invariant (unlike, for example, the components, in a certain coordinate system, of the segment joining these points). More generally, physical quantities are classified according to their mode of transformation during changes of reference frames. Group theory and tensor calculus allow identifying certain canonical types of variance (thus the notion of three-dimensional vector has an immediate analog in four-dimensional space-time). The use of such invariants or covariants allows a great improvement in theoretical calculations, and the comparison of modern works with those from half a century ago shows the progress made. As always, the condensation of writing reveals a conceptual deepening even more than a formal economy. The theory of relativity thus appears rather poorly named from the modern point of view, as Sommerfeld already remarked 50 years ago, since its role is ultimately to identify invariant, absolute physical properties (independent of the reference frame).

Let us assume that the Maxwell-Hertz equations are valid for the system at rest K, so that we have:

$$\frac{1}{V}\frac{\partial X}{\partial t} = \frac{\partial N}{\partial y} - \frac{\partial M}{\partial x}, \quad \frac{1}{V}\frac{\partial L}{\partial t} = \frac{\partial Y}{\partial x} - \frac{\partial Z}{\partial y},$$
$$\frac{1}{V}\frac{\partial Y}{\partial t} = \frac{\partial L}{\partial x} - \frac{\partial N}{\partial x}, \quad \frac{1}{V}\frac{\partial M}{\partial t} = \frac{\partial Z}{\partial x} - \frac{\partial X}{\partial x},$$
$$\frac{1}{V}\frac{\partial Z}{\partial t} = \frac{\partial M}{\partial x} - \frac{\partial L}{\partial y}, \quad \frac{1}{V}\frac{\partial N}{\partial t} = \frac{\partial X}{\partial y} - \frac{\partial Y}{\partial x},$$

where (X, Y, Z) mean the vector of the electric force, (L, M, N) that of the magnetic force.

Wave Equation

An electromagnetic field in vacuum is determined by Maxwell's equations, in which one must set $\rho = 0$, $\mathbf{j} = \mathbf{0}$.
Let us write them once more:

$$\mathrm{rot}\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}, \qquad \mathrm{div}\mathbf{H} = 0,$$
$$\mathrm{rot}\mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}, \qquad \mathrm{div}\mathbf{E} = 0.$$

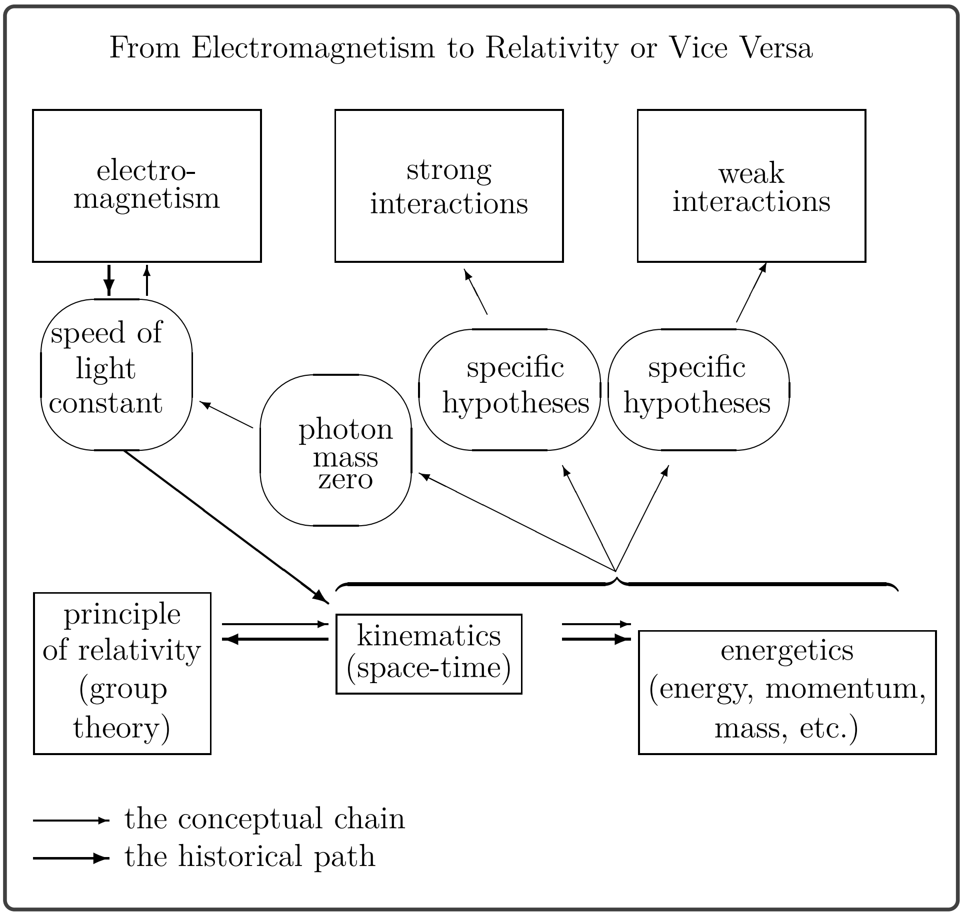
These equations can admit non-zero solutions. This means that the electromagnetic field can exist even in the absence of charges.

We will derive again the wave equation in four-dimensional form. For this purpose, we write the second group of Maxwell's equations for a field in the absence of charges in the form:

$$\frac{\partial F^{ik}}{\partial x^k} = 0$$

«From Formulas of Relativity to the Relativity of Formulas». The writing of formulas that express a physical law depends on the general theoretical framework in which this law is inscribed. The broadening of this framework, reflecting the deepening of concepts, generally allows for an increasingly synthetic expression. This formal economy is clearly manifested in the appearance of Maxwell's equations, which govern the electromagnetic field. In (a), the form of part of these equations as written by Einstein himself in his 1905 memoir. In (b), the «vector» form of the equations in the modern treatise by Landau and Lifshitz, and in (c), in the same work, a «covariant» form that fully incorporates the theory of relativity.

The consolidating abstraction, if it very quickly allowed the reformulation of the theory, for a long time only slightly affected the interpretation and foundations. Despite the generality of the geometric point of view and the universality of its application to all types of interactions, the very bases of relativity are still very often linked today to the particular category of electromagnetic physical phenomena. In the initial Einsteinian construction, the invariance of the speed of light, or more generally the form of Maxwell's equations for the electromagnetic field, served as the cornerstone. But it now seems necessary to reverse the historical order: the invariance of the speed of light is today understood as deriving from the fact that the photon, elementary particle mediator of electromagnetism, has zero mass. It then follows from the theory that its speed is equal to the limit speed; but this is also the case for the neutrino, at least if its mass is indeed zero. It could indeed be that photon and neutrino have infinitesimal but non-zero masses and move only approximately at the limit speed. However, this fact would in no way invalidate the theory of relativity. On the contrary, it would serve to establish a modified form of electromagnetic theory, as it serves today to build Maxwell's theory. We now know how to build the conceptual edifice of relativity from very general hypotheses concerning only the structure of space-time, without particular assumptions concerning such physical phenomenon, propagation of light or other. This theoretical construction of relativity relies essentially on the theory of transformation groups. It is interesting to note that this abstract and general modification of the bases of relativity also saw the light of day as early as 1910 (Ignatowski, Frank, Rothe). It nevertheless remained largely ignored and was periodically rediscovered by various researchers; it seems only very recently to be in a position to be recognized, if not generally accepted.



This is a striking example of delay in the overhaul of a physical theory, a delay certainly heavy with epistemological and pedagogical consequences. In particular, we must now recognize that the theory of relativity rests on bases of such solidity that it is very difficult to find plausible generalizations or modifications for it. The idea is indeed natural to envisage a future replacement of Einsteinian theory, as it replaced Galilean theory. However, the construction of a theory of relativity on the general bases mentioned necessarily leads to Einsteinian theory, or to its Galilean approximation, but not to a more general theory (a slight reservation must be made to this assertion, but it is too technical to concern us here). Any eventual contradiction from experimental origin would therefore constitute a major upheaval in theoretical physics.

General Relativity: The End of a Splendid Isolation

The Einsteinian theory of relativity discussed so far is often called «special relativity» in opposition to «general relativity». While Einstein's role in the first was to brilliantly and decisively crown the work of an entire generation of theorists, the second was a solitary creation, perhaps the last example of an individual work in modern physics. Einstein's objective was to build a theory of gravitation (at the time the only interaction recognized besides electromagnetism) adequate to the new conception of space-time, as Newton's theory was to the old one. Einstein started from the elementary but profound remark of the identity between inertial mass (the coefficient of inertia, translating a body's resistance to the modification of its state of motion) and gravitational mass (the gravitational «charge», one should rather say, which expresses the intensity of gravitational interactions exerted on, and by, a body). It results from this identity that the trajectory of a body in a gravitational field does not depend on its mass; an artificial satellite of 1 ton and a dust particle of 1 mg placed initially with the same speed at the same altitude will follow the same orbit around the Earth, the first undergoing a force a billion times greater than the second, but responding to it with an inertia a billion times greater too. Gravitational trajectories are therefore independent of physical properties, and can be characterized in a purely geometric way. Einstein thus constructed a geometric theory of gravitation, where «forces» of the Newtonian type are replaced by local modifications, «curvatures» of space-time. This point of view naturally led him to employ the formalism of differential geometry and to express the theory in a form that was valid in any reference frame, and not only in reference frames in uniform relative motion of «special» relativity. From there comes the name of «general relativity». Here again, however, one must not confuse the construction of the theory with its interpretation, its genesis with its exegesis. Several theorists noted fairly quickly that the requirement of general relativity, namely the possibility of formulating the theory in any reference frame was in itself devoid of physical meaning and could be imposed on any theory (by roughly introducing terms of the «centrifugal force» type characterizing the arbitrary nature of the reference frame). Conversely, and this is a still current debate, it could be that this formal equivalence of all reference frames masked the privileged role of some of them. Finally, the discovery of nuclear interactions, strong and weak, considerably weakened the hope of a total geometrization of physics: more or less successful attempts were made to integrate electromagnetism into a «unified» theory, but nuclear interactions remained rebellious. If one adds that the specific effects predicted by general relativity, distinguishing it from the classical Newtonian theory, were weak and limited, one understands that it remained for a long time in a splendid isolation.

For about fifteen years the situation has changed a lot. The progress of astrophysical observations has led to studying more and more situations where recourse to a relativistic theory (in the Einsteinian sense) of gravitation was imposed. The discovery of pulsars has shown that there exist objects (neutron stars) of such density that in their vicinity the curvature of space, to use orthodox terminology, is no longer an epiphenomenon but an essential aspect of the physical situation. This would be even more true for «black holes» still hypothetical but objects of relentless research, like gravitational waves, which are not even conceivable in Newtonian space-time, no more than electromagnetic waves. Cosmology finally, when it studies «the first three minutes of the universe», also relies on general relativity. The latter thus constitutes the theoretical core of a very active field of physics. However, general relativity is not the only possible theory of gravitation in agreement with «special» relativity, and part of the research aims precisely to test the validity of these various theories. If several of them, yet seductive in certain respects (like that of Brans-Dicke), are practically eliminated, general relativity so far holds firm; its coherence and simplicity allow it moreover to retain a privileged status. This permanence does not however exclude important modifications in its interpretation and understanding. Thus, a current of «degeometrization» of general relativity is developing. It is indeed possible to build a relativistic theory of gravitation on the model of electromagnetism and other interactions, that is, as a field theory. With very natural hypotheses, one thus arrives at a theory formally identical to general relativity, thus entailing the same physical consequences, but conceptually different: space-time there is that of «special» relativity, without curvature, where a gravitational field reigns that simulates such a curvature. Gravitation thus loses the incomprehensible privilege it seemed to hold and its theory is no longer «general», nor even a «relativity». This point of view, born essentially from high-energy physics, reflects the current hegemony of field theories (classical and quantum) over all physics. Ideas – still problematic – like that of «supergravity» and «gauge theories», allow hoping for a possible unification in this framework of physical theories describing various interactions. This realization of the objective that Einstein pursued in vain during his last thirty years would thus be obtained in a direction exactly identical to the one he followed but in the opposite sense: instead of geometrizing all other interactions like gravitation, one restores to the latter its status as a field theory. No doubt the humor of the situation would have amused Einstein.

FOR FURTHER READING

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