Einstein's development of special relativity

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Abstract

Einstein has presented highlights of how he developed his special theory of relativity. I present some of them here.

1 Introduction

I presume that the reader has already had some Newtonian mechanics. If so, then you have already tasted relativity – Galilean relativity that is! The laws of Newtonian mechanics have the same form when they are coordinate transformed (using the Galilean transformation) from one inertial reference frame to any other (the Principle of Galilean Relativity). This is called "covariance" of the form. And any law of Newtonian mechanics which is covariant with respect to transformation of coordinates among any two inertial reference frames can be said to be a "general law of Newtonian mechanics." One of these general laws is $\sum_i \mathbf{F}_i = m\mathbf{a}_i$, where the index i ranges over all known forces acting on a particle of mass m.

Newtonian mechanics can be defined as the theory of all phenomena (modeled as interacting point mass particles) whose descriptions are by laws which are Galilean covariant. In Newtonian mechanics:

1. No inertial reference frame has better status for the description of mechanical phenomena than does any other inertial reference frame.
2. Velocities are relative, though accelerations are treated as absolute.

Now, remember that the term "description" just means "laws that account for," and it has no necessary relationship to our naive and prejudicial speculations about what's supposedly "really going on." The problem with adding in electromagnetics to Newton's "mechanics" is that Maxwell's equations describing light phenomena are not Galilean covariant, and thus are not "mechanical" phenomena by the above definition of such. (Now, I grant that "mechanical phenomena" can be defined differently than I have done so above, but I am trying to set up at least a reasonable heuristic argument to aid one's accepting of the postulates of SR. Furthermore, it seems to me that Newton's theory has a weakness that, although it tells us how to model "mechanical phenomena," it fails to define exactly what "mechanical phenomena" is.)

Maxwell's equations are covariant under a different set of coordinate transformations than are used for Galilean relativity. This other set of transformations is called the Lorentz transformation of coordinates, or just the "Lorentz transformation" for short.

2 The Evidence

Let's go back to this freedom we have to "define things as we want to" to make it a little clearer. This happens because there is a lot of room in theoretical physics to invent models and concepts and to accept such principles as "fundamental" as we please, so long as in the end the theory so constructed is internally consistent and works well to describe the phenomena that it set out to describe. The sense that I mean "principle" is either a specific law of physics, empirically derived, or a trustworthy heuristic rule. Either of which would give one strong confidence in their ability to act as a founding postulate of a theory, right? And if one has strong confidence in the founding principles of the theory and in the deductive process that leads to specific predictions, then why would one not also have strong confidence in the predictions themselves? Logical deduction is confidence preserving.

Einstein said this:

> Physical concepts are free creations of the human mind, and are not, however it may seem, uniquely determined by the external world. (*The Evolution of Physics*, Einstein & Infeld, Touchstone, 1938, p. 31.)[1]

Now, H. A. Lorentz published a theory on the electrodynamics of moving bodies (1904) that speculated (at least formally so) that there exists a fixed ether distributed throughout all space (which is the embodiment of an absolute rest space) in which light is "really" propagated at the "speed of light" c. But Einstein just could not accept this concept into his formal point of view, simply because it introduced a special inertial frame that restricted the symmetry of reference frames more than did the Principle of Galilean Relativity of Newtonian mechanics – not so much in practice as in the conceptual nature of the problem.

Einstein wrote:

> H. A. Lorentz even discovered the "Lorentz transformation," later called after him, though without recognizing its group character. To him Maxwell's equations in empty space held only for a particular coordinate system distinguished from all other coordinate systems by its state of rest. This was a truly paradoxical situation because the theory seemed to restrict the inertial system more strongly than did

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[1] When I first read this claim of Einstein's in the late 1980s, I was amazed and I became an instant believer in it to this day. Based on this dogma, I would evolve my own philosophy of physics, which I learned has a name – Scientific Instrumentalism, by which the physicist has great freedom to invent physical models.

> classical mechanics. This circumstance, which from the empirical point of view appeared completely unmotivated, was bounded to lead to the theory of special relativity.
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> — "H. A. Lorentz, Creator and Personality," *Ideas and Opinions*, p. 75.

OK, what Einstein means about this paradox is that if we remember our experience of the world around us carefully, we cannot remember ourselves in any situation in which the laws of physics are any different in one inertial reference frame than in any other inertial frame, yet Lorentz is claiming that there exists this undetectable inertial reference frame that is special (in that it is used to define a unique "rest" frame) and, furthermore, is fundamental to the founding of the unification of mechanics and electrodynamics. Einstein was clearly unsatisfied by this state of affairs. What he must have asked himself is this simple question: Is physics really required to destroy the integrity of the principle of relativity, which seems so unequivocal in classical mechanics, just to unify mechanics and electrodynamics? Einstein's genius was to find a way of performing this integration without sacrificing the purity of the principle of relativity (equivalence of all inertial reference frames in every way).

Einstein stated all this is more detail in his essay "Relativity and the Problem of Space":

> The ether-theory brought with it the question: how does the ether behave from the mechanical point of view with respect to ponderable bodies? Does it take part in the motions of the bodies, or do its parts remain at rest relatively to each other? Many ingenious experiments were undertaken to decide this question. The following important facts should be mentioned in this connection: the "aberration of the fixed stars in consequence of the annual motion of the earth, and the Doppler effect," i.e., the influence of the relative motion of the fixed stars on the frequency of the light reaching us from them, for known frequencies of emission. The results of all these facts and experiments, except for one, the Michelson-Morley experiment, were explained by H. A. Lorentz on the assumption that the ether does not take part in the motions of ponderable bodies, and that the parts of the ether have no relative motions at all with respect to each other. Thus the ether appeared, as it were, as the embodiment of a space absolutely at rest. But the investigation of Lorentz accomplished still more. It explained all the electromagnetic and optical processes within ponderable bodies known at that time, on the assumption that the influence of ponderable matter on the electric field—and conversely—is due solely to the fact that the constituent particles of matter carry electrical charges, which share the motion of the particles. Concerning the experiment of Michelson and Morley, H. A. Lorentz showed that the result obtained at least does not contradict the theory of an ether at rest.

> In spite of all these beautiful successes the state of the theory was not yet wholly satisfactory, and for the following reasons. Classical mechanics, of which it could not be doubted that it holds with a close degree of approximation, teaches the equivalence of all inertial systems or inertial "spaces" for the formulation of natural laws, i.e., the invariance of natural laws with respect to the transition from one inertial system to another. Electromagnetic and optical experiments taught the same thing with considerable accuracy. But the foundation of electromagnetic theory taught that a particular inertial system must be given preference, namely, that of the luminiferous ether at rest. This view of the theoretical foundation was much too unsatisfactory. Was there no modification that, like classical mechanics, would uphold the equivalence of inertial systems (special principle of relativity)?
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> The answer to this question is the special theory of relativity. This takes over from the theory of Maxwell-Lorentz the assumption of the constancy of the velocity of light in empty space. In order to bring this into harmony with the equivalence of inertial systems (special principle of relativity), the idea of the absolute character of simultaneity must be given up; in addition, the Lorentz transformations for the time and the space coordinates follow for the transition from one inertial system to another. The whole content of the special theory of relativity is included in the postulate: the laws of nature are invariant with respect to the Lorentz transformations. The importance of this requirement lies in the fact that it limits the possible natural laws in a definite manner.
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> — Found in: "Relativity and the Problem of Space," *Ideas and Opinions*, pp. 369–370.

Einstein debunkers love to claim that Einstein merely stole the Lorentz transformation from Lorentz. The truth of the matter seems too subtle for them to understand. Of course Einstein had to derive the Lorentz transformation equation because it is the transformation that leaves Maxwell's equation invariant, and which places all inertial reference frames on an equal footing from the observational standpoint. Nevertheless, people can invent imaginary (theoretical) absolute rest spaces, even if they can't be detected. For if there is in fact an absolute rest frame for optical phenomena (the rest frame of the ether), then it can never be detected by the electromagnetic phenomena it was invented to support. Why? Because the Lorentz transformation and experience proves that any other inertial frame could be substituted for this 'absolute' rest frame and perform the same function. What Einstein accomplished was to found a theory of electrodynamics in such a way as to produce the Lorentz transformation, yet did not need to assume the existence of a ghostly absolute frame of rest — a frame, which if it really existed, would do what classical mechanics did not need to do: assign an instantaneous absolute velocity to the motion of every mass particle.

Both special relativity (SR) and the Lorentz ether theory (LET) have the same set of predictions concerning electromagnetic phenomena, though they have very different interpretations of their meanings. Thus, the two theories are truly "different" theories. Furthermore, it was very easy for Einstein to generalize his SR principle of relativity to go from only electromagnetic forces to any nongravitational force at all. But Lorentz's theory was not so easily generalized from its electrodynamic nature, because light phenomena was regarded in Lorentz's theory as an actual state of the ether itself. And even more, the apparent corpuscular nature of light is not as easily accounted for by an ether model as it is by the photon model introduced on top of the postulates of SR. The general rule is this: The sooner one introduces a specific model into a theory, the sooner that model becomes an albatross to the generalization of the theory.[2] So, instead of "explaining" electromagnetic phenomena as states of an ether, Einstein chose to just leave the electric and magnetic fields as irreducible concepts.

Einstein accepted the task of building a theory of the electrodynamics of moving bodies that did not have this added restriction to Newton's mechanics that voided the spirit of the "symmetry" of (the inherent egalitarian nature of) all inertial reference frames implicit within the principle of relativity, at least as he saw it. He said that he played with this construction for a long time, until one day the means to a solution suddenly came to him. And this was when he realized that the solution rested on the fact — within the confines of his freely accepted formal point of view — that time cannot be absolutely defined. Now, it's very important to understand that Einstein was not making a judgment about Newton's metaphysical time (except to declare that it has no physical content), but about *measured time* as it is determined by actual clocks in the lab, so to speak. This notion of defining a measurable variable in terms of the measurement process itself is referred to as an "operational definition" of the variable.

So, the question is this: Given that light and matter interact with each other, such as in the phenomena of the photo-electric effect,

1) How strongly do you 'feel' that this interaction phenomena ought to be describable by some kind of general laws of physics, just as Newton's mechanical phenomena is? (Einstein was strongly inclined to believe this based on his belief in the "pre-established harmony" of Nature. It seems that Einstein viewed covariance as proof of, and the very embodiment of, this harmony. [See Einstein's essay, "Principles of Research," *Ideas and Opinions*, pp. 226-7.]

2) If you do not 'feel' strongly that human physics is to be guided by the principle that all phenomena that humans encounter of a metrical nature is describable by general laws of physics, then do you believe that the Galilean covariance found in Newton's mechanics is just an irrelevant "accident of Nature" resulting from our particular arbitrary manner of constructing mathematical

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[2] This rule is broken strongly by modern quantum field theories, yet even in this there are other ways of proceeding.

descriptions of phenomena, and that it is not a guide (or "heuristic") in how to formulate generalizations of Newtonian mechanics to include other phenomena?

The main point of SR to Einstein is that it is reasonable to adopt the formal point of view that one can build a theory extending Newton's theory in which

1) all metrical non-gravitational phenomena as measured from inertial reference frames are describable by general laws of physics, 2) the covariance of those laws which describe mechanics, optics, and electromagnetics is Lorentzian (1905 version of the SR principle of relativity) and reduces to Galilean in the limit as velocities are much less than that of the speed of light, thus making SR a generalization of Newtonian mechanics on its domain of applicability.

Since Einstein was committed to adopting a minimal set of postulates (what he referred to as "logical economy," which was another feature of his formal point of view) for this extension of Newtonian physics, he accepted as fundamental additions to that theory the Light Principle (i.e., the masured speed of light made from within any inertial reference frame in a vacuum is a constant) and the SR principle of relativity, and he chose not to speculate in SR as to any "explanation" of **how** the Light Principle works from a mechanical point of view.

Einstein referred to SR as a "principle theory," which I shall also refer to as a "principled extension" to Newton's theory. Einstein referred to Newton's theory as a "constructive theory," which attempts to explain all phenomena within the theory as the emergent properties of the interactions of the parts of one or more fundamental substances, which in the case of Newton's theory is the mutual interactions of point mass particles, interacting "at a distance," which just means that the interactions between particles always occurs instantaneously and along the direction of the lines connecting them in pairs.

If you are in the process of learning special relativity and yet have doubts about it, take time to learn SR properly. For the moment give it the benefit of the doubt. You have the rest of your life to learn about alternatives. Don't get stressed out by non-intuitive conclusions of SR. Just concentrate on

1) the reasonableness (or lack thereof) of the principles which found SR as an extension to Newtonian mechanics,

2) the correctness of the deductions from the purely mathematical standpoint, and

3) agreement (or lack thereof) of SR predictions to experiment.

If you can get confident in these first two aspects of SR, then why would you not have confidence in the predictions of SR, even before the experiments which test them? Confidence going in should mean confidence coming out!

3 Hints to generalizing to all coordinate systems

Einstein's long-term research program was to build a theory of all metrical phenomena in which there is no use of an absolute velocity space, or of an absolute acceleration space, and that noncontact interactions are modeled by fields whose disturbances propagate through "empty space" at finite speed, and that all metrical phenomena are describable by laws which have the same form under any reasonable change of coordinates (which includes both inertial and noninertial reference frames) – which is called the "general principle of relativity."

Now, it all comes down to how you personally answer this question posed by Einstein:

> What has nature to do with our coordinate systems and their state of motion? If it is necessary for the purpose of describing nature, to make use of a coordinate system arbitrarily introduced by us, then the choice of its state of motion ought to be subject to no restriction; the laws ought to be entirely independent of this choice (general principle of relativity).
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> (First printed in 1919. Appeared in *Albert Einstein's General Relativity*, Crown Publication, New York, 1979, p. 63.)

Well, is it necessary to introduce coordinates to do physics? Of course is. How else is an experimentalist to make measurements if not within a frame of reference, coordinatized to make those measurements?

In SR, Einstein extended the Galilean principle of relativity to include all of mechanics, optics, and electrodynamics (1905 version). In it, he maintained velocities as relative, though he left accelerations as absolute, as they were also treated in Newton's mechanics. It was Einstein's desire to drop the absoluteness of accelerated (noninertial) reference frames that led him to his final generalization of the principle of relativity to the "general" form indicated in the above quote. The equivalence of inertial and gravitational mass was his specific empirical foundation to this extension.

So, the evolution of the foundations to physics over the last 400 years can be crudely gauged by the evolution of the Principle of Relativity over the same period. Starting off with the Principle of Galilean Relativity, we have the negative principle that inspires it as:

> It is impossible to perform any contained "mechanical" experiment within an inertial reference frame that can determine that frame's so-called absolute velocity.

Einstein's generalization of this to get his SR Principle of Relativity (1905) starts from the empirical fact (stated as a negative principle) that inspires it as:

> It is impossible to perform any contained mechanical, optical, or electrodynamical experiment within an inertial reference frame that can determine that frame's so-called absolute velocity.

Einstein later generalized this 1905 version of his SR Principle of Relativity to be force nonspecific (except for gravity) as:

> It is impossible to perform any contained experiment within an inertial reference frame that can determine that frame's so-called absolute velocity. (The nature of the experiments would be mechanical or optical.)

And finally, Einstein's generalization of his SR Principle of Relativity to arrive at his GR Principle of Relativity starts from the empirical fact (again stated as a negative principle) that inspires it as:

> It is impossible to perform any contained experiment within any reference frame that can determine either that frame's absolute velocity or absolute acceleration.

4 Conclusion

To Einstein, the effort to extend the Mechanical Program to include electrodynamics, noble an effort as it was, provided terrible returns on investment: too many additional parts for too little harmony and logical economy. A simplification was in order by creating a replacement theory as a principle theory, the result being special relativity. Modern physics has never looked back.