How Did Einstein Discover Relativity?

By John Stachel

This reprints an essay written ca. 1983, "'What Song the Syrens Sang': How Did Einstein Discover Special Relativity?" in John Stachel, Einstein from "B" to "Z".

If you have read Edgar Allen Poe's "The Murders in the Rue Morgue," perhaps you remember the epigraph that Poe chose for this pioneer detective story:

> What song the Syrens sang, or what name Achilles assumed when he hid himself among women, though puzzling questions, are not beyond all conjecture.[1]

I believe that the problem of how Einstein discovered the special theory of relativity (SRT) falls into this category of "puzzling questions," that "are not beyond *all* conjecture."[2] Let me begin by explaining why.

When I started work on the Einstein Papers, there was already a large literature on the origins of SRT compared, say, to the rather scanty amount published on the origins of the general theory of relativity (GRT). So I assumed that the development of SRT must be fairly clear. However, I soon learned that the amount of work published on the origin of SRT and GRT are just about inversely proportional to the available primary source material. For GRT, we have a series of Einstein's papers from 1907 to 1915, capturing the successive steps of his search for the final version of the theory. In addition, there is extensive contemporary correspondence on the subject, several research notebooks, records of lectures given by Einstein during this period, not to mention a number of later reminiscences and historical remarks by Einstein.[3]

For SRT we have the paper *On the Electrodynamics of Moving Bodies*, in which the theory was first set forth in 1905 in its finished form, indeed a rather polished form (which is not to say that it bears no traces of its gestation process). The only earlier documentary evidence consists of literally a couple of sentences to be found in the handful of preserved early Einstein letters (I will quote both sentences later). We do have a number of later historical remarks by Einstein himself, sometimes transmitted by others (Wertheimer, Reiser-Kayser, Shankland, Ishiwara, for example), which raise many problems of authenticity and accuracy; and some very late Einstein letters, answering questions such as whether he had prior knowledge of the Michelson-Morley experiment, what works by Lorentz he had read, the influence of Poincaré, Mach, Hume, etc., on his ideas; Einstein's replies are not always self-consistent, it must be noted.[4]

Yet the urge to provide an answer to the question of the discovery of SRT has proven irresistible to many scholars. It is not hard to see why: A twenty-six year old patent expert (third class), largely self-taught in physics, who had never seen a theoretical physicist (as he later put it), let alone worked with one, author of several competent but not particularly distinguished papers, Einstein produced four extraordinary works in the year 1905, only one of which (not the relativity paper) seemed obviously related to his earlier papers. These works exerted the most profound influence on the development of physics in the 20th Century. How did Einstein do it? Small wonder that Tetu Hirosige, Gerald Holton, Arthur I. Miller, Abraham Pais, John Earman, Clark Glymour, Stanley Goldberg, Robert Rynasiewicz, Roberto Torretti, *et al.*, have been moved to study this question. I shall not try to record my debts to and differences with each of these scholars, lest this survey become even longer and more tedious than it is already; but must at least acknowledge the influence of their work on my own.[5] I resisted the urge to conjecture for some years, but have finally succumbed, so I can well understand the temptation.

Contrary to my original, naive expectation, no general consensus has emerged from all this work. Given the nature of the available documentation and the difficulty of understanding any creative process-let alone that of a genius-this really is not surprising. I now believe that the most one can hope to do in discussing the discovery of SRT is to construct a plausible conjecture. Such a conjecture will be based upon a certain weighting of the scanty evidence we possess, based upon certain methodological hypotheses, as well as the imagination of the conjecturer.[6] There are bound to be differences of opinion in these matters. All one can demand is that it be made clear on what methodological hypotheses a conjecture is based, and a demonstration that the conjecture is in accord with the available evidence when the latter is weighted in accord with these hypotheses.

Let me emphasize that no such account can hope to encompass those elements of the creative process that Einstein referred to as "the irrational, the inconsistent, the droll, even the insane, which nature, inexhaustibly operative, implants into the individual, seemingly for her own amusement," for "These things are singled out only in the crucible of one's own mind." Yet one may draw courage for the type of conjecture I have in mind from another remark of Einstein:

"A new idea comes suddenly and in a rather intuitive way. That means it is not reached by conscious logical conclusions. But, thinking it through afterwards, you can always discover the reasons which have led you unconsciously to your guess and you will find a logical way to justify it. Intuition is nothing but the outcome of earlier intellectual experience."

I shall discuss only this intellectual, logical side of Einstein's struggles. Before trying to reconstruct these struggles, it is well to note that his outward existence was far from tranquil during the period when he was developing SRT. While attending the Polytechnic at Zurich, thanks to the support of maternal relatives, he was plagued by the thought that he was unable to help his family, which was in dire financial straits due to constant business reverses. He was the only graduate in his section (VIA) not to get an academic post, and lived a hand-to-mouth existence for almost two years, until he got a job at the Swiss Patent Office thanks to help from a friend's father. During this period he was under severe family pressure to break with his fiancee, whom he only married in 1903 after his father's death. His first child was born in 1904, and he had to support wife and child on his modest income from the Patent Office, while his mother found work as a housekeeper. So one must not think of Einstein as a tranquil academic, brooding at leisure on weighty intellectual problems. Rather one must imagine him fitting his intellectual work into the interstices of a professional career and personal life that might have overwhelmed someone with a different nature.

The main methodological hypothesis guiding my conjecture was stated by Hans Reichenbach some time ago: "...the logical schema of the theory of relativity corresponds surprisingly with the program which controlled its discovery." To put it in more hifalutin' terms, also due to Reichenbach, I believe that "the context of justification" of SRT used by Einstein can shed light on "the context of its discovery."[7] This hypothesis suggests that we can learn a good deal about the development of the theory by paying close attention to the logical structure of its initial presentation in 1905, and to the many accounts of the theory that Einstein gave afterwards. Of course, I have tried not to neglect any scrap of evidence known to me, including the pitifully small amount of contemporary documentation and the later reminiscences. But I have given special weight to Einstein's early papers, letters, and lectures, in which he sought to justify the theory to his contemporaries. Intellectually, Einstein was an exceedingly self-absorbed person, willing to go over and over the grounds for the theory again and again. These accounts, given over a number of years, are remarkably self-consistent. They provide evidence for a number of conjectures about the course of development of his own ideas, and occasionally even include explicit statements about it. I assume that by and large memory tends to deteriorate with time, and (worse) that pseudo "memories" tend to develop and even displace correct recollections. So, a second methodological hypothesis which I shall adopt is that, in case of discrepancies between such accounts, earlier ones are to be given greater weight than later ones. Explicit remarks that Einstein makes about the discovery of SRT in the course of his later expositions must always be given great weight, but the earlier he made them the greater the weight I give to them. Of course, if some feature of Einstein's accounts remains unchanged over many years, I take this as evidence for giving such a point the most weight.[8]

It follows from these methodological assumptions that I must preface my conjectures with a brief resume of the "logical schema of the theory of relativity" as it was first published in the 1905 paper. In this paper, as in almost all subsequent accounts, Einstein bases SRT on two fundamental principles: the principle of relativity and the principle of the constancy of the velocity of light. The principle of relativity originated in Galilean-Newtonian mechanics: Any frame of reference in which Newton's law of inertia holds (for some period of time) is now called an inertial frame of reference. From the laws of mechanics it follows that, if one such inertial frame exists, then an infinity of them must: All frames of reference (and only such frames) moving with constant velocity with respect to a given inertial frame are also inertial frames. All mechanical experiments and observations proved to be in accord with the (mechanical) principle of relativity: the laws of mechanics take the same form in any of these inertial frames. The principle of relativity, as Einstein stated it in 1905, asserts that *all* the laws of physics take the same form in any inertial frame-in particular, the laws of electricity, magnetism, and optics in addition to those of mechanics.

The second of Einstein's principles is based on an important consequence of Maxwell's laws of electricity, magnetism, and optics, as interpreted by H. A. Lorentz near the end of the nineteenth century. Maxwell had unified optics with electricity and magnetism in a single theory, in which light is just one type of electromagnetic wave. It was then believed that any wave must propagate through some mechanical medium. Since light waves easily propagate through the vacuum of interstellar space, it was assumed that any vacuum, though empty of ordinary, ponderable matter, was actually filled by such a medium, to which our senses did not respond: the ether. The question then arose, how does this medium behave when ordinary matter is present? In particular, is it dragged along by the motion of matter? Various possible answers were considered in the course of the nineteenth century, but finally only one view seemed compatible with (almost) all the known experimental results, that of H. A. Lorentz: The ether is present everywhere. Ordinary matter is made up of electrically charged particles, which can move through the ether, which is basically immobile. These charged particles, then called "electrons" or "ions", produce all electric and magnetic fields (including the electromagnetic waves we perceive as light), which are nothing but certain excited states of the immovable ether. The important experimental problem then arose of detecting the motion of ponderable matter-the earth in particular-through the ether.

No other theory came remotely close to Lorentz's in accounting for so many electromagnetic and especially optical phenomena. This is not just my view of Lorentz's theory, it was Einstein's view. In particular, he again and again cites the abberration of starlight and the results of Fizeau's experiment on the velocity of light in flowing water as *decisive* evidence in favor of Lorentz's interpretation of Maxwell's equations.

A direct consequence of Lorentz's conception of the stationary ether is that the velocity of light with respect to the ether is a constant, independent of the motion of the source of light (or its frequency, amplitude, or direction of propagation in the ether, etc.).

Einstein adopted a slightly-but crucially-modified version of this conclusion as his second principle: There is an *inertial frame* in which the speed of light is a constant, independent of the velocity of its source. A Lorentzian ether theorist could agree at once to this statement, since it was always tacitly assumed that the ether rest frame is an inertial frame of reference and Einstein had "only" substituted "inertial frame" for "ether." But Einstein's omission of the ether was deliberate and crucial: by the time he formulated SRT he did not believe in its existence. For Einstein a principle was just that: a principle-a starting point for a process of deduction, not a deduction from any (ether) theory. (I am here getting ahead of my story and will return to this point later.) The Lorentzian ether theorist would add that there can only be *one* inertial frame in which the light principle holds. If the speed of light is a constant in the ether frame, it must be non-constant in every other inertial frame, as follows from the (Newtonian) law of addition of velocities. The light principle hence *seems* to be incompatible with the relativity principle. For, according to the relativity principle, *all* the laws of physics must be the same in any inertial frame. So, if the speed of light is constant in one inertial frame, and that frame is not physically singled out by being the rest frame of some medium (the ether), then the speed of light *must* be the same (universal) constant in every other inertial frame (otherwise the democracy of inertial frames is violated). As Einstein put it in 1905, his two principles are "apparently incompatible." Of course, if they really were incompatible logically or physically, that would be the end of SRT.[9]

Einstein showed that they are not only logically compatible, but compatible with the results of all optical and other experiments performed up to 1905 (and since, we may add). He was able to show their logical compatibility by an analysis of the concepts of time, simultaneity, and length, which demonstrated that the speed of light really could have the privileged status, implied by his two principles, of being a universal speed, the same in every inertial frame of reference.[10]

Now I shall begin my conjecture about Einstein's discovery of SRT. In a 1921 lecture, Einstein stated that SRT originated from his interest in the problem of the optics of moving bodies. He seems to have been fascinated from an early age by the nature of light, a fascination that persisted throughout his life. From an essay he wrote in 1895, (at age 16), we know that he then believed in the ether, and had heard of Hertz's experiments on the propagation of electromagnetic waves; but he does not show any knowledge of Maxwell's theory. In much later reminiscences, he reports that during the following year (1895-1896) he conceived of a thought experiment: what would happen if an observer tried to chase a light wave? Could s/he catch up with it? If so, s/he ought to see a non-moving light wave form, which somehow seemed strange to him. In retrospect, he called this "the first childish thought-experiment that was related to the special theory of relativity." Reliable accounts inform us that during his second year (1897-98) at the Swiss Federal Technical Institute, or Poly as it was then called, he tried to design an experiment to measure the velocity of the earth through the ether, being then unacquainted with either the theoretical work on this problem by Lorentz or the experiment of Michelson and Morley (M-M). A precious bit of contemporary documentary evidence reinforces this later account. In a letter to his schoolmate and friend Marcel Grossmann, written in the summer of 1901 (by then both had graduated from the Poly), Einstein wrote:

> A considerably simpler method for the investigation of the relative motion of matter with respect to the light ether has again occurred to me, which is based on ordinary interference experiments. If only inexorable destiny gives me the time and peace necessary to carry it out.

At first sight, it would seem remarkable for Einstein to have written these words (which also show that he had not yet abandoned the concept of the ether), if he knew about the M-M experiment at this time.

However, while still at the Poly (i.e., before 1901) he appears to have studied Maxwell's theory (not covered in his school lectures) on his own, perhaps from the new textbook of August Föppl (which, in various reincarnations, such as Föppl-Abraham, Abraham-Becker, Becker-Sauter, has stayed in print to this day). Föppl discusses a problem which evidently made a strong and lasting impression on Einstein, since he opens the 1905 paper with a discussion of it. This is the problem of the relative motion of a magnet and a conducting wire loop. If the loop is at rest in the ether and the magnet is moved with a given velocity, a certain electric current is induced in the loop. If the magnet is at rest, and the loop moves with the *same* relative velocity, a current of the same magnitude and direction is induced in the loop. However, the ether theory gives a different explanation for the origin of this current in the two cases. In the first case an electric field is supposed to be created in the ether by the motion of the magnet relative to it (Faraday's law of induction). In the second case, no such electric field is supposed to be present since the magnet is at rest in the ether, but the current results from the motion of the loop through the magnetic field (Lorentz force law). This asymmetry of explanation, not reflected in any difference in the phenomena observed, must already have been troubling to Einstein. Even more troubling was the knowledge, when he acquired it, that all attempts to detect the motion of ponderable matter through the ether had failed. This was an "intolerable" (his word, about 1920) situation. Observable electromagnetic phenomena depend only on the *relative* motions of ponderable matter; their explanations differ, however, depending on the presumed state of motion of that matter relative to the hypothetical ether; yet all attempts to detect this presumed motion of ordinary matter relative to the ether end in failure! He later (c. 1920) recalled that the phenomenon of electromagnetic induction compelled him to adopt the relativity principle.

In 1938 he wrote "The empirically suggested non-existence of such an [ether wind] is the main starting point [point of departure] for the special theory of relativity."[11] It is not clear when the significance of the failure of all attempts to detect the motion of ordinary matter through the ether first struck him. The letter quoted above suggests that it was after the summer of 1901. We know from a letter to another friend, Michele Besso, dating from early 1903, that he had decided to "carry out comprehensive studies in electron theory." No later than that, and quite possibly earlier, he read Lorentz's 1895 book, "Attempt at a Theory of Electrical and Optical Phenomena in Moving Bodies." Einstein surely learned about, the many such failures by reading this book, since one of its main purposes was to show that such failures were compatible with Lorentz's stationary ether theory. His later comments suggest that study of this book (Einstein says this is the only work by Lorentz he read before 1905) convinced him of the essential superiority of Lorentz' approach to the optics of moving bodies; yet it also convinced him that the Lorentz theory was still not fully satisfactory. Lorentz could explain away the failure to detect motion of matter relative to the ether convincingly to Einstein in all cases but one: the M-M experiment. To explain this, Lorentz had to introduce a special hypothesis, which to Einstein seemed completely unconnected with the rest of the theory: the famous Lorentz contraction. To Einstein, such an approach was not a satisfactory way out of the "intolerable dilemma." It seemed preferable to him to accept at face value the failure of the M-M and all similar experiments to detect motion of matter relative to the ether. Taken by themselves, these negative results suggested to Einstein that the relativity principle applied to electromagnetism, while the ether should be dropped as superfluous. There has been some confusion on this important point, so I shall expand on it. Sometimes the case is presented in such a way as to suggest that it was the "philosophical concept" of the relativity of all motion, as Einstein once called it, which was the key step in his rejection of the ether. But the concept of a stationary ether, as well as of a moving ether, is quite compatible with this philosophical concept of the relativity of motion: one need only assume that motions relative to the ether in the first case, as well as relative motions of the parts of the ether in the second, have physical efficacy. The leading advocates of both the dragged-along and the immovable ether concepts, Hertz and Lorentz, respectively, both understood this and both were read by Einstein.[12]

By the time he gave up the ether concept, Einstein most likely took this philosophical conception of the relativity of all motion for granted, presumably under the influence of his early reading of Mach's *Mechanics* (around 1897). What bothered him now was that no phenomenon existed that could be interpreted as empirical evidence for the physical efficacy of the motion of ordinary matter relative to the ether, in spite of repeated efforts to find one. Yet the best available theory- Lorentz's theory-could only attempt to explain away such failures. These explanations were satisfactory, within the framework of Lorentz' theory, in almost all known cases (i.e., for all experiments sensitive only to order v/c), and Einstein even seems to have been tempted to give up what we may call his physical relativity principle (with no ether needed). But Lorentz's explanation of the M-M experiment seemed to Einstein so artificial that he resisted this temptation, opting for the physical relativity principle. After eliminating the ether from the story altogether, one can simply take the results of the M-M and similar experiments as empirical evidence for the equivalence of all inertial frames for the laws of electricity, magnetism and optics as well as those of mechanics. I believe Einstein gave up the ether concept and definitely opted for the physical relativity principle at least a couple of years before the final formulation of SRT, perhaps even earlier. At any rate, at some point well before the 1905 formulation of the theory, he made this choice and adhered to it thereafter.

There was a related motive for his skepticism with regard to the ether, which I shall now mention. Not only was Einstein working on problems of the optics of moving bodies, he was also working on problems related to the emission and absorption of light by matter and of the equilibrium behavior of electromagnetic radiation confined in a cavity-the so-called black body radiation problem. He was using Maxwell's and Boltzmann's statistical methods, which he had redeveloped and refined in several earlier papers, to analyze this problem. This was itself a daring step, since these methods had been developed to help understand the behavior of ordinary matter while Einstein was applying them to the apparently quite different field of electromagnetic radiation.[13] The "revolutionary" conclusion to which he came was that, in certain respects, electromagnetic radiation behaved more like a collection of particles than like a wave. He announced this result in a paper published in 1905, three months before his SRT paper. The idea that a light beam consisted of a stream of particles had been espoused by Newton and maintained its popularity into the middle of the 19th century. It was called the "emission theory" of light, a phrase I shall use. The need to explain the phenomena of interference, diffraction and polarization of light gradually led physicists to abandon the emission theory in favor of the competing wave theory, previously its less-favored rival. Maxwell's explanation of light as a type of electromagnetic wave seemed to end the controversy with a definitive victory of the wave theory. However, if Einstein was right (as events slowly proved he was) the story must be much more complicated. Einstein was aware of the difficulties with Maxwell's theory-and of the need for what we now call a quantum theory of electromagnetic radiation-well before publishing his SRT paper. He regarded Maxwell's equations as some sort of statistical average-of what he did not know, of course-which worked very well to explain many optical phenomena, but could not be used to explain all the interactions of light and matter. A notable feature of his first light quantum paper is that it almost completely avoids mention of the ether, even in discussing Maxwell's theory. Giving up the ether concept allowed Einstein to envisage the possibility that a beam of light was "an independent structure," as he put it a few years later, "which is radiated by the light source, just as in Newton's emission theory of light."

So abandonment of the concept of the ether was a most important act of liberation for Einstein's thought in two respects: It allowed Einstein to speculate more boldly on the nature of light and it opened the way for adoption of his relativity principle as a fundamental criterion for all physical laws. I must add a word about Einstein's use of such principles as a guide to further research. In 1919 he explicitly formulated a broad distinction between constructive theories and theories of principle. Constructive theories attempt to explain some limited group of phenomena by means of some model, some set of postulated theoretical entities. For example, many aspects of the behavior of a gas could be explained by assuming that it was composed of an immense number of constantly colliding molecules. Theories of principle formulate broad regularities, presumably obeyed by all physical phenomena, making these principles criteria ("rules of the game") that any constructive theory must satisfy. For example, the principles of thermodynamics are presumed to govern all macroscopic phenomena. They say nothing about the, micro-structure or detailed behavior of any particular gas, but do constitute limitations on any acceptable constructive theory of such a gas. Any theory not conserving the energy of the gas, for example, would be immediately rejected. Since the turn of the century, Einstein had been searching for a constructive theory of light, capable of explaining all of its properties on the basis of some model, and was to continue the search to the end of his days. But, "Despair[ing] of the possibility of discovering the true answer by constructive efforts," as he later put it, he decided that the only possible way of making progress in the absence of such a constructive theory was to find some set of principles that could serve to limit and guide the search for a constructive theory.[14] There is no contemporary evidence showing when Einstein adopted this point of view (he first indicated it in print as early as 1907). I believe he had done so by 1905. The structure of the 1905 SRT paper is certainly compatible with his having done so. It is based on the statement of two such principles, deduction of various kinematic consequences from them, and their application to Maxwell's electrical and optical theory.

To return to the main thread of my conjecture, I believe that Einstein dropped the ether hypothesis and adopted his relativity principle by 1903 or 1904 at the latest. This is by no means the end of the story. It seemed that he must then drop Lorentz's version of Maxwell's theory, based as it was on the ether hypothesis. With what was he to replace it? There is good evidence suggesting he spent a great deal of effort trying to replace it with an emission theory of light-the sort of theory suggested by his concurrent researches into the quantum nature of light.[15] An emission theory is perfectly compatible with the relativity principle. Thus, the M-M experiment presented no problem; nor is stellar abberration difficult to explain on this basis.[16]

Einstein seems to have wrestled with the problems of an emission theory of light for some time, looking for a set of differential equations describing such a theory that could replace the Maxwell-Lorentz equations; and trying to explain a number of optical experiments, notably the Fizeau experiment, based on some version of the emission theory. He could not find any such equations, and his attempt to explain the Fizeau experiment led him to more and more bizarre assumptions to avoid an outright contradiction. So he more-or-less abandoned this approach (you will soon see why I say more-or-less), after perhaps a year or more of effort, and returned to a reconsideration of the Maxwell-Lorentz equations. Perhaps there was a way of making these equations compatible with the relativity principle once one abandoned Lorentz's interpretation via the ether concept.

But here he ran into the most blatant-seeming contradiction, which I mentioned earlier when first discussing the two principles. As noted then, the Maxwell-Lorentz equations imply that there exists (at least) one inertial frame in which the speed of light is a constant regardless of the motion of the light source. Einstein's version of the relativity principle (minus the ether) requires that, if this is true for one inertial frame, it must be true for all inertial frames. But this seems to be nonsense. How can it happen that the speed of light relative to an observer cannot be increased or decreased if that observer moves towards or away from a light beam? Einstein states that he wrestled with this problem over a lengthy period of time, to the point of despair. We have no details of this struggle, unfortunately.

Finally, after a day spent wrestling once more with the problem in the company of his friend and patent office colleague Michele Besso, the only person thanked in the 1905 SRT paper, there came a moment of crucial insight. In all of his struggles with the emission theory as well as with Lorentz's theory, he had been assuming that the ordinary Newtonian law of addition of velocities was unproblematic. It is this law of addition of velocities that allows one to "prove" that, if the velocity of light is constant with respect to one inertial frame, it cannot be constant with respect to any other inertial frame moving with respect to the first. It suddenly dawned on Einstein that this "obvious" law was based on certain assumptions about the nature of time always tacitly made. In particular, the concept of the velocity of an object with respect to an inertial frame depends on time readings made at two different places in that inertial frame. (He later referred to this moment of illumination as "the step.")[17]

How do we know that time readings at two such distant places are properly correlated? Ultimately this boils down to the question: how do we decide when events at two different places in the same frame of reference occur at the same time, i.e., simultaneously? Isn't universal simultaneity an intuitively obvious property of time? Here, I believe, Einstein was really helped by his philosophical readings. He undoubtedly got some help from his readings of Mach and Poincaré, but we know that he was engaged in a careful reading of Hume at about this time; and his later reminiscences attribute great significance to his reading of Hume's *Treatise on Human Nature*. What could he have gotten from Hume? I think it was a relational-as opposed to an absolute-concept of time and space. This is the view that time and space are not to be regarded as self-subsistent entities; rather one should speak of the temporal and spatial aspects of physical processes; "The doctrine," as Hume puts it, "that time is nothing but the manner, in which some real object exists." I believe the adoption of such a relational concept of time was a crucial step in freeing Einstein's outlook, enabling him to consider critically the tacit assumptions about time going into the usual arguments for the "obvious" velocity addition law. This was the second great moment of liberation of his thought.

I shall not rehearse Einstein's arguments here, but it led to the radically novel idea that, once one physically defines simultaneity of two distant events relative to one inertial frame of reference, it by no means follows that these two events will be simultaneous when the *same* definition is used relative to another inertial frame moving with respect to the first. It is not logically excluded that they *are* simultaneous relative to all inertial frames. If we make that assumption, we are led back to Newtonian kinematics and the usual velocity addition law, which is logically quite consistent. However, if we adopt the two Einstein principles, then we are led to a new kinematics of time and space, in which the velocity of light is a universal constant, while simultaneity is different with respect to different inertial frames; this is also logically quite consistent. The usual velocity addition law is then replaced by a new one, in which the velocity of light "added" to any other velocity ("added" in a new sense-it would be better to say "compounded with") does not increase, but stays the same!

The Maxwell-Lorentz equations, when examined with the aid of this new kinematics, prove to take the same form in every inertial frame. They are, therefore, quite compatible with the relativity principle, which demands that the laws of electricity, magnetism and optics have this property. The presence or absence of an electric or magnetic field, is then also found to be relative to an inertial frame, allowing a completely satisfactory relativistic analysis of the example of the conducting wire loop and magnet in relative motion. Within six weeks of taking "the step," Einstein later recalled, he had worked out all of these consequences and submitted the 1905 SRT paper to *Annalen der Physik*.

This does not imply that Lorentz's equations are adequate to explain all the features of light, of course. Einstein already knew they did not always correctly do so-in particular in the processes of its emission, absorption and its behavior in black body radiation. Indeed, his new velocity addition law is also compatible with an *emission* theory of light, just *because* the speed of light compounded with any lesser velocity still yields the same value. If we model a beam of light as a stream of particles, the two principles can still be obeyed. A few years later (1909), Einstein first publicly expressed the view that an adequate future theory of light would have to be some sort of fusion of the wave and emission theories. This is an example of how the special theory of relativity functioned as a theory of principle, limiting but not fixing the choice of a constructive theory of light.

Here I shall end my conjectures on how Einstein arrived at SRT. To briefly recapitulate, I believe that the first principle, the relativity principle, recapitulates his struggles with the mechanical ether concept which led finally to the first crucial liberation of his thought-the abandonment of the ether. The second principle, the principle of the constancy of the speed of light, recapitulates his struggle, once he had definitely opted for the relativity principle, first to evade the Maxwell-Lorentz theory by an emission theory; then to isolate what was still valid in the Maxwell Lorentz theory after giving up the ether concept and abandoning absolute faith in the wave theory of light. The struggle to reconcile the two principles could only end successfully after the second great liberation of his thought: the relativisation of the concept of time. The resulting theory did not force him to choose between wave and emission theories of light, but rather led him to look forward to a synthesis of the two. This synthesis was finally achieved, over twenty years later, in the quantum theory of fields, to the satisfaction of most physicists, but ironically, never to that of Einstein.

I cannot ask you to accept my conjectures after all of my warnings at the outset of this paper, but will be content if you say "Si non è vero, è ben trovato," "If it isn't true, it's well contrived."

You can EXIT to Einstein's own words on "Ether and the Theory of Relativity" (1920 address)

Notes

1. Poe is quoting Sir Thomas Browne's *Hydrotaphia*. BACK

2. A preliminary question is raised by my use of the word "discovery." Is it better to speak of the "discovery" or the "creation" of a theory like SRT? "Discovery" suggests the finding of some pre-existent, objective structure, as when we say "Columbus discovered America." "Creation" suggests an individual, subjective act, as when we say "Tolstoy created *Anne Karenina*." Neither word seems really appropriate to describe what goes on in the scientific endeavor. Einstein apparently preferred the word "Erfindung" (invention) to describe how scientific theories come into being. Speaking of Mach, Einstein says: "Er meinte gewissermassen, dass Theorien durch *Entdeckung* und nicht durch *Erfindung* entstehen." (*Einstein-Besso Correspondence* (Hermann, Paris 1972), p. 191, dated January 6, 1948. BACK

3. In the study of the discovery of GRT, therefore, one may hope to formulate conjectures which can be either confirmed or refuted. For example: A study of Einstein's published papers and private correspondence between 1912-1915 convinced me that the standard explanation for his failure to arrive at the correct gravitational field equations until the end of this period-namely, his presumed lack of understanding of the meaning of freedom of coordinate transformations in a generally covariant theory and the ability to impose coordinate conditions that this freedom implied-could not be correct (see "Einstein's Search for General Covariance, 1912-1915," presented at the Ninth International Conference on General Relativity and Gravitation, July 17, 1980, in Stachel *Einstein from "B" to "Z"*, pp. 301338). On the basis of his study of a research notebook of Einstein from the early part of this period, John Norton was able to prove that Einstein already was aware of the possibility of imposing coordinate conditions on a set of field equations, and indeed had used the harmonic coordinate conditions (see John Norton, "How Einstein found his field equations: 1912-1915," *Historical Studies in the Physical Sciences 14*, 253 (1984). For reasons discussed in the text, one cannot hope to confirm or disconfirm most conjectures about the origins of SRT.BACK

4. For a survey of this material for the period up to 1923, see J. Stachel, "Einstein and Michelson: The Context of Discovery and the Context of Justification," Astron. Nachricht. **303**, 47 (1982). Unless otherwise noted, quotations from Einstein are cited from this paper, which gives the full references. [See Stachel, *Einstein from "B" to "Z"*, pp. 177-190].BACK

5. See Arthur I. Miller, *Albert Einstein's Special Theory of Relativity* (Addison-Wesley, Reading 1981), which contains references to his earlier papers as well as those of Holton, Hirosige and many others; Abraham Pais, 'Subtle is the Lord. . .' *The Science end the Life of Albert Einstein* (Oxford U.P., New York 1982); Stanley Goldberg, *Understanding Relativity* (Birkhauser, Boston 1984); Roberto Torretti, *Relativity end Geometry* (Pergamon, Oxford 1983). Earman, Glymour and Rynasiewicz have not yet published a full account of their views; I thank them for making available copies of several preprints on this subject. BACK

6. A popular epigram among historians runs: "God is omnipotent, but even He cannot change the past. That is why He created historians." BACK

7.See the reference in footnote 4 for the source of the citations from Reichenbach. If my thesis here is correct, this argues against the still widely held view that these two contexts should be rigorously separated. But in this paper I shall not elaborate on the wider issue. BACK

8. For example, Einstein's statements of the second principle of SRT, the light principle, remained remarkably consistent throughout his lifetime (see the discussion of this principle below). Indeed, an apparent exception in the printed text of his article "What is the Theory of Relativity?," published originally in English translation in the *Times* of London in 1919, proved to be based upon an incorrect transcription of his manuscript. BACK

9. Much of the anti-relativity literature, which still continues to grow in volume if not in weight, is based on attempts to show that the two principles are indeed logically incompatible. BACK

10. Sometimes (e.g., by Pais and Goldberg), this consequence of Einstein's two principles is asserted to be his second principle. This is incorrect factually (Einstein's account of the second principle is one of the most consistent features of his discussions of SRT over the years-see footnote 8), and disturbing for several reasons: a) it makes it impossible to explain why Einstein refers to the two principles as apparently contradictory. There is no contradiction apparent between the relativity principle and this deduction from it; b) it is logically defective, since the two principles would no longer be logically independent, as they are in Einstein's formulation; c) most important for present purposes, this formulation deprives us of important clues to Einstein's reasoning that led to the development of SRT. BACK

11. Einstein to Max Talmey, June 6, 1938. The German text reads: "Die empirisch suggerierte Nichtexistenz einer solchen bevorzugten 'Wind-Richtung' ist der Haupt-Ausgangspunkt der speziellen Relativitatstheorie."

BACK

12. Hertz said: "... the absolute motion of a rigid system of bodies has no effect upon any internal electromagnetic processes whatever in it, provided that all the bodies under consideration, including the ether as well, actually share the motion." (*Electromagnetic Waves*, p. 246). Lorentz said:

> That one cannot speak of the absolute rest of the ether, is self-evident indeed; the expression wouldn't even have any meaning. If I say for short, the ether is at rest, this only means that one part of this medium is not displaced with respect to the others and that all perceptible movements of the heavenly bodies are relative movements with respect to the ether. [*Versuch*, p. 4 (1895).] BACK

13. He was not alone in transferring statistical methods from ordinary matter to radiation. Planck had already done so, but Einstein did not see the relation of his work to Planck's until after publishing his first paper on the subject. BACK

14. See Albert Einstein, *Autobiographical Notes* (Open Court, LaSalle 1979), pp. 48 (German text) and 49 (English translation). BACK

15. One such piece of evidence, not cited in my earlier paper (see footnote 4), has only recently come to light. It occurs in the most complete review of SRT that Einstein ever wrote. It was prepared in 1912 but never published, and is still in private hands. Luckily, a copy has come into the possession of the Einstein Archive. In it, Einstein explains at some length the difficulties that are encountered (and presumably these are the ones he had encountered), if one tries to explain the results of the Fizeau experiment on the basis of an emission theory of light combined with the relativity principle and Galilei-Newtonian kinematics. [See The *Collected Papers of Albert Einstein*, vol. 4. *The Swiss Years: Writings 1912-1914* (Princeton University Press, Princeton 1995), Doc. 1, "Manuscript on the Special Theory of Relativity," pp. 32-36]. BACK

16. Indeed, the earliest explanation of stellar abberation had been based on the emission theory. BACK

17. Abraham Pais has mentioned this in describing his conversations with Einstein. BACK

This is the text of "'What Song the Syrens Sang': How Did Einstein Discover Special Relativity?" as printed in John Stachel, *Einstein from "B" to "Z"* (Boston : Birkhäuser, 2002), pp. 157-169. It is an English text of "Quale canzone cantarono le sirene: come scopro Einstein la teoria speciale della relatività?" published in *L'Opera di Einstein* (1989), pp. 21-37.

***John Stachel** is Professor of Physics Emeritus and Director of the Center of Einstein Studies at Boston University. He has written a variety of articles on aspects of the history of both special and general relativity and other topics, and has edited or co-edited a number of books dealing with Einstein and relativity.*
