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The Light-Velocity Postulate

The Essential Difference between the Theories of Lorentz-Poincaré and Einstein

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Abstract. Einstein, who had already developed the light-quantum theory, knew the inadequacy of Maxwell's theory in the microscopic sphere. Therefore, in writing his paper on special relativity, he had to set up the light-velocity postulate independently of the relativity postulate in order to make the electromagnetic foundation of physics compatible with Planck's radiation formula. This constitutes the essential difference between the theories of Lorentz-Poincaré and Einstein. The reason that students of the history of special relativity hitherto overlooked this fact lies in a crucial error contained in Einstein's 'Autobiographical Notes'. The correction, introduced first in the German edition of 1955, revealed that the first core ingredient of Einstein's research program was 'thermodynamics'. Einstein's theory survived the quantum revolution, while Lorentz-Poincaré's did not. Some educational implications are also discussed.

1. Introduction

The so-called Lorentz-Einstein problem, i.e., the question of whether or not the theory constructed by Hendrik A. Lorentz (1904) and Henri Poincaré (1905, 1906) slightly before Albert Einstein (1905d) was the special theory of relativity (abbr. as STR below), has been the subject of many controversies. The proponents of the view that the Lorentz-Poincaré theory was STR are Sir Edmond Whittaker (1953), Elie Zahar (1973) and Olivier Darrigol (1996), while the opponents are Max Born (1956), Tetu Hirosige (1960), Gerald Holton (1960) and Stanley Goldberg (1967).

In this paper, I will present an obvious and crucial discrimination between Lorentz-Poincaré's theory and Einstein's STR, as well as the reason why so many excellent students of the history of STR hitherto overlooked this obvious point. I will further discuss Einstein's research program in contrast with Lorentz's research program.

My discrimination rests on the difference between the constancy of light-velocity and the light-velocity postulate. Both Lorentz-Poincaré and Einstein believed in the constancy of light-velocity. But, it was Einstein and only he that elevated it to the status of the postulate. The crucial point of departure was his encounter with Planck's derivation of the radiation-formula (Abiko 2000a), and Einstein's resultant distrust of contemporary electromagnetic theory.

In the following, I use the abbreviations below. *Letters*: Renn, J. & Schulmann, R. (eds.), 1992, *Albert Einstein - Mileva Marič, Love Letters*, Princeton. 'Notes': Einstein, A., 1949, 'Autobiographical Notes', in P. A. Schilpp (ed.), *Albert Einstein: Philosopher-Scientist*, Evanston, 1–95.

2. The Origin of the Relativity-Postulate

Before entering into the discussion on the light-velocity postulate, I comment briefly on the origin of the relativity-postulate.

At about the age of 16, Einstein wrote a small essay on the state of the ether in a magnetic field, in which he did not adopt Lorentz's view of the stationary ether. He discussed in it, 'The motion of the ether produced by an electric current' and 'the deformation produced by the motion of the ether' (Einstein 1895, p. 5). Therefore, as far as Einstein viewed the ether as a movable (i.e., draggable) mechanical entity, he had no reason to doubt the validity of the Galilean principle of relativity in this case, which was known to be valid then for mechanical phenomena.

In fact, in his 'Notes', Einstein described a paradox, which he hit upon at the same age of 16, and which contained the germ of the relativity-postulate. He imagined himself pursuing a ray of light with velocity *c* and seeing a spatially periodical electromagnetic field at rest. He stated:

> From the very beginning it appeared to me intuitively clear that, judged from the standpoint of such an observer, everything would have to happen according to the same law as for an observer, who, relative to the earth, was at rest. For how should the first observer know, i.e., be able to determine, that he is in a state of fast uniform motion? ('Notes', pp. 52–53)[1]

According to my interpretation, the above statement is a consequence of Einstein's conjecture that, due to the Galilean principle of relativity, there would be no way of determining whether one is in a state of fast uniform motion or not (Abiko 2004).

I have pointed out another possible origin of the relativity-postulate, consistent with the above, buried in his doctoral dissertation published in 1905 (Abiko 1991, p. 22; Einstein 1905a). There he solved the viscous hydrodynamic equation in the coordinate system of a suspended solute particle. He utilized at this point the Galilean transformation of the hydrodynamic equation from the rest frame of the solvent to the moving coordinate of the solute. Though he submitted his dissertation in 1905, it is certain that he was familiar with this method from his student years 1896–1900.[2] Similarly, he treated in the paper on STR (Einstein 1905d), the coordinate transformation of the electromagnetic equation from the rest to the moving frame. He later utilized the latter result to solve the electromagnetic equation in the coordinate system of a small mirror suspended in a cavity filled with blackbody radiation (Einstein 1909; Einstein & Hopf 1910).

Thus, the first step leading to the relativity-postulate seems to have been the application of the Galilean transformation in the continuous medium.

3. The Constancy of Light-Velocity and the Revision of the Concept of Time

Einstein's Kyoto address, which I introduced in a previous paper (Abiko 2000b), tells almost the same story for the construction of STR as that given by Max Wertheimer (1959) based on a conversation with Einstein in 1916. In both of these accounts, Einstein began with the conviction that (a) Maxwell's equations are valid and that (b) Maxwell's equations - and all other laws of nature – must have the same form in all inertial systems, i.e., the relativity-postulate. The latter proposition, however, seemed inconsistent with the classical additivity of velocities, which required that the light-velocity in vacuo c should depend on the velocity of the observer. Einstein tried some way of keeping Maxwell's equations valid for all inertial systems while allowing c to vary, but in vain.

It was around this point that he became aware of the Michelson-Morley experiment, [3] which implied the conclusion to which Einstein's thinking had already led him: that c is constant for all observers. Gradually, he focused on the question of the meaning of the measurement of a moving body and, finally, on the meaning of the judgment of simultaneity involved in such experiments. Thus, Einstein arrived at his famous operational definition of distant simultaneity in terms of simultaneity in the same place by using the presumed constancy of light-velocity.

Einstein's seemingly innocuous requirement that simultaneity be operationally defined led to the rejection of the concept of an absolute time valid in all coordinate systems. On this matter, Kyoto address testifies to the important role played in the revision of the concept of time by the conversation with his friend Michele Besso, who had introduced Einstein to Ernst Mach's *Mechanik*, and to whom Einstein acknowledged his debt for 'many a valuable suggestion' in his STR paper of 1905.

If the accomplishment of Einstein's STR were no more than what has been presented so far, the distance between Einstein's and other contemporary reflections and methods would not have been as great as often claimed. In fact, it is well known that Einstein read around 1903, together with his friends of the circle named the 'Academie Olympia', Poincaré's book *La Science et l'Hypothèse* published in 1902. Topics treated in it, and in Poincaré's paper of 1898 'Mesure de Temps' cited therein, include the introduction of the relativity-postulate, the constancy of light-velocity, and the revision of the concept of time.

Despite all of these, Lorentz throughout his life clung to the concept of the stationary ether, upon which his electron theory was built (Lorentz 1895, 1904). The situation was almost the same with Poincaré, who persuaded Lorentz to make the latter's theory conform to the relativity-postulate, and revised it himself in his 1905 and 1906 papers (Poincaré 1905, 1906). In short, their theory rested on Maxwell's equations and the relativity-postulate, the combination of which permitted them to deduce the constancy of light-velocity. Therefore, they felt no necessity for setting up the light-velocity postulate.

4. Einstein's Introduction of the Light-Velocity Postulate

The situation was much different in the case of Einstein. Einstein expressed his doubt about the existence of the ether as early as 1899 in his letter to his fiancée, Mileva Marič, as follows:

> I'm convinced more and more that the electrodynamics of moving bodies as it is presented today doesn't correspond to reality, and that it will be possible to present it in a simpler way. The introduction of the term "ether" into theories of electricity has led to the concept of a medium whose motion we can describe, without, I believe, being able to ascribe physical meaning to it. I think that electrical forces can be directly defined only for empty space, something also emphasized by Hertz. (*Letters*, pp. 10–11, 10 August 1899)

Heinrich Hertz referred to in the above, who was a famous advocate of the movable and draggable ether, regarded the presence of ether in bodies as a hypothesis (Hertz 1893, p. 242). Thus, the above quotation testifies that Einstein was already doubtful in 1899 of the existence of the ether and the validity of Maxwell's electrodynamics based on it. Therefore, we should regard Einstein's STR as a theory constructed upon these doubts from the start (Abiko 2004).

In fact, Einstein's letter of 1955, which Max Born quoted in his Berne lecture, reads as follows:

> The new feature of [STR] was the realization of the fact that the bearing of the Lorentz-transformations transcended their connection with Maxwell's equations and was concerned with the nature of space and time in general. A further new result was that the "Lorentz invariance" is a general condition for any physical theory. This was for me of particular importance because I had already previously found that Maxwell's theory did not account for the microstructure of radiation and could therefore have no general validity. ... (Born 1956, pp. 248-249, 1969, p. 104)[4]

Born commented on Einstein's statement given above, 'The last sentence of this letter is of particular importance. For, it shows, that Einstein's paper of 1905 on relativity and on the light quantum were not disconnected' (Born 1956, p. 250, 1969, p. 105).

The above account is also confirmed by Einstein's comment on Max Laue's book on STR (Laue, 1911). Einstein's letter to Laue, 17 Jan. 1952, states, 'When one looks over your collection of proofs of [STR], one becomes of the opinion that Maxwell's theory is unquestionable. But in 1905 I already knew certainly that Maxwell's theory leads to false fluctuations of radiation pressure and, with it, to an incorrect Brownian motion in a Planckian cavity'.[5]

Einstein's STR paper of 1905 consists of two parts: 'I. Kinematical Part' and 'II. Electrodynamical Part'. As distinct from Lorentz's 1904 paper, which starts with the equations of Maxwell and of Lorentz-force, the 'Kinematical Part' of Einstein's STR paper contains neither of them. Instead, this paper starts with an indication of a defect contained in Maxwell's contemporary electrodynamics. Therefore, in spite of its title 'On the Electrodynamics of Moving Bodies (Zur Electrodynamik bewegter Körper)', this paper does not premise Maxwell's electrodynamics, but it aims at transcending the latter.

In order to derive Lorentz-transformation equations, however, Einstein required the constancy of light-velocity, the validity of which had already led him to the revision of the concept of time. Therefore, in order to transcend Maxwell's electrodynamics, he had no choice but to elevate the constancy of light-velocity deduced from the latter to the status of the light-velocity postulate (Abiko 1991, p. 21). Thus, the essential difference between the theory of Lorentz-Poincaré and that of Einstein lies in the fact of whether or not the light-velocity postulate is set up independently of the relativity-postulate. In other words, Lorentz-Poincaré's theory lacks the 'Kinematical Part' essential for STR.

5. Einstein's Autobiographical Error

Why did so many excellent researchers of the history of STR overlook the obvious fact presented in the preceding section? The reason might lie in a crucial error contained in 'Autobiographical Notes' in the first and the second editions of *Albert Einstein: Philosopher-Scientist*, published in 1949 and 1951 respectively. The problem occurred in the following lines:

> Reflections of this type made it clear to me as long ago as shortly after 1900, i.e., shortly after Planck's trailblazing work, that neither mechanics nor *thermodynamics* (except in limiting cases) claim exact validity. By and by I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. (italics added, 'Notes', pp. 50–53)

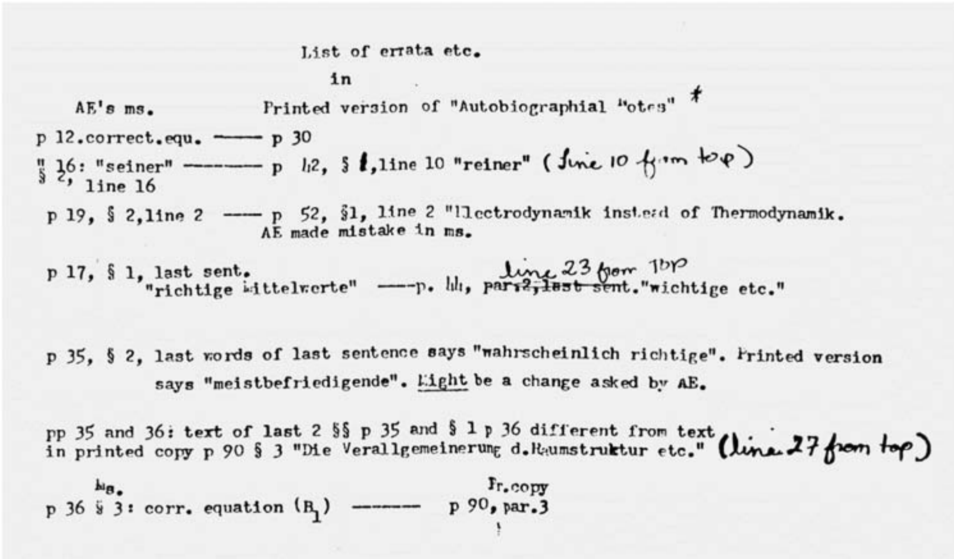
Einstein intended to write 'electrodynamics' rather than 'thermodynamics'. The above passage hides the fact that the correct version was published first in 1955, the year of Einstein's death, as the German edition in Stuttgart (Einstein 1955, p. 19).[6] This edition identifies itself as 'The only authorized transcription of the volume published in 1949 (Einzig autorisierte Übertragung des 1949 erscheinenen Bandes)'. Einstein himself approved the correction. This error misled students of the history of STR to believe that Einstein regarded electrodynamics as holding good instead of thermodynamics.

I asked The Albert Einstein Archives in Jerusalem how the error and the correction took place. The archivist Barbara Wolff replied:

> When "Autobiographisches" was published in 1949, someone found several errors in the printed version (we do not know who) and Helen Dukas [Einstein's secretary] marked the corrections in Einstein's copy of the book. ... In addition, she typed a "list of errata" (undated, supposedly just after the 1949 edition).

Dukas' 'List of errata etc.' is reproduced in Figure 1, where we can recognize the note: 'Electrodynamik instead of Thermodynamik. AE [Albert Einstein] made mistake in ms [manuscript]'. The relevant passages in the manuscript and the correction on the printed version are in Figures 2a and 2b.

The necessity of the correction is evident even from three other passages in 'Notes'.



List of errata etc.
in
AE's ms. Printed version of "Autobiographial Notes" ✝

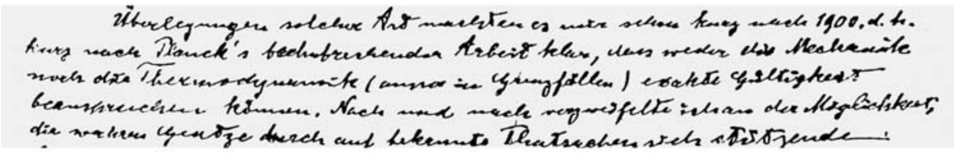
p 12.correct.equ. —— p 30
" 16: "seiner" —— p 42, § 1, line 10 "reiner" (line 10 from top)
§ 2, line 16
p 19, § 2, line 2 —— p 52, §1, line 2 "Electrodynamik instead of Thermodynamik.
AE made mistake in ms.
p 17, § 1, last sent.
"richtige Mittelwerte" ——p. 44, par.2, ~~last sent.~~ line 23 from top "wichtige etc."

p 35, § 2, last words of last sentence says "wahrscheinlich richtige". Printed version says "meistbefriedigende". Might be a change asked by AE.

pp 35 and 36: text of last 2 §§ p 35 and § 1 p 36 different from text in printed copy p 90 § 3 "Die Verallgemeinerung d.Raumstruktur etc." (line 27 from top)

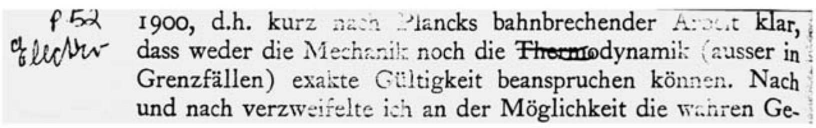
Ms. Pr.copy
p 36 § 3: corr. equation (B_1) —— p 90, par.3

Figure 1. 'List of errata' for Einstein's 'Notes'. The relevant mistake is on p. 19 of Einstein's manuscript and on p. 52 of the printed version of the first (1949) and the second (1951) editions, which was corrected in the German (1955) and the third (1969) editions. Two other important corrections are also stated: 'seiner (his)' on p. 16 of the manuscript was misread as 'reiner (pure)' on p. 42 of the printed version, which was also corrected. 'richtge (exact)' on p. 17 of the manuscript was misread as 'wichtige (important)' on p. 44 of the printed version, which, however, was not corrected. Permission granted by the Albert Einstein Archives, The Jewish National & University Library, The Hebrew University of Jerusalem, Israel.



Überlegungen solcher Art machten es mir schon kurz nach 1900, d.h. kurz nach Planck's bahnbrechender Arbeit klar, dass weder die Mechanik noch die Thermodynamik (ausser in Grenzfällen) exakte Gültigkeit beanspruchen können. Nach und nach verzweifelte ich an der Möglichkeit, die wahren Gesetze durch auf bekannte Thatsachen sich stützende

(a)



p 52 Electro

1900, d.h. kurz nach Plancks bahnbrechender Arbeit klar, dass weder die Mechanik noch die ~~Thermo~~dynamik (ausser in Grenzfällen) exakte Gültigkeit beanspruchen können. Nach und nach verzweifelte ich an der Möglichkeit die wahren Ge-

(b)

Figure 2. (a) Einstein's manuscript. (b) The correction on the printed version. In (a), on the third line, 'Thermodynamik' reads. In (b), 'Thermo' is corrected as 'Electro', where the handwriting is Dukas'. Permission granted by the Albert Einstein Archives, The Jewish National & University Library, The Hebrew University of Jerusalem, Israel.

- [Thermodynamics] is the only physical theory of universal content concerning which I am convinced that, within the framework of the applicability of its basic concepts, *it will never be overthrown*. (italics added, 'Notes', pp. 32–33)
- [Planck's] derivation [of his radiation formula] presupposes implicitly that energy can be absorbed and emitted by the individual resonator only in "quanta" of $h\nu, \ldots$ in contradiction to the laws of mechanics and *electrodynamics*. (italics added, 'Notes', pp. 44–45)
- The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results. The example I saw before me was *thermodynamics*. (italics added, 'Notes', pp. 52–53)

The correction was indispensable in order to make the text consistent.

6. Einstein's Research Program

'Notes' make clear that, of the three theories of classical physics (i.e., mechanics, electromagnetic theory, thermodynamics), Einstein regarded thermodynamics as the only physical theory of universal content that will never be overthrow within its sphere of applicability. On the other hand, 'shortly after Planck's trailblazing work', he realized that neither mechanics nor electromagnetic theory could claim such status. Therefore, it is certain that the first core ingredient of Einstein's research program was thermodynamics.

But, the range of applicability of the basic concepts of thermodynamics is very restricted. We can get a glimpse of the direction of Einstein's efforts to broaden it from his letters to his fiancée (*Letters*, pp. 17–18, 10 Oct. 1899; p. 37, 23 Mar. 1901; p. 40, 27 Mar. 1901; p. 41, 4 April 1901; p. 47, 30 April 1901; p. 54, 28 May 1901). These portions of *letters* make it certain that Einstein was paying keen attention to the microscopic mechanisms of energy transformation. Their descriptions coincide with the following paragraph in 'Notes',

> All of this [i.e., insufficiency of mechanics and electromagnetic theory] was quite clear to me shortly after the appearance of Planck's fundamental work; so that, without having a substitute for classical mechanics, I could nevertheless see to what kind of consequences this law of temperature-radiation leads for the photo-electric effect and for other related phenomena of the transformation of radiation-energy, as well as for the specific heat of (especially) solid bodies. ... My major question was: What general conclusions can be drawn from the radiation-formula concerning the structure of radiation and even more generally concerning the electromagnetic foundation of physics? ('Notes', pp. 44–47)

Dissatisfied with Planck's theory and yet admitting the agreement of Planck's radiation-formula with experimental results, Einstein was eager to find a new theory. Thus, the secret of his research program seems to reside in 'the structure of radiation' and 'the electromagnetic foundation of physics' stated above.

The actualization of his program took place in the following manner. In his first two papers, he tried to make some microscopic inference on the macroscopic phenomena of capillarity and of the contact potential difference. The third paper, the first of the statistical trio papers, derives the law of thermal equilibrium and the second law of thermodynamics from the equations of mechanics and the probability calculus (Einstein 1902). The fourth and fifth papers, the second and the third of the statistical trio, do not rely upon mechanics, but treat a generalized thermodynamical system expressed by the state-variables (Einstein 1903, 1904). Therefore, the theory presented in these papers should more properly be called as 'statistical thermodynamics' rather than 'statistical mechanics' as it usually is. Leaving the realm of mechanics, Einstein could safely apply his theory to the blackbody radiation in the last part of the fifth paper (Einstein 1904, pp. 75–77). The resultant statistical thermodynamics and the theory of fluctuation derived from it underlay his doctoral dissertation (Einstein 1905a), the theory of Brownian movement (Einstein 1905b), the theory of light-quantum (Einstein 1905c), and the theory of specific heat (Einstein 1907; Abiko 2000a).

How then did STR emerge from this research program? Having referred to 'the structure of radiation' and 'the electromagnetic foundation of physics', his 'Notes' goes on to the Brownian movement of a small mirror suspended in a cavity filled with thermal radiation. On Maxwell's theory, the fluctuation of the radiation pressure was not sufficient to impart to the mirror the average kinetic energy $kT/2$ required by the equipartition law of statistical thermodynamics. To investigate more precisely the structure of radiation, Einstein needed Maxwell's equations in the coordinate system of the moving mirror. At this point he set the basis for STR. We know, of course, that he was much interested in the 'electrodynamics of moving bodies' even from his adolescence. But, from the viewpoint of Einstein's research program, the more urgent purpose of the construction of STR at that time seems to have been the investigation into 'the structure of radiation' and more generally into 'the electromagnetic foundation of physics' (Abiko 1991, p. 19).

7. Survival through the Quantum Revolution

The first Solvay conference was convened to discuss Einstein's contributions on the 'Radiation Theory and Quanta' in 1911. In the discussion after his lecture, Einstein stated as follows:

> This [untenability of the classical mechanics] raises the question of which general laws of physics we can still expect to be valid in the domain with which we are concerned. To begin with, we will all agree that the energy principle is to be retained. In my opinion, another principle whose validity we must maintain unconditionally is Boltzmann's definition of entropy through probability. (Einstein 1911)

As the two laws Einstein referred to above correspond to the first and the second laws of thermodynamics, this statement endorses my conjecture that the first core ingredient of Einstein's research program was thermodynamics.

The *Proceedings* of this conference (Langevin et al. 1912) left grave impressions among physicists, two fruits of which were Bohr's theory of atomic structure in 1913 (Bohr 1913)[7] and Louis de Broglie's theory of material wave in 1923 (de Broglie, 1923).[8] Moreover, Einstein's statistical thermodynamics gave rise to the first quantum theory of matter in his paper of 1906 (Einstein 1906; Abiko 2000a), for which, as well as for the theory of light-quantum, he was awarded the Nobel Prize in 1921.

Thus, Einstein's research program opened a new era in the history of physics. On the other hand, Lorentz's electron theory (Lorentz 1895, 1904), which is the embodiment of Lorentz's research program, could not survive this new era. Einstein's STR was utilized to explain the fine structure of atomic spectra by Arnold Sommerfeld in his paper of 1916 (Sommerfeld 1916), while Lorentz-Poincaré's theory was not. Moreover, Einstein's STR gave rise to Paul Dirac's relativistic quantum theory of electron in 1928 (Dirac 1928), where Lorentz's and Poincaré's electron theories were fruitless. In short, while Lorentz-Poincaré's theory remained the 'classical theory', Einstein's STR survived the quantum revolution.

8. Educational Implications

In this paper, I have presented the emergence of STR in the following way. First, Einstein examined Planck's theory of thermal radiation and realized that classical mechanics and electromagnetic theory could not claim exact validity. Second, he recognized thermodynamics as the only surviving classical theory and tried to broaden its applicability by constructing the statistical thermodynamics. Third, he utilized in his dissertation the Galilean postulate of relativity to solve the viscous hydrodynamic equation in the moving coordinate of solute molecule, and also discussed the diffusion of solute molecules. Fourth, the combination of statistical thermodynamics and methods in his dissertation led him to construct theories of the Brownian movement and the light quantum. Fifth, in order to investigate structure of radiation, he examined Brownian movement of a small mirror suspended in blackbody radiation. Sixth, he needed electromagnetic equation in the moving coordinate of the small mirror, and extended the postulate of relativity so as to be applicable to this case. Seventh, the combination of electromagnetic equation and the relativity postulate deduced constancy of light-velocity. Eighth, so as to applicable to the case of the light quantum, he elevated it to the status of the postulate of light-velocity, and derived the Lorentz-transformation equations.

On the other hand, usual physics textbooks introduce STR in much simpler ways. There are two representative ways of its introduction. One is to regard STR as a revision in electromagnetic theory and to stress the role of the concept of "field" in contrast to Newtonian concept of force as well as the role of the light-velocity in contiguous action. This way was first adopted by Einstein & Infeld in their *The Evolution of Physics* (Einstein & Infeld 1938), and fully developed in Landau & Lifshitz *The Classical Theory of Fields* in their Course of Theoretical Physics (Landau & Lifshitz 1975). The other is to regard STR as a revision in mechanics and to stress the role of "Michelson-Morley experiment" as the crucial experiment requiring the revision. This way was fully developed in *The Feynman Lectures on Physics, Vol. I* (Feynman et al. 1965), and adopted by almost all elementary physics textbooks. This latter way was severely criticized by Holton as ahistorical (Holton 1969).

There have also been several attempts to introduce STR in some historical manner. For example, in the textbook of myself written in Japanese, *Physics along Its History*, the chapter on "Light-Velocity Experiments and Lorentz's Electron Theory" precedes that on "Einstein's Relativity Theory". The latter chapter begins with the section on "Mach's criticism of Newtonian mechanics", and introduces STR by the following statements; "Einstein, who had already denied absolute space following Mach, felt the only character Lorentz left on the ether, the absolute rest, curious" and "The absolute time in Newtonian mechanics with action-at-a-distance is replaced by the constancy of light-velocity in the relativity theory with contiguous action". (Abiko 1981, p. 126).

As far as I know, however, there have been few introductions of STR stressing the role of thermodynamics. We must remark here the conspicuous similarity between the characters of thermodynamics and STR. As noted by Martin J. Klein, both theories are the "theory of principle", i.e., both are based on several principles set as axioms (Klein 1967). Besides that, what is salient is that both theories do not provide laws of causality, but provide some prerequisite conditions restricting physical theories. Why are they so similar to each other?

It was Stephen Brush, famous historian of science, who characterized the "Second Scientific Revolution" as the transition from the "clockwork mechanism" of Newtonian science to the "evolutionary process" of modern science. He states (Brush 1967, pp. 35–36):

> [I]t will be necessary to challenge the traditional view, that 19th-century physical science was a relatively peaceful continuation of the Newtonian era, and that the revolutionary changes began only at the beginning of the 20th century. On the contrary, I will claim that the Second Scientific Revolution really began at the beginning of 19th century, and was essentially complete around the middle of the 20th century; and that the dramatic events of 1900 and 1905 were only the more visible manifestation of a larger historical process that was already well under way.

The first epoch-making event in this revolutionary period was nothing but the formulation of the laws of thermodynamics. Thus, we realize that the conspicuous similarity between thermodynamics and STR is a reflection from the "evolutionary process" characteristic of modern science. The evolutionary processes would not necessarily be reproduced by laws of causality, but reproduced within some restrictive conditions based on principles.

Let us stop here to consider, what is "science education"? In my view, "science" has both its "intension" and "extension". The "intension of science" is the content of some scientific theory, while the "extension of science" is the process of its emergence and acceptance as well as the relationship to other scientific theories and to surrounding social factors. The traditional "science education" severely restricted itself to the education of "intension of science". In order to make students understand, however, teachers often add some experimental evidences or historical topics. But, they are by no means enough to constitute the "extension of science".

In my view, science education is not complete without teaching both the intension and the extension of science intrinsic to it. In the case of STR, the process of its emergence presented here might constitute the major part of its extension.

My view of science stated above is inspired by the book, *Teaching and Learning about Science and Society*, of John Ziman, famous theoretical physicist and advocator of STS (Science, Technology & Society). He states (Ziman 1980, p. 30):

> [Science education] is carried on as if the historical, philosophical, sociological and economic aspects of life were quite non-existent, and unworthy of the slightest attention by a serious teacher or his dutiful pupils. In my opinion, this is not a necessary characteristic of science education. ... On the contrary, their neglect conveys to the student images of science, images of the scientist, and images of the role of science in society, which are damaging to science, to scientists, and to society itself.

He also criticizes the differentiation of science as follows (Ziman 1980, pp. 29–30):

> All formal instruction relates to theoretical or categorical schemes derived from the hard core and validated by research, without reference to confusions, complexities or downright ignorance about the real world. Every branch of science becomes differentiated into a speciality, whose exclusiveness is held to be a sign of purity.

In this way, STR and quantum mechanics are taught quite separately from each other, which are in fact related as the two visible manifestations of the same "Second Scientific Revolution". In order to introduce students to modern science, it would be indispensable to teach the emergence and development of the "Second Scientific Revolution" as well as the characteristic of modern science, i.e., "evolutionary process" (e.g., Prigogine 1996).

The intension of science indicates the ideal science, while the extension of science the real one. They are complementary to each other in science education. This is the reason why I contend that science education is not complete without teaching both of them.

Notes

Besides those presented in Section 1, the following abbreviations are used. *AJP*: American Journal of Physics; *Brownian*: R. Fürth ed., *Investigations on the Theory of the Brownian Movement*, London, 1926; reprint New York, 1956; *CPEE: The Collected Papers of Albert Einstein, English Translation*, vol. 1 – (Princeton, 1987); *HSPS*: Historical Studies in the Physical and Biological Sciences; *LCP*: *H. A. Lorentz Collected Papers* (9 vols., The Hague, 1934–1939); *Miraculous*: J. Stachel ed., *Einstein's Miraculous Year* (Princeton, 1998); *Origins*: G. Holton, *Thematic Origins of Scientific Thought* (Cambridge MA; 1973); *Pr*: A. Sommerfeld ed., *The Principle of Relativity* (London, 1923, reprint New York, 1952).

* The present paper is a revised version of my previous paper (Abiko 2003). I am grateful to the Albert Einstein Archives, Jewish National & University Library, Jerusalem, for furnishing me with materials and information.

[1] I have omitted, in the last sentence of the quoted part in Schilpp's translation, the word 'otherwise', which has no German counterpart in Einstein's original text and seems a mistranslation.

[2] This method of calculation is on Kirchhoff, G. (W. Wien ed.): 1887, *Vorlesungen über Mechanik*, Leipzig, which Einstein cited in his dissertation. He also stated, while he was a student at ETH, 'The

balance of time I used in the main in order to study at home the works of Kirchhoff, Helmholtz, Hertz, etc.' ('Notes', pp. 14–15).

[3] *Letters*, p. 15, 28 Sept. 1899, cites Wien's 1898 paper referring to the Michelson-Morley experiment; *Letters*, p. 72, 28 Dec. 1901, cites Lorentz, 1895 explaining the result of this experiment, the relevant part is on *pr* 1–7.

[4] This letter was first published on *Technische Rundschau* N. 20, Jg. 47, Bern, 6 May 1955.

[5] Unpublished letter quoted in G. Holton: 'Influences on Einstein's early work', *The American Scholar*, 37 (1967–1968), 5-9-79; *Origins*, 197–217 on 201–202.

[6] I am indebted to Professor Masakatsu Yamazaki of the Tokyo Institute of Technology for having notified me of the existence of this German edition.

[7] This *Proceedings* is cited on p. 2 of Bohr 1913.

[8] This *Proceedings* is referred to in L. de Broglie: 1935, *Physicien et Penseur*, Paris, 458.

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