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ARTICLE

Special Theory of Relativity in South Korean High School Textbooks and New Teaching Guidelines

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Abstract South Korean high school students are being taught Einstein's Special Theory of Relativity. In this article, I examine the portrayal of this theory in South Korean high school physics textbooks and discuss an alternative method used to solve the analyzed problems. This examination of how these South Korean textbooks present this theory has revealed two main flaws: First, the textbooks' contents present historically fallacious backgrounds regarding the origin of this theory because of a blind dependence on popular undergraduate textbooks, which ignore the revolutionary aspects of the theory in physics. And second, the current ingredients of teaching this theory are so simply enumerated and conceptually confused that students are not provided with good opportunities to develop critical capacities for evaluating scientific theories. Reviewing textbooks used in South Korea, I will, first, claim that the history of science contributes to understand not merely the origins but also two principles of this theory. Second, in addition to this claim, I argue that we should distinguish not only hypotheses from principles but also phenomena from theoretical consequences and evidence. Finally, I suggest an alternative way in which theory testing occurs in the process of evaluation among competitive theories on the basis of data, not in the simple relation between a hypothesis and evidence.

1 Introduction

Probably most people agree that Einstein's theory of relativity is one of the most influential scientific achievements of the twentieth century. The special theory of relativity (henceforth called the STR) played a particularly significant role in the conceptual and theoretical

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changes within physics in the early twentieth century. In Newtonian mechanics, masses, lengths and time intervals are constant irrespective of an observers' movement. However, the STR predicts that the quantitative results of measurements of body masses and lengths and time intervals depend upon relative motion of the measurer. Einstein also claimed that space and time are not separate entities.

A number of countries do not yet teach the STR at the high school level. Thus, studies of teaching the STR in science education have only focused on the undergraduate level. Hewson (1982) discussed the influence of prior knowledge of students on learning the STR. Villani and Arruda (1998) analyzed attitudes of undergraduates in Brazil who not only resisted acceptance of the STR but also regarded Galileo's law of addition of velocities as valid. Pietrocola and Zylbersztajn (1999) studied undergraduate physics students' understanding of the principle of relativity, and Scherr et al. (2001, 2002) discussed the ideas of undergraduate students regarding simultaneity and reference frames.

As the number of high school courses on the STR has gradually increased, studies of teaching the STR have increased as well. Velentzas et al. (2013) focused on the educational value of Einstein's thought experiments for students learning the STR. Guisasola et al. (2009) suggested a learning method as a tool for teaching-learning the STR that included visits to a science museum in Spain. Yildiz (2012) and De Ambrosis and Levrini (2010) discussed teachers' comprehension of the STR and pedagogical innovation. Giannetto (2009) and Zhang (2005) emphasized the need to teach the STR in electrodynamics courses. Arriassecq and Greca (2007) presented an analysis of the representation of the STR used in Argentinian high school and university textbooks, and on the basis of this analysis, Arriassecq and Greca (2012) suggested a teaching-learning sequence for the STR in high school courses that would be historically and epistemologically contextualized. Dimitriadi and Halkia (2012) investigated Greek students' learning processes in STR courses and also suggested a teaching-learning sequence of five sessions.

In the case of South Korea, students in high school were not taught the STR in science classes until 2012, and, before that, their first opportunity to study the theory came after entering university. However, it is noteworthy that they began to be taught the STR recently, that is, since the national curriculum of science education was reformed in the early 2010s. So, it is important that the educational contents of the STR within new physics textbooks in South Korea should be selected carefully and be organized structurally as students encounter this modern theory in classrooms for the first time. Nonetheless, there is not yet a systematic analysis of the textbooks and the learning ingredients in the new STR curriculum. For these reasons, a review is needed of the physics textbooks.

Unfortunately, when scrutinized, the educational contents in the STR in South Korean high school textbooks are severely problematic. This article aims to examine the educational content and structures in two kinds of high school physics textbooks and point out historical and philosophical problems within them. In the process of reviewing these textbooks, this article employs literature from the history and philosophy of science that have close connections to the genesis and epistemology of the STR, and then the article suggests new guidelines for adequate teaching-learning of the STR for South Korean classrooms.

2 Examination of High School Physics Textbooks in South Korea

2.1 Analysis of the Structure and Content of the STR

To begin with, what do high school students learn about the STR in South Korea now? To answer this question, we have to consider how physics textbooks used in South Korea have been made.[1] Some educational experts in physics and science education are appointed by the Ministry of Education of the South Korean government to select learning ingredients. The experts then make standards that high school students ought to achieve. After that, authors start to write textbooks. In the case of the STR, the achievement standard is to explain the fundamental *principles* of the STR, such as the constancy of the speed of light, time dilation, length contraction, simultaneity and the inter-convertibility of rest mass and energy (Ministry of Education 2012, p. 104). In South Korea, there are the only two textbooks covering the STR, written by Kim et al. (2013) and Kwak et al. (2013a). In this article, each authors' Physics I textbooks are simply referred to as 'textbooks' from now on. Kim et al. present three learning goals, (1) knowing the historical background of the STR, (2) understanding basic *hypotheses* of the STR and (3) finally knowing examples of experiments or observations relating to *phenomena* of the STR in accordance with the achievement standard (Kim et al. 2013, p. 66). The textbooks' educational contents on the STR are outlined in Table 1.

The main educational categories of the STR are divided into three aspects. The Michelson-Morley Experiment (the MME) is presented as a historical background of the STR in both textbooks. However, there is no detailed information about the MME itself within these textbooks. When students read historical episodes within the textbooks, they cannot comprehend why Michelson and Morley set up their experimental devices or even what theoretical characteristics were presupposed in their devices. Instead, the textbook authors present students with an analogy of a boat in a river current, with no real data from the MME. Meanwhile, according to Kim et al., the theoretical aspect of the STR is divided into two sub-parts again. One is referred to as the *hypotheses* of the STR, which includes the relativity postulate and the light postulate. The other is referred to as *phenomena* that occurred in the STR, including: relativity of simultaneity, length contraction, time dilation, the inter-convertibility of rest mass and energy and the muon lifetime experiment. Of special interest is that Kim et al. integrate both theoretical and empirical aspects into a single expression, the *phenomena*. The muon lifetime experiment is not included in the achievement standard of the STR established by the South Korean government. Supposedly, Kim et al. inserted the results of the experiment into one of phenomena cases of the STR because the experiment is considered empirical evidence of time dilation.

How are these theoretical ingredients of the STR referred to in another textbook, published by Kwak et al. (2013a)? In contrast to Kim et al., the term *principle* is used when indicating the two postulates: The so-called Principle of Relativity and the Principle of Constant Speed of Light. Furthermore, aside from these two postulates, they also refer to other theoretical characteristics. Specifically, simultaneity, time dilation, length contraction and inter-convertibility of rest mass and energy are all referred to as 'very strange *conclusions*' from these principles (Kwak et al. 2013a, p. 57). What we need not forget is that, as noted above, the term *principle* is employed to embrace all of the theoretical

[1] South Korean students in high school study physics with three stages of textbooks depending on the level of difficulty: *Science*, *Physics I* and *Physics II*. Among them, the STR is included in *Physics I*, which is generally used by 17-year-old students.

Table 1 Examples of the educational contents on the special theory of relativity in Kim et al. (2013)

Category	Educational contents	Expression of learning ingredients in Kim et al.
Historical aspect	Michelson-Morley experiment	
Theoretical aspect	Relativity postulate	*Hypotheses* of STR
	Light postulate	
	Relativity of simultaneity	*Phenomena* occurred in STR
	Length contraction	
	Time dilation	
	Inter-convertibility of rest mass and energy	
Empirical aspect	Muon lifetime experiment	

components of the STR when experts make an achievement standard for the STR. Furthermore, Kwak et al. separate empirical evidence from theoretical sub-components (such as time dilation, etc.) and refer to the latter as '*phenomenon* by the STR' (Kwak et al. 2013a, p. 60).

However, Kwak et al. do not consistently maintain these conceptual distinctions. According to a teaching manual or guide book of textbooks published by Kwak et al., the STR is divided into two parts, *hypotheses* of the STR and the STR *itself* (Kwak et al. 2013b, p. 70). Whereas the two postulates belong to the former, the rest belong to the latter. That is to say, the two postulates are separated from the theoretical structure of the STR and are dealt with as just presuppositions. Nevertheless, in this textbook, both time dilation and length contraction are also referred to as 'phenomena' in the 'quick quiz on key concepts' part as follows: (1) What do we call the *phenomenon* that time for a rapidly moving body is measured more slowly than time measured by a resting observer? (2) What do we call the *phenomenon* that the length of a body measured by an observer moving with respect to the body is always less than the length of the body measured by another observer at rest relative to the body? In other words, like Kim et al., Kwak et al. also employ the term *phenomenon* as a notion embracing both experimental evidence *and* theoretical conclusions from the two postulates.

In sum, the MME is presented as the historical background of the STR with an analogy, and there are conceptual inconsistencies when referring to the two postulates and other theoretical components. The next section begins by discussing historical issues and then goes on to a discussion on conceptual issues.

2.2 Problems in the Historical Background of the STR in Textbooks

2.2.1 A Main Argument Regarding the Background of the STR in Textbooks

Let me first present the historical descriptions of the STR in two textbooks.

> In the late nineteenth century, there was a problem, that is, whether the 'ether' (a proposed medium of electromagnetic waves and light) exists or not. In 1887, Michelson and Morley measured the speed of the light relative to the motion of earth in order to confirm the existence of the ether, but they failed.…They conducted an experiment while assuming that the ether is at rest in cosmic space and that the speed of light would change when earth passes through the ether. However, the speed of light was not changed. In fact, when light passed by, the effect of the ether's wind was undetectable. In the end, Einstein gave up the concept of the ether. It was very inconvenient to assume the complex

> ether's wind.…In other words, the ether does not exist, even though light obviously is a wave, and that light passes through a vacuum without any medium. Moreover, Einstein reinterpreted Michelson and Morley's experimental result as evidence for invariance of the speed of light, no matter what an observer's position or motion (Kim et al. 2013, pp. 66–67).

> Michelson and Morley tried to identify the existence of the ether by making an interferometer by which the speed of light was measured. If there was ether in the universe, then earth moves and does not stop in the ether because earth revolves around Sun that also moves in our galaxy. On the surface of earth, it seemed likely that the ether moved backward. Thus, the speed of light, propagating through the ether, will also change relative to the direction of earth. Michelson and Morley performed their exquisite experiment repeatedly, but they could not but conclude that there is no ether in the world. From their experimental results, Einstein set up an assumption that the speed of light is constant regardless of an observer's motion. (Kwak et al. 2013a, pp. 54–55)

These passages can be briefly summarized as follows:

1. *Michelson and Morley's Research Purpose*: To confirm the existence of ether.
2. *Main Experimental Instrument*: Interferometer.[2]
3. *Michelson and Morley's Test Hypothesis* ($E \rightarrow I$): If the ether really exists in the world (E), then interference fringe shift will be capable of being detected (I).
4. *Null Result* ($\neg I$): Interference fringe shift was not detected.
5. *Falsification* (by *modus tollens*, $\therefore \neg E$): There is no ether in the world.
6. *From the MME to the STR*: Non-existence of the ether *entails* that the speed of light is constant in all inertial frames, regardless of the velocity of the observer or the velocity of the source emitting the light.

The core portions in this summarized argument are from (3) to (6). The basic logical rule of this argument is *modus tollens*. This rule was emphasized as a scientific method for justification of theories by a philosopher of science, Popper (1935). In this argument, some of the above statements are fallacious except for the following: (2) the MME instrument and (4) their null result. In fact, the descriptions demonstrated in the two textbooks are historically wrong in their explanation of Michelson and Morley's research purpose, their test hypothesis and conclusion, and the relationship between the MME and the STR. I will illustrate these flaws in detail below.

2.2.2 Michelson and Morley Intended to Measure the Relative Motion of Earth to the Ether

Why did Michelson and Morley make an interferometer? The answer in both textbooks is that they wanted to confirm the existence of ether. Perhaps this answer seems reasonable when we only notice the following excerpt in their paper: "On the undulatory theory, first, the ether is supposed to be at rest except in the interior of transparent media, in which, secondly, it is supposed to move with a velocity less than the velocity of the medium in the ratio $\frac{n^2-1}{n^2}$, where n is the index of refraction.…The second hypothesis must be considered as fully proved.…The experimental trial of the first hypothesis forms the subject of the present paper" (Michelson and Morley 1887a, p. 334). However, this judgment is very suspicious when we look at quite detailed descriptions of their experimental design. Their paper published in 1887 included their own experimental device, its vast data and a simple

[2] As seen above, there was no explanation of Michelson's interferometer in the two South Korean textbooks. In addition, both textbook authors never took into account the 'displacement of interferometer fringes' at all. They just explain Michelson and Morley's key idea with the river's current analogy. Kwak et al. just show a picture of Michelson's interferometer device without any mention of it.

interpretation concerning their result. Among them, they concentrated on explaining and emphasizing the precision and accuracy of their own experimental device and dedicated a considerable numbers of pages to these. Thus, we can grasp their genuine intention when focusing on their research paper without any bias.

What is notable is that Michelson by himself had already announced that there was no fringe shift with his interferometer in 1881 (Michelson 1881). Without Morley, he almost completed the interferometer device at that time. However, Hendrik Lorentz pointed out Michelson overlooked an effect of the motion of earth through the ether when a ray of light moves from a half-silvered mirror to a vertical mirror (Lorentz 1886; Michelson and Morley 1887a, p. 335; Lorentz et al. 1923). When the ray travels in the vertical pathway, the interferometer also moves in a perpendicular direction to the ether. So, the real pathway that the ray moves is not perpendicular but slightly inclined to the ether. Michelson accepted this error and then recalculated the length of light in the vertical pathway together with Morley in 1887. The fully developed apparatus generally has been called the 'Michelson interferometer.'

It is taken for granted that all experimental designs are built on some theoretical backgrounds. The Michelson interferometer was no exception. It means theory-laden measurements. The theoretical assumptions of his interferometer were as follows: (1) assumptions about the characteristics of mirrors or the plated effect of the surface of mirror; (2) interference/reflection/refraction hypothesis of light; (3) Galilean theorem of addition of velocities of light. These assumptions are necessary to employ the Michelson interferometer and to interpret its data. The first and second assumptions play an instrumental role in the designing of concrete devices. If these assumptions were accepted in a scientific community, this device could then be stabilized in the associated research field. These assumptions were significant in regards to the interferometer because they provided a theoretical foundation for the concept of interference. Each physical property of the light within the Michelson interferometer is embraced in a wave theory of the light. For example, Augustin-Jean Fresnel argued that light is not corpuscular but in fact a wave, and that as the wave propagates in a particular medium, the light is also transmitted through luminiferous ether. Michelson, who advocated the wave theory of light, decided to design his interferometer to measure the relative speed of some light to the ether in 1881. The third assumption is a mathematical theorem regarding the combination of different velocities. This theorem presumes that there is absolute space and time. In the case of light, the ether was generally considered to be this absolute space and time during the nineteenth century. Thus, the wave theory of light and the Galilean theorem of addition of velocities are compatible with each other.

Notice that the term *ether* was a core component in the wave theory of light and was presumed when Michelson and Morley built their interferometer and interpreted their data. What then was the test hypothesis in the Michelson interferometer experiment? We can find a clue to the answer to this question once we first explore how their apparatus was based on various theoretical assumptions (as seen above). In their experiment, the ether is the most fundamental assumption. Michelson and Morley thought that if earth moves through the ether, there is an effect of the ether's wind on the surface of earth. By assuming that this hypothetical ether was at rest, they endeavored to measure the velocity of earth relative to the ether. Consequently, the existence of the ether is not the target of MME but, in fact, one of the chief theoretical assumptions. Their test hypothesis was that the relative speed of earth to the ether could be measured.

In sum, the MME was not performed to confirm or falsify the existence of the ether. The term the *ether* was just an essential assumption of their experiment. They strove to detect fringe shift relative to the ether, but failed. Their experiment was not to evaluate an experimental assumption of their interferometer instrument but to confirm their expectation of the relative motion of earth.

2.2.3 Michelson and Morley Did Not Themselves Deny the Existence of Ether

After Michelson and Morley failed to detect fringe shift, how did they judge this unexpected result? Recalling the fact that they did not intend to confirm the existence of the ether but just identify the motion of earth relative to the *fictional* ether, we can imagine some options that they selected.

The first option is to doubt their experimental procedures. When they dealt with the interferometer device, unnoticed errors could remain. The second option is to suspect the background theories and assumptions that were employed in their experiment. In fact, the ontological assumption of the 'ether' is one of the most significant background assumptions, but it is unclear why Michelson and Morley necessarily falsified the existence of the ether.

If the Michelson interferometer is precise, as it was, then the first option was abandoned. After that, they had the second option, that is, to be suspicious of the background theories and assumptions of the device. Michelson and Morley might have been sufficiently able to have the idea that if interference fringe shift was not detected, then the ether really did not exist immediately after 1887. In other words, it seems that there was a possibility that they could have denied the existence of the ether with their negative result. The two textbooks also describe that Michelson and Morley concluded that the ether did not exist. However, this inference is historically groundless.

In order to comprehend Michelson and Morley's final conclusion from their experiment, let us reconsider their original purpose. The measurement of the velocity of earth relative to the immobile ether was closely coupled with the phenomenon of stellar aberration,[3] which James Bradley discovered in 1729. There were two hypotheses explaining this phenomenon through the wave theory of light. One hypothesis was suggested by Fresnel in 1818, who insisted that luminiferous ether pervades all material bodies in a stationary state. He considered the ether as an ordinary matter, which is either a solid or a fluid medium. When a material body moves through the ether, the body and their medium physically interact with each other so that the ether partially drags the light propagating in it with some friction. Due to the friction, the light ray is refracted; thus, if the index of refraction of the stationary ether is n, then Fresnel formulated the dragging coefficient, $\left(1 - \frac{1}{n^2}\right)$. In short, earth is moving through the immobile ether, but the ether within earth is partially carried along with earth. This was Fresnel's *ether-wind* hypothesis, in which the light propagating in the luminiferous ether was partially dragged. This hypothesis was empirically confirmed by Hippolyte Fizeau, who successfully demonstrated the Fresnel coefficient with a moving water experiment in 1851. However, in 1845 George Gabriel Stokes proposed another hypothesis in which the ether was dragged along by earth *as a whole* and the velocity of the ether on the surface of earth was equal to that of earth so that its relative velocity was zero. In short, Stokes insisted there was no ether wind on the surface (Stokes

[3] The phenomenon of stellar aberration can be understood by using the following analogy: When a person is walking on the street in the wind-free rain, he or she observes the apparent direction of the falling rain as the vector sum of the rain's velocity and his or her own velocity. So in order to avoid getting wet, the person must tilt their umbrella. Similarly, when an astronomer observes a fixed star with a telescope, he or she should slightly tilt their telescope in order to detect the light from the star.

1845). He considered the ether as being a glue-water jelly possessing elasticity (Harman 1982, p. 27). According to Stokes' view, light rays are 'totally' refracted during their passage through the ether so that the ether is fully dragged along by the light. Thus, in Stokes' *dragged-along* hypothesis the ether was not at rest but moving along some bodies (see Stokes 1846a, b).

In 1881, Michelson published a paper that drew this conclusion: "The interpretation of this [negative] result is that there is no displacement of the interference bands. The result of the hypothesis of the stationary ether is thus shown to be incorrect, and the necessary conclusion follows that the hypothesis is erroneous" (Michelson 1881, p. 128). In the meantime, Michelson decided to return to the measurement of the velocity of light because his experiment and its bold conclusion did not draw much attention. Together with his new colleague Morley, Michelson cautiously performed the interference experiment by modifying his interferometer on the basis of Lorentz's criticism in 1886. Nevertheless, they finally acquired the same null result and concluded: "It appears, from all that precedes, reasonably certain that if there be any relative motion between earth and the luminiferous ether, it must be small; quite small enough entirely to refute Fresnel's explanation of aberration" (Michelson and Morley 1887a p. 341). In the end, Michelson and Morley advocated Stokes' hypothesis in which the ether is still regarded as 'real.'[4]

Also, if we take a look at the letter that Michelson wrote Lord Rayleigh in 1887, this revised conclusion is again supported. In that letter, he wrote, "the experiments on the relative motion of earth and ether have been completed and the results are decidedly negative.…As displacement is proportional to the square of the relative velocities, it follows that if the ether does slip past the relative velocity is less than one sixth of earth's velocity" (Shankland 1964, p. 32). Historically, there are no clear sources that show Michelson and Morley abandoned the ether after they completed the famous 'failed' experiment. Afterwards, Michelson stopped ether drift experiments and began to use their newly developed apparatus to establish the wavelength of light as a standard of length (Michelson and Morley 1887b, 1889; Michelson 1897). Moreover, Morley and his colleague, Dayton Miller, continuously conducted ether-drift experiments (Morley and Miller 1904, 1905; Swenson 1972). In light of these facts, it is evident that Michelson and Morley did not determine the non-existence of ether after 1887.

Even if Michelson and Morley still believed in the existence of ether directly after their 'failed' experiment, this conservative attitude is not odd. Most scientists directly never deny a web of theories that they firmly believe even though they confront unexpected experimental results. When scientists within a paradigm, according to Thomas Kuhn (1962), find an anomaly, most of them do not lose faith in their paradigm but suspect their ability to perform experiments. The negative result with the interferometer was an anomaly for Michelson and Morley within the wave paradigm, but they did not renounce the undulatory theory directly. Instead, they tinkered with the prevailing paradigm by adopting Stokes' hypothesis, the one wherein the ether is dragged along a moving body. Hence, no matter how Michelson and Morley found a historically significant result, there is no need to link it to Einstein's light postulate without manifest reasons.[5]

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[4] For more detailed information about the ether theory in the nineteenth century, see Whittaker (1910), Schaffner (1972), Swenson (1972), Janssen and Stachel (2004) and Stachel (2005). Also, for the purpose of gaining a comprehensive understanding of physics in the nineteenth century, see Harman (1982).

[5] In the philosophy of science, there were controversies on an issue whether the MME in 1887 was a crucial experiment to determine which one of hypotheses between the undulatory theory of light, claimed by Fresnel and Stokes, and Einstein's STR was true. Popper (1935) argued that the MME was a crucial experiment because the null result not only contradicted the ether theory but also confirmed Einstein's later

2.2.4 There is No Historical Evidence Einstein Made the Light Postulate Directly from the Null Result of the MME

The third historical issue concerns the relationship between the MME and the STR. The textbooks' authors assume that Einstein created the STR, especially the light postulate, because of the null result of the MME. They suggest that because no interference fringe shift was discovered, the reality of the ether was falsified, and consequently the speed of light is constant.

However, on the basis of historical analyses of historians of physics and physicists in the twentieth century, it is not enough to claim that Einstein built the light postulate from the MME (see Robertson 1949; Shankland 1964; Holton 1969; Zahar 1973a, b; Stachel 1982; Darrigol 2000, 2005; Collins and Pinch 2012). Let us look at a letter Einstein wrote to his lover Mileva Marić. In 1898, he felt in his bones that electromagnetic theory was incomplete by saying that

> I am more and more convinced that the electrodynamics of moving bodies, as it is presented today, does not agree with the truth, and that it should be possible to present it in a simpler way. The introduction of the name 'ether' into the electric theories has led to the notion of medium of whose motion one could speak of without being able, I believe, to associate a physical meaning to the statement. I believe that electric force can be directly defined only for empty space, [which is] also emphasized by Hertz (Darrigol 2000, p. 373).

For this reason, he tried designing an experiment "for investigating which effect the relative motion of bodies with respect to the luminiferous ether has on the velocity of propagation of light in transparent bodies" (*ibid*, p. 375). He sent his idea to Heinrich Weber, Einstein's physics professor, who recommended he read a paper by Wilhelm Wien that accounted for Lorentz's theory and ten negative results of experiments concerning relative motion between earth and the ether (Wien 1898). After reading Wien's paper, Einstein confessed that "Fizeau's measurements on the speed of light in moving water" influenced the setup of the STR more than the MME, among the optical and electrical ether-drift experiments (Shankland 1963, p. 48). An interviewer, Robert Shankland, was so astonished by Einstein's denial of the direct role of the MME for the development of the STR that he asked Einstein where he had first heard of Michelson and his experiment. Einstein replied,

> I was not conscious that it had influenced me directly during the seven years that relativity had been my life.…he had also been conscious of Michelson's result before 1905 partly through his reading of the papers of Lorentz and more because he had simply assumed this result of Michelson to be true. (*ibid*, p. 55)

Footnote 5 continued
theory. However, Imre Lakatos (1978) criticized Popper since the null result of the MME did not decide between the ether theory and Einstein's theory. Even though Lakatos' criticism was considerably reasonable, Ian Hacking (1983) pointed out Lakatos was focusing too much on the context of theory test and neglected James Maxwell's influence on the MME. Lakatos argued that 'Michelson first devised an experiment in order to test Fresnel's and Stoke's contradictory theories about the influence of the motion of earth on the ether' (Lakatos 1978, p. 73). Hacking, however, said that is not true because Michelson made his interferometer device not to prove Fresnel's and Stoke's theories, but just to measure the motion of earth relative to the ether. Maxwell (1878) said the measurement would be *impossible*, but Michelson wanted to do it (Hacking 1983, pp. 256–261). Hacking focused on Michelson as an experimenter and emphasized the fact that experiments do not just play a supportive role in testing theories.

The reason why Einstein was interested in Fizeau's experiment was that the speed of an electromagnetic wave in empty space derived from Maxwell's equations was very close to the speed of the light measured by Fizeau. Meanwhile, Einstein considered the MME true in that the MME failed to attempt to detect earth's motion in the ether and finally began to doubt the existence of the ether.

Nonetheless, the non-existence of luminiferous ether did not *entail* the light postulate of the STR as textbook authors describe, such that, if the ether does not exist in the world, then there is no ether wind effect, and the speed of light is constant regardless of the direction of the light. We cannot find any clue in his 1905 paper why he proposed the light postulate. He just suggested the postulate by defining it, "which light is always propagated in empty space with a definite velocity *c* which is independent of the state of motion of the emitting body" (Einstein 1905[1923], p. 38). What we have to pay attention to is that he mentioned the constant velocity of the light irrespective not of the ether, but of the state of motion of the *emitting source*. According to an emission theory at that time, the velocity of light, *c, in vacuum* is constant with respect not to the ether, but to the source that emits the light. Einstein had considered this emission theory seriously before 1905 in order to solve a paradox in Maxwell's equations. He shared a striking thought experiment containing the paradox in his autobiographical notes. He recalled,

> A paradox upon which I had already hit at the age of sixteen: If I pursue a beam of light with the velocity *c* (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, neither on the basis of experience nor according to Maxwell's equations. 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 laws as for an observer who, relative to 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? (Einstein 1951, pp. 52–53)

This is Einstein's thought experiment, which is called *the thought experiment of chasing the light* (Norton 2013). He had been immersed deeply in the contradiction between the principle of relative motions and electromagnetism since he had learned Maxwell's theory. If an observer measures the light moving at *c*, it means that the observer is at rest with respect to the ether. If another observer measures the light frozen, this observer moves at *c* with respect to the ether. In these two cases, since these observers can determine their absolute motions with respect to the ether, Maxwell's theory is incompatible with the principle of relativity. Einstein took into account the emission theory as an alternative to Maxwell's theory. In the emission theory, what the observer perceives as the constant speed of light *c* means that the observer is stationary with respect to the emitter. And, if the beam of light is frozen, the observer is moving at *c* from the emitter. Apparently, the emission theory seems to be compatible with the principle of relative motion. However, Einstein finally gave up the emission theory because of two flaws: (1) This theory cannot characterize light waves solely by intensity, color and polarization, but would need the addition of a velocity property, which light is known not to possess, and (2) it cannot be formulated in terms of differential equations, which could have solutions representing waves whose velocity depends on the motion of the source (Norton 2013, p. 133; for more detailed discussions, see Shankland 1963, p. 49; Darrigol 2000, p. 380; Norton 2004, pp. 69–82). For these reasons, Einstein emphasized the independence of the velocity of light from emitting sources in the light postulate. Therefore, the non-existence of the ether was not intimately linked with the light postulate. Rather, the denial of the ether could be connected to the significance of the relativity postulate of the STR owing to the failure of the effects of the ether wind (Darrigol 2000, p. 376). In brief, the null result of the MME implied that the Galilean theorem of addition of different velocities, which was an assumption of the MME, was so doubtful that a new theorem of addition of the velocities would be required in order to maintain the principle of relativity. Einstein suggested a new theorem for the composition of velocities in 1905.

The link between the MME and the STR in textbooks is also based on a methodological connection. This connection means that an abstract theory is inductively generalized from empirical data. In the case of the STR, the null result of the MME is obviously empirical data, which is quite stabilized or robust. The negative result of the MME was accepted as a scientific fact in the late nineteenth century. According to the two textbooks, it seems that the STR is introduced from the MME automatically by an inductive method, and then the ether theory was falsified in the end. This view can be found in discussions of empiricists in the philosophy of science. Popper, an advocate of falsifiability, said "what compels the theorist to search for a better theory is almost always the experimental *falsification* of a theory, so far accepted and corroborated: it is the outcome of tests guided by theory. Famous examples are the Michelson-Morley experiment which led to the theory of relativity" (Popper 1935 [2002], p. 90). This empiricist's view oversimplifies not only the origins of the STR, but also the pros and cons of the null result from the MME among proponents of the wave paradigm (see Allchin 2004).

Even though abandonment of ether seems to be linked to the relativity postulate instead of the light postulate, Einstein never adopted the relativity postulate *inductively* from negative results accumulated from ether-drift experiments. (Unfortunately, the introductory course on the relativity postulate in textbooks is not illustrated at all!) The reason that Einstein focused on this principle was closely related with his reading before 1905. Since Einstein had entered the Zurich Polytechnikum in 1896, he studied Maxwell's theory by himself from Drude's *Physik des Aethers*, Hertz's and Hermann Helmholtz's books and enjoyed reading Ernst Mach's *The Science of Mechanics* and David Hume's *A Treatise of Human Nature* (see Norton 2010). Especially, once Einstein was aware of the term *local time* from reading Lorentz's *Versuch* of 1895, he decided to study an electron theory elaborated by Lorentz and Max Abraham. He also read Henri Poincare's *Science and Hypothesis*, in which the principle of relativity and the concept of simultaneity were discussed (Miller 1998, pp. 115–133; Darrigol 2000, pp. 380–382; Darrigol 2005, pp. 20–23). In the meantime, the case of relative motions between a magnet and a conductor presented in Föppl's electrodynamics textbook fascinated Einstein's curiosity. This *magnet-conductor thought experiment* also appears in Einstein's influential article, 'On the Electrodynamics of Moving Bodies' (Einstein 1905):

> It is known that Maxwell's electrodynamics…when applied to moving bodies, leads to *asymmetries* which do not appear to be inherent in the phenomena. Take, for example, the reciprocal electrodynamic action of a magnet and a conductor.…If the magnet is in motion and the conductor at rest, there arises in the neighborhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated. But if the magnet is stationary and the conductor in motion, no electric field arises in the neighborhood of the magnet. In the conductor, however, we find an electromotive force, to which *per se* there is no corresponding energy, but which gives rise—assuming equality of relative motion in the two cases discussed—to electric currents of the same path and intensity as those produced by the electric forces in the former case. (*emphasis added*)

This paragraph in the introduction of Einstein's paper can be described in more detail as follows. When the conductor is at rest, the moving magnet leads to a change of flux of the magnetic field (B). According to Faraday's law, the change of flux of the magnetic field induces an electric field (E), which drives a current in the conductor. So, the electric force (F_E) acts on a charged particle (q) in the conductor, $F_E = qE$. If, on the other hand, the magnet is at rest and the conductor moves over the magnet, then a current of the same magnitude, as seen in the former case, is still generated in the conductor. In this case, there is no electric field around an immobile magnet, and the charged particle moving with the speed of v in the magnetic field has a magnetic force (F_B). That force is called the Lorentz force ($F_B = qv \times B$) (Topper 2013, p. 43). In the two cases, what is at rest and what is moving are different, respectively. But, different kinds of forces act on this relative relation. This asymmetry in Einstein's thought experiment was a puzzle for him when he studied Maxwell's equations and electromagnetism. Thus, he asserted the relativity postulate to urge a law of transformation by which the two cases can be symmetric. Therefore, it is not true that Einstein empirically generalized the relativity postulate from the null result of the MME.[6] Instead of the rule of induction, the STR was invented not by derivation from empirical facts, but by creative imagination through his thought experiment.[7]

2.3 Problems in Conceptual Expressions of the STR in Textbooks

In this section, I will discuss a conceptual issue in textbooks. All of the terminology for notions important to the STR used by the South Korean government and two publishers of the textbooks is summarized in Table 2. Notice that several notions, such as principle, hypothesis, phenomenon, evidence and conclusion, are used *inconsistently* by experts in science education. This conceptual confusion brings up questions such as: Does the term *hypotheses* have an equal meaning to *postulates*? Do *hypotheses* have the same meaning as *principles*? What is a phenomenon? What is the difference between postulates and other theoretical sub-components? Does the term *principle* simultaneously embrace both theoretical sub-components and postulates of the STR? Is it right to classify observational evidence as a *phenomenon?*

One might think that principles, hypotheses and phenomena can be used interchangeably. One might think further that whatever we choose among these concepts when teaching the STR, it never affects whether or not students achieve the given goals. However, this optimistic view gives rise to severe misunderstandings of not only the theoretical structure, but also of the historical origins of the STR.

To begin with, every theoretical ingredient in the STR should not be identified by using only one term as the South Korean government has used the term *principle*. The term *principle* should only be used to refer to the two postulates. These two postulates are *structurally* and *functionally* distinguished from the other sub-theoretical components such as time dilation. Principles are a kind of *commitment* or *template* to theorizing (see Giere 2006). In the STR, the two postulates restrict the STR in which basic physical quantities are observed to take on different values when the observations are made from two different observational frames with relative motion between the observational frames. In Newtonian mechanics, the Galilean law of transformation was enough, but in electromagnetism it is not. So, Einstein confronted a requirement for a new law of transformation and finally acquired a satisfactory solution in 1905. In his thought experiments Einstein introduced a

[6] There was an historical debate on whether the MME influenced the creation of the STR among historians of physics. The widely received view is that Einstein had already known the MME before 1905, but that the STR had arisen from a problem in electromagnetism not from optics (see Stachel 2002; Faraoni 2013).

[7] See Darrigol (1996, 2000, 2005) for the sake of comprehensive understanding of the origin of the STR from electrodynamics. For the relation between Einstein and Poincare in more detail, see Darrigol (2004) and Messager et al. (2012). In addition, see Abiko (2005) for the relation between the STR and thermodynamics.

Table 2 A comparison between important concepts for the STR with terminologies used in two textbooks and two other educational resources

Theoretical ingredients of STR	Terminology			
	Achievement standard (government)	Kim et al. (textbook) (teaching manual)	Kwak et al. (textbook)	Kwak et al. (teaching manual)
Two postulates	Principles	Hypotheses	Principles	Hypotheses of STR
Other theoretical sub-components	Principles	Phenomena	Conclusions/ phenomena	Theories of STR/ phenomena
Empirical evidence	•	Phenomena	Phenomena	Phenomena

useful tool referred to as the 'light signal.' The light signal is used in cases where two observers are positioned at two distant points, point A and point B. It is possible to synchronize each observer's clock at points A and B by utilizing the light postulate.

On the basis of the two postulates plus the relativity of simultaneity, several *kinematic consequences* can be derived as follows: (1) Lorentz's law of transformation and relativistic theorem of addition of different velocities; (2) a time interval Δt measured by a stationary observer is longer than the same time interval measured by a moving observer (time dilation); (3) the length L of a linear rod measured by an observer who is moving with respect to the rod and in the direction co-linear with the rod is shorter than the proper length L_P of the linear rod measured by an observer who is stationary to relative to the linear rod (length contraction); (4) rest mass m and energy E can be converted one into the other (with any such conversion obeying the well-known formula $E = mc^2$, where c is the speed of light in a vacuum). Without the postulates, the reformulation of time and space (which includes time dilation and length contraction) would not appear. The consequences can be employed when we need to quantitatively predict time intervals and lengths in cases where something moves at a large fraction of the speed of light, e.g., 0.9 c. In other words, sub-components in the STR play a *predictive* role in various imaginary (or actual) cases. Therefore, the two postulates and the kinematic consequences from them can and should be distinguished conceptually in order to understand the structure of the STR.

Second, let us examine the textbook authors' practice of denoting the two postulates as mere 'hypotheses' in their publications. The term *hypothesis* generally has two meanings with regard to methods of research in scientific practice. Let me introduce them in the case of classical mechanics. On the one hand, a *generalized* hypothesis is a tentative law produced inductively by gathering a series of empirical resources within limited regions and periods. The Titius-Bode law is a typical instance of it. This law gives the distances of the planets from the sun in the solar system. The lengths of the semi-major axes of several planets such as Mercury, Venus, Earth and Jupiter are approximately predicted by this law. However, according to this law, there should be a planet, called Ceres, between Mars and Jupiter, but Ceres is now classified as one of the dwarf planets. Moreover, Neptune's authentic axis length is significantly different from the prediction of the law. Whereas the Titius-Bode law cannot be derived from Newton's law of gravitation, Newton's theory is compatible with Kepler's first law of planetary motion, which was also discovered on the basis of astronomical data to explain aspects of the orbits of the then observed planets in the solar system. If Galileo's law as well as Kepler's first law as generalized hypotheses are supported by sufficient evidence and/or unified by a comprehensive theory such as Newton's theory, then they are granted the status of 'scientific law.' On the other hand, Newton's second law of motion is a fundamental equation. A fundamental equation, including Schrödinger equation, can be specified by adding some conditions to it in order to explain some aspect of the physical world. For example, the equation of simple harmonic oscillation can be derived from Newton's second law plus Hook's law. Following this example, an equation derived from basic principles implies a test hypothesis, which can be compared with empirical data. A test hypothesis deduced from highly abstract principles for explaining oscillatory systems is generally called an *explanatory* hypothesis. Consequently, all hypotheses are observational or empirical statements, which can be confirmed or falsified (whether or not they are accepted).

In the case of the STR, there are no generalized hypotheses because Einstein did not set up the two postulates inductively from empirical data. Rather, the structure of the STR is similar to that of Newton's mechanics in that the two dynamical theories are both based on fundamental principles. The relativity postulate and the light postulate, like Newton's second law of motion, function to generate empirically specified hypotheses, which will explain or predict particular aspects of the physical world if and only if the hypotheses are confirmed and not falsified. Hence, the two postulates in the STR are more correctly called 'principles' rather than 'hypotheses.' Furthermore, in circumstances where the STR is tested, the term *hypotheses* should be used to refer to *consequences* of the two postulates, such as time dilation.

Third, as seen in Table 2, the term *phenomena* embraces both theoretical consequences from postulates and empirical evidence supporting theoretical predictions of the STR. Kwak et al. (2013a) refer to a result of the muon lifetime experiment as 'a phenomenon occurred *by* the STR' and employ the term *phenomena* when referring to time dilation and length contraction. Kim et al. (2013) also introduce the sub-components of the STR and the muon lifetime experiment as both 'phenomena *occurred in* the STR.' In short, the authors of both textbooks seem to think that the term *phenomena* can cover both theoretical and empirical aspects. However, is this usage conceptually proper?

In order to figure out the relations among the terms *phenomena*, *theoretical consequences* and *evidence* or *data*, it is helpful to refer to the philosophical literature. According to Bogen and Woodward, phenomena are "detected through the use of data" (Bogen and Woodward 1988, p. 306) and "stable, repeatable effects or processes that are potential objects of prediction and systematic explanation by general theories and which can serve as evidence for such theories" (Woodward 2000, p. S163). Traditionally people think phenomena are in the world, not within our ideas. Whether phenomena exist in the world or not can be determined by collecting empirical data. Data are "public records produced by measurement and experiment that serve as evidence for the existence of phenomena or for their possession of certain features" (*ibid*). In short, data play the role of evidence for claims concerning phenomena, and phenomena whose reality is supported by data are explained through scientific theory. Therefore, phenomena as objects to be represented should be distinguished from scientific theories such as the STR representing the phenomena.

In the case of the STR, theoretical consequences from two postulates predict and explain a specific phenomenon in the world.[8] The dependence of the mass of an electron on

[8] The MME and Kennedy-Thorndike experiments seem likely to be directly concerned with two principles. But because the two experiments are based on ether, data from them are not used as evidence for the existence of phenomena associated with the STR. The difference between them is that while the former's result was about the independence of the speed of light on the orientation direction of a measuring apparatus, the latter, which first was conducted in 1932, showed that the speed of light does not depend on the velocity of two fixed measuring devices (Kennedy and Thorndike 1932).

the electron's speed was one of the phenomena closely related with the STR. Several experiments were carried out by Walter Kaufumann, Max Abraham, Alfred Bucherer and Günther Neumann from 1901 to 1915 to test the relativistic mass of moving electrons (see Cushing 1981; Miller 1998, Ch. 12). Besides, the Ives-Stilwell experiment in 1938 and 1941 was designed to test the relativistic Doppler effect and time dilation with a moving clock (Ives and Stilwell 1938, 1941). However, Ives and Stilwell claimed that their experimental result confirmed not Einstein's STR, but the Lamor-Lorentz theory, which was based on the concept of ether and was competitive with the STR. In contrast to the Ives and Stilwell experiment, the muon lifetime experiment serves as *determinate* evidence for the existence of time-dilated and length-contracted phenomena.[9] A muon is approximately 200 times more massive than an electron and can travel at nearly 98 % the speed of light. Muons have a mean lifetime of about 2.2 μs when at rest, and muons decay into an electron, and some combination of two neutrinos and antineutrinos. The initial experiment was performed by Bruno Rossi and his colleagues between 1941 and 1943 (Rossi and Hall 1941; Rossi and Nereson 1942; Nereson and Rossi 1943). However, their result was quantitatively a bit inaccurate. More accurate measurements were carried out by scientists at the laboratory of the European Council for Nuclear Research (CERN) in 1977 (Bailey et al. 1977). This effort conducted a series of experiments with muons, so that we eventually acquired an empirical data set that supplied critical evidence of the existence of phenomena related to time dilation and length contraction. For example, given a muon created in the upper atmosphere with a speed of 0.98 relative to earth, in such a muon's reference frame, during an average lifetime of 2.2 μs, earth moves approximately 650 m relative to the muon. Changing reference frames, a person or measuring instrument at rest on earth's surface measures a much longer muon lifetime (owing to time dilation), and such an earth-bound person or measuring instrument measures the average distance of muon travel as 4800 m (before decaying). With CERN's experimental data, we can say that time dilation and length contraction were finally confirmed; furthermore, the STR had successfully predicted phenomena.

Based on the above discussion, we can easily conclude that the descriptive conceptual expressions of the STR in the two textbooks are absurd. The expression 'a phenomenon occurred *by* the STR' is unreasonable because any abstract theory has no power to produce physical quantities that will be observed or measured through instruments. With empirical data, we can obviously recognize the existence of a true phenomenon. Moreover, Einstein did not know about muons when he announced the STR, so that he never had plans to design any experiments with muons for the sake of justifying the STR.[10] Another expression, 'phenomena occurred *in* the STR,' is also problematic. The domain of phenomena is different from that of the STR. The reality of phenomena can be disclosed by empirical data, so they are empirical and concrete. However, the STR typically is one of

[9] Later, I will show a competitive relationship between the STR and an ether-based theory, the Lorentz and FitzGerald contraction hypothesis. The latter theory, suggested by Lorentz, FitzGerald and Lamor, provided a theoretical explication of the null result of the MME. However, the muon lifetime experiment plays a determinate role between the two theories. In other words, the phenomenon that muons are detected by observers on the ground of earth can be saved by the former but not by the latter because the motion of muons does not need the concept of ether.

[10] Stachel argued that "Einstein was concerned with the theoretical and experimental aspects of the electrodynamics of moving bodies from at least 1899 on, and he was very much interested in ether drift experiments, and appears to have designed at least two, which he hoped to carry out himself" (Stachel 1987, p. 47). However, the experiment Einstein wished to perform was similar to rather than the same as the MME and had nothing to do with muons at all.

the abstract theories, which will be confirmed or disconfirmed by data. Therefore, if we use the term *phenomena* the way the textbook authors have, then students are likely to misunderstand not only the STR but also an *epistemological* relationship between theoretical consequences and evidence.

Let me reconstruct the learning components of the STR based upon the above discussion. The two postulates are principles. Assuming these principles, together with some mathematical theorems, several consequences can be calculated such as time dilation, length contraction and the potential to convert rest mass and energy between each other. Hence, the structure of the STR contains two principles that can produce some theoretical consequences. In the context of theory testing, a predictive model among theoretical consequences of the STR that represents a specific phenomenon will be capable of being compared with models of data (which are experimental products made by scientists interpreting and manipulating raw data). Next, if the predictive model coincides with the models of data within an error range, then the data become evidence to confirm that the STR is a successful representation of some phenomena in the external world.

3 Causes of Errors and Perils in High School Textbooks

3.1 Why is the Historical Content About the Background of the STR Incorrect?

Most philosophers and historians of physics, except Popper, endorse that the MME had not directly influenced the STR in the late nineteenth century (see Holton 1960, 1969; Swenson 1972; Zahar 1973a, b; Lakatos 1978; Hacking 1983; Stachel 2002). Nevertheless, why has the MME still been presented in textbooks as the only background to the STR? I will briefly examine some plausible reasons for this portrayal by focusing on an important article written by a representative author of textbooks. He said,

> I followed a traditional way of introducing the STR in the high school curriculum used in *Introduction to Physics* (or *University Physics*, *College Physics* etc.)….Of course, we could consider another way. But, if so, we believe, many teachers who had studied in their university with those undergraduate textbooks will have considerable trouble in teaching students in high school. Hence, we clung to the traditional way. (Kim 2012, p. 6)

Perhaps, 'the traditional way' means the tendency to write high school textbooks with reference to undergraduate textbooks. The representative author emphasizes the necessity of maintaining a common format of educational contents between high school and university. As a result of comparison between two kinds of high school textbooks and undergraduate textbooks, which are popularly used in the main universities in Seoul, such as *Modern Physics* (Serway et al. 2005), *Principles of Physics: A Calculus-based Text* (Serway and Jewett 2006), *Physics for Scientists and Engineering with Modern Physics* (Serway and Jewett 2010), *Essentials of College Physics* (Serway and Vuille 2007) *and College Physics* (Serway and Vuille 2012), I identify a striking resemblance between them.[11] Actually, many of the content's descriptions and figures are similar to each other.

[11] Many universities in South Korea also widely use *Fundamentals of Physics* (Halliday et al. 2011). Interestingly, in this textbook, the MME is not mentioned as having influenced the STR. However, all of the five undergraduate textbooks written by Raymond Serway and his colleagues include the MME within the STR chapters. Thus, it is certain that high school textbooks' authors mainly referred to Serway et al.'s textbooks. These undergraduate textbooks of Serway et al. are translated into Korean now.

The main problem is that much fallacious content in undergraduate textbooks remains intact throughout these high school textbooks. An example of this fallacious content from Serway et al. is the following, "the negative results of the MME not only contradicted the ether hypothesis but also showed that it was impossible to measure the absolute velocity of earth with respect to the ether frame" (Serway et al. 2005, pp. 7–10; Serway and Jewett 2006, pp. 262–263; Serway and Vuille 2007, p. 674; Serway and Jewett 2010, pp. 1148–1150; Serway and Vuille 2012, pp. 887–888). Strictly speaking, the latter is true, but the former is false. As we examined earlier, Michelson and Morley did not deny the notion of the ether. And their theoretical conclusion, namely Stoke's *drag-along* hypothesis, is completely ignored here. Of course, if their genuine conclusion were to be mentioned in Serway et al.'s textbooks, the size of the text would immediately increase. Seeing that most undergraduate textbooks are more than 1000 pages long, it is understandable that not all historical details are included. However, we cannot deny the fact that this incorrect description of the MME's conclusion brings about the consequence that many preservice science teachers misunderstand the origin of the STR.

Furthermore, the description concerning the relationship between the MME and the STR portrayed in undergraduate textbooks is also false. In the textbooks of Serway et al., it is said that "Einstein offered a postulate in his special theory of relativity that places quite a different interpretation on these null results.…In 1905 Albert Einstein proposed a theory that explained the result of the Michelson-Morley experiment and completely altered our notions of space and time" (Serway and Vuille 2012, p. 888). This description tends to suggest that Einstein proposed the STR in order to interpret the null result of the MME and that the MME had influence on the formation of the STR in some way. As long as the MME is portrayed as being some kind of an influence behind the STR, it is difficult to remove the expectation of a logical or methodological connection between them. Probably the reason why this expectation still remains is that Serway et al., who are mostly physicists, think that a great scientific theory like the STR could not have been discovered as a result of an aesthetic factor such as symmetry.

Another problem still remains as long as high school students and college undergraduates learn the STR with these textbooks by Serway et al. If the only historical background to the STR given in textbooks is some brief comments surrounding the MME, then many students in South Korea are being deprived of an opportunity to study the significant, interesting and didactic ideas developed through both Einstein's thought experiments and how, over years, Einstein solved the asymmetry problem in electromagnetism. Before the twentieth century, Einstein first faced the induction current puzzle between a magnet and a conductor given in Föppl's textbook, which includes an emphasis on the contradiction between the Maxwell-Lorentz equations and the relativity principle (Holton 1973; Darrigol 2000, p. 378). Föppl's textbook, *Maxwell's theory of electricity (Theorie der Elektriztät)*, was written for the purpose of providing a simple and clear explanation of Maxwell's theory for engineers. We can realize the impact of Föppl's textbook on Einstein in that the title of Einstein's paper in 1905, "On the Electrodynamics of Moving Bodies" (in the original German "Zur Electrodynamik bewegter Körper"), is very similar to the title of the fifth chapter in Föppl's textbook. Thus, seeing how textbooks can be very influential, it is imperative they are written extremely carefully.

These historical errors in undergraduate textbooks originated from ignorance of a significant characteristic of the STR in the history of science. I think that many physicists, such as Serway and his colleagues, have in their minds that science is a cumulatively progressive practice. This view is closely related to the empiricist's viewpoint in the philosophy of science (as Popper noted above). However, this view of science is too naïve to comprehend the nature of changes to theory. In the case of the STR, this theory triggered a revolutionary transition from previous paradigms in physics (Kuhn 1962). When a revolutionary shift occurs, concepts are changed. In contrast to the Newtonian paradigm, in the Einsteinian paradigm core physical quantities such as time interval, length, mass and momentum, etc., are changeable. Space and time are not independent concepts but closely interdependent in the STR. In addition, through a paradigm change, research questions are also changed. In Fresnel's undulatory paradigm, the measurement of speeds of light relative to the ether was a puzzle that Michelson and Morley had to solve. However, in the STR that the puzzle was no longer a research task. Instead, with the STR, investigations start of physical phenomena of objects moving close to the speed of light. Furthermore, when we take up a new paradigm, our worldview is transformed. If we take for granted Newtonian mechanics, then we cannot help but consider the STR as strange. Rather, however, if we adopt the STR and accept the inter-dependent nature of space and time, then Newtonian mechanics just becomes a wrong theory. In other words, depending on what paradigm we take, fundamental viewpoints of the world may change. Therefore, ignorance of the revolutionary features of the STR is a fundamental cause of incorrect descriptions of the theory's background.

It is highly apparent that the connection between South Korean high school and university science curriculums is significant. However, without consideration of the history of science, descriptions of the background of scientific theories are easily mistaken. Therefore, textbook authors must check in great detail all of the content in undergraduate textbooks from the standpoint of the history of science. Without such critical examination, there is a great possibility that students will obtain a skewed understanding of fundamental theories such as the STR.

To summarize, historical errors in textbooks stem from an uncritical and blind attitude held by authors of South Korean physics textbooks depending on a few undergraduate textbooks such as those of Serway et al. Furthermore, many textbook authors have an artificial or ignorant attitude toward the development of the STR. They implicitly assume all scientific theories are constructed by an inductive method on the basis of empirical results and that the eventual progress of science has been cumulative. Based on these empiricist's accounts, students in high school inevitably misunderstand important historical facts, such as, Michelson and Morley's research purpose and their final conclusion, Einstein's research questions before 1905, and even the relation between the STR and paradigms in the nineteenth century, such as the undulatory theory of light, electromagnetism and Newtonian mechanics.

3.2 Conceptual Confusion and its Perils

Why do these (as seen before) conceptual confusions occur? I think the major reason is that learning components of the STR are just *enumerated* in high school textbooks. I am sure that everyone can notice what students study in the textbooks about the STR, but that students can never be aware of the relations between the two postulates, time dilation, and the muon lifetime experiment. With the contents just listed, students, and even teachers, often have the idea that the STR is just a 'strange' theory. However, the idea that the STR is strange is understandable when we take Newtonian mechanics for granted. Fortunately, no scientists believe Newtonian mechanics is true. Thus, as students simply learn the listed ingredients of the STR, they cannot help but consider that the STR is still strange and difficult. Thus, the editing mode in which theoretical ingredients are simply enumerated brings about a decline in interest in physics.

Another side effect of this editing mode is the possibility of misunderstanding scientific practice. Due to a conceptual confusion in referring to theoretical ingredients in the STR, students cannot grasp how the STR is systemized, how novel predictions can be made by the STR and what features are uniquely valuable in Einstein's solution in contrast to other theories such as Lorentz's. I will discuss the confrontation between Einstein and Lorentz (together with FitzGerald) concerning the MME below (see Darrigol 2005, p. 25). Moreover, if theoretical consequences and empirical evidence are not plainly (categorically) made distinct from each other, then there are epistemological troubles for students accepting the STR.

Without clear designations for each learning element in the STR, a simply enumerated construction of them hinders a significant educational purpose of science education, that is, the scientific literacy and scientific thinking/reasoning. Many countries emphasize the importance of scientific thinking (or literacy) in science education. South Korea is no exception. According to the curriculum of science education in South Korea, scientific literacy is a core basis of four kinds of educational objectives that all instructors ought to consider when teaching science in the classroom.[12] With these textbooks, regretfully, it is very hard for high school students to develop not only a capacity to investigate with scientific methods but also hard to develop a curiosity and interest in nature. Furthermore, they are implicitly obliged to memorize theoretical ingredients of the STR rather than to develop a critical capacity for scientific reasoning.

Therefore, it is necessary to search for a new way, so as to avoid the historical and conceptual problems pointed out so far as well as to improve the content within textbooks. But, it is impossible to suggest a perfect recipe for teaching and learning the STR. In the next chapter, I will first review key studies of teaching-learning the STR and then seek to overcome the above problems and to find alternative guidelines relevant to South Korean circumstances.

4 How to Teach the STR: A Search for New Guidelines

4.1 Education of the STR: Review of Previous Discussions

I have examined two textbooks used in South Korea and focused on historical and philosophical aspects of the STR. It is necessary, however, to compare my analysis with previous discussions in science education because there are interesting findings concerning the genesis and epistemology of the STR. Arriassecq and Greca (2007) analyzed textbooks used in the high schools and universities of Argentina by categorizing historical, epistemological and repercussive aspects of the STR. I totally agree with claims of theirs, such as the following statement: "A proper historical contextualization on the rise of the STR should consider aspects such as a view of the state of physics in the time the theory develops and the contributions of researchers who paved the way for the STR" (Arriassecq and Greca 2007, p. 68). They showed "the incompatibility of the Mechanicist Newtonian

[12] The government establishes four kinds of main objectives that high school students should achieve. The first is to understand synthetic scientific concepts necessary for understanding the universe, life and modern civilization. The second is both to develop a capacity to investigate nature scientifically and to understand the developmental or forming processes of scientific knowledge and technologies. The third is to improve both attitudes for developing curiosity and interests in phenomena of nature and scientific learning and capabilities to solve ordinary problems. The fourth is to both understand the interaction among science, technology and society and to develop a capacity for making decisions rationally.

Programme with the physics…related to electromagnetic phenomena" (*ibid*, p. 69). This point of view on the historical backgrounds of the STR is closely related to the literature emphasizing the significance of electrodynamics for the development of the STR (Giannetto 2009; Zhang 2005). Arriassecq and Greca also successfully pointed out a distorted vision in textbooks on the role of experimentation in the genesis of the STR by saying that "the idea of Einstein was of an extreme simplicity. It consisted of considering Michelson's results step by step" (*ibid*, p. 74), which is "influenced by the scientists' empiricist view" (Arriassecq and Greca 2012, p. 832). This view corresponds to Popper's methodological position.

However, Arriassecq and Greca's descriptions of the historical context of STR are too simple. They introduce the concept of ether in the relationship of the STR with electromagnetism (*ibid*, p. 849). In contrast to their views, I illustrated the circumstances of nineteenth century physics in more detail, not by merely focusing on the incompatibility between Newtonian mechanics and electrodynamics, but also by exposing the reasons why the MME had only an 'indirect' influence on the genesis of the STR (see discussion in chapter 2). I pointed out the logical fallacies of the empiricist's view concerning the MME, too. With my discussion, I expect that people would be able to understand the MME clearly with regard to the reason why Michelson and Morley made their interferometer, their conservative response to the failure of the MME (such as continuing to believe in the existence of ether) and the irrelevance of the STR to the MME. In particular, comprehending the MME with reference to the undulatory paradigm is essential in order to know Einstein's overall point of view of light in the STR as well as in his quantum theory. Einstein offered a quantum theory (contradictory to the undulatory paradigm of light) so as to explain the photoelectric effect in 1905. Furthermore, as I mentioned, it is not a fact that the MME was not related to Einstein's (1905) paper at all. Even though the MME affected the STR indirectly, it was highly likely that a series of failures of ether-drift experiments, including the MME, caused Einstein to consider the ether as being 'superfluous' (Einstein 1905).

Arriassecq and Greca's suggestion of a teaching-learning sequence for the STR at the high school level is inclusive and systematic. However, I cannot overlook their usage of the term *epistemology*. They presented Mach and Poincare's ideas, which affected the development of the STR (Arriassecq and Greca 2007, pp. 71–72; 2012, p. 831). I totally agree with their theories. However, Arriassecq and Greca employed *epistemology* to embrace heterogeneous elements, such as reflections on the genesis of a theory, its empirical aspects and its applications, and the role of the scientific community in the development of a theory. In particular, they seem to think that epistemology is capable of covering the process of *building* the concept of space and time in the STR (Arriassecq and Greca 2012, p. 836). However, from the viewpoint of the philosophy of science, *epistemology* is a theory of knowledge (see *Epistemology* in Stanford Encyclopedia of Philosophy). In this tradition, knowledge is a justified true belief. In other words, it is better to use *epistemology* not in the context of discovery but in the context of justification.

Perhaps when Arriassecq and Greca used the term *epistemology* they were referring to either the mental processing of conceptual discovery (such as in the STR) or the study of the meaning of abstract concepts such as relativity, time and space. Strictly speaking, the former is not epistemology, and the latter is just semantics. If the term *epistemology* is abused when unifying distinct mental processes in different research fields, or if it is misused when understanding abstract concepts, then students and even teachers will have trouble grasping the nature of scientific knowledge and scientific methods. The STR as scientific knowledge is a set of (deductive) logically consistent statements. When a statement in the STR is used to explain a phenomenon, the statement then becomes an explanatory hypothesis that can be tested by empirical data collected inductively from experiments or observations. I have tried to maintain this kind of usage of 'epistemology' in my previous discussion, especially regarding the conceptual issues of the STR.

In practical contexts, it is difficult to apply Arriassecq and Greca's suggestion to the South Korean science classroom. Their suggestion may be an ideal teaching-learning sequence for the STR. However, it is not applicable in every circumstance. They would recommend spending more than six hours in teaching and learning pre-steps of the STR such as Aristotelian cosmology, the revision of Newtonian mechanics and the aspects of electromagnetism linked to the STR (*ibid*, pp. 848–849). Moreover, when students in high school learn the STR, a minimum of 10 h is required. This is impractical, since South Korean physics teachers must currently make a plan to teach the STR in only 2 or 3 h. As a matter of fact, it is impossible to make use of the plan of Arriassecq and Greca's in South Korea. Therefore, what is inevitable is to select the teaching-learning ingredients for the STR carefully in accordance with the achievement standards established by the South Korean government.

Dimitriadi and Halkia (2012) presented alternate processes for teaching-learning the STR. They suggested five teaching sessions in the following sequence: (1) the principle of relativity, (2) the invariance of the speed of light, (3) the relativity of simultaneity, (4) the relativity of time and (5) the relativity of length (*ibid*, pp. 2573–2575). These five sessions are also selected in South Korea in order to teach the STR. In addition, they distinguish two principles of the STR from other theoretical components. However, their educational content does not seem better than that in South Korean textbooks. For example, according to them, the principle of relativity is taught with a content of instruction, "It is not possible to realize whether you are moving with a uniform speed or whether you are not moving at all (not even by carrying out an experiment). These two situations are equivalent" (*ibid*, p. 2573). With the content out of the STR's historical context, unfortunately, students cannot grasp Einstein's genuine idea. Dimitriadi and Halkia's suggestion is too deviated from history to understand how and why Einstein developed the STR. Given that South Korean textbooks contain a historical episode, even if the episode concerning the MME is flawed, their suggestion is fundamentally not applicable to South Korea.

Based on my previous discussions and reviews of key suggestions in science education, I now suggest basic guidelines that physics teachers as well as textbook authors ought to pursue. First of all, it is necessary to use the history of science in teaching and learning not only as supplementary backgrounds of the STR but also as useful resources in order to understand the STR *itself*, in particular the two postulates. History of science triggers a student's interest or curiosity in science. No one can deny the fact that the history of the STR is a typical example of creative practice.

Second, it is necessary to break down the sharp dichotomy between learning the history of a theory and learning the theory itself. South Korean textbooks implicitly assume this distinction. No matter how little students know of the historical background of the STR, it seems that it does not affect their capacity to actually learn the STR itself. However, in order to learn modern physics, including the STR and quantum theory, high abstract mathematics or concepts are required in contrast to Newtonian mechanics, which are relatively intuitive. Therefore, it is better to learn them with the aid of the historical processes through which modern physics was developed rather than to focus only on theoretical products. In addition, the history of modern physics is studied at its best when many historical resources are utilized.

Third, it is necessary to emphasize the epistemological aspect in science education. The reason why the STR is being taught to students in high school may be that we are able to predict unexpected phenomena through the STR, such as nuclear reactions. In addition, students are able to learn the fact that all well-formed scientific theories in physics should be supported by observations or experiments. Therefore, they have to study the derivative processes of time dilation and length contraction from the two postulates as well as the confirmative experiments, which collected and analyzed empirical data.

I have set up three kinds of requirements for teaching and learning the STR in South Korean classes. Based on these requirements, I will outline more detailed educational ingredient courses on the STR from a history and philosophy of science viewpoint.

4.2 Teaching-Learning Ingredients of the STR

4.2.1 Historical Ingredients of the STR

As noted above, the MME did not have a direct influence on the development of the STR. Furthermore, the understanding of the wave theory of light and electrodynamics in the nineteenth century is necessary to grasp how and why Einstein developed the two postulates. Here I will not give the whole historical narrative in detail, but I will show the essential ingredients that are necessary in order to overcome the errors noted before. I will suggest three ingredients.

The first ingredient is an overall introduction of the circumstance of nineteenth century physics. The beginning is the ether theory. In the early nineteenth century, people believed that light, waves, heat, electricity and magnetism had their own ether to mediate propagation. In 1820, an interactive phenomenon between electricity and magnetism was discovered by Hans Christian Oersted, proving that electric ether is equivalent to magnetic ether. In addition, it was known that heat is a kinematic energy of molecules in the 1850s so that people gave up the term *heat ether*. In 1865, Maxwell predicted the speed of electromagnetic waves and calculated their velocity, which was closely approximate to the speed of light. A young German physicist, Heinrich Hertz, verified Maxwell's equations in 1888. In the end, luminiferous ether and electromagnetic ether were integrated. Consequently, in the late nineteenth century people only believed in matter and electromagnetic (or luminiferous) ether.

As the second ingredient, which is the most important, two kinds of thought experiments will help students comprehend Einstein's own motives for developing the STR. The thought experiments are the magneto-induction current case and the frozen electromagnetic wave in chasing the light, as noted earlier. Students may discover the processes by which Einstein had become interested in electrodynamics and why he considered the principle of relativity significant. Maxwell's equations and failures of the emission theory of light are closely related with the light postulate. But students on the high school level can hardly derive the constant velocity of electromagnetic waves from Maxwell's equations on their own. Furthermore, differential equations are beyond the course levels of most high school students, so it is better to introduce the relationship between the light postulate and electromagnetism descriptively not mathematically. Recall that Einstein's (1905) paper also did not include any experimentally supporting evidence on the light postulate!

The MME can be introduced as the third ingredient. In the late nineteenth century, many physicists were immersed in the problem that an effect of the motion of matter relative to the luminiferous ether could not be detected. Michelson was one of the physicists to solve the problem. Even though the MME did not affect the development of the two postulates in the STR and Michelson and Morley's research goal was never connected to Einstein, it was an obvious fact that Einstein knew the MME and its null result. Moreover, Einstein's final determination regarding the 'luminiferous ether' as being superfluous was closely associated not only with Lorentz's unsatisfactory explanation of the null result of the MME, but also a series of failures of measurement of the velocity of earth relative to the ether. Thus, an imaginary debate between Lorentz and Einstein on the issue of the existence of the ether is not historically groundless. Furthermore, it would actually make learning the STR more appealing for students. I would introduce Lorentz's (and FitzGerald's) explanation of the failure of the MME as follows:

> Michelson and Morley's research problem was the measurement of the relative speed of earth to luminiferous ether. The world, according to the wave theory of light, is filled with the ether in earth and the light that moves. Michelson and Morley conducted their experiments with the interferometer device on the basis of Fresnel's theory, the so-called ether-wind hypothesis, and in the end, an interference fringe shift was not detected. Once this happened, many physicists who supported the wave paradigm of the light theory confronted an unexpected anomaly. They suggested several theoretical models for explaining this null result. Among them, the most influential model was the *Lorentz-FitzGerald Contraction Hypothesis* (henceforth, the LFC hypothesis). The LFC hypothesis addressed the phenomenon of the shortening of an object along the direction of its motion relative to the ether. The LFC hypothesis was compatible with Fresnel's theory, so there was no need to abandon the notion of ether. An estimated value could be calculated from Fresnel's theory plus the LFC hypothesis. Since the LFC hypothesis was presented before 1905, there were no any stronger rival theories during this time. However, after 1905, circumstances changed. A predictive value similar to the LFC hypothesis could also be calculated using the STR. The regions of expected value from both the LFC hypothesis and the STR equally agree with the null result of the MME. Thus, the null result of the MME was inconclusive when it comes to determining which model fits the world.[13]

These three ingredients correspond to Einstein's own discourse found in the introduction of his 1905 paper (see Einstein 1905). Thus, my suggestion is historically authentic and valid.

4.2.2 Philosophical Ingredients of the STR

Philosophical ingredients of the STR consist of two parts, (1) understanding of the structure of the STR and (2) the evaluation of theories. The first part is comprised of three portions again, (1-a) knowing the meaning of the two postulates and the incompatible relationship between them, (1-b) the introduction of the relativity of simultaneity and (1-c) the theoretical deviations of consequences of the STR such as time dilation and length contraction, and so on. Speaking concretely, the two postulates generally are introduced by definition in most textbooks. This format is not too bad, but I think historical backgrounds of the two thought experiments should also be presented for students to grasp the meaning of them easily.

In particular, the two thought experiments should be adopted for introducing the relativity postulate because descriptions about this postulate in textbooks are very problematic. Kwak et al. say, "An observer moving with a constant velocity cannot perceive whether he or she is really moving. But an observer who is accelerating sufficiently is aware of his or her own motion state.…Therefore, a non-accelerating frame of reference is very special.…'The inertial frame of reference' is the frame applied by the law of inertia. And the

[13] For more detailed and philosophically interesting discussions on this issue, see the debates between Zahar (1973a, b) and Schaffner (1974) and between Lakatos (1978) and Hacking (1983).

inertial frame of reference is also the frame moving at a constant speed relative to other inertial frames of reference. The 'Principle of Relativity' means that the laws of mechanics should be the same in all inertial frames of reference" (Kwak et al. 2013a, p. 55). Unfortunately, the 'Principle of Relativity' only refers to that of 'Galilean relativity.' Einstein's contribution for us was to point out the limits of Galilean transformations in electromagnetism in contrast to these transformations' sufficiency in Newtonian mechanics. Nevertheless, their descriptions of the 'Principle of Relativity' together with Newton's second law of motion are added in the textbook, so those descriptions are unhelpful and unnecessary in understanding Einstein's relativity postulate. This drawback is also found in the textbook of Kim et al. (2013, p. 68). It is highly unfortunate that this error occurs, even though Kim, who is the representative author among Kim et al., had already put emphasis on Einstein's insight of the new concept of space and time in distinction to Galilean and Newtonian mechanics (Kim 2012, p. 6). The new concept of relativity must be explained by new and modern cases just as new wine must be put into fresh wineskins.

The light postulate is introduced in textbooks in ways that are no better than the relativity postulate. Kim et al. (2013, p. 69) simply state that the speed of light emitted in a train moving at speed v is also c not $(v + c)$. A figure illustrating this description is unhelpful for grasping why Einstein introduced the light postulate. Kwak et al. (2013a, p. 56) still state that the MME proved the light postulate. More surprisingly, they mention an experiment performed with muons at CERN as evidence of the light postulate. These descriptions are serious impediments to a proper understanding of the development of the STR and Einstein's research. Therefore, understanding the principles needs the aid of historical context.

The relativity of simultaneity is introduced in textbooks with Einstein's train thought experiment. This thought experiment has been used as a typical way to understand it and is well appreciated as an effective tool (Velentzas and Halkia 2013). However, in science education there is no research emphasizing the significance of the relativity of simultaneity in that it plays a unifying role between the two postulates. In Einstein's 1905 paper, he said that the relativity postulate 'is only apparently irreconcilable' with the light postulate (Einstein 1905). On the basis of the wave theory and the emission theory of the light, the principle of Galilean relativity is incompatible with the light postulate. So, Einstein denied the existence of the ether and accepted the constant value of the speed of light from Maxwell's equations. In order to maintain the principle of relativity, Einstein dealt with light as a 'light signal' and thought it was a great idea that the simultaneity of two events at different locations depends on the observer's state of motion. He said, "we have not defined a common 'time' for A and B [located at different points], for the latter cannot be defined at all unless we establish by definition that the 'time' required by light to travel from A to B equals the 'time' it requires to travel from B to A" (*ibid*). In other words, owing to the relativity of simultaneity the two postulates eventually became compatible with each other by giving up 'absolute simultaneity' and 'absolute time' (see Stachel 2002; Norton 2014; Janssen 2014). In spite of a critical role for the relativity of simultaneity to develop the STR, many researchers have regarded it just as a theoretical consequence from the two postulates (Angotti et al. 1978; Arriassecq and Greca 2012; Dimitriadi and Halkia 2012). Thus, when the STR is taught in the classroom, this misunderstanding of the relativity of simultaneity should be modified.

Theoretical derivations from the two postulates can be taught sufficiently well with the train (or spacecraft) thought experiment as well. But both Kim et al. (2013) and Kwak et al. (2013a) only present formulas of time dilation and length contraction, but do not explain how the formulas can be derived. I claim that students in high school should be provided with an opportunity to calculate them from the two postulates. The derivation is not difficult because only a simple mathematical device, the Pythagorean theorem, is needed. Thus, it is better for students to experience the derivation rather than just to implant it without proper understanding.

The second part is comprised of two portions, (2-a) two theoretical consequences or predictions from the STR, time dilation and length contraction are supported by the muon lifetime experiment and by contrast with (2-b) the LFC hypothesis on the basis of Lorentz's 'molecular forces hypothesis' (MF hypothesis, for short), which has not been supported by experiment. This part is epistemological. By studying this aspect, it is expected that students can distinguish abstract characteristics of the STR from empirical facts of phenomena and data. Furthermore, they should know that, in the context of the justification of a theory, what would be tested by comparing with data is called a 'theoretical hypothesis' and that the models of data play an evidential role in supporting the existence of phenomena, which are represented by the theory. In the case of the STR, a theoretical consequence such as time dilation plays a predictive role, and it is right to call it a 'theoretical hypothesis.' When time dilation's hypothesis was confirmed in the 1970s, the data from the muon lifetime experiment were 'evidence' for the STR. Also, that the physical event of a muon reaching the surface of earth from a muon creation event (caused by a cosmic ray interacting with an air molecule high in the atmosphere) can be called a 'phenomenon' of the STR.

Contrary to the STR, there was no expected value of the LFC hypothesis to correspond with the muon lifetime experiment. At that time, Lorentz proposed the MF hypothesis, which predicts no novel or additional, empirically testable phenomena. The LFC hypothesis was suggested for the purpose of saving the null result of the MME. Hence, the results of the muon lifetime experiment determined that the STR was in fact confirmed, and the circumstance of theory under-determination was resolved in the end.

What is significant is that students should notice with this program that theory-evaluation is not the test of a *single* hypothesis with data but that of *competitive* hypotheses with data. The MME did not determine whether or not the LFC hypothesis based on Fresnel's wave theory or the STR was true. However, the muon lifetime experiment determined that the STR is better confirmed than the LFC hypothesis. According to Kuhn, "In the sciences the testing situation never consists, as puzzling-solving does (within a paradigm), simply in the comparison of a single paradigm with nature. Testing occurs as a part of the competition between two rival paradigms for the allegiance of the scientific community" (Kuhn 1972 [1996], p. 145). Kuhn's insight regarding the context of theory evaluation ought not to be lost. It is an essential element that high school students require in order fully to comprehend the STR.

Table 3 is a summary that I have not discussed until now. I divide two historical flows. One is from the wave theory of light to Einstein's STR. The other is from electromagnetism to the STR. In the first flow, a main topic is whether the ether exists in the world. Fresnel and Stokes' hypotheses, the MME and the LFC hypothesis appear in this flow. In the second flow, the origins of the two postulates of the STR are highlighted. In this flow Oersted, Faraday and Maxwell are selected as key physicists in electromagnetism, and Einstein's two thought experiments are considered as the 'direct' origins of the STR. Einstein's (1905) paper was mainly divided in two parts: kinematic and electromagnetic

Table 3 Main flows of teaching and learning ingredients for the STR

Topics	Historical Flow (1)	Historical Flow (2)
Backgrounds Of Special Theory Of Relativity	**Wave Theory of Light** -Fresnel's Ether-wind Hypothesis -Stokes' Ether-along Hypothesis -Fizeau's Experiment for Measurement of the Speed of Light -Luminiferous Ether	**Electromagnetism** -Oersted's Discovery -Faraday's Law -Maxwell's Equations -Electromagnetic Ether
	Hertz's Verification of Maxwell's Equations -Integration of Light and Electromagnetic Wave -Integration of Luminiferous Ether and Electromagnetic Ether	
	A Puzzle in the Wave Paradigm -Measurement of the Relative Velocity of Earth to Ether -Michelson and Morley Experiment -Lorentz-FitzGerald Contraction (LFC) Hypothesis	**A Puzzle in Electromagnetism** -Asymmetry of Conductor and Magnet -Einstein's two Thought Experiments
Einstein's Special Theory Of Relativity	**Einstein's Introduction in the STR (1)** -"Ether is Superfluous" **Theory Underdetermination** -The LFC Hypothesis VS. Einstein's STR	**Einstein's Introduction in the STR (2)** -Two Postulates - Relativity Principle - Light Principle
	Einstein's Derivation of the Postulates (1) (1) Kinematic Part -Definition of Synchronicity -Relativity of Simultaneity -Lorentz's Law of Transformation -Time Dilation -Length Contraction -Relativistic Law for Velocity Addition -Inter-Convertibility of Rest Mass and Energy	**Einstein's Derivation of the Postulates (2)** (1) Electromagnetic Part (***Optional***) -Covariance of Maxwell's Equations -Doppler Effect -Derivation of Stellar Aberration
Epistemology	**Confirmation of the STR** -Evidence : Muon lifetime Experiment -Resolution of Theory Under-determination	
Discussion	**Final Discussion : Conceptual Comparison of Space & Time and Mass & Energy between Newton and Einstein** -Space and Time -Mass and Energy	

(see Einstein 1905). The kinematic derivation from the two postulates is essential in teaching-learning the STR, but the electromagnetic part is optional because of its mathematical difficulty. Next, the case of the muon lifetime experiment provides an example confirming the STR and resolving the theory under-determination between the LFC hypothesis and the STR. Finally, students discuss conceptual differences between Newtonian mechanics and the STR by focusing on the notions of space, time and mass (and energy).

4.3 Methodological Strategy: Argumentation

Previously, I discussed the historical and philosophical ingredients of the STR. I emphasized the necessity of conceptual distinctions among principle, hypothesis, phenomena, consequence and evidence in order to understand the structural characteristics of the STR and its epistemological aspect. I also showed that the MME was related to Einstein's denial of the concept of ether even though it did not directly affect the development of the two postulates within the STR. Thus, I regarded the MME as a useful episode in order to study the STR. In this section, I discuss a methodological strategy that is employed for the purpose of organizing and integrating the learning ingredients of the STR.

I focus on *argumentation* in science education because this is closely related to the educational goals of the achievement standards of the STR as noted above. Furthermore, this method is very useful when students solve epistemological questions such as how the STR could be accepted in scientific communities (see Jimenez-Aleixandre and Erduran 2007). Bottcher and Meisert define argumentation as "the process of the critical evaluation of models in the sense of verifying the appropriateness of one or multiple rival models according to their logical coherence and the available, empirical data" (Bottcher and Meisert 2011, p. 111). The term *models* refers to scientific theories, including the STR. Appropriateness is determined by two criteria: (1) in relation to logical coherence between models and (2) in relation to model predictions and empirical data (*ibid* 119). The first criterion is connected to the consistency of models within scientific theory. Students can also determine the appropriateness of the STR by deriving theoretical consequences from the two postulates. The second criterion is linked to the epistemological aspect of the theory. Appropriateness of the STR can be evaluated when it is compared with either empirical data or another rival theory. In case of the STR, the LFC hypothesis is a rival theory. Both of them can be employed to save the null result of the MME. The muon lifetime experiment also played a critical role in determining that the STR was acceptable, but that the LFC was not. Table 4 is a summarized collection of argumentative activities in reference to Table 3 (Bottcher and Meisert 2011, pp. 119–124).

Bottcher and Meisert's idea of argumentation strongly depends on Ronald Giere's view of scientific reasoning and theories (Bottcher and Meisert 2011, pp. 107–111). Giere suggested a six-step program for understanding scientific reasoning (Giere et al. 2006, pp. 34–35). His program is suitable for my guidelines because it satisfies all of the requirements as noted above. The program consists of six components for the purpose of determining whether a hypothesis can be supported by evidence or not. The components are (1) *real world*, the phenomenon, e.g., the object or process under investigation, (2) *model*, the theoretical family to represent the real world, (3) *prediction*, derived from the model and experimental setups describing what the data should be such as whether the model does fit the real world, (4) *data*, generated through interactions with the real world, (5) *negative evidence judgment* and (6) *positive evidence judgment*. Several brief inferential procedures within this program are outlined below:

Step 1. *The real world (phenomena)*: Identify the aspect of the real world that is the focus of study in the episode at hand. These are things or processes in the world that can be described mostly in everyday terms together with a few widely used scientific terms.

Step 2. *Scientific theory (model)*: Identify a theoretical model whose description of the real world is an issue (to be decided). Describe the model, using appropriate scientific terminology as needed.

Step 3. *Predictive consequence (predictive value)*: Identify a prediction, based on the model and experimental setup identified, that says what data should be obtained if the model actually provides a good description of the real world.

Table 4 Process, model and data levels of argumentation between the LFC hypothesis and the STR

Scientific theory			Real world		
Model level		Process level	Data Level		Process level
Prediction	Model		Phenomena	Data	
Fringe shift	Fresnel's wave theory	(1-a) (1-b)	The motion of earth relative to ether	No fringe shift	(1-c)
No fringe shift	Lorentz-FitzGerald contraction hypothesis in Fresnel's theory	(1-a) (1-b)	The motion of earth relative to ether	No fringe shift	(1-c)
No fringe shift	Special theory of relativity	(2-a) (2-b)	The motion of earth relative to ether	No fringe shift	(2-c)
Time dilation	Special theory of relativity	(2-a) (2-b)	Lifetimes of muon	Time dilation	(2-c)

Index of process level for models

(1-a) In relation to logical coherence
(1-b) for or against the appropriateness of a model
(1-c) in relation to model predictions and empirical data

Index of process level for models against rival models

(2-a) In relation to logical coherence
(2-b) for or against the appropriateness of an advocated or a rival model
(2-c) in relation to model predictions and empirical data

Step 4. *Data (observational value)*: Identify the data that have actually been obtained by observation or experimentation involving the real-world objects being studied.
Step 5. *Negative evidence judgment*: Do the data agree with the prediction? If not, conclude that the data provide good evidence that the model does not fit the real world. If the data do agree with the prediction, go to step 6.
Step 6. *Positive evidence judgment*: Was the prediction likely to agree with the data even if the model under consideration does not provide a good description of the real world? This requires considering whether there are other clearly different, but also plausible, models that would yield the same prediction about the data. If there are no such alternative models, the answer to the question is "no." In this case, conclude that the data do provide good evidence that the model does describe the real world. If the answer to the above question is "yes," conclude that the data are inconclusive regarding the fit of the model to the real world.

Briefly, let me apply this program to learning the STR with Fig. 1. In the first step, a teacher introduces differences between the STR and Newtonian mechanics. Classical mechanics can just be applied to motions that we experience in ordinary life, but relativistic mechanics can be applied to objects moving quite rapidly, such as light. When we want to understand motions of elementary particles, such as muon, or various kinds of electromagnetic radiation, such as γ-rays and cosmic rays, we can employ the STR rather than Newtonian mechanics. The lifetime of the muon phenomenon is a typical example. In this step, students determine objects and regions of the world that are explained by the STR.

From the second step to the third, students learn the structure of the STR. Scientific theory is a set of heterogeneous models, including physical, scale, analog and mathematical models, and so forth (Giere 2006). Models refer to non-linguistic entities that are similar to the world. Models play a role in representing the world in some respects and

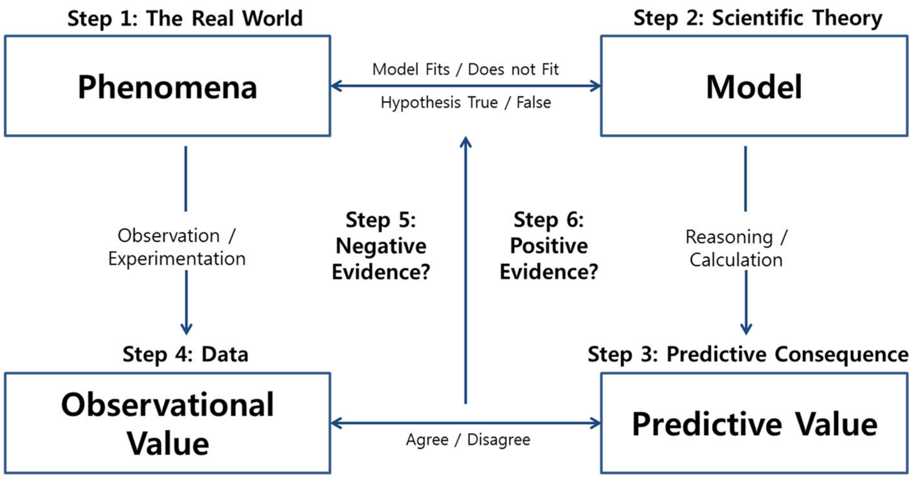

Fig. 1 Diagrammatic form of the reasoning program for evaluating a theoretical hypothesis

to a high degree of approximation. The STR, as we see above, consists of two principles and several representational models derived from principled models (see Giere 2010). In the second step, students understand the difference between the two postulates or principles and the derived consequences. Students also practice how to deduce time dilation from the two postulates, for instance. Next, in the third step, among several theoretical consequences students select a test hypothesis, which is connected with the targeted phenomena. Students predict a particular value that is expected to correspond with the hypothesis.

In the fourth step, teachers introduce representative examples that support the STR and notice difficulties with experiments or measurements that cannot be performed in the classroom. Instead, teachers present either historical episodes or well-guided simulations on web sites. Students indirectly experience inductive procedures with them. Teachers should point out to students the fact that a simulation has to be closely related to the targeted phenomenon.

From the fifth step to the sixth, students evaluate the test hypothesis by comparing a predicted value with an empirical data. If the predicted value coincides with the data, then the empirical data provide evidence that the STR successfully describes the phenomenon, and there is good evidence to accept the STR. If there is a discrepancy between the two values, then students can judge that the data do not provide good evidence to support the STR. Students cannot leap to conclusions that the STR was falsified or false because a discrepancy occurred. A discrepancy between a pair of predicted and measured values can be caused by immature operations of devices, errors of auxiliary hypotheses, and so on. Finally, in the event that empirical data agree with prediction, students have to consider whether alternative hypotheses exist or not. If there are no alternatives, students can conclude that the STR is true. However, if there is an alternative, then students cannot determine whether the test hypothesis is confirmed on the basis of the data.

How do students learn the two historical flows of the STR by using this program? I consider the MME to be an educationally useful case for the purpose of studying the circumstances of late nineteenth century physics before Einstein invented the STR, even if the MME did not motivate Einstein. An appendix shows diagrams of teaching sequences for the STR with the outlined two episodes given briefly above. These diagrams may be useful as student worksheets.

5 Conclusion

Throughout this discussion, we have examined various errors in South Korean high school textbooks regarding the interpretation of historical and philosophical aspects of the STR. I have highlighted these errors by focusing on some examples as they badly portray the STR, and I have even explored reasons why these problems have occurred. I pointed out the main problems in textbooks, regarding the STR, originated from a blind dependence on Raymond Serway's undergraduate textbooks, which ignore the revolutionary aspects of the STR. Furthermore, the components of the STR that should be learned are just *enumerated* in textbooks, and this hinders students from fostering their critical capacities to evaluate scientific theories. So, I have outlined an alternative way by emphasizing that the history of science is very useful for grasping the origins as well as the meanings of the two postulates of the STR. I have discussed the conceptual and historical issues in the main body of this study, and I have extended my exploration to briefly show students' actual applications. It is quite certain that this study is essential and that it is valuable to fully connect teaching science with the history and philosophy of science. I think that, even though I have discussed the STR by focusing on analyzing the two South Korean textbooks of physics, my discussion is informative and useful for researchers in science education in other countries.

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Appendix: Diagrams of the Teaching-Learning of the STR

See Figs. 2, 3, 4 and 5.

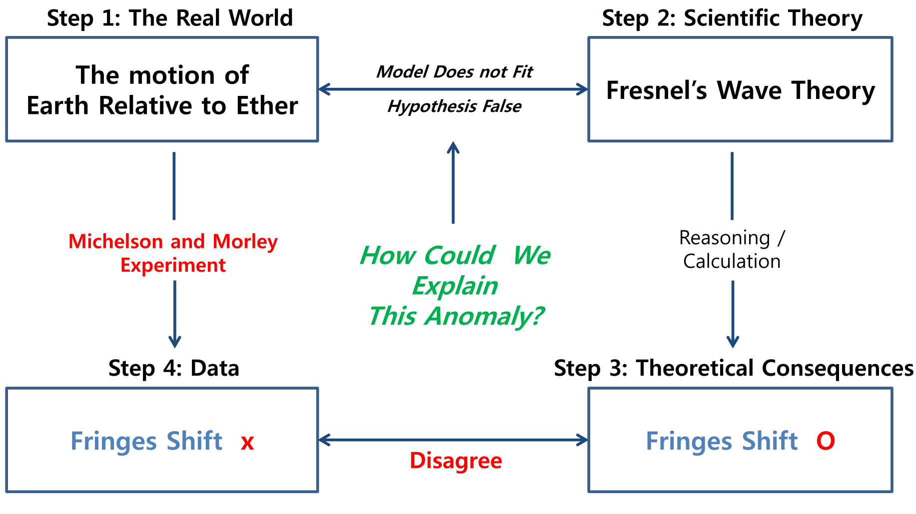

Fig. 2 The MME and Fresnel's theory

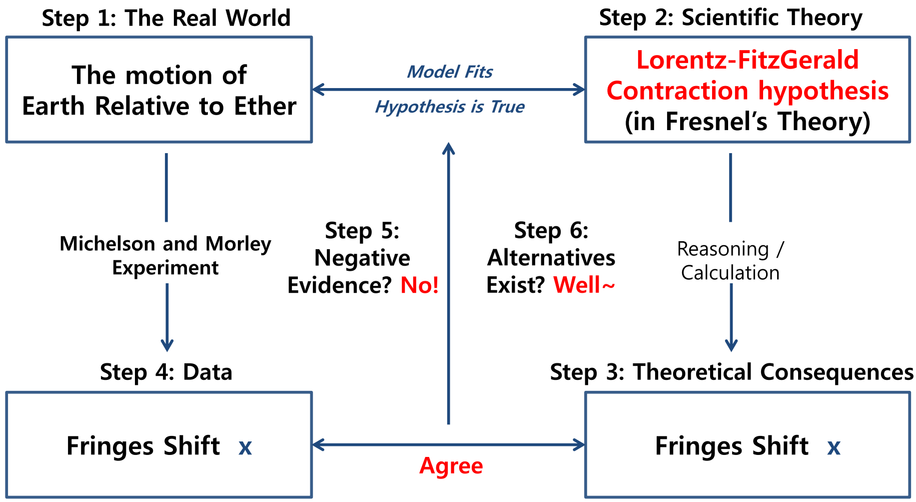

Fig. 3 Saving the negative result of the MME by Lorentz and FitzGerald

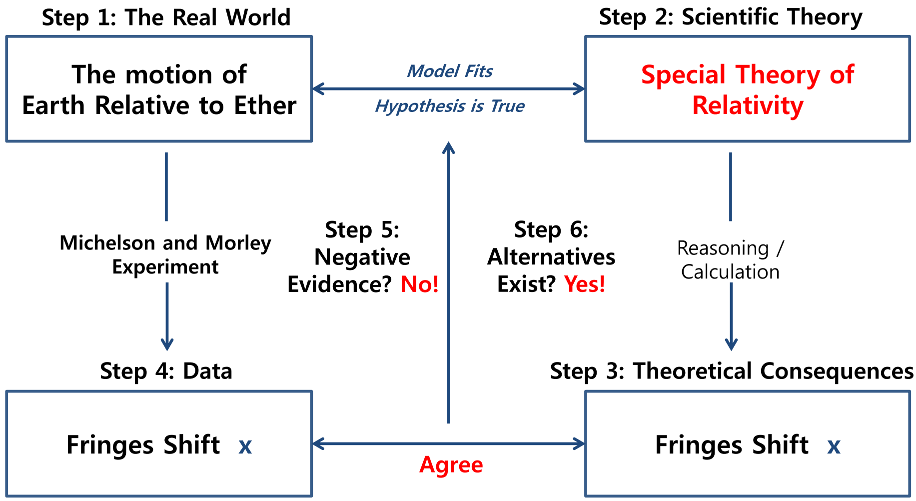

Fig. 4 Under-determination between the LFC hypothesis and the STR

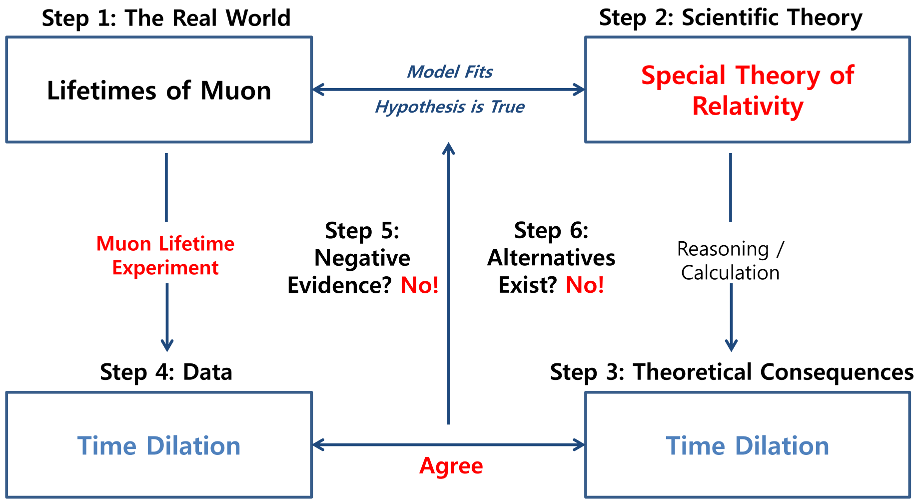

Fig. 5 Confirmation of the STR by the muon lifetime experiment

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