On the scientific method learned from Albert Einstein in 2005—the World Year of Physics

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We review the physics at the end of the nineteenth century and summarize the process of the establishment of Special Relativity by Albert Einstein in brief. Following in the giant’s footsteps, we outline the scientific method which helps to do research. We give some examples in illustration of this method. We discuss the origin of quantum physics and string theory in its early years of development. Discoveries of the neutrino and the correct model of solar system are also presented.

I. HISTORICAL REVIEW AND A METHOD DEDUCED

The year 2005 was declared the World Year of Physics which is an international celebration of physics. It marks the hundredth anniversary of the pioneering contributions of Albert Einstein, the greatest man in the twentieth century as chosen by Time magazine.

In 1905, one hundred year ago, a Swiss patent employee, Albert Einstein, published a paper entitled “On the Electrodynamics of Moving Bodies” which described what is now known as Special Relativity. It drastically changed human fundamental concepts of motion, space and time. The year 1905 was the miraculous year for Einstein. In the same year he also published three other trailblazing papers. One accounted for the photoelectric phenomena and made up a part of the foundation of quantum mechanics. He won the Nobel Prize in physics due to the ideas of this paper in 1921. The second one was about the explanation of Brownian motion and helped to establish the reality of the molecular nature of matter and to present convincing evidence for the physical existence of the atom. The third one gave the most famous and beautiful equation in special relativity, 

\[ E = mc^2 \]

which has received various experimental verifications and has had wide application in modern physics. These groundbreaking papers have shattered many cherished scientific beliefs and greatly promoted the development of modern physics. They won for Einstein the greatest physicist as Newton in all human history. Next, we will follow the process of the establishment of Special Relativity and summarize some useful skills in research.

One of the most famous puzzles at the end of the nineteenth century was the ether which was proposed as a medium to support the electromagnetic wave propagation. Maxwell’s fundamental equations about the electromagnetic field were published in 1862. It leads to the electromagnetic wave equation in free space,

\[ \nabla^2 \phi - \frac{1}{c^2} \frac{\partial^2 \phi}{\partial t^2} = 0 \]  

where \( \phi \) is any component of \( \vec{E} \) or \( \vec{B} \). Classical mechanics tells us that wave propagation needs a medium to support it. For example, sound waves have to travel in the air medium. For the propagation of electromagnetic wave, physicists presumed an ether medium which was entirely frictionless, pervaded all space, and was devoid of any interaction with matter. Although many ingenious physics papers during 1885-1905 were dedicated to verifying it, the ether refused to reveal its presence to the pursuers.

In 1881, a 28-year-old American physicist, Albert Michelson, realised the possibility of an experimental test for the existence of ether by measuring the motion of the earth through it. He performed the experiment in Potsdam, Germany. Although he got negative results in detecting the relative motion of the earth and ether, his measurement is not so accurate as to give an important result. Six years later, Albert Michelson and Edward Morley in Cleveland, Ohio carried out a high-precision experiment to demonstrate the existence of ether with an interferometer, which is now called the Michelson interferometer. This experiment is a high-precision repetition of Michelson’s experiment in Potsdam. In their experiment shown in FIG. 1, a beam of light from the source was directed at an angle of 45 degree at a half-silvered mirror and was split into two beams 1 and 2 at point O by the mirror too. These beams 1 and 2 traveled at a right angle to each other. The two beams were reflected by separate mirrors, then recombined and entered a telescope to form a fringe pattern. The fringe pattern would shift if there was an effect due to the relative motion of the earth and ether. This experiment was a high-precision repetition of Michelson’s experiment in Potsdam. In their experiment shown in FIG. 1, a beam of light from the source was directed at an angle of 45 degree at a half-silvered mirror and was split into two beams 1 and 2 at point O by the mirror too. These beams 1 and 2 traveled at a right angle to each other. The two beams were reflected by separate mirrors, then recombined and entered a telescope to form a fringe pattern. The fringe pattern would shift if there was an effect due to the relative motion of the earth and ether. This experiment was a high-precision repetition of Michelson’s experiment in Potsdam.

Therefore, by monitoring the changes in the fringe pattern, they could tell the relative motion of the earth and ether. Even with the high-precision apparatus, they did not find any experimental evidence for the existence of relative motion of the earth or ether. These results indicated that either there is no ether or the earth is in the ether rest frame all the time during the experiment. Since the earth is always altering its velocity when moving around the sun, the experimental result appeared to show that there was no existence of ether. All the repetitions of their experiment in the succeeding years were still unable to detect any relative motion of the earth and the ether.

But ether died hard. Many physicists including Michelson himself made great efforts to retain the ether...
yet explain the Michelson experiment. He attributed the negative results to the earth dragging some of the ether along with its motion. As a consequence the ether was motionless with respect to the earth near its surface.

George FitzGerald put forward another possible explanation in 1892 following the Lorentz-FitzGerald contraction equation, as we now know,

$$L = L_0 \sqrt{1 - \frac{v^2}{c^2}} \quad (1.2)$$

where $L_0$ is called the proper length of an object which is measured in the rest frame of the object. To a moving observer of velocity $v$, any length along the direction of motion undergoes a length contraction by a factor of $\sqrt{1 - \frac{v^2}{c^2}}$. He proposed that the experimental apparatus would shorten in the direction parallel to the motion through the ether. This shrinkage would compensate the light paths and prevent a displacement of the fringes due to the relative motion of the earth and the ether.

Hendrik Lorentz discovered the well-known Lorentz transformation in 1904 under which the electromagnetic theory expressed by the celebrated Maxwell equations were in form invariant in all inertial frames.

where we assume coordinate system $\Sigma$ moves relative to another one $\Sigma'$ in the $x$-axes with uniform velocity $v$ and $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$. Although he laid the foundation for the theory of relativity with his mathematical equations, Lorentz still tried to fit these remarkable equations into the ether hypothesis and save the ether from the contradiction of the Michelson experiment.

All these efforts failed to explain the Michelson experiment while retaining the ether. It was genius Albert Einstein who abandoned the ether entirely. He wrote in his celebrated paper on relativity in 1905:

"The introduction of a ‘light ether’ will prove to be superfluous, inasmuch as in accordance with the concept to be developed here, no ‘space at absolute rest’ endowed with special properties will be introduced, nor will a velocity vector be assigned to a point of empty space at which electromagnetic processes are taking place."

Furthermore he developed the Special Relativity by conjecturing two postulations:

1. The laws of nature are the same in all coordinate systems moving with uniform motion relative to one another.
2. The speed of light is independent of the motion of its source.

Of which, the first one is a natural generalization for all kinds of physical experience since it is reasonable to expect that the laws of nature are the same with respect to different inertial frames of reference. Whereas the second one just represents a simple experimental fact. In Michelson’s experiment, the speed of light was found to be constant with respect to the earth. Put in other words, the speed of light is the same for observers in different inertial frames of reference since an observer on the earth at two different times may be regarded as an observer in two different inertial frames of reference. It is only a small jump to the postulate of Einstein’s Special Relativity that the speed of light is independent of the motion of its source.

From the above condensed outline of the establishment of special relativity, we learn that when proposing an idea or theory with which we may account for some unexplained phenomena, they should be based upon the given facts of experiment or phenomena. Sometimes, the ideas may contradict well-known theories which are not experimentally proved, such as the ether. If the problem is subtle and complicated, especially in physics, we should make incisive analyses, see through the general appearance and grasp the underlying nature. The above method is of practical use in research which could be seen from the following four examples.

II. FOUR EXAMPLES

A good example in illustration of the method is the origin of quantum physics which now plays an important role in various scientific areas. At the end of the nine-
teenth century, classical physics achieved great success. But some experimental results were incompatible with
the classical physics such as the specific heat of a solid, the photoelectric effect and the thermal radiation of a
black body. Kirchhoff initiated his theoretical research on thermal radiation in the 1850s. By the end of the
nineteenth century two important empirical formulae on black-body radiation had been derived based upon the
fundamental thermodynamics. Wien proposed a formula for the energy density inside a black body in 1896,
\[ \rho(\nu, T) = c_1 \nu^2 e^{\frac{h\nu}{cT}} \]
where \( T \) is the temperature of the wall of a black body, \( \nu \) is the radiation frequency and \( c_1, c_2 \) are two constants. Rayleigh and Jeans derived a result from a different ap-
proach in 1990,
\[ \rho(\nu, T) = \frac{8\pi\nu^2}{c^3} kT \]
where \( k \) is the Boltzmann’s constant. The Rayleigh-Jeans formula was in agreement with the experimental curve
at low frequencies whereas the Wien formula fitted the experimental curve well at high frequencies. It was a
great discrepancy at the turn of twentieth century that they failed to completely explain black-body radiation.
Seemingly there was no way out since these formulae were based upon the fundamentals of classical physics.

Things changed on Dec. 14, 1900 when at a German Physical Society meeting Max Planck presented his pa-
er entitled “On the theory of energy distribution law of normal spectrum” which not only solved the puzzel of
black-body radiation but uncovered the quantum world. It marks the birth of quantum physics. He assumed that
this energy could take on only a certain discrete set of values such as 0, \( h\nu, 2h\nu, 3h\nu, \ldots \), where \( h \) is now known as
Planck’s constant. These values are equally spaced rather than being continuous. This assumption apparently con-
tradicted the equipartition law and common sense. He argued that the wall of a black body emitted radiation in the
form of quanta with energy of integer multiple of \( h\nu \). Based on this bold assumption, Planck gave a formula of the
energy density at frequency \( \nu \),
\[ \rho(\nu, T) = \frac{8\pi\nu^2}{c^3} \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1} \]
which were in complete agreement with experimental results on general grounds. His formula was an inge-
nious interpolation between the Wien formula and the Rayleigh-Jeans formula. We now know that it gives the
correct explanation of the black body radiation spectrum. This proposal established his status in science. As Ein-
stein said:

“Very few will remain in the shrine of science, if we eliminate those moved by ambition, calculation, of what-
ever personal motivations; one of them will be Max Planck.”

Another example concerns the situation of string theory in its early stage. We know that quantum field theory
worked well in the unification of quantum mechanics and electromagnetism in the 1940s. That it could also de-
scribe the weak and strong interactions was understood by the end of 1960s. It has played a significant role in
our understanding of particle physics in many ways, from the formulation of the four-fermion interaction theory to
the unification of electromagnetic and weak interactions. But when we attempted to incorporate it with
gravity at high energy scale, severe problems appeared. For example, when \( E > M_p \), the interaction of gravita-
tion can not be negligible, where
\[ M_p = \left( \frac{h \epsilon}{G} \right)^{1/2} c^2 \approx 1.2 \times 10^{19} \text{GeV} \]
is Planck energy. The short-distance divergence problem of quantum gravity arouse. It was non-renormalizable
even though we have employed the usual renormalization extracting the meaningful physical terms from the
divergences.

String theory solved this severe problem. According to the postulates in string theory, all elementary partic-
les, as well as the graviton were regarded as one dimen-
sional strings rather than point-like particles which were
generally accepted at the time. But the generally ac-
cepted point-like particle concept was not experimentally
proved. Each string has a lot of different harmonics and
the different elementary particles were regarded as differ-
ent harmonics in string theory. Therefore the world-line of a particle in quantum field theory shown in FIG. 2 was
replaced by its analog in string theory, the world-sheet of a string which could join the world-sheet of another
string smoothly. As a consequence, the vertex of an in-
teraction in a Feynman diagram was smeared out. In
string theory the massless spin two particle in the string
spectrum was just right identified as the graviton which
mediates gravitation. At low energy scale the interac-
tion of massless spin two particle is the same as that
required by general relativity. From this simple string
postulate, string theory leads to a number of fruitful re-
sults. It is the only currently known consistent theory
of quantum gravity which does not have the above di-
vergence problem. One of the vibrational forms of the
string possesses just the right property—spin two—to be
a graviton whose couplings at long distance are those of
general relativity. It admits chiral gauge couplings which
have been the great difficulty for other unifying mod-
els. In addition, string theory predicts supersymmetry and
generates Yang-mills gauge fields and it has found
many applications to mathematics in the area of topology
and geometry. Also in string theory there are no dimen-
sionless adjustable parameters which generally appear in
quantum field theory, such as the fine-structure constant
\( \frac{e^2}{4\pi\alpha\hbar c} \). Nowadays, string theory (Detailed descriptions
may be found in Refs. [12]) has already become one of
the most active areas of research in physics. Thanks to
the postulate of one dimensional string. It sheds light
The third example is upon the process of the discovery of the neutrino. (In this paper, all neutrino mean ν only.) In 1896, radioactivity was discovered by Henri Becquerel which marked the birth of modern nuclear physics. Subsequently three types of radioactive rays were identified. They were called alpha ray, beta ray and gamma ray separately. Becquerel established that the beta rays were high-speed electrons in 1900. Employing electric and magnetic fields, he deflected beta rays and found that they were negatively charged and that the ratio of charge to mass of the beta particle was the same as that of an electron. After more accurate measurements on beta decays physicists found a serious problem. Unlike alpha decay and gamma decay in which the emitted particles carried away the well-defined energy which is equal to the total energy difference of the initial and final states, beta decay emitted electrons with a continuous energy spectrum. It meant that a particular nucleus emitted an electron bearing unpredictable energy in a particular transition. This experimental result apparently violated the conservation laws of energy and momentum. Wolfgang Pauli proposed an entirely new particle-neutrino in order to solve this serious problem. In his open letter to the group of radioactives at the meeting of the regional society in Tubingen on December 4, 1930, he proposed the neutrino based on the given fact of experiment:

"...This is the possibility that there might exist in the nuclei electrically neutral particles, which I shall call neutrons, which have spin 1/2, obey the exclusion principle and moreover differ from light quanta in not travelling with the velocity of light."

"... I admit that my remedy may perhaps appear unlikely from the start, since one probably would long ago have seen the neutrons if they existed. But 'nothing venture, nothing win', and the gravity of the situation with regard to the continuous beta spectrum is illuminated by a pronouncement of my respected predecessor in office, Herr Debye, who recently said to me in Brussels 'Oh, it's best not to think about it at all-like the new taxes'. One ought to discuss seriously every avenue of rescue."

In his letter, Pauli called his new proposed particle-the "neutron" which is now called neutrino due to Enrico Fermi. Pauli proposed that this new speculative neutral particle might resolve the nonconservation of energy. If the proposed neutrino and the electron were emitted simultaneously, the continuous spectrum of energy might be explained by the sharing of energy and momentum of emitted particles in beta decay. It is worth mentioning that long before the neutrino was experimentally detected, Enrico Fermi incorporated Pauli's proposal in his brilliant model for beta decay in the framework of quantum electrodynamics in 1934. He showed clearly with his beta decay theory that the neutron decayed into a proton, an electron and a neutrino simultaneously. The neutrino was experimentally detected by Fred Reines and Clyde Cowan, at the Los Alamos lab in 1956 using a liquid scintillation device. This important discovery won the 1956 Nobel prize in physics. A lot of famous phenomena and problems solved and unsolved, related with the neutrino were found. Parity violation takes place whenever there is the neutrino taking part in a weak interaction. This is just as the behavior of monopole under parity. They may be the same particle we think drawing inspiration from Einstein. So it causes the above violation. Time reversal violation of this kind of weak interaction also is due to sign change of charges. When detecting neutrino emitted from the sun, fewer solar neutrino capture rate than the predicted capture rate in chlorine from detailed models of the solar interior was found in 1968. This is the solar neutrino puzzel. We explain the flavor change easily by the new nature of neutrino in solar neutrino puzzel. In short, the change is by pair creation and annihilation. Later the same phenomena were also observed by other groups using different materials. As the most fascinating particle, the neutrino is so important that neutrino physics has become one of the most significant branches of modern physics. Thanks to the conjecture of the neutrino by Pauli. Although his proposal contradicted the well-accepted knowledge at the time on beta decay process, his new beta decay process involving the neutrino was not completely impossible experimentally. With this proposal we could overcome the serious problem and rescue the fundamental conservation laws of energy and momentum. The little neutrino has found its application to a number of different research areas in physics, such as in particle physics, nuclear physics, cosmology and astrophysics.

![FIG. 2: A point particle’s world-line (left) in spacetime and its analog in string theory, world-sheet, traced out by a closed string (right) in spacetime.](image-url)
centered model of the universe. He proved that the earth was round and the gravity everywhere pointed to the center of the earth. Every planet moved along an epicycle whose center revolved around the earth just as the sun and the moon revolving around the earth. The epicycle was carried along on a larger circle like a frisbee spinning on the rim of a rotating wheel shown in FIG. 3. He postulated the epicycle to explain the looping motion of a planet. The people on the earth would not see the observed irregular motion of a planet if the planet moved around the earth in a circular orbit, rather than in an epicycle. The Ptolemaic model of the universe was the obvious and direct inference when people observed the motion of the sun day after day and the motions of the moon and the planets night after night. Therefore Ptolemy’s theory was well-accepted and prevailed for a long time.

He could not prove his radical helio-centric model at the time. Although he simplified the cumbersome Ptolemaic system, both the earth-centered model and the helio-centric model could account for the observations of motion of the celestial bodies. Copernicus’s theory gives an alternative theory of Ptolemy. Even though the problem was subtle and complicated, we should grasped the hidden nature behind the phenomena. As Copernicus pointed out that the extremely massive sun must rule over the much smaller planet and the earth. He therefore drew his conclusion that it was the earth that moved around rather than the sun. It was Isaac Newton who provided the correct explanation of Kepler’s laws and convinced people that the earth and other planets revolved around the massive sun due to the attractive force with his ingenious universal law of gravitation\[17\].

$$F = G \frac{Mm}{r^2} \quad (2.5)$$

where $F$ is the universal gravitation force between the two bodies with mass $M$ and $m$ respectively, $G$ is called the gravitational constant, and $r$ is the distance between the centers of mass of the two bodies. Galileo Galilei first observed the four satellites orbited around Jupiter which exhibited undoubtedly that the earth were not the center of all circular motions of the celestial bodies utilizing his telescopes. He stated the four small bodies moved around the larger planet-Jupiter like Venus and Mercury around the sun. Also he observed the phases of Venus which was the direct result of the planet moving around the sun.

III. SUMMARY AND CONCLUSION

We have reviewed the process of the establishment of Special Relativity against the background of physics around the turn of the twentieth century in our paper. Moreover we have outlined the scientific method which helps to do research. Some examples are presented in order to illustrate the usefulness of the method. We have discussed the origin of quantum physics and string theory in its early years of development. Discoveries of the neutrino and the correct model of solar system have also been demonstrated. We have shown that the method is of practical use in a wide range, from physics to astronomy, from ancient science to modern ones. This year is the unprecedented World Year of Physics which acknowledges the contribution of physics to the world. It marks the hundredth anniversary of the pioneering contributions of Albert Einstein in 1905 as well as the fiftieth anniversary of his death in 1955. We dedicate this paper to Albert Einstein.
FIG. 4: An illustration of the Copernican model in which the planets, including the earth, all orbited around the sun. His heliocentric concept contradicted Ptolemy’s model, the well-accepted model treated with respect at the time.

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