A short introduction to the history of physics, and string theory as a "Theory of Everything"

String theory (also known as 'superstring theory') is a theory that models everything in our universe with one-dimensional objects known as 'strings.' Interestingly, according to string theory, our universe is 11 dimensional, as opposed to visible 4 dimensions (3 spatial dimensions + 1 time-like dimension).[1] In this article, I will provide a concise overview of the history of physics to explain what the so-called theory of everything (TOE) is about and how it is related to string theory.

1 History of Classical Physics

Physicists have always been trying to explain the principles of our Universe. They try to describe as many physical phenomena as possible in terms of few principles or few mathematical formulas. It would be reasonable to say that the birth of physics dates back to the 17th century when Newton discovered the law of gravity. Newton surprised the world by showing that a simple formula $F = -\frac{GMm}{r^2}$ can be used to explain diverse and seemingly-unrelated phenomena such as an apple falling to the ground, the planets orbiting around the sun, the moon orbiting around the earth, and the ebb and flow of tides caused by the moon and so on.[2]

Two hundred years later, physicists found out that electricity and magnetism are very much related. For example, the direction of a compass's arrow changes when electric current is turned on nearby. Also, if you move magnet around an electric wire, a current is induced in the electric wire. In the 19th century Maxwell summarized all these phenomena in the following four simple equations.[3]

[1] Read our article "Manifold" to learn more about this.

[2] We will talk more about Newton's work in "History of Astronomy from the late 17th century to the early 20th century." To learn about this formula, read "The inverse square law and the 3-dimensional world" and then "Gravitational field on the surface of the Earth."

[3] Precisely speaking, Maxwell came up with twelve equations. Heaviside re-expressed them by the four equations.

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad (1)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \quad (3)$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \epsilon_o \mu_0 \frac{\partial \vec{E}}{\partial t} \quad (4)$$

These equations explain all electromagnetic phenomena, including electric generators, current transformers, electromagnets, motors, compasses and static electricity. Moreover, Maxwell determined that light is an electromagnetic wave. (Maxwell calculated the speed of electromagnetic waves which coincided with the speed of light. Later, Hertz experimentally confirmed that light is indeed an electromagnetic wave.) Therefore, all phenomena of light, including refraction, interference, and reflection, are electromagnetic phenomena. In other words, all electromagnetic phenomena including light can be explained by these four simple equations. (If you use a notation called differential forms, you can write these four equations in two equations as follows: $dF = 0, dF^* = j$. Doesn't this look so simple? Personally speaking, I was convinced that there must be a simple theory of everything after I had learned these two equations in my math class.)

2 History of Modern Physics

Then, there were two big revolutions in the physics community in early 20th century: Einstein's theories of special and general relativity, and Heisenberg and Schrödinger's quantum mechanics.

Einstein's theory of special relativity starts out from an observation that the speed of light is always constant; the speed of light is always 300,000 km/s. To elaborate this in more detail, I will give you an example. Naively, you might think that the speed of light would be observed as 10,000 km/s if you followed a 300,000 km/s beam of light at a speed of 290,000 km/s. However, it turns out that the speed of light still appears to be 300,000 km/s no matter how fast you follow the light. The constancy of the speed of light was observed by Michelson and Morley. From this principle, Einstein showed by calculation that the clock of an object moving fast goes slowly, and the object becomes thinner. Otherwise the constancy of speed of light is not satisfied. You will learn how exactly slowly the clock of a moving object goes in our article, "Time dilation in Einstein's theory of special relativity," which does not require any other physics background than the equation: speed=distance/time. There, you will be invited to calculate that during 10 hours, a stationary observer will see that 10 hours 1.25×10^{-8} less will elapse for an object moving with 900 km/h, a common speed of commercial airplanes.

However, there is a discrepancy between Newton's law of gravity and Einstein's theory of special relativity. According to Newton's gravity, the force between two objects only depends on their mass and the distance between them. However, if you are faithful to Newton's law of gravity, and if an object A changes its position, thereby the distance between the object A and another object B has changed, the force exerted on the object B would be changed at the instance that the object A's position has changed. But, according to the theory of special relativity, no information can be transported faster than light so it should take some time for object B to realize that the object A's position has changed. Einstein removed this paradox by his theory of general relativity, which is actually another theory of gravity. According to Einstein's theory, the information that the observer A's position has changed is transported at the speed of light. In other words, the force exerted on the object B won't be changed until the information that the object A's position has changed arrives at the object B. (Actually, this was mathematically shown the following year Einstein first came up with the theory of general relativity.) Moreover, as empirical confirmation, the theory of general relativity explained the orbit of Mercury where Newton's theory of gravity had failed. (There is a very small discrepancy between the orbits of Mercury calculated by Newton's theory of gravity and by Einstein's theory of general relativity.) Einstein also correctly predicted how much the light coming out from stars should be bent by the gravitation of the sun. This phenomenon was observed and measured during the total eclipse of the sun in 1919, bringing Einstein fame among the public. Also, after the theory of general relativity had been published in 1916, many physicists studied it and showed by calculation that there could exist a black hole from which even light could not get out. Astronomers later obtained the indirect observational evidence of the existence of such a black hole. Therefore, not only does Einstein's theory of gravity explain all the phenomena explained by Newton's theory of gravity, but also it explains phenomena not fully explained by Newton's theory of gravity, from the bending of light by the gravitation of the sun, to the orbit of Mercury, to the existence of black holes. What Einstein actually showed was that general relativity predicts the same or almost the same experimental or the observational results as Newton's gravity, when the gravity is not strong. Only when the gravity is strong, or experimental apparatus is sensitive enough to notice the difference between Newton's gravity prediction and general relativity prediction, is general relativity needed.[4]

In the 19th century, it was found that there were not only these macroscopic phenomena but also microscopic phenomena, which could not be explained by Newton's laws or Maxwell's equations. These microscopic phenomena, happening in the atomic world, were explained in 1920s by quantum mechanics, invented independently by Heisenberg by the method of matrices and by Schrödinger by the method of differential equations. Subsequently, Pauli, using matrices, and Schrödinger, using differential equations, independently calculated the wavelength of the spectral line emissions of the hydrogen atom[5], and surprisingly, both of

[4] We will talk more about general relativity in "History of Astronomy from the early 20th century to the early 21th century."

[5] Read our article "Rydberg formula" to learn what the spectral line emissions of the hydrogen atom are.

their calculations agreed with the experimental results. This is remarkable, because matrices and differential equations are very different objects, as you may understand if you know a little bit of mathematics. Soon thereafter, Schrödinger showed by himself that Heisenberg's matrix mechanics and Schrödinger's differential equations are equivalent, even though they look very different. I note furthermore the following quote from the preface of quantum mechanics textbook by co-workers of Heisenberg. "We believe that the new mechanics (i.e. quantum mechanics) does not represent an approximation to classical idea⋯ but rather their systematic extension to a logically consistent system."[6]

After quantum mechanics had been invented, most physicists devoted several years to solving Schrödinger's equations in diverse situations in order to explain diverse microscopic phenomena. Surprisingly, every calculation agreed with the real experimental results. Also, not long after quantum mechanics had been invented, Ehrenfest showed that quantum mechanics boils down to Newton's laws when it is applied to macroscopic phenomena. In other words, quantum mechanics can explain every phenomenon which Newton's laws can explain. Moreover, after supercomputers had been invented, physicists could solve Schrödinger's equations in more complicated cases, demonstrating again and again that Schrödinger's equations can explain all chemical phenomena and properties such as the periodic table or the characteristics of molecules at least in principle if not in practice.[7]

Two or 3 years after quantum mechanics had been invented, Dirac found his eponymous equation by modifying Schrödinger's equation to be compatible with the theory of special relativity. Dirac's equation predicted the existence of positron, a particle that has the same mass as the electron, but an opposite electric charge.[8] The positron was experimentally discovered later.

About twenty years after quantum mechanics had been invented, Feynman, Tomonaga and Schwinger invented quantum electrodynamics which explained diverse microscopic electromagnetic phenomena to surprisingly accuracy. As Feynman put it, the prediction of quantum electrodynamics agreed with the experiment to the extent that the distance between New York and Los Alamos was calculated to the accuracy of the width of a hair. (The distance between New York and Los Alamos is about 3000 km or 2000 miles.) Just as quantum mechanics reduces to Newtonian mechanics in macroscopic world, quantum electrodynamics can explain all electromagnetic phenomena explained by Maxwell's plus many new microscopic equations.

[6] p. VI, Born and Jordan. Elementare Quantenmechanik (Zweiter Band der Vorlesungen über Atommechanik), Berlin: J, Springer Verlag, 1930. translated in "The historical development of quantum theory, volume 3," p92

[7] We will explain "periodic table" in "The structure of atoms and the periodic table." We will explicitly see some examples of how quantum mechanics can explain some chemical properties of atoms in our later article entitled "Hydrogen atom."

[8] Read our article "The structure of atoms and the periodic table" to learn about the electron and the electric charge.

3 Standard Model

So far, we have only talked about two forces: gravitation and electromagnetic force. Physicists later found out that there are a total of four forces (gravitation, electromagnetic force, strong force and weak force) in our Universe.[9] Among these forces, a quantum theory[10] that explains electromagnetic force, and weak force was discovered in the late 1960s and another quantum theory that explains strong force was discovered in the early 1970s. These two theories are collectively called 'the Standard Model.'

All known phenomena in our universe are based on these four forces. For example, psychological phenomena are based on biological phenomena. Biological phenomena are based on chemical phenomena such as DNA molecular reactions or chemical reactions in brain. Chemical reactions regarding molecules such as DNA molecule are based on physical principle such as quantum mechanics. In summary, complicated psychological phenomena are based on the principles of physics in principle.

However, in practice, explaining every phenomenon by the Standard Model and the theory of general relativity is very hard, even though they explain the four forces in principle. As I noted earlier, you need a supercomputer to explain the atoms. Therefore, explaining complicated molecules such as DNA, or germs, would require a much more powerful supercomputer. In fact, you cannot solve the Schrödinger's equation of the simplest organism by the most powerful supercomputer in the world. Moreover, it is not easy to explain psychological phenomena by biology or biological phenomena by chemistry. So, there is a big difference between being based on and being explicable. Nevertheless, it is a great achievement to find out that all these phenomena are based on these four forces.

Even though physicists found out that the Standard Model and gravitation (Einstein's theory of general relativity) are the basic building blocks of all phenomena in our universe, it didn't mean that physicists' quest stopped there. First of all, there is a question why the Standard Model is as it is; why can't it be another model? It is known that there are more than 20 free parameters in the Standard Model. Free parameters are parameters that cannot be deduced from theories alone, but can be only determined by experiments. In other words, there is a priori no reason why these free parameters cannot have other values than the observed ones. An example of such free parameters is the Weinberg angle, which determines the ratio between electromagnetic force and weak force. Nobody knows why the Weinberg angle is approximately 29 degrees. Nobody knows a reason why it could not have other values. Second, the theory of general relativity has not yet been fully written to be compatible with quantum mechanics. (It is claimed that loop quantum gravity does this job, but that theory is not widely accepted yet.) If we want to describe how the gravity behaves not only in the macroscopic world, but also in the microscopic world, we need to write the

[9] Strong force binds the nucleus and weak force is responsible for beta decay. More about it in our article "The structure of atoms and the periodic table."

[10] A theory that can describe the microscopic world, in addition to the macroscopic world, must be necessarily written in the language compatible with quantum mechanics.

theory of general relativity in a way compatible with quantum mechanics. Such a theory is called "quantum gravity." In our everyday lives, quantum gravity may not be needed. Earlier, we mentioned that we need general relativity only when gravity is strong. Thus, a theory of quantum gravity is needed, only when gravity is strong even in a microscopical realm. Such a situation is not common in our daily lives. In our daily lives, gravity is strong only when we come to a big scale. For example, as we have seen, we need to consider general relativity for light passing near the Sun or for the orbit of Mercury, because the gravitation of the Sun is strong near its vicinity. However, the Sun is huge. If it were not that huge, its gravitation would not have been strong, which makes the consideration of relativistic effect unnecessary. Thus, we see that the realm in which quantum gravity effect is important is very rare. It should be tiny as atoms, but yet its gravitation needs to be as strong as the Sun. We could as well say that such realm is not important, as it is rare, but without a proper theory of quantum gravity, it would be hard to say that we have a genuine theory of everything, because a theory of everything has to be applicable in whole range. However, it is known that constructing a theory of quantum gravity is not easy. The trick to quantize (i.e., constructing a quantum version of) electromagnetic force, strong force and weak force does not work for gravitational force.

4 String Theory as Theory of Everything

However, string theory has the potential to answer these two questions. (I say it "has the potential," because string theory has not done this yet.) There are no free parameters in string theory. In other words, string theory has the potential to calculate constants such as the Weinberg angle. Moreover, it has the potential to find out why there are four forces in our universe (not three or not five) and has the potential to explain the characteristics of each force. Moreover, string theory not only can quantize general relativity but also can naturally derive general relativity without assuming it. How string theory has the potential to do all this is amazing. Loosely speaking, there are only two assumptions in string theory. First, the action of a string is given by the area swiped by the string. The action is a concept from which physicists can derive all the dynamics. The second assumption is supersymmetry.[11] Then, string theorists work based on these two assumptions. Then, they find principles, and work based on these principles again. Then, they find new principles, and re-apply these new principles and so on. This may sound somewhat strange, but Richard Feynman said:

> We can deduce, often, from one part of physics like the law of gravitation, a principle which turns out to be much more valid than the derivation. This doesn't happen in mathematics, that the theorems come out in places where they're not supposed to be!

[11] I explained what supersymmetry is in "Supersymmetry: an exposition for laymen."

It is truly surprising how far physicists have come and how rich the field has become starting from these simple basic assumptions and following their principles. To help you understand what I mean here by simple basic assumptions, let me give you a similar example. (I would have harder time to explain finding principles.) In the early 20th century, regarding fluid mechanics, physicists didn't know whether the simple concepts such as the Navier-Stokes equation sufficed for complicated phenomenon such as turbulent motion, or whether more concepts were needed. Heisenberg proved that the former was the case. In a 1924 paper he wrote, "all results obtained thus far, which partially seem to contradict one another, can be described with the help of simple basic assumptions in a unified mathematical way."[12] Similarly, string theorists believe that the two simple assumptions that I mentioned, along with unified mathematical framework and mathematical consistency that combine principles that they found, are more or less enough to account all the diverse, and complicated phenomena that Standard Model and general relativity can explain.

In summary, we have the following analogy:

Quantum Mechanics: Chemistry = String Theory: (the Standard Model+General Relativity)

In other words, as chemistry is explained by quantum mechanics, string theory has a possibility to explain the Standard Model and the theory of general relativity. As the Standard Model and the theory of general relativity explains "everything," string theory is a candidate for "Theory of Everything."

5 Controversies

Despite its success, string theory has been criticized by many prominent physicists. They say that string theory makes no concrete predictions that can be confirmed or falsified by experiments. Some say that string theory is just math devoid of the touchable reality. They also note that particles predicted by supersymmetry which are essential for string theory have not been discovered at the LHC, the current most powerful accelerator. This could be indeed a serious problem; particle physicists had a plausible reasoning on roughly how much scale the masses of these particles would be. However, this scale was reached by the LHC, and now surpassed, but no such particles had been detected yet. Nevertheless, I do believe that the particles predicted by supersymmetry will be detected at the LHC when it will run at higher scale. I also do believe that string theory will predict all the so-called "free parameters" of the Standard Model one day, perhaps not in my life time though.

Moreover, string theory has a mathematical beauty. Dualities among the five different string theories are good examples. (More about this in our next article.) The five string theories were neither invented nor concocted to fit into these dualities; the dualities were discovered about ten years after these five string theories had been found, and they are too

[12] Über die Stabilität und Turbulenz von Flüssigkeitsströmen, Ann. d. Phys. (4) 74, p627, translated in "The historical development of quantum theory, volume 2," p60-61

elegant to believe that they are coincidences.

Furthermore, string theory has been contributing to mathematics enormously. This is something that even staunchest string theory critics agree. Thus, even if string theory were wrong, the research on string theory cannot be considered useless considering its impact on mathematics. New fields in mathematics have emerged due to string theory, and connections between different branches of mathematics were discovered by motivation from string theory. Some mathematical problems have been solved by approaches inspired by string theory. In 1995, the winner of the Fields medal-which is equivalent to the Nobel Prize in mathematics-and single most renowned string theorist Edward Witten said: “The mathematics of the next millennium will be dominated by string theory.” Indeed, the very fact that a string theorist won the Fields medal shows the impact of string theory on mathematics. String theorist Shiraz Minwalla mentioned in 2007 that, according to his mathematician friend, about 30 percents of recent papers published at the top journals on algebraic geometry (i.e., a branch of mathematics) would not have been there, hadn’t string theory existed. Now, more and more mathematicians are working on string theory.

Further reading

There are several books that deal with string theory for laymen. Brian Greene’s “the Elegant Universe” is one example. PBS made a documentary based on this book, and it is available at http://www.pbs.org/wgbh/nova/elegant/ Also, http://superstringtheory.com has a lot of useful material for laymen. However, to study string theory concretely, a year of quantum field theory as a prerequisite is desirable.

Summary

- Newton’s law of gravity can be regarded as the birth of physics. Newton’s simple formula explains diverse and seemingly-unrelated phenomena such as an apple falling to the ground, the moon orbiting around the earth, and the ebb and flow of tides and so on.

- Maxwell’s four simple equations explain all electromagnetic phenomena. Maxwell calculated the speed of electromagnetic waves which coincided with the speed of light. Thus, Maxwell determined that light is an electromagnetic wave.

- Einstein’s theory of special relativity starts out from an observation that the speed of light is always constant. Taking this as a principle, Einstein showed by calculation that the clock of an object moving fast goes slowly, and the object becomes thinner. He also showed that no information can be transported faster than light.

- Einstein’s theory of general relativity explains all the phenomena explained by Newton’s theory of gravity, but also it explains the bending of light by the gravitation of the sun, and the orbit of Mercury.

- Microscopic phenomena, which could not be explained by Newton's laws or Maxwell's equations, were explained by quantum mechanics, invented independently by Heisenberg by the method of matrices and by Schrödinger by the method of differential equations. It was soon proved that the two formulations are equivalent.
- It was also soon shown that quantum mechanics can explain every phenomenon which Newton's laws can explain.
- Dirac's equation is Schrödinger's equation modified to be compatible with the theory of special relativity.
- Quantum electrodynamics, invented by Feynman and others, can explain all electromagnetic phenomena explained by Maxwell's plus many new microscopic equations.
- Physicists found out that there are a total of four forces in our universe, and the Standard Model describes three of them, except gravity.
- All known phenomena in our universe are based on these four forces. However, in practice, explaining every phenomenon by the Standard Model and the theory of general relativity is very hard, even though they explain the four forces in principle.
- Even though the Standard Model is found, there is a still question why God could not have chosen any other model. Also, Einstein's theory of general relativity needs to be written to be compatible with quantum mechanics.
- String theory, as a candidate for theory of everything, has the potential to answer these two questions with minimum assumptions.
- Some claim that string theory is just math devoid of the touchable reality. Nevertheless, even staunchest string theory critics agree that string theory has been contributing to mathematics enormously.