FEATURE

Principal Investigator Hirosi Ooguri
Research Area: Theoretical Physics

Gravity's Holography

In Director's Corner in the previous issue, Hiroshi Murayama explained the notion of the unification of forces in nature by invoking his personal story about the fall of the Berlin wall. In this article, we will expand on this topic and introduce superstring theory, which is a candidate for the ultimate unified theory of all the forces. We will also discuss the holographic principle, which is an important feature of quantum gravity.

Maxwell Theory and Discovery of Electromagnetic Waves

In the late 19th century, J.C. Maxwell discovered the unified description of electricity and magnetism by a single set of equations. According to the Maxwell equations, a change in an electric field induces a magnetic field and vice versa. Maxwell found a wave-like solution to the equations, in which an electric field and a magnetic field induce each other and the resulting wave propagates at the speed of light. Maxwell's theoretical prediction was confirmed experimentally by H. Hertz 15 years later. By the beginning of the 20th century, transatlantic transmission became reality. Maxwell's unification has set the foundation of modern information technology.

Geometry of Space and Time

While the electromagnetic force is communicated by an electromagnetic field, the gravitational force has a more profound origin in plasticity of space and time. The Einstein equation describes how space and time are warped by matter. Einstein predicted a gravitational wave as a solution to his equation, where ripples of space and time propagate at the speed of light. 60 years later, R. Hulse and J. Taylor discovered evidences that gravitational waves are emitted by a binary pulsar. Several detectors, including TAMA 300 in Japan, are currently in operation to capture a gravitational wave directly.

Einstein's theory of gravity is an indispensable tool in our study of the Universe, but it also plays roles in our everyday life. For example, the GPS navigation device determines its location by receiving signals from atomic clocks on satellites. However, since the satellites are moving at high velocities and at high altitudes, where Earth's gravitational field is weak, the atomic clocks run slightly faster by relativity effects. The GPS would be useless unless such errors are corrected by Einstein's theory.

Renormalization

Quantum mechanics is the second pillar of modern physics. Except for gravity, all known forces in nature have been incorporated in quantum mechanics. For example, the unification of Maxwell's theory of electromagnetism with quantum

Where has the information gone?

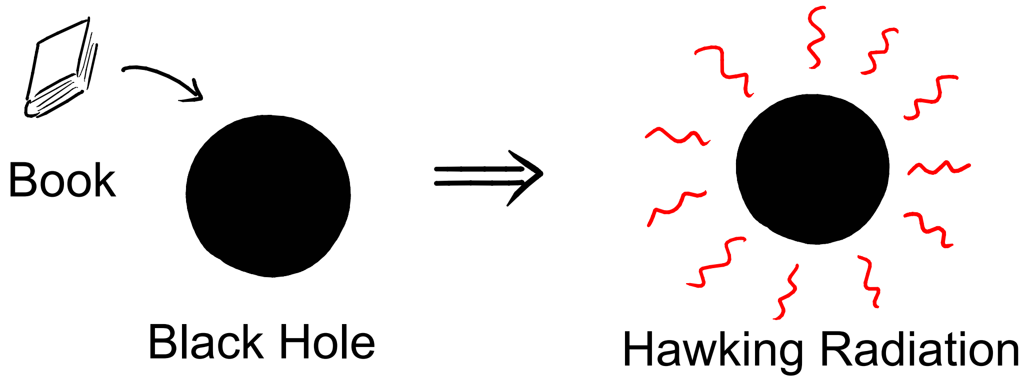

Figure 1. The black hole information paradox

mechanics was attempted by W. Heisenberg and W. Pauli and completed by the renormalization theory of R. Feynman, J. Schwinger and S. Tomonaga.

According to the uncertainty principle of Heisenberg, such familiar quantities as positions and velocities of a particle fluctuate in the microscopic world of quantum mechanics. If we try to combine Maxwell's theory with quantum mechanics, an electromagnetic field would also fluctuate. Since the field can vary in space and time, combining quantum fluctuations at all locations leads to infinities in computations. The renormalization provides a way to remove the infinities and to make testable predictions of quantum electromagnetism.

Paradoxes of Quantum Gravity

Similarly, an attempt to quantize Einstein's theory of gravity produces infinities, but these cannot be removed by renormalization. Moreover, since the gravitational force is a property of space and time, quantizing gravity means that space and time themselves must fluctuate. This has lead to various paradoxes and posed challenges to physicists.

In 1974, S. Hawking showed that a black hole generates heat by quantum mechanical effects and may evaporate away. Based on this theoretical result, he claimed that causal determinism must be violated in quantum gravity. Determinism is one of the most fundamental ideas in science, which states that, if we know everything that is happening now, the past and future are completely determined by fundamental laws of nature.

Let us consider throwing a book in a black hole, as shown in Figure 1. The black hole would gain weight by absorbing the book, but the effect would radiate away. According to Hawking's computation, throwing in a different book with the same weight would produce exactly the same radiation. If we cannot tell the book by measuring the resulting radiation, we would have lost the information on the past, contradicting determinism. This is the black hole information paradox [1].

Superstring Theory

The unification of quantum mechanics and general relativity has been an outstanding problem in theoretical physics, and various attempts have been made to find its solution. Among them, the only known theory that is consistent and has any hope of reproducing a realistic model of elementary particles is superstring theory. It solves the problem of infinities by postulating that fundamental building blocks of matter are strings rather than particles.

The strings vibrate like violin strings, and each vibration mode corresponds to an elementary particle. T. Yoneya, while still a graduate student, discovered that one of such modes mediates the gravitational force. J. Scherk and J. Schwarz, who made the same discovery independently, proposed to use superstring theory to construct the ultimate unified theory of all forces.

However, superstring theory remained on the sideline for about 10 years since then. One of the reasons was that it was not known how to incorporate "parity violation," which is an essential property of elementary particles. It seems that everything we experience can also happen if it is reflected on a mirror, but this reflection symmetry called "parity" is violated in the world of elementary particles. Nevertheless, Schwarz continued to study the theory almost by himself for the 10 years, and discovered with M. Green a remarkable mechanism to incorporate parity violation in superstring theory, opening a way to construct a unified theory using superstring theory.

Holographic Principle

After 25 years since the breakthrough by Green and Schwarz, superstring theory has made great progress. Here we will discuss the holographic principle, which is one of its surprising outcomes.

In quantum mechanics, there is a notion of wave-particle duality. For example, an electromagnetic wave is a wave-like solution to the Maxwell equations. However, if we apply quantum mechanics, the electromagnetic wave becomes a particle called the photon. The electron, which we think of as a particle, is also a wave obeying the Schrödinger equation. In the early history of quantum mechanics, there were debates on whether the electron is a particle or a wave. Nowadays, we view that the two properties are not contradictory but are complementary aspects of the whole picture.

Take a look at Rubin's vase in Figure 2. If we pay attention to the white area, we see a vase. On the other hand, the black area seems to indicate that there are two people facing each other. We cannot say that which interpretation is correct. This is another example of duality.

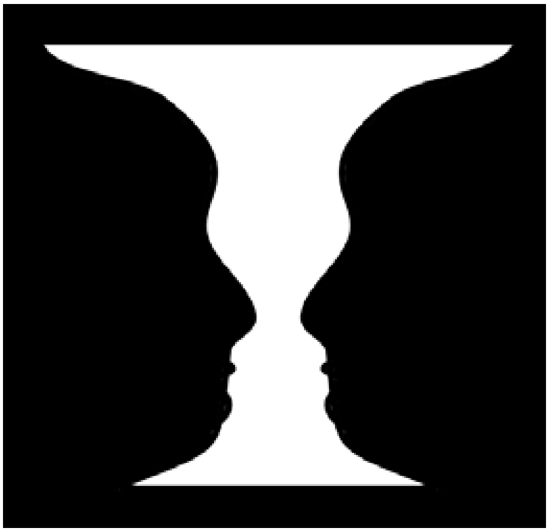

Figure 2. Rubin's vase

The holographic principle is yet another example of duality. Holography is a term in optics, which means encoding geometric data of a 3-dimensional object on a 2-dimensional surface so that the 3-dimensional image can be reconstructed later. In superstring theory, all the phenomena in quantum gravity can be projected onto a screen located at boundaries of space, and they can be described using a quantum theory without gravity defined on the screen. Borrowing the terminology of optics, this idea is called gravity's holography.

By using the holographic principle it has become possible to solve deepest puzzles of quantum gravity such as Hawking's paradox by translating them into problems in ordinary quantum mechanics without gravity. This has led to major progress toward constructing a unified theory with gravity.

Conversely, it has also become possible to translate difficult problems in quantum mechanics into the language of quantum gravity and solve them by using geometric methods. This has broadened applications of superstring theory, providing new perspectives to a variety of problems ranging from hadron physics and theomodynamical properties of quark-gluon plasma to strongly correlated phenomena in condensed matter physics such as quantum criticality and quantum fluids. There is even a hope of understanding the mechanism of high temperature superconductivity using superstring theory [2].

Superstring theory is a candidate for the ultimate unified theory. It is also a theoretical tool to solve a variety of problems in physics beyond the scope of elementary particle physics. These two aspects are related by the duality called the holographic principle. At IPMU, we are pursuing both of these two directions by involving a wide range of scientists from pure mathematicians to condensed matter physicists.

References:
[1] H. Ooguri, Black Holes and the Fate of Determinism, a talk at the Caltech Alumni Day, http://today.caltech.edu/theater/29930_56k.ram
[2] S. Hartnoll, Lectures on holographic methods for condensed matter physics, arXiv:0903.3246