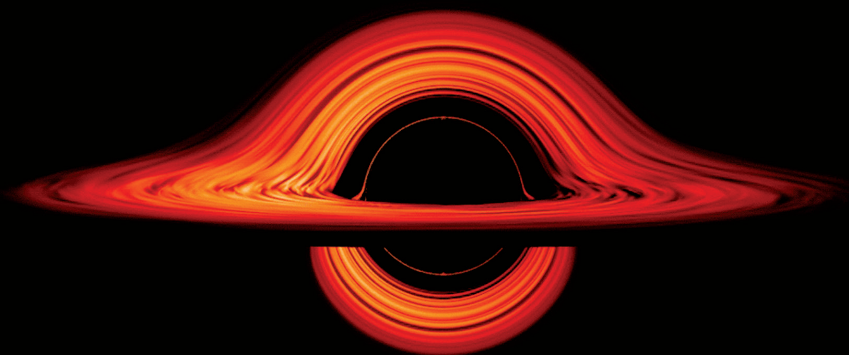
'A MAJESTIC STORY'
Financial Times

MICHIO KAKU



THE GOD EQUATION

The Quest for a Theory of Everything

PENGUIN BOOKS

The God Equation

Michio Kaku is a Professor of Physics at the City University of New York, co-founder of string field theory, and the author of several widely acclaimed science books, including *Hyperspace*, *Beyond Einstein*, *Physics of the Impossible* and *Physics of the Future*.

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To my loving wife, Shizue, and my daughters,
Dr. Michelle Kaku and Alyson Kaku

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The God Equation

INTRODUCTION TO THE FINAL THEORY

It was to be the final theory, a single framework that would unite all the forces of the cosmos and choreograph everything from the motion of the expanding universe to the most minute dance of subatomic particles. The challenge was to write an equation whose mathematical elegance would encompass the whole of physics.

Some of the most eminent physicists in the world embarked upon this quest. Stephen Hawking even gave a talk with the auspicious title "Is the End in Sight for Theoretical Physics?"

If such a theory is successful, it would be science's crowning achievement. It would be the holy grail of physics, a single formula from which, in principle, one could derive all other equations, starting from the Big Bang and moving to the end of the universe. It would be the end product of two thousand years of scientific investigation ever since the ancients asked the question, "What is the world made of?

It is a breathtaking vision.

EINSTEIN'S DREAM

I first came across the challenge this dream posed as a child of eight. One day, the newspapers announced that a great scientist had just died. There was an unforgettable picture in the paper.

It was an image of his desk, with an open notebook. The caption announced that the greatest scientist of our time could not finish the work he had started. I was fascinated. What could possibly be so hard that even the great Einstein could not solve it?

That book contained his unfinished theory of everything, what Einstein called the unified field theory. He wanted an equation, perhaps no more than one inch long, that would allow him to, in his words, "read the mind of God."

Not fully appreciating the enormity of this problem, I decided to follow in the footsteps of this great man, and hoped to play a small role in finishing his quest.

But many others have also tried and failed. As Princeton physicist Freeman Dyson once said, the road to the unified field theory is littered with the corpses of failed attempts.

Today, however, many leading physicists believe that we are finally converging on the solution.

The leading (and to my mind, only) candidate is called string theory, which posits the universe was not made of point particles but of tiny vibrating strings, with each note corresponding to a subatomic particle.

If we had a microscope powerful enough, we could see that electrons, quarks, neutrinos, etc. are nothing but vibrations on minuscule loops resembling rubber bands. If we pluck the rubber band enough times and in different ways, we eventually create all the known subatomic particles in the universe. This means that all the laws of physics can be reduced to the harmonies of these strings. Chemistry is the melodies one can play on them. The universe is a symphony. And the mind of God, which Einstein eloquently wrote about, is cosmic music resonating throughout spacetime.

This is not just an academic question. Each time scientists have unraveled a new force, it has changed the course of civilization and altered the destiny of humanity. For example, Newton's discovery of the laws of motion and gravity laid the groundwork for the machine age and the Industrial Revolution. Michael Faraday and James Clerk Maxwell's explanation of electricity and magnetism paved the way for the illumination of our cities and gave us powerful electric motors and generators as well as instantaneous communication via TV and radio. Einstein's $E = mc^2$ explained the power of the stars and helped to unravel the nuclear force. When Erwin Schrödinger, Werner Heisenberg, and others unlocked the secrets of the quantum theory, they gave us the high-tech revolution of today, with supercomputers, lasers, the internet, and all the fabulous gadgets in our living rooms.

Ultimately, all the wonders of modern technology owe their origin to the scientists who gradually discovered the fundamental forces of the world. Now, scientists may be converging on the theory that unifies these four forces of nature—gravity, the electromagnetic force, and the strong and weak nuclear forces—into a single theory. Ultimately, it may answer some of the deepest mysteries and questions in all of science, such as:

- What happened before the Big Bang? Why did it bang in the first place?
- What lies on the other side of a black hole?
- Is time travel possible?
- Are there wormholes to other universes?
- Are there higher dimensions?
- Is there a multiverse of parallel universes?

This book is about the quest to find this ultimate theory and all the bizarre twists and turns of what is undoubtedly one of the strangest chapters in the history of physics. We will review all the previous revolutions, which have given us our technological marvels, starting with the Newtonian revolution, leading up to the mastery of the electromagnetic force, the development of relativity and the quantum theory, and the string theory of today. And we will explain how this theory may also unravel the deepest mysteries of space and time.

AN ARMY OF CRITICS

However, hurdles remain. For all the excitement generated by string theory, the critics have been keen to point out its defects. And after all the hype and frenzy, real progress has stalled.

The most glaring problem is that, for all the flattering press extolling the beauty and complexity of the theory, we have no solid, testable evidence. Once, it was hoped that the Large Hadron Collider (LHC) outside Geneva, Switzerland, the biggest particle accelerator in history, would find concrete evidence for the final theory, but this has remained elusive. The LHC was able to find the Higgs boson (or the God particle), but this particle was only a tiny missing piece of the final theory.

Although ambitious proposals have been made for an even more powerful successor to the LHC, there is no guarantee that these costly machines will find anything at all. No one knows for certain at what energy we will find new subatomic particles that could verify the theory.

But perhaps the most important criticism of string theory is that it predicts a multiverse of universes. Einstein once said that the key question was: Did God have a choice in making the universe? Is the universe unique? String theory by itself is unique, but it probably has an infinite number of solutions. Physicists call this the landscape problem—the fact that our universe may be just one solution among an ocean of other equally valid ones. If our universe is one of many possibilities, then which one is ours? Why do we live in this particular universe and not another? What, then, is the predictive power of string theory? Is it a theory of everything or a theory of anything?

I admit I have a stake in this search. I have been working on string theory since 1968, ever since it emerged accidentally, unannounced, and totally unexpected. I have seen the remarkable evolution of the theory that developed from a single formula into a discipline with a whole library's worth of research papers. Today, string theory forms the basis of much of the research being done in the world's leading laboratories. This book will hopefully give you a balanced, objective analysis of string theory's breakthroughs and limitations.

It will also explain why this quest has seized the imagination of the world's top scientists, and why this theory has generated so much passion and controversy.

1

UNIFICATION—THE ANCIENT DREAM

Gazing at the magnificent splendor of the night sky, surrounded by all the brilliant stars in the heavens, it is easy to be overwhelmed by its sheer, breathtaking majesty. Our concerns turn to some of the most mysterious questions of all.

Is there a grand design to the universe?

How do we make sense of a seemingly senseless cosmos?

Is there a rhyme and reason to our existence, or is it all pointless?

I am reminded of the poem by Stephen Crane:

A man said to the universe:

"Sir, I exist!"

"However," replied the universe,

"The fact has not created in me a sense of obligation."

The Greeks were among the first to make serious attempts to sort through the chaos of the world around us. Philosophers like Aristotle believed that everything could be reduced to a mixture of four fundamental ingredients: earth, air, fire, and water. But how do these four elements give rise to the rich complexity of the world?

The Greeks proposed at least two answers to this question. The first was given by the philosopher Democritus, even before Aristotle. He believed that everything could be reduced to tiny, invisible, indestructible particles he called atoms (meaning "indivisible" in Greek). The critics, however, pointed out that direct evidence for atoms was impossible to acquire because they were too small to be observed. But Democritus could point out compelling, indirect evidence.

Consider a gold ring, for example. Over the years, the ring begins to wear down. Something is being lost. Every day some tiny bits of matter have been worn off the ring. Hence, although atoms are invisible, their existence can be measured indirectly.

Even today most of our advanced science is done indirectly. We know the composition of the sun, the detailed structure of DNA, and the age of the universe, all due to measurements of this kind. We know all this, even though we have never visited the stars or entered a DNA molecule or witnessed the Big Bang. This distinction between direct and indirect evidence will become essential when we discuss attempts to prove a unified field theory.

A second approach was pioneered by the great mathematician Pythagoras.

Pythagoras had the insight to apply a mathematical description to worldly phenomena like music. According to legend, he noticed similarities between the sound of plucking a lyre string and the resonances made by hammering a metal bar. He found that they created musical frequencies that vibrated with certain ratios. So something as aesthetically pleasing as music has its origin in the mathematics of resonances. This, he thought, might show that the diversity of the objects we see around us must obey these same mathematical rules.

So at least two great theories of our world emerged from ancient Greece: the idea that everything consists of invisible, indestructible atoms and that the diversity of nature can be described by the mathematics of vibrations.

Unfortunately, with the collapse of classical civilization, these philosophical discussions and debates were lost. The concept that there could be a paradigm explaining the universe was forgotten for almost a thousand years. Darkness spread over the Western world, and scientific inquiry was largely replaced by belief in superstition, magic, and sorcery.

REBIRTH DURING THE RENAISSANCE

In the seventeenth century, a few great scientists rose to challenge the established order and investigate the nature of the universe, but they faced stiff opposition and persecution. Johannes Kepler, who was one of the first to apply mathematics to the motion of the planets, was an imperial adviser to Emperor Rudolf II and perhaps escaped persecution by piously including religious elements in his scientific work.

The former monk Giordano Bruno was not so lucky. In 1600, he was tried and sentenced to death for heresy. He was gagged, paraded naked in the streets of Rome, and finally burned at the stake. His chief crime? Declaring that life may exist on planets circling other stars.

The great Galileo, the father of experimental science, almost met the same fate. But unlike Bruno, Galileo recanted his theories on pain of death. Nonetheless, he left a lasting legacy with his telescope, perhaps the most revolutionary and seditious invention in all of science. With a telescope, you could see with your own eyes that the moon was pockmarked with craters; that Venus had phases consistent with its orbiting the sun; that Jupiter had moons, all of which were heretical ideas.

Sadly, he was placed under house arrest, isolated from visitors, and eventually went blind. (It was said because he once looked directly at the sun with his telescope.) Galileo died a broken man. But the very year that he died, a baby was born in England who would grow up to complete Galileo's and Kepler's unfinished theories, giving us a unified theory of the heavens.

NEWTON'S THEORY OF FORCES

Isaac Newton is perhaps the greatest scientist who ever lived. In a world obsessed with witchcraft and sorcery, he dared to write down the universal laws of the heavens and apply a new mathematics he invented to study forces, called the calculus. As physicist Steven Weinberg has written, "It is with Isaac Newton that the modern dream of a final theory really begins." In its time, it was considered to be the theory of everything—that is, the theory that described all motion.

It all began when he was twenty-three years old. Cambridge University was closed because of the black plague. One day in 1666, while walking around his country estate, he saw an apple fall. Then he asked himself a question that would alter the course of human history.

If an apple falls, then does the moon also fall?

Before Newton, the church taught that there were two kinds of laws. The first were the laws found on Earth, which were corrupted by the sin of mortals. The second were the pure, perfect, and harmonious laws of the heavens.

The essence of Newton's idea was to propose a unified theory that encompassed the heavens and the Earth.

In his notebook, he drew a fateful picture (see figure 1).

If a cannonball is fired from a mountaintop, it goes a certain distance before hitting the ground. But if you fire the cannonball at increasing velocities, it travels farther and farther before coming back to Earth, until it eventually com-

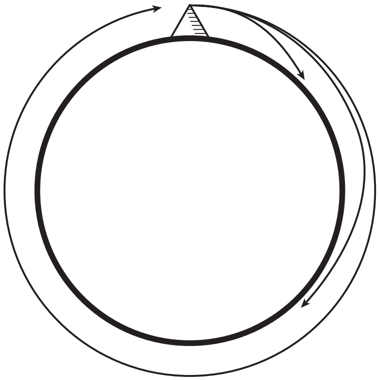

Figure 1. One can fire a cannonball with increasing energy, so that it eventually goes completely around the Earth and returns to its starting point. Newton then said that this explains the orbit of the moon, thereby unifying the physical laws found on Earth with the laws of heavenly bodies.

pletely circles the Earth and returns to the mountaintop. He concluded that the natural law that governs apples and cannonballs, gravity, also grips the moon in its orbit around the Earth. Terrestrial and heavenly physics were the same.

The way he accomplished this was to introduce the concept of forces. Objects moved because they were pulled or pushed by forces that were universal and could be measured precisely and mathematically. (Previously, some theologians thought that objects moved because of desires, so that objects fell because they yearned to be united with the Earth.)

Thus, Newton introduced the key concept of unification.

But Newton was a notoriously private man and kept much of his work a secret. He had few friends, was incapable of small talk, and was often immersed in bitter priority battles with other scientists about his discoveries.

In 1682, a sensational event happened that changed the course of history. A blazing comet sailed over London. Everyone, from kings and queens to beggars, was buzzing with the news. Where did it come from? Where was it going? What did it portend?

One man who took an interest in this comet was astronomer Edmond Halley. He took a trip to Cambridge to meet the famous Isaac Newton, already well-known for his theory of light. (By shining sunlight through a glass prism, Newton showed that white light separated into all the colors of the rainbow, thereby demonstrating that white light is actually a composite color. He also invented a new type of telescope that used reflecting mirrors rather than lenses.) When Halley asked Newton about the comet that everyone was talking about, he was shocked to hear that Newton could show that comets moved in ellipses around the sun and that he could even predict their trajectory using his own theory of gravity. In fact, he was tracking them with the telescope he invented, and they moved just as he predicted.

Halley was stunned.

He immediately realized that he was witnessing a landmark in science and volunteered to pay for the printing costs of what would eventually become one of the greatest masterpieces in all science, *Mathematical Principles of Natural Philosophy*, or simply *Principia.*