SEVEN BRIEF LESSONS ON PHYSICS

CARLO ROVELLI

INTERNATIONAL BESTSELLER

SEVEN BRIEF LESSONS ON PHYSICS

CARLO ROVELLI

TRANSLATED BY SIMON CARNELL AND ERICA SEGRE

RIVERHEAD BOOKS
NEW YORK
2016

RIVERHEAD BOOKS
An imprint of Penguin Random House LLC
375 Hudson Street
New York, New York 10014

First American edition published by Riverhead Books 2016

Originally published in Italian under the title *Sette brevi lezioni di fisica* by Adelphi Edizioni, Milan
English translation published in Great Britain by Allen Lane, an imprint of Penguin Random House UK

ISBN 978-0-399-18441-3

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

Book design by Lauren Kolm

CONTENTS

PREFACE

These lessons were written for those who know little or nothing about modern science. Together they provide a rapid overview of the most fascinating aspects of the great revolution that has occurred in physics in the twentieth and twenty-first centuries, and of the questions and mysteries that this revolution has opened up. Because science shows us how to better understand the world, but it also reveals to us just how vast is the extent of what is still not known.

The first lesson is dedicated to Albert Einstein's general theory of relativity, the "most beautiful of theories."

The second to quantum mechanics, where the most baffling aspects of modern physics lurk. The third is dedicated to the cosmos: the architecture of the universe that we inhabit; the fourth to its elementary particles. The fifth deals with quantum gravity: the attempts that are under way to construct a synthesis of the major discoveries of the twentieth century. The sixth is on probability and the heat of black holes. The final section of the book returns to ourselves and asks how it is possible to think about our existence in the light of the strange world described by physics.

The lessons are expansions of a series of articles published in the Sunday supplement of the Italian newspaper *Il Sole 24 Ore*. I would like to thank in particular Armando Massarenti, who can be credited with opening up the cultural pages of a Sunday paper to science and allowing light to be thrown on the role of this integral and vital aspect of our culture.

FIRST LESSON

The Most Beautiful of Theories

In his youth Albert Einstein spent a year loafing aimlessly. You don't get anywhere by not "wasting" time—something, unfortunately, that the parents of teenagers tend frequently to forget. He was in Pavia. He had joined his family, having abandoned his studies in Germany, unable to endure the rigors of his high school there. It was the beginning of the twentieth century, and in Italy the beginning of its industrial revolution. His father, an engineer, was installing the first electricity-generating power plants in the Paduan plains. Albert was reading Kant and attending occasional lectures at the University of Pavia: for pleasure, without being registered there or having to think about exams. It is thus that serious scientists are made.

After this he registered at the University of Zurich and immersed himself in the study of physics. A few years later, in 1905, he sent three articles to the most prestigious scientific journal of the period, the *Annalen der Physik*. Each of these is worthy of a Nobel Prize. The first shows that atoms really exist. The second lays the first foundation for quantum mechanics, which I will discuss in the next lesson. The third presents his first theory of relativity (known today as "special relativity"), the theory that elucidates how time does not pass identically for everyone: two identical twins find that they are different in age if one of them has traveled at speed.

Einstein became a renowned scientist overnight and received offers of employment from various universities. But something disturbed him: despite its immediate acclaim, his theory of relativity does not fit with what we know about gravity, namely, with how things fall. He came to realize this when writing an article summarizing his theory and began to wonder if the law of "universal gravity" as formulated by the father of physics himself, Isaac Newton, was in need of revision in order to make it compatible with the new concept of relativity. He immersed himself in the problem. It would take ten years to resolve. Ten years of frenzied studies, attempts, errors, confusion, mistaken articles, brilliant ideas, misconceived ideas.

Finally, in November 1915, he committed to print an article giving the complete solution: a new theory of gravity, which he called "The General Theory of Relativity," his masterpiece and the "most beautiful of theories," according to the great Russian physicist Lev Landau.

There are absolute masterpieces that move us intensely: Mozart's *Requiem*, Homer's *Odyssey*, the Sistine Chapel, *King Lear*. To fully appreciate their brilliance may require a long apprenticeship, but the reward is sheer beauty—and not only this, but the opening of our eyes to a new perspective upon the world. Einstein's jewel, the general theory of relativity, is a masterpiece of this order.

I remember the excitement I felt when I began to understand something about it. It was summer. I was on a beach at Condofuri in Calabria, immersed in the sunshine of the Hellenic Mediterranean, and in the last year of my university studies. Undistracted by schooling, one studies best during vacations. I was studying with the exist. He aimed at understanding how this "gravitational field" worked and how it could be described with equations.

And it is at this point that an extraordinary idea occurred to him, a stroke of pure genius: the gravitational field is not *diffused through* space; the gravitational field *is that space* itself. This is the idea of the general theory of relativity. Newton's "space," through which things move, and the "gravitational field" are one and the same thing.

It's a moment of enlightenment. A momentous simplification of the world: space is no longer something distinct from matter—it is one of the "material" components of the world. An entity that undulates, flexes, curves, twists. We are not contained within an invisible, rigid infrastructure: we are immersed in a gigantic, flexible snail shell. The sun bends space around itself, and Earth does not turn around it because of a mysterious force but because it is racing directly in a space that inclines, like a marble that rolls in a funnel. There are no mysterious forces generated at the center of the funnel; it is the curved nature of the walls that causes the marble to roll. Planets circle around the sun, and things fall, because space curves.

How can we describe this curvature of space? The most outstanding mathematician of the nineteenth century, Carl Friedrich Gauss, the so-called prince of mathematicians, had written mathematical formulas to describe two-dimensional curvilinear surfaces, such as the surfaces of hills. Then he had asked a gifted student of his to generalize the theory to encompass spaces in three or more dimensions. The student in question, Bernhard Riemann, had produced an impressive doctoral thesis of the kind that seems completely useless. The result of Riemann's thesis was that the properties of a curved space are captured by a particular mathematical object, which we know today as Riemann's curvature and indicate with the letter R. Einstein wrote an equation that says that R is equivalent to the energy of matter. That is to say: space curves where there is matter. That is it. The equation fits into half a line, and there is nothing more. A vision—that space curves—became an equation.

But within this equation there is a teeming universe. And here the magical richness of the theory opens up into a phantasmagorical succession of predictions that resemble the delirious ravings of a madman but have all turned out to be true.

To begin with, the equation describes how space bends around a star. Due to this curvature, not only do planets orbit around the star but light stops moving in a straight line and deviates. Einstein predicted that the sun causes light to deviate. In 1919 this deviance was measured and the prediction verified. But it isn't only space that curves; time does too. Einstein predicted that time passes more quickly high up than below, nearer to Earth. This was measured and turned out to be the case. If a person who has lived at sea level meets up with his twin who has lived in the mountains, he will find that his sibling is slightly older than he. And this is just the beginning.

When a large star has burned up all of its combustible substance (hydrogen), it goes out. What remains is no longer supported by the heat of the combustion and collapses under its own weight, to a point where it bends space to such a degree that it plummets into an actual hole. These are the famous "black holes." When I was studying at university they were considered to be the barely credible predictions of an esoteric theory. Today they are observed in the sky in their hundreds and are studied in great detail by astronomers.

But this is still not all. The whole of space can expand and contract. Furthermore, Einstein's equation shows that space cannot stand still; it *must be* expanding. In 1930 the expansion of the universe was actually observed. The same equation predicts that the expansion ought to have been triggered by the explosion of a young, extremely small, and extremely hot universe: by what we now know as the "big bang." Once again, no one believed this at first, but the proof mounted up until "cosmic background radiation"—the diffuse glare that remains from the heat generated by the original explosion—was actually observed in the sky. The prediction arising from Einstein's equation turned out to be correct. And further still, the theory contends that space moves like the surface of the sea. The effects of these "gravitational waves" are observed in the sky on binary stars and correspond to the predictions of the theory even to the astonishing precision of one part to one hundred billion. And so forth.

In short, the theory describes a colorful and amazing world where universes explode, space collapses into bottomless holes, time sags and slows near a planet, and the unbounded extensions of interstellar space ripple and sway like the surface of the sea . . . And all of this, which emerged gradually from my mice-gnawed book, was not a tale told by an idiot in a fit of lunacy or a hallucination caused by Calabria's burning Mediterranean sun and its dazzling sea. It was reality.

Or better, a glimpse of reality, a little less veiled than our blurred and banal everyday view of it. A reality that seems to be made of the same stuff that our dreams are made of, but that is nevertheless more real than our clouded, quotidian dreaming.

All of this is the result of an elementary intuition: that space and gravitational field are the same thing. And of a simple equation that I cannot resist giving here, even though you will almost certainly not be able to decipher it. Perhaps anyone reading this will still be able to appreciate its wonderful simplicity:

$$R_{ab} - \frac{1}{2} R\, g_{ab} = T_{ab}$$

That's it.

You would need, of course, to study and digest Riemann's mathematics in order to master the technique to read and use this equation. It takes a little commitment and effort. But less than is necessary to come to appreciate the rarefied beauty of a late Beethoven string quartet. In both cases the reward is sheer beauty and new eyes with which to see the world.