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SCIENCE AND ULTIMATE REALITY

Quantum Theory, Cosmology, and Complexity

This volume provides a fascinating preview of the future of physics, covering fundamental physics at the frontiers of research. It comprises a wide variety of contributions from leading thinkers in the field, inspired by the pioneering work of John A. Wheeler. Quantum theory represents a unifying theme within the book, along with topics such as the nature of physical reality, the arrow of time, models of the universe, superstrings, gravitational radiation, quantum gravity, and cosmic inflation. Attempts to formulate a final unified theory of physics are discussed, along with the existence of hidden dimensions of space, spacetime singularities, hidden cosmic matter, and the strange world of quantum technology.

John Archibald Wheeler is one of the most influential scientists of the twentieth century. His extraordinary career has spanned momentous advances in physics, from the birth of the nuclear age to the conception of the quantum computer. Famous for coining the term "black hole," Professor Wheeler helped lay the foundations for the rebirth of gravitation as a mainstream branch of science, triggering the explosive growth in astrophysics and cosmology that followed. His early contributions to physics include the *S* matrix, the theory of nuclear rotation (with Edward Teller), the theory of nuclear fission (with Niels Bohr), action-at-a-distance electrodynamics (with Richard Feynman), positrons as backward-in-time electrons, the universal Fermi interaction (with Jayme Tiomno), muonic atoms, and the collective model of the nucleus. His inimitable style of thinking, quirky wit, and love of the bizarre have inspired generations of physicists.

John Archibald Wheeler, 1987. (Photograph by Robert Matthews, courtesy of Princeton University.)

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Quantum Theory, Cosmology, and Complexity

Edited by

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Foreword

I am immensely pleased with this wonderful volume, and humbled by it. It demonstrates the incredible vibrancy of fundamental physics, both theoretical and experimental, as a new century gets under way. Just as unimagined vistas of the physical world were revealed in the early years of the twentieth century, so too we are encountering unimagined wonders a hundred years later. If there is an end to physics, an end to understanding the reasons for existence, it lies far in the future.

Who would have guessed in 1925, or even in 1950, that quantum mechanics would remain for so many decades such a fertile field of research? Who would have guessed then that its reason for being would remain mysterious for so long? Like many of the authors in this book, I remain convinced that some deeper reason for quantum mechanics will one day emerge, that eventually we will have an answer to the question, “How come the quantum?” And to the companion question, “How come existence?”

And who could have guessed in 1975 – when the black hole was coming to be accepted, when an explanation of pulsars was at hand, when primordial black-body radiation had been identified – who could have guessed then that an incredible confluence of deep thinking and stunning experimental techniques would push our understanding of cosmology – of the beginnings, the history, and the fate of the universe – to its present astonishing state?

Niels Bohr liked to speak of “daring conservatism” in pursuing physics. That is what I see in this volume. Nearly every chapter reveals a scientist who is hanging on to what is known and what is valid while, with consummate daring (or should I say derring-do?), pushing beyond the limit of what current observation confirms onward to the outer limit of what current theory allows. Here are scientists daring to share their visions of where future knowledge may lie.

The organizers of the symposium on which this book is based are to be congratulated for pulling together and so beautifully integrating the threads of quantum physics, cosmology, and the emergence of complexity. In the 1920s and 1930s, as my own career got started, I was inspired by Niels Bohr, Werner Heisenberg, Albert Einstein, and others. I hope that the young people who read this volume will find similar inspiration in it.

Princeton University
Princeton, New Jersey

John A. Wheeler

Editors' preface

This book project began as part of a special program, *Science and Ultimate Reality*, developed in honor of the ninetieth birthday of renowned theoretical physicist John Archibald Wheeler.[1] Having long yearned for a comprehensive, integrated understanding of the nature of the universe, Wheeler has blended scientific rigor with an unusually adventurous approach to research in physics and cosmology over a career spanning almost 70 years. Known for investigating many of the most fundamental and challenging issues in physics, Wheeler has often worked at the frontiers of knowledge where science and philosophy meet, probing the deep nature of physical reality. His vision, shaped in part by his influential mentor Niels Bohr, still flourishes today amid ongoing research activities pursued by several generations of those he has influenced over the course of much of the twentieth century.

With Wheeler as its inspiration, the *Science and Ultimate Reality* program was developed with a focus on the future. It brought together a carefully selected group of outstanding contemporary research leaders in the physics community to explore the frontiers of knowledge in areas of interest to Wheeler and to map out major domains and possibilities for far-reaching future exploration. Its two principal components – (1) this book and (2) a previously held symposium[2] – were developed to take Wheeler's vision forward into a new century of expanding discovery.

In addition to his role as a research leader in physics, Wheeler has been an inspirational teacher of many of the twentieth century's most innovative physicists. In this context, the program developers, many of whom contributed chapters to this volume, were asked to offer recommendations for their best candidates – not only

[1] Born July 9, 1911 in Jacksonville, Florida.
[2] The symposium, *Science and Ultimate Reality: Celebrating the Vision of John Archibald Wheeler*, was held March 15–18, 2002 in Princeton, New Jersey, United States. See www.metanexus.net/ultimate_reality/ for more information and to order the symposium proceedings on DVD. We wish to acknowledge the support of Dr. William Grassie, Executive Director of the Metanexus Institute, and his expert staff for helping to organize the symposium and for hosting this website. Also see Appendix A for a listing of the program committee members.

distinguished, well-established research leaders, but also highly promising, up-and-coming young innovators – to address the great questions of physical science in the twenty-first century. It is well known that, in physics and mathematics at least, the most powerful insights often come from surprisingly young people. By including young researchers in the Science and Ultimate Reality program, its developers hoped to identify future research leaders for the coming decades.[3]

In formulating the program, the developers purposely solicited research topics in areas close to some of Wheeler's most passionate interests. Some of the questions the developers kept in mind were: What can Wheeler's vision imply for the century ahead? What surprises lie in store for physics? What are the best ways to obtain deep insights into the heart of reality? What are the great unsolved problems of cosmology? How might the next generation of researchers tackle some of Wheeler's "Really Big Questions," such as: "Why the quantum?" "How come existence?" "It from bit?" "A participatory universe?" "What makes 'meaning'?"

This book is intended to stimulate thinking and research among students, professional physicists, cosmologists, and philosophers, as well as all scholars and others concerned with the deep issues of existence. Authors were invited to be bold and creative by developing themes that are perhaps more speculative than is usual in a volume of this sort. Specifically, they were asked to reflect on the major problems and challenges that confront fundamental science at this time and to animate their discussions by addressing the "Really Big Questions" for which Wheeler is so famous. This book is therefore more than a retrospective celebration of Wheeler's ideas and inspirations, or a simple survey of contemporary research. Rather, the editors sought to develop a collection of chapters that also point to novel approaches in fundamental research.

The book's first two chapters provide an overview of John Wheeler's contributions (Part I) and an historian's look at scientific speculation through the ages (Part II). The remaining twenty-eight chapters are grouped according to four themes:

Part III: Quantum reality: theory
Part IV: Quantum reality: experiment
Part V: "Big questions" in cosmology
Part VI: Emergence, life, and related topics.

The *Science and Ultimate Reality* program has provided a high-level forum in which some of the most visionary and innovative research leaders in science today could present their ideas. It continues to be an important mechanism for funding serious

[3] In conjunction with the program, a special Young Researchers Competition was held in which 15 young scientists chosen competitively from among applicants under age 32 presented short talks at the symposium. One of the researchers who tied for first place – Fotini Markopoulou – contributed a chapter to this volume. See www.metanexus.net/ultimate_reality/competition.htm/ for more information. Also see Appendix B for a listing of the competition participants and overseers.

scientific research and to engage with issues of "ultimate reality" in fascinating ways. Its overarching goal is to provide a risk-taking stimulus for research leading to (at least a few) major advances in knowledge of the nature of physical reality. We hope that John A. Wheeler's example will continue to stimulate the imaginations of new generations of the world's best and brightest students and researchers in science and that this book will serve to carry that vision forward.

University of Cambridge *John D. Barrow*
Macquarie University *Paul C.W. Davies*
John Templeton Foundation *Charles L. Harper, Jr.*

Preface

My first encounter with John Archibald Wheeler was in the fall of 1945 in the reading room of the Science Library in London, a warm and comfortable place where anyone could walk in off the street to escape from rain and fog or to browse at leisure in scientific books and journals. I had just been released from war service and was eager to get back into science. I found the classic paper of Bohr and Wheeler, "The mechanism of nuclear fission," in volume 56 of the *Physical Review*, pages 426–450. It was published on September 1, 1939, the day on which Hitler's armies marched into Poland and the Second World War began. Bohr and Wheeler wrote the paper in Princeton, where Bohr was visiting in the spring of 1939, a few months after the discovery of fission. The paper is a masterpiece of clear thinking and lucid writing. It reveals, at the center of the mystery of fission, a tiny world where everything can be calculated and everything understood. The tiny world is a nucleus of uranium 236, formed when a neutron is freshly captured by a nucleus of uranium 235.

The uranium 236 nucleus sits precisely on the border between classical and quantum physics. Seen from the classical point of view, it is a liquid drop composed of a positively charged fluid. The electrostatic force that is trying to split it apart is balanced by the nuclear surface tension that is holding it together. The energy supplied by the captured neutron causes the drop to oscillate in various normal modes that can be calculated classically. Seen from the quantum point of view, the nucleus is a superposition of a variety of quantum states leading to different final outcomes. The final outcome may be a uranium 235 nucleus with a re-emitted neutron, a uranium 236 nucleus with an emitted gamma-ray, or a pair of fission-fragment nuclei with one or more free neutrons. Bohr and Wheeler calculate the cross-section for fission of uranium 235 by a slow neutron and get the right answer within a factor of two. Their calculation is a marvelous demonstration of the power of classical mechanics and quantum mechanics working together. By studying this process in detail, they show how the complementary views provided by classical and quantum pictures are both essential to the understanding of nature. Without the combined power of classical and quantum concepts, the intricacies of the fission process could never have been understood. Bohr's notion of complementarity is triumphantly vindicated.

The Wheeler whose dreams inspired this book is another Wheeler, different from the one I encountered in London. Throughout his life, he has oscillated between two styles of writing and thinking that I like to call prosaic and poetic. In the fission paper, I met the prosaic Wheeler, a master craftsman using the tools of orthodox physical theory to calculate quantities that can be compared with experiment. The prosaic Wheeler always has his feet on the ground. He is temperamentally conservative, taking the existing theories for granted and using them with skill and imagination to solve practical problems. But from time to time, we see a different Wheeler, the poetic Wheeler, who asks outrageous questions and takes nothing for granted. The poetic Wheeler writes papers and books with titles such as "Beyond the black hole," "Beyond the end of time," and "Law without law." His message is a call for radical revolution. He asks, "Should we be prepared to see someday a new structure for the foundations of physics that does away with time?" He proclaims, "Proud unbending immutability is a mistaken ideal for physics; this science now shares, and must forever share, the more modest mutability of its sister sciences, biology and geology." He dreams of a future when "as surely as we now know how tangible water forms out of invisible vapor, so surely we shall someday know how the universe comes into being."

The poetic Wheeler is a prophet, standing like Moses on the top of Mount Pisgah, looking out over the Promised Land that his people will one day inherit. Moses did not live long enough to lead them into the Promised Land. We may hope that Wheeler will live like Moses to the age of 120. But it is the young people now starting their careers who will make his dreams come true. This book is a collection of writings by people who take Wheeler's dreams seriously and dare to think revolutionary thoughts. But in science, as in politics and economics, it is not enough to think revolutionary thoughts. If revolutionary thoughts are to be fruitful, they must be solidly grounded in practical experience and professional competence. What we need, as Wheeler says here in his Foreword, is "daring conservatism." Revolutionary daring must be balanced by conservative respect for the past, so that as few as possible of our past achievements are destroyed by the revolution when it comes.

In the world of politics as in the world of science, revolutionary leaders are of two kinds, conservative and destructive. Conservative revolutionaries are like George Washington, destroying as little as possible and building a structure that has endured for 200 years. Destructive revolutionaries are like Lenin, destroying as much as possible and building a structure that withered and collapsed after his death.

The people who will lead us into the new world of physics must be conservative revolutionaries like Wheeler, at home in the prosaic world of practical calculation as well as in the poetic world of speculative dreams. The prosaic Wheeler and the poetic Wheeler are equally essential. They are the two complementary characters that together make up the John Wheeler that we know and love.

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The editors wish to acknowledge the John Templeton Foundation (see www.templeton.org), and Sir John Templeton personally, for making this project possible. Sir John was enthusiastic about recognizing John A. Wheeler as one of the greatest living scientific leaders exemplifying a bold and far-sighted vision combined with tough-minded scientific rigor. We would also like to thank The Peter Gruber Foundation (see www.petergruberfoundation.org) for additional financial support.

Freeman Dyson and Max Tegmark, contributors to this volume, played key roles in organizing the program. Artur Ekert, Robert Laughlin, Charles Misner, William Phillips, and Charles Townes also provided valuable program advisory assistance, as did many of the contributors to this volume. (See Appendix A for a listing of the program committee members.)

Pamela Bond, working with the John Templeton Foundation, deserves special thanks for her dedicated work. Pam helped to organize the symposium and oversaw and coordinated the communications, manuscripts, artwork, and other practical aspects of producing this book.

We wish to express our special gratitude to Kenneth Ford, a long-time Wheeler colleague, who served as Senior Program Consultant for both the book and the symposium. Ken worked tirelessly to bring a bold idea into fruition. His commitment, skillful diplomacy, and hard work are deeply appreciated.

Finally, we wish to thank Cambridge University Press, and particularly Tamsin van Essen, for their support of this book project.