Science and Ultimate Reality: Quantum Theory, Cosmology and Complexity, *Edited by John D. Barrow, Paul C.W. Davies and Charles L. Harper Jr.*, Cambridge University Press, 2004, pp: 721, ISBN 052183113X (hc); Price: US$55.

This is an adventurous book exploring the deepest foundations of physics. It is a collection of papers presented at the 2002 symposium "Science and Ultimate Reality: Celebrating the Vision of John Archibald Wheeler" which honour Wheeler's 90th birthday by addressing his "Really Big Questions" about the physics of the universe and of our existence. The symposium was organized by the Metanexus Institute[1] and was held in Princeton, New Jersey.

Wheeler is probably best known today in connection with terms that he coined: *black holes*, *quantum foam* and *wormholes*. He is co-author of the hefty classic *Gravitation* (1973) as well as the excellent undergraduate-level books *Spacetime Physics* (1992) and *Exploring Black Holes: Introduction to General Relativity* (2000). But his precocious brilliance, originality, and "austerity in thinking" (p. 201) put him in exalted company even as he began his career in the 1930s and 40s. He did postgraduate work under Neils Bohr and he participated in the Manhattan Project (with his ever-impertinent Ph.D. student Richard Feynman).

In his postwar career, Wheeler concentrated on the mysteries of general relativity, quantum mechanics and the evolution of physical laws. Iconoclastic, yet eminently likeable, he dared to express some of the most outrageous hypotheses. One of Wheeler's mind-benders is encapsulated in the phrase "Law without law": the idea that at the very instant of the Big Bang, there were no laws at all! He believes it possible that the laws emerged in a completely random fashion, but that they became increasingly restricted by the principle that they could never be contradictory. This implies that the laws may still be changing (although orders of magnitude more slowly). Wheeler also speculates, on the basis of the "delayed-choice" experiment applied on a universal scale, that the appearance of law-like behaviour in nature might be linked to cascades of collapsing wave functions that bestow reality on what previously were only probabilities. He calls this notion " 'It' from 'bit'," or matter emerging from an initial state of pure information.

Canada's Perimeter Institute of Theoretical Physics (PI) is well represented in four papers: Lucien Hardy's "Why is nature described by quantum theory?" (Ch. 3), Aephraim Steinberg's "Speakable and unspeakable, past and future" (Ch. 12), Lee Smolin's "Quantum theories of gravity: results and prospects" (Ch. 22), and Fotini Markopoulu's "Planck-scale models of the universe" (Ch. 24). The paper by Markopoulu (*née*, now Markopoulu-Kalamara) was actually submitted to the concurrent 2002 Young Researchers Competition, in which she tied for first place.

Each of the 30 papers presented forms one chapter of the book and these are grouped into five parts. The first two are brief, having only one paper each. Part I presents a summary of Wheeler's contributions and an overview of the symposium's topics. In Part II, historian Jaroslav Pelikan discusses Wheeler's "itch to speculate" and traces the traditions of scientific speculation through the ages, starting with the philosopher Heraclitus of Ancient Greece.

The real "meat" of the book begins with Part III, "Quantum Reality: Theory," (8 papers). In Chapter 3, Lucien Hardy looks at two of Wheeler's Really Big Questions: "How come existence?" and "How come the quantum?" One point brought out here is that although quantum mechanics is "at root" a probability theory, it nevertheless differs from classical probability theory in important ways. Freeman Dyson, in his paper, "Thought-experiments in honor of John Archibald Wheeler," (Ch. 4) speculates that Einstein was so little interested in black holes for the same reason that Wheeler *embraced* them, namely because "they show most sharply the contingent and provisory character of physical law." (p. 72). One of Dyson's thought-experiments led him to conclude that "quantum-mechanical description can be consistently applied only to the future and not to the past." Dyson also raises the possibility of testing, in the laboratory, whether the Heisenberg uncertainty principle is truly inviolable. His candor is refreshing: in the closing section he says, "I hope this chapter has left you as confused as it leaves me." Richard Feynman had said that he didn't really understand QM; Dyson confirms that there is still much to understand.

Other papers in Part III address "quantum Darwinism", quantum computers, quantum gravity as "an ordinary gauge theory," and the Everett interpretation of QM.

Part IV, "Quantum Reality: Experiment" has seven papers. Anton Zeilinger's discusses experiments for three of Wheeler's challenges (Ch. 11). Something I found interesting is that the largest objects for which quantum interference has been demonstrated (up to 1999) are molecules of the fullerene C_{70}. In Chapter 12, Aephraim Steinberg focuses on "the new trend towards attempting to talk about *history* in quantum mechanics." Raymond Chiao (Ch. 13) examines the "experimental consequences" of the "three conceptual tensions" between QM and general relativity. These are (1) QM's *spatial nonseparability* versus GR's *spatial separability* of physical systems; (2) QM's *uncertainty principle* versus GR's *equivalence principle*; and (3) the *mixed state* in GR (e.g. one of a pair of quantum-entangled particles disappearing into a black hole while the other flies off to infinity) versus the *pure state* in QM. Serge Haroche, in "Breeding nonlocal Schrödinger's cats" (Ch. 14) presents his thought-experiment to "explore the quantum-classical boundary." The last three chapters discuss quantum measurement, quantum feedback (in the quantum-classical transition) and quantum computers.

Part V is "Big Questions in Cosmology" (8 papers). Andreas Albrecht (Ch. 18) discusses the "thermodynamic arrow of time", which he regards as being equivalent to the "radiation", "psychological", and "QM" arrows of time. His is one of the longest and richest papers, discussing cosmic inflation under various initial conditions, the *ekpyrotic universe* that results from colliding branes in a higher-dimensional space, the cyclic universe, variable speed of light, and more. He concludes that for there to be an arrow of time, all the mechanisms he discusses need "some kind of rare fluctuation to function."

John Barrow (Ch. 19) discusses whether our accepted constants of nature, such as the fine-structure constant, could in fact be varying so as to keep the universe stable while retaining zero vacuum energy. Andrei Linde's paper, "Inflation, quantum cosmology, and the anthropic principle" (Ch. 20) asks, "Is it possible that consciousness, like spacetime, has its own intrinsic degrees of freedom, and that neglecting these will lead to a description of the universe that is fundamentally incomplete?" (p. 451).

Max Tegmark's paper (Ch. 21) on parallel universes gives two interesting diagrams. Figure 21.7 (p. 479) is a family tree of physical theories as they would relate to a master theory at the top that successfully unites GR with quantum field theory; and Figure 21.8 (p. 481) shows the (tangled) interconnections between all of the areas of mathematics relevant for understanding GR and QM — a handy guide for beginning researchers.

In Chapter 22, Lee Smolin closely compares the current status of *loop quantum gravity* versus *string theory*. He presents a comprehensive list of 24 criteria, compares each theory one criterion at a time, then tabulates the results (Table 22.1, p. 521). Smolin himself is in the former camp, and claims that string theory is not a theory in the conventional sense, but rather a *research program* called "string theory" in search of the *definition* of a true theory to be called "STRING THEORY". Regardless of one's "religion" in this regard, the table provides a good bird's-eye view on where ignorance is currently profoundest.

The radical concepts of varying fine-structure constant and varying light speeds are discussed in João Magueijo's paper, "A genuinely evolving universe" (Ch. 23). I was struck by his taunt, "Most current efforts in quantum gravity and string theory are doomed to fail, because those proposing them have no interest whatsoever in obtaining inspiration from observations. Instead they have arrogantly relied on what might be called 'mathematical beauty,' usually a byword for theoretical prejudice." (p. 541) Fighting words, these.

In Chapter 24, Fotini Markopoulou describes how *causal spin networks*, or *spin foams*, successfully combine background independence (i.e., no spacetime manifold) and quantum theory, as is required for a theory of quantum gravity. A radical consequence is that at the Planck scale (length $\approx 10^{-33}$ cm, time $\approx 10^{-43}$s,), the spacetime manifold is not continuous, but the idea is still amenable to confirmation (or refutation) by fine-tuning the models and comparing their predictions to experimental data. Lisa Randall's paper (Ch. 25) looks at the implications of additional spatial dimensions in cosmology.

The last section, Part VI, "Emergence, Life and Related Topics," contains the most speculative papers (5 in all). Philip Clayton's "Emergence: us from it" (Ch. 26) gives several examples of self-organization (or emerging structures) in artificial systems (e.g., cellular automata) and living systems (e.g. nerve nets). George Ellis looks at "true complexity", causality, and their relation to ultimate reality. The paper by Marcelo Gleiser, "The three origins: cosmos, life, and mind," (Ch. 28) shows how local and global emergent complex behaviour can arise from simple field models. Chapter 29, "Autonomous agents" by Stuart Kauffman, discusses systems that "can act on their own behalf in an environment." The last chapter is Shou-Cheng Zhang's "To see a world in a grain of sand," describing how superfluid helium films and the 4-D quantum Hall effect can exhibit emergent behaviour.

The paper, print and binding of this book are of high quality despite its relatively low price. Graduate-level mathematics is used only when necessary. Each paper also provides many references for further reading.

It is not surprising that some of Wheeler's far-out ideas were co-opted by nonscientists to justify their own work in the paranormal. However, Wheeler was always careful to distance himself from the realm of pseudoscience. For example, in 1969, when Wheeler was on the board of directors of the AAAS[2], he (unsuccessfully) voted against admitting the Parapsychological Association as an affiliate organization.

At the start of the 20th century, mathematician David Hilbert challenged future mathematicians with his 23 unsolved problems.[3] At the start of the 21st century stand Wheeler's "Really Big Questions" to challenge future generations of physicists. These questions are at the heart of *Science and Ultimate Reality: Quantum Theory, Cosmology and Complexity*, making it a valuable sourcebook of research topics in theoretical physics. In Wheeler's own words (p. xii): "I was inspired by Neils Bohr, Werner Heisenberg, Albert Einstein, and others. I hope that the young people who read this volume will find similar inspiration in it."

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1. http://www.metanexus.net
2. American Association for the Advancement of Science
3. Some are still unsolved. See: http://mathworld.wolfram.com/HilbertsProblems.html