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Part I

An overview of the contributions of John Archibald Wheeler

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John Archibald Wheeler and the clash of ideas

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History will judge John Archibald Wheeler as one of the towering intellects of the twentieth century. His career spanned the transition from the celebrated Golden Age of physics to the New Physics associated with the Space Age, the information revolution and the technological triumphs of quantum and particle physics. His contributions, ranging from trailblazing work in nuclear physics to general relativity and astrophysics, are too numerous to list here.[1] His influence on three generations of physicists is immense.

But Wheeler has been more than a brilliant and influential theoretical physicist. The decision to hold a symposium *Science and Ultimate Reality* in his honor reflects the fact that he is also an inspiring visionary who brought to physics and cosmology a unique style of thought and mode of reasoning, compared by Jaroslav Pelikan in this volume to that of the Greek philosopher Heraclitus.

"Progress in science," Wheeler once remarked to me, "owes more to the clash of ideas than the steady accumulation of facts." Wheeler has always loved contradiction. After all, the Golden Age of physics was founded on them. The theory of relativity sprang from the inconsistency between the principle of relativity of uniform motion, dating back to Galileo, and Maxwell's equations of electromagnetism, which predicted a fixed speed of light. Quantum mechanics emerged from the incompatibility of thermodynamics with the continuous nature of radiation energy.

Wheeler is perhaps best known for his work in the theory of gravitation, which receives its standard formulation in Einstein's general theory of relativity. Although hailed as a triumph of the human intellect and the most elegant scientific theory

[1] See Wheeler's autobiography *Geons, Black Holes, and Quantum Foam: A Life in Physics* (W. W. Norton, New York, 1998) for more background information.

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known, the general theory of relativity was for decades a scientific backwater. Its renaissance in the 1950s and 1960s was due in large measure to the work and influence of John Wheeler and his many talented students. It was Wheeler who coined the terms *black hole*, *wormhole*, *spacetime foam*, *no-hair theorems*, and many other ubiquitous expressions of gravitational physics. And it was in the theory of gravitation that Wheeler confronted the starkest contradiction, the most iconoclastic clash of ideas in science, and one that underscored so much of his imaginative later work. In the 1960s, astronomical evidence began to accumulate that compact massive bodies such as the cores of burnt-out heavy stars could not avoid imploding, suddenly and catastrophically, under their own immense weight, a phenomenon dubbed gravitational collapse. Wheeler was fascinated by the paradox implied by the final stages of collapse – the formation of a so-called spacetime singularity, in which matter is squeezed into a single point of infinite density, and the gravitational field rises without limit. The fate of a star in this respect resembles on a small scale and in time reverse the origin of the entire universe in a big bang, where spacetime is hypothesized to have exploded into existence from an initial singularity.

Gravitational collapse evidently signals the end of . . . what? The general theory of relativity? The concept of spacetime? Physical law itself? Here was a state of affairs in which a physical theory contained within itself a prediction of its own demise, or at least its own inherent limitation. "Wheeler's style," a colleague once told me, "is to take a perfectly acceptable physical theory, and extrapolate it to the ultimate extreme, to see where it must fail." With gravitational collapse, that ultimate extreme encompassed not just the obliteration of stars but the birth and perhaps death of the entire universe.

Two words that recur frequently in the Wheeler lexicon are *transcendence* and *mutability*. At what point in the extrapolation of a theory would the physical situation become so extreme that the very concepts on which the theory is built are overtaken by circumstances? No topic better epitomizes this philosophy than the black hole. When a massive star collapses the gravitational field rises higher and higher until even light itself is trapped. The material of the core retreats inside a so-called event horizon and effectively disappears as far as the outside universe is concerned. What, one may ask, happens to the imploding matter? What trace does it leave in the outside universe of its erstwhile existence? Theory suggests that only a handful of parameters survive the collapse – mass, electric charge, and angular momentum being the three principal conserved quantities. Otherwise, cherished conservation laws are not so much violated as transcended; they cease to be relevant. For example, a black hole made of matter cannot be distinguished from one made of antimatter, or neutrinos, or even green cheese, if the few conserved parameters are the same.

Although the concept of the black hole had been implicit in the general theory of relativity for some decades, it was only in the late 1960s, in large part through the work of John Wheeler, together with Roger Penrose, Stephen Hawking, Robert Geroch, Brandon Carter, and others, that the extraordinary physical properties of such objects became understood. Already in those early days it was clear that one very basic law of physics – the second law of thermodynamics – was threatened by the existence of black holes, since they could apparently swallow heat and thus reduce the entropy of the universe. Conversely, if a black hole is perfectly black, its own entropy (normally measured as energy divided by temperature) would seem to be infinite. Again, physical theory extrapolated to the limit led to a nonsensical result. Wheeler brilliantly spotted that quantum mechanics might provide a way around this and come to the rescue of the second law of thermodynamics, in some ways the most cherished of all physical laws. Together with his student Jacob Bekenstein, Wheeler surmised that the event horizon area of the black hole constitutes a completely new form of entropy, so that when a black hole swallows heat, it swells in size, and its entropy will rise by at least the loss of heat entropy.

These early ideas were placed on a sound theoretical basis in 1975 when Hawking showed by applying quantum mechanics to black holes that they are not black at all, but glow with heat radiation at a temperature directly related to their mass. So quantum mechanics rescues the second law of thermodynamics from an apparent absurdity when it is combined with general relativity. This episode provides a wonderful example of the internal consistency of theoretical physics, the fact that disparate parts of the discipline cunningly conspire to maintain the deepest laws.

But what of the fate of the imploding matter? The general theory of relativity makes a definite prediction. If the core of the star were a homogeneous spherical ball, continued shrinkage can result in one and only one end state: all matter concentrated in a single point of infinite density – the famed *singularity*. Since the general theory of relativity treats gravitation as a warping or curvature of spacetime, the singularity represents infinite curvature, which can be thought of as an edge or boundary to spacetime. So here is a physical process that runs away to infinity and rips open space and/or time itself. After that, who can say what happens?

As a general rule, infinity is a danger signal in theoretical physics. Few physicists believe that any genuinely infinite state of affairs should ever come about. Early attempts to solve the problem of spacetime singularities by appealing to departures from symmetry failed – a wonky star may not implode to a single point, but, as Penrose proved, a spacetime singularity of some sort is unavoidable once the star has shrunk inside an event horizon or something similar.

To Wheeler, the singularity prediction was invested with far-reaching significance that conveyed his core message of mutability. He likened the history of physics to a staircase of transcendence, at each step of which some assumed physical property dissolved away to be replaced by a new conceptual scheme. Thus Archimedes established the density of matter as an important quantity, but later high-pressure technology showed it was not conserved. Nuclear transmutations transcended the law of conservation of the elements. Black holes transcended the law of conservation of lepton number. And so on. Wheeler went on to conclude:

> At the head of the stairs there is a last footstep of law and a final riser of law transcended. There is no law of physics that does not require "space" and "time" for its statement. Obliterated in gravitational collapse, however, is not only matter, but the space and time that envelop that matter. With that collapse the very framework falls down for anything one ever called a law of physics.

The lesson to be learned from this? "Law cannot stand engraved on a tablet of stone for all eternity . . . All is mutable." Indeed, mutability was Wheeler's own choice when I asked him, in the mid 1980s, what he regarded as his most important contribution to physics. He summed up his position with a typical Wheelerism: "There is no law other than the law that there is no law."

It has always been Wheeler's belief that gravitational collapse is a pointer to a deeper level of reality and a more fundamental physical theory, and that this deeper level will turn out to be both conceptually simple and mathematically elegant: "So simple, we will wonder why we didn't think of it before," he once told me. But delving beyond the reach of known physical law is a daunting prospect, for what can be used as a guide in such unknown territory? Wheeler drew inspiration from his "law without law" emblem. Perhaps there are no ultimate laws of physics, he mused, only chaos. Maybe everything "comes out of higgledy-piggledy." In other words, the very concept of physical law might be an emergent property, in two senses. First, lawlike behavior might emerge stepwise from the ferment of the Big Bang at the cosmic origin, instead of being mysteriously and immutably imprinted on the universe at the instant of its birth: "from everlasting to everlasting," as he liked to put it. In this respect, Wheeler was breaking a 400-year-old scientific tradition of regarding nature as subject to eternal laws. Second, the very appearance of lawlike behavior in nature might be linked in some way to our observations of nature – subject and object, observer and observed, interwoven. These were radical ideas indeed.

One beacon that Wheeler has employed throughout his search for a deeper level of reality is quantum mechanics. The quantum is at once both an obstacle and an opportunity. Twentieth-century physics was built largely on the twin pillars of the general theory of relativity and quantum mechanics. The former is a description of space, time, and gravitation, the latter a theory of matter. The trouble is, these two very different sorts of theories seem to be incompatible. Early attempts at combining them by treating the gravitational field perturbatively like the electromagnetic field, with hypothetical gravitons playing a role analogous to photons, ran into severe mathematical problems. Although a few physical processes could be satisfactorily described by this procedure, most answers were infinite in a way that could not be circumvented by simple mathematical tricks. The predictive power of this approach to quantum gravity was fatally compromised.

In spite of these severe conceptual and mathematical problems, Wheeler realized that at some level quantum effects must have a meaningful impact on gravitational physics, and since the gravitational field receives a geometrical interpretation in Einstein's general theory of relativity, the net result must be some sort of quantum spacetime dynamics, which Wheeler called quantum geometrodynamics. Here, spacetime geometry becomes not only dynamical, but subject to quantum rules such as Heisenberg's uncertainty principle.

One expression of the uncertainty principle is that physical quantities are subject to spontaneous, unpredictable fluctuations. Thus energy may surge out of nowhere for a brief moment; the shorter the interval the bigger the energy excursion. Simple dimensional analysis reveals that for durations as short as 10^{-43} s, known after Max Planck as the Planck time, these energy fluctuations should be so intense that their own gravity seriously distorts the microscopic structure of spacetime. The size scale for these distortions is the Planck length, 10^{-33} cm, about 20 powers of ten smaller than an atomic nucleus, and hence in a realm far beyond the reach of current experimental techniques. On this minuscule scale of size and duration, quantum fluctuations might warp space so much that they change the topology, creating a labyrinth of wormholes, tunnels, and bridges within space itself. As ever, Wheeler was ready with an ingenious metaphor. He compared our view of space to that of an aviator flying above the ocean. From a great height the sea looks flat and featureless, just as spacetime seems flat and featureless on an everyday scale of size. But with a closer look the aviator can see the waves on the surface of the sea, analogous to ripples in spacetime caused by quantum fluctuations in the gravitational field. If the aviator comes down low enough, he can discern the foam of the breaking waves, a sign that the topology of the water is highly complex and shifting on a small scale. Using this reasoning, Wheeler predicted in 1957 the existence of spacetime foam at the Planck scale, an idea that persists to this day.

In his later years Wheeler drew more and more inspiration from the quantum concept. In 1977 he invited me to spend some time with him in Austin at the University of Texas, where he was deeply involved with the nature of quantum observation. He was fond of quoting the words of his mentor Niels Bohr concerning the thorny question of when a measurement of a quantum system is deemed to have taken place. "No measurement is a measurement until it is brought to a close by an irreversible act of amplification," was the dictum. Accordingly, I delivered a lecture on quantum mechanics and irreversibility that I hoped might have some bearing on this project, but it was clear that Wheeler saw something missing in mere irreversibility per se. A true observation of the physical world, he maintained, even something as simple as the decay of an atom, must not only produce an indelible record, it must somehow impart *meaningful information*. Measurement implies a transition from the realm of mindless material stuff to the realm of knowledge. So it was not enough for Wheeler that a measurement should record a bit of information; that lowly bit had to *mean* something. Applying his usual practice of extrapolating to the extreme, he envisaged a community of physicists for whom the click of the Geiger counter amounted to more than just a sound; it was connected via a long chain of reasoning to a body of physical theory that enabled them to declare "The atom has decayed!" Only then might the decay event be accorded objective status as having happened "out there" in the physical world.

Thus emerged Wheeler's idea of the *participatory universe*, one that makes full sense only when observers are implicated; one that is less than fully real until observed. He envisaged a *meaning circuit*, in which atomic events are amplified and recorded and delivered to the minds of humans – events transformed into meaningful knowledge – and then conjectured a return portion of that meaning circuit, in which the community of observers somehow loops back into the atomic realm.

To bolster the significance of the "return portion" of the circuit, Wheeler conceived of a concrete experiment. It was based on an adaptation of the famous Young's two-slit experiment of standard quantum mechanics (see Fig. 1). Here a pinhole light source illuminates a pair of parallel slits in an opaque screen, closely spaced. The image is observed on a second screen, and consists of a series of bright and dark bands known as interference fringes. They are created because light has a wave nature, and the waves passing through the two slits overlap and combine. Where they arrive at the image screen in phase, a bright band appears; where they are out of phase a dark band results.

According to quantum mechanics light is also made up of particles called photons. A photon may pass through either one slit or the other, not both. But since the interference pattern requires the overlap of light from *both* slits there seems to be a paradox. How can particles that pass through either one slit or the other make a wave interference pattern? One answer is that each photon arrives at a specific spot on the image screen, and many photons together build up a pattern in a speckled sort of way. As we don't know through which slit any given photon has passed, and as the photons are subject to Heisenberg's uncertainty principle, somehow each photon "knows" about both slits. However, suppose a mischievous experimenter stations a detector near the slit system and sneaks a look at which slit each photon traverses? There would then be a contradiction if the interference pattern persists, because each photon would be seen to encounter just a single slit. It turns out that if this intervention is done, the pattern gets washed out. One way to express this is to say that the experimenter can choose whether the wavelike or particlelike nature of light shall be manifested. If the detector is positioned near the slits, light takes on the properties of particles and there is no wave interference pattern. But if the experimenter relinquishes information about which slit each photon traverses, light behaves like a wave and the pattern is observed. In this manner the experimenter helps determine the nature of light, indeed, the nature of reality. The experimenter *participates* in deciding whether light is made up of waves or particles.

Wheeler's distinctive adaptation of this experiment came from spotting that the experimenter can delay the choice – wave or particle – until *after* the light has passed through the slit screen. It is possible to "look back" from the image screen and deduce through which slit any given photon came. The conclusion is that the experimenter not only can participate in the nature of physical reality that is, but also in the nature of physical reality that *was*. Before the experimenter decided, the light was neither wave not particle, its status in limbo. When the decision was made, the light achieved concrete status. But . . . this status is bestowed upon the light at a time *before* the decision is made! Although it seems like retrocausation, it isn't. It is not possible for the experimenter to send information back in time, or to cause a physical effect to occur in the past in a controlled way using this set-up.

In typical Wheeler fashion, John took this weird but secure result and extrapolated it in the most extreme fashion imaginable. I first learned about this when I ran into Wheeler at a conference in Baltimore in 1986. "How do you hold up half the ghost of a photon?" he asked me quizzically. What he had in mind was this. Imagine that the light source is not a pinpoint but a distant quasar, billions of light years from Earth. Suppose too that the two slits are replaced by a massive galaxy that can bend the light around it by gravitational lensing. A given photon now has a choice of routes for reaching us on Earth, by skirting the galaxy either this way or that. In principle, this system can act as a gigantic cosmic interferometer, with dimensions measured in billions of light years. It then follows that the experimenter on Earth today can perform a delayed choice experiment and thereby determine the nature of reality that was *billions of years ago*, when the light was sweeping by the distant galaxy. So an observer here and now participates in concretizing the physical universe at a time that life on Earth, let alone observers, did not yet exist! John's query about holding up half the ghost of a photon referred to the technical problem that the light transit times around the galaxy might differ by a month or so, and light coming around one way might have to be coherently stored until the light coming round the other way arrives in order to produce an interference pattern.

So Wheeler's participatory universe ballooned out from the physics lab to encompass the entire cosmos, a concept elegantly captured by his most famous emblem, shown in Fig. 26.1 on p. 578. The U stands for universe, which originates in a Big

Bang, evolves through a long and complicated sequence of states to the point where life emerges, then develops intelligence and "observership." We, the observers, can look back at photons coming from the early universe and play a part in determining the reality that was, not long after the Big Bang. In this symbol, Wheeler seeks to integrate mind and cosmos via quantum physics in a dramatic and provocative manner. He is not claiming that the physical universe doesn't exist unless it is observed, only that past states are less than real (if by real one means possessing a full set of physical attributes, such as all particles having a definite position, motion, etc.), and that present observers have a hand in determining the actuality of the past – even the remote past.

The universe according to Wheeler is thus a "strange loop" in which physics gives rise to observers and observers give rise to (at least part of) physics. But Wheeler seeks to go beyond this two-way interdependence and turn the conventional explanatory relationship

$$\text{matter} \rightarrow \text{information} \rightarrow \text{observers}$$

on its head, and place observership at the base of the explanatory chain

$$\text{observers} \rightarrow \text{information} \rightarrow \text{matter}$$

thus arriving at his famous "it from bit" dictum, the "it" referring to a physical object such as an atom, and the "bit" being the information that relates to it. In it from bit, the universe is fundamentally an information-processing system from which the appearance of matter emerges at a higher level of reality.

The symposium *Science and Ultimate Reality* held in Princeton, March 15–18, 2002, sought to honor John Wheeler in his ninetieth birthday year and to celebrate his sweeping vision of the physical universe and humankind's place within it. In keeping with Wheeler's far-sightedness, the symposium dwelt less on retrospection and more on carrying Wheeler's vision into a new century. To this end, papers were presented by leading scientists working at the forefront of research in fields that have drawn inspiration from Wheeler's ideas. In addition, 15 young researchers were invited to deliver short addresses on their groundbreaking work. The presentations were organized around three broad themes: "Quantum reality," "Big questions in cosmology," and "Emergence." The full texts of those papers appear in the later chapters of this volume.[2]

In seeking a deeper level of reality, Wheeler returned again and again to quantum mechanics as a guide. The vast majority of scientists take quantum mechanics for

[2] See http://www.metanexus.net/ultimate_reality/competition.htm for more information on the competition and http://www.metanexus.net/ultimate_reality/main.htm for more information on the symposium.

granted. Students often ask *why* there is indeterminism in the atomic domain, or where Schrödinger's equation comes from. The standard answer is simply, "The world just happens to be that way." But some scientists, following Wheeler's lead, are not content to simply accept quantum mechanics as a God-given package of rules: they want to know *why* the world is quantum mechanical. Wheeler's insistent question, "How come the quantum?" received a good deal of attention at the symposium.

One way to approach this problem is to ask if there is anything special about the logical and mathematical structure of quantum mechanics that singles it out as a "natural" way for the universe to be put together. Could we imagine making small changes to quantum mechanics without wrecking the form of the world as we know it? Is there a deeper principle at work that translates into quantum mechanics at the level of familiar physics?

Lucien Hardy of the Centre for Quantum Computation at the University of Oxford has attempted to construct quantum mechanics from a set of formal axioms. Boiled down to its essentials, quantum mechanics is one possible set of probabilistic rules with some added properties. The question then arises as to whether it has specially significant consequences. Could it be that quantum mechanics is the simplest mechanics consistent with the existence of conscious beings? Or might quantum mechanics be the structure that optimizes the information processing power of the universe? Or is it just an arbitrary set of properties that the world possesses reasonlessly?

The flip side of the challenge "How come the quantum?" is to understand how the familiar classical world of daily experience emerges from its quantum underpinnings, in other words, "How come the classical?" Few disputes in theoretical physics have been as long-running or as vexed as the problem of how the quantum and classical worlds join together. Since the everyday world of big things is made up of little things, quantum mechanics ought to apply consistently to the world as a whole. So why don't we see tables and chairs in superpositions of states, or footballs doing weird things like tunnelling through walls?

Melding the madhouse world of quantum uncertainty with the orderly operation of cause and effect characteristic of the classical domain is a challenge that has engaged many theorists. Among them is Wojciech Zurek from the Los Alamos National Laboratory. In a nutshell, Zurek's thesis is that quantum systems do not exist in isolation: they couple to a noisy environment. Since it is central to the quantum description of nature that matter has a wave aspect, then quantum weirdness requires the various parts of the waves to retain their relative phases. If the environment scrambles these phases up, then specifically quantum qualities of the system are suppressed. This so-called "decoherence" seems to be crucial in generating a quasi-classical world from its quantum components, and Zurek has played a leading