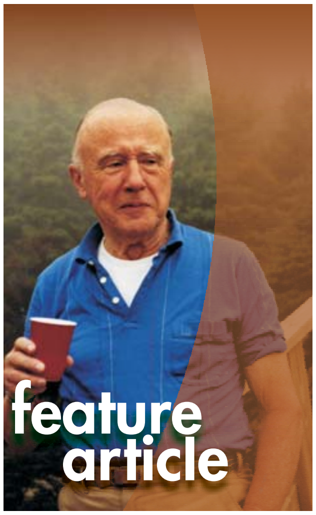

John Wheeler, relativity, and quantum information

Charles W. Misner, Kip S. Thorne, and Wojciech H. Zurek

From the mid-1950s on, John Wheeler's "radical conservative-ism" allowed him to explore without fear crazy-sounding ideas that often led to profound physical insights.

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In spring 1952, as John Wheeler neared the end of design work for the first thermonuclear explosion, he plotted a radical change of research direction: from particles and atomic nuclei to general relativity.

With only one quantitative observational contact (the perihelion shift of Mercury) and two qualitative ones (the expansion of the universe and gravitational light deflection) general relativity in the early 1950s had become a backwater of physics. It was more a branch of mathematics than of physics, and a not very interesting one. Among the world's leading physicists at the time, only Wheeler envisioned a future in which curved spacetime would be fundamental to the nature of matter and the astrophysical universe. Because, in his words, "relativity is too important to leave to the mathematicians," Wheeler set out to discover its roles. Through that quest, over the subsequent two decades, he, his students, and their intellectual descendants would revitalize general relativity and make it an exciting field for other researchers.

"If you would learn, teach!" was one of Wheeler's favorite aphorisms (figure 1). So as the first step in his quest, he taught a course in relativity at Princeton University—the first such course since 1941. In his 1952–53 course, he began to develop his own physical and geometric viewpoint on the subject, a viewpoint that would later be enshrined in his textbook *Gravitation*.[1]

"Everything is fields"

While teaching his first relativity course, Wheeler realized there could exist, at least in principle, a spherical or toroidal object made up of electromagnetic waves that hold themselves together gravitationally, with the waves' gravitational binding produced by their energy. He called such an object a geon (gravitational–electromagnetic entity), and he explored its properties in depth as a classical model for an elementary particle.[2] (For "geon" and other terms coined by Wheeler, see box 1.) More interesting, he realized a bit later, was a purely gravitational geon: a bundle of gravitational waves held together gravitationally. Such a geon would pull on its surroundings, thereby exhibiting mass, but it would not contain any material mass. Mass without mass, he called it.

The geon in one sense was a dead end. As Wheeler soon realized, the conditions for creating a geon almost certainly do not exist in our universe except possibly in its earliest moments. And once a geon was created, not only would its waves leak out slowly but a collective instability would destroy it in a short time. Nevertheless, for Wheeler the geon was crucial: It hinted at a richness that might reside, as yet unexplored, in Albert Einstein's general theory of relativity; it gave him the courage to enlist students and postdocs in his quest for that richness; and it gave him the idea that fundamental particles might actually be built, in some manner, from curved spacetime—quantum mechanical variants of a geon.

Charge without charge might also exist: Resurrecting a 1924 idea of Hermann Weyl, Wheeler imagined electric field lines threading topological handles in the structure of space (for which he coined the word "wormhole"). One mouth of the wormhole would have electric fields entering it and thus exhibit negative charge, and the fields emerging from the other mouth would make it positively charged. Could an electron's or proton's charge be some quantum variant of that scenario?

By 1955, when Wheeler published his first geon paper[2] (including remarks about charge without charge and wormholes), he was bubbling over with ideas for general-relativity research projects and was starting to feed them to his first set of relativity students. He was also developing an approach to physics that he called *radical conservative-ism*: Insist on adhering to well-established physical laws (be conservative), but follow those laws into their most extreme domains (be radical), where unexpected insights into nature might be found. He attributed that philosophy to his own revered mentor, Niels Bohr.

In that spirit, in the mid- and late 1950s Wheeler and his entourage explored geons of all conceivable types, cylindrical gravitational waves, the interaction of neutrinos with curved spacetime, the interface between general relativity and quantum theory, the physical interpretation of quantum mechanics, and a closed universe made from a large number of wormhole mouths with collective gravitational pulls sufficient to bend the universe's space up into a topological 3-sphere. In a tour de force, Wheeler and his group of nine

Figure 1. John Wheeler lecturing at a conference in Cambridge, UK, in 1971. Wheeler's style was to cover the blackboard with inspirational colored-chalk diagrams and phrases before the lecture, then work his way through them, one by one.

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students, postdocs, and visitors presented papers on all those issues at the First International Conference on General Relativity and Gravitation—held in Chapel Hill, North Carolina, in January 1957—and wrote them up,[3] mostly as eight papers in the July 1957 issue of *Reviews of Modern Physics*.

As with Wheeler's geon paper, some of those papers are now historical curiosities, but four laid crucial foundations for major developments. Joseph Weber used his paper with Wheeler on cylindrical gravitational waves as a springboard for launching his pioneering research on gravitational-wave experiments—research that underpins today's gravitational-wave observatories. A paper, discussed below, by Tullio Regge and Wheeler became the foundation for future studies of black hole pulsations. Hugh Everett laid out in his paper what has come to be called the many-worlds interpretation of quantum mechanics, and in an accompanying paper Wheeler explained Everett's ideas in different language. Despite his own misgivings about "many worlds," which he more modestly called the relative-state formulation of quantum mechanics, Wheeler recognized the importance of Everett's ideas: He encouraged Everett and helped disseminate those ideas, and even returned to them in 2001 in one of his last published papers.[4]

The gravitational geon and the model universe constructed from wormholes were entities made solely from spacetime curvature—entities whose geometries must evolve as time passes. Wheeler realized they were examples of geometrodynamics—a term he coined by analogy with electrodynamics to denote the structure and dynamics of curved spacetime. He chose *Geometrodynamics* as the title of his first long treatise on relativity, mostly a collection of his early relativity publications. In his students' hands, those early ideas have had a huge impact:[5] In 1960 Wheeler's postdoc Dieter Brill and undergraduate James Hartle fleshed out the gravitational geon by developing a two-length-scale expansion technique to solve Einstein's vacuum field equations. That technique, in the hands of Richard Isaacson, a student under one of us (Misner), morphed into the rigorous description of gravitational-wave energy that forms the buttress of today's gravitational-wave searches.

While working on thermonuclear weapons in the early 1950s, Wheeler had learned the power of numerical simulations, so he encouraged his students to begin laying foundations for numerical relativity. He envisioned an era, which has now arrived, when numerical simulations would reveal the nonlinear dynamics of curved spacetime—geometrodynamics under the most extreme circumstances. Seminal papers by Richard Arnowitt, Stanley Deser, and Misner expressed geometrodynamics in the mathematical form that would become for decades the preferred starting point for computational work.[6] Papers on binaries made from wormholes attracting each other, written in the late 1950s and early 1960s by Wheeler's students Brill, Misner, and Richard Lindquist, are still used today, a half century later, to provide initial data[7] for some simulations of binary black holes. And an elegant, analytical solution of the constraint equation, suggested by Wheeler and carried through by Brill, is used today as the starting point for simulations of highly distorted black holes that vibrate wildly, emitting copious gravitational waves, before settling down into a quiescent state. Fifty years ago Wheeler could only dream of the 21st-century simulations that are now teaching us wonderful things about nonlinear geometrodynamics.

In 1953 or 1954, while pondering geons in the quantum domain, Wheeler identified the characteristic length scale ($\sim 10^{-33}$ cm) and time scale ($\sim 10^{-43}$ s) on which general relativity must break down and be replaced by new laws of quantum gravity. The lengths and times had been introduced into physics a half century earlier by Max Planck, so Wheeler gave them the names "Planck length" and "Planck time." (In

Box 1. Wheeler coinages

John Wheeler believed that the names given to concepts or to descriptions of an idea strongly influence how we think about concepts and ideas, even how we work on them and build on them. In short, the word inspires the deed. Accordingly, Wheeler spent many hours (often soaking in a warm bathtub) searching for the most apt terms. Here, in rough chronological order, are some of his coinages:

***S*-Matrix** the scattering operator in quantum mechanics
Sum over histories Richard Feynman's path-integral method
Moderator the material that slows neutrons in a nuclear reactor
Stellarator a plasma magnetic confinement device
Planck length, Planck time the scales at which quantum gravity dominates
Geon an object made from waves bound together by their energy's gravity
Mass without mass gravitating object containing no massive particles
Charge without charge wormholes as sources and sinks of electric field lines
Wormhole a topological "handle" in the geometry of curved space
Quantum foam quantum fluctuations in the geometry of spacetime
Black hole* the object formed by implosion of a sufficiently massive star
A black hole has no hair a classical black hole's properties are determined by only its mass, spin angular momentum, and charge
Space tells matter how to move and matter tells space how to curve the summarized content of general relativity
Law without law** emergence of law from random processes
It from bit** a physical world built of information units
Mutability** susceptibility of physical law to evolution and change
Observer-participancy** influence of the observer on reality
The universe as a self-excited circuit** shaping the past from the present
A single quantum cannot be cloned a theorem that puts a limit on quantum amplifiers

* The phrase "black hole" appears to have been used first, for the object formed by stellar implosion, by one or more non-physicists shortly after the 1963 discovery of quasars, but it did not stick. Wheeler recalls adopting it in 1968 after somebody at a lecture he was giving shouted it out as a suggestion, and in his hands it was quickly adopted worldwide.
**An influential, speculative idea due to Wheeler.

recognition of Wheeler's identifying their quantum gravity roles, they are now sometimes called the Planck–Wheeler length and time.) Wheeler commented on them in his first geon paper,[2] but he needed several more years and extensive discussions with Misner and others to flesh out his seminal ideas about quantum gravity: Space and time, even if very flat on atomic and larger scales, must, on the Planck scales, exhibit huge quantum mechanical fluctuations of curvature and topology—a "quantum foam," as he called it.

Wheeler reasoned that a wavefunction analogous to Erwin Schrödinger's must exist that describes the probability distribution for quantum foam—and on larger length scales, the probability distribution for tiny fluctuations away from general relativity's classical spacetime geometry. Through discussions with Misner, Bryce DeWitt (then at the University of North Carolina), and others, Wheeler came to understand the arena for that wavefunction: It is defined on the space of all possible geometries for three-dimensional space. One of us (Thorne) recalls DeWitt frequently visiting Wheeler at Princeton in the early 1960s for long discussions of that wavefunction, the wave equation that governs it (which came to be called the Wheeler–DeWitt equation), the sum-over-histories action principle for the equation, and the subtle way in which time is encoded in it. DeWitt's own seminal contributions to quantum gravity were much influenced by those discussions, and Stephen Hawking and others would later use the Wheeler–DeWitt equation and its sum-over-histories action as a foundation for their own work on quantum gravity. Today string theorists, with their own more modern geometric approach to quantum gravity, debate the existence and strength of quantum foam and its role in fundamental physics.[8]

The issue of the final state: Pulsars and black holes

In 1958, soon after his first burst of relativity papers, Wheeler identified a major question in fundamental physics and astrophysics: What are all the possible final states of a star that has exhausted its nuclear fuel, contracted or collapsed under the pull of its own gravity, and then cooled off? In the 1930s, physicists had identified three possible final states: a cold white dwarf (identified by Subrahmanyan Chandrasekhar and others), a neutron star (studied by Fritz Zwicky and others), and an implosion, investigated by J. Robert Oppenheimer and Hartland Snyder, that produced an ill-understood object Wheeler called a Schwarzschild singularity and later would rename "black hole."

To help elucidate the issue of the final state, Wheeler enlisted graduate students Kent Harrison and Masami Wakano and showed them how to bring to bear on that task the combined tools of atomic physics, nuclear physics, and general relativity. Methodically they mapped out the previously unknown range of densities between white dwarfs ($\sim 10^{10}$ g cm^{-3}) and neutron stars ($\sim 10^{14}$ g cm^{-3}) and began a study of configurations at still higher densities—configurations they showed to be unstable. That study made crystal clear and inevitable what previously had been surmised: Any star heavier than about two of our suns must shed its excess mass or wind up as a Schwarzschild singularity.[9]

To Wheeler, a Schwarzschild singularity was an ideal playground for radical conservative-ism. At the object's center, the Riemann curvature tensor (the tidal gravitational field) is physically singular, diverging to infinity. Anything, even fundamental particles, falling into a Schwarzschild singularity would be torn apart. Such a thing cannot really happen, Wheeler reasoned. General relativity must fail at the central singularity and be replaced by a "fiery marriage," as he called it, of general relativity and quantum physics, by the new laws of quantum gravity that he, Misner, DeWitt, and others were beginning to seek.

Throughout his life, Wheeler, like Einstein, attempted through physical reasoning to see far beyond the frontiers of knowledge. The laws of quantum gravity were not then, nor are they today, understood well enough to deduce how quantum gravity will modify the singularity. In the late 1950s and early 1960s, until talked out of it by his students David Sharp and Thorne, Wheeler speculated that some sort of radiation would emerge from the incipient Schwarzschild singularity, preventing its formation.[9] A decade later Hawking would

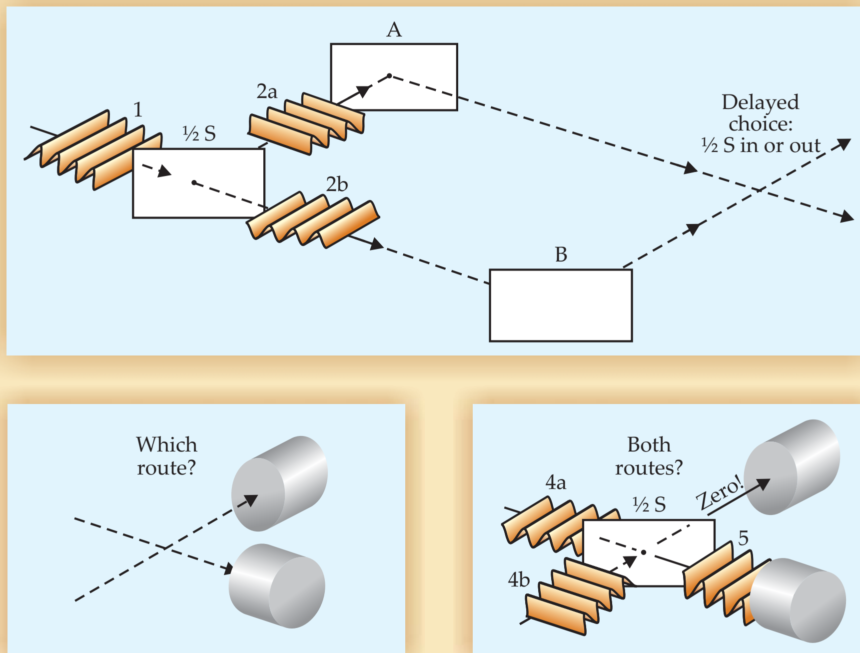

Figure 2. John Wheeler's original, conceptual version of the delayed-choice experiment (from ref. 16, page 183). Upper diagram: A wavepacket of light, 1, containing a single photon passes through a half-silvered mirror and gets split into two wavepackets, 2a and 2b, that reflect off mirrors and then intersect. After the packet is split in two, an observer–participator decides whether to insert another half-silvered mirror at the intersection point. Lower diagrams: If the mirror is not inserted (left), then the photon behaves like a particle—it goes into either the upper or the lower photodetector, revealing which path it took. If the mirror is inserted (right), the two wavepackets interfere at the splitter—the photon behaves like a wave—with destructive interference toward the upper photodetector, constructive toward the lower (wavepacket 5). The observer–participator's decision, made after the wavepacket is split in two, determines whether it will behave like a particle or a wave.

discover a form of radiation remarkably similar to Wheeler's speculation, and Hartle and Hawking would show that Hawking radiation can actually be regarded as emerging from the central singularity.[10] Here as elsewhere, Wheeler was remarkably adept at divining truth far beyond the frontiers of knowledge, but he lacked the tools to verify his guess. He was a decade too soon.

At the 11th Solvay Conference in Brussels (1958), where Harrison, Wakano, and Wheeler presented their final-state research, there was a famous confrontation between Wheeler and Oppenheimer.[11] Recalling his own 1939 calculation with Snyder, Oppenheimer insisted that an imploding spherical star must inevitably cut itself off from the external universe, hiding its singular center from view. Wheeler firmly rejected that assertion. In 1958 it was easy to reject. As Evgeny Lifshitz later told Thorne, it was far from clear, physically, how one should interpret Oppenheimer's calculation. In Moscow, Lifshitz and Lev Landau had studied the Oppenheimer–Snyder paper, puzzled over its physics, and reached no clear understanding.

The physics became lucid in 1959–62, through insights[12] by David Finkelstein (remarkably not a Wheeler student, but in a related collaboration with Misner) and members of Wheeler's entourage: Martin Kruskal, Misner, and Misner's undergraduate student David Beckedorff. By 1962 the physical nature of the horizon surrounding a Schwarzschild singularity was clear; Wheeler was convinced that Oppenheimer had been right, and he began urging his students to seek deeper insights into that strange horizon-endowed singularity—an object that he would rename black hole in 1968 (box 1).

Kruskal's seminal paper is remarkable for what it says about Wheeler. A plasma physicist working at Princeton's Project Matterhorn A (controlled fusion), Kruskal devised a radically new coordinate system for the full Schwarzschild spacetime geometry that surrounds the singularity. His coordinates revealed a wormhole that is created, expands to a maximum size, then contracts and pinches off before anything can travel through—a fabulous example of geometrodynamics. When Wheeler heard of Finkelstein's insights (which dealt with only half of the Schwarzschild geometry and revealed its horizon and thence its role as a black hole), he suddenly understood the importance of Kruskal's work for his wormhole ideas. Kruskal was away from Princeton, so Wheeler wrote a paper describing the dynamical wormhole, complete with rich Wheelerian diagrams and prose, and submitted it to the *Physical Review* with Kruskal as the sole author. The first Kruskal knew of the paper was when page proofs arrived. Despite Kruskal's entreaties, Wheeler refused to have his own name added: The insights were largely Kruskal's, not Wheeler's.

Mathematical physicist Regge provides another remarkable example of Wheeler's role with students. In 1955, when Wheeler had just published his geon paper and was beginning to struggle with the issue of the final state, he met Regge at the first Rochester Conference on High Energy Physics. Regge, an Italian graduate student, was introduced to Wheeler as "mathematically brilliant," so Wheeler suggested he work out the theory of weak perturbations of a Schwarzschild singularity. Wheeler, knowing roughly how the calculation should go, wrote a draft of a paper titled "On the Stability of the Schwarzschild Singularity" with the equations left blank and invited Regge to calculate the details and fill in the equations. Remarkably, it all worked out more or less as planned, and their paper has become a classic.[13] A few years later, when the correct boundary conditions at the Schwarzschild horizon became clear,[13] the Regge–Wheeler analysis made it absolutely firm: A nonspinning black hole is stable against small perturbations.

Wheeler regarded review articles and conference

Box 2. Quantum measurement: Wheeler's last blackboard

John Wheeler taught a two-year course on quantum measurement at the University of Texas at Austin, in 1977–79. In the course's final class, according to notes taken at the time by one of us (Zurek), Wheeler wrote the following list of ideas and then discussed them:

1. We don't understand how the universe came into being.
2. We will first understand how simple is the universe when we recognize how strange it is.
3. When we understand how it came into being, it will seem so compelling that we will all say how stupid we have been.
4. Therefore, we can afford many mistakes in the search. The main thing is to make them as fast as possible.
5. No explanation is an explanation that does not explain how the universe comes into being out of nothingness; not out of the vacuum of physics with its fluctuations and virtual particles, but out of nothingness. No laws, no particles, nothing.
6. *Omnibus ex nihil ducendis sufficit unum.* (One principle suffices to obtain everything from nothing.)
7. No principle is more appealing for this purpose than the principle that many a game is not a game until the line is drawn across the empty courtyard: complementarity and the distinction between observer and system observed.
8. Physics has to give up its impossible ideal of a proud unbending immutability and adopt the more modest mutability of its sister sciences, biology and geology.
9. If the kingdom of life and the highest mountain ranges are brought into being by the accumulation of multitudes of small individual processes, it is difficult to see what else can give rise to the universe itself.
10. What other possibility is there for "law without law" except the statistics of large numbers of lawless events?
11. No elementary process is as attractive for this statistics as the elementary act of observer-participatorship.
12. The quantum theory of fluctuations of geometry tells us that the concepts of "before" and "after" lose all application at distances of order the Planck length or less. If the concept of time fails anywhere, it must fail everywhere.
13. Time is not a primary category, and the asymmetry of time between past and future is not a primary category in the description of nature. It is secondary and derived.
14. The elementary act of observer-participatorship transcends the category of time (delayed-choice double slit).
15. No working picture that can be offered today is so attractive as this: the universe brought into being by acts of observer-participatorship; the observer–participator brought into being by the universe ("self-excited circuit").
16. The laws of physics reveal as little about the deeper structure of the universe as the laws of elasticity reveal about the quantum mechanics of the solid state. Symmetry principles summarize law but also hide machinery behind the law.
17. Philosophy is too important to be left to the philosophers.

proceedings as opportunities to take stock of what he knew and push forward in new directions. A remarkable example was his 1966 review article on superdense stars.[14] Not content to just review his group's work on the issue of the final state, Wheeler reviewed the astrophysical context for white dwarfs, neutron stars, and what he would soon rename black holes. For example, he used his superb mastery of electrodynamics and plasma physics to speculate about the roles of neutron stars in the universe: A spinning, magnetized neutron star residing at the center of the Crab nebula would pour out a huge flux of electromagnetic energy, he reasoned, a flux capable of energizing the nebula. A year later pulsars were discovered, and then the Crab pulsar. Pulsars were deduced to be spinning, magnetized neutron stars, and the Crab is now known definitively to be energized by its pulsar. As he moved in more and more speculative directions, Wheeler did not lose touch with well-established physics nor his ability to use it for prediction. But that was not where his heart resided. His spinning-neutron-star explanation for the Crab's energy was so unimportant to him that he did not even mention it in his autobiography.

From the mid-1960s to mid-1970s, Wheeler served as an inspiration and sounding board for physicists studying black holes, gravitational waves, and geometrodynamics. A superb group in Cambridge, UK—including Roger Penrose, Hawking, and Brandon Carter—drew inspiration from his lectures, and Penrose made long visits to Princeton. Wheeler inspired Thorne's students at Caltech and Brill's and Misner's at the University of Maryland. When Wheeler's student Jacob Bekenstein learned from Hawking that a black hole's surface area cannot decrease, he speculated that the area is the hole's entropy in disguise. Wheeler suggested making that quantitative: Divide by the Planck length squared (since the entropy must somehow be connected to quantum gravity, Wheeler reasoned) and multiply by Boltzmann's constant; you then should have the entropy to within a factor of order unity. Hawking's subsequent discovery of Hawking radiation revealed that factor, ¼, and we now speak of the Bekenstein–Hawking entropy.

In the new worldwide intellectual milieu, Wheeler kept his students in close contact with the other major players in the field (see Robert Geroch's remarks in the box on page 58). A few examples: Geroch made significant contributions to the Hawking–Penrose singularity theorems (the inevitability of physical singularities and thence quantum gravity inside black holes and in the birth of the universe); William Unruh made major contributions to the new field of quantum field theory in curved spacetime, which underlies Hawking radiation; Frank Zerilli and Robert Wald were seminal in fleshing out the theory of black hole pulsations; and Wheeler's postdoc James York simplified curved spacetime's dynamical degrees of freedom and brought the Arnowitt-Deser-Misner geometrodynamics into a form beautifully suited for numerical simulations. Unruh recalls of that golden age of relativity research that Wheeler himself was the source of the key initial ideas for most everyone's research in a group that grew to roughly 15 people in the early 1970s.[15]

"Everything is information"

Though Wheeler, in the early 1970s, was an inspiration for relativity theorists worldwide, and though much of his energy was going into creating a pedagogical legacy for future generations by writing his classic textbook *Gravitation*,[1] his heart was turning elsewhere.

Thorne recalls vividly a lunch with Wheeler and Richard Feynman in 1971 at the Burger Continental Restaurant near Caltech. Over Armenian food, Wheeler described to his two former students his idea that the laws of physics are mutable: Those laws must have come into being in our universe's Big

Bang birth, and surely there are other universes, each with its own set of laws. “What principles determine which laws emerge in our universe and which in another?” he asked.

Feynman, Wheeler’s student in the 1940s, turned to Thorne, Wheeler’s student in the 1960s, and said, “This guy sounds crazy. What people of your generation don’t know is that he has *always* sounded crazy. But when I was his student, I discovered that if you take one of his crazy ideas and you unwrap the layers of craziness from it one after another like lifting the layers off an onion, at the heart of the idea you will often find a powerful kernel of truth.” Feynman then recounted Wheeler’s 1942 idea that positrons are electrons going backward in time and the importance of that idea in Feynman’s Nobel Prize–winning formulation of quantum electrodynamics.

Today string theorists are struggling to figure out what determines which of the plethora of quantum vacua in the string theory landscape actually occur in the birth of our universe or any other universe—a concrete variant of Wheeler’s question, informed by 37 intervening years of quantum gravity research. (For more on mutability and other topics in this section, see box 2.)

In 1976 Wheeler and his wife, Janette, pulled up roots from Princeton and he joined the faculty of the University of Texas, Austin. That move marked a clean break with his “everything is fields” curved spacetime era and the beginning of “everything is information”—of which the mutability of physical law was part, as we shall see below.

Quantum mechanics in 1976 was the backbone of atomic, nuclear, and condensed-matter physics as well as quantum chemistry. Yet the essence of “the quantum” was a mystery that gripped Wheeler’s attention; quantum measurement, he thought, was the crux of the mystery. Why? Because quantum measurement is only a euphemism for the relation between observers—us—and the rest of the physical universe. So quantum measurement, he said, is where “the quantum gets personal.”

At that time students and junior scientists were discouraged from becoming interested in the quantum. Devoting time to an area so moribund and philosophical was a kiss of death to one’s career. There were essentially no real experiments, only a few worn-out *gedanken* experiments, and no applications in sight. Moreover, there was a feeling that since the fathers of quantum physics, including Einstein and Bohr, could not figure it out, who could?

Still, in the fall of 1977, when Wheeler announced a graduate course on quantum measurement, the Texas classroom was overflowing with registered students and several faculty members. There was no textbook; but readings of many authors—ranging from mathematician John von Neumann to Jean Piaget, a child psychologist who analyzed how perception evolves in early human development—were debated. The class, which Wheeler taught for four semesters, often turned into a seminar where visitors and students reported their research or interesting new papers.

Wheeler was pointing the way toward a revitalization of quantum measurement theory, similar to his 1950s revitalization of relativity. Among those around him who would go on to play major roles in today’s blooming quantum information science were students Benjamin Schumacher, William Wootters, and one of us (Zurek); postdocs David Deutsch and Wolfgang Schleich; young faculty member Jeff Kimble; and visitors Asher Peres and Unruh. Among the experts from previous generations who participated in Wheeler’s class were DeWitt and Eugene Wigner. A compilation of seminal readings produced by Wheeler and Zurek for that class[16] became an important resource for other institutions in revitalizing interest in the foundations and fundamental applications of quantum physics. Through his impact on others, Wheeler helped usher in a change of climate, so that many of the old *gedanken* experiments would actually be carried out in the laboratory and now are becoming centerpieces of applications.

Looking back on Wheeler’s 10 years at Texas, many quantum information scientists now regard him, along with IBM’s Rolf Landauer, as a grandfather of their field. That, however, was not because Wheeler produced seminal research papers on quantum information. He did not—with one major exception, his delayed-choice experiment (see below). Rather, his role was to inspire by asking deep questions from a radical conservative viewpoint and, through his questions, to stimulate others’ research and discovery. His viewpoint, in brief, was this:

The passive observer of Newton’s classical universe becomes, in our quantum world, a participator. The participator’s selection of what to measure determines the set of possible outcomes. When the preexisting quantum state is not one of those possible outcomes, it is doomed: The measured system will jump into one of the possible outcomes, with a probability given by Max Born’s famous rule, $p_k = |\Psi_k|^2$. In effect, as Wheeler saw it, the wavefunction of the universe was reset in the process. So in our quantum world, the future is determined in part by the questions posed by observer–participators, and by measurement-induced random quantum jumps.

“No phenomenon is a phenomenon until it is a recorded phenomenon” was Wheeler’s pithy summary of Bohr’s similar viewpoint, and he pushed that viewpoint to the limit. He even tried to turn the tables on the measurement problem by making the act of measurement central and to derive all of quantum physics by starting from the quantum jumps.

For Wheeler, it was essential that those seemingly crazy ideas be linked to experiment. To dramatize the role of the observer–participator, he proposed his now famous delayed-choice experiment (figure 2), which shows that even the past of a quantum state can be altered by the observer–participator’s choice of what to measure.

Bell’s inequality was also a source of inspiration: Wheeler and his Texas entourage discussed it at great length. Bell’s inequality must be violated if, as Wheeler expected, no form of classical causality underlies quantum processes. There was great excitement in Wheeler’s group when the violation was indeed reported in an experiment by Edward Fry of Texas A&M University, and even more so when Alain Aspect confirmed its violation in measurements that are

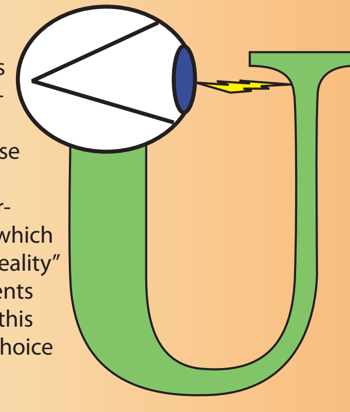

Figure 3. John Wheeler’s diagram of the universe as a self-excited circuit: Starting small (thin part of “U” at upper right), the universe grows (loop of “U”) and in time gives rise to observer-participancy (upper left), which in turn imparts “tangible reality” to even the earliest moments of the universe. Compare this notion with the delayed-choice experiment of figure 2.

spacelike separated and hence causally independent.[17] Wheeler encouraged his students to devise macroscopic experiments, which led Wootters and Zurek to devise a theorem that says an unknown quantum state cannot be cloned, which in turn places limits on quantum amplifiers.[17] They originally submitted their paper, with a boring title, to the *American Journal of Physics*; Wheeler suggested adding "cloning" to the title and switching to the journal *Nature*, where the impact would be higher. (See Wootters and Zurek's discussion of the theorem in PHYSICS TODAY, February 2009, page 76.)

The contact with experiment was enhanced when Vladimir Braginsky in Moscow, Wheeler's former students Unruh and Thorne, and Thorne's student Carlton Caves proposed quantum nondemolition techniques to enhance the sensitivity of gravitational-wave detectors. That promised an experimental advance on two fronts close to Wheeler's heart: improved gravitational-wave technology and an era in which human-sized objects can be observed behaving quantum mechanically. Here was an ideally radical realm, Wheeler reasoned, for exploring the applicability of quantum physics, for seeing whether cracks in our understanding might appear, and for trying to peer through those cracks. Such human-scale quantum experiments are now being designed,[18] thanks to Wheeler's intellectual descendants.

In Texas, returning full circle to the mutability of physical law, Wheeler speculated that the universe's ultimate building block, its ultimate mechanism for existence, might be information. "It from bit" was the aphorism he chose to describe the idea. As a concrete embodiment of "it from bit," Wheeler speculated that universes governed by sensible laws could come to be inhabited by observer–participators. And when that happens, the observers' actions, as participators who collect information about the universe, might actually be retroactively responsible for the creation of the universe. Wheeler's "universe as a self-excited circuit" (figure 3) stands causality on its head, but it has a close epistemological tie to his delayed-choice experiment. Wheeler's many successes entitled him to examine crazy-sounding ideas without fear, one by one, aiming to discover which ones must be discarded and whether any of them should be taken seriously and might even lead to an experiment.

Wheeler's poetic imagination—with its deep, almost philosophical questions such as How come the quantum? and How come existence?—combined with his engineering common sense that brought many of his lofty ideas down to earth was his trademark way of doing physics. This is his enduring legacy: Do not be afraid to think big, but make sure that in the end you have a blueprint for an experiment.

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