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Quantum Reality

Beyond the New Physics

Nick Herbert

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BEYOND THE NEW PHYSICS

Nick Herbert



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Preface

One of the curious features of modern physics is that in spite of its overwhelming practical success in explaining a vast range of physical phenomena from quark to quasar, it fails to give us a single metaphor for how the universe actually works. The old mechanical metaphor “The world is a giant clock” condensed in one image the principal features of Newtonian physics—namely, atomicity, objectivity, and determinism. However, physicists today do not possess a single metaphor that unites in one image the principal features of quantum theory. The main purpose of *Quantum Reality* is to examine several tentative images of the world proposed by quantum physicists.

The search for a picture of “the way the world really is” is an enterprise that transcends the narrow interests of theoretical physicists. For better or for worse, humans have tended to pattern their domestic, social, and political arrangements according to the dominant vision of physical reality. Inevitably the cosmic view trickles down to the most mundane details of everyday life.

In the Middle Ages, when virtually everyone believed the world to be the personal creation of a divine being, society mirrored the hierarchy that supposedly existed in the heavens. Dante’s picture of this world as a series of concentric spheres—heaven the largest; next, the planets’ crystalline spheres; down through our Earth’s concentric “elements,” the world supported by the seven circles of hell—gave everything and everyone his proper place in the medieval scheme of things, from the divine right of kings down to the abject obedience of the lowliest serf. Most people accepted this hierarchical structure without question because it represented the way the world really is.

The Newtonian revolution toppled the reign of the crystal spheres and replaced it with a physics of ordinary matter governed by mathematical laws rather than divine command. Coincident with the rise of Newtonian physics was the ascent of the modern democratic ideal, which stresses a “rule of laws rather than men” and which posits a theoretical equality between the parts of the social machinery. The Declaration of Independence, for example, “We hold these truths to be self-evident” reads more like a mathematical theorem than a political document. As above, so below. The egalitarian mechanism that Newton discovered in the heavens has insinuated itself into every aspect of ordinary life. For better or for worse, we live today in a largely mechanistic world.

Just as Newton shattered the medieval crystal spheres, modern quantum theory has irreparably smashed Newton’s clockwork. We are now certain that the world is *not* a deterministic mechanism. But what the world is we cannot truly say. The search for quantum reality is a search for a single image that does justice to our new knowledge of how the world actually works.

Many aspects of quantum theory are public knowledge, such as the notion that all elementary events occur at random, governed only by statistical laws; that there is a “least thing that can happen”—Max Planck’s irreducible constant of action; and that Heisenberg’s famous uncertainty principle forbids an accurate knowledge of a quantum particle’s position

and momentum. A successful quantum reality would incorporate this knowledge, and much more, into a single comprehensive metaphor for the way the world really is.

I first encountered the quantum reality question in graduate school when I learned to describe the behavior of atoms, molecules, and elementary particles in the mathematical language of quantum theory. Quantum theory is peculiar in that it describes a *measured atom* in a very different manner than an *unmeasured atom*.

The measured atom always has definite values for its attributes (such as position and momentum), but the unmeasured atom never does. Every atom in the world that's not actually being measured possesses (in the mathematical description at least) not one but a whole range of possible attribute values, somewhat like a broken TV set that displays all its channels at the same time.

Of course I wondered what sort of reality this strange symbolization of the unmeasured world actually stood for. Were the attributes of unmeasured atoms multivalued, fuzzy, nonexistent, or simply unknown?

However, when I asked my teachers what quantum theory actually meant—that is, what was the *reality* behind the mathematics—they told me that it was pointless for a physicist to ask questions about reality. Best to stick with the math and the experimental facts, they cautioned, and stop worrying about what was going on behind the scenes. No one has expressed physicists' reluctance to deal with quantum reality better than Richard Feynman, Nobel laureate now at Cal Tech, who said, "I think it is safe to say that no one understands quantum mechanics. Do not keep saying to yourself, if you can possibly avoid it, 'but how can it be like that?' because you will go 'down the drain' into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that."

For the sake of having *something* in mind while I did my quantum calculations, I imagined that an atom always possessed definite values for all its attributes (just like an ordinary object) whether that atom was measured or not. However, the process of measurement disturbs the atom so profoundly that its measured attributes bear only a statistical relation to its unmeasured attributes. I felt sure that such a "disturbance model" of measurement was capable of accounting for quantum randomness, the Heisenberg uncertainty relations, and other quantum mysteries as well. In this "disturbance" picture, an atom's *actual* position and momentum are always definite but usually unknown; its *measured* position and momentum cannot be accurately predicted because the measuring device necessarily changes what it measures.

My belief in this disturbance model of reality was strengthened when I read that young Werner Heisenberg once held a similar view of the quantum world. It did not occur to me to wonder why Heisenberg quickly abandoned such an obvious explanation to take up the more obscure and mystical Copenhagen interpretation, which most physicists endorse today.

In brief, the Copenhagen interpretation holds that in a certain sense the unmeasured atom is not real: its attributes are created or realized in the act of measurement.

I regarded the Copenhagen interpretation as sheer mystification compared to the clarity and common sense of my disturbance model. Blissfully ignorant concerning the real issues surrounding the quantum reality question, I got my degree and continued my career as an industrial and academic physicist.

In the summer of 1970 my friend Heinz Pagels, a physicist at Rockefeller University,

showed me a paper published in an obscure new journal. “Here’s something strange that should interest you, Nick,” he said. This strange new thing was Bell’s theorem, a mathematical proof which puts strict conditions on any conceivable model of reality, quantum or otherwise.

Bell’s theorem is easy to understand but hard to believe. This theorem says that *reality must be non-local*. “Non-local” means, in terms of my disturbance model, that the atom’s measured attributes are determined not just by events happening at the actual measurement site but by events arbitrarily distant, including events outside the light cone—that is, events so far away that to reach the measurement site their influence must travel faster than light. In other words, when I probe an atom’s momentum with a momentum meter, its true momentum is disturbed, according to Bell’s theorem, not just by the momentum meter itself but by a vast array of distant events—events that are happening right now in other cities, in other countries, and possibly in other galaxies. According to John Bell, the act of measurement is not a private act, but a public event in whose details large portions of the universe instantly participate.

Bell’s theorem is a mathematical proof, not a conjecture or supposition. That is, once you accept a few simple premises his conclusion certainly follows. Thus Bell does not merely permit or suggest that reality is nonlocal; he actually proves it.

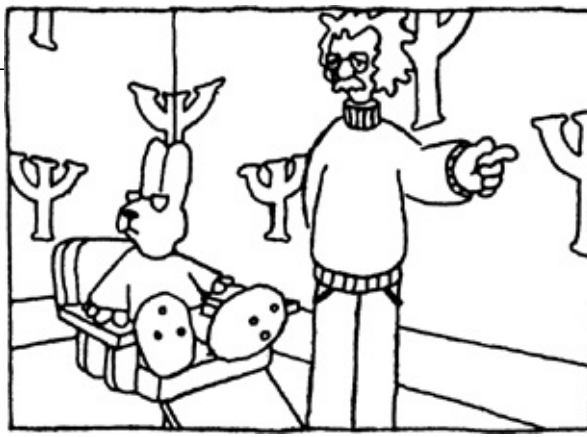
Bell’s theorem has immensely clarified the quantum reality question. For instance we now know for certain that no local model (such as my naïve disturbance model) can explain the quantum facts. Bell’s theorem has important consequences for all models of quantum reality, including the Copenhagen interpretation, and its effects continue to reverberate in physics circles. This book explores various quantum realities (models of the world consistent with quantum theory) in the light of Bell’s important discovery.

Many people have helped me in my search for quantum reality, either through their books and articles or through personal contact. I can mention only a few but I’m grateful to all.

I would like to honor the memory of Randy Hamm, friend and talented animator whose collaboration on *Benjamin Bunny Faces Reality*, an unfinished animated film which explores some of the same concepts contained in this book, inspired me to think in new directions.

I would like to thank Mike and Dulce Murphy for opening Esalen Institute, Big Sur, to physics conferences on quantum reality. Thanks also to the many participants in the Esalen conferences, especially Henry Stapp, Saul-Paul Sirag, John Clauser, David Finkelstein, John Cramer, Larry Bartell, H. Dieter Zeh and Bernard d’Espagnat, from whom I received much enlightenment concerning the quantum mysteries.

Thanks to Charles Brandon and The Reality Foundation for encouragement and a time-lapse graphics grant, to Lynn Miller for her skillful illustrations, to Shirlee and David Byrd for editorial assistance, and to Doubleday’s Phil Pochoda, Dave Barbor, and Chaucy Bennetts for their patience and good advice.



A frame from Benjamin Bunny Faces Reality: the "Professor" readies Benjamin for a "reality check."

Thanks to my wife Betsy and son Khola for keeping me awake and aware of other extraordinary realities.

The Quest for Reality

The essential point in science is not a complicated mathematical formalism or a ritualized experimentation. Rather the heart of science is a kind of shrewd honesty that springs from really wanting to know what the hell is going on!

Saul-Paul Sirag

When I was six my parents gave me a set of children's books—fourteen orange, black, and gold bound volumes of stories, games, and songs. *Science* was Volume 12, the only book without text, containing instead dozens of black-and-white photographs of big machines and unusual natural phenomena. One picture in particular fascinated me; recalling it today still makes me shiver. This picture showed a nest of eggs. But hatching out of these eggs were baby snakes.

This disturbing photo brought together in one image my vague fears that beneath the surface of commonplace things lurks an utterly strange (and probably sinister) reality.

Many years later I experienced that same feeling—a lightning realization that this world is not what it seems—precipitated not by a picture in a children's book but by a mathematical argument in a physics journal. Bell's theorem is a simple but powerful proof concerning the structure of physical reality, and had the same effect on my imagination as that snake's nest. Bell's theorem is one of the clearest windows that physicists possess into the nature of deep reality. I invite you in [Chapter 12](#) to look through this window too.

Physicists are interested in how the world is put together—out of what sorts of basic objects, interacting via what sorts of basic forces. Physics began in antiquity as a kind of natural history, a folk museum of unexplained marvels and peculiar facts laid out in haphazard fashion: the world as *lore*, direct observation scrambled up with fantastical travelogue, with medieval bestiaries and alchemical recipes.

In the seventeenth century Galileo, Newton and other natural philosophers discovered that an enormous body of physical facts could be encompassed in a few mathematical formulas. For instance with only three mathematical laws Newton could explain all motion in heaven and on Earth. Why should mathematics, developed primarily to keep track of human business transactions, have anything at all to do with the way the non-human world operates? Nobel laureate Eugene Wigner refers to this magical match between human mathematics and non-human facts as “the unreasonable effectiveness of mathematics in the natural sciences.” “The unreasonable effectiveness,” writes Wigner, “is a wonderful gift which we neither understand nor deserve.”

Although mathematics originates in the human mind, its remarkable effectiveness in explaining the world does not extend to the mind itself. Psychology has proved unusually resistant to the mathematization that works so well in physics.

The German philosopher Immanuel Kant was deeply impressed by Newton's mathematical method and sought to explain its success as well as to understand its limitations. Kant began his analysis by dividing knowledge into three parts: appearance, reality, and theory. Appearance is the content of our direct sensory experience of natural phenomena. Reality (Kant called it the "thing-in-itself") is what lies behind all phenomena. Theory consists of human concepts that attempt to mirror both appearance and reality.

Kant believed that the world's appearances were deeply conditioned by human sensory and intellectual apparatus. Other beings no doubt experience the same world in radically different ways. Scientific facts—the appearances themselves—are as much a product of the observer's human nature as they are of an underlying reality. We see the world through particular human goggles. Kant felt that the participation of human nature in the creation of appearances explained both the remarkable ability of human concepts to fit the facts and the natural limits of such abilities.



FIG. 1.1 *Eighteenth-century reality researcher Immanuel Kant sought to define the outer limits of human knowledge.*

Our concepts appear to match the facts, according to Kant, because both facts and concepts have a common origin—the human condition. Insofar as human nature is entwined with the appearances, human concepts will be successful in explaining those appearances. Because we can only explain those aspects of the world which we ourselves bring to it, the nature of deep reality must remain forever inaccessible. Man is fated to know, either directly or through conceptualization, merely the world's appearances and of these appearances only that part which is of human origin.

Kant's position is an example of the pessimistic pole of reality research, which might be expressed this way: human senses and intellectual equipment evolved in a biological context concerned mainly with survival and reproduction of humankind. The powers that such clever animals may possess are wholly inadequate to picture reality itself, which belongs to an order that utterly transcends our domestic concerns.

On the other hand, reality researchers of an optimistic bent argue that since humans are part of nature, deeply natural to the core, nothing prevents us from experiencing or conceptualizing reality itself. Indeed some of our experiences and/or some of our ideas may already be making contact with rock-bottom reality.

Besides the optimism/pessimism split, another difference separates researchers into two different attitudes toward the nature of reality: the pragmatist/realist division. A pragmatist believes only in facts and mathematics and refuses in principle to speculate concerning deep reality, such questions being meaningless from his point of view. Sir James Jeans, the distinguished physicist and astronomer, sums up this pragmatic orientation: "The final truth about a phenomenon resides in the mathematical description of it; so long as there is no imperfection in this, our knowledge of the phenomenon is complete. We go beyond the mathematical formula at our own risk; we may find a model or picture which helps us understand it, but we have no right to expect this, and our failure to find such a model or picture need not indicate that either our reasoning or our knowledge is at fault. The making of models or pictures to explain phenomena by mathematical formulas and the phenomena they describe is not a step towards, but a step away from, reality; it is like making graven images of a spirit."

A realist, on the other hand, believes that a good theory explains the facts because it makes contact with a reality behind those facts. The major purpose of science, according to the realists, is to go beyond both fact and theory to the reality underneath. As Einstein, the most famous realist of them all, put it, "Reality is the real business of physics."

The pragmatist treats his theory like a *cookbook* full of recipes which are useful for ordering and manipulating the facts. The realist sees theory as a *guidebook* which lays out for the traveler the highlights of the invisible landscape that lies just beneath the facts.

Most physicists are complex mixtures of pragmatist and realist, at once both optimistic and pessimistic about their chances for making solid contact with deep reality. Like many other human enterprises, the practice of science requires a constantly shifting balance between the two extremes, a sensitivity to the middle way, as French experimentalist Jean Perrin put it: "between the instincts of prudence and audacity necessary to the slow progress of human science."

I do not wish to get specific about what might be meant by "reality itself" lest we hamper our search with needless preconceptions. Like the solution to a puzzle or cryptogram, contact with deep reality will no doubt carry its own validation: we'll know it when we see it. However, as an illustration of the kinds of realities we might be looking for in physics, I review here two case histories: the stories of a reality that failed and a reality that succeeded.

THE LUMINIFEROUS ETHER

In 1864 Scottish physicist James Clerk Maxwell discovered the basic equations that govern electricity and magnetism. To everyone's surprise these phenomena turned out to be two aspects of a single entity—the electromagnetic field. Today physicists are seeking for a way to unify all of nature's fields. Maxwell was the first physicist to show that the task of field unification is not futile.

A theoretical bonus which Maxwell reaped from his fusion of two fields into one was the discovery that waves in his electromagnetic field traveled at the same speed as the measured

velocity of light. On the basis of this numerical coincidence, Maxwell conjectured that light in reality, was an electromagnetic vibration at a particular frequency. The experimental production by Heinrich Hertz of low-frequency electromagnetic radiation (radio waves) which were identical in all respects save frequency to light confirmed Maxwell's bold conjecture.

All known waves vibrate in some medium (such as air or water). The medium in which light presumably travels was dubbed the "luminiferous ether." Late nineteenth-century physicists gave top priority to research into the ether's mechanical properties. Maxwell described the subject of this research in these words: "Whatever difficulties we may have in forming a consistent idea of the constitution of the ether, there can be no doubt that the interplanetary and interstellar spaces are not empty but are occupied by a material substance or body, which is certainly the largest, and probably the most uniform body of which we have any knowledge."

From light's well-known attributes one could infer many of this hypothetical ether's properties. For instance, since light travels so fast the elasticity of the ether must be enormous, millions of times more resilient than the hardest spring steel. Since light is a transverse wave—vibrating sidewise rather than back and forth—the ether must be a solid. Gases and liquids can support only back-and-forth vibrations (sound is an example), while solids transmit both kinds of vibration (earthquake waves, for example, vibrate in all directions). The fact that light vibrates only sidewise (no back-and-forth light has ever been observed) had to be explained by complex structures in the ether which suppressed altogether this otherwise natural back-and-forth vibration but which permitted sidewise vibrations to propagate with extreme rapidity.

Although the universe was filled with a transparent "glass" much harder than steel, this glass offered not the slightest resistance to the passage of material bodies. The Earth's motion was seemingly unaffected by the presence of the luminiferous ether. Some physicists proposed that the ether might act like a solid for rapid motions such as light, but like a fluid for slow motions, such as planets, in the manner of certain waxlike solids with deformation-rate dependent viscosities. In modern terms, such a hypothesis amounts to assuming that the universe is filled brim to brim with a kind of Silly Putty.

In 1887 two American physicists performed a simple experiment whose purpose was to determine the velocity of the Earth through this ever-present vibrating solid. Albert Abraham Michelson and Edward Williams Morley set up a kind of optical racetrack that pitted a light beam moving north and south between parallel mirrors against an east/west beam. Depending on the direction of the "ether wind," one or the other of these beams had the track advantage and was sure to win. The result of the Michelson-Morley experiment was always a photo finish. Despite the enormous velocity of the Earth through space, a velocity that constantly changes its direction during the year, the two experimenters could detect no movement whatsoever of the luminiferous ether past the Earth.

Michelson and Morley's failure to detect the "ether wind" led physicists to propose that massive bodies such as the Earth trap the ether and carry it along with them. However, attempts to detect this "ether drag" near massive rotating bodies in the laboratory were unsuccessful. Ether drag should also distort the apparent positions of distant stars, an effect which was also noticeably absent.

To explain the failure of Michelson and Morley to detect an “ether wind,” even more preposterous effects were invoked. Dutch physicist Hendrik Antoon Lorentz and Irish physicist George Francis FitzGerald independently proposed that motion through the ether resulted in a tiny contraction of all physical bodies in the direction of motion. The Lorentz-FitzGerald contraction—a kind of “ether squeeze”—could not be directly observed, because measuring rods also supposedly shrank when oriented in the ether wind’s direction. The so-called function of the Lorentz-FitzGerald contraction was to even the odds in the Michelson-Morley optical racetrack: the light beam that would have lost the race, by virtue of the Lorentz contraction would now travel a shorter path, and consequently both beams would reach the finish line at precisely the same time. This hypothetical “ether squeeze” was a desperate attempt to save appearances by loading the already peculiar ether with yet one more unusual attribute.

Although its properties grew more preposterous with each new investigation, the existence of the ether itself was never called into question. One of England’s leading physicists, the eminent William Thomson, Lord Kelvin, expressed physicists’ general attitude a few years after the Michelson-Morley experiment when he said, “One thing we are sure of, and that is the reality and substantiality of the luminiferous ether.”

Despite physicists’ strong faith in the existence of the luminiferous ether, a few years after Lord Kelvin’s profession of belief the ether was swept away into the junkyard of obsolete physical concepts in company with phlogiston, caloric, and the fabled philosopher’s stone.

Albert Einstein, an unknown clerk in the Zurich patent office, published in 1905 a new theory of space and time which came to be called the special theory of relativity. The cornerstone of Einstein’s theory was that only *relative* motions were of any consequence for the basic laws of physics. According to Einstein, there is no physical means by which one can observe a body’s *absolute* motion through space.

Einstein’s innocent assumption had far-reaching experimental consequences. For instance, two observers in relative motion measuring the positions and times of the same events would get different results. For Einstein, time and space are *relative* concepts, different for every observer. Another important consequence of relativity is the famous $E = mc^2$ relation, which predicts that an object’s mass is equivalent to a certain amount of energy, with an enormous conversion factor—the square of the speed of light.

Although space, time, and motion are relative concepts in Einstein’s theory, certain other physical quantities are absolute—the same for everyone. Einstein’s major insight, the key to relativity theory, is that all valid physical laws must be built from these absolute quantities alone. Only in this way can these laws be made the same for all observers.

One of Einstein’s absolutes is the speed of light: it is the same for an observer on Mars as for an observer on Earth. Another Einsteinian absolute is the so-called *space-time interval*. Although space and time by themselves are different for each observer, a certain mathematical combination of space and time, chosen so that changes in space cancel the changes in time, is the same for everyone. Relativity’s intimate linkage of space and time through the invariant space-time interval gives rise to the notion that in reality the world is *four-dimensional*—consisting of three spatial dimensions and one time dimension. The space-time interval is a kind of “distance” in that four-dimensional space.

According to Einstein, only such absolute quantities can be used as the ingredients of

valid physical law. Laws built to Einstein's specifications are called "covariant." Today we know for sure that if a physical theory does not have a covariant formulation it cannot represent the facts. By looking at where it's not covariant—wherever it uses a relative concept rather than an absolute one—we can even predict exactly how it must fail.

The luminiferous ether—a body that's "standing still in space"—is a manifestly non-covariant concept because it is standing still for only one observer. According to Einstein, the physics governing the interaction of bodies A and B can depend only on their relative motion, not on their velocity measured with respect to some special reference frame. If Einstein's theory is correct—and it has been abundantly verified—the concept of the ether can never enter into any correct physical law. The ether is quite literally a useless concept: there is no use for it in physics. However a light wave travels through space—light's manner of propagation is still a bit of a mystery—it cannot go via a medium made of invisible Silly Putty which fills up the universe.

Despite its central role in Victorian science, the luminiferous ether plays no part whatsoever in modern physics. The ether is a reality that failed. We consider next a reality that succeeded—the notion that matter is made out of atoms.

THE ATOMICITY OF MATTER

The idea that the world consists of standard little parts originated in antiquity. It would be hard to find a more eloquent statement of the atomic hypothesis than that of Democritus of Abdera, who wrote (about 500 B.C.): "By convention sour, by convention sweet, by convention colored; in reality, nothing but Atoms and the Void."

The atomic hypothesis existed side by side with the belief that the world consisted of transformations of a single continuous substance which some called "Fire," others "Air" or "Water". The commonplace observation that water could take solid, liquid, or gaseous form depending on temperature was taken as an example of how one seamless substance might be able to simulate the world's enormous variety. However, until the nineteenth century the arguments for the continuum and the atomic hypotheses were mainly rhetorical; little evidence existed for either of these views.

In 1808 the British chemist John Dalton discovered that chemical substances combine according to fixed ratios—one part oxygen, for example, combines with two parts hydrogen to make water, provided each of these parts is assigned a standard weight. The standard weight of oxygen is sixteen times the standard weight of hydrogen. Dalton proposed that these constant combining ratios represented the combination of actual atoms whose atomic weights were proportional to the standard weights. According to Dalton, bulk hydrogen combines with bulk oxygen in a two-to-one ratio because water, in reality, is composed of two hydrogen atoms plus an oxygen atom. Dalton took these constant chemical ratios as tokens of an invisible atomic reality.

Most scientists were convinced by Dalton's arguments and accepted the real existence of atoms as an explanation of chemical reactions. However, a small but prestigious minority opposed the atomic hypothesis on the grounds that it went beyond the facts.

In 1826 Dalton received the Royal Society of London's medal of honor from famous British chemist Humphry Davy. While celebrating the importance of Dalton's work, Davy cautioned

that the word “atom” could only realistically have the meaning “chemical equivalent”—that the atom was a unit of chemical reaction rather than a material entity. Davy praised Dalton for his discovery of the law of chemical proportions and predicted that his fame would rest on this practical discovery rather than on his speculations concerning invisible entities behind the phenomena.

Chemists of diverse nationalities united to oppose the atomic hypothesis. For instance, the distinguished French chemist Jean Baptiste Dumas proclaimed: “If I were master of the situation, I would efface the word atom from Science, persuaded that it goes further than experience, and that in chemistry, we should never go further than experience.” The German chemist Kekulé, famous for his discovery of the benzene ring (which he presumably interpreted purely symbolically) had this to say about atoms: “The question whether atoms exist or not has little significance from a chemical point of view; its discussion belongs rather to metaphysics. In chemistry we have only to decide whether the assumption of atoms is a hypothesis adapted to the explanation of chemical phenomena.”

“And who has ever seen a gas molecule or an atom?” chided Marcelin Berthelot, expressing the disdain that many of his fellow chemists felt for invisible entities inaccessible to experiment. Even its defenders saw little hope of ever directly verifying the atomic hypothesis: the size of these elementary entities—if they were really there at all—was estimated to be thousands of times smaller than a wavelength of light, hence technically forever invisible.

Wilhelm Ostwald, a German chemist who later received the Nobel Prize, turned to the field of chemical thermodynamics for an alternative to the atomic hypothesis. The two laws of thermodynamics—which require conservation of energy and an entropy-based limit on the energy’s utilization—had been extended by Maxwell and Gibbs to describe successfully the intimate details of physical and chemical reactions without recourse to the atomic hypothesis. The success of the thermodynamic approach convinced Ostwald and his followers that molecules and atoms were imaginative fictions and that the real underlying component of the universe was energy, in its various forms.

Because of their faith in energy rather than atoms as an explanatory principle, Ostwald and his colleagues were called “energeticists.” Debates in the journals and at scientific conferences between the supporters of the atomic hypothesis and the energeticists were sharp and emotional. The bitter opposition of the anti-atomists to his work on the kinetic theory of gases may have been partly responsible for the suicide of Ludwig Boltzmann, a brilliant but troubled theoretical physicist, in 1906.

In 1905, the same year he conceived the theory of relativity which demolished the luminiferous ether, Einstein published a paper on Brownian motion that pointed the way to conclusive experiments bearing on the real existence of atoms.

Whenever micron-sized particles are suspended in a liquid they undergo a perpetual quivering dance whose origin had been a mystery since its discovery in 1828 by Scottish botanist Robert Brown. Early experiments on Brownian motion were performed with pollen grains and the activity was believed to be of biological origin. I remember my first glimpse of what I took to be “cells” under a powerful microscope, and was fascinated by their ceaseless pulsations like tiny heartbeats until my teacher told me that I was looking at the Brownian motion of dirt particles. (Actually, when I finally spotted the real cells they didn’t seem s

interesting as the dancing dirt.) When it was discovered that any sort of finely divided matter would show such agitation (even stone from the Sphinx was pulverized and made to dance under the microscope), the biological hypothesis was discarded and various physical mechanisms proposed: temperature gradients, surface tension, obscure electrochemical effects. None of these quite worked. Brownian motion remained a minor mystery tucked away in an obscure corner of physics.

Einstein explained Brownian motion as the action of numerous atoms in motion colliding with the Brownian particle. This explanation had been previously rejected because the atoms were millions of times less massive than the Brownian particle, and their collective pressure could lead to no net motion because equal amounts of atoms were pushing in every direction.

Einstein showed that although the number of atoms striking the Brownian particle from each direction is equal on the average, the fluctuations away from this average lead to unbalanced forces in random directions. In any random process, the relative fluctuations from an average value is inversely proportional to the square root of the number of samples—the smaller the sample, the bigger the fluctuations. For a large particle, the bulk pressure of the surrounding atoms is indeed evenly balanced, but for a small particle, the fluctuations in the number of impinging atoms is sufficient to propel it in an unpredictable direction with a predictable force. Einstein showed how this random force would vary with temperature and particle size. If atoms existed, Einstein's model of Brownian motion would allow you actually to count the number of atoms striking a Brownian particle by measuring how far it drifts in response to these fluctuation forces.

In a series of ingenious experiments the French physicist Jean Baptiste Perrin verified Einstein's model and succeeded for the first time in actually counting the number of atoms in a drop of water. Perrin published his direct verification of the atomic hypothesis in 1913, in a book called simply *Les Atomes*.

In 1895 Ostwald railed against the atomic hypothesis in a speech entitled "On Overcoming Scientific Materialism": "We must renounce the hope of representing the physical world by referring natural phenomena to a mechanics of atoms. 'But'—I hear you say—"but what will we have left to give us a picture of reality if we abandon atoms?" To this I reply: "Thou shalt not take unto thee any graven image, or any likeness of anything." Our task is not to see the world through a dark and distorted mirror, but directly, so far as the nature of our mind permits. The task of science is to discern relations among *realities*, i.e., demonstrable and measurable quantities ... It is not a search for forces we cannot measure, acting between atoms we cannot observe."

But in response to the work of Einstein and Perrin, the leader of the energeticists bowed to the experimental evidence and finally accepted the real existence of atoms: "I am now convinced," said Ostwald, "that we have recently become possessed of experimental evidence of the discrete or grained nature of matter, which the atomic hypothesis sought in vain for hundreds and thousands of years. [Experiments such as Perrin's] justify the most cautious scientist in now speaking of the experimental proof of the atomic nature of matter. The atomic hypothesis is thus raised to the position of a scientifically well-founded theory."

More recently (1957) philosopher of science Hans Reichenbach summed up the modern opinion concerning the atomic hypothesis: "The atomic character of matter belongs to the most certain facts of our present knowledge ... we can speak of the existence of atoms with

the same certainty as the existence of stars.” The actuality of atoms is a reality that has succeeded. Nobody today doubts that atoms really exist.

According to the pragmatists, science is like a cookbook—mere recipes for ordering phenomena. Once you have a recipe that works, what more could you ask for? Realists want more. They believe that a good theory should act as a guidebook to what’s really out there in the world. In the words of Michael Polanyi, a distinguished scientific realist: “A theory which we acclaim as rational in itself is accredited with prophetic powers. We accept it in the hope of making contact with reality; so that being really true, our theory may yet show forth its truth through future centuries in ways undreamed of by its authors.”

Quantum theory has been universally successful in describing phenomena at all levels accessible to experiment. It’s a perfect cookbook, for whatever we choose to cook up. However, this comprehensive practical success has been accompanied by an unprecedented disagreement as to what quantum theory actually means, and a corresponding confusion as to what sort of reality supports the phenomenal world. In the next chapter I examine some of the contradictory quantum realities which different physicists claim to be the “real reality” that lies behind the external appearances of this world we live in.

Physicists Losing Their Grip

No development of modern science has had a more profound impact on human thinking than the advent of quantum theory. Wrenched out of centuries-old thought patterns, physicists of a generation ago found themselves compelled to embrace a new metaphysics. The distress which this reorientation caused continues to the present day. Basically physicists have suffered a severe loss: their hold on reality.

Bryce DeWitt
Neill Graham

One of the best-kept secrets of science is that physicists have lost their grip on reality.

News of the reality crisis hardly exists outside the physics community. What shuts out the public is partly a language barrier—the mathematical formalism that facilitates communication between scientists is incomprehensible to outsiders—and partly the human tendency of physicists to publicize their successes while soft-peddling their confusions and uncertainties. Even among themselves, physicists prefer to pass over the uncomfortable reality issue in favor of questions “more concrete”. Recent popularizations such as Heinrich Pagels’ *Cosmic Code* have begun to inform the public about the reality crisis in physics. In *Quantum Reality* I intend to examine how physicists deal with reality—or fail to deal with it—in clear and unprecedented detail.

Nothing exposes the perplexity at the heart of physics more starkly than certain preposterous-sounding claims a few outspoken physicists are making concerning how the world really works. If we take these claims at face value, the stories physicists tell resemble the tales of mystics and madmen. Physicists are quick to reject such unsavory associations and insist that they speak sober fact. We do not make these claims out of ignorance, they say, like ancient mapmakers filling in terra incognitas with plausible geography. Not ignorance but the emergence of unexpected knowledge forces on us all new visions of the way things really are.

The new physics vision is still clouded, as evidenced by the multiplicity of its claims, but whatever the outcome it is sure to be far from ordinary. To give you a taste of quantum reality, I summarize here the views of its foremost creators in the form of eight realities which represent eight major guesses as to what’s really going on behind the scenes. Later we will look at each of these realities in more detail and see how different physicists use the same data to justify so many different pictures of the world.

Quantum Reality # 1: The Copenhagen interpretation, Part I (There is no deep reality.) No one has influenced more our notions of what the quantum world is really about than Danish physicist Niels Bohr, and it is Bohr who puts forth one of quantum physics’ most outrageous claims: that there is no deep reality. Bohr does not deny the evidence of his senses. The wor

we see around us is real enough, he affirms, but it floats on a world that is not as real. Everyday phenomena are themselves built not out of phenomena but out of an utterly different kind of being.

Far from being a crank or minority position, “There is no deep reality” represents the prevailing doctrine of establishment physics. Because this quantum reality was developed at Niels Bohr’s Copenhagen institute, it is called the “Copenhagen interpretation.” Undaunted by occasional challenges by mavericks of realist persuasion, the majority of physicists swear at least nominal allegiance to Bohr’s anti-realist creed. What more glaring indication of the depth of the reality crisis than the official rejection of reality itself by the bulk of the physics community?

Einstein and other prominent physicists felt that Bohr went too far in his call for ruthless renunciation of deep reality. Surely all Bohr meant to say was that we must all be good pragmatists and not extend our speculations beyond the range of our experiments. From the results of experiments carried out in the twenties, how could Bohr conclude that no future technology would ever reveal a deeper truth? Certainly Bohr never intended actually to *deny* deep reality but merely counseled a cautious skepticism toward speculative hidden realities.

Bohr refused to accept such a watered-down version of the Copenhagen doctrine. In words that must chill every realist’s heart, Bohr insisted: “*There is no quantum world. There is only an abstract quantum description.*”

Werner Heisenberg, the Christopher Columbus of quantum theory, first to set foot on this new mathematical world, took an equally tough stand against reality-nostalgic physicists such as Einstein when he wrote: “The hope that new experiments will lead us back to objective events in time and space is about as well founded as the hope of discovering the end of the world in the unexplored regions of the Antarctic.”

The writings of Bohr and Heisenberg have been criticized as obscure and open to many interpretations. Recently Cornell physicist N. David Mermin neatly summed up Bohr’s anti-realist position in words that leave little room for misunderstanding: “We now know that the moon is demonstrably not there when nobody looks.” (We will take a look at Mermin’s “demonstration” in [Chapter 13](#).)

Quantum Reality #2: The Copenhagen interpretation, Part II (Reality is created by observation.) Although the numerous physicists of the Copenhagen school do not believe in deep reality, they do assert the existence of *phenomenal reality*. What we see is undoubtedly real, they say, but these phenomena are not really there in the absence of an observation. The Copenhagen interpretation properly consists of two distinct parts: 1. There is no reality in the absence of observation; 2. Observation creates reality. “You create your own reality” is the theme of Fred Wolf’s *Taking the Quantum Leap*.

Which of the world’s myriad processes qualify as observations? What special feature of an observation endows it with the power to create reality? Questions like these split the observer-created reality school into several camps, but all generally subscribe to quantum theorist John Wheeler’s memorable maxim for separating what is real in the world from what is not. “No elementary phenomenon is a real phenomenon until it is an observed phenomenon,” Wheeler proclaims. Without a doubt, Mermin’s description of the invisible moon qualifies him for membership in the observer-created reality school.

The belief that reality is observer-created is commonplace in philosophy, where it serves as the theme for various forms of idealism. Bertrand Russell recalls his fascination with idealism during his student days at Trinity College: “In this philosophy I found comfort for a long time ... There was a curious pleasure in making oneself believe that time and space are unreal, that matter is an illusion and that the world really consists of nothing but mind.”

Since pondering matter is their bread and butter, not many physicists would share Russell's enjoyment of matter as mere mirage. However, like it or not, through their conscientious practice of quantum theory more than a few physicists have strayed within hailing distance of the idealist's dreamworld.

Quantum Reality #3 (Reality is an undivided wholeness.) The views of Walter Heitler, author of a standard textbook on the light/matter interaction, exemplify a third unusual claim of quantum physicists: that in spite of its obvious partitions and boundaries, the world's actuality is a seamless and inseparable whole—a conclusion which Fritjof Capra develops in *Tao of Physics* and connects with the teachings of certain oriental mystics. Heitler accepts an observer-created reality but adds that the act of observation also dissolves the boundary between observer and observed: “The observer appears, as a necessary part of the whole structure, and in his full capacity as a conscious being. The separation of the world into an ‘objective outside reality’ and ‘us,’ the self-conscious onlookers, can no longer be maintained. Object and subject have become inseparable from each other.”

Physicist David Bohm of London's Birkbeck College has especially stressed the necessary wholeness of the quantum world: “One is led to a new notion of unbroken wholeness which denies the classical analyzability of the world into separately and independently existing parts ... The inseparable quantum interconnectedness of the whole universe is the fundamental reality.”

Quantum wholeness is no mere replay of the old saw that everything is connected to everything else, no twentieth-century echo, for instance, of Newton's insight that gravity links each particle to every other. All ordinary connections—gravity, for one—inevitably fade off with distance, thus conferring overwhelming importance on nearby connections while distant connections become irrelevant. Undoubtedly we are all connected in unremarkable ways, but close connections carry the most weight. Quantum wholeness, on the other hand, is a fundamentally new kind of togetherness, undiminished by spatial and temporal separation. No casual hookup, this new quantum thing, but a true mingling of distant beings that reaches across the galaxy as forcefully as it reaches across the garden.

Quantum Reality #4: The many-worlds interpretation (Reality consists of a steadily increasing number of parallel universes.) Of all claims of the New Physics none is more outrageous than the contention that myriads of universes are created upon the occasion of each measurement act. For any situation in which several different outcomes are possible (flipping a coin, for instance), some physicists believe that *all outcomes actually occur*. In order to accommodate different outcomes without contradiction, entire new universes spring into being, identical in every detail except for the single outcome that gave them birth. In the case of a flipped coin, one universe contains a coin that came up heads; another, a coin showing tails. Paul Davies champions this claim, known as the many-worlds interpretation, in his book *Other Worlds*. Science fiction writers commonly invent parallel universes for the sake

of a story. Now quantum theory gives us good reason to take such stories seriously.

Writing in *Physics Today*, a major magazine of the American physics community, Bryce DeWitt describes his initial contact with the many-worlds interpretation of quantum theory:

“I still recall vividly the shock I experienced on first encountering this multiworld concept. The idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense ...”

Invented in 1957 by Hugh Everett, a Princeton graduate student, the many-worlds interpretation is a latecomer to the New Physics scene. Despite its bizarre conclusion, that innumerable parallel universes each as real as our own actually exist, Everett’s many-worlds picture has gained considerable support among quantum theorists. Everett’s proposal is particularly attractive to theorists because it resolves, as we shall see, the major unsolved puzzle in quantum theory—the notorious quantum measurement problem.

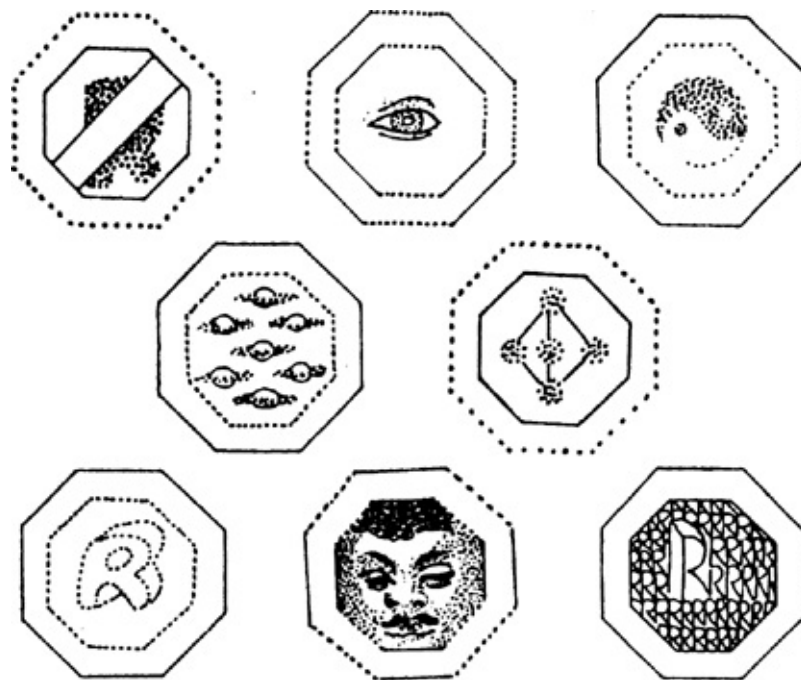


FIG. 2.1 *Eight emblems of quantum reality: which of these worlds, if any, lies behind the quantum facts?*

These four quantum realities should give you some feeling for the diversity of claims regarding the world’s ultimate nature. While followers of Everett bear witness to uncountable numbers of quantum worlds, plus more on the way, students of Bohr and Heisenberg insist that there is *not even one* quantum world. In their struggle to gain firm footing amidst the slippery bricks of quantum fact, physicists have invented more realities than four. Keep your wits about you as we press on.

Quantum Reality #5: Quantum logic (The world obeys a non-human kind of reasoning. Quantum logicians argue that the quantum revolution goes so deep that replacing new concepts with old will not suffice. To cope with the quantum facts we must scrap our very mode of reasoning, in favor of a new quantum logic.

Logic is the skeleton of our body of knowledge. Logic spells out how we use some of the shortest words in the language, words such as *and*, *or*, and *not*. The behavior of these little linguistic connectors governs the way we talk about things, and structures, in turn, the way we think about them. For two thousand years, talk about logic (in the West) was cast in the syllogistic mold devised by Aristotle. In the mid-nineteenth century, George Boole, an Irish schoolteacher, reduced logical statements to simple arithmetic by inventing an artificial symbolic language which laid bare the logical bones of ordinary language.

Boole's clear codification of the rules of reason jolted logic out of the Middle Ages and launched the now-flourishing science of mathematical logic. Outside the mathematical mainstream, a few creative logicians amused themselves by constructing "crazy logics" using rules other than Boole's. These deviant designs for *and/or/not*, although mathematically consistent, were considered mere curiosities since they seemed to fit no human pattern of discourse.

However, according to some New Physicists, one of these crazy logics may be just what we need to make sense out of quantum events. Listen to quantum theorist David Finkelstein calling for mutiny against the rules of Boole:

"Einstein threw out the classical concept of *time*; Bohr throws out the classical concept of *truth* ... Our classical ideas of logic are simply wrong in a basic practical way. The next step is to learn to think in the right way, to learn to think quantum-logically."

As an example of the usefulness of changing your mind rather than changing your physics, quantum logicians point to Einstein's general theory of relativity, which achieved in the realm of geometry what they propose to do with logic.

Geometry is the science of points and lines. For two thousand years only one geometry existed, its rules compiled by the Greek mathematician Euclid in his bestselling book *The Elements*, which once rivaled the Bible in popularity. The latest revival of Euclid's *Elements* is your high school geometry book.

Coincident with Boole's pioneer work in logic, a few adventurous mathematicians thought up "crazy geometries," games points and lines could play outside of Euclid's rules. Chief architect of the New Geometry was the Russian Nikolai Lobachevski along with German mathematicians Karl Gauss and Georg Riemann. Their cockeyed geometries were regarded like non-Boolean logics, as high mathematical play, clever business but out of touch with reality. Euclidean geometry, as everyone knows, was *the* geometry, being after all, nothing but common sense applied to triangles and other geometric figures.

However, in 1916 Einstein proposed a radical new theory of gravity that demolished the Euclidean monopoly. Einstein, in opposition to Newton and everybody else, declared that *gravity is not a force but a curvature in space-time*. Objects in free fall are truly free and move in lines as straight as can be—that is, lines straight by the standards of a *gravity-warped geometry*. Einstein's theory has testable consequences: for instance the deflection of starlight grazing the sun (confirmed by Eddington in 1919) and the existence of black holes (according to astrophysicists, in the constellation Cygnus, black hole Cygnus X-1 resides). On Earth, where our common sense was formed, gravity is weak and space almost Euclidean; out near X-1, high school geometry flunks.

Einstein's lesson is plain to see, say the quantum logicians. The question of the world's true

geometry is not settled by common sense but by experiment. Likewise with logic. For the rules of right reason, look not inside your own head but get thee to a laboratory.

Quantum Reality #6: Neorealism (The world is made of ordinary objects.) An *ordinary object* is an entity which possesses attributes of its own whether observed or not. With certain exceptions (mirages, illusions, hallucinations), the world outside seems populated with objectlike entities. The clarity and ubiquity of ordinary reality has seduced a few physicists—I call them neorealists—into imagining that this familiar kind of reality can be extended into the atomic realm and beyond. However, the unremarkable and common-sense view that ordinary objects are themselves made of objects is actually the blackest heresy of establishment physics.

“Atoms are not things,” says Heisenberg, one of the high priests of the orthodox quantum faith, who likened neorealists to believers in a flat earth. “There is no quantum world,” warned Bohr, the pope in Copenhagen; “there is only an abstract quantum description.”

Neorealists, on the other hand, accuse the orthodox majority of wallowing in empirical formalism and obscuring the world’s simplicity with needless mystification. Instead they preach return to a pure and more primitive faith. Chief among neorealist rebels was Einstein whose passion for realism pitted him squarely against the quantum orthodoxy: “The Heisenberg-Bohr tranquilizing philosophy—or religion?—is so delicately contrived that, for the time being, it provides a gentle pillow for the true believer from which he cannot very easily be aroused. So let him lie there.”

Despite their Neanderthal notions, no one could accuse neorealists of ignorance concerning the principles of quantum theory. Many of them were its founding fathers. Besides Einstein, prominent neorealists include Max Planck, whose discovery of the constant of action sparked the quantum revolution; Erwin Schrödinger, who devised the wave equation every quantum system must obey; and Prince Louis de Broglie, who took quantum theory seriously enough to predict the wave nature of matter.

De Broglie, a French aristocrat whose wartime involvement in radio swerved his research from church history into physics, fought for ordinary realism until 1928 when he converted to the *statistical interpretation* (another name for Copenhagenism). Twenty years later, however, influenced by David Bohm’s neorealist revival, de Broglie recanted and returned to the faith of his youth:

“Those interested in the psychology of scientists may be curious about the reasons for my unexpected return to discarded ideas ... I am thinking not so much of my constant difficulties in developing a statistical interpretation of wave mechanics, or even of my secret hankering after Cartesian clarity in the midst of the fog which seemed to envelop quantum physics [but] the fact that, as I examined the statistical picture] I could not help being struck by the force of the objections to it and by a certain obscurity in the arguments in its defense ... too abstract ... too schematic ... I realized that I had been seduced by the current fashion, and began to understand why I had been so uneasy whenever I tried to give a lucid account of the probability interpretation.”

One of the physics community’s few traditions is the custom of celebrating the birthdays of its great men with a *Festschrift*—a festival of papers. In 1982, Louis de Broglie, ninety years

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