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Quantum Reality

Beyond the New Physics

Nick Herbert

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Anchor Books
A DIVISION OF RANDOM HOUSE, INC.
NEW YORK

ANCHOR BOOKS EDITIONS, 1985, 1987

Library of Congress Cataloging-in-Publication Data
Herbert, Nick.
Quantum reality.
1. Quantum theory—Popular works. I. Title.
QC174.12.H47 1985 530.1′2 82-46033
eISBN: 978-0-307-80674-1

www.anchorbooks.com

v3.1

To my father

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Preface

One of the curious features of modern physics is that in spite of its overwhelming practic success in explaining a vast range of physical phenomena from quark to quasar, it fails to giv us a single metaphor for how the universe actually works. The old mechanical metaphor "Th 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 single metaphor that unites in one image the principal features of quantum theory. The ma purpose of *Quantum Reality* is to examine several tentative images of the world proposed b quantum physicists.

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

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

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

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

Many aspects of quantum theory are public knowledge, such as the notion that a elementary events occur at random, governed only by statistical laws; that there is a "lea thing that can happen"—Max Planck's irreducible constant of action; and that Heisenberg famous uncertainty principle forbids an accurate knowledge of a quantum particle's positio and momentum. A successful quantum reality would incorporate this knowledge, and muc 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 t describe the behavior of atoms, molecules, and elementary particles in the mathematic language of quantum theory. Quantum theory is peculiar in that it describes *a measured ato* in a very different manner than *an unmeasured atom*.

The measured atom always has definite values for its attributes (such as position an momentum), but the unmeasured atom never does. Every atom in the world that's no actually being measured possesses (in the mathematical description at least) not one but a possible attribute values, somewhat like a broken TV set that displays all its channels at th same time.

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

However, when I asked my teachers what quantum theory actually meant—that is, wh was the *reality* behind the mathematics—they told me that it was pointless for a physicist t ask questions about reality. Best to stick with the math and the experimental facts, the cautioned, and stop worrying about what was going on behind the scenes. No one ha 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 understand quantum mechanics. Do not keep saying to yourself, if you can possibly avoid it, 'but ho can it be like that?' because you will go 'down the drain' into a blind alley from whic 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 imagine that an atom always possessed definite values for all its attributes (just like an ordinar object) whether that atom was measured or not. However, the process of measureme disturbs the atom so profoundly that its measured attributes bear only a statistical relation t its unmeasured attributes. I felt sure that such a "disturbance model" of measurement wa capable of accounting for quantum randomness, the Heisenberg uncertainty relations, an other quantum mysteries as well. In this "disturbance" picture, an atom's *actual* position an momentum are always definite but usually unknown; its *measured* position and momentu cannot be accurately predicted because the measuring device necessarily changes what measures.

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

In brief, the Copenhagen interpretation holds that in a certain sense the unmeasured ato 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 clarit and common sense of my disturbance model. Blissfully ignorant concerning the real issu surrounding the quantum reality question, I got my degree and continued my career as a industrial and academic physicist.

In the summer of 1970 my friend Heinz Pagels, a physicist at Rockefeller Universit showed me a paper published in an obscure new journal. “Here’s something strange th should interest you, Nick,” he said. This strange new thing was Bell’s theorem, mathematical proof which puts strict conditions on any conceivable model of realit quantum or otherwise.

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

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

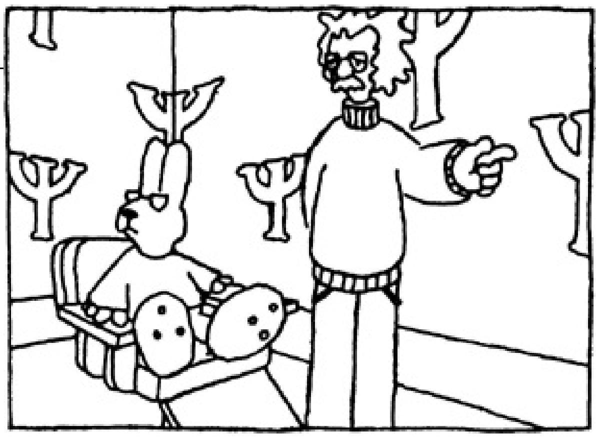
Bell’s theorem has immensely clarified the quantum reality question. For instance we no know for certain that no local model (such as my naïve disturbance model) can explain th quantum facts. Bell’s theorem has important consequences for all models of quantum realit including the Copenhagen interpretation,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

Many people have helped me in my search for quantum reality, either through their book 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 whos collaboration on *Benjamin Bunny Faces Reality*, an unfinished animated film which explore 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, physics conferences on quantum reality. Thanks also to the many participants in the Esale conferences, especially Henry Stapp, Saul-Paul Sirag, John Clauser, David Finkelstein, Joh Cramer, Larry Bartell, H. Dieter Zeh and Bernard d’Espagnat, from whom I received muc enlightenment concerning the quantum mysteries.

Thanks to Charles Brandon and The Reality Foundation for encouragement and a timel graphics grant, to Lynn Miller for her skillful illustrations, to Shirlee and David Byrd fo editorial assistance, and to Doubleday’s Phil Pochoda, Dave Barbor, and Chaucy Bennetts fo 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 oth
extraordinary realities.

1

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, ar gold bound volumes of stories, games, and songs. *Science* was Volume 12, the only boo without text, containing instead dozens of black-and-white photographs of big machines ar unusual natural phenomena. One picture in particular fascinated me; recalling it today st makes me shiver. This picture showed a nest of eggs. But hatching out of these eggs wer baby snakes.

This disturbing photo brought together in one image my vague fears that beneath th 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 not what it seems—precipitated not by a picture in a children's book but by a mathematic argument in a physics journal. Bell's theorem is a simple but powerful proof concerning th structure of physical reality, and had the same effect on my imagination as that snake's nes Bell's theorem is one of the clearest windows that physicists possess into the nature of dee 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 bas objects, interacting via what sorts of basic forces. Physics began in antiquity as a kind natural history, a folk museum of unexplained marvels and peculiar facts laid out haphazard fashion: the world as *lore*, direct observation scrambled up with fantast travelogue, with medieval bestiaries and alchemical recipes.

In the seventeenth century Galileo, Newton and other natural philosophers discovered th an enormous body of physical facts could be encompassed in a few mathematical formula For instance with only three mathematical laws Newton could explain all motion in heave and on Earth. Why should mathematics, developed primarily to keep track of human busine transactions, have anything at all to do with the way the non-human world operates? Nob laureate Eugene Wigner refers to this magical match between human mathematics and no human facts as "the unreasonable effectiveness of mathematics in the natural sciences." "Th unreasonable effectiveness," writes Wigner, "is a wonderful gift which we neither understar nor deserve."

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

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

Kant believed that the world's appearances were deeply conditioned by human sensory ar intellectual apparatus. Other beings no doubt experience the same world in radically differe ways. Scientific facts—the appearances themselves—are as much a product of the observe 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 appearances explained both the remarkable ability of human concepts to fit the facts and th 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 concep have a common origin—the human condition. Insofar as human nature is entwined with th appearances, human concepts will be successful in explaining those appearances. Because w can only explain those aspects of the world which we ourselves bring to it, the nature of dee reality must remain forever inaccessible. Man is fated to know, either directly or throug conceptualization, merely the world's appearances and of these appearances only that pa which is of human origin.

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

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

Besides the optimism/pessimism split, another difference separates researchers into th nature of reality: the pragmatist/realist division. A pragmatist believes only in facts an mathematics and refuses in principle to speculate concerning deep reality, such questio being meaningless from his point of view. Sir James Jeans, the distinguished physicist an astronomer, sums up this pragmatic orientation: "The final truth about a phenomenon resid in the mathematical description of it; so long as there is no imperfection in this, o knowledge of the phenomenon is complete. We go beyond the mathematical formula at ou own risk; we may find a model or picture which helps us understand it, but we have no rig to expect this, and our failure to find such a model or picture need not indicate that eith our reasoning or our knowledge is at fault. The making of models or pictures to expla mathematical formulas and the phenomena they describe is not a step towards, but a ste 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 mak contact with a reality behind those facts. The major purpose of science, according to th realists, is to go beyond both fact and theory to the reality underneath. As Einstein, the mo 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 fo ordering and manipulating the facts. The realist sees theory as a *guidebook* which lays out fo 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 an pessimistic about their chances for making solid contact with deep reality. Like many oth human enterprises, the practice of science requires a constantly shifting balance betwe extremes, a sensitivity to the middle way, as French experimentalist Jean Perrin put i "between the instincts of prudence and audacity necessary to the slow progress of huma science."

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

The Luminiferous Ether

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

A theoretical bonus which Maxwell reaped from his fusion of two fields into one was th discovery that waves in his electromagnetic field traveled at the same speed as the measur velocity of light. On the basis of this numerical coincidence, Maxwell conjectured that ligh in reality, was an electromagnetic vibration at a particular frequency. The experiment production by Heinrich Hertz of low-frequency electromagnetic radiation (radio wave which were identical in all respects save frequency to light confirmed Maxwell's bo conjecture.

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

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

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

In 1887 two American physicists performed a simple experiment whose purpose was determine the velocity of the Earth through this ever-present vibrating solid. Albert Abraha Michelson and Edward Williams Morley set up a kind of optical racetrack that pitted a lig beam moving north and south between parallel mirrors against an east/west bean Depending on the direction of the "ether wind," one or the other of these beams had the trac advantage and was sure to win. The result of the Michelson-Morley experiment was always photo finish. Despite the enormous velocity of the Earth through space, a velocity th constantly changes its direction during the year, the two experimenters could detect movement whatsoever of the luminiferous ether past the Earth.

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

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

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

Despite physicists’ strong faith in the existence of the luminiferous ether, a few years aft Lord Kelvin’s profession of belief the ether was swept away into the junkyard of obsole 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 ne theory of space and time which came to be called the special theory of relativity. Th cornerstone of Einstein’s theory was that only *relative* motions were of any consequence f the basic laws of physics. According to Einstein, there is no physical means by which one ca observe a body’s *absolute* motion through space.

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

Although space, time, and motion are relative concepts in Einstein’s theory, certain oth physical quantities are absolute—the same for everyone. Einstein’s major insight, the key relativity theory, is that all valid physical laws must be built from these absolute quantiti 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 an observer on Earth. Another Einsteinian absolute is the so-called *space-time interv* Although space and time by themselves are different for each observer, a certa mathematical combination of space and time, chosen so that changes in space cancel th changes in time, is the same for everyone. Relativity’s intimate linkage of space and time the invariant space-time interval gives rise to the notion that in reality the world is *fou dimensional*—consisting of three spatial dimensions and one time dimension. The space-tim 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 w know for sure that if a physical theory does not have a covariant formulation it cann represent the facts. By looking at where it's not covariant—wherever it uses a relativ 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 no covariant concept because it is standing still for only one observer. According to Einstein, th physics governing the interaction of bodies A and B can depend only on their relative motio not on their velocity measured with respect to some special reference frame. If Einstein theory is correct—and it has been abundantly verified—the concept of the ether can neve enter into any correct physical law. The ether is quite literally a useless concept: there is n use for it in physics. However a light wave travels through space—light's manner propagation is still a bit of a mystery—it cannot go via a medium made of invisible Sil Putty which fills up the universe.

Despite its central role in Victorian science, the luminiferous ether plays no pa whatsoever in modern physics. The ether is a reality that failed. We consider next a realit 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 b hard to find a more eloquent statement of the atomic hypothesis than that of Democritus Abdera, who wrote (about 500 B.C.): "By convention sour, by convention sweet, by conventio colored; in reality, nothing but Atoms and the Void."

The atomic hypothesis existed side by side with the belief that the world consisted transformations of a single continuous substance which some called "Fire," others "Air" "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 b able to simulate the world's enormous variety. However, until the nineteenth century th arguments for the continuum and the atomic hypotheses were mainly rhetorical; litt evidence existed for either of these views.

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

Most scientists were convinced by Dalton's arguments and accepted the real existence atoms as an explanation of chemical reactions. However, a small but prestigious minori 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 Britis chemist Humphry Davy. While celebrating the importance of Dalton's work, Davy caution that the word “atom” could only realistically have the meaning “chemical equivalent”—th the atom was a unit of chemical reaction rather than a material entity. Davy praised Dalto for his discovery of the law of chemical proportions and predicted that his fame would re on this practical discovery rather than on his speculations concerning invisible entities behi the phenomena.

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

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

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

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

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

Whenever micron-sized particles are suspended in a liquid they undergo a perpetu quivering dance whose origin had been a mystery since its discovery in 1828 by Scottis botanist Robert Brown. Early experiments on Brownian motion were performed with polle grains and the activity was believed to be of biological origin. I remember my first glimpse what I took to be “cells” under a powerful microscope, and was fascinated by their ceasele pulsations like tiny heartbeats until my teacher told me that I was looking at the Browni motion of dirt particles. (Actually, when I finally spotted the real cells they didn’t seem interesting as the dancing dirt.) When it was discovered that any sort of finely divided matte would show such agitation (even stone from the Sphinx was pulverized and made to danc under the microscope), the biological hypothesis was discarded and various physic mechanisms proposed: temperature gradients, surface tension, obscure electrochemic effects. None of these quite worked. Brownian motion remained a minor mystery tucke away in an obscure corner of physics.

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

Einstein showed that although the number of atoms striking the Brownian particle fro each direction is equal on the average, the fluctuations away from this average lead t unbalanced forces in random directions. In any random process, the relative fluctuations fro an average value is inversely proportional to the square root of the number of samples—th smaller the sample, the bigger the fluctuations. For a large particle, the bulk pressure of th surrounding atoms is indeed evenly balanced, but for a small particle, the fluctuations in th number of impinging atoms is sufficient to propel it in an unpredictable direction with predictable force. Einstein showed how this random force would vary with temperature ar particle size. If atoms existed, Einstein's model of Brownian motion would allow you actual to count the number of atoms striking a Brownian particle by measuring how far it drifts response to these fluctuation forces.

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

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

But in response to the work of Einstein and Perrin, the leader of the energeticists bowed t the experimental evidence and finally accepted the real existence of atoms: "I am no convinced," said Ostwald, "that we have recently become possessed of experimental eviden of the discrete or grained nature of matter, which the atomic hypothesis sought in vain f hundreds and thousands of years. [Experiments such as Perrin's] justify the most cautio scientist in now speaking of the experimental proof of the atomic nature of matter. Th 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 moder opinion concerning the atomic hypothesis: "The atomic character of matter belongs to th most certain facts of our present knowledge … we can speak of the existence of atoms wi the same certainty as the existence of stars.” The actuality of atoms is a reality th succeeded. Nobody today doubts that atoms really exist.

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

Quantum theory has been universally successful in describing phenomena at all leve accessible to experiment. It’s a perfect cookbook, for whatever we choose to cook u However, this comprehensive practical success has been accompanied by an unprecedente disagreement as to what quantum theory actually means, and a corresponding confusion as what sort of reality supports the phenomenal world. In the next chapter I examine some 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.

2

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 th public is partly a language barrier—the mathematical formalism that facilitate communication between scientists is incomprehensible to outsiders—and partly the huma tendency of physicists to publicize their successes while soft-pedalling their confusions an uncertainties. Even among themselves, physicists prefer to pass over the uncomfortab reality issue in favor of questions “more concrete”. Recent popularizations such as Hei Pagels’ *Cosmic Code* have begun to inform the public about the reality crisis in physics. I *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 certa preposterous-sounding claims a few outspoken physicists are making concerning how th world really works. If we take these claims at face value, the stories physicists tell resemb the tales of mystics and madmen. Physicists are quick to reject such unsavory associatio and insist that they speak sober fact. We do not make these claims out of ignorance, they sa like ancient mapmakers filling in terra incognitas with plausible geography. Not ignoranc but the emergence of unexpected knowledge forces on us all new visions of the way thin really are.

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

Quantum Reality # 1: The Copenhagen interpretation, Part I (There is no deep reality.) N one has influenced more our notions of what the quantum world is really about than Danis physicist Niels Bohr, and it is Bohr who puts forth one of quantum physics’ most outrageou 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 rea
Everyday phenomena are themselves built not out of phenomena but out of an utter
different kind of being.

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

Einstein and other prominent physicists felt that Bohr went too far in his call for ruthle
renunciation of deep reality. Surely all Bohr meant to say was that we must all be goo
pragmatists and not extend our speculations beyond the range of our experiments. From th
results of experiments carried out in the twenties, how could Bohr conclude that no futur
technology would ever reveal a deeper truth? Certainly Bohr never intended actually to *den*
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 word
that must chill every realist's heart, Bohr insisted: "*There is no quantum world*. There is onl
an abstract quantum description."

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

The writings of Bohr and Heisenberg have been criticized as obscure and open to man
interpretations. Recently Cornell physicist N. David Mermin neatly summed up Bohr's ant
realist position in words that leave little room for misunderstanding: "We now know that th
moon is demonstrably not there when nobody looks." (We will take a look at Mermin
"demonstration" in Chapter 13.)

Quantum Reality #2: The Copenhagen interpretation, Part II (Reality is created b
observation.) Although the numerous physicists of the Copenhagen school do not believe
deep reality, they do assert the existence of *phenomenal reality*. What we see is undoubted
real, they say, but these phenomena are not really there in the absence of an observatio
The Copenhagen interpretation properly consists of two distinct parts: 1. There is no realit
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 a
observation endows it with the power to create reality? Questions like these split th
observer-created reality school into several camps, but all generally subscribe to quantu
theorist John Wheeler's memorable maxim for separating what is real in the world from wh
i s not. "No elementary phenomenon is a real phenomenon until it is an observe
phenomenon," Wheeler proclaims. Without a doubt, Mermin's description of the inconsta
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 a the theme for various forms of idealism. Bertrand Russell recalls his fascination with idealis during his student days at Trinity College: “In this philosophy I found comfort for time … There was a curious pleasure in making oneself believe that time and space a 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 enjoyment of matter as mere mirage. However, like it or not, through their conscientiou practice of quantum theory more than a few physicists have strayed within hailing distance the idealist’s dreamworld.

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

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

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

Quantum Reality #4: The many-worlds interpretation (Reality consists of a steadi increasing number of parallel universes.) Of all claims of the New Physics none is mo outrageous than the contention that myriads of universes are created upon the occasion each measurement act. For any situation in which several different outcomes are possib (flipping a coin, for instance), some physicists believe that *all outcomes actually occur*. order to accommodate different outcomes without contradiction, entire new universes sprin into being, identical in every detail except for the single outcome that gave them birth. In th case of a flipped coin, one universe contains a coin that came up heads; another, a co showing tails. Paul Davies champions this claim, known as the many-worlds interpretation, his book *Other Worlds*. Science fiction writers commonly invent parallel universes for the sa 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, Bry
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 concep
The idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into furth
copies, which ultimately become unrecognizable, is not easy to reconcile with comm
sense …"

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

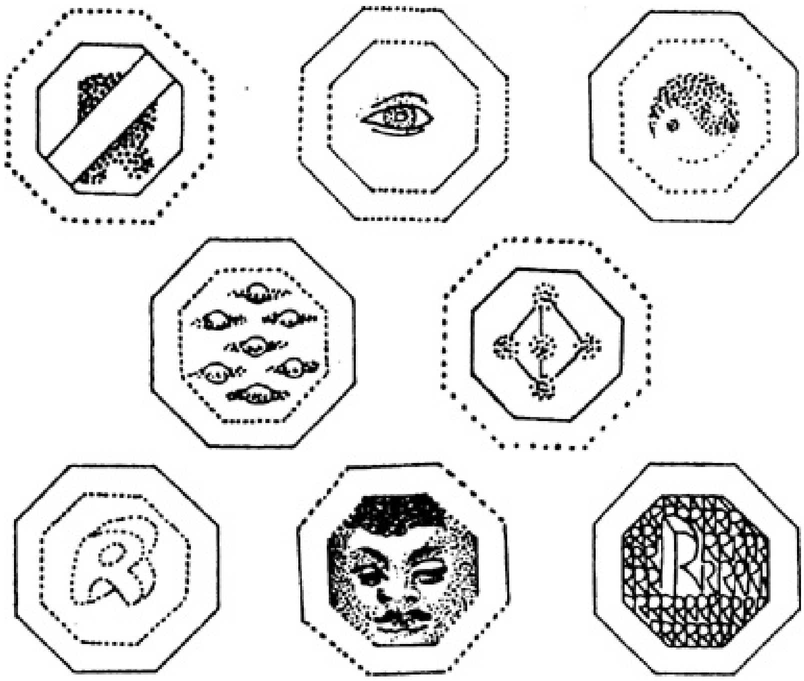


Fig. 2.1 *Eight emblems of quantum reality: which of these worlds, if any, lies behind the quantum facts*?

These four quantum realities should give you some feeling for the diversity of clai
regarding the world's ultimate nature. While followers of Everett bear witness to uncountab
numbers of quantum worlds, plus more on the way, students of Bohr and Heisenberg insi
that there is *not even one* quantum world. In their struggle to gain firm footing amidst t
slippery bricks of quantum fact, physicists have invented more realities than four. Keep yo
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 ne
concepts with old will not suffice. To cope with the quantum facts we must scrap our ve
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 th shortest words in the language, words such as *and, or*, and *not*. The behavior of these litt linguistic connectors governs the way we talk about things, and structures, in turn, the wa we think about them. For two thousand years, talk about logic (in the West) was cast in th syllogistic mold devised by Aristotle. In the mid-nineteenth century, George Boole, an Iris schoolteacher, reduced logical statements to simple arithmetic by inventing an artifici 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 an launched the now-flourishing science of mathematical logic. Outside the mathematic mainstream, a few creative logicians amused themselves by constructing "crazy logics" usin rules other than Boole's. These deviant designs for *and/or/not*, although mathematical consistent, were considered mere curiosities since they seemed to fit no human pattern discourse.

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

"Einstein threw out the classical concept of *time*; Bohr throws out the classical concept *truth* … Our classical ideas of logic are simply wrong in a basic practical way. The next step 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 physic quantum logicians point to Einstein's general theory of relativity, which achieved in th realm of geometry what they propose to do with logic.

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

Coincident with Boole's pioneer work in logic, a few adventurous mathematicians thoug up "crazy geometries," games points and lines could play outside of Euclid's rules. Chi architect of the New Geometry was the Russian Nicolai Lobachevski along with Germa mathematicians Karl Gauss and Georg Riemann. Their cockeyed geometries were regarde like non-Boolean logics, as high mathematical play, clever business but out of touch wi reality. Euclidean geometry, as everyone knows, was *the* geometry, being after all, nothin but common sense applied to triangles and other geometric figures.

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

Einstein's lesson is plain to see, say the quantum logicians. The question of the world's tru geometry is not settled by common sense but by experiment. Likewise with logic. For th 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 *ordina object* is an entity which possesses attributes of its own whether observed or not. With certa exceptions (mirages, illusions, hallucinations), the world outside seems populated wi 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 in the atomic realm and beyond. However, the unremarkable and common-sense view th ordinary objects are themselves made of objects is actually the blackest heresy establishment physics.

"Atoms are not things," says Heisenberg, one of the high priests of the orthodox quantu 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 emp formalism and obscuring the world's simplicity with needless mystification. Instead the preach return to a pure and more primitive faith. Chief among neorealist rebels was Einstei whose passion for realism pitted him squarely against the quantum orthodoxy: "Th Heisenberg-Bohr tranquilizing philosophy—or religion?—is so delicately contrived that, f the time being, it provides a gentle pillow for the true believer from which he cannot ve easily be aroused. So let him lie there."

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

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

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

One of the physics community's few traditions is the custom of celebrating the birthdays its great men with a *Festschrift*—a festival of papers. In 1982, Louis de Broglie, ninety yea sample content of Quantum Reality: Beyond the New Physics

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