7.

Restoring Reality

So irrelevant is the philosophy of quantum mechanics to its use, that one begins to suspect that all the deep questions about the meaning of measurement are really empty, forced upon us by our language, a language that evolved in a world governed very nearly by classical physics.

Steven Weinberg[1]

Subverting Common Sense

At the price of some repetition, let me bring together what we have we found in our survey of the interpretations of quantum mechanics and their various implications.

The Copenhagen interpretation, promulgated by Bohr, Heisenberg, and their followers in the late 1920s but somewhat evolved since, is still presented in one form or another in most quantum textbooks. When they stand in front of a quantum mechanics class, most physicist professors follow these texts and speak a Copenhagen-inspired language that unfortunately leads to considerable misinterpretation of the ontological meaning of quantum mechanics.

The words used are intended to explain and motivate the formalism. However, since the formalism is precise and unchallenged, while the words are vague and controversial, it perhaps would be better to skip the latter all together. But then, you can't walk into a classroom the first day of the semester and simply start writing equations on the board.

In my own classes in the past I have said things like: "the act of measurement causes the wave function of the electron to collapse" and "the electron in an atom has no position until it is measured." Only in recent years have I begun to appreciate the caveats behind these words and the depth of the philosophical debate over the meaning of quantum mechanics that has been carried on from its inception.

As a student, I did not learn from any professor or textbook that alternate interpretations can be found that lead to the same formal theory and predict the same experimental results as Copenhagen. I became aware of this by virtue of my side-research on pseudoscience and science mysticism, rather than through any work I have done in three decades as a physics teacher and researcher.

Few physicists share my interest in the borderlands of science. Perhaps a handful are vaguely aware of other quantum languages such as hidden variables, many worlds, or decoherent histories, but they pay them little attention. And few will take notice until one language is shown to be superior either in terms of making unique, testable predictions or making their calculations easier and more powerful.

The Copenhagen interpretation is often associated with the philosophical school of positivism. Relativity and quantum mechanics underscored the critical role of the measuring apparatus in defining what is measured, which is a prime tenet of positivism. Time is defined by clocks, temperature by thermometers. But taken to its extreme, the dubious conclusion is drawn that measurements constitute the extent of reality. This view subverts the commonsense belief in an objective reality independent of and external to human consciousness. Surely the universe does not care about human existence!   Common sense can be wrong, but it must be amply demonstrated to be wrong before one we should take seriously any proposed violation of common sense.

Within the philosophy and sociology of science today, three schools of thought, in addition to positivism, have been identified: realism, relativism, and pragmatism.[2] Although scientists often write books and articles that utilize a positivist perspective, most probably think of themselves vaguely as realists and pragmatists. Certainly they believe that what they do as scientists bears some relation to objective reality, that it’s not just all in their heads.

Few disagree that the best case to be made for science is that it provides benefits and practical applications that anyone plainly can see. However much you debate the philosophical foundations and moral value of science, it works better than any other mode of thought we humans have been able to invent so far.

To the practicing scientist, this is sufficient justification for the scientific enterprise no matter what philosophers, sociologists, and preachers say about it. Buried in the pleasurable details of their research, most scientists are at best dimly aware that this practical perspective on the nature of science is not automatically endorsed by everyone.

Perhaps the most annoying challenge to the contented view that scientists hold about their profession is the new relativism. As my Hawaii colleague and anti-relativist philosopher Larry Laudan defines it, relativism is “the thesis that the natural world and such evidence as we have about that world do little or nothing to constrain our beliefs.”[3]

The beliefs referred to here are not just those of churchmen and laymen, but those of scientific professionals as well. Science, in the relativist view, is akin to every other human activity - primarily a social phenomenon. And the so-called theories and laws of physics have less to do with the real world than they have to do with the traditions and interactions of the scientific community.

Among the views of those who write on modern metaphysics from perspectives outside mainstream science we can glimpse elements of relativism, and no little New Age solipsism: Reality is what we make it to be, by our conscious acts of observation and measurement. Growing to a great extent out of the work of Thomas Kuhn,[4] who denies he is a relativist, relativism has now spread its wings beyond science to where it has become the fashionable view among postmodernists and deconstructionists in the humanities.

However, I cannot think of a single working physical scientist who is a relativist. That handful who are even aware of Kuhn’s work (most would not even recognize his name) scoff at the idea that scientific truth is an arbitrary social convention. They all can produce examples that belie the notion.

One of my favorite examples is the magnetic moment of the electron, mentioned in Chapter 1, which is both calculated and measured to one part in ten billion with the two results in perfect agreement. To characterize this spectacular achievement as nothing more than social convention is absurd. The magnetic moment of the electron (and thus the electron itself) is as objectively real as any concept that humans can bring to mind, including the chair you are sitting on.

Another example is the precession of the perihelion of Mercury. In 1859, the French astronomer Joseph Le Verrier found that observations of the precession disagreed with Newtonian calculations by 43 arc seconds per century, an incredibly small but none-the-less measurable amount. In 1915, Einstein used his general theory of relativity to compute this anomalous precession and obtained exact agreement with the observations. After a decade of accurate, modern measurements terminating in 1976, the measured value was 43.11±0.21 compared to the best calculated value of 42.98.[5] When confronted with a success like this, it is again difficult to see how anyone can maintain that science is simply a social activity, like Church Bingo, with no deeper connection to reality (and perhaps less).

Positivism has not been so readily dismissed in scientific circles as has relativism. Obviously, our knowledge of the physical world depends on our sensory apparatus and how we design detection devices. Time can be given no unambiguous meaning without the concept of a clock. And my beloved electron magnetic moment depends on the operational definition of magnetism. This is common sense. Yet, the application of extreme positivism to quantum mechanics has encouraged the nonsensical notion that human consciousness is the agent that creates physical reality.

David Bohm offered a possible route to (but not a workable specific model for) a realistic, causal sub-quantum theory that avoided the consciousness connection. He proposed that still-unknown forces act as the agents of quantum behavior, the way once-invisible atoms produce thermal behavior. At first glance, Bohm's theory appeared to provide an alternative that restores traditional deterministic ideas and practical common sense to quantum phenomena, answering ontological questions about the source of quantum phenomena. But John Bell, and the experiments that tested his theorem, showed that sub-quantum agents, if they exist at all, must be nonlocal and thus allow for superluminal connections that violate at least the spirit of Einstein's relativity.

This was not regarded as a fatal blow to Bohm's theory, though perhaps it should have been. The invisible agents were simply said to be nonlocal - holistic - as Bohm later said he knew all along. Although this conclusion appears to conflict with Einstein's speed limit, Bohm and other proponents of hidden variables have argued that no signals are transferred faster than the speed of light, and thus no violation of relativity is implied. .

However, I regard this as a disingenuous position. The proof that no superluminal signals exist in Bohm's theory and other published alternate interpretations of quantum mechanics utilizes the formalism of conventional relativistic quantum field theory.[6] It does not invoke any unique features of hidden variables or other sub-quantum theories, and applies in general for any theory that gives the same results as conventional quantum mechanics. Since Bohm's theory gives the same results, it cannot allow superluminal communication despite its nonlocality.

One often hears the statement that Bohm's hidden variables are consistent with relativity. Technically this is true. But as we have seen, superluminal motion is actually allowed by relativity, provided the particles that move superluminally always do so. That is, they must represent a new class of particles, called tachyons, that are not simply normal particles accelerated beyond the light barrier. Einstein's speed limit resulted from the additional hypothesis of causal precedence and is supported not so much by theoretical argument as experimental fact: no tachyons have yet been observed. Thus a Bohmian sub-quantum theory with tachyons would not be in conflict with relativity, but would require that the labels cause and effect depend on the choice of reference frame.

It is not a virtue but a vice for a theory to agree with all conceivable experiments. For then it cannot be tested, and no way exists for it to be shown to be right or wrong. It is useless, since it makes no contribution to knowledge or technology. I cannot see how one can escape the conclusion that nonlocal hidden variables, to have any unique observable effects that make the notion meaningful and useful, must yield superluminal motion.

The way to demonstrate the validity of hidden variables theories is clear: Measure superluminal effects. The primary characteristic of the hidden variables would be their superluminality. In the absence of observed superluminal effects, or some other comparably unique prediction of the theory, no evidence exists for hidden variables.

The holistic ideas that follow from nonlocal hidden variables, such as Bohm's holomovement and the implicate order, have great emotional appeal. They provide some people with a reason to believe that they are not simply insignificant specks of matter but instead are intertwined with the totality of existence. Unfortunately, this comforting conclusion has no rational basis. So far, nonlocal phenomena have not been observed and the nonlocality of objectively real quantities is not required to explain the results of any experiment.

As we have seen, the nonlocality that many believe is inescapable in quantum mechanics resides in sub-quantum theories or interpretations in which the wave function is assumed to be a real field associated with individual particles. Nonlocality in the behavior of objectively real objects, not just abstract mathematical functions, does not exist in conventional quantum mechanics - nor in any actual observations. And even if superluminal motion exists at the elementary level, it still may have no role to play in human life which can be very well-understood in familiar, local terms. That is, the quantum world could be superluminal with cause and effect relative while the macroscopic world remains exactly as demanded by common sense.

At present it is incorrect to state, as is often done, that the EPR experiments require nonlocality in the real world. These experiments, if correct, only require nonlocality in any theory that provides a quasi-Newtonian causal mechanism for the motion of individual particles, or retains some other classical notion of the role of physical theory, such as completeness or separability. I have shown how the simple procedure of viewing the Bohm-EPR experiment in a time-reversed frame of reference leads to a perfectly local picture, provided indeterminism is retained. Paradox only appears when you insist on imposing the time direction of common experience, which need not apply to quantum events.

While these issues remain the subjects of intense debate, the indeterministic nature of conventional quantum mechanics appears sufficient to retain pragmatic locality and still agree with EPR experiments. And, if it does not, perhaps an effort needs to be made to cast quantum mechanics in such a form, rather than taking for granted that the universe is nonlocal. At least this would put an end to mystical speculations about quantum mechanics demanding a holistic universe.

Two Steps are Better than One

The existence of a deterministic universe ruled by real, nonlocal hidden variables can probably never be totally ruled out. But, in the words of Pauli from another context, such a theory is “not even wrong” as long as it remains untestable.

To the extent that the models of Bohm and de Broglie are not testable, they should not be taken as seriously as they are in the popular and philosophical literature. Their main merit was to show that multiple interpretations of quantum mechanics were possible. This got us out of the metaphysical morass of the consciousness connection that pervades the common misinterpretation of Copenhagen. But hidden variables contribute a metaphysical morass of their own by requiring superluminal motion and its attendant implausibilities.

The many-worlds interpretation provides a way of viewing the entire universe as a quantum system that is not possible in the Copenhagen picture where a classical observation device resides outside the quantum system under study. Something different from Copenhagen is a necessity for quantum cosmology. Many worlds also avoids the notion of wave function collapse, though, as we have seen, collapse represents no philosophical problem for Copenhagen once we recognize that it does not require the wave function be a real field. Many worlds has itself been interpreted as requiring a continual splitting of the universe into parallel branches, again a rather bizarre, non-testable notion that obscures the real virtue of Everett’s original work in developing a quantum formalism that incorporates the detection apparatus.

Out of the Metaphysical Morass

The more recent, post-Everett re-interpretation of many worlds in terms of alternate, consistent, or decoherent histories seems to offer the most promise in solving our conceptual problems. In this modern view, the wave function of the universe contains all the information needed to predict the probabilities for the alternate paths particles can take, but these paths are taken by chance.

The universe, by virtue of its atomicity, is fundamentally discrete or coarse-grained. This was the first observation of Planck - what put the *quantum* in quantum mechanics. In the alternate, consistent, decoherent histories view, particle paths cannot be precisely defined unless they pass through spatial regions containing other matter from which they scatter and decohere. Quantum mechanics allows you to calculate the probability for each such path, but does not predict with certainty which one is actually taken except when that probability turns out to be close to unity.

The wave function of the universe not only describes the paths that are taken by all the particles of the universe, it also describes all the other possible paths that might have been taken consistent with the laws of physics. Note that the theory does not tell us “why” the universe takes a particular path, that no further selection is made beyond a probabilistic one.

Although the analogy is not perfect, one might compare the alternate histories of quantum mechanics with the alternate histories of the theory of evolution. Evolutionary theories cannot predict the exact path along which species will evolve. The unknowns are too many and random effects play too large a role. At best, theory can predict which paths are more likely than others. Quantum mechanics may be very much like that.

Those, following Einstein, who desire a deterministic universe will be unsatisfied and will regard theories such as alternate histories (or evolution) as incomplete. Perhaps an underlying hidden determinism still exists; the issue is not settled. But after almost a century of quantum mechanics, the prospect is likely that an element of indeterminism, or randomness, will remain.

If indeterministic quantum mechanics is the complete story, then the choice of paths is done by a toss of the dice, despite Einstein’s horror at the prospect. If, on the other hand, quantum mechanics is incomplete, then some underlying causal mechanism, yet undiscovered, may decide on the path taken (although an underlying indeterministic theory is still possible). Proposals for the underlying mechanism range from Bohm’s quantum potential to the “mind” itself. With no evidence supporting any such mechanism, and with nonlocality as the consequence, an application of Occam’s razor leaves as the most rational alternative a non-mechanistic, noncausal, random selection of particle paths.

The idea of consistent histories and decoherence along allowed paths may not turn out to be the final solution to the mysteries of quantum mechanics. Some think they are insufficient as they stand and need to be supplemented by additional axioms.[7] But, at the very least, these notions demonstrate that the metaphysics of either holistic hidden variables or many worlds is not currently required to move beyond

Copenhagen to a modern, pragmatic interpretation of quantum mechanics.

Decoherence produced by the measuring apparatus or environment provides for wave function collapse without paradox or mysticism. . Certainly the qualities and quantities of observation are objectively real, not existing solely in the mind of the observer.

Further, a rational notion of objective reality is retained. The decoherent histories approach provides a clear concept of reality consistent with common usage. Sequences of real events in spacetime form sets of paths for which relative probabilities can be assigned.

The probability for a given path need not be either zero or 100 per cent, as in classical physics where all motion is determined by previous motion. The actual paths that occur in the quantum universe are randomly selected from the allowed set of paths according to their probabilities.[8] If the probability for following branch A along a particular path, given by the square of the wave function of the universe at the point where the paths diverge, is 75 percent, and the probability for path B is 25 percent, then path A is three times as likely to be followed - though by no means guaranteed. (One way to think of this example is to visualize four paths of which three follow branch A and one follows B, with all four equally likely).

The laws of physics are then associated with setting limits and likelihoods for events, and restrictions on the possible paths. They do not determine that a given event will happen in an exact way at a given place and time.

Physical reality is associated with predictability, and predictability with probability, but not necessarily with certainty or determinism. We imagine a huge wave function that describes the whole universe (technically, ensemble of similarly-prepared universes), including observers and measuring devices. This wave function contains the information needed to compute the probabilities for all allowed histories, but only broadly controls the outcome of events which are random within limits prescribed by conservation principles. These events are real, by definition. The contents of dreams and illusions have neither limits nor predictability, and so are not real by an application of common notions of reality.

Obviously we have not yet developed the cosmological theory that enables us to compute the full wave function of the universe. Such a theory may be beyond human capacity. But we do have partial theories that enable us to compute various pieces of that wave function. In this regard, we retain the practical notion of reductionism, which asserts we can usefully analyze the parts of a system without knowing all the details about the whole. This, after all, is the best we can do. The popular alternative of holism is empty of utility, insisting as it does that we must know everything before we know something, that we must be God before we can become a scientist.

From the pieces of the wave function calculated reductively, we are able to compute the probabilities of alternative histories for the particular region of the universe under study. Now, the relative probabilities for two alternative paths of a particle can only be calculated when the wave functions for the two paths decohere. This decoherence can be produced by a particle detector, or by particles in the environment itself. Quantum mechanics gives the same results as classical mechanics when wave functions decohere, and so objectively real histories represent our familiar observations, which are conventionally described in classical, macroscopic terms.

The Source of Quantum Effects

Quantum effects are not limited to the microscopic realm. Authors usually point this out with examples such as superconductivity or SQUIDs (Superconducting Quantum Interference Devices). But light provides a more familiar example.

The interference and diffraction of light, effects observable to the naked eye, are fundamentally quantum in nature. True they can be “explained” by the classical wave theory of light, but once we accept the fact that light is composed of photon *particles*, we must acknowledge that light interference is a quantum phenomenon - just as is the interference of electrons. It simply was not originally recognized as such. Indeed, interference and diffraction occur at some level for all objects in the universe.

Quantum effects, microscopic or macroscopic, manifest themselves in observations that themselves are described in classical terms because we and our devices are macroscopic. In the Copenhagen interpretation, a distinction seems to be made between the quantum system being observed, and the classical apparatus doing the observing. This, to many, is unsatisfactory since the detection apparatus is fundamentally quantum - made up of atoms just like everything else in the universe.

In the language of post-Everett quantum mechanics, quantum effects result from the ultimate granularity or discreteness of the universe - the discreteness first elucidated by Planck when he observed that light is not continuous but exists in quanta. Classical effects result when this granularity is too small to be observable. In the classical world, matter, light, and force fields appear continuous.

The apparent continuity of the classical gravitational, electric, and magnetic fields is only approximate, as is the apparent continuity of matter on the macroscopic scale. Ultimately these are discrete. Although effects of quantum gravity are yet to be observed, the detection of photons testifies to the quantization of electromagnetism. Electromagnetism is fundamentally not a continuous field phenomenon, despite the great utility of describing it that way for many practical applications.

If light and matter were smooth and continuous on all scales, infinitely divisible as was believed by many in the nineteenth century (despite the already widely-known atomic theory), then the alternate histories of post-Everett quantum mechanics would be completely fine grained. That is, the universe would have no granularity at all; every path through space would be a possible, real, decohering path.

Furthermore, some paths would be allowed and others forbidden. The motion of bodies would be determined - predictable with unit probability. Deterministic classical physics implicitly assigns unit probability to one path, and zero for all the others. Indeterministic quantum mechanics leads to deterministic classical mechanics in the fine-grained limit, as it must if it is to agree with the great bulk of human observation.

Undoubtedly, the classical picture works to a good approximation for most phenomena of common human experience. And determinism naturally follows in this limit from the Feynman path-integral picture. The wave function, in the classical limit, decoheres at each point because something material exists at that point. (Recall that the classical “vacuum” contains an all-pervading etheric medium for the propagation of light).

Put another way, a completely fine-grained alternate histories version of quantum mechanics is indistinguishable from continuous, deterministic classical mechanics. Thus we do not have to make an arbitrary division between the classical and the quantum, between the observed and the observer. Everyday phenomena are fundamentally quantum, like everything else, but are largely well-explained by classical mechanics because of the high level of decoherence of most of the macroscopic world.

With the important exception of light, we live in a world that is accurately described by the classical limit of quantum mechanics. No wonder light has been always regarded as a mystery, something more profound than mundane matter. It is the one quantum phenomenon that is part of everyday experience.

The limit to divisibility implied by the ideas of Planck and the other founders of quantum mechanics is interpreted, in post-Everett quantum mechanics, as a coarse-graining of the allowed alternative histories that exists as a fact of nature. This is what leads to quantum effects. When a detector or an environmental particle is present at a particular point in space, then an allowable path can pass through that point and the alternate histories then include that path. The objective reality of that path exists, independent of conscious observers.

For example, suppose the double slit experiment is conducted in a transparent medium in which the photons in the beam have a wavelength larger than the distance between slits. Since the medium is transparent, the photons negligibly decohere. With no detectors behind the slits, so that no decoherence occurs there, the coarse graining of the experiment is such that specific photon paths through either slit are not predictable by standard quantum theory.

Now consider this experiment from the point of view of the photons incident on the slits. Suppose the photons are monoenergetic (same color or wavelength). The higher the photon energy E, the lower its wavelength $\lambda = hc/E$. When the energy is high enough so the wavelength is very small compared to the slit separation d, then the photons “see” both slits and each photon passes through one slit or the other in the normal, classical way. In this case, no observable interference pattern results.[9]

If, on the other hand, the energy is low enough so λ is comparable to or larger than d, then the photons do not resolve the two slits. From the point of view of someone using those photons to observe the screen containing the slits, two separated slits are undetectable. In that case, the photons are not known to pass through one or the other and the rules of quantum mechanics tell you to add their amplitudes rather than their probabilities. An interference pattern is then the result.

If we place a detector behind one slit we return to the classical picture because the experimenter now has sufficient information to resolve the slits, although we still cannot predict, before the fact, which slit the photon passes though. Alternatively, the environment can cause the paths to decohere, also leading us back to the classical picture.

Here is where much of the confusion about whether or not quantum mechanics is local can be cleared up. If we are to insist that the photon has a predictable path in all cases, then we must introduce some nonlocal influence such as the quantum potential that passes simultaneously through both slits. But if we simply admit that the slit through which the photons passes is unpredictable at the level of coarse graining that exists in the region of space that encloses the experiment, then nonlocality need not be introduced.

While we cannot escape the role of experiment in defining the quantities observed, this role is not so exclusive as it is in Copenhagen physics or positivist philosophy. We can simply view the placement of a detector at a particular point as a change in the environment produced by humans - sort of like the ozone hole. We simply place a decoherer at a place where nature originally did not provide one. At other places, nature provides.

Decoherence is produced by the environment, including any human modifications. We are part of the environment too, as are the detectors we place at different points when we perform experiments. No artificial distinction should be made between observer and observed.

Even far from the atmosphere and oceans of earth, well beyond the scope of human intervention, macroscopic regions of totally empty space are impossible. Low energy photons in the 2.7^{o}K microwave background pervade all space, and so-called “virtual” particles are constantly being created and destroyed in the vacuum, according to modern quantum field theories. These will produce some decoherence at all levels, but especially on macroscopic scales. In fact, decoherence caused by the environment explains why the macroscopic world appears classical, why the moon does not appear in one place in the sky at one instant and some other place at another instant.

In the decoherent histories view, the coarse graining of the universe can be of macroscopic dimensions when the environment of a particle is highly transparent to that particle. Such is the case with visible photons in air, water, glass, or the vacuum. An extreme example is provided by neutrinos, to which even the earth appears as empty space and the corresponding coarse graining has astronomical dimensions.

Thus the granularity of the universe is not the same for all forms of matter, but depends on interactions between particles and their energies. Our current theories of particles and forces enable us to calculate the granularity for photons and the other known particles as they move through known media. Thereby we can predict, with some uncertainty, the paths these particles will take.

The Time-Symmetric View

As we probe deeper, we find that the various interpretations of quantum mechanics overlap more than they may appear to on the surface. The one characteristic that they all share, what seems to be a minimal requirement for any quantum theory, is *contextuality*. Explain contextuality and you explain quantum mechanics.

Contextuality refers to the fact that quantum theories must consider the entire experiment in making their predictions, not just one detector off in some corner. Changing a detector off in another corner, changes the experiment.

Contextuality can be shown to be a natural feature that follows directly from a fundamental fact about quantum phenomena, the apparent symmetry of time. When no distinction is made between past and future, the future experimental arrangement of detection devices, such as polarizer orientations, must have as much effect on the system as any initial conditions. Final and initial conditions are conceptually equivalent.

How contextuality follows from time symmetry can be easily understood from the illustration in Fig. 7.1. There a system is seen to start from some initial state *i*. In classical mechanics, the final state *f* is completely determined. In quantum mechanics, a range of final states is possible for a given initial state. These are illustrated by *f1*, *f2*, and *f3* in the figure.

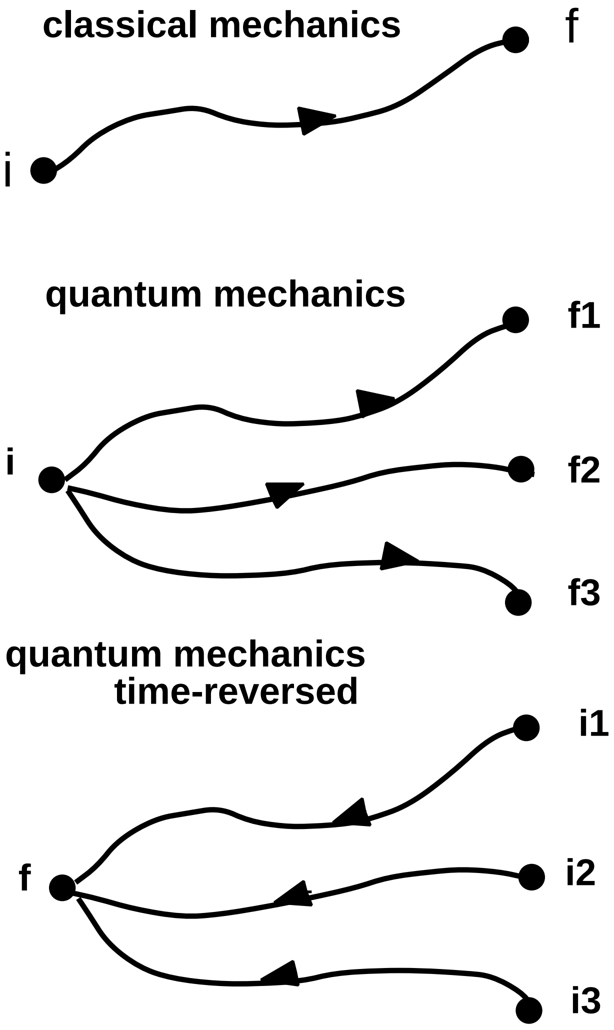

Fig. 7.1. How time-symmetry implies contextuality.
In classical mechanics, a particle in an initial state i will always move to a specific final state f. In quantum mechanics multiple final states are possible. In the time-reversed situation, the three final states shown become different initial states, and thus different experiments. Thus both intial and final state must be specified for a given experiment.

When we then consider the time-reversed situation, these three final states becomes different initial states *i1, i2,* and *i3*. From this point of view, we have three separate experiments corresponding to the three different starting points. The only way we can maintain time symmetry is to insist that both the initial state and final state be specified in any given experiment. Quantum mechanics then calculates the probability for the transition *i-f* to take place.

Time symmetry also goes at least part of the way in satisfying our need for visualizations of quantum phenomena that correspond closely to commonsense experience, though this can never be fully achieved since quantum phenomena (and time symmetry) deviate from commonsense experience. Consider once more the double slit experiment. One of the “mysteries” of quantum mechanics is how the interference pattern can depend on a choice of detector arrangement made after the particles are emitted from the source. Furthermore, the very existence of the interference pattern seems to defy any attempt to describe the process in terms of familiar particle paths. How can a photon or electron go through both slits simultaneously so that their corresponding wave functions can interfere?

I have shown in Chapter 5 how the notion of multiple specific paths for a single particle can be retained in the double slit experiment by viewing the particle as going through one slit to the detector, then *back in time* to the source through the second slit and finally forward in time once more through either slit to the detector (see Fig. 5. We also saw how the EPR experiment becomes trivially local in a time-symmetric scenario.

The transactional interpretation of John Cramer, with its physically real offer and confirmation waves, represents a similar approach that utilizes time symmetry. However, we are not required to introduce the novel concept of offer and confirmation waves to solve the alleged paradoxes of quantum mechanics. This can be done with the picture of particle and antiparticles travelling in both time directions that has been part of our picture of fundamental interactions since Feynman and others first suggested the idea over forty years ago.

While the time-symmetric picture may not totally satiate the hunger for commonsense descriptions, at least it allows for the visualization of multiple interfering paths. In fact, time symmetry at the fundamental level requires that paths in both time directions be given equal weight. Our common sense leads us astray here because of its insistence in a uni-directional flow of time.

Note that my multiple path description of the double slit violates Bohr’s positivist insistence that we can only talk about what is measurable. The multiple paths are inherently undetectable, since once we place a detector in one path we destroy the coherence and introduce a unique time direction.

Do these multiple paths “really” exist? We may never know. But this should not stop us from using a picture based on common notions such as particle paths, even when they are not directly observable, if that picture aids in our understanding and can be used to obtain results that agree with that experiments that are conducted. In this case, the multiple path picture leads to the observed interference pattern.

Finally, I cannot emphasize too strongly that speaking about time symmetry at the level of fundamental interactions implies nothing about the possibilities of human travel backward in time. The arrow of time remains present in macroscopic or many-body phenomena as the direction of most probable occurrences. At the scale of human experience, the random scatterings of particles in many-body systems that is responsible for decoherence and quantum phenomena appearing classical is also responsible for the generation of entropy that defines the direction of time. Going backward in time is technically possible, but statistically so improbable that we cannot expect it to happen for a single macroscopic body in the age of the universe. Humans are governed, for all practical purposes, by the emergent properties of many-body systems, including cause and effect and the second law of thermodynamics.

Uncertainty and Rationality

Consider again how classical mechanics is viewed from the perspective of decoherent histories, as the limit in which the universe has no granularity, where every point in space can decohere a particle moving through that point. In this case, all paths in spacetime are possible paths, since they all have definable probabilities. But note: Nothing in this statement requires that these probabilities be either zero or unity, that all allowed paths are necessarily completely certain. This occurs only as an approximation in the classical limit.

In the usual formulation of classical mechanics, the certainty of specific paths results from an additional assumption that given the initial position and momentum of a particle, the future path of that particle is completely determined by certain equations of motion, or equivalently, by the principle of least action. As mentioned previously, the Feynman path integral formulation of quantum mechanics can be used to establish the classical principle of least action. This is the determinism of the Newtonian world machine. It results in a probability calculation yielding essentially 100 percent for one path and zero percent for all others.

But classical calculations rarely make predictions with 100 percent certainty. Any application of the classical equations of motion to predict the path of a particle requires an exact knowledge of the initial conditions, which is impossible since such measurements cannot be made with infinite accuracy.

Measurement errors are inevitable, even where we can imagine building a measuring device with unlimited precision. To represent the position of a particle in a continuous universe with perfect precision would require an infinitely long number. However, calculations must be performed with calculators or computers (or fingers) using numbers of finite length. This is not a practical problem for many of the traditional applications of classical mechanics, where sufficient accuracy for a very precise calculation can be made and compared with an equally precise measurement.

As we will see in a later chapter, certain physical systems, even if modelled by the completely deterministic equations that are found in Newtonian physics, can be so sensitive to initial conditions as to be unpredictable for all practical purposes. These systems are chaotic.

Physics is Counting

The mathematical representation of completely continuous, fine-grained space, time, and matter requires the use of **irrational** numbers. These are taken for granted in classical physics, and even the formulas of quantum mechanics. For example, when we solve Schrödinger's equation, we assume the resulting wave function Y is a function of continuous spatial coordinates x,y and z, and a continuous time coordinate t. Infinitesimal calculus is utilized, which is a mathematics of irrational numbers.

However, physics is counting. Physical observables are operationally defined by counting procedures and so in principle should always be represented by **rational** numbers - integers or ratios of integers. The observables of physics are only approximately represented by continuous, irrational numbers, despite the widespread belief of the opposite - that the irrationals are fundamental and the rationals are approximations.

Consider time. By international agreement, a time interval equal to one second is operationally defined as 9,192,631,770 vibrations of Cesium-133, an integer. Suppose we count the number of Cesium vibrations between two events. The result will be an integer N. Of course, the time interval can be less than one second, or less than one Cesium vibration. We can easily accommodate smaller times by dividing the second into fractions and write $t = N / M$. Since N and M are both integers, t is a rational number.

Now the above definition is arbitrary and not the source of the ultimate discreteness of time. The minimum definable time is given by quantum mechanics and gravitational theory to be 10^{-43} second, the *Planck time*, which will be discussed in the next chapter. In principle, a time interval is the number of Planck times between two events - an integer.

Irrational numbers, as applied to physical quantities, occur only in a universe without granularity, or in the granular universe as a process of approximation that should not be taken as valid to unlimited precision. We normally assume that the time t can take on an infinite number of values in any time interval. That is, we take t to be part of a continuum. But ultimately time intervals can be no smaller than the Planck time.

Distance, the quantity of space between two points, is also by international convention defined to be proportional to the time it takes for light to go between the two points in a vacuum. If that time is one second, the distance is 299,792,458 meters, again an integer. We call this number c, the "speed of light" in a vacuum, but note that this is simply the definition of the meter and the Einstein principle that c is a constant (in a vacuum) is assumed. More generally, where time is in fractional units, distance will be a rational number, say cN / M. The smallest distance is c times the Planck time, 10^{-35} meter, called the *Planck length.*

In the second century B.C.E., Euclid, assuming a continuum of space, proved that the length of the diagonal of a unit square was not a rational number. This length is conventionally written as √2. However, if you measure the diagonal of a square by counting the number of spatial units from one end to the other, you will have an integer in those units. The diagonal becomes an irrational number only if space is a continuum.

Another familiar irrational number is π = 3.14159 . . . The surface area of a sphere of radius r as $4\pi r^2$. But our measurements are fundamentally rational numbers, such as the number of unit area squares that fit on the surface of a sphere. And in computations we approximate π by a rational number such as 3.14159 = 314,159 / 100,000.

Discreteness, manifested by rational numbers, is built into the way in which we operationally define and perform actual numerical calculations on the quantities of physics. Continuity, manifested by irrational numbers and associated with mathematical tools such as calculus, is applied in physics only as a convenient approximation.

This is not to say that we should give up our “irrational” mathematical methods. They, along with the rest of the mathematics of real and complex numbers, which includes infinitesimal calculus and other powerful methods, have proven their immense value in the classical physics that applies, to an excellent approximation, for most of the macroscopic world. My point here is simply this: We should not regard as logical paradoxes any conclusion drawn from a mathematical analysis applying our system of irrational numbers, infinities, and infinitesimals to a universe that is fundamentally rational, finite, and not continuously divisible.

As we have seen over and over again, the problems and paradoxes of quantum physics are the direct result of thinking in continuum terms. That darn aether refuses to die. At the most esoteric levels of quantum field theories, infinities occur in calculations that utilize conventional continuum mathematics and a very elaborate trick called *renormalization* must be used to get finite results. This trick often works, but not always. When it does not work, then discrete calculations must be employed. Unfortunately, these are far more laborious than the techniques of continuum calculus, though super computers are making the procedure increasingly viable.

At the more elementary level, we can show how the uncertainty principle arises naturally once we accept the fundamental granularity of space and time. Imagine a time sequence as a discrete series of unit steps. That is, if we start at $t = 0$, the next time is $t = 1$, the next $t = 2$, and so on. Let x give the position of a particle of mass m at a certain time and x' give the position at the next time step. Then the velocity of the particle is $(x'-x)/1$ and its momentum $p = m(x'-x)$. Since the position of the particle at two different times is needed to measure p, we conclude that position and momentum cannot be measured simultaneously.[10]

In other words, the indeterminism in quantum mechanics is not some added assumption in the theory but a fundamental consequence of the discreteness or granularity of the universe. Any deterministic sub-quantum theory will have to restore the spacetime continuum to physics.

One of the questions that has been raised about the decoherence mechanism is that it only makes the interference terms small, not identically zero. Thus Schrödinger's cat is not half alive and half dead, but 0.999999 probability alive and 0.000001 probability dead, which still presents us with a logical paradox. Discreteness rescues us from this dilemma by effectively rounding the irrational numbers to the nearest rational number, in this case 1 and 0.

Full (but Subluminal) Speed Ahead

And so, the fundamental granularity of the universe seems an inescapable fact about nature, at least when we attempt to describe nature in terms of familiar concepts such as distance, time, mass, and energy. But continuity is so deeply embedded in our thinking that even when they developed the discrete quantum theory, physicists retained many of the notions of classical continuity - in particular those of a space-time continuum underlying all reality, with spatial coordinates and time intervals represented by the infinite set of irrational numbers.

The persistence of the notion of continuity within the formulation of quantum mechanics has not prevented it from being applied with great success. That can be attributed to the fact that the ultimate granularity of space and time occurs at the Planck scale (smallest distance 10^{-35} meter, smallest time 10^{-43} second) far beyond existing experimental reach. So, treating space and time as continuous is a perfectly justifiable approximation at current levels of observation, as long as we recognize it as an approximation and do not cry “Paradox!” when it leads to inconsistent results.

Where the discreteness of nature is manifest in observational data, such as with mass, energy, and angular momentum, it is built into the theory, and has been since the 1920’s. But right from the beginning, conceptual problems raised their heads when it was attempted to explain quantum effects in familiar terms. In the Bohr atom, for example, the electron jumps “instantaneously” from one orbit to another - at infinite speed, if you insist on space-time continuity in the picture you form of the event in your mind.

Note how the paradox disappears in the discrete view: the electron jumps from x at time 0 to x’ at some time t that can be no less than one unit. Its speed is (x’-x)/t, which is finite.

Bohr’s energy level formula correctly reproduced the observed spectral lines of hydrogen that had no classical explanation, so his theory must have had something to do with reality. With the more powerful tools that were later developed, atomic theory was extended to the rest of the Periodic Table of the elements, providing an understanding of the fundamental basis of chemistry. Armed with that knowledge, twentieth century chemists have been able to develop thousands of new and useful substances.

The unique spectra of atoms are used to determine the chemical composition of materials, in the laboratory and in the cosmos billions of light-years distant. X-rays produced by atoms excited by high voltages are now as common a medical diagnostic tool as the stethoscope.

Studies of the nuclei of atoms have lead to nuclear power, medical applications of nuclear radiation, and radioactive dating for the study of human and earth history. Though nuclear energy is regarded by most as at best a mixed blessing, its development also provides dramatic testimony that the world of the quantum is not a fantasy but a very real component of our universe. These results amply demonstrate that the universe is not a continuum in space, time, matter or energy.

All these developments came about without the settling of the philosophical disputes over the interpretation of quantum mechanics. To they extent that those disputes rest on the assumption of a continuum and an arrow of time, they may be safely set aside while we get on with the business of further developing and utilizing our new knowledge of the structure of the universe.

Notes

1. Weinberg 1992. p. 84.

2. See Laudan 1990.

3. Laudan, p. viii.

4. Kuhn 1970.

5. Will 1986, pp. 93-95.

6. Eberhard 1989.

7. Dowker 1994.

8. The word random technically means equally likely. This does not preclude the notion of unequal probabilities. For example, in the toss of two dice we assume all faces are equally likely to fall facing up, but a total of seven still has six times the probability of two ones, or “snake eyes.” These probabilities are determined by adding the various ways that the desired result can happen assuming an equally-likely 1/6 chance for each face on each die. Snake eyes can happen only one way, both die falling with aces up (1/6)(1/6) = 1/36 of the time, while a seven can happen six different ways for a probability of 6/36 = 1/6.

9. Interference patterns are observable with l small compared to d if the screen is placed sufficiently far away. I am considering here the case when $l << d$ and the interference pattern collapses to a point in any practical experiment. This can be regarded as taking the classical limit, where the quantum wavepacket still exists,

but is very narrow compared to the other relevant dimensions of the experiment.

10. For a discussion of discrete physics, see Kauffman 1994 and Noyes 1994.