THE LANDSCAPE OF THEORETICAL PHYSICS: A GLOBAL VIEW

From Point Particles to the Brane World and Beyond, in Search of a Unifying Principle

MATEJ PAVŠIČ
Jožef Stefan Institute
Jamova 39
SI-1000 Ljubljana
Slovenia

Kluwer Academic Publishers
Boston/Dordrecht/London

Contents

Part IV Beyond the Horizon

Preface

Today many important directions of research are being pursued more or less independently of each other. These are, for instance, strings and membranes, induced gravity, embedding of spacetime into a higher-dimensional space, the brane world scenario, the quantum theory in curved spaces, Fock–Schwinger proper time formalism, parametrized relativistic quantum theory, quantum gravity, wormholes and the problem of "time machines", spin and supersymmetry, geometric calculus based on Clifford algebra, various interpretations of quantum mechanics including the Everett interpretation, and the recent important approach known as "decoherence".

A big problem, as I see it, is that various people thoroughly investigate their narrow field without being aware of certain very close relations to other fields of research. What we need now is not only to see the trees but also the forest. In the present book I intend to do just that: to carry out a first approximation to a synthesis of the related fundamental theories of physics. I sincerely hope that such a book will be useful to physicists.

From a certain viewpoint the book could be considered as a course in theoretical physics in which the foundations of all those relevant fundamental theories and concepts are attempted to be thoroughly reviewed. Unsolved problems and paradoxes are pointed out. I show that most of those approaches have a common basis in the theory of unconstrained membranes. The very interesting and important concept of membrane space, $\mathcal{M}$, the tensor calculus in $\mathcal{M}$ and functional transformations in $\mathcal{M}$ are discussed. Next I present a theory in which spacetime is considered as a 4-dimensional unconstrained membrane and discuss how the usual classical gravity, together with sources, emerges as an effective theory. Finally, I point out that the Everett interpretation of quantum mechanics is the natural one in that theory. Various interpretational issues will be discussed and the relation to the modern "decoherence" will be pointed out.

If we look at the detailed structure of a landscape we are unable to see the connections at a larger scale. We see mountains, but we do not see the mountain range. A view from afar is as important as a view from nearby. Every position illuminates reality from its own perspective. It is analogously so, in my opinion, in theoretical physics also. Detailed investigations of a certain fundamental theory are made at the expense of seeing at the same time the connections with other theories. What we need today is some kind of atlas of the many theoretical approaches currently under investigation. During many years of effort I can claim that I do see a picture which has escaped from attention of other researchers. They certainly might profit if they could become aware of such a more global, though not as detailed, view of fundamental theoretical physics.

MATEJ PAVŠIČ

Chapter 11

THE LANDSCAPE OF THEORETICAL PHYSICS: A GLOBAL VIEW

In the last Part, entitled "Beyond the Horizon", I am going to discuss conceptual issues and the foundations of theoretical physics. I shall try to outline a broader[1] view of the theoretical physics landscape as I see it, and, as seems to me, is becoming a view of an increasing number of researchers. The introductory chapter of Part IV, bearing the same title as the whole book, is an overview aimed at being understandable to the widest possible circle of readers. Therefore use of technical terminology and jargon will be avoided. Instead, the concepts and ideas will be explained by analogies and illustrative examples. The cost, of course, is a reduced scientific rigor and precision of expression. The interested reader who seeks a more precise scientific explanation will find it (but without much maths and formulas) in the next chapters, where many concepts will be discussed at a more elaborate level.

Throughout history people have been always inventing various cosmological models, and they all have always turned out to be wrong, or at least incomplete. Can we now be certain that a similar fate does not await the current widely accepted model, according to which the universe was born in a "big bang"? In 1929 an american astronomer Edwin Hubble discovered that light coming from galaxies is shifted towards the red part of the spectrum, and the shift increases with galactic distance. If we ascribe the red shift to galactic velocity, then Hubble's discovery means that the universe is expanding, since the more distant a galaxy is from us the greater is its velocity; and this is just a property of expansion. Immediately after that discovery Einstein recognized that his equation for gravity admitted

[1]The outline of the view will in many respects be indeed "broader" and will go beyond the horizon.

precisely such a solution which represented the expansion of a universe uniformly filled with matter. In fact, he had already come to just such a result in 1917, but had rejected it because he had considered it a nonsense, since an expanding universe was in disagreement with the static model of the universe widely accepted at that time. In 1917 he had preferred to modify his equation by adding an extra term containing the so called "cosmological constant". He had thus missed the opportunity of predicting Hubble's discovery, and later he proclaimed his episode with the cosmological constant as the biggest blunder in his life.

General relativity is one of the most successful physical theories. It is distinguished by an extraordinary conceptual elegance, simplicity of the basic postulates, and an accomplished mathematical apparatus, whilst numerous predictions of the theory have been tested in a variety of important and well known experiments. No experiment of whatever kind has been performed so far that might cast doubt on the validity of general relativity. The essence of the theory is based on the assumption (already well tested in special relativity) that space and time form a four-dimensional continuum named *spacetime*. In distinction with special relativity, which treats spacetime as a *flat* continuum, in general relativity spacetime can be curved, and curvature is responsible for gravitational phenomena. How spacetime is curved is prescribed by Einstein's equation. Strictly speaking, Einstein's equations determine only in which many different possible ways spacetime can be curved; how it is actually curved we have to find out at "the very place". But how do we find this? By observing particles in their motion. If we are interested in spacetime curvature around the Sun, then such particles are just planets, and if we are interested in the curvature of the Universe as the whole, then such particles are galaxies or clusters of galaxies. In flat spacetime, in the absence of external forces, all particles move uniformly along straight lines, whilst in a curved spacetime particles move non-uniformly and in general along curved lines. By measuring the relative acceleration and velocity of one particle with respect to another, nearby, particle we can then calculate the curvature of spacetime in a given point (occupied by the particle). Repeating such a procedure we can determine the curvature in all sample points in a given region of spacetime. The fact that a planet does not move along a straight line, but along an elliptic trajectory, is a consequence of the curvature of spacetime around the Sun. The gravitational "force" acting on a planet is a consequence of the curvature. This can be illustrated by an example of a curved membrane onto which we throw a tiny ball. The ball moves along a curved trajectory, hence a force is acting on the ball. And the latter force results from the membrane's curvature.

Another very successful theory is quantum mechanics. Without quantum mechanics we would not be able to explain scattering of electrons by crystals, nor the ordered stable crystal structure itself, nor the properties of electromagnetic waves and their interactions with matter. The widely known inventions of today, such as the laser, semiconductors, and transistors, have developed as a result of understanding the implications of quantum mechanics. Without going into too much detail, the essence of quantum mechanics, or at least one of its essential points, can be summarized in the following simplified explanation. There exists a fundamental uncertainty about what the universe will be like at a future moment. This uncertainty is the bigger, as more time passes after a given moment. For instance, it is impossible to predict precisely at which location an electron will be found, after leaving it to move undisturbed for some time. When we finally measure its position it will be, in principle, anywhere in space; however, the probability of finding the electron will be greater at some places than at others. To everyone of those possible results of measurements there corresponds a slightly different universe. In classical, Newtonian, physics the uncertainty about the future evolution of the universe is a consequence of the uncertainty about the present state of the universe. If the present state could be known precisely, then also the future evolution of the universe could be precisely calculated. The degree of precision about the prediction of the future is restricted by the degree of precision with which the initial conditions are determined. (I am intentionally speaking about the whole universe, since I wish to point out that the size of the observed system and its complexity here does not, in principle, play any role.) In quantum mechanics, on the contrary, such uncertainty is of quite a different kind from that in classical mechanics. No matter how precisely the present state of an observed system is known, the uncertainty about what position of the particles we shall measure in the future remains. A generic state of a system can be considered as a superposition of a certain set of basis states. It can be described by the *wave function* which enables calculation of *the probability* to observe a definite quantum state upon measurement. The latter state is just one amongst the states belonging to the set of basis states, and the latter *set* itself is determined by the measurement situation. Such a probability or statistical interpretation of quantum mechanics was unacceptable for Einstein, who said that "God does not play dice". And yet everything points to him having been wrong. So far no experiment, no matter how sophisticated, has disproved the probability interpretation, whilst many experiments have eliminated various rival interpretations which assume the existence of some "hidden variables" supposedly responsible for the unpredictable behavior of quantum systems.

* * *

We thus have two very successful theories, *general relativity* on the one hand, and *quantum mechanics* on the other, which so far have not been falsified by any experiment. What is then more natural than to unify those two theories into a single theory? And yet such a unification has not yet been successfully achieved. The difficulties are conceptual as well as mathematical and technical. As it appears now, final success will not be possible without a change of paradigm. Some of the basic principles the two theories rest on will have to be changed or suitably generalized. Certain significant moves in this direction have already been made. In the following I will briefly, and in a simplified way, discuss some of those, in my opinion, very important approaches. Then I will indicate how those seemingly unconnected directions of research lead towards a possible solution of the problem of quantum gravity, and hence towards an even more profound understanding of the universe and the role of an intelligent observer in it.

Before continuing, let me point out that some epochs in history are more ready for changes, other less. The solution of a certain basic scientific problem or a significantly improved insight into the nature of Nature is nearly always a big shock for those who have been used to thinking in the old terms, and therefore do their best to resist the changes, while regretfully they do not always use the methods of scientific argument and logic only. Copernicus did not publish his discoveries until coming close to his death, and he had reason for having done so. The idea that the whole Earth, together with the oceans, mountains, cities, rivers, is moving around the Sun, was too much indeed! Just as were Wegener's theory about the relative motions of the continents, Darwin's theory about the origin and evolution of the species, and many other revolutionary theories. I think that we could already have learned something from the history of science and be now slightly more prudent while judging new ideas and proposals. At least the "arguments" that a certain idea is much too fantastic or in disagreement with common sense should perhaps not be used so readily. The history of science has taught us so many times that many successful ideas were just such, namely at first sight crazy, therefore in the future we should avoid such a "criterion" of judging the novelties and rather rely less on emotional, and more on scientific criteria. The essence of the latter is a cold, strictly rational investigation of the consequences of the proposed hypotheses and verification of the consequences by experiments. However, it is necessary to have in mind that a final elaboration of a successful theory takes time. Many researchers may participate in the development and every contribution is merely a piece of the whole. Today it is often stressed that a good theory has to able to incorporate all the known phenomena and predict new ones, not yet discovered. This is, of course, true, but it holds for a finished theory, and not for the single contributions of scientists who enabled the development of the theory.

In 1957 the American physicist Hugh Everett [107] successfully defended his PhD thesis and published a paper in which he proposed that all the possibilities, implicit in the wave function, actually exist. In other words, all the possible universes incorporated in the wave function actually exist, together with all the possible observers which are part of those universes. In addition to that, Everett developed the concept of *relative state*. Namely, if a given physical system consists of two mutually interacting subsystems, then each of them can be described by a wave function which is relative to the possible states of the other subsystem. As one subsystem we can take, for example, an intelligent observer, and as the other subsystem the rest of the universe. The wave function of the remaining universe is relative to the possible states of the observer. The quantum mechanical correlation, also known under the name “entanglement”, is established amongst the possible quantum states of the observer and the possible quantum states of the remaining universe. As an example let us consider an observer who measures the radioactive gamma decay of a low activity source with short life time. A Geiger counter which detects the particles (in our example these are photons, namely gamma rays) coming from the source will then make only single sounds, e.g., one per hour. Imagine now that we have isolated a single atom containing the nucleus of our radioactive source. At a given moment the wave function is a superposition of two quantum states: the state with photon emission and the state without the photon emission. The essence of Everett’s thesis (for many still unacceptable today) lies in assuming that the states of the Geiger counter, namely the state with the sound and the state without the sound, also enter the superposition. Moreover, even the states of the observer, i.e., the state in which the observer has heard the sound and the state in which the observer has not heard the sound, enter the superposition. In this example the quantum correlation manifests itself in the following. To the state in which the observer became aware[2] that he has heard the sound there corresponds the state in which the detector has detected a photon, and to the latter state, in turn, there correspond the state in which the excited nucleus has emitted the photon. And similarly, to the state in which the observer has not heard the sound, there corresponds the state in which the detector has not detected and the

[2]In this example we are using a *male* observer and the source of gamma rays. In some other example we could use a *female* observer and laser beams instead. In fact, throughout the book I am using female or male observers interchangely for doing experiments for my illustrations. So I avoid using rather cumbersome (especially if frequently repeated) “he or she”, but use “he” or “she” instead. When necessary, “he” may stand for a generic observer. Similarly for “she”.

source has not emitted a photon. Each of those two chains of events belongs to a different universe: in one universe the decay has happened and the observer has perceived it, whilst in the other universe at the given moment there was no decay and the observer has not perceived the decay. The total wave function of the universe is a superposition of those two chains of events. In any of the chains, from the point of view of the observer, there is no superposition.

The Everett interpretation of quantum mechanics was strongly supported by John Archibald Wheeler [109]. Somewhat later he was joined by many others, among them also Bryce DeWitt who gave the name "many worlds interpretation", that is, the interpretation with many worlds or universes. Today the majority of physicists is still opposed to the Everett interpretation, but it is becoming increasingly popular amongst cosmologists.

Later on, Wheeler distanced himself from the Everett interpretation and developed his own theory, in which he put the quantum principle as the basis on which rests the creation and the functioning of the universe [111]. The *observer* is promoted to the *participator*, who not only perceives, but is actively involved in, the development of the universe. He illustrated his idea as follows. We all know the game "twenty questions". Person A thinks of an object or a concept—and person B poses questions to which the answer is *yes* or *no*. Wheeler slightly changed the rules of the game, so that A may decide what the object is *after* B asks the first question. After the second question A may change the idea and choose another object, but such that it is in agreement with his first answer. This continues from question to question. The object is never completely determined, but is only determined within the set of possible objects which are in agreement with the questions posed (and the answers obtained) so far. However, with every new question the set of possible objects is narrowed, and at the end it may happen that only one object remains. The player who asked questions, with the very choice of her questions, has herself determined the set of possible answers and thus the set of possible objects. In some way reality is also determined by the question we ask it. The observer observes the universe by performing various measurements or experiments. With the very choice of experiment she determines what the set of possible results of measurement is, and hence what the set of possible universes at a given moment is. The observer is thus involved in the very creation of the universe she belongs to. In my opinion Wheeler's approach is not in disagreement with Everett's, but completes it, just as it also completes the commonly accepted interpretation of quantum mechanics.

Nowadays a strong and influential supporter of the Everett interpretation is an Oxford professor David Deutsch. In his book *The Fabric of Reality*

[112] he developed the concept of *multiverse*, which includes all possible universes that are admitted by a wave function. In a 1991 *Physical Review* article [113] he proved that the paradoxes of so called *time machines* can be resolved by means of the Everett interpretation of quantum mechanics. Many theoretical physicists study in detail some special kinds of solutions to the Einstein equation, amongst them the best known are *wormwholes* [114]. These are special, topologically non-trivial, configurations of spacetime which under certain conditions allow for *causal loops*. Therefore such solutions are called *time machines*. A particle which enters a time machine will go back in time and meet itself in the past. Such a situation is normally considered paradoxical and the problem is how to avoid it. On the one hand, if we believe the Einstein equations such time machines are indeed possible. On the other hand, they are in conflict with the principle of causality, according to which it is impossible to influence the past. Some researchers, therefore, have developed a hypothesis of a self-consistent arrangement of events which prevents a particle from meeting itself in the past; the time machine may exist and a particle may enter it and travel back into the past, but there is no means by which it can arrive at a point in spacetime at which it had already been. Others, with Stephen Hawking as the leader, on the contrary, are proving that quantum mechanics forbids the formation of time machines, since the quantum fluctuations in the region of the supposed formation of a time machine are so strong that they prevent the formation of the time machine. However, Deutsch has shown that, exactly because of quantum mechanics and the Everett interpretation, causal loops are not paradoxical at all! Namely, a particle never travels a well defined trajectory, but its quantum mechanical motion is spread around an average trajectory. According to the Everett interpretation this means that there exist many copies of the particle, and hence many universes which distinguish between themselves by the slightly different positions the particle occupies in each and every of those universes. If a particle travels in a time machine and meets its copy in the past, the result of such a collision will be quantum mechanically undetermined within the range of spreading of the wave function. To every possible pair of directions to which the two particles can recoil after the collision there corresponds a different universe. We have a causal paradox only if we assume the existence of a single universe. Then the collision of a particle with its own copy in the past necessarily changes *the initial history*, which is the essence of the causal paradox. But if we assume that a set of universes exists, then there also exists a set of histories, and hence a journey of a particle into the past does not imply any paradox at all. A similar resolution [115] of the causal paradox has also been proposed for *tachyons*. Tachyons are so far unobserved particles moving with a speed faster than light . The equations of relativity in prin-

ciple admit not only the existence of *bradyons* (moving slower than light) and *photons* (moving with the speed of light), but also of tachyons. But tachyons appear problematic in several respects[3], mainly because they allow for the formation of causal loops. This is one of the main arguments employed against the possibility that tachyons could be found in nature. However, the latter argument no longer holds after assuming the validity of the Everett interpretation of quantum mechanics, since then causal loops are not paradoxical, and in fact are not "loops" at all.

We have arrived at the following conclusion. If we take seriously the equations of general relativity, then we have also to take seriously their solutions. Amongst the solutions there are also such configurations of spacetime which allow for the formation of causal loops. We have mentioned wormholes. Besides, there also exists the well known Gödel solution for spacetime around a rotating mass. If such solutions are in fact realized in nature, then we have to deal with time machines and such experimental situations, which enables us to *test* the Everett interpretation of quantum mechanics. In this respect the Everett interpretation distinguishes itself from the other interpretations, including the conventional *Copenhagen interpretation*. In the other experimental situations known so far the Everett interpretation gives the same predictions about the behavior of physical systems as the rival interpretations (including the Copenhagen interpretation).

* * *

Life, as we know it, requires the fulfilment of certain strict conditions. It can develop only within a restricted temperature interval, and this can be realized only on a planet which is at just the right distance from a star with just the right activity and sufficiently long life time. If the fundamental constants determining the strength of the gravitational, electromagnetic, weak and strong forces were slightly different those conditions would not have been met, the universe would be different to the extent that a life of our kind would not be possible in it. In physics so far no a reliable principle or law has been discovered according to which the values of the fundamental constant could be determined. Just the contrary, all values of those constants are possible in principle. The fact that they are "chosen" just as they are, has been attempted to be explained by the so called *anthropic principle* [116]. According to that principle there exists a fundamental relationship between the values of the fundamental constants and our existence; our existence in the universe conditions the values of those

[3]Some more discussion about tachyons is provided in Sec. 13.1.

constants. Namely, the world must be such that we the observers can exist in it and observe it. However, by this we have not explained much, since the question remains, why is the universe just such that it enables our life. Here we can again help ourselves by employing the Everett interpretation which says that everything which physically can happen actually does happen—in some universe. The physical reality consists of a collection of universes. There exist all sorts of universes, with various values of the fundamental constants. In a vast majority of the universes life is not possible, but in few of them life is, nevertheless, possible, and in some universes life actually develops. In one such universe we live. We could say as well that "in one of *those* universes we live". The small probability of the occurrence of life is not a problem at all. It is sufficient that the emergence of life is possible, and in some universes life would have actually developed. Hence in the Everett interpretation the anthropic principle is automatically contained.

* * *

It is typical for general relativity that it deals merely with the intrinsic properties of spacetime, such as its metric and the intrinsic curvature. It disregards how spacetime looks "from the outside". The practitioners of general relativity are not interested in an eventual existence of an embedding space in which our spacetime is immersed. At the same time, paradoxically, whenever they wish to illustrate various solutions of the Einstein equations they actually draw spacetime as being embedded in a higher-dimensional space. Actually they draw spacetime as a 2-dimensional surface in 3-dimensional space. If they had known how to do it they would have drawn it as a 4-dimensional surface in a higher-dimensional space, but since this is not possible[4] they help themselves by suppressing two dimensions of spacetime.

How can we talk at all about a fourth, fifth, or even higher dimension, if we are unable to perceive them. For a description of a point in a three dimensional space we need three numbers, i.e., coordinates. In order to describe its motion, that is the trajectories, we need three equations. There is an isomorphism between the algebraic equations and geometric objects, for instance curves in space. This we can generalize, and instead of three equations take four or more equations; we then talk about four- or higher-dimensional spaces.

Instead of considering the embedding of spacetime in a higher-dimensional space merely as a usefull tool for the illustration of Einstein's equations,

[4]By using suitable projection techniques this might be in fact possible, but such drawings would not be understandable to an untrained person.

some physicists take the embedding space seriously as an "arena" in which lives the 4-dimensional surface representing spacetime. Distribution of matter on this surface is determined by the distribution of matter in the embedding space[5]. The motion of the latter surface (actually the motion of a 3-brane which sweeps a 4-dimensional surface, called a *worldsheet*) can be considered as being a classical motion, which means that the surface and its position in the embedding space are well determined at every moment. However, such a classical description does not correspond to the reality. The motion of the 3-brane has to obey the laws of quantum mechanics, hence a generic state of the brane is represented by a wave function. The latter function in general does not represent a certain well determined brane's worldsheet, but is "spread" over various worldsheets. More precisely, a wave function is, in general, a superposition of the particular wave functions, every one of them representing some well defined worldsheet. Such a view automatically implies that our spacetime worldsheet is not the only possible one, but that there exist other possible worldsheets which represent other possible universes, with different configurations of geometry and matter, and thus with different possible observers. But they all stay in a quantum mechanical superposition! How can we then reconcile this with the fact that at the macroscopic level we observe a well determined spacetime, with a well determined matter configuration? We again employ the Everett interpretation. According to Everett all those spacetime worldsheets together with the corresponding observers, which enter the superposition, are not merely *possible*, but they actually exist in the multiverse. Relative to every one of those observers the wave function represents a state with a well determined universe, of course up to the accuracy with which the observer monitors the rest of his universe. This is the "objective" point of view. From a "subjective" point of view the situation looks as follows. If I "measure" the position of a single atom in my surroundings, then the positions of all the other atoms, say in a crystal, will be irrevocably determined forever and I shall never observe a superposition of that crystal. Moreover, since the crystal is in the interaction with its surroundings and indirectly also with the entire universe, I shall never be able to observe a superposition of the universe, at least not at the macroscopic level[6]. Of

[5]In Chapter 8 we have developed a model in which our spacetime surface is a worldsheet of a brane. Assuming that there are many other similar branes of various dimensionality which can intersect our world brane we obtain, as a result of the intersection, the matter on our world brane in the form of point particles, strings, 2-branes and 3-branes (i.e., space filling branes). All those other branes together with our world brane form the matter in the embedding space. Moreover, we have shown that the embedding space is actually identified with all those branes. Without the branes there is no embedding space.

[6]In fact, I measure the position of an atom in a crystal by the very act of looking at it. So my universe actually is no longer in such a macroscopic superposition after the moment I looked at it

course, a superposition of the universe at the microscopic level remains, but is reduced every time we perform a corresponding measurement.

According to the conventional Copenhagen interpretation of quantum mechanics it is uncertain which of the *possible* universes will be realized after a measurement of a variable. According to the Everett interpretation, however, all those universes actually exist. This is an 'objective' point of view. By introducing the concept of *relative wave function* Everett explains that from a "subjective" point of view it is uncertain in which of those universes the observer will happen to "find himself". In this respect the Everett interpretation coincides with the Copenhagen interpretation. The questions "what universe?" and "which universe?" are intertwined in the Everett interpretation, depending on whether we look at it from an "objective" or a "subjective" point of view.

* * *

The quantum theory of the spacetime worldsheet in an embedding space, outlined in rough contours in this chapter, is in my opinion one of the most promising candidates for the quantum description of gravity. In its future development it will be necessary to include the other interactions, such as the electromagnetic, weak and strong interactions. This could be achieved by following the Kaluza–Klein idea and extend the dimensionality of the spacetime sheet from four to more dimensions. Also fermions could be included by performing a supersymmetric generalization of the theory, that is by extending the description to the anticommuting Grassmann coordinates, or perhaps by taking a polyvector generalization of the theory.

(or even touched it) for the first time. *Relative to me* the universe certainly was in a superposition (and consequently I was not aware of anything) before my embryo started to evolve, and will be again in a superposition after my death. The latter metaphor attempts to illustrate that a conscious observer and the corresponding definite macroscopic universe are in a tight relationship.

Chapter 12

NOBODY REALLY UNDERSTANDS QUANTUM MECHANICS

Quantum mechanics is a theory about the relative information that subsystems have about each other, and this is a complete description about the world

—Carlo Rovelli

The motto from a famous sentence by Feynman [117] will guide us through this chapter. There are many interpretations of quantum mechanics (QM) described in some excellent books and articles. No consensus about which one is "valid", if any, has been established so far. My feeling is that each interpretation has its own merits and elucidates certain aspects of QM. Let me briefly discuss the essential points (as I see them) of the three main interpretations[1].

Conventional (Copenhagen) interpretation. The wave function ψ evolves according to a certain evolution law (the Schrödinger equation). ψ carries the information about *possible* outcomes of a measurement process. Whenever a measurement is performed the wave function collapses into one of its eigenstates. The absolute square of the scalar product of ψ with its eigenfunctions are the probabilities (or probability densities) of the occurrence of these particular eigenvalues in the measurement process [120, 121].

Collapse or the reduction of the wave function occurs in an observer's mind. In order to explain how the collapse, which is extraneous

[1]Among modern variants of the interpretations let me mention the *relational quantum mechanics* of Rovelli [118], and the *many mind interpretation* of Butterfield [119]

to the Schrödinger evolution of ψ, happens at all, one needs something more. If one postulates that the collapse occurs in a (say, macroscopic) measuring apparatus the problem is not solved at all, since also the interaction of our original system (described by ψ) with the measuring apparatus is governed by the Schrödinger evolution for the combined system–apparatus wave function. Therefore also the measuring apparatus is in a state which is a superposition of different eigenstates corresponding to different results of measurement[2]. This is true even if the result of measurement is registered by a magnetic tape, or punched tape, etc.. A conscious observer has to look at the result of measurement; only at that moment is it decided which of various possibilities actually occurs [122]. Meanwhile, the tape has been in a state which is a superposition of states corresponding to the eigenvalues in question.

Everett, Wheeler, Graham many worlds interpretation. Various quantum possibilities actually occur, but in different branches of the world [107, 109, 110]. Every time a measurement is performed the observed world splits into several (often many) worlds corresponding to different eigenvalues of the measured quantities. All those worlds coexist in a higher universe, the *multiverse*. In the multiverse there exists a (sufficiently complicated) subsystem (e.g., an automaton) with memory sequences. To a particular branching path there corresponds a particular memory sequence in the automaton, and vice versa, to a particular memory sequence there belongs a particular branching path. No collapse of the wave function is needed. All one needs is to decide which of the possible memory sequences is the one to follow. (My interpretation is that there is no collapse in the multiverse, whilst a particular memory sequence or stream of consciousness experiences the collapse at each branching point.) A particular memory sequence in the automaton actually defines a possible life history of an observer (e.g., a human being). Various well known paradoxes like that of Einstein–Podolsky–Rosen, which are concerned with correlated, non-interacting systems, or that of Schrödinger's cat, etc., are easily investigated and clarified in this scheme [107].

Even if apparently non-related the previous three interpretations in fact illuminate QM each from its own point of view. In order to introduce the reader to my way of looking at the situation I am now going to describe some of my earlier ideas. Although not being the final word I have to say about QM, these rough ideas might provide a conceptual background which will facilitate understanding the more advanced discussion (which will also

[2]For a more detailed description of such a superposition and its duration see the section on decoherence.

take into account the modern *decoherence* approach) provided later in this chapter. A common denominator to the three views of QM discussed above we find in the assumption that a 3-dimensional simultaneity hypersurface Σ moves in a higher-dimensional space of *real* events[3]. Those events which are intersected by a certain Σ-motion are observed by a corresponding observer. Hence we no longer have a conflict between realism and idealism. There exists a certain physical reality, i.e., the world of events in a higher-dimensional space. In this higher universe there exist many 4-dimensional worlds corresponding to different quantum possibilities (see also Wheeler [123]). A particular observer, or, better, his mind chooses by an act of free will one particular Σ-surface, in the next moment another Σ-surface, etc.. A sequence of Σ-surfaces describes a 4-dimensional world[4]. A consequence of the act of free choice which happens in a particular mind is the wave function reduction (or collapse). Before the observation the mind has certain information about various *possible* outcomes of measurement; this information is incorporated in a certain wave function. Once the measurement is performed (a measurement procedure terminates in one's mind), one of the *possible* outcomes has become the *actual* outcome; the term actual is relative to a particular stream of consciousness (or memory sequence in Everett's sense). Other possible outcomes are actual relative to the other possible streams of consciousness.

So, which of the possible quantum outcomes will happen is–as I assume–indeed decided by mind (as Wigner had already advocated). But this fact does not require from us to accept an idealistic or even solipsistic interpretation of the world, namely that the external worlds is merely an illusion of a mind. The duty of mind is merely *a choice of a path* in a higher-dimensional space, i.e., a choice of a sequence of Σ-hypersurfaces (the three dimensional "nows"). But various possible sequences exist independently of a mind; they are real and embedded in a timeless higher-dimensional world.

However, a strict realism alone, independent of mind or consciousness is also no more acceptable. There does not exist a *motion* of a real external object. The external "physical" world is a static, higher-dimensional structure of events. One gets a dynamical (external) 4-dimensional world by postulating the existence of a new entity, a *mind*, with the property of *moving* the simultaneity surface Σ into any permissible direction in the higher space. This act of Σ-*motion* must be separately postulated; a consequence

[3] We shall be more specific about what the "higher-dimensional space" is later. It can be either the usual higher-dimensional configuration space, or, if we adopt the brane world model then there also exists an infinite-dimensional membrane space $\mathcal{M}$. The points of $\mathcal{M}$-space correspond to the "coordinate" basis vectors of a Hilbert space which span an arbitrary brane state.

[4] This is elaborated in Sec. 10.1.

of this motion is the subjective experience that the (3-dimensional) external world is continuously changing. *The change* of the (3-dimensional) external world is in fact an illusion; what really changes with time is an observer's mind, while the external world —which is more than (3+1)-dimensional)— is real and static (or timeless).

Let us stress: only *the change* of an external (3-dimensional) world is an illusion, not *the existence* of an external world as such. Here one must be careful to distinguish between the concept of time as a coordinate (which enters the equations of special and general relativity) and the concept of time as a subjective experience of change or becoming. Unfortunately we often use the same word 'time' when speaking about the two different concepts[5].

One might object that we are introducing a kind of metaphysical or non physical object —mind or consciousness— into the theory, and that a physical theory should be based on *observable* quantities only. I reply: how can one dismiss mind and consciousness as something non-observable or irrelevant to nature, when, on the contrary, our own consciousness is the most obvious and directly observable of all things in nature; it is through our consciousness that we have contacts with the external world (see also Wigner [122]).

12.1. THE 'I' INTUITIVELY UNDERSTANDS QUANTUM MECHANICS

If we think in a really relaxed way and unbiased with preconcepts, we realize the obvious, that the wave function is consciousness. In the following I will elaborate this a little. But before continuing let me say something about the role of extensive verbal explanations and discussions, especially in our attempts to clarify the meaning of quantum mechanics. My point is that we actually need as much such discussion as possible, in order to develop our inner, intuitive, perception of what quantum mechanics is about. In the case of Newtonian (classical) mechanics we already have such an intuitive perception. We have been developing our perception since we are born. Every child intuitively understands how objects move and what the consequences are of his actions, for instance what happens if he throws a ball. Imagine our embarrassment, if, since our birth, we had no direct contact with the physical environment, but we had nevertheless been indirectly taught about the existence of such an environment. The precise situation

[5]One of the goals of the present book is to formalize such a distinction; see the previous three parts of the book.

is not important for the argument, just imagine that we are born in a space ship on a journey to a nearby galaxy, and remain fixed in our beds with eyes closed all the time and learning only by listening. Even if not seeing and touching the objects around us, we would eventually nevertheless learn indirectly about the functioning of the physical world, and perhaps even master Newtonian mechanics. We might have become very good at solving all sorts of mechanical problem, and thus be real experts in using rigorous techniques. We might even be able to perform experiments by telling the computer to “throw” a stone and then to tell us about what has happened. And yet such an expertise would not help us much in *understanding* what is behind all the theory and “experiments” we master so well. Of course, what is needed is a direct contact with the environment we model so well. In the absence of such a direct contact, however, it will be indispensable for us to discuss as much as possible the functioning of the physical environment and the meaning of the theory we master so well. Only then would we have developed to a certain extent an intuition, although indirect, about the physical environment.

An analogous situation, of course, should be true for quantum mechanics. The role of extensive verbalization when we try to understand quantum mechanics can now be more appreciated. We have to read, discuss, and think about quantum mechanics as much as we are interested. When many people are doing so the process will eventually crystalize into a very clear and obvious picture. At the moment we see only some parts of the picture. I am now going to say something about how I see my part of the picture.

Everything we know about the world we know through consciousness. We are describing the world by a wave function. Certain simple phenomena can be described by a simple wave function which we can treat mathematically. In general, however, phenomena are so involved that a mathematical treatment is not possible, and yet conceptually we can still talk about the wave function. The latter is our information about the world. Information does not exist *per se*, information is relative to consciousness [124]. Consciousness has information about something. This could be pushed to its extreme and it be asserted that information is consciousness, especially when information refers to itself (self-referring information). On the other hand, a wave function is information (which is at least a certain very important aspect of wave function). Hence we may conclude that a wave function has a very close relation with consciousness. In the strongest version we cannot help but conclude that a wave function should in fact be identified with consciousness. Namely, *if, on the one hand, the wave function is everything I can know about the world, and, on the other, the content of my consciousness is everything I can know about the world, then consciousness is a wave function.* In certain particular cases the content of my consciousness can be very clear: after having prepared an experiment I *know* that an electron is localized in a given box. This situation can be described precisely by means of a mathematical object, namely, the wave function. If I open the box then I know that the electron is no longer localized within the box, but can be anywhere around the box. Precisely how the probability of finding it in some place evolves with time I can calculate by means of quantum mechanics. Instead of an electron in a box we can consider electrons around an atomic nucleus. We can consider not one, but many atoms. Very soon we can no longer do maths and quantum mechanical calculation, but the fact remains that our knowledge about the world is encoded in the wave function. We do not know any longer a precise mathematical expression for the wave function, but we still have a perception of the wave function. The very fact that we see definite macroscopic objects around us is a signal of its existence: so we know that the atoms of the objects are localized at the locations of the object. Concerning single atoms, we know that electrons are localized in a well defined way around the nuclei, etc.. Everything I know about the external world is encoded in the wave function. However, consciousness is more than that. It also knows about its internal states, about the memories of past events, about its thoughts, etc.. It is, indeed, a very involved self-referring information system. I cannot touch upon such aspects of consciousness here, but the interesting readier will profit from reading some good works [125, 126].

The wave function of an isolated system evolves freely according to the Schrödinger evolution. After the system interacts with its sorroundings, the system and its surroundings then become entangled and they are in a quantum mechanical superposition. However, there is, in principle, a causal connection with my brain. For a distant system it takes some time until the information about the interaction reaches me. The collapse of the wave function happens at the moment when the information arrives in my brain. Contrary to what we often read, the collapse of the wave function does not spread with infinite speed from the place of interaction to the observer. There is no collapse until the signal reaches my brain. Information about the interaction need not be explicit, as it usually is when we perform a controlled experiment, e.g., with laser beams. Information can be implicit, hidden in the many degrees of freedom of my environment, and yet the collapse happens, since my brain is coupled to the environment. But why do I experience the collapse of the wave function? Why does the wave function not remain in a superposition? The collapse occurs because the information about the content of my consciousness about the measured system cannot be in superposition. Information about an external degree of freedom can be in superposition. *Information about the degrees of freedom which are the carriers of the very same information cannot remain in a superposi-*

tion. This would be a logical paradox, or the Gödel knot [125, 126]: it is resolved by the collapse of the wave function. My consciousness “jumps” into one of the possible universes, each one containing a different state of the measured system and my different knowledge about the measurement result. However, from the viewpoint of an external observer no collapse has happened until the information has arrived in his brain. Relative to him the measured system and my brain have both remained in a superposition.

In order to illustrate the situation it is now a good point to provide a specific example.

A single electron plane wave hits the screen. Suppose an electron described by a wide wave packet hits a screen. Before hitting the screen the electron’s position was undetermined within the wave packet’s localization. What happens after the collision with the screen? If we perform strictly quantum mechanical calculations by taking into account the interaction of the electron with the material in the screen we find that the location of the traces the interaction has left within the screen is also undetermined. This means that the screen is in a superposition of the states having a “spot” at different places of the screen. Suppose now that an observer $\mathcal{O}$ looks at the screen. Photons reflected from the screen bear the information about the position of the spot. They are, according to quantum mechanical calculations, in a superposition. The same is true for an observer who looks at the screen. His eyes’ retinas are in a superposition of the states corresponding to different positions of the spot, and the signal in the nerves from the retina is in a superposition as well. Finally, the signal reaches the visual center in the observer’s brain, which is also in the superposition. Before the observer has looked at the screen the latter has been in a superposition state. After having looked, the screen state is still in a superposition, but at the same time there is also a superposition of the brain states representing different states of consciousness of the observer $\mathcal{O}$.

Read carefully again: different brain (quantum mechanical) states *represent* different *consciousness* states. And what is the content of those consciousness state? Precisely the information about the location of the spot on the screen. But the latter information is, in fact, *the wave function* of the screen, more precisely the collapsed wave function. So we have a direct piece of evidence about the relation between the wave function about an external state and a conscious state. The external state is *relative* to the brain state, and the latter state in turn represents a state of consciousness. At this point it is economical to identify the relative “external” state with the corresponding consciousness state.

Relative to the observer $\mathcal{O}$’s consciousness states there is no superposition of the screen states. “Subjectively”, a collapse of the wave function has occurred relative to the observer's consciousness state, but "objectively" there is no collapse.

The term *objective* implies that there should exist an "objective" wave function of the universe which never collapses. We now ask "is such a concept of an objective, universal, wave function indeed necessary?" Or, put it differently, what is "the universal wave function"? Everett himself introduced the concept of *the relative wave function*, i.e., the wave function which is relative to another wave function. In my opinion the relative wave function suffices, and there is no such a thing as an objective or universal wave function. This will become more clear after continuing with our discussion.

Now let us investigate how I experience the situation described above. Before I measure the position of the electron, it was in a superposition state. Before I had any contact with the screen, the observer $\mathcal{O}$, or their environment, they were altogether in a superposition state. After looking at the screen, or after communicating with the observer $\mathcal{O}$, there was no longer superposition relative to my consciousness. However, relative to another observer $\mathcal{O}'$ the combined state of the screen S, $\mathcal{O}$, and my brain can remain in superposition until $\mathcal{O}'$ himself gets in contact with me, $\mathcal{O}$, S, or the environment of S, $\mathcal{O}$, and me. A little more thought in such a direction should convince everybody that a wave function is always *relative* to something, or, better, to somebody. There can be no "objective" wave function.

If I contemplate the electron wave packet hitting the screen I know that the wave packet implies the existence of the multiverse, but I also know, after looking at the screen, that I have found myself in one of those many universes. I also know that according to some other observer my brain state can be a superposition. But I do not know how my brain state could *objectively* be a superposition. Who, then is this objective observer? Just think hard enough about this and you will start to realize that there can be no objective wave function, and if so, then a wave function, being always relative to someone's consciousness, can in fact be identified with someone's consciousness. The phrase "wave function is relative to someone's consciousness" could be replaced by "wave function is (someone's) consciousness". All the problems with quantum mechanics, also the difficulties concerning the Everett interpretation, then disappear at once.

I shall, of course, elaborate this a little bit more in due course. At the moment let me say again that the difficulties concerning the understanding of QM can be avoided if we consider a wave function as a measure of the information an observer has about the world. A wave function, in a sense, *is* consciousness. We do not yet control all the variables which are relevant to consciousness. But we already understand some of those variables, and we are able to define them strictly by employing mathematics: for instance, those variables of the consciousness which are responsible for the perception of physical experiments by which we measure quantum observables, such as a particle's position, spin, etc..

12.2. DECOHERENCE

Since the seminal work by Zurek [127] and Zeh [128] it has becomes very clear why a macroscopic system cannot be in a superposition state. A system S which we study is normally coupled to its environment E. As a consequence S no longer behaves as a quantum system. More precisely, the partial wave function of S relative to E is no longer a superposition of S's eigenstates. The combined system SE, however, still behaves as a quantum system, and is in a superposition state. Zurek and Zeh have demonstrated this by employing the description with *density matrices*.

The density matrix. A quantum state is a vector $|\psi\rangle$ in *Hilbert space*. The projection of a generic state onto the position eigenstates $|x\rangle$ is *the wave function*

$$\psi(x) \equiv \langle x|\psi\rangle. \tag{12.1}$$

Instead of $|\psi\rangle$ we can take the product

$$|\psi\rangle\langle\psi| = \hat{\rho}\,, \tag{12.2}$$

which is called *the density operator*. The description of a quantum system by means of $|\psi\rangle$ is equivalent to description by means of $\hat{\rho}$.

Taking the case of a single particle we can form the sandwich

$$\langle x|\hat{\rho}|x'\rangle \equiv \rho(x,x') = \langle x|\psi\rangle\langle\psi|x'\rangle = \psi(x)\psi^*(x'). \tag{12.3}$$

This is *the density matrix* in the coordinate representation. Its diagonal elements

$$\langle x|\hat{\rho}|x\rangle = \rho(x,x) \equiv \rho(x) = |\psi(x)|^2 \tag{12.4}$$

form *the probability density* of finding the particle at the position x. However, the off-diagonal elements are also different from zero, and they are responsible for interference phenomena. If somehow the off-diagonal terms vanish, then the interference also vanishes.

Consider, now, a state $|\psi\rangle$ describing a spin $\frac{1}{2}$ particle coupled to a detector:

$$|\psi\rangle = \sum_i \alpha_i |i\rangle\langle d_i|\,, \tag{12.5}$$

where

$$|i\rangle = |\tfrac{1}{2}\rangle,\ |-\tfrac{1}{2}\rangle \tag{12.6}$$

are spin states, and

$$|d_i\rangle = |d_{1/2}\rangle,\ |d_{-1/2}\rangle \tag{12.7}$$

are the detector states.

The density operator is

$$|\psi\rangle\langle\psi| = \sum_{ij} \alpha_i \alpha_j^* |i\rangle|d_i\rangle\langle j|\langle d_j|. \tag{12.8}$$

It can be represented in some set of basis states $|m\rangle$ which are rotated relative to $|i\rangle$:

$$|m\rangle = \sum_k |k\rangle\langle k|m\rangle\ , \quad |d_m\rangle = \sum_{d_k} |d_k\rangle\langle d_k|d_m\rangle \tag{12.9}$$

We then obtain the density matrix

$$\langle d_m, m|\psi\rangle\langle\psi|n, d_n\rangle = \sum_{ij} \alpha_i \alpha_J^* \langle d_m, m|i, d_i\rangle\langle j, d_j|n, d_n\rangle. \tag{12.10}$$

which has non-zero off diagonal elements. Therefore the combined system *particle–detector* behaves quantum mechanically.

Let us now introduce yet another system, namely, the environment. After interacting with the environment the evolution brings the system to the state

$$|\psi\rangle = \sum_i \alpha_i |i\rangle|d_i\rangle|E_i\rangle\ , \tag{12.11}$$

where

$$|E_i\rangle = |E_{1/2}\rangle\ ,\ |E_{-1/2}\rangle \tag{12.12}$$

are the environment states after the interaction with the *particle–detector* system.

The density operator is

$$|\psi\rangle\langle\psi| = \sum_{ij} \alpha_i \alpha_j^* |i\rangle|d_i\rangle|E_i\rangle\langle j|\langle d_j|\langle E_j| \tag{12.13}$$

The combined system *particle–detector–environment* is also in a *superposition state*. The density matrix has-non zero off-diagonal elements.

Whilst the degrees of freedom of the particle and the detector are under the control of an observer, those of the environment are not. The observer cannot distinguish $|E_{1/2}\rangle$ from $|E_{-1/2}\rangle$, therefore he cannot know the total density matrix. We can define *the reduced density operator* which takes into account the observer's ignorance of $|E_i\rangle$. This is achieved by summing over the environmental degrees of freedom:

$$\sum_k \langle E_k|\psi\rangle\langle\psi|E_k\rangle = \sum_i |\alpha_i|^2|i\rangle|d_i\rangle\langle i|\langle d_i|. \qquad (12.14)$$

We see that the reduced density operator, when represented as a matrix in the states $|i\rangle$, has only the diagonal terms different from zero. This property is preserved under rotations of the states $|i\rangle$.

We can paraphrase this as follows. With respect to the environment the density matrix is diagonal. Not only with respect to the environment, but with respect to any system, the density matrix is diagonal. This has already been studied by Everett [107], who introduced the concept of *relative state*. *The reduced density matrix* indeed describes the relative state. In the above specific case the state of the system *particle–detector* is relative to the environment. Since the observer is also a part of the environment the state of the system *particle–detector* is relative to the observer. The observer *cannot* see a superposition (12.5), since very soon the system evolves into the state (12.11), where $|E_i\rangle$ includes the observer as well. After the interaction with environment the system *particle–detector* loses the interference properties and behaves as a classical system. However, the total system *particle–detector–environment* remains in a superposition, but nobody who is coupled to the environment can observe such a superposition after the interaction reaches him. This happens very soon on the Earth, but it may take some time for an observer in space.

The famous *Schrödinger's cat* experiment [129] can now be easily clarified. In order to demonstrate that the probability interpretation of quantum mechanics leads to paradoxes Schrödinger envisaged a box in which a macroscopic object —a cat— is linked to a quantum system, such as a low activity radioactive source. At every moment the source is in a superposition of the state in which a photon has been emitted and the state in which no photon has been emitted. The photons are detected by a Geiger counter connected to a device which triggers the release of a poisonous gas. Schrödinger considered the situation as paradoxical, as the cat should remain in a superposition state, until somebody looks into the box. According to our preceding discussion, however, the cat could have remained in a superposition only if completely isolated from the environment. This is normally not the case, therefore the cat remains in a superposition for a very short time, thereafter the combined system *cat–environment* is in a superposition state. The environment includes me as well. But I cannot be in a superposition, therefore my consciousness jumps into one of the two branches of the superposition (i.e., the cat alive and the cat dead). This happens even *before* I look into the box. Even before I look into the box it is already decided into which of the two branches my consciousness resides. This is so because I am coupled to the environment, to which also the cat is coupled. Hence, I am already experiencing one of the branches. My consciousness, or, better subconsciousness, has already decided to choose one of the branches, even before I became aware of the cat's state by obtaining the relevant information (e.g., by looking into the box). What counts here is that the necessary information is available in principle: it is implicit in the environmental degrees of freedom. The latter are different if the cat is alive or dead.

12.3. ON THE PROBLEM OF BASIS IN THE EVERETT INTERPRETATION

One often encounters an objection against the Everett interpretation of quantum mechanics that is known under a name such as "the problem of basis". In a discussion group on internet (Sci.Phys., 5 Nov.,1994) I have found a very lucid discussion by Ron Maimon (Harvard University, Cambridge, MA) which I quote below.

> It's been about half a year since I read Bell's analysis, and I don't have it handy. I will write down what I remember as being the main point of his analysis and demonstrate why it is incorrect.
>
> Bell claims that Everett is introducing a new and arbitrary assumption into quantum mechanics in order to establish collapse, namely the "pointer basis". His claim is that it is highly arbitrary in what way you split up the universe into a macroscopic superposition and the way to do it is in no way determined by quantum mechanics. For example, if I have an electron in a spin eigenstate, say $|+\rangle$ then I measure it with a device which has a pointer, the pointer should (if it is a good device) be put into an eigenstate of its position operator.
>
> This means that if we have a pointer which swings left when the electron has spin up, it should be put into the state "pointer on the left" if the electron was in the state $|+\rangle$. If it similarly swings right when the electron is in the state $|-\rangle$ then if the electron is in the state $|-\rangle$ the pointer should end up in the state "pointer on the right".
>
> Now, says Bell, if we have the state $(1/\sqrt{2})(|+\rangle + |-\rangle)$ then the pointer should end up in the state $(1/\sqrt{2})(|\text{right}\rangle + |\text{left}\rangle)$. According to Bell, Everett says that this is to be interpreted as two universes, distinct and noninteracting, one in which the pointer is in the state "right" and one in which the pointer is in the state "left".
>
> But aha! says Bell, this is where that snaky devil Everett gets in an extra hypothesis! We don't have to consider the state $1/\sqrt{2}(|\text{right}\rangle + |\text{left}\rangle)$ as a superposition—I mean it is a state in its own right. Why not say that there has been no split at all, or that the split is into two universes, one in which the pointer is in the state
>
> $$a_1|\text{right}\rangle + a_2|\text{left}\rangle \qquad (12.15)$$

and one where it is in the state

$$b_1|\text{right}\rangle + b_2|\text{left}\rangle \tag{12.16}$$

So long as $a_1 + b_1 = a_2 + b_2 = 1/\sqrt{2}$ this is allowed. Then if we split the universe along these lines we again get those eerie macroscopic superpositions.

In other words, Everett's unnatural assumption is that the splitting of the universes occurs along the eigenstates of the pointer position operator. Different eigenstates of the pointer correspond to different universes, and this is arbitrary, unnatural, and just plain ugly.

Hence Everett is just as bad as anyone else.

Well this is WRONG.

The reason is that (as many people have mentioned) there is no split of the universe in the Everett interpretation. The state

$$\frac{1}{\sqrt{2}}(|\text{right}\rangle + |\text{left}\rangle) \tag{12.17}$$

is no more of a pair of universe than the state $1/\sqrt{2}(|+\rangle + |-\rangle)$ of spin for the electron.

Then how comes we never see eerie superpositions of position eigenstates?

Why is it that the "pointer basis" just happens to coincide with him or her self. This is the "state of mind" basis. The different states of this basis are different brain configurations that correspond to different states of mind, or configurations of thoughts.

Any human being, when thrown into a superposition of state of mind will split into several people, each of which has a different thought. Where before there was only one path of mind, after there are several paths. These paths all have the same memories up until the time of the experiment, and these all believe different events have occurred. This is the basis along which the universe *subjectively seems to split*.

There is a problem with this however—what guarantees that eigenstates of my state of mind are the same as eigenstates of the pointer position. If this wasn't the case, then a definite state of mind would correspond to an eerie neither here nor there configuration of the pointer.

The answer is, NOTHING. It is perfectly possible to construct a computer with sensors that respond to certain configurations by changing the internal state, and these configurations are not necessarily eigenstates of position of a needle. They might be closer to eigenstates of momentum of the needle. Such a computer wouldn't see weird neither-here-nor-there needles, it would just "sense" momenta, and won't be able to say to a very high accuracy where the needle is.

So why are the eigenstates of our thoughts the same as the position eigenstates of the needle?

They aren't!

They are only very approximately position eigenstates of the needle.

This can be seen by the fact that when we look at a needle it doesn't start to jump around erratically, it sort of moves on a smooth trajectory. This means that when we look at a needle, we don't "collapse" it into a position eigenstate, we only "collapse it into an approximate position eigenstate. In Everett's language, we are becoming correlated with a state that is neither an eigenstate of the pointer's position, nor its momentum, but approximately an eigenstate of both, constrained by the uncertainty principle. This means that we don't have such absurdly accurate eyes that can see the location of a pointer with superhigh accuracy.

If we were determining the *exact* position of the needle, we would have gamma ray sensor for eyes and these gamma rays would have enough energy to visibly jolt the needle whenever we looked at it.

In order to determine exactly what state we are correlated with, or if you like, the world (subjectively) collapses to, you have to understand the mechanism of our vision.

A light photon bouncing off a needle in a superposition

$$\frac{1}{\sqrt{2}}(|\text{right}\rangle + |\text{left}\rangle) \tag{12.18}$$

will bounce into a superposition of the states $|1\rangle$ or $|2\rangle$ corresponding to the direction it will get from either state. The same photon may then interact with our eyes. The way it does this is to impinge upon a certain place in our retina, and this place is highly sensitive to the direction of the photon's propagation. The response of the pigments in our eyes is both higly localized in position (within the radius of a cell) and in momentum (the width of the aperture of our pupil determines the maximal resolution of our eyes). So it is not surprising that our pigment excitation states become correlated with approximate position and approximate momentum eigenstates of the needle. Hence we see what we see.

If we had good enough mathematical understanding of our eye we could say in the Everett interpretation *exactly* what state we seem to collapse the needle into. Even lacking such information it is easy to see that we will put it in a state resembling such states where Newton's laws are seen to hold, and macroscopic reality emerges.

A similar reasoning holds for other information channels that connect the outside world with our brane (e.g., ears, touch, smell, taste). The problem of choice of basis in the Everett interpretation is thus nicely clarified by the above quotation from Ron Maimon.

12.4. BRANE WORLD AND BRAIN WORLD

Let us now consider the model in which our world is a 3-brane moving in a higher-dimensional space. How does it move? According to the laws of quantum mechanics. A brane is described by a wave packet and the latter is a solution of the Schrödinger equation. This was more precisely discussed in Part III. Now I will outline the main ideas and concepts. An example of a wave packet is sketched in Fig. 12.1.

If the brane self-intersects we obtain *matter* on the brane (see Sec. 8.3). When the brane moves it sweeps a surface of one dimension more. A 3-brane sweeps a 4-dimensional surface, called a *world sheet* or a *spacetime sheet*.

We have seen in Sec. 10.2 that instead of considering a 3-brane we can consider a 4-brane. The latter brane is assumed to be a possible spacetime sheet (and thus has three space-like and one time-like intrinsic dimensions). Moreover, it is assumed that the 4-brane is subjected to dynamics along an invariant evolution parameter τ. It is one of the main messages of this book to point out that such a dynamics naturally arises within the description of geometry and physics based on Clifford algebra. Then a scalar and a pseudoscalar parameter appear naturally, and evolution proceeds with respect to such a parameter.

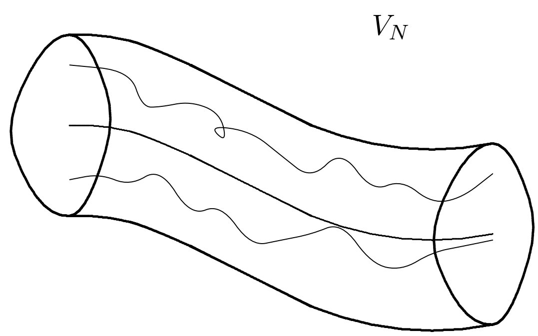

Figure 12.1. An illustration of a wave packet describing a 3-brane. Within the effective region of localization any brane configuration is possible. The wavy lines indicate such possible configurations.

A 4-brane state is represented by a wave packet localized around an average 4-surface (Fig. 12.2)

It can be even more sharply localized within a region P, as shown in Fig. 10.2 or Fig. 12.3. (For convenience we repeat Fig. 10.3.)

All these were mathematical possibilities. We have a Hilbert space of 4-brane kinematic states. We also have the Schrödinger equation which a dynamically possible state has to satisfy. As a dynamically possible state we obtain a wave packet. A wave packet can be localized in a number of possible ways, and one is that of Fig. 10.3, i.e., localization within a region P. How do we interpret such a localization of a wave packet? What does it mean physically that a wave packet is localized within a 4-dimensional region (i.e., it is localized in 3-space and at "time" $t \equiv x^0$)? This means that the 4-brane configuration is better known within P than elsewhere. Since the 4-brane represents spacetime and matter (remember that the 4-brane's self-intersections yield matter on the 4-brane), such a localized wave packet tells us that spacetime and matter configuration are better known within P than elsewhere. Now recall *when*, according to quantum mechanics, a matter configuration (for instance a particle's position) is better known than otherwise. It is better known after a suitable measurement. But we have also seen that a measurement procedure terminates in one's brain, where it is decided —relative to the brain state— about the outcome of the measurement. Hence the 4-brane wave packet is localized within P, because an observer has measured the 4-brane's configuration. Therefore the wave packet (the wave function) is *relative* to that observer.

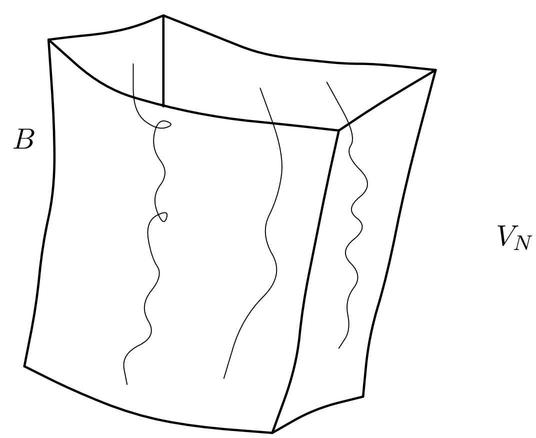

Figure 12.2. A 4-brane wave packet localized within an effective boundary B. A wavy line represents a possible 4-brane.

The 4-brane configuration after the measurement is not well known at every position on the 4-brane, but only at the positions within P, i.e., within a certain 3-space region and within a certain (narrow) interval of the coordinate x^0. Such a 4-brane configuration (encompassing a matter configuration as well) can be very involved. It can be involved to the extent that it forms the structure of an observer's brain contemplating the "external" world by means of sense organs (eyes, ears, etc.).

We have arrived at a very important observation. *A wave packet localized within P can represent the brain structure of an observer $\mathcal{O}$ and his sense organs, and also the surrounding world*! Both the observer and the surrounding world are represented by a single (very complicated) wave packet. Such a wave packet represents the observer's knowledge about his brain's state and the corresponding surrounding world—all together. It represents the observer's consciousness! This is the most obvious conclusion; without explicitly adopting it, the whole picture about the meaning of QM remains foggy.

One can now ask, "does not the 4-brane wave packet represent the brain structure of another observer $\mathcal{O}'$ too?" Of course it does, but not as completely as the structure of $\mathcal{O}$. By "brain" structure I mean here also the content of the brain's thought processes. The thought processes of $\mathcal{O}'$ are not known very well to $\mathcal{O}$. In contrast, his own thought processes are very well known to $\mathcal{O}$, at the first person level of perception. Therefore, the 4-brane wave packet is well localized within $\mathcal{O}$'s head and around it.

Such a wave packet is relative to $\mathcal{O}$. There exists, of course, another possible wave packet which is relative to the observer $\mathcal{O}'$, and is localized around $\mathcal{O}'$'s head.

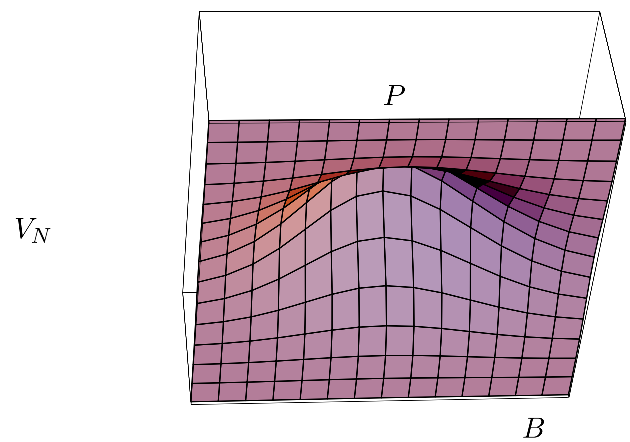

Figure 12.3. Illustration of a wave packet with a region of sharp localization P.

Different initial conditions for a wave function mean different initial conditions for consciousness. A wave function can be localized in another person's head: my body can be in a superposition state with respect to that person (at least for a certain time allowed by decoherence). If I say (following the Everett interpretation) that there are many Matejs writing this page, I have in mind a wave function relative to another observer. Relative to me the wave function is such that I am writing these words right now. In fact, I am identical with the latter wave function. Therefore at the basic level of perception I intuitively understand quantum mechanics.

An 'I' intuitively understands quantum mechanics. After clarifying this I think that I have acquired a deeper understanding of quantum mechanics. The same, I hope, holds for the careful reader. I hope, indeed, that after reading these pages the reader will understand quantum mechanics, not only at the lowest, intuitive, level, but also at a higher cognitive level of perception. An ultimate understanding, however, of what is really behind quantum mechanics and consciousness will probably never be reached by us, and according to the Gödel incompleteness theorem [125, 126] is even not possible.

Box 12.1: Human language and multiverse[a]

In the proposed brane world model spacetime, together with matter, is represented by a 4-dimensional self-intersecting surface V_4. An observer associated with a V_4 distinguishes present, past, and future events. Because of the quantum principle an observer is, in fact, associated not with a definite V_4, but with a corresponding wave function. The latter takes into account all *possible* V_4s entering the superposition.

We see that within the conceptual scheme of the proposed brane world model all the principal tenses of human language —present, past, future tenses, and *conditional*— are taken into account. In our human conversations we naturally talk not only about the actual events (present, past, future), but also about possible events, i.e., those which could have occurred (conditional). According to Piaget [135] a child acquires the ability of formal logical thinking, which includes use of alternatives and conditional, only at an advanced stage in his mental development. Reasoning in terms of possible events is a sign that an individual has achieved the highest stage on the Piaget ladder of conceptual development.

Now, since the emergence of quantum mechanics, even in physics, we are used to talking about possible events which are incorporated in the wave function. According to the Everett interpretation of quantum mechanics as elaborated by Deutsch, those possible events (or better states) constitute the *multiverse*.

[a]This idea was earlier discussed in ref. [88]. Later it was also mentioned by Deutsch [112].

12.5. FINAL DISCUSSION ON QUANTUM MECHANICS, AND CONCLUSION

In classical mechanics different initial conditions give different *possible* trajectories of a dynamical system. Differential equations of motion tell us only what is a possible set of solutions, and say nothing about which one is actually realized. Selection of a particular trajectory (by specifying initial conditions) is an *ad hoc* procedure.

The property of classical mechanics admitting many possible trajectories is further developed by Hamilton–Jacobi theory. The latter theory naturally suggests its generalization—quantum mechanics. In quantum mechanics different possible trajectories, or better, a particle's positions, are described by means of a wave function satisfying the Schrödinger equation of motion.

In quantum mechanics different initial conditions give different *possible* wave functions. In order to make discussion more concrete it turns out to be convenient to employ a brane world model in which spacetime together with matter in it is described by a self-intersecting 4-dimensional sheet, a worldsheet V_4. According to QM such a sheet is not definite, but is described by a wave function[6]. It is spread around an average spacetime sheet, and is more sharply localized around a 3-dimensional hypersurface Σ on V_4. Not all the points on Σ are equally well localized. Some points are more sharply localized within a region P (Fig. 10.3), which can be a region around an observer on V_4. Such a wave function then evolves in an invariant evolution parameter τ, so that the region of sharp localization P *moves* on V_4.

Different *possible* wave functions are localized around different observers. QM is a mechanics of consciousness. Differently localized wave functions give different possible consciousnesses and corresponding universes (worlds).

My brain and body can be a part of somebody's else consciousness. The wave function relative to an observer $\mathcal{O}'$ can encompass my body and my brain states. Relative to $\mathcal{O}'$ my brain states can be in a superposition (at least until decoherence becomes effective). Relative to $\mathcal{O}'$ there are many Matejs, all in a superposition state. Relative to me, there is always one Matej only. All the others are already out of my reach because the wave function has collapsed.

According to Everett a wave function never does collapse. Collapse is subjective for an observer. My point is that subjectivity is the essence of wave function. A wave function is always relative to some observer, and hence is subjective. So there is indeed collapse, call it subjective, if you

[6]For simplicity we call it a 'wave function', but in fact it is a wave functional—a functional of the worldsheet embedding functions $\eta^a(x^\mu)$.

wish. Relative to me a wave function is collapsing all the time: whenever the information (direct or indirect—through the environmental degrees of freedom) about the outcome of measurement reaches me.

There is no collapse[7] if I contemplate other observers performing their experiments.

Let us now consider, assuming the brane world description, a wave packet of the form given in Fig. 12.2. There is no region of sharp localization for such a wave packet. It contains a superposition of all the observers and worlds within an effective boundary B. Is this then the *universal wave function*? If so, why is it not spread a little bit more, or shaped slightly differently? The answer can only make sense if we assume that such a wave function is relative to a super-observer $\mathcal{O}_S$ who resides in the embedding space V_N. The universe of the observer $\mathcal{O}_S$ is V_N, and the wave packet of Fig. 12.2 is a part of the wave function, relative to $\mathcal{O}_S$, describing $\mathcal{O}_S$'s consciousness and the corresponding universe.

To be frank, we have to admit that the wave packet itself, as illustrated in Fig. 10.3, is relative to a super-observer $\mathcal{O}_S$. In order to be specific in describing our universe and a conscious observer $\mathcal{O}$ we have mentally placed ourselves in the position of an observer $\mathcal{O}_S$ outside our universe, and envisaged how $\mathcal{O}_S$ would have described the evolution of the consciousness states of $\mathcal{O}$ and the universe belonging to $\mathcal{O}$. The wave packet, relative to $\mathcal{O}_S$, representing $\mathcal{O}$ and his world could be so detailed that the super-observer $\mathcal{O}_S$ would have identified himself with the observer $\mathcal{O}$ and his world, similarly as we identify ourselves with a hero of a novel or a movie.

At a given value of the evolution parameter τ the wave packet represents in detail the state of the observer $\mathcal{O}$'s brain and the belonging world. With evolution the wave packet spreads. At a later value of τ the wave packet might spread to the extent that it no longer represents a well defined state of $\mathcal{O}$'s brain. Hence, after a while, such a wave packet could no longer represent $\mathcal{O}$'s consciousness state, but a superposition of $\mathcal{O}$'s consciousness states. This makes sense relative to some other observer $\mathcal{O}'$, but not relative to $\mathcal{O}$. From the viewpoint of $\mathcal{O}$ the wave packet which describes $\mathcal{O}$'s brain state cannot be in a superposition. Otherwise $\mathcal{O}$ would not be conscious. Therefore when the evolving wave packet spreads too much, it collapses relative to $\mathcal{O}$ into one of the well defined brain states representing well defined states of $\mathcal{O}$'s consciousness . Relative to another observer $\mathcal{O}'$, however, no collapse need happen until decoherence becomes effective.

[7]There is no collapse until decoherence becomes effective. If I am very far from an observer $\mathcal{O}'$, e.g., on Mars, then $\mathcal{O}'$ and the states of his measurement apparatus are in a superposition relative to me for a rather long time.

If the spreading wave packet would not collapse from time to time, the observer could not be conscious. The quantum states that represent $\mathcal{O}$'s consciousness are given in terms of certain basis states. The same wave packet can be also expanded in terms of some other set of basis states, but those states need not represent (or support) consciousness states. This explains why collapse happens with respect to a certain basis, and not with respect to some other basis.

We have the following model. An observer's consciousness and the world to which he belongs are defined as being represented by an evolving wave packet. At every moment τ the wave packet says which universes ($\equiv$ consciousness state + world belonged to) are at disposal. A fundamental postulate is that from the first person viewpoint the observer (his consciousness) necessarily finds himself in one of the available universes implicit in the spreading wave packet. During the observer's life his body and brain retain a well preserved structure, which poses strict constraints on the set of possible universes: a universe has to encompass one of the available consciousness states of $\mathcal{O}$ and the "external" worlds coupled to those brain states. This continues until $\mathcal{O}$'s death. At the moment of $\mathcal{O}$'s death $\mathcal{O}$'s brain no longer supports consciousness states. $\mathcal{O}$'s body and brain no longer impose constraints on possible universes. The set of available universes increases dramatically: every possible world and observer are in principle available! If we retain the fundamental postulate, and I see no logical reason why not to retain it, then the consciousness has to find itself in one of the many available universes. Consciousness jumps into one of the available universes and continues to evolve. When I am dead I find myself born again! In fact, every time my wave packets spreads too much, I am dead; such a spread wave packet cannot represent my consciousness. But I am immediately "reborn", since I find myself in one of the "branches" of the wave packet, representing my definite consciousness state and a definite "external" world.

A sceptical reader might think that I have gone too far with my discussion. To answer this I wish to recall how improbable otherwise is the fact that I exist. (From the viewpoint of the reader 'I' refers to himself, of course.) Had things gone slightly differently, for instance if my parents had not met each other, I would not have been born, and my consciousness would not not have existed. Thinking along such lines, the fact that I exist is an incredible accident!. Everything before my birth had to happen just in the way it did, in order to enable the emergence of my existence. Not only my parents, but also my grandparents had to meet each other, and so on back in time until the first organisms evolved on the Earth! And the fact that my parents had become acquainted was not sufficient, since any slightly different course of their life together would have led to the birth not of me, but of my brother or sister (who do not exist in this world). Any sufficiently deep reasoning in such a direction leads to an unavoidable conclusion that (i) the multiverse in the Everett–Wheeler–DeWitt–Deutsch sense indeed exist, and (ii) consciousness is associated (or identified) with the wave function which is relative to a sufficiently complicated information processing system (e.g., an observer's brain), and *evolves* according to (a) the Schrödinger evolution and (b) experiences *collapse* at every measurement situation. In an extreme situation (death) available quantum states (worlds) can include those far away from the states (the worlds) I have experienced so far. My wave function (consciousness) then collapses into one of those states (worlds), and I start experiencing the evolution of my wave functions representing my life in such a "new world".

All this could, of course, be put on a more rigorous footing, by providing precise definitions of the terms used. However, I think that before attempting to start a discussion on more solid ground a certain amount of heuristic discussion, expounding ideas and concepts, is necessary.

A reader might still be puzzled at this point, since, according to the conventional viewpoint, in Everett's many worlds interpretation of quantum mechanics there is no collapse of the wave function. To understand why I am talking both about the many worlds interpretation (the multiverse) and collapse one has to recall that according to Everett and his followers collapse is a subjective event. Precisely that! Collapse of the wave function is a subjective event for an observer, but such also is the wave function itself. The wave function is always relative and thus subjective. Even the Everett "universal" wave function has to be relative to some (super-) observer.

In order to strengthen the argument that (my) consciousness is not necessarily restricted to being localized just in my brain, imagine the following example which might indeed be realized in a not so remote future. Suppose that my brain is connected to another person's brain in such a way that I can directly experience her perceptions. So I can experience what she sees, hears, touches, etc.. Suppose that the information channel is so perfect that I can also experience her thoughts and even her memories. After experiencing her life in such a way for a long enough time my personality would become split between my brain and her brain. The wave function representing my consciousness would be localized not only in my brain but also in her brain. After long time my consciousness would become completely identified with her life experience; at that moment my body could die, but my consciousness would have continued to experience the life of her body.

The above example is a variant of the following thought experiment which is often discussed. Namely, one could gradually install into my brain small electronic or bioelectronic devices which would resume the functioning of my brain components. If the process of installation is slow enough my biological brain can thus be replaced by an electronic brain, and I would not have noticed much difference concerning my consciousness and my experience of 'I'.

Such examples (and many others which can be easily envisaged by the reader) of the transfer of consciousness from one physical system to another clearly illustrate the idea that (my) consciousness, although currently associated (localized) in my brain, could in fact be localized in some other brain too. Accepting this, there is no longer a psychological barrier to accepting the idea that the wave function (of the universe) is actually closely related, or even identified, with the consciousness of an observer who is part of that universe. After becoming habituated with such, at first sight perhaps strange, wild, or even crazy ideas, one necessarily starts to realize that quantum mechanics is not so mysterious after all. It is a mechanics of consciousness.

With quantum mechanics the evolution of science has again united two pieces, matter and mind, which have been put apart by the famous Cartesian cut. By separating mind from matter[8] —so that the natural sciences have disregarded the question of mind and consciousness— Decartes set the ground for the unprecedented development of physics and other natural sciences. The development has finally led in the 20th century to the discovery of quantum mechanics, which cannot be fully understood without bringing mind and consciousness into the game.

[8] There is an amusing play of words[130]:

What is matter? — Never mind!
What is mind? — No matter!