THE LANDSCAPE OF THEORETICAL PHYSICS: A GLOBAL VIEW

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

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Chapter 11

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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

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[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.

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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

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[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).

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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

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[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.

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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,

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[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

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[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.

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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.