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Controversies in Physics at the Planck Scale*

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Abstract

Both at extremely large and at the very tiniest distance scales, the Laws of Physics are poorly understood. The best we can de is to extrapolate those Laws of Nature that we do understand. Where obstacles are encountered, opinions on how to proceed diverge wildly. The author's own position is presented here.

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1. Introduction

One upon a time, there was a point. The point had no extension in space, nor in time. Yet the point was very special — nothing else existed, not even was there a Universe surrounding it. It was just a point.

Then the point exploded. It was the most violent event ever to take place, It was at this explosion that the fabric of space and time itself was being created. It was the beginning of the Universe. What happened, immediately after this explosion, is the domain of theoretical speculations. We do know for certain that the Universe underwent a spectacular expansion such that, in an extremely tiny fraction of a second, the spatial dimensions became huge, much larger than the distance light could have travelled in this short time interval[1]. Detailed calculations using all we know today about the laws of Nature, lead to the expectation that the Universe must have been filled with light, and that this light fluctuates. The earliest direct experimental evidence concerning this history is a snapshot made with microwaves. The picture obtained shows very little structure unless we enhance the contrast by a factor of nearly one million. This leads to the picture of Fig. 1.

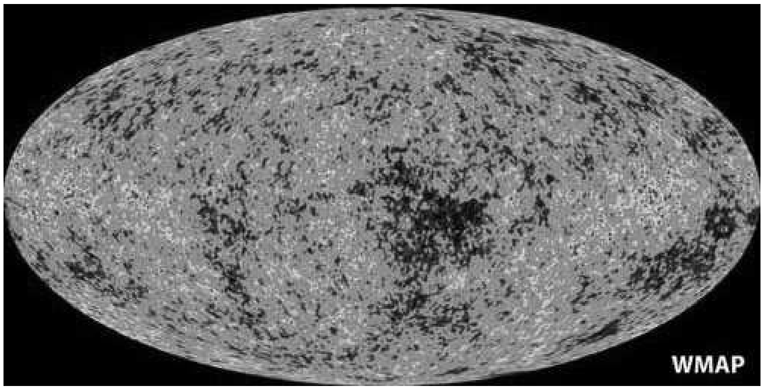

Figure 1: The Wilkinson Microwave Anisotropy Probe generated this picture of the Universe at age 380,000 years.

The Universe must have been approximately 380,000 years old when this light was generated. What is exciting about this picture is the intricate pattern of correlations, which is being analyzed by theoreticians. These correlations appear to be fossils dating way back to the tiniest fractions of a second after the Big Bang. At that time, the spatial dimensions of the fluctuations were like those of the atomic nuclei or smaller, but after a few million years, they began to accumulate matter around them, and eventually became galaxies, or groups of galaxies.

The next picture made of the Universe is shown in Fig. 2. It shows galaxies at great distance from us, indeed so far away that they are seen at a considerably younger age than that of the Universe today. Therefore, these galaxies look different from galaxies much closer to us, such as the Andromeda Nebula. Indeed, they are smaller. Today's galaxies each are the result of numerous accumulations of smaller star systems into bigger ones.

Figure 2: The Hubble Space Telescope took this picture of the Universe when it was only a few billions of years old.

2. Gravity

The dominating force in the Universe at large, appears to be the gravitational one. It is this force that causes galaxies to form, and to accumulate into bigger ones, that causes dust and gas clouds to contract, forming stars and planets, and it is the force controlling the orbits of stars, planets and moons everywhere. As was discovered by Einstein in 1915, the gravitational force results from geometrical properties of space and time. This basic discovery had far-reaching implications.

In 1865, Jules Verne wrote his famous science fiction story *From the Earth to the Moon*. It tells the story of three well-to-do members of the 'Baltimore Gun Club', who decided to build the biggest canon ever, whose bullets could reach to the Moon. A hollow bullet housing three astronauts, a dog and some chicken is fired to the Moon. What Jules Verne knew was that, somewhere between the Earth and the Moon, there is a so-called Lagrange point, a point where the gravitational field of the Moon counter balances the force from the Earth. When the space ship reached that point, suddenly the inhabitants felt complete weightlessness.

This, we now know, wasn't quite right. The astronauts must have been weightless throughout the journey, as long as the stayed outside the Earth's atmosphere. The reason for this is that the inhabitants of the bullet underwent the same gravitational forces as the bullet itself, so they were following exactly parallel trajectories. There was no reason for the travellers to be moving towards any of the walls, the floor or the ceiling of their ship. If we were to introduce a set of coordinates describing all points in space and in time, describing the immediate neighborhood of the spacecraft, then all freely falling objects would follow straight lines in this coordinate frame. Therefore, we say, space and time in the neighborhood of the spacecraft, in a very good approximation, are flat.

In Fig. 3, an artist's impression is given of curved space near a heavy star or planet.

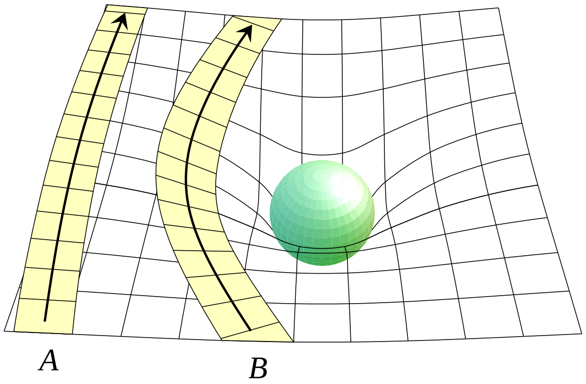

Figure 3: Curved space and time near a heavy star or planet.

The coordinate frame is distorted by the curvature. If we follow a single particle, we can surround it by more or less flat coordinates, but then its trajectory becomes curved, with respect to more distant reference points. This curvature is bigger close to the planet (B) than far away from it (A). This way, one can understand gravity as being a geometrical effect.

Gravity has the peculiar feature that it is *always* attractive, and it is cumulative, with which we mean to say that massive objects tend to attract other massive objects, become even more massive and generating even stronger attraction. This situation is unstable. If large enough amounts of mass accumulate, this attraction can become so strong that nothing can be allowed to escape, even light cannot escape. The resulting configuration is called a *black hole*; the space-time curvature here becomes so strong that a singular situation is reached. One can calculate that then a 'wormhole' may form, a natural connection between one piece of the Universe with another, or perhaps with an entirely different universe. Unfortunately, this wormhole only exists in an idealized, mathematically pure black hole. As soon as something falls into the black hole, disturbances would actually block the exit towards the other universe, so the wormhole cannot be used in the way speculated upon by science fiction authors, to travel from one spot in the Universe to another one, illegally violating the light speed limit.

3. Particles

At tiny distance scales, the forces that play a dominant role are quite different ones. There, we are dealing with the building blocks of matter: molecules, atoms, and the sub-atomic particles. There are more than 10^{80} sub-atomic particles moving around in the small part of the Universe that is presently visible to us. When particles are in each other's vicinity, the three basic forces that determine their behavior are the *weak*, the *electro-magnetic*, and the *strong* force. All three of these forces have been shown to be special cases of a Yang-Mills theory. They obey the very basic Yang-Mills equations, which are generalizations of the Maxwell equations for electro-magnetism. The particles also interact with a ubiquitous scalar field, the Higgs field, and they owe much of their special structures, such as their masses, to this interaction with the Higgs field. All this is described by what is now known as the Standard Model[2], and the basic outlines of this model are so transparent that they can be pictured on a necktie.

As seen from the perspective of the sub-atomic particles, the world looks very different from the large-distance description provided by astronomy. In this domain, all dynamical features of particles and fields have to be tailored in accordance with Quantum Mechanics. Quantum Mechanics is a magnificent achievement of 20^{th} century physics, providing a logically coherent and exhaustive framework for all interactions. Yet Quantum Mechanics is also a bit mysterious, since it is not attempting to describe what exactly is going on between these particles, but directly produces expressions for the *probabilities* of the results of experiments. Well, even if Nature's laws were completely deterministic, then still the initial conditions of an experiment, such as the exact locations of particles inside a beam of particles, would not be well enough known to enable us to give more precise predictions than probabilistic ones, so in practice, nothing is lost. However, Quantum Mechanics not only does not describe the histories of individual particles, but indeed *cannot* provide with any particular possible history of the motion of particles, and this fact is considered disturbing by some physicists.

There are different ways to interpret these observations[3]. The first approach that has been considered over the years, is to assume that the motion of individual particles is confounded by the action of additional degrees of freedom that are difficult to monitor, or even to identify. Perhaps every particle carries with it a "flag" that indicates which of its observable operators is in a precisely defined state. It was demonstrated, however, that such ideas are untenable. The "hidden variables" would have to obey non-local equations of motion, and logically acceptable, or 'natural' models for such scenarios were not obtained.

Alternatively, one could presume that the quantum wave functions have some ontological meaning, and that the motion of an individual particle is determined in a deterministic fashion by apparently stochastic phenomena in conjunction with the wave function[4]. The ensuing pilot wave function theory can be showed to be equivalent to quantum mechanics mathematically, but its complex, non-local nature has not made it very popular.

It would perhaps be better to search for a theory where the wave function plays exactly the same role as probability distribution functions in classical statistical physics, an approach that is being pursued by the present author. In this approach[5], all present notions of particles and fields should be replaced by different, ontological parameters, which unfortunately have not yet been identified or modelled in a satisfactory manner.

A majority of physicists, however, accepts the idea that we have to take quantum mechanics as it is, declaring questions about its ontological meaning as being illegal ones to ask. This attitude has proven to be so successful in the past, that today almost all fundamental theories about forces and matter, about space and time, have been modelled with the notion of a quantum mechanical Hilbert space as a primary starting point, and all one has to do is to identify the operators and their algebraic relations, assuming our universe to evolve as a state in this Hilbert space.

Experimental investigations have corroborated the Standard Model op to distance scales of the order of 10^{-18} m., but theoretically the model can be extrapolated to distance scales much tinier than that. In order for this extrapolation not to be too unnatural, one is forced to assume the existence of large classes of elementary particles that have not yet been explicitly identified. The simplest way to do this is to assume an enhancement of the presently observed symmetry pattern into a *supersymmetric* one: every bosonic particle must have a fermionic partner and *vice versa*. We can then reach down to the order of 10^{-33} m, where all known forces, except gravity, become of equal strength. It is assumed that further unification of forces takes place there. At the *Planck length*, 10^{-35} m, also gravity joins in.

It may seem that we are closing a circle here: gravity dominates at the extremely large scales in the Universe, and finally at the very tiniest distance scales, again the gravitational force takes over. There are however fundamental differences between these extreme ends of the spectrum of scales: at the smallest scales, quantum mechanics must be playing a very dominant role as well. The dominant role of gravity modifies space and time so much at these tiny scales, that we will be forced eventually to abandon the familiar picture of nature where in a background fabric of space and time particles follow well defined trajectories — particles make their own space and time. We will argue, however, that the standard description of quantum mechanics itself may have to be modified if we want to understand better what is going on.

4. Quantum gravity

In several respects, the gravitational force is remarkably similar to the other forces that are affecting particles. First, all fundamental forces appear to be based on a $1/r^2$ law. This distance dependence is a simple consequence of the action principle, when field equations are cast into an Euler-Lagrange form. Just as is the case with the other forces, the gravitational force can be viewed in a quantum setting by attributing it to the exchange of force carrying particles. The particles transmitting gravity, the *gravitons* only differ from photons, gluons and the weak charge carriers that they have spin *two*, a necessary consequence of the tensor nature of the gravitational field in general relativity.

The reasons why the graviton has spin two, can be illustrated graphically (see Figure 4). The gravitational field of the Moon is felt on Earth only indirectly, through the tidal force. This force causes water on Earth to be attracted towards the Moon wherever it is closer to the Moon then the Earth's own center of gravity. Masses of water further away from the Moon, are catapulted away because of the orbital motion of the Earth around the center of gravity that Earth and Moon have jointly. Thus, there is high tide both on parts of the Earth facing the Moon, and on parts facing away from the Moon, and there is low tide on spots 90° from the direction of the Moon. While the Earth rotates with respect to the Moon, we have twice high tide and low tide during a full (relative) rotation. Thus the strength of the tidal force oscillates with two complete periods during one full rotation. This is the wave function of "something" with spin-angular momentum of two units. Thus, the graviton has spin two. We should stress, of course, that this argument

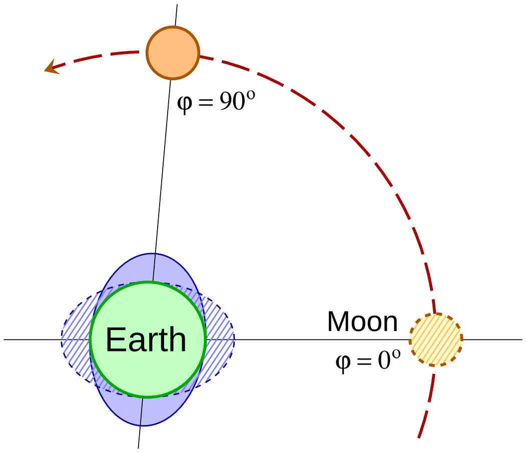

Figure 4: The tidal force transmitted by gravity switches sign when the Moon is displaced by $90°$, so it oscillates twice when the Moon goes full circle.

should merely serve as an illustration. It does exhibit the mathematical nature of gravity, but more trustworthy derivations come from more accurate quantum field theoretical arguments.

We already mentioned a subtle difference between gravity and many of the other forces, the fact that, in gravity, sources of the same sign attract rather than repel. Since all masses are positive, all objects in nature feel attractive gravitational forces. This feature is directly related to the spin of the carrier. The rule is: force-carrying particles of odd spin, such as the photon, will cause objects whose charges are of opposite sign to attract, while charges of equal sign repel. In the case of spin 2, this is the other way around, just as in the case of spin zero: the nuclear force holding protons and neutrons together inside an atomic nucleus, is also attractive between all protons and neutrons (they all carry the same sign). The force carrier there is the pion, which has spin zero. At much smaller distances, the rho meson with spin one keeps the nucleons from approaching one another too closely.

An other subtle but important distinction enjoyed by the gravitational force is the fact that it acts on *mass* rather than charge. Indeed, there exists no other candidate sources for tensor fields than mass, because the *only* Euler-Lagrange system for relativistic tensor fields is the one that exhibits the local invariance structure of general relativity. The consequences of these minor differences are catastrophic. Since like masses attract, gravity causes an accumulation of mass. The resulting mass concentrations generate stronger and stronger gravitational fields. This may lead to a fundamental instability of gravitating systems against implosion, an instability that sometimes inevitably leads to the formation of black holes. We may also relate this instability to the fact that gravitational fields have a *negative* energy density.

Mass carries the dimensionality of energy, which is an inverse length, in units where the speed of light $c = 1$. Since

$$M = \frac{E}{c^2} \;\rightarrow\; \frac{h/c}{\text{wavelength}}\ , \tag{4.1}$$

the distance dependence of the gravitational force in a quantum-relativistic environment boils down to

$$\text{Force} \;\rightarrow\; G \times \frac{M_1 \times M_2}{R^2} \;\rightarrow\; \frac{G\,h^2}{c^2} \times \frac{1}{R^4}\ . \tag{4.2}$$

Thus, gravity will become more singular at small distances than the other forces.

The Planck scale is defined to be the domain of physics where gravity becomes a strong force, comparable to other strong forces among fundamental particles. Using

$$\begin{aligned} h/2\pi \;=\; \hbar \;&=\; 1.0546 \times 10^{-34} && \text{kg m}^2\ \text{sec}^{-2}\ , \\ G_N \;&=\; 6.672 \times 10^{-11} && \text{m}^3\ \text{kg}^{-1}\ \text{sec}^{-2}\ , \\ c \;&=\; 2.99792458 \times 10^{8} && \text{m/sec}\ , \end{aligned} \tag{4.3}$$

one arrives at the natural units of length, mass and time:

$$\begin{aligned} L_{\text{Planck}} &= \sqrt{\frac{\hbar\,G_N}{c^3}} &&= 1.616 \times 10^{-33}\ \text{cm}\ , \\ M_{\text{Planck}} &= \sqrt{\frac{\hbar\,c}{G_N}} &&= 21.8\ \mu\text{g}\ , \\ T_{\text{Planck}} &= \sqrt{\frac{\hbar\,G_N}{c^5}} &&= 5.39 \times 10^{-44}\ \text{sec}\ . \end{aligned} \tag{4.4}$$

Phenomena that take place at these extreme scales of length, time and mass, require Relativity Theory, Gravity Theory and Quantum Mechanics for a proper description. All these effects are than comparably strong. Attempts to understand their consequences, are hampered by several quite severe difficulties, leading to intense disputes among theoreticians:

> - Space-time fluctuations run put of control; consequently, ultraviolet contributions to the quantum amplitudes are dominated by infinities that cannot be handled by any of the standard renormalization schemes.

Superstring theory is making strong claims of being able to handle these infinities[6]. The superstring diagrams do not require infinite renormalizations, so they should act as ‘regulators’ for these infinities. However, in superstring theories only the *on shell* amplitudes are finite; the others are ill-defined. Analogously to conventional field theories, this appears to mean that, although the theory can make predictions for experimental output, it is not properly describing what goes on at small distances. Therefore, we obtain no physical insight as to what it exactly is that happens at small distance scales.

> - The definition of *time* becomes ambiguous; one cannot talk of the 'state of the Universe' at a given time.

Here, the standard answer is that the Schrödinger equation is to be replaced by the Wheeler - DeWitt equation[7]. There is a similar objection here. The Wheeler - DeWitt equation cannot tell us how, at any given time, the state of the Universe evolves and how this evolution can be tested against unitarity and causality. In *perturbative* quantum gravity, we encounter no such problem. In perturbative gravity, we still are allowed to keep clocks and yard sticks at spatial infinity, and define time by imposing gauge conditions on Cauchy surfaces. This theory is unitary and causal in the usual sense[8].

> - The Universe might close into itself, in which case the exact interpretation of quantum amplitudes in terms of the 'probability' that something happens, becomes problematic.

The answer to this puzzle is usually assumed to be that we have to consider the 'statistics of possible universes'. However, the real universe does not close into itself, and experimental tests of the abundances of different universes are fundamentally impossible.

> - Notions such as"distance" and "locality" become ambiguous.

Some theoreticians see no problem here; they claim that the ultimate laws of physics apparently are non-local. Admitting non-locality, however, would be like opening Pandora's box. We would no longer be able to assume a chain of deductive arguments explaining the physics of large scale phenomena in terms of smaller scale phenomena, and the internal logic of our attempts to understand things would be seriously undermined.

We should address such problems with extreme care and try to keep our links with conventional, well-understood theories as strong as possible. We could start with asking the question: if indeed gravitational fields are causing such severe problems for us when they become strong, then exactly which are the circumstances where these field take the *strongest* possible values? What are the most essential features of the gravitational force in that case?

5. Black Holes

The strongest gravitational fields are found near black holes[9]. At the horizon of a black hole, the gravitational potential has the highest possible value, which is always such that, in a test body, it cancels the rest energy, mc^2 , entirely. The gravitational field strength is the highest for the tiniest black holes. A black hole is a completely legitimate solution of Einstein's gravitational field equations, and, at least in principle, there seems to be no limit to the size of a black hole: it could be very large or very small, as long as quantum effects can be neglected. Only when the size is assumed to be comparable to the Planck size, L_{Planck} , the quantum effects are expected to become so large that the notion of a black hole ceases to make sense.

A nice feature of black holes is that applying quantum corrections seems to be straightforward. Field operators can be assumed to be present in the geometry of space and time defined by the black hole, and we can investigate what the known laws of nature tell us about how they evolve. As was discovered by Hawking[10], one must conclude that there is a steady emission of particles. A possible interpretation of this emission process is as follows. Outside the black hole, in the part of the universe accessible to us, called region I, quantum fluctuations take place, generating pairs of particles with positive or negative energies, such that the total energy has the fixed value zero. Negative energy particles cannot exist freely, since there exist no solutions to their field equations with negative energy, so these particles quickly annihilate against other fluctuating particles that happen to have positive energies.

However, some of these fluctuating particles might enter into the black hole, in a region called region II. There, different laws hold: particles are allowed to have negative energies, but they are not allowed to emerge from the black hole; they proceed inwards towards the singularity at the center. If a particle pair is formed right at the horizon separating regions I and II, it may happen that the negative energy particle falls into the black hole, and the positive energy particle escapes to infinity. Since negative energy is fed into the black hole, it looses energy, hence it looses mass, and becomes smaller. This result is not much disputed, although one might question the validity of the usual normalization conditions for amplitudes at a horizon; it could be that an unusual normalization condition should be required, which could strongly affect the intensity of the radiation: the radiation temperature could be twice of what one usually expects.

The implication of this radiation phenomenon is astounding. If we would take *any* tiny material object that is capable of both absorbing and emitting particles, such as a molecule that can emit or absorb radiation, or a snowflake that can condense or evaporate, in short, an object for which an interaction as well as the time reverse of that interaction can be calculated, then we find that the *ratio* of the probability of an event and that of its time reverse to be determined by an essential factor: the *total phase space of all of its states.* The logarithm of the number of these states turns out to be the total entropy of the object. For black holes, this simple observation directly yields the value of their entropy. It turns out that the entropy of a black hole is equal to the area of its horizon, multiplied with a universal coefficient with Planckian dimensions. Or, in other words, a black hole carries one bit of information for every $.724 \times 10^{-65}\ \mathrm{cm}^2$ of its horizon area.

Thus, black holes come in distinct states, and as such, they are now very reminiscent of elementary particles, which also come in distinct states that can be listed in tables such as the ones published yearly by the Particle Data Group. The theory of General Relativity now suggests that all physical properties of the horizon of a black hole can be *mapped* onto the properties of a practically flat, and empty, space-time, so we should be able to determine in great detail everything we wish to know about this list. Unfortunately, this is not at all so straightforward. If black holes were like elementary particles, it should be possible to represent them as *pure* quantum states. In contrast, the thermal nature of the Hawking emission process, at first sight appears to imply that the horizon can only be understood as a quantum mechanically *mixed* state.

The way one arrives at the Hawking radiation feature, one starts out with particles in well-defined quantum states before they enter into the horizon of a black hole. The Hilbert space of states then evolves as a product of two such spaces, one consisting of particles inside the black hole (region II), and one consisting of all particles that can still be observed from the outside (region I). Since one cannot observe the particles in region II, one has to trace out the contributions of their wave functions, and, as is well-known in statistical physics, this procedure leaves us behind with a quantum mixture. However, ordinary quantum systems cannot spontaneously evolve from pure states into mixed states. If they would, then there would not exist such a thing as a scattering matrix for black holes. Something is wrong.

6. The Horizon

In the 1980s, when they became more acutely aware of the problem, the community of physicists divided into three different schools of thought. The dividing lines were roughly along the lines that separated specialists in General Relativity from those in Superstring Theory and those of more down-to-earth elementary particle physics:

i The first group[11] accepted the fact that black holes entire do not obey quantum Schrödinger equations. They are 'doorways to an other universe', and so they cannot be quantum mechanically unitary — unless one includes the entire Hilbert space of that other universe — which is far too large to generate the discrete states mentioned in the previous Section. There would be a problem with energy non-conservation, which could be circumnavigated, at the expense of some fundamental non-locality. But one then cannot sustain the hope that black holes just extend the spectrum of elementary particles, and a fundamental bit of predictability of the physical laws will be lost. Since black holes can be formed as vacuum fluctuations at the Planck scale, this would mean a complete loss of quantum predictability at the Planck scale. But then why is it that Quantum Mechanics survives so beautifully at larger distance scales?

ii The second school of thought was that, if particle physicists really want information to be preserved, they can have it, but the information would be piled up inside the black hole until its last moments of evaporation. At that point, black holes would be forbidden to decay entirely into ordinary particles, so, they would leave some balls of information behind, the 'black hole remnants'[12], a kind of dust grains with masses comparable to the Planck mass, but containing a practically *infinite* amount of information. These remnants would be fundamentally different from ordinary particles of matter, since they are basically non-quantum mechanical. It sounded as by far the ugliest theory, but it was seriously proposed and defended.

iii Only a small minority saw the real truth[13]. Black holes *are* quantum mechanical, but the 'quantum information' simply leaks out disguised as Hawking radiation. This would turn black holes into completely conventional forms of matter, and it

> would be exactly what one gets if a calculation is done in a limit where the number of degrees of freedom becomes large and has to be treated statistically. The only point here is, that Hawking's derivation then isn't *exactly* right, but only in a statistical sense. This is very important. It is not a criticism against Hawking's derivation, because it was exact, but it made use of the laws of Nature *as we know them today.* Do we know them sufficiently accurately? There is no reason to believe that. If we would even try to imagine a pure quantum state at the horizon, it would require a particle density there that goes beyond the reach of the presently known Standard Model. Presumably, this model has to be modified under such circumstances. In fact, we *know* it has to be modified there, since the particle density would otherwise tend to diverge.

Superstring theoreticians later all converted to this latter view, although the exact details of a generic horizon continue to be mysterious in this language. Only recently some of the pure-sang general relativists were converted[14]. Hawking radiation carries out the information that was brought in by the imploding matter. How does this happen? At first sight, it seems to be very odd. As seen by the outside observer, ingoing particles only cross the horizon at $t \to \infty$, whereas the Hawking particles formally were already there at $t \to -\infty$. If these Hawking particles are supposed to carry all the information of the ingoing matter, would this not violate causality?

Our claim is that it does not[15]. The point is, that on their way out, the Hawking particles interact with the ingoing matter. Indeed, this interaction is very strong, since their *gravitational* interaction becomes very strong. As seen by a local observer, the center-of-mass energy of these two sets of particles exponentially diverges to infinity, and since gravity couples to energy, the gravitational interaction rapidly grows out of control. The argument that quantum purity in black holes would be lost, was hinging upon ignoring this infinite force.

We found how the dominant part of this force can be taken into account[16]: it implies that ingoing particles cause a shift in the coordinates of the outgoing ones. This shift goes across the horizon, and therefore completely upsets the original picture. If we include the shift, we do obtain an interesting pure scattering matrix for black holes. However, so-far we were only able to account for the longitudinal parts of the gravitational force properly, whereas it is understood that also the transverse parts are needed if one wishes to understand the finite information density at the horizon.

Anticipating the results of a correct and complete calculation, we expect the following picture of space-time and its matter contents: we may have

- elementary particles of the usual kinds, such as the ones being detected today, forming ingredients of the Standard Model;
- bound states of such particles, such as atoms and molecules, and, eventually, planets and stars;
- imploded bound states, or small black holes: they form literally little voids in space-time, surrounded by horizons that are populated by quantum states with a finite

information density on their surface; and

- very large black holes. They have horizons that are nearly flat, and in spite of the fact that they do not fundamentally differ from the horizons of tiny black holes, they have the striking property that they can be viewed by observers ‘falling in’, who mistake these horizons for (practically) empty sections of space and time. It is this latter feature that necessarily follows from General Relativity, but is the most difficult to understand.

These four types of matter cannot be distinguished very sharply; there may be gradual transition regions between all of them.

7. Superstrings and the Landscape

Superstring theory has been mentioned many times. This author has repeatedly ventured his objections against calling this approach a ‘theory’. We have very little direct evidence that the laws of Nature should be those of a string or superstring. The ‘theory’ was in fact too poorly formulated to allow it to be compared with experimental data at all, even if we would have been able to do experiments at the Planck scale. When it was found that several versions of (super-)string theory exist, attempts were made to prove that they are all ‘equivalent’. What this would mean for experimental observations at the Planck scale would be obscure, because certainly the spectrum of states in the different theories would be different. It was hoped that it meant the following: Nature has only one true ground state, and if these theories are equivalent in the sense that transitions from one mode into another would be allowed, then Nature would choose exactly the one configuration where the vacuum has the lowest energy.

But this hope had to be abandoned. The equivalence is merely a mathematical one: the equations of one theory are related to those of the others, but only if their interaction parameters would be allowed to grow beyond the perturbative domain. Apart from the dubious nature of such statements, this also implies a concession: there are many different competing vacuum states, and only experiment will be able to tell us which of these we are living in at present. Our optimism turned into despair when it was subsequently realized that we do not just have five different string theories, as was thought for some time, but nearly uncountably many. Numbers such as 10^{500} were quoted, but what they really mean, of course, is that the number of string theories is unlimited, though presumably denumerable in the mathematical sense.

Then the cosmological viewpoint arrived[1][17]. All these 10^{500} or so solutions exist somewhere in our universe, or rather, in a more grandiose world called the ‘omniverse’. It could be that, during its evolution our Omniverse shows distinct regions of expansion, where different vacuum states are approached. An important role is here played by the Cosmological Constant, which only allows expanding universes to be worth-while when it is sufficiently tiny. Its natural value is not very tiny, but certainly a substantial subset of the 10^{500} expanding regions *does* have a tiny or practically vanishing cosmological constant.

Is this an unavoidable direction for theoretical physics to go? If so, then we would no longer be able to use fundamental principles to determine the ultimate laws of physics. Historically, it would be a drastic departure from the way science in general, and physics in particular, has developed. We have always been able to identify new principles helping us to pin down which of the numerous possibilities is actually realized in Nature. Is this course of our chain of discoveries coming to an end? My suspicion is that there are other options.

The clue is in Quantum Mechanics itself. A philosopher recently asked me the question: "Suppose that the Big Bang would occur again, with *exactly* the same initial conditions as before, steered by exactly the same laws of physics. Would everything evolve in exactly the same way? Would the same meteorite terminate the same dinosaurs exactly as it did before? Would we be sitting here dressed the same way?" I had to answer that, according to what we know presently, the answer is a resounding "NO!". Everything would be different. Quantum mechanics would only give us the same probabilities, but they could, and would, be realized differently.

But I don't believe this answer. Yes, we do not know the laws of physics very well, but why should that imply that they don't exist? Is it not by far more natural to suspect that the Universe *would* evolve exactly as before? Quantum Mechanics is a mere reflection of the sobering reality that *we* are not able to make accurate predictions at all. But maybe deterministic laws of nature do exist[5]. In fact, we can imagine schemes[18] that could explain how such deterministic laws could produce random behavior simply because the solutions are too complex to be completely and fully analyzed. The rule of statistics could be what we call 'Quantum Mechanics' today. Since String Theory, Super- or not, assumes Quantum Mechanics as a starting point in lieu of a deterministic mechanism, it cannot be more than a crude approximation of reality. If this is so, string theories should be treated for what they really are: they are *models*, not theories. This view makes sense. String theory started out as a crude model for hadronic physics; it may well turn out to become useful as a more accurate model for QCD, for instance in the large N limit, provided we learn to understand not only how to break supersymmetry, but also how to realize some spontaneous breakdown of General Relativity, in a manner similar to the Higgs mechanism for vector gauge theories.

In this respect then, String Theory might turn out to be the opposite of the Standard Model. The Standard Model, in its first concoctions, was proposed indeed as a model, a mere idealization of reality. It came as a surprise for many that the Standard Model would turn out to be much more than that: it is the Standard *Theory* now. It conforms to the experimental observations with impressive accuracy. String Theory was propelled as a 'theory', but it could not be confirmed. It may never represent reality very closely. It should be called a Model. As such, string theory, superstring theory and their holographic projections may well become extremely valuable, but their status as representatives of reality should be corrected.

References

[1] A. Linde, in *The Future of Theoretical Physics and Cosmology*, eds. G. Gibbons et al, Cambridge Univ. Press, 2003, p. 801.

[2] R.P. Crease and C.C. Mann, *The second creation: makers of the Revolution in Twentieth-century Physics* (New York, Macmillan, 1986), ISBN 0-02-521440-3; L. Hoddeson et al., *The Rise of the Standard Model*, Cambridge Univ. Press (1997), ISBN 0-521-57816-7 (pbk).

[3] M. Jammer, "The conceptual Development of Quantum Mechanics (Mc. Graw-Hill, 1966).

[4] D. Bohm, *Phys. Rev.* **85**, 180 (1952).

[5] G. 't Hooft, Quantum Gravity as a Dissipative Deterministic System, SPIN-1999/07, gr-qc/9903084; *Class. Quant. Grav.* **16** (1999) 3263

[6] J.H Schwarz, "Introduction to Superstrings", in *Supersymmetry and Supergravity '84*, Proc. of the Trieste Spring School 4-14 April 1984, p. 426; id., "The future of string theory", in *Unification of Fundamental Interactions*, Proc. Nobel Symp. 67, Marstrand, Sweden, June 2-7, 1986, *Physica Scripta* **T15** (1987) 197.

[7] B.S. DeWitt, *Phys. Rev.* **160** (1967) 1113.

[8] G. 't Hooft, Perturbative Quantum Gravity, in Proceedings of the International School of Subnuclear Physics, Erice 2002, From Quarks and Gluons to Quantum Gravity, Subnuclear Series Vol. 40, ed. A. Zichichi, World Scientific, p 249.

[9] K.S. Thorne, *Black Holes: the Membrane Paradigm*, Yale Univ. press, New Haven, 1986; S. Chandrasekhar, *The Mathematical Theory of Black Holes*, Clarendon Press, Oxford University Press.

[10] S.W. Hawking, *Commun. Math. Phys.* **43** (1975) 199

[11] S.W. Hawking, *Phys. Rev.* **D14** (1976) 2460; *Commun. Math. Phys.* **87** (1982) 395

[12] Y. Aharonov, A. Casher and S. Nussinov, *Phys. Lett.* **B191** (1987) 51; T. Banks, M. O'Loughlin and A. Strominger, *Phys. Rev.* **D47** (1993) 4476.

[13] G. 't Hooft, *Nucl. Phys.* **B256** (1985) 727; id., *Phys. Scripta* **T15** (1987) 143; G. 't Hooft, C.R. Stephens and B.F. Whiting, *Class. Quantum Grav.* **11** (1994) 621.

[14] S.W. Hawking, *Phys. Rev.* **D72** (2005) 084013, hep-th/0507171.

[15] G. 't Hooft, Horizons. Erice Lecture Notes (2003), ITF-UU-04/01, SPIN-04/01, gr-qc/0401027.

[16] G. 't Hooft, *The Holographic Mapping of the Standard Model onto the Black Hole Horizon*, Part I: Abelian Vector Field, Scalar Field and BEH Mechanism, *Class. Quant. Grav.* **22** (2005) 4179, ITP-UU-05/17, SPIN-05/13, gr-qc/0504120 (Note: some sign corrections and further elucidations in the published version).

[17] L. Susskind, , The Anthropic Landscape of String Theory, hep-th/0302219.

[18] G. 't Hooft, The mathematical basis for deterministic quantum mechanics, ITP-UU-06/14, SPIN-06/12, quant-ph/0604008