On the Paradigms of Quantum Gravity 2016

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Introduction

One hundred years of quantum and gravity have not been enough to solve the riddle of the fundamental structure of our universe. Still there is an unquenchable strive to achieve the ultimate understanding of nature in the face of almost secure defeat. As the protagonists of this scientific field try to paint a picture of our physical reality in its utter completeness, I will now step back to attempt a reflection of their work process from an epistemological point of view.

Situation

In the first half of the 20th century two theories emerged, which described distinct natural phenomena on very different length scales. One is called *quantum mechanics* being concerned with the physics of light and particles on (sub)atomic levels, the other one is *general relativity*, which describes gravitational effects like the observable motion and attraction of astronomical bodies e.g. stars and planets. Both theories were considered very radical changes of paradigm at the time and though they have been tested successfully to astonishing accuracy by now, people are still unsatisfied enough to work on the next change of paradigm, which will (hopefully) be the unification of both: *quantum gravity*

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Quantum Theory

The advent of quantum mechanics was stimulated by the desire to know, what the physics of the microcosm of particles really is, since there were some phenomena, which could not be explained by the classical atomic models. To many physicists quantum mechanics is nothing but a vast apparatus of mathematics, which coincidentally describes the physics of particles. Their aversion arises in part by the theory's incompatibility with human intuition. This can be shown by the question: "What is light?" In the classical thinking light can *either* be a wave *or* a particle. Quantum mechanics, however, tells us that light is "quantum", i.e. it exhibits qualities of waves and particles equally, which is termed the *wave-particle-dualism*. This term alone signals how physicists cling to the traditional classification still today, instead of accepting that light is something new, which they cannot grasp with thinking in classical patterns.

While this is not an easy notion to digest, the world of physics has been shaken even more, as quantum theory revealed its probabilistic nature. To the horror of all scientists nature turned out to be not deterministic on the microscopic level. While one part of the scientific community accepts that chance, randomness and non-predictability is a fundamental concept of nature itself, the other part still hopes to resolve this undesired feature in a new quantum (gravity) theory, e.g. by introducing "hidden variables". That this desire could be solely rooted in the psychological constitution of the human mind seems to be consequently overlooked.

Independent of all these doubts quantum mechanics has been developed further over the course of the last one hundred years to what is known as *quantum field theory*. This powerful tool is able to describe three of the four fundamental forces of nature as fields of quantum states, namely electromagnetism, the weak and the strong interaction. However, any attempt to include the force of gravity into this picture has failed to this day.

Gravity

Newton's classical theory of gravitation has been challenged by Albert Einstein in 1915 as he postulated his theory of general relativity, which lead to the prediction of black holes and gravitational waves. The new idea was that space (and time) cannot be regarded as absolute quantities, rather they are subject to deformations or *curvature* caused by the existence of matter (or energy). Motion in a gravitational field can now be considered as geodesic motion in curved spacetime. Again the scientific community reacted with great reluctance to this new approach awarding Einstein the Nobel prize in 1921 for his quantum interpretation of the photoelectric effect, since there was no experimental proof of the correctness of general relativity. This should change in the following decades and today general relativity is tested successfully to similar accuracy as quantum mechanics.

Defining the Problem

Summarizing that we have two very successful theories on their own domain respectively we have to ask: Where is the problem?

To answer this question it could be helpful to differentiate between two different types of problems.

(i) The problem occurs, when we attempt to combine quantum mechanics and general relativity. While the first is a linear non-deterministic theory, the second is a non-linear deterministic one. From the conceptual point of view alone both theories differ fundamentally in their structure. One can now argue that this is nothing but an aesthetic flaw, which should play no role in the scientific edifice of ideas. However, the true physical problem becomes evident, if we try to drag gravitational effects to the microscopic quantum world of particles. On a mathematical level the so-called *quantization of gravity*, i.e. the description of spacetime by quantum states leads to physically inconsistent results (if a result is achieved at all). With this physicists are groping in the dark when describing gravity on short length scales.

(ii) Additionally scientists observe phenomena in experiment and theory, whose explanation goes well beyond the scope of their current theories. Examples for these are the existence and nature of dark energy and dark matter as well as the occurrence of singularities in black holes and the big bang. It is hoped that these problems might be resolved within a new theory of quantum gravity. However, one should point out that the phenomena mentioned need not necessarily have to do with either quantum or gravity theory. Like in the case of particles, waves and light it could turn out that we have to deal with something completely new.

Approaches to Quantum Gravity

The notion above is usually ignored and deemed quite "alternative", so that people hope to solve problem (ii) automatically by solving problem (i). To achieve this two mainstream theories have been developed: *string theory* and *loop quantum gravity*. The first imagines particles as vibrating strings sweeping through world branes, which sounds not too unreasonable, since many phenomena in physics are described by oscillations. The second tries to quantize spacetime and apply techniques of quantum field theory. After more than two decades neither theory can provide a satisfying picture of the world without coming up with other undesired features like the requirement of more than four spacetime dimensions in the case of string theory. Admittedly it is a priori not ruled out that nature provides 27 spactime dimensions of which 23 are curled up so tinily that we cannot detect them, but it reveals the true bane of quantum gravity, which is that we lack experimental evidence of basically everything. No particle accelerator has enough energy to delve into the microscopic structure of strings and most probably none will ever have. By this illustration "scientists" can walk freely on the playground of quantum gravity and propose any theory they want, since it is not falsifiable anyway. Tuning all the parameters they have string theory alone provides 10^{500} different versions of its own. Since it cannot be hoped to reduce this to a reasonable number of candidates in the absence of very conclusive measurements, "alternative" approaches become attractive once more. But again the creativity of physicists, which is needed to solve the problem, is to the same extent its own downfall, since the possibilities are countless. Without any observational hints of quantum gravity the only directive that serves as a boundary condition is the necessity of the new theory to reduce to quantum mechanics and general relativity in the low energy limit.

Black Holes and Analog Gravity

Straight forward thinking leads the "experimental search for quantum gravity" to places, where energy densities take on values well beyond human imagination in the truest of all senses. Such places cannot be found on earth or even the solar system, but general relativity predicts the existence of infinetely dense points in spacetime that lie at the centers of black holes. Though black holes are astrophysically detectable by their gravitational attraction on their surroundings, their notion does not come along with some peculiar difficulties. First of all the spacetime singularities themselves are deemed unphysical and should not exist within a framework of quantum gravity. This is not a big deal for astrophysicists but a huge dilemma for theorists, since general relativity predicts the existence of black holes, while black holes predict the breakdown of general relativity. Unfortunately we are not half way done with black hole peculiarities, since they classically form what is called event horizons around them. These event horizons effectively prevent any insight "into" a black hole and in the words of the *cosmic censorship hypothesis* the black hole's singularity and with it all of quantum gravity is shielded away behind such an event horizon. So it could very well be that quantum gravity itself is simply not part of our universe.

One loop hole, however, might exist and it triggers debates for nearly four decades now, also being addressed at the ESQG conference many times. It is the assumption that black holes emit thermal Hawking radiation. With time they would shrink in size, loose mass and eventually explode revealing their interior. Again such a scenario brings along new undesired features like the information loss paradox and evaporation times are so large that the decay time of the most stable particle in the universe (the proton) is but a blink of an eye in the lifetime of a black hole, rendering the effect basically unobservable. Efforts in loop quantum gravity lead to shorter evaporation times, but still the astrophysical laboratory of black holes remains fairly intangible.

So what else can we do, if the natural systems of quantum gravity so successfully avoid experimental detection? Well, we can do analogies, literally, going from photons to phonons. Much like black holes trap light particles (=photons), Jeff Steinhauer managed to trap "sound particles" (=phonons) in the laboratory by creating an artificial event horizon. This can be achieved by accelerating a quantum gas beyond its own speed of sound. Pairs of phonons that are spontaneously created within such a gas can never reach the fleeing edge and become trapped. If such a pair is created exactly on the event horizon, it can happen that one of the phonon partners becomes trapped, while the other one escapes into the subsonic region becoming visible as "sound radiation". This process is the accurate analogy to Hawking radiation at black hole event horizons, just that we now deal with sound instead of light. With Steinhauer claiming the measurement of entanglement between the phonon partners, many of the community are hesitant about the findings as it has always been in the history of physics. However, the more fundamental question is not about the validity of analog Hawking radiation, but about what exactly such an artificial black hole can tell us about a true astrophysical black hole. What conclusive power has a non-gravitational system about a gravitating one? Where does the analogy break down? Though Steinhauer's experiment might have the potential to become more than a footnote in the quest for quantum gravity, pessimists seem to have good arguments, when they say that this cannot solve the information loss paradox, since no information is lost in the first place and eventually one cannot possibly hope that artificial event horizons for sound are able to shed light on the gravitational physics on smallest lengths.

Giving up Symmetry?

The edifice of (theoretical) physics has been strengthened over the course of centuries and is built on very fundamental concepts that somehow came to savor the status of sanctity. These concepts are overarchingly known as *symmetries* and represent very powerful (mathematical) tools to describe nature and derive many of its properties. This is because symmetries preserve (phenomenological) appearances of a system under transformations, i.e. a system A looks the same as a system B after applying a transformation "x" to it. Eventually this procedure acts like a boundary condition for the system und reduces the degrees of freedom (=fewer parameters to adjust), thus *simplifying* it. Since the entire complexity of nature is well beyond the grasp of human understanding, physicists try to find and apply as many symmetries as possible, generating highly reduced and simplified systems.

Seemingly nature exhibits many of such symmetries, especially in the field of particle physics. One theorem states that our universe could be reproduced or "mirrored" exactly by inverting three particle properties simultaneously, which are $\underline{\text{C}}$harge, $\underline{\text{P}}$arity and $\underline{\text{T}}$ime, representing *CPT-symmetry*. The idea is that a universe filled with antimatter (C-symmetry), inversion of spatial coordinates (P-symmetry) and reversal of time itself (T-symmetry) would yield exactly the same laws of particle physics as our original one. While to date all experiments are in accordance with CPT-symmetry, the picture changes, if one looks separately at CP-symmetry and T-symmetry, who do not need to be preserved each by itself, but only as the combination of CPT. In fact electroweak interaction *demands* the violation of CP-symmetry (and consequently T-symmetry) to explain the observed decay of certain particles, while it still preserves

CPT-symmetry as a whole. Contrarily CP-violation has not been observed for the case of strong interaction of quarks and gluons.

Another very fundamental concept of symmetry is the one of *Lorentz covariance*,[1] which states that physical laws are invariant under the transformation of coordinate systems. Obviously there is some connection between Lorentz symmetry and P- and T-symmetry, but furthermore it represents the corner stone of genera l relativity, which describes gravity as an effect of geometrically curved spacetime. Now Lorentz invariance demands that gravitation appears the same regardless of the choice of coordinates, which is also an appealing feature for any quantum theory. This apparent common thread of quantum gravity, its success and applicational power promoted Lorentz invariance to something that most physicists are not willing to give up. Also in experiment Lorentz invariance holds true at least as a *hidden* symmetry. Actually the theoretical description of the above mentioned phonons requires the spontaneous symmetry breaking of Lorentz invariance, i.e. the underlying equations still exhibit Lorentz symmetry, while their solutions and thus the phenomenology does not making the symmetry a *hidden* one.

It is the need to solve the riddle of quantum gravity that makes some physicists question the sacred paradigm of Lorentz invariance sparking an expanding field of search for Lorentz violating effects both in theory and experiment. E.g. Hořava-Lifshitz gravity as a modern alternative to general relativity explicitly breaks Lorentz invariance on the fundamental level and restores it in the large scale limit, rendering Lorentz symmetry an *emergent* or *effective* symmetry. So the question arises how fundamental a symmetry has to be. Actually symmetries seem to appear only on certain scales and under appropriate strategies of reductionism, which can be enlightened by numerous examples. The whole of Quantum Chormodynamics[2] (QCD) relies on the isospin symmetry, which implies that protons and neutrons have the same mass. However, we *know* from experiment that protons and neutrons have slightly different masses, but still the theory established on an incorrect assumption works out surprisingly well.

In the case of quantum gravity the concept of symmetric particles has been incorporated in some versions of superstring theory. The idea is that every fermion has a bosonic counterpart so that the standard model of particle physics is extended to one exhibiting a hidden supersymmetry, which is spontaneously broken at low energies, so that we again experience an asymmetric world of particles. So far no evidence of superstring theory has been found and the critical question to address is: Why are people so intent on finding and preserving symmetries, even when nature tells them straight in the face that there are none? The answer has already been given above with symmetries providing perfect tools of simplification, which is exactly what the human mind desires. Symmetries are easy to understand, they bring an order to the chaos, which nature unfurls before us, and order satisfies our natural psychological need for security. There is no scientific reason to believe in the fundamental symme-

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[1] The terms Lorentz *covariance*, Lorentz *invariance* and Lorentz *symmetry* are used synonymously in this text.

[2] QCD is the theory of the strong interaction of quarks and gluons.

try of quantum gravity other than our own human constitution, which *wants* nature to be symmetric, to make it understandable, ordered and secure.

The philosophical implication draws an analogy between our own universe and the ones artificially created in the industry of game design. Usually the virtual worlds are not created by imposing profound symmetry conditions, but game designers finetune parameters so that the emergent result exhibits an approximate symmetry and simply keeps the system functioning. Why should our universe be so different and perfectly ordered? Everything that nature has *really* told us so far, is that symmetry is being broken the deeper we look into it.

The Bottom Line

The chapter of quantum gravity in the book of nature remains fairly empty and everybody is welcome to take a blank page and fill it as one may see fit. Under such unbounded circumstances creativity lets scientists blend into artists of thought searching for the next change of paradigm, ignoring its complete inapplicability, just for curiosity's sake. Unwilling to accept the status quo of physics they make up the tiny community, who does sometimes not even believe in itself, which is highlighted by an anecdote of the ESQG conference, when Niayesh Afshordi said with a straight face: "I have evidence of quantum gravity."
Everybody laughed.