Emergent gravity and the spatiotemporal limits of knowledge

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Are we moving in the right direction on the road to quantum gravity? It seems to me that there is a serious conceptual problem with most current approaches. I discuss a simple guiding principle which I believe to be quite obvious, but which has nevertheless been largely neglected so far. This leads me to argue that the most relevant approach to quantum gravity might be a framework of emergent gravity based on insights from condensed matter physics. Within this framework, I discuss a thought experiment based on the idea to describe quantum gravity in a first approximation simply as a Minkowski spacetime containing nearly-point-like objects or 'atoms' of spacetime, from which the geometry of our universe and its physics emerge as an effective, internal description based on collective excitations. Based on this thought experiment, I will try to convince you that there are strong spatiotemporal limits on the knowledge that we can possibly achieve with respect to quantum gravity.

I. INTRODUCTION

As an engineer, I got used to the idea that any mathematical model describing a real situation or device was always approximate. At the end of your calculation, no matter how intricate, you always had to include a safety margin of two to make sure your electronic coating would not melt, or ten to make sure your bridge would not collapse.

While studying philosophy, I became acquainted with lots of –isms, including postmodernism and structuralism, which question the absoluteness of human knowledge. I learned that we do not necessarily have to throw away the belief that our knowledge of reality is somehow related to 'the true structure of reality', but that 25 centuries of attempts to put this relation on a firm, human-independent ground have largely failed.

I have therefore long been intrigued, not to say quite skeptical, to hear that some theoretical physicists claimed to be on the brink of unravelling the deepest secrets of the universe and formulating the ultimate 'Theory of Everything' describing all of matter, space and time in a single comprehensive framework. Now that I have studied the question for a few years, I have become even more skeptical. I hope to present some of the reasons for my skepticism in the following tour that will lead us along Bohr, Einstein, Lorentz and Michelson on the path to quantum gravity.

II. BOHR

There exists a long-ranging debate within the philosophy of science between realist and constructivist views on science. The question is whether the essence of science implies *uncovering* the elements of external reality and their relations, or rather *constructing* a framework whose truth-value is determined in part by human (for example, social) standards. As usual in such cases, the truth probably lies somewhere in the middle. With Popper, I believe that the *aim* of science is intrinsically realistic: it is to formulate true explanatory theories [1]. Science acquires such a realistic component by the confrontation with reality through experiments and observations. However, in its *method*, science is obviously constructive: theories are not formulated out of the box in a form which corresponds to reality. Reality does not lie there ("like a virgin", as Madonna would say), waiting for us to be moulded into a scientific theory. Rather, scientific theories are constructed, sometimes by the brilliant sweep of a single genius (such as general relativity), more often through painstaking trial and error and collaborations between dozens of people, in which social elements often indeed play a significant role[1].

It might be useful to already note here that any observation or experiment is always *spatiotemporal*: we observe something at a certain time (or in a certain time span) at a certain location (or between a set of locations), using experimental apparatuses with a certain extension. I will extensively come back to this point later.

Even when repeatedly confronted with reality, scientific theories never fully achieve their realistic aim. This is in a large part due to the underdetermination of theory by experiment. No matter how large a set of measurements, there are still a huge amount (in principle, an infinity) of theories that could fit all the data. Therefore, on top of the requirement of a satisfactory correspondence with observation, additional guidelines are needed when constructing scientific theories. Some criteria, such as predictive power and falsifiability, have become generally accepted. Others, such as mathematical elegance, are less explicitly outspoken and more subjective, but nevertheless also important. The harder it is for a field of science to make contact with observation, the more it needs to rely on such additional and partly arbitrary constructive criteria. Quantum gravity is an exemplary case where such additional criteria are needed, due to the scarcity of experimental or observational input.

The guideline that I wich to defend here is loosely based on one of Bohr's legendary principles, though by far not as (in)famous as his principle of complementarity. I am referring to the *principle of classicality*. This is most succinctly defined by the following excerpt: "Every description of natural processes must be based on ideas which have been introduced and defined by the classical theory" [2]. Also: "It is decisive to realize that however far the phenomena [of atomic systems] transcend the range of ordinary experience, the description of the experimental arrangement and the recording of observations must be based on common language" [3]. Against Bohr, it seems to me that, when our intertwined theoretical and experimental control of such strange phenomena increases sufficiently, we are no longer so strictly bound to explaining or interpreting them in terms of classical or common-sensical concepts. This is an advance in at least two ways. First, because quantum-mechanical phenomena can obviously not fully be grasped in terms of classical concepts. Therefore, freeing them from the classical straightjacket is certainly positive. Second, as we acquire a sufficient technical (mathematical) control of these phenomena, and the need to explain them in terms of common classical language decreases, the building blocks of such a technical description can in their turn serve to explain or interpret more complex phenomena. However, in another sense, this process entails the risk of a purely instrumental view on science, which no longer aspires to understand nature but merely to describe it.

In any case, the need for an interpretation in familiar concepts can only be (partially) given up when there is a sufficiently strong body of observational and experimental material, in combination with a satisfactory technical mathematical description. As long as these conditions are not fulfilled, we have no other remedy in order to make sense out of strange phenomena than to rely on well-understood, well-controlled concepts.

Bohr's interpretative principle is just one step away from a constructive one. Whenever we are confronted with a

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[1] usually, though not always, with good reason. Who would you rather believe: a hotshot scientist from M.I.T. with hundreds of citations, or some lazy ass who escaped from rainy Belgium and pretends to be working on quantum gravity under the Spanish sun?

new problem, be it through the observation of some strange phenomenon or because there seems to exist a logical necessity, the first step must always necessarily consist of the tentative construction of a framework in terms of well-understood and well-controlled concepts. Through a gradual process of testing and correcting this framework, we refine the concepts involved, and perhaps we even have to replace them by totally new concepts. It might be impossible to explain the significance of these new concepts and their interplay in terms of previously well-understood ones, but that is all right as long as our technical description has abundantly stood the test of experimental verification.

Why am I putting so much emphasis on something that should hopefully seem quite obvious? Because what I am arguing for is largely the contrary of what is currently going on in most approaches to quantum gravity. We have so far not a single experimental test for any framework on quantum gravity, yet the conceptual machinery involved ranges from dimensional compactification through Calabi-Yau manifolds over holonomies and spin-foam networks to causal sets and twistors. These are all handled as if they were nearly primitive concepts on which a whole framework for quantum gravity is constructed using mainly criteria of mathematical consistency. To be fair, all approaches to quantum gravity are based on important lessons from known physics. And of course, there is nothing wrong with a little extrapolation through a requirement of mathematical consistency. Such extrapolation has sometimes led to spectacular results in the past, such as Pauli's prediction of antimatter. But in all the cases where this approach has led to interesting results, the energy range of extrapolation was limited. In contrast, the extrapolation from the highest energy at which we have a decent understanding of physics to the Planck level where quantum gravity is assumed to come into play is comparable to an attempt at describing the atomic structure of hydrogen by observing the moon, positing the existence of some abstract building block (say, a 'moonit' or a 'lunit') based on lessons drawn from this observation, and extrapolating to the atomic level through a guideline of mathematical consistency.

Does this observation impose a limit on the power of science? Not really. It does however impose a limit on the power of mathematics, and therefore on naive mathematical realism as a guideline in physics. And since the moonits and lunits, in some form or other, seem to have become the path preferred by the immense majority of researchers working on quantum gravity, perhaps this should worry us a little.

III. EINSTEIN

Einstein introduced the special theory of relativity in an *operational* way. Einstein did not claim that spacetime, geometry or simultaneity *are* such or so, but that they *can be defined* such or so. In particular, Einstein gives an operational definition for how to extend the locally intuitive concept of simultaneity to one that is useful "to connect in time series of events occurring at different places" [4]. This definition is preceded by the innocently sounding "if we wish to describe the motion of a material point". He then goes on to re-derive "the theory of the transformation of co-ordinates and times from a stationary system to another system in uniform motion of translation relatively to the former," i.e., the well-known Lorentz transformation.

Using terminology later introduced by Minkowski, one can rephrase this as follows. A spacetime geometry can be constructed by extending locally intuitive processes in the way described by Einstein. The essential element that allows a formal description using the Lorentz transformations is the availability of a constant signalling speed, independent of the inertial reference frame: the speed of light. Einstein introduced this element as an *assumption* "in agreement with experience" (and not as a postulate, contrarily to what is often said). Furthermore, what was only begun to be understood at the time is that the crucial role played by the velocity of light is not merely a geometrical question. In fact, *any* constant velocity would be perfectly adequate to construct a geometry in a similar operational fashion. For example, bats and dolphins use a sonar system to orient themselves, i.e. to perform what we could call in anthropocentric terms the ‘construction of a geometry’ based on the speed of sound. The privileged role of the velocity of light is due to the double fact that *a)* it is indeed a well-established experimental fact that the velocity of light in vacuum is a universal reference-frame-independent constant, and *b)* the internal structure of all matter, as far as we know, is also governed by (mainly electromagnetic) processes modulated by the speed of light. Therefore, bats and dolphins do *not* experience strange effects such as length contraction or the twin paradox when travelling at speeds near the speed of *sound*.

You might be surprised that I am talking so much about special relativity, and so little about Einstein’s general masterpiece. But even in curved spacetimes, the Lorentz transformation is still *locally* valid. The operational point of view just mentioned can therefore be carefully extended to general relativity and curved spacetimes.

The question which I want to address next on the road to quantum gravity is the following. Do we know of any real, well-controlled and well-understood examples in nature where such curved spacetimes exist, and preferrably where the underlying microscopic or ‘quantum’ building blocks are also well-controlled and well-understood? The answer is yes. We know plenty of examples. Particularly interesting ones come from condensed matter physics. In what sense do these reproduce the Lorentz transformation required for such a geometry?

IV. LORENTZ

The Lorentz symmetry is the symmetry which follows by construction from the Lorentz transformation. In special relativity, the Lorentz symmetry is a global symmetry. In general relativity it is preserved as a local symmetry. In the condensed matter examples that I just mentioned, such a local Lorentz symmetry is realised at low energies. For example, in Bose–Einstein condensates, it is realised for phonons or sound waves at low energies. The constant velocity which takes over the role of the speed of light in the Lorentz transformation is now the speed of sound, characteristic of these phonons. At some high energy level[2], this local Lorentz symmetry is violated: the high-energy modes no longer move at the constant low-energy speed of sound, but have an effective speed of propagation which is typically higher. It is an important question whether the local Lorentz symmetry of general relativity is also broken for the spacetime describing our universe. If so, then this should be an important feature of our quantum theory of gravity, and there might be important lessons to be drawn from the condensed matter examples.

Various mechanisms have been studied by which such a Lorentz symmetry violation could occur. None of these have been experimentally confirmed so far. Several of them have actually been nearly ruled out at the Planck level, for example by extrapolation from the observation of ultra-high-energy cosmic rays [5]. However, there is a very simple (and in my opinion: pretty good) reason to believe that the Lorentz symmetry of our universe is nevertheless only an effective rather than a perfect symmetry: perfect symmetries are just not very popular in mother nature. We do not know of a single example of a perfect symmetry, preserved over every range of energy. Moreover, in particle

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[2] ‘High energy’ should be taken with a grain of salt here, since in atomic Bose–Einstein condensates we are typically talking about temperatures of no more than a few microKelvins above the absolute zero.

physics, the emphasis is heavily on symmetries that are formed towards higher energies, and therefore broken below some critical energy barrier. In particular, it is hoped that the critical energy barrier for the Brout-Englert-Higgs mechanism lies within reach of the Large Hadron Collider to put the cherry on the standard particle cake. However, there are also plenty of opposite examples where a symmetry is formed towards lower energies. This actually forms the heart of condensed matter physics. A particularly interesting case might therefore be that the Lorentz invariance of our universe could be a low-energy, effective symmetry, broken at some extremely high energy.

There is one spiny problem with regard to symmetries. When you are right in the middle of a symmetry (i.e., if you are at an energy range sufficiently far away–either above or below–from the critical energy at which the symmetry is violated), then there is no way of knowing when or how it will be violated. Actually, from a position in the middle of the symmetry, the symmetry looks perfect. The reason why we understand the symmetries of particle physics so well is that they are broken at the energies which we typically handle, and we can see their evolution towards higher energies, where they are formed. Analogously, the symmetries of condensed matter physics are also broken at our everyday energies, and we can observe how they are realised at sufficiently low energies. This problem means that we have no way of predicting with any certainty when (at which energy) and how (by which mechanism) the Lorentz symmetry of our universe will be violated.

There is another important collateral consequence. One of the dominant lines of research in high-energy physics consists in looking for an overarching 'fundamental' high-energy symmetry group from which all the symmetries of the standard model of particles would split off one by one toward *lower* energies. However, if one of our most fundamental symmetries, namely Lorentz symmetry, is indeed an effective symmetry broken at *high* energies, then there is no reason to believe that such a line of research would indeed lead to a universally valid (energy-independent) Theory of Everything. This discussion is related to the long-standing debate between reductionism and emergence, on which much has been said by people much more qualified than myself. I will therefore limit myself to point out that, as usual, the truth probably lies somewhere in the middle, and we need a pinch of both on the road to quantum gravity.

V. MICHELSON

I just mentioned that an effective Lorentz symmetry and an associated effective curved spacetime emerge for low-energy phonons in some condensed matter systems, with the speed of *sound* as basic parameter. This effective or emergent spacetime is still embedded in the 'fundamental' spacetime of our universe, which for a condensed matter system in a laboratory is locally well-approximated by Minkowski spacetime, in which the key parameter is now again the usual suspect: the speed of *light*. We are dealing with what is known as a bi-metric system: there are two geometries. First, the 'fundamental' geometry containing the laboratory and the atoms composing the condensed matter system, with the speed of light as Lorentz parameter. Second, there is an 'effective' geometry describing the collective excitations in the condensed matter system (in the simplest case, the phonons), with the speed of sound as key parameter.

Let us then proceed with the following thought experiment [6, 7]. Assume that there exists a condensed matter system of sufficient complexity such that it contains a whole internal universe. Apart from the basic phonons, this universe would also need to contain more complex collective excitations out of which clocks and rods can be constructed in order for Einstein's synchronising procedure to build up an effective geometry. Whatever mechanism would be available for the construction of these rods, their internal structure would always be governed by the characteristic speed of this internal physics, i.e., by the speed of *sound.* Any experiment that an internal observer in such an emergent universe could conduct would always be tied up by this speed of sound.

I stressed earlier that all our experiments are spatiotemporal, both in the sense that we can only observe limited portions of spacetime and in the sense that our experimental apparatuses have a geometrical or spatial extension. When the internal observer in our thought experiment sets out to explore the boundaries of his internal geometry, and in particular wants to check whether his internal emergent universe is embedded in an absolute universe with a fundamental geometry, he would typically try to conduct some 'acoustic' interferometric experiment *à la* Michelson–Morley, using sound signals rather than light signals. *But he would simply not be able to detect any external geometry.* No matter how ingenious the internal observer, any device that he constructs would always be determined by the speed of sound and limited to the internal geometry. These devices would therefore 'contract' and 'expand' relative to the speed of sound. Therefore, assuming a perfect match between the speed governing the internal structure of the devices and the speed of the signals used in Einstein's synchronising procedure (which underlies the effective geometry), any such interferometric experiment would *necessarily* lead to a null result. Contrarily to bats and dolphins, whose internal structure is determined by the speed of light, these internal rods would indeed contract with respect to the speed of sound.

Is this not exactly what Michelson and Morley proved [8]? Not quite, since their interferometers were not constructed from collective excitations, but from individual particles. And they did not use emergent signals such as phonons in their experiments but fundamental ones, namely photons. Or did they?

VI. QUANTUM GRAVITY

I made the case earlier for a 'new' guiding principle in the quest for quantum gravity, loosely based on Bohr's classicality principle. This principle is not respected by most approaches to quantum gravity, which postulate abstract building blocks and rely mainly on principles of mathematical consistency. However, there exists a way of looking at quantum gravity which relies on the solid, well-tested physics of condensed matter systems, along the line of the thought experiment that I described above. This can be interpreted at various levels.

The most conservative level of interpretation is simply that certain phenomena of high-energy physics, such as Hawking radiation, should be reproducable (by analogy) in condensed matter systems such as Bose–Einstein condensates. One then speaks of *analogue gravity* [9]. A first important step has recently been taken in this direction, namely the realisation of an 'acoustic' black hole in such a Bose–Einstein condensate [10].

The most speculative level of interpretation is that our universe truly shares many properties with laboratory condensed matter systems. Gravity might be an emergent property much in the way that collective phenomena arise in condensed matter systems [11, 12]. There might then exist a more fundamental level of physics, which in a first approximation can simply be described by nearly-point-like objects (fermionic spinwaves) or 'atoms' of spacetime, situated in a 'fundamental' Minkowski spacetime, and with some basic velocity, probably much higher than the speed of light. The physics that we know and the geometry of our universe would then be relegated to the effective, emergent or internal level. The conclusion of the previous section would then also be valid for the relation between the 'effective' physics that we observe and the 'fundamental' level of quantum gravity: the geometrical limitation to which we, as inhabitants of the effective level, are condemned, is that there does simply not exist any direct path to the fundamental level of quantum gravity.

This idea of *emergent gravity* perhaps seems extravagant, and moreover it suffers from the same order of magnitude of extrapolation as other approaches to quantum gravity. However, it does not require the postulation of abstract new building blocks, or the development of new high-tech mathematics. What it relies on is the speculation that the principles of thermodynamics and statistical quantum physics are sufficiently universal for us to extrapolate them to the level of quantum gravity. Speculative, true, but in my opinion not as speculative as the belief that moonits or lunits can explain the atomic structure of hydrogen.

Two important observational motivations to take an emergent approach based on insights from condensed matter seriously are the following.

First, the fundamental 'quantum gravity' theory is generally assumed to have the Planck level as its characteristic scale. Expressed as a temperature, this Planck level lies at approximately 10^{32} K. On the other hand, almost all of the observable universe has temperatures that barely exceed the cosmic background radiation temperature of a few Kelvins. Even the interior of a star such as the sun is more than 20 orders of magnitude colder than the Planck temperature, while the highest energies that are planned to be produced at the Large Hadron Collider are still roughly 15 orders of magnitude lower than the Planck scale. So the degrees of freedom of quantum gravity, independently of their fundamental structure, are probably effectively frozen out in most of our universe, just like in a condensed matter system in a low-temperature laboratory.

A second motivation to take emergent gravity seriously, is that it has something sensible to say about the accelerated expansion of the universe, which seems to require the existence of some form of repulsive 'dark energy'. Dark energy and quantum gravity are probably intimately related. This can be understood as follows. First, although there is a myriad of alternative approaches to dark energy, the cosmological constant is in many ways the most sensible candidate, if only because none of the other approaches explains why the cosmological constant should be (approximately) zero, i.e., why the zero-point energy of the quantum matter fields is not huge, as a naive calculation from quantum field theory seems to indicate [14]. Second, the equations of motion for matter fields are invariant under the presence of a uniform field of constant energy such as a cosmological constant. But the gravitational sector is obviously not invariant under such a shift. That condensed matter physics in low-temperature systems can probably teach us a lot about the nature of dark energy should then not come as a great surprise. Indeed, physical states close to the zero-point state are realised and studied precisely in these low-temperature systems.

The essential argument from condensed matter physics related to dark energy is the following [13]. First note that it seems reasonable to require that the universe should be describable as an isolated system, i.e., without recurring to any external quantities such as an external pressure. This suggests the analogy with a liquid-like system, since liquids can be in a self-sustained equilibrium without external pressure. The vacuum in a condensed matter system is a dynamic entity which adapts itself to the amount of quasi-particle excitations in order to restore the equilibrium of pressures. In an isolated pure vacuum state at zero temperature, i.e. one without any quasi-particle excitations and without external pressure, the equilibrium of pressures in a liquid implies that the vacuum pressure should be zero. Hence the energy content of the vacuum must also vanish. According to this argument, such a pure vacuum state in equilibrium and in the absence of external pressure is therefore non-gravitating.

At non-zero temperatures, thermal fluctuations lead to the creation of quasi-particle excitations, and hence to a quasi-matter pressure component. In the absence of external pressure, this matter pressure is compensated by the vacuum pressure in order to restore the equilibrium. The vacuum thereby acquires a non-zero energy and becomes gravitating.

This argument is a long way from being experimentally confirmed, and still leaves many open questions. Nonetheless, from a direct extrapolation to our universe, one would expect the vacuum energy of the universe to be approximately equal to the energy content of the matter component (baryonic or 'normal' matter plus dark matter): a 50-50 distribution. Observations indicate that the distribution is in fact approximately 70% dark energy and 30% matter. By cosmological standards, 50-50 is an excellent prediction, certainly better than simply saying that the vacuum energy is a random value from a range of roughly 10^{500} possibilities, as is sometimes claimed. But nevertheless, it is an intriguing difference, especially since observations seem to indicate that the dynamical evolution of dark energy is actually towards a further increase relative to the matter component, rather than an evolution towards 50-50 as we would expect from the above argument in equilibrium.

According to the view that quantum gravity and dark energy are intimately related, a combined observational and theoretical study of dark energy, and in particular of the dynamical 'anomaly' just mentioned might provide the most valuable clue available on the road to quantum gravity. Perhaps a very indirect clue, but nevertheless one to scrutinise closely.

VII. CONCLUSION

What is then ultimately achievable and not achievable with respect to quantum gravity? According to the argument that I have set out here, the limits are quite tight. All our measuring devices are necessarily made up of 'effective' building blocks, governed by the rules of our emergent universe. No direct contact is therefore possible with the 'fundamental' level of quantum gravity, not even a direct detection of its mere presence. An exact characterisation of the building blocks of quantum gravity therefore seems hard, if not impossible. Instead, we have to look for general characteristics, for universal properties, preferrably based on concepts that are tried and tested in real physical situations. Moreover, we must recognise indirect clues about quantum gravity when we see them. Dark energy is probably exactly such a clue, and crucially: one that is so far not satisfactorily being addressed in most approaches to quantum gravity.

The road to quantum gravity is still long, and we will probably never discover in detail where it leads to. But there should be plenty of interesting clues along the journey.

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