

Quantum spacetime: what do we know?

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Abstract

I discuss nature and origin of the problem of quantum gravity. I examine the knowledge that may guide us in addressing this problem, and the reliability of such knowledge. In particular, I discuss the subtle modification of the notions of space and time engendered by general relativity, and how these might merge into quantum theory. I also present some reflections on methodological questions, and on some general issues in philosophy of science which are raised by, or a relevant for, the research on quantum gravity.

1 The incomplete revolution

Quantum mechanics (QM) and general relativity (GR) have modified our understanding of the physical world in depth. But they have left us with a general picture of the physical world which is unclear, incomplete, and fragmented. Combining what we have learn about our world from the two theories and finding a new synthesis is a major challenge, perhaps *the* major challenge, in today's fundamental physics.

The two theories have a opened a major scientific revolution, but this revolution is not completed. Most of the physics of this century has been a sequel of triumphant explorations of the new worlds opened by QM and GR. QM lead to nuclear physics, solid state physics, and particle physics. GR to relativistic astrophysics, cosmology and is today leading us towards gravitational astronomy. The urgency of applying the two theories to larger and larger domains, the momentous developments, and the dominant pragmatic attitude of the middle of this century, have obscured the fact that a consistent picture of the physical world, more or less stable for three centuries, has been lost with the advent of QM and GR. This pragmatic attitude cannot be satisfactory, or productive, in the long run. The basic Cartesian-Newtonian notions such as matter, space, time, causality, have been modified in depth. The new notions do not stay together. At the basis of our understanding of the world reigns a surprising confusion. From QM and GR we know that we live in a spacetime with quantum properties, that is, a *quantum spacetime*. But what is a quantum spacetime?

In the last decade, the attention of the theoretical physicists has been increasingly focusing on this major problem. Whatever the outcome of the enterprise, we are witnessing a large scale intellectual effort for accomplishing a major aim: completing the XXth scientific revolution, and finding a new synthesis.

In this effort, physics is once more facing *conceptual* problems: *What is matter? What is causality? What is the role of the observer in physics? What is time? What is the meaning of “being somewhere”? What is the meaning of “now”? What is the meaning of “moving”? Is motion to be defined with respect to objects or with respect to space?* These foundational questions, or sophisticated versions of these questions, were central in the thinking and in the results of Einstein, Heisenberg, Bohr, Dirac and their colleagues. But these are also precisely the same questions that Descartes, Galileo, Huygens, Newton and their contemporaries debated with passion – the questions that lead them to create modern science. For the physicists of the middle of this century, these questions were irrelevant: one does not need to worry about first principles in order to apply the Schrödinger equation to the helium atom, or to understand how a neutron star stays together. But today, if we want to find a novel picture of the world, if we want to understand what is quantum spacetime, we have to return, once again, to those foundational issues. We have to find a new answer to these questions –different from Newton’s answer– which took into account what we have learned about the world with QM and GR.

Of course, we have little, if any, direct empirical access to the regimes in which we expect genuine quantum gravitational phenomena to appear. Anything could happen at those fantastically small distance scales, far removed from our experience. Nevertheless, we do have information about quantum gravity, and we do have indications on how to search it. In fact, we are precisely in one of the very typical situations in which good fundamental theoretical physics has been working at its best in the past: we have learned two new extremely general “facts” about our world, QM and GR, and we have “just” to figure out what they imply, when taken together. The most striking advances in theoretical physics happened in situations analogous to this one.

Here, I present some reflections on these issues.¹ What have we learned about the world from QM and, especially, GR? What do we know about space, time and matter? What can we expect from a quantum theory of spacetime? To which extent does taking QM and GR into account force us to modify the notion of time? What can we already say about quantum spacetime?

I present also a few reflections on issues raised by the relation between philosophy of science and research in quantum gravity. I am not a philosopher, and I can touch philosophical issues only at the risk of being naive. I nevertheless take this risk here, encouraged by Craig Callender and Nick Huggett extremely stimulating idea of this volume. I present some methodological considerations –How shall we search? How can the present successful theories can lead us towards a theory that does not yet exist?– as well as some general consideration. In particular, I discuss the relation between physical theories that superseded each others and the attitude we may have with respect to the truth-content of a physical theory, with respect to the reality of the theoretical objects the theory postulates in particular, and to its factual statements on the world in general.

I am convinced of the reciprocal usefulness of a dialog between physics and philosophy (Rovelli 1997a). This dialog has played a major role during the other periods in which science faced foundational problems. In my opinion, most physicists underestimate the effect of their own epistemological prejudices on their research. And many philosophers underestimate the influence –positive or negative– they have on fundamental research. On the one hand, a more acute philosophical awareness would greatly help the physicists engaged in fundamental research: Newton, Heisenberg and Einstein couldn’t have done what they have done if they weren’t nurtured by (good or bad) philosophy. On the other hand, I wish contemporary philosophers concerned with science would be more interested in the ardent lava of the foundational problems science is facing today. It is here, I believe, that stimulating and vital issues lie.

¹For recent general overviews of current approaches to quantum gravity, see (Isham 1999) and (Rovelli 1999).

2 The problem

What is the task of a quantum theory of gravity, and how should we search for such a theory? The task of the search is clear and well defined. It is determined by recalling the three major steps that lead to the present problematic situation.

2.1 First step. A new actor on the stage: the field

The first step is in the works of Faraday, Maxwell and Einstein. Faraday and Maxwell have introduced a new fundamental notion in physics, the field. Faraday's book includes a fascinating chapter with the discussion of whether the field (in Faraday's terminology, the "lines of force") is "real". As far as I understand this subtle chapter (understanding Faraday is tricky: it took the genius of Maxwell), in modern terms what Faraday is asking is whether there are independent degrees of freedom in the electric and magnetic fields. A degree of freedom is a quantity that I need to specify (more precisely: whose value and whose time derivative I need to specify) in order to be able to predict univocally the future evolution of the system. Thus Faraday is asking: if we have a system of interacting charges, and we know their positions and velocities, is this knowledge sufficient to predict the future motions of the charges? Or rather, in order to predict the future, we have to specify the instantaneous configuration of the field (the fields degrees of freedom), as well? The answer is in Maxwell equations: the field has independent degrees of freedom. We cannot predict the future evolution of the system from its present state unless we know the instantaneous field configuration. Learning to use these degrees of freedom lead to radio, TV and cellular phone.

To which physical entity do the degrees of freedom of the electromagnetic field refer? This was one of the most debated issues in physics towards the end of last century. The electromagnetic waves have aspects in common with water waves, or with sound waves, which describe vibrations of some material medium. The natural interpretation of the electromagnetic field was that it too describes the vibrations of some material medium – for which the name "ether" was chosen. A strong argument supports this idea: The wave equations for water or sound waves fail to be Galilean invariant. They do so because they describe propagation over a medium (water, air) whose state of motion breaks Galilean invariance and defines a preferred reference frame. Maxwell equations break Galilean invariance as well and it was thus natural to hypothesize a material medium determining the preferred reference frame. But a convincing dynamical theory of the ether compatible with the various experiments (for instance on the constancy of the speed of light) could not be found.

Rather, physics took a different course. Einstein *believed* Maxwell theory as a fundamental theory and *believed* the Galilean insight that velocity is relative and inertial system are equivalent. Merging the two, he found special relativity. A main result of special relativity is that the field cannot be regarded as describing vibrations of underlying matter. The idea of the ether is abandoned, and *the field has to be taken seriously as elementary constituent of reality*. This is a major change from the ontology of Cartesian-Newtonian physics. In the best description we can give of the physical world, there is a new actor: the field. The electromagnetic field can be described by the Maxwell potential $A_\mu(x)$, $\mu = 0, 1, 2, 3$. The entity described by $A_\mu(x)$ (more precisely, by a gauge-equivalent class of $A_\mu(x)$'s) is one of the elementary constituents of the physical world, according to the best conceptual scheme physics has find, so far, for grasping our world.

2.2 Second step. Dynamical entities have quantum properties

The second step (out of chronological order) is the replacement of the mechanics of Newton, Lagrange and Hamilton with quantum mechanics (QM). As did classical mechanics, QM provides a very general framework. By formulating a specific dynamical theory within this framework, one has a number of important physical consequences, substantially different from what is implied by the Newtonian scheme. Evolution is probabilistically determined only; some physical quantities can take certain discrete values only (are “quantized”); if a system can be in a state A , where a physical quantity q has value a , as well as in state B , where q has value b , then the system can also be in states (denoted $\Psi = c_a A + c_b B$) where q , has value a with probability $|c_a|^2/(|c_a|^2 + |c_b|^2)$, or, alternatively, b with probability $|c_b|^2/(|c_a|^2 + |c_b|^2)$ (superposition principle); conjugate variables cannot be assumed to have value at the same time (uncertainty principle); and what we can say about the properties that the system will have the-day-after-tomorrow is not determined just by what we can say about the system today, but also on what we will be able to say about the system tomorrow. (Bohr would had simply said that observations affect the system. Formulations such as Bohm’s or consistent histories force us to use intricate wording for naming the same physical fact.)

The formalism of QM exists in a number of more or less equivalent versions: Hilbert spaces and self-adjoint observables, Feynman’s sum over histories, algebraic formulation, and others. Often, we are able to translate from one formulation to another. However, often we cannot do easily in one formulation, what we can do in another.

QM is not the theory of micro-objects. It is our best form of mechanics. If quantum mechanics failed for macro-objects, we would have detected the boundary of its domain of validity in mesoscopic physics. We haven’t.² The classical regime raises some problems (why effects of macroscopic superposition are difficult to detect?). Solving these problems requires good understanding of physical decoherence and perhaps more. But there is no reason to doubt that QM represents a deeper, not a shallower level of understanding of nature than classical mechanics. Trying to resolve the difficulties in our grasping of our quantum world by resorting to old classical intuition is just lack of courage. We have learned that the world has quantum properties. This discovery will stay with us, like the discovery that velocity is only relational or like the discovery that the Earth is not the center of the universe.

The empirical success of QM is immense. Its physical obscurity is undeniable. Physicists do not yet agree on what QM precisely says about the world (the difficulty, of course, refers to physical meaning of notions such as “measurement”, “history”, “hidden variable”, ...). It is a bit like the Lorentz transformations before Einstein: correct, but what do they mean?

In my opinion, what QM means is that the contingent (variable) properties of any physical system, or the state of the system, are relational notion which only make sense when referred to a second physical system. I have argued for this thesis in (Rovelli 1996, Rovelli 1998). However, I will not enter in this discussion here, because the issue of the interpretation of QM has no direct connection with quantum gravity. Quantum gravity and the interpretation of QM are two major but (virtually) completely unrelated problems.

QM was first developed for systems with a finite number of degrees of freedom. As discussed in the previous section, Faraday, Maxwell and Einstein had introduced the field, which has an infinite number of degrees of freedom. Dirac put the two ideas together. He *believed* quantum mechanics

²Following Roger Penrose’s opposite suggestions of a failure of conventional QM induced by gravity (Penrose 1995), Antony Zeilinger is preparing an experiment to test such a possible failure of QM (Zeilinger 1997). It would be very exciting if Roger turned out to be right, but I am afraid that QM, as usual, will win.

and he *believed* Maxwell’s field theory much beyond their established domain of validity (respectively: the dynamics of finite dimensional systems, and the classical regime) and constructed quantum field theory (QFT), in its first two incarnations, the quantum theory of the electromagnetic field and the relativistic quantum theory of the electron. In this exercise, Dirac derived the existence of the photon just from Maxwell theory and the basics of QM. Furthermore, by just *believing* special relativity and *believing* quantum theory, namely assuming their validity far beyond their empirically explored domain of validity, he predicted the existence of antimatter.

The two embryonal QFT’s of Dirac were combined in the fifties by Feynman and his colleagues, giving rise to quantum electrodynamics, the first nontrivial interacting QFT. A remarkable picture of the world was born: quantum fields over Minkowski space. Equivalently, à la Feynman: the world as a quantum superposition of histories of real and virtual interacting particles. QFT had ups and downs, then triumphed with the standard model: a consistent QFT for all interactions (except gravity), which, in principle, can be used to predict anything we can measure (except gravitational phenomena), and which, in the last fifteen years has received nothing but empirical verifications.

2.3 Third step. The stage becomes an actor

Descartes, in *Le Monde*, gave a fully relational definition of localization (space) and motion (on the relational/substantialist issue, see Earman and Norton 1987, Barbour 1989, Earman 1989, Rovelli 1991a, Belot 1998). According to Descartes, there is no “empty space”. There are only objects, and it makes sense to say that an object A is contiguous to an object B. The “location” of an object A is the set of the objects to which A is contiguous. “Motion” is change in location. That is, when we say that A moves we mean that A goes from the contiguity of an object B to the contiguity of an object C³. A consequence of this relationalism is that there is no meaning in saying “A moves”, except if we specify with respect to which other objects (B, C,...) it is moving. Thus, there is no “absolute” motion. This is the same definition of space, location, and motion, that we find in Aristotle.⁴

Relationalism, namely the idea that motion can be defined only in relation to other objects, should not be confused with Galilean relativity. Galilean relativity is the statement that “rectilinear uniform motion” is a priori indistinguishable from stasis. Namely that velocity (but just velocity!), is relative to other bodies. Relationalism holds that *any* motion (however zigzagging) is a priori indistinguishable from stasis. The very formulation of Galilean relativity requires a nonrelational definition of motion (“rectilinear and uniform” with respect to what?).

³“We can say that movement is the transference of one part of matter or of one body, from the vicinity of those bodies immediately contiguous to it, and considered at rest, into the vicinity of some others”, (Descartes, *Principia Philosophiae*, Sec II-25, pg 51).

⁴Aristotle insists on this point, using the example of the river that moves with respect to the ground, in which there is a boat that moves with respect to the water, on which there is a man that walks with respect to the boat Aristotle’s relationalism is tempered by the fact that there is, after all, a preferred set of objects that we can use as universal reference: the Earth at the center of the universe, the celestial spheres, the fixed stars. Thus, we can say, if we desire so, that something is moving “in absolute terms”, if it moves with respect to the Earth. Of course, there are *two* preferred frames in ancient cosmology: the one of the Earth and the one of the fixed stars; the two rotates with respect to each other. It is interesting to notice that the thinkers of the middle ages did not miss this point, and discussed whether we can say that the stars rotate around the Earth, rather than being the Earth that rotates under the *fixed* stars. Buridan concluded that, on ground of reason, in no way one view is more defensible than the other. For Descartes, who writes, of course, after the great Copernican divide, the Earth is not anymore the center of the Universe and cannot offer a naturally preferred definition of stillness. According to malignants, Descartes, fearing the Church and scared by what happened to Galileo’s stubborn defense of the idea that “the Earth moves”, resorted to relationalism, in *Le Monde*, precisely to be able to hold Copernicanism without having to commit himself to the absolute motion of the Earth!

Newton took a fully different course. He devotes much energy to criticise Descartes' relationalism, and to introduce a different view. According to him, *space* exists. It exists even if there are no bodies in it. Location of an object is the part of space that the object occupies. Motion is change of location.⁵ Thus, we can say whether an object moves or not, irrespectively from surrounding objects. Newton argues that the notion of absolute motion is necessary for constructing mechanics. His famous discussion of the experiment of the rotating bucket in the *Principia* is one of the arguments to prove that motion is absolute.

This point has often raised confusion because one of the corollaries of Newtonian mechanics is that there is no detectable preferred referential frame. Therefore the notion of *absolute velocity* is, actually, meaningless, in Newtonian mechanics. The important point, however, is that in Newtonian mechanics velocity is relative, but any other feature of motion is not relative: it is absolute. In particular, acceleration is absolute. It is acceleration that Newton needs to construct his mechanics; it is acceleration that the bucket experiment is supposed to prove to be absolute, against Descartes. In a sense, Newton overdid a bit, introducing the notion of absolute position and velocity (perhaps even just for explanatory purposes?). Many people have later criticised Newton for his unnecessary use of absolute position. But this is irrelevant for the present discussion. The important point here is that Newtonian mechanics requires absolute acceleration, against Aristotle and against Descartes. Precisely the same does special relativistic mechanics.

Similarly, Newton introduce absolute time. Newtonian space and time or, in modern terms, spacetime, are like a *stage* over which the action of physics takes place, the various dynamical entities being the actors.

The key feature of this stage, Newtonian spacetime, is its metrical structure. Curves have length, surfaces have area, regions of spacetime have volume. Spacetime points are at fixed *distance* the one from the other. Revealing, or measuring, this distance, is very simple. It is sufficient to take a rod and put it between two points. Any two points which are one rod apart are at the same distance. Using modern terminology, physical space is a linear three-dimensional (3d) space, with a preferred metric. On this space there exist preferred coordinates x^i , $i = 1, 2, 3$, in terms of which the metric is just δ_{ij} . Time is described by a single variable t . The metric δ_{ij} determines lengths, areas and volumes and defines what we mean by straight lines in space. If a particle deviates with respect to this straight line, it is, according to Newton, accelerating. It is not accelerating with respect to this or that dynamical object: it is accelerating in absolute terms.

Special relativity changes this picture only marginally, loosing up the strict distinction between the "space" and the "time" components of spacetime. In Newtonian spacetime, space is given by fixed 3d planes. In special relativistic spacetime, which 3d plane you call space depends on your state of motion. Spacetime is now a 4d manifold M with a flat Lorentzian metric $\eta_{\mu\nu}$. Again, there are preferred coordinates x^μ , $\mu = 0, 1, 2, 3$, in terms of which $\eta_{\mu\nu} = \text{diag}[1, -1, -1, -1]$. This tensor, $\eta_{\mu\nu}$, enters all physical equations, representing the determinant influence of the stage and of its metrical properties on the motion of anything. Absolute acceleration is deviation of the world line of a particle from the straight lines defined by $\eta_{\mu\nu}$. The only essential novelty with special relativity is that the "dynamical objects", or "bodies" moving over spacetime now include the fields as well. Example: a violent burst of electromagnetic waves coming from a distant supernova has *traveled across space* and has reached our instruments. For the rest, the Newtonian construct of a fixed background stage over which physics happen is not altered by special relativity.

⁵ "So, it is necessary that the definition of places, and hence local motion, be referred to some motionless thing such as extension alone or *space*, in so far as space is seen truly distinct from moving bodies", (Newton *De gravitatione et Aequipondio Fluidorum* 89-156). Compare with the quotation of Descartes in the footnote above.

The profound change comes with general relativity (GR). The central discovery of GR, can be enunciated in three points. One of these is conceptually simple, the other two are tremendous. First, the gravitational force is mediated by a field, very much like the electromagnetic field: the gravitational field. Second, Newton’s *spacetime*, the background stage that Newton introduced introduced, against most of the earlier European tradition, *and the gravitational field, are the same thing*. Third, the dynamics of the gravitational field, of the other fields such as the electromagnetic field, and any other dynamical object, is fully relational, in the Aristotelian-Cartesian sense. Let me illustrate these three points.

First, the gravitational field is represented by a field on spacetime, $g_{\mu\nu}(x)$, just like the electromagnetic field $A_\mu(x)$. They are both very concrete entities: a strong electromagnetic wave can hit you and knock you down; and so can a strong gravitational wave. The gravitational field has independent degrees of freedom, and is governed by dynamical equations, the Einstein equations.

Second, the spacetime metric $\eta_{\mu\nu}$ disappears from all equations of physics (recall it was ubiquitous). At its place –we are instructed by GR– we must insert the gravitational field $g_{\mu\nu}(x)$. This is a spectacular step: Newton’s background spacetime was nothing but the gravitational field! The stage is promoted to be one of the actors. Thus, in all physical equations one now sees the direct influence of the gravitational field. How can the gravitational field determine the metrical properties of things, which are revealed, say, by rods and clocks? Simply, the inter-atomic separation of the rods’ atoms, and the frequency of the clock’s pendulum are determined by explicit couplings of the rod’s and clock’s variables with the gravitational field $g_{\mu\nu}(x)$, which enters the equations of motion of these variables. Thus, any measurement of length, area or volume is, in reality, a measurement of features of the gravitational field.

But what is really formidable in GR, the truly momentous novelty, is the third point: the Einstein equations, as well as *all other equations of physics* appropriately modified according to GR instructions, are fully relational in the Aristotelian-Cartesian sense. This point is independent from the previous one. Let me give first a conceptual, then a technical account of it.

The point is that the only physically meaningful definition of location that makes physical sense within GR is relational. GR describes the world as a set of interacting fields and, possibly, other objects. One of these interacting fields is $g_{\mu\nu}(x)$. Motion can be defined only as positioning and displacements of these dynamical objects relative to each other (for more details on this, see Rovelli 1991a and especially 1997a).

To describe the motion of a dynamical object, Newton had to assume that acceleration is absolute, namely it is not relative to this or that other dynamical object. Rather, it is relative to a background space. Faraday Maxwell and Einstein extended the notion of “dynamical object”: the stuff of the world is fields, not just bodies. Finally, GR tells us that the background space is itself one of these fields. Thus, the circle is closed, and we are back to relationalism: Newton’s motion with respect to space is indeed motion with respect to a dynamical object: the gravitational field.

All this is coded in the active diffeomorphism invariance (diff invariance) of GR.⁶ Because active

⁶Active diff invariance should not be confused with passive diff invariance, or invariance under change of coordinates. GR can be formulated in a coordinate free manner, where there are no coordinates, and no changes of coordinates. In this formulation, there field equations are *still* invariant under active diffs. Passive diff invariance is a property of a formulation of a dynamical theory, while active diff invariance is a property of the dynamical theory itself. A field theory is formulated in manner invariant under passive diffs (or change of coordinates), if we can change the coordinates of the manifold, re-express all the geometric quantities (dynamical *and non-dynamical*) in the new coordinates, and the form of the equations of motion does not change. A theory is invariant under active diffs, when a smooth displacement of the dynamical fields (*the dynamical fields alone*) over the manifold, sends solutions of the equations of motion into solutions of the equations of motion. Distinguishing a truly dynamical field, namely a field with independent degrees of freedom,

diff invariance is a gauge, the physical content of GR is expressed only by those quantities, derived from the basic dynamical variables, which are fully independent from the points of the manifold.

In introducing the background stage, Newton introduced two structures: a spacetime manifold, and its non-dynamical metric structure. GR gets rid of the non-dynamical metric, by replacing it with the gravitational field. More importantly, it gets rid of the manifold, by means of active diff invariance. In GR, the objects of which the world is made do not live over a stage and do not live on spacetime: they live, so to say, over each other's shoulders.

Of course, nothing prevents us, if we wish to do so, from singling out the gravitational field as “the more equal among equals”, and declaring that location is absolute in GR, because it can be defined with respect to it. But this can be done within any relationalism: we can always single out a set of objects, and declare them as not-moving by definition⁷. The problem with this attitude is that it fully misses the great Einsteinian insight: that Newtonian spacetime is just one field among the others. More seriously, this attitude sends us into a nightmare when we have to deal with the motion of the gravitational field itself (which certainly “moves”: we are spending millions for constructing gravity wave detectors to detect its tiny vibrations). There is no absolute referent of motion in GR: the dynamical fields “move” with respect to each other.

Notice that the third step was not easy for Einstein, and came later than the previous two. Having well understood the first two, but still missing the third, Einstein actively searched for non-generally covariant equations of motion for the gravitational field between 1912 and 1915. With his famous “hole argument” he had convinced himself that generally covariant equations of motion (and therefore, in this context, active diffeomorphism invariance) would imply a truly dramatic revolution with respect to the Newtonian notions of space and time (on the hole argument, see Earman and Norton 1987, Rovelli 1991a, Belot 1998). In 1912 he was not able to take this profoundly revolutionary step (Norton 1984, Stachel 1989). In 1915 he took this step, and found what Landau calls “the most beautiful of the physical theories”.

2.4 Bringing the three steps together

At the light of the three steps illustrated above, the task of quantum gravity is clear and well defined. He have learned from GR that spacetime is a dynamical field among the others, obeying dynamical equations, and having independent degrees of freedom. A gravitational wave is extremely similar to an electromagnetic wave. We have learned from QM that every dynamical object has quantum properties, which can be captured by appropriately formulating its dynamical theory within the general scheme of QM.

Therefore, spacetime itself must exhibit quantum properties. Its properties, including the metrical properties it defines, must be represented in quantum mechanical terms. Notice that the strength of this “therefore” derives from the confidence we have in the two theories, QM and GR.

Now, there is nothing in the basics of QM which contradicts the physical ideas of GR. Similarly, there is nothing in the basis of GR that contradicts the physical ideas of QM. Therefore, there is no a priori impediment in searching for a quantum theory of the gravitational fields, that is, a quantum theory of spacetime. The problem is (with some qualification) rather well posed: is there a quantum

from a nondynamical field disguised as dynamical (such as a metric field g with the equations of motion $\text{Riemann}[g]=0$) might require a detailed analysis (for instance, hamiltonian) of the theory.

⁷Notice that Newton, in the passage quoted in the footnote above argues that motion must be defined with respect to motionless space “in so far as space is seen truly distinct from moving bodies”. That is: motion should be defined with respect to something that has no dynamics.

theory (say, in one formulation, a Hilbert space H , and a set of self-adjoint operators) whose classical limit is GR?

On the other hand, all previous applications of QM to *field* theory, namely conventional QFT's, rely heavily on the existence of the “stage”, the fixed, non-dynamical, background metric structure. The Minkowski metric $\eta_{\mu\nu}$ is essentially for the construction of a conventional QFT (it enters everywhere; for instance, in the canonical commutation relations, in the propagator, in the Gaussian measure . . .). We certainly cannot simply replace $\eta_{\mu\nu}$ with a quantum field, because all equations become nonsense.

Therefore, to search for a quantum theory of gravity, we have two possible directions. One possibility is to “disvalue” the GR conceptual revolution, reintroduce a background spacetime with a non-dynamical metric $\eta_{\mu\nu}$, expand the gravitational field $g_{\mu\nu}$ as $g_{\mu\nu} = \eta_{\mu\nu} + \text{fluctuations}$, quantize only the fluctuations, and hope to recover the full of GR somewhere down the road. This is the road followed for instance by perturbative string theory.

The second direction is to be faithful to what we have learned about the world so far. Namely to the QM and the GR insights. We must then search a QFT that, genuinely, does not require a background space to be defined. But the last three decades have been characterized by the great success of conventional QFT, which neglects GR and is based on the existence of a background spacetime. We live in the aftermath of this success. It is not easy to get out from the mental habits and from the habits to the technical tools of conventional QFT. Still, this is necessary if we want to build a QFT which fully incorporates active diff invariance, and in which localization is fully relational. In my opinion, this is the right way to go.

3 Quantum spacetime

3.1 Space

Spacetime, or the gravitational field, is a dynamical entity (GR). All dynamical entities have quantum properties (QM). Therefore spacetime is a quantum object. It must be described (picking one formulation of QM, but keeping in mind that others may be equivalent, or more effective) in terms of states Ψ in a Hilbert space. Localization is relational. Therefore these states cannot represent quantum excitations localized in some space. They must define space themselves. They must be quantum excitations “of” space, not “in” space. Physical quantities in GR, that capture the true degrees of freedom of the theory are invariant under active diff. Therefore the self-adjoint operators that correspond to physical (predictable) observables in quantum gravity must be associated to diff invariant quantities.

Examples of diff-invariant geometric quantities are physical lengths, areas, volumes, or time intervals, of regions determined by dynamical physical objects. These must be represented by operators. Indeed, a measurement of length, area or volume is a measurement of features of the gravitational field. If the gravitational field is a quantum field, then length, area and volume are quantum observables. If the corresponding operator has discrete spectrum, they will be quantized, namely they can take certain discrete values only. In this sense we should expect a discrete geometry. This discreteness of the geometry, implied by the conjunction of GR and QM is very different from the naive idea that the world is made by discrete bits of something. It is like the discreteness of the quanta of the excitations of an harmonic oscillator. A generic state of spacetime will be a continuous quantum superposition of states whose geometry has discrete features, not a collection of elementary discrete objects.

A concrete attempt to construct such a theory, is loop quantum gravity. I refer the reader to Rovelli (1997b) for an introduction to the theory, an overview of its structure and results, and full references.

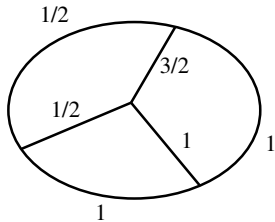


Figure 1: A simple spin network.

Here, I present only a few remarks on the theory. Loop quantum gravity is a rather straightforward application of quantum mechanics to hamiltonian general relativity. It is a QFT in the sense that it is a quantum version of a field theory, or a quantum theory for an infinite number of degrees of freedom, but it is profoundly different from conventional, non-general-relativistic QFT theory. In conventional QFT, states are quantum excitations of a field over Minkowski (or over a curved) spacetime. In loop quantum gravity, the quantum states turn out to be represented by (suitable linear combinations of) spin networks (Rovelli and Smolin 1995a, Baez 1996, Smolin 1997). A spin network is an abstract graphs with links labeled by half-integers. See Figure 1.

Intuitively, we can view each node of the graph as an elementary “quantum chunk of space”. The links represent (transverse) surfaces separating the quanta of space. The half-integers associated to the links determine the (quantized) area of these surfaces. The spin network represent relational quantum states: they are not located in a space. Localization must be defined in relation to them. For instance, if we have, say, a matter quantum excitation, this will be located on the spin network; while the spin network itself is not located anywhere.

The operators corresponding to area and volume have been constructed in the theory, simply by starting from the classical expression for the area in terms of the metric, then replacing the metric with the gravitational field (this is the input of GR) and then replacing the gravitational field with the corresponding quantum field operator (this is the input of QM). The construction of these operators requires appropriate generally covariant regularization techniques, but no renormalization: no infinities appear. The spectrum of these operators has been computed and turns out to be discrete (Rovelli and Smolin 1995b, Ashtekar Lewandowski 1997a, 1997b). Thus, loop quantum gravity provides a family of precise quantitative predictions: the quantized values of area and volume. For instance, the (main sequence) of the spectrum of the area is

$$A = 8 \pi \hbar G \sum_{i=1,n} \sqrt{j_i(j_i + 1)}$$

where $(j_i) = (j_1 \dots j_n)$ is any finite sequence of half integers. This formula gives the area of a surface pinched by n links of a spin network state. The half integers $j_1 \dots j_n$ are ones associated with the n links that pinch the surface. This illustrates how the links of the spin network states can be viewed as transversal “quanta of area”. The picture of macroscopic physical space that emerges is then that of a tangle of one-dimensional intersecting quantum excitation, called the weave (Ashtekar Rovelli and Smolin 1992). Continuous space is formed by the weave in the same manner in which the continuous 2d surface of a T-shirt is formed by weaved threads.

3.2 Time

The aspect of the GR's relationalism that concerns space was largely anticipated by the earlier European thinking. Much less so (as far as I am aware) was the aspect of this relationalism that concerns time. GR's treatment of time is surprising, difficult to fully appreciate, and hard to digest. The time of our perceptions is very different from the time that theoretical physics finds in the world as soon as one exits the minuscule range of physical regimes we are accustomed to. We seem to have a very special difficulty in being open minded about this particular notion.

Already special relativity teaches us something about time which many of us have difficulties to accept. According to special relativity, there is absolute no meaning in saying "right now on Andromeda". There is no physical meaning in the idea of "the state of the world right now", because which set of events we consider as "now" is perspectival. The "now" on Andromeda for me might correspond to "a century ago" on Andromeda for you. Thus, there is no single well defined universal time in which the history of the universe "happens". The modification of the concept of time introduced by GR is much deeper. Let me illustrate this modifications.

Consider a simple pendulum described by a variable Q . In Newtonian mechanics, the motion of the pendulum is given by the evolution of Q in time, namely by $Q(T)$, which is governed by the equation of motion, say $\ddot{Q} = -\omega Q$, which has (the two-parameter family of) solutions $Q(T) = A \sin(\omega T + \phi)$. The state of the pendulum at time T can be characterized by its position and velocity. From these two, we can compute A and ϕ and therefore $Q(T)$ at any T . From the physical point of view, we are really describing a situation in which there are *two* physical objects: a pendulum, whose position is Q , and a clock, indicating T . If we want to take data, we have to repeatedly observe Q and T . Their *relation* will be given by the equation above. The relation can be represented (for given A and ϕ) by a line in the (Q, T) plane.

In Newtonian terms, time flows in its absolute way, the clock is just a devise to keep track of it, and the dynamical system is formed by the pendulum alone. But we can view the same physical situation from a different perspective. We can say that we have a physical system formed by the clock and the pendulum together and view the dynamical system as expressing the relative motion of one with respect to the other. This is precisely the perspective of GR: to express the relative motion of the variables, with respect to each other, in a "democratic" fashion.

To do that, we can introduce an "arbitrary parameter time" τ as a coordinate on the line in the (Q, T) plane. (But keep in mind that the physically relevant information is in the line, not in its coordinatization!). Then the line is represented by two functions, $Q(\tau)$ and $T(\tau)$, but a reparametrization of τ in the two functions is a gauge, namely it does not modify the physics described. Indeed, τ does not correspond to anything observable, and the equations of motion satisfied by $Q(\tau)$ and $T(\tau)$ (easy to write, but I will not write them down here) will be invariant under arbitrary reparametrizations of τ . Only τ -independent quantities have physical meaning.

This is precisely what happens in GR, where the "arbitrary parameters", analogous to the τ of the example, are the coordinates x^μ . Namely, the spatial coordinate \vec{x} and the temporal coordinate t . These have no physical meaning whatsoever in GR: the connection between the theory and the measurable physical quantities that the theory predict is only via quantities independent from \vec{x} and t . Thus, \vec{x} and t in GR have a very different physical meaning than their homonymous in non-general-relativistic physics. The later correspond to readings on rods and clocks. The former, correspond to nothing at all. Recall that Einstein described his great intellectual struggle to find GR as "understanding the meaning of the coordinates".

In the example, the invariance of the equations of motion for $Q(\tau)$ and $T(\tau)$ under reparametriza-

tion of τ , implies that if we develop the Hamiltonian formalism in τ we obtain a constrained system with a (weakly) vanishing hamiltonian. This is because the hamiltonian generates evolutions in τ , evolution in τ is a gauge, and the generators of gauge transformations are constraints. In canonical GR we have precisely the same situation: the hamiltonian vanishes, the constraints generate evolution in t , which is unobservable – it is gauge. GR does not describe evolution in time: it describes the relative evolution of many variables with respect to each other. All these variables are democratically equal: there isn't a preferred one that “is the true time”. This is the temporal aspect of GR's relationalism.

A large part of the machinery of theoretical physics relies on the notion of time (on the different meanings of time in different physical theories, see Rovelli 1995). A theory of quantum gravity should do without. Fortunately, many essential tools that are usually introduced using the notion of time can equally well be defined without mentioning time at all. This, by the way, shows that time plays a much weaker role in the structure of theoretical physics than what is mostly assumed. Two crucial examples are “phase space” and “state”.

The phase space is usually introduced in textbooks as the space of the states of the systems “at a given time”. In a general relativistic context, this definition is useless. However, it is known since Lagrange that there is an alternative, equivalent, definition of phase space as the space of the solutions of the equations of motion. This definition does not require that we know what we mean by time. Thus, in the example above the phase space can be coordinatized by A and ϕ , which coordinatize the space of the solutions of the equations of motion.

A time independent notion of “state” is then provided by a point of this phase space, namely by a particular solution of the equations of motion. For instance, for an oscillator a “state”, in this atemporal sense, is characterized by an amplitude A and a phase ϕ . Notice that given the (time-independent) state (A and ϕ), we can compute any observable: in particular, the value Q_T of Q at any desired T . Notice also that Q_T is independent from τ . This point often raises confusion: one may think that if we restrict to τ -independent quantities then we cannot describe evolution. This is wrong: the true evolution is the relation between Q and T , which is τ -independent. This relation is expressed in particular by the value (let us denote it Q_T) of Q at a given T . Q_T is given, obviously, by

$$Q_T(A, \phi) = A \sin(\omega T + \phi).$$

This can be seen as a one-parameter (the parameter is T) family of observables on the gauge invariant phase space coordinatized by A and ϕ . Notice that this is a perfectly τ -independent expression. In fact, an explicit computation shows that the Poisson bracket between Q_T and the hamiltonian constraint that generates evolution in τ vanishes.

This time independent notion of states is well known in its quantum mechanical version: it is the Heisenberg state (as opposed to Schrödinger state). Similarly, the operator corresponding to the observable Q_T is the Heisenberg operator that gives the value of Q at T . The Heisenberg and Schrödinger pictures are equivalent if there is a normal time evolution in the theory. In the absence of a normal notion of time evolution, the Heisenberg picture remains viable, the Schrödinger picture becomes meaningless.⁸ In quantum gravity, only the Heisenberg picture makes sense (Rovelli 1991c, 1991d).

⁸In the first edition of his celebrated book on quantum mechanics, Dirac used Heisenberg states (he calls them relativistic). In later editions, he switched to Schrödinger states, explaining in a preface that it was easier to calculate with these, but it was nevertheless a pity to give up the Heisenberg states, which are more fundamental. In what was perhaps his last public seminar, in Sicily, Dirac used just a single transparency, with just one sentence: “The Heisenberg picture is the right one”.

In classical GR, a point in the physical phase space, or a state, is a solution of Einstein equations, up to active diffeomorphisms. A state represents a “history” of spacetime. The quantity that can be univocally predicted are the ones that are independent from the coordinates, namely that are invariant under diffeomorphisms. These quantities have vanishing Poisson brackets with all the constraints. Given a state, the value of each of these quantities is determined. In quantum gravity, a quantum state represents a “history” of quantum spacetime. The observables are represented by operators that commute with *all* the quantum constraints. If we know the quantum state of spacetime, we can then compute the expectation value of any diffeomorphism invariant quantity, by taking the mean value of the corresponding operator. The observable quantities in quantum gravity are precisely the same as in classical GR.

Some of these quantities may express the value of certain variables “when and where” certain other quantities have certain given values. They are the analog of the reparametrization invariant observable Q_T in the example above. These quantities describe evolution in a way which is fully invariant under the parameter time, unphysical gauge evolution (Rovelli 1991d, 1991e). The corresponding quantum operators are Heisenberg operators. There is no Schrödinger picture, because there is no unitary time evolution. There is no need to expect or to search for unitary time evolution in quantum gravity, because there is no time in which we should have unitary evolution. A prejudice hard to die wants that unitary evolution is required for the consistency of the probabilistic interpretation. This idea is wrong.

What I have described is the general form that one may expect a quantum theory of GR to have. I have used the Hilbert space version of QM; but this structure can be translated in other formulations of QM. Of course, physics works then with dirty hands: gauge dependent quantities, approximations, expansions, unphysical structures, and so on. A fully satisfactory construction of the above does not yet exist. A concrete attempt to construct the physical states and the physical observables in loop quantum gravity is given by the spin foam models approach, which is the formulation one obtains by starting from loop quantum gravity and constructing a Feynman sum over histories (Reisenberger Rovelli 1997, Baez 1998, Barret and Crane 1998). See (Baez 1999) in this volume for more details on ideas underlying these developments.

In quantum gravity, I see no reason to expect a fundamental notion of time to play any role. But the *nostalgia for time* is hard to resist. For technical as well as for emotional reasons. Many approaches to quantum gravity go out of their way to reinsert in the theory what GR is teaching us we should abandon: a preferred time. The time “along which” things happen is a notion which makes sense only for describing a limited regime of reality. This notion is meaningless already in the (gauge invariant) general relativistic classical dynamics of the gravitational field. At the fundamental level, we should, simply, forget time.

3.3 Glimpses

I close this section by briefly mentioning two more speculative ideas. One regards the emergence of time, the second the connection between the relationalism in GR and the relationalism in QM.

(i) In the previous section, I have argued that we should search for a quantum theory of gravity in which there is no independent time variable “along” which dynamics “happens”. A problem left open by this position is to understand the emergence of time in our world, with its features, which are familiar to us. An idea discussed in (Rovelli 1993a 1993b, Connes and Rovelli 1994) is that the notion of time isn’t dynamical but rather thermodynamical. We can never give a complete account of the state of a system in a field theory (we cannot access the infinite amount of data needed to

completely characterize a state). Therefore we have at best a statistical description of the state. Given a statistical state of a generally covariant system, a notion of a flow (more precisely a one-parameter group of automorphisms of the algebra of the observables) follows immediately. In the quantum context, this corresponds to the Tomita flow of the state. The relation between this flow and the state is the relation between the time flow generated by the hamiltonian and a Gibbs state: the two essentially determine each other. In the absence of a preferred time, however, any statistical state selects its own notion of statistical time. This statistical time has a striking number of properties that allow us to identify it with the time of non-general relativistic physics. In particular, a Schrödinger equation with respect to this statistical time holds, in an appropriate sense. In addition, the time flows generated by different states are equivalent up to inner automorphisms of the observable algebra and therefore define a common “outer” flow: a one parameter group of outer automorphisms. This determines a state independent notion of time flow, which shows that a general covariant QFT has an intrinsic “dynamics”, even in the absence of a hamiltonian and of a time variable. The suggestion is therefore that the temporal aspects of our world have statistical and thermodynamical origin, rather than dynamical. “Time” is ignorance: a reflex of our incomplete knoweldge of the state of the world.

(ii) What is QM really telling us about our world? In (Rovelli 1996, 1998), I have argued that what QM is telling us is that the contingent properties of any system –or: the state of any system– must be seen as relative to a second physical system, the “observing system”. That is, quantum state and values that an observables take are relational notions, in the same sense in which velocity is relational in classical mechanics (it is a relation between two systems, not a properties of a single system). I find the consonance between this relationalism in QM and the relationalism in GR quite striking. It is tempting to speculate that they are related. Any quantum interaction (or quantum measurement) involving a system A and a system B requires A and B to be spatiotemporally contiguous. Viceversa, spatiotemporal contiguity, which is the grounding of the notions of space and time (derived and dynamical, not primary, in GR) can only be verified quantum mechanically (just because any interaction is quantum mechanical in nature). Thus, the net of the quantum mechanical elementary interactions and the spacetime fabric are actually the same thing. Can we build a consistent picture in which we take this fact into account? To do that, we must identify two notions: the notion of a spatiotemporal (or spatial?) region, and the notion of quantum system. For intriguing ideas in this direction, see (Crane 1991) and, in this volume, (Baez 1999).

4 Considerations on method and content

4.1 Method

Part of the recent reflection about science has emphasized the “non cumulative” aspect in the development of scientific knowledge. According to this view, the evolution of scientific theories is marked by large or small breaking points, in which, to put it very crudely, the empirical facts are just reorganized within new theories. These would be to some extent “incommensurable” with respect to their antecedent. These ideas have influenced physicists.

The reader has remarked that the discussion of quantum gravity I have given above assumes a different reading of the evolution of scientific knowledge. I have based the above discussion on quantum gravity on the idea that the central physical ideas of QM and GR represent our best guide for accessing the extreme and unexplored territories of the quantum-gravitational regime. In my opinion, the emphasis on the incommensurability between theories has probably clarified an important aspect of science, but risks to obscure something of the internal logic according to which, historically, physics

finds knowledge. There is a subtle, but definite, cumulative aspect in the progress of physics, which goes far beyond the growth of validity and precision of the empirical content of the theories. In moving from a theory to the theory that supersedes it, we do not save just the verified empirical content of the old theory, but more. This “more” is a central concern for good physics. It is the source, I think, of the spectacular and undeniable predicting power of theoretical physics.

Let me illustrate the point I am trying to make with a historical case. There was a problem between Maxwell equations and Galilei transformations. There were two obvious way out. To disvalue Maxwell theory, degrading it to a phenomenological theory of some yet-to-be-discovered ether’s dynamics. Or to disvalue Galilean invariance, accepting the idea that inertial systems are not equivalent in electromagnetic phenomena. Both ways were pursued at the end of the century. Both are sound applications of the idea that a scientific revolution may very well change in depth what old theories teach us about the world. Which of the two ways did Einstein take?

None of them. For Einstein, Maxwell theory was a source of great awe. Einstein rhapsodizes about his admiration for Maxwell theory. For him, Maxwell had opened a new window over the world. Given the astonishing success of Maxwell theory, empirical (electromagnetic waves), technological (radio) as well as conceptual (understanding what is light), Einstein admiration is comprehensible. But Einstein had a tremendous respect for Galileo’s insight as well. Young Einstein was amazed by a book with Huygens’ derivation of collision theory virtually out of Galilean invariance alone. Einstein understood that Galileo’s great intuition –that the notion of velocity is only relative– *could not be wrong*. I am convinced that in this faith of Einstein in the core of the great Galilean discovery there is very much to learn, for the philosophers of science, as well as for the contemporary theoretical physicists. So, Einstein *believed the two theories, Maxwell and Galileo*. He assumed that they would hold far beyond the regime in which they had been tested. He assumed that Galileo had grasped something about the physical world, which was, simply, *correct*. And so had Maxwell. Of course, details had to be adjusted. The core of Galileo’s insight was that all inertial systems are equivalent and that velocity is relative, not the details of the galilean transformations. Einstein knew the Lorentz transformations (found, of course, by Lorentz, not by Einstein), and was able to see that they do not contradict Galileo’s insight. If there was contradiction in putting the two together, the problem was ours: we were surreptitiously sneaking some incorrect assumption into our deductions. He found the incorrect assumption, which, of course, was that simultaneity could be well defined. It was Einstein’s faith in the *essential physical correctness* of the old theories that guided him to his spectacular discovery.

There are innumerable similar examples in the history of physics, that equally well could illustrate this point. Einstein found GR “out of pure thought”, having Newton theory on the one hand and special relativity –the understanding that any interaction is mediated by a field– on the other; Dirac found quantum field theory from Maxwell equations and quantum mechanics; Newton combined Galileo’s insight that acceleration governs dynamics with Kepler’s insight that the source of the force that governs the motion of the planets is the sun . . . The list could be long. In all these cases, confidence in the insight that came with some theory, or “taking a theory seriously”, lead to major advances that largely extended the original theory itself. Of course, far from me suggesting that there is anything simple, or automatic, in figuring out where the true insights are and in finding the way of making them work together. But what I am saying is that figuring out where the true insights are and finding the way of making them work together is the work of fundamental physics. This work is grounded on the *confidence* in the old theories, not on random search of new ones.

One of the central concerns of modern philosophy of science is to face the apparent paradox that scientific theories change, but are nevertheless credible. Modern philosophy of science is to some extent an after-shock reaction to the fall of Newtonian mechanics. A tormented recognition that an

extremely successful scientific theory can nevertheless be untrue. But it is a narrow-minded notion of truth the one which is questioned by the event of a successful physical theory being superseded by a more successful one.

A physical theory, in my view, is a conceptual structure that we use in order to organize, read and understand the world, and make prediction about it. A successful physical theory is a theory that does so effectively and consistently. At the light of our experience, there is no reason not to expect that a more effective conceptual structure might always exist. Therefore an effective theory may always show its limits and be replaced by a better one. On the other hand, however, a novel conceptualization cannot but rely on what the previous one has already achieved.

When we move to a new city, we are at first confused about its geography. Then we find a few reference points, and we make a rough mental map of the city in terms of these points. Perhaps we see that there is part of the city on the hills and part on the plane. As time goes on, the map gets better. But there are moments, in which we suddenly realize that we had it wrong. Perhaps there were indeed two areas with hills, and we were previously confusing the two. Or we had mistaken a big red building for the City Hall, when it was only a residential construction. So we adjourn the mental map. Sometime later, we have learned names and features of neighbors and streets; and the hills, as references, fade away. The neighbors structure of knowledge is more effective that the hill/plane one . . . The structure changes, but the knowledge increases. And the big red building, now we know it, is not the City Hall, and we know it forever.

There are discoveries that are forever. That the Earth is not the center of the universe, that simultaneity is relative. That we do not get rain by dancing. These are steps humanity takes, and does not take back. Some of these discoveries amount simply to cleaning our thinking from wrong, encrusted, or provisional credences. But also discovering classical mechanics, or discovering electromagnetism, or quantum mechanics, are discoveries forever. Not because the details of these theories cannot change, but because we have discovered that a large portion of the world admits to be understood in certain terms, and this is a *fact* that we will have to keep facing forever.

One of the thesis of this essay, is that general relativity is the expression of one of these insights, which will stay with us “forever”. The insight is that the physical world does not have a stage, that localization and motion are relational only, that diff-invariance (or something physically analogous) is required for any fundamental description of our world.

How can a theory be effective even outside the domain for which it was found? How could Maxwell predict radio waves, Dirac predict antimatter and GR predict black holes? How can theoretical thinking be so magically powerful? Of course, we may think that these successes are chance, and historically deformed perspective. There are hundred of theories proposed, most of them die, the ones that survive are the ones remembered. There is alway somebody who wins the lottery, but this is not a sign that humans can magically predict the outcome of the lottery. My opinion is that such an interpretation of the development of science is unjust, and, worse, misleading. It may explain something, but there is more in science. There are tens of thousand of persons playing the lottery, there were only two relativistic theories of gravity, in 1916, when Einstein predicted that the light would be defected by the sun precisely by an angle of $1.75''$. Familiarity with the history of physics, I feel confident to claim, rules out the lottery picture.

I think that the answer is simpler. Somebody predicts that the sun will rise tomorrow, and the sun rises. It is not a matter of chance (there aren't hundreds of people making random predictions on each sort of strange objects appearing at the horizon). The prediction that tomorrow the sun will rise, is sound. However, it is not granted either. A neutron star could rush in, close to the speed of light, and sweep the sun away. More philosophically, who grants me the right of induction? Why

should I be confident that the sun would rise, just because it has been rising so many time in the past? I do not know the answer to *this* question. But what I know is that the predictive power of a theory beyond its own domain is *precisely of the same sort*. Simply, we learn something about nature (whatever this mean). And what we learn is effective in guiding us to predict nature's behavior. Thus, the spectacular predictive power of theoretical physics is nothing less and nothing more than common induction. And it is as comprehensible (or as incomprehensible) as my ability to predict that the sun will rise tomorrow. Simply, nature around us happens to be full of regularities *that we understand*, whether or not we understand why regularities exist at all. These regularities give us strong confidence -although not certainty- that the sun will rise tomorrow, as well as in the fact that the basic facts about the world found with QM and GR will be confirmed, not violated, in the quantum gravitational regimes that we have not empirically probed.

This view is not dominant nowadays in theoretical physics. Other attitudes dominate. The “pragmatic” scientist ignores conceptual questions and physical insights, and only cares about developing a theory. This is an attitude, that has been successful in the sixties in getting to the standard model. The “pessimistic” scientist has little faith in the possibilities of theoretical physics, because he worries that all possibilities are open, and anything might happen between here and the Planck length. The “wild” scientist observes that great scientists had the courage of breaking with old and respected ideas and assumptions, and explore new and strange hypothesis. From this observation, the “wild” scientist concludes that to do great science one has to explore strange hypotheses, and *violate respected ideas*. The wildest the hypothesis, the best. I think wilderness in physics is sterile. The greatest revolutionaries in science were extremely, almost obsessively, conservative. So was certainly the greatest revolutionary, Copernicus, and so was Planck. Copernicus was pushed to the great jump from his pedantic labor on the minute technicalities of the Ptolemaic system (fixing the equant). Kepler was forced to abandon the circles by his extremely technical work on the details of Mars orbit. He was using ellipses as approximations to the epicycle-deferent system, when he begun to realize that the approximation was fitting the data better than the (supposedly) exact curve. And extremely conservative were also Einstein and Dirac. Their vertiginous steps ahead were not pulled out of the blue sky. They did not come from violating respected ideas, but, on the contrary, from respect towards physical insights. In physics, novelty has always emerged from new data and from a humble, devoted interrogation of the old theories. From turning these theories around and around, immersing into them, making them clash, merge, talk, until, through them, the missing gear could be seen. In my opinion, precious research energies are today lost in these attitudes. I worry that a philosophy of science that downplays the component of factual knowledge in physical theories might have part of the responsibility.

4.2 On content and truth in physical theories

If a physical theory is a conceptual structure that we use to organize, read and understand the world, then scientific thinking is not much different from common sense thinking. In fact, it is only a better instance of the same activity: thinking about the world. Science is the enterprise of continuously exploring the possible ways of thinking about the world, and constantly selecting the ones that work best.

If so, there cannot be any qualitative difference between the theoretical notions introduced in science and the terms in our everyday language. A fundamental intuition of classical empiricism is that nothing grants us the “reality” of the referents of the notions we use to organize our perceptions. Some modern philosophy of science has emphasized the application of this intuition to the concepts

introduced by science. Thus, we are warned to doubt the “reality” of the theoretical objects (electrons, fields, black holes ...). I find these warning incomprehensible. Not because they are ill founded, but because they are not applied consistently. The fathers of empiricism consistently applied this intuition to *any* physical object. Who grants me the reality of a chair? Why should a chair be more than a theoretical concept organizing certain regularities in my perceptions? I will not venture here in disputing nor in agreeing with this doctrine. What I find incomprehensible is the position of those who grant the solid status of reality to a chair, but not to an electron. The arguments against the reality of the electron apply to the chair as well. The arguments in favor of the reality of the chair apply to the electron as well. A chair, as well as an electron, is a concept that we use to organize, read and understand the world. They are equally real. They are equally volatile and uncertain.

Perhaps, this curious schizophrenic attitude of being antirealist with electrons and iron realist with chairs is the result of a complex historical evolution. First there was the rebellion against “metaphysics”, and, with it, the granting of confidence to science alone. From this point of view, metaphysical questioning on the reality of chairs is sterile – true knowledge is in science. Thus, it is to scientific knowledge that we apply empiricist rigor. But understanding science in empiricists’ terms required making sense of the raw empirical data on which science is based. With time, the idea of raw empirical data showed more and more its limits. The common sense view of the world was reconsidered as a player in our picture of knowledge. This common sense view should give us a language and a ground from which to start – the old anti-metaphysical prejudice still preventing us, however, from applying empiricist rigor to this common sense view of the world as well. But if one is not interested in questioning the reality of chairs, for the very same reason why should one be interested in questioning the “reality of the electrons”?

Again, I think this point is important for science itself. The factual content of a theory is our best tool. The faith in this factual content does not prevent us from being ready to question the theory itself, if sufficiently compelled to do so by novel empirical evidence or by putting the theory in relation to other things *we know* about the world. Scientific antirealism, in my opinion, is not only a short sighted application of a deep classical empiricist insight; it is also a negative influence over the development of science. H. Stein (1999) has recently beautifully illustrated a case in which a great scientist, Poincaré, was blocked from getting to a major discovery (special relativity) by a philosophy that restrained him from “taking seriously” his own findings.

Science teaches us that our naive view of the world is imprecise, inappropriate, biased. It constructs better views of the world. Electrons, if anything at all, are “more real” than chairs, not “less real”, in the sense that they ground a more powerful way of conceptualizing the world. On the other hand, the process of scientific discovery, and the experience of this century in particular, has made us painfully aware of the provisional character of *any* form of knowledge. Our mental and mathematical pictures of the world are only mental and mathematical pictures. This is true for abstract scientific theories as well as from the image we have of our dining room. Nevertheless, the pictures are powerful and effective and we can’t do any better than that.

So, is there anything we can say with confidence about the “real world”? A large part of the recent reflection on science has taught us that raw data do not exist, and that any information about the world is already deeply filtered and interpreted by the theory. Further than that, we could even think, as in the dream of Berkeley, that there is no “reality” outside there. The European reflection (and part of the American as well) has emphasized the fact that truth is always internal to the theory, that we can never exit language, we can never exit the circle of discourse within which we are speaking. It might very well be so. But, if the only notion of truth is internal to the theory, then *this internal truth* is what we mean by truth. We cannot exit from our own conceptual scheme. We cannot put

ourself outside our discourse. Outside our theory. There may be no notion of truth outside our own discourse. But it is precisely “from within the language” that we can assert the reality of the world. And we certainly do so. Indeed, it is more than that: it is structural to our language to be a language *about* the world, and to our thinking to be a thinking *of* the world. Therefore, precisely because there is no notion of truth except the one in our own discourse, precisely for this reason, there is no sense in denying the reality of the world. The world is real, solid, and understandable by science. The best we can say about the physical world, and about what is there in the world, is what good physics says about it.

At the same time, our perceiving, understanding, and conceptualizing the world is in continuous evolution, and science is the form of this evolution. At every stage, the best we can say about the reality of the world is precisely what we are saying. The fact we will understand it better later on does not make our present understanding less valuable, or less credible. A map is not false because there is a better map, even if the better one looks quite different. Searching for a fixed point on which to rest our restlessness, is, in my opinion, naive, useless and counterproductive for the development of science. It is only by believing our insights and, at the same time, questioning our mental habits, that we can go ahead. This process of cautious faith and self-confident doubt is the core of scientific thinking. Exploring the possible ways of thinking of the world, being ready to subvert, if required, our ancient prejudices, is among the greatest and the most beautiful of the human adventures. Quantum gravity, in my view, in its effort to conceptualize quantum spacetime, and to modify in depth the notion of time, is a step of this adventure.

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