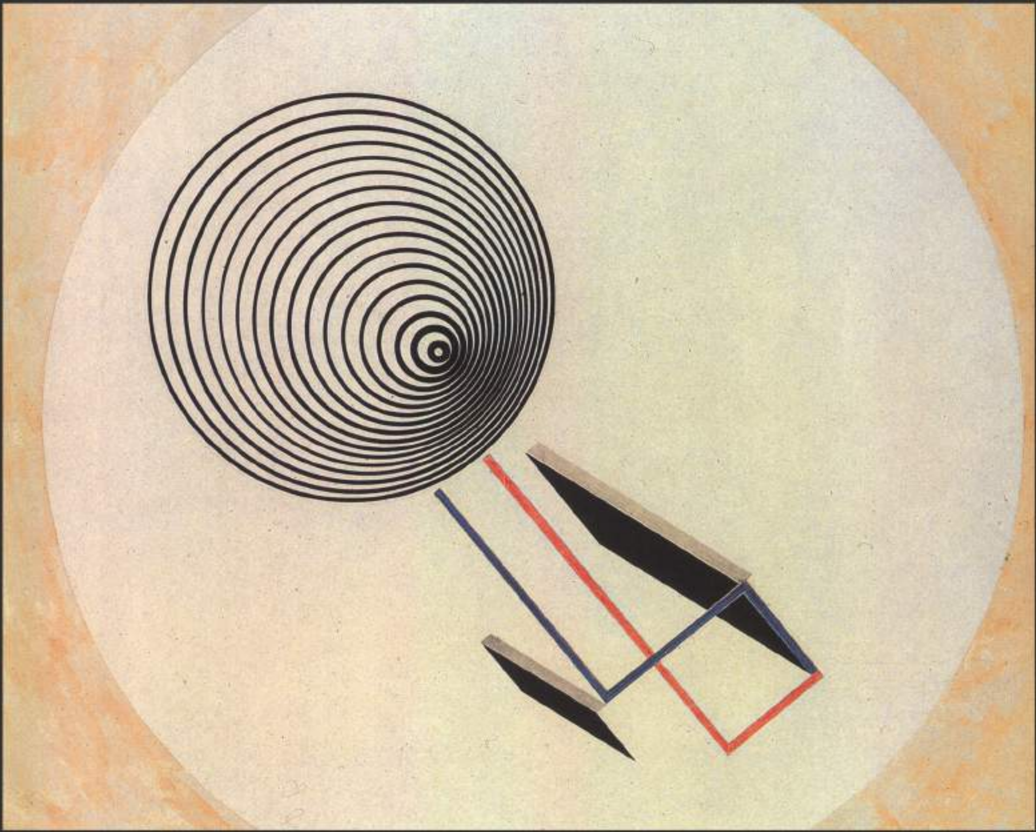

Quantum Gravity Physics & Philosophy

ERC PROJECT PHILOSOPHY OF CANONICAL QUANTUM GRAVITY

October 24 – 27, 2017 Institut des Hautes Etudes Scientifiques (IHES)

Research in quantum gravity represents a particularly suitable ground for a productive confrontation between physics and philosophy. But for this to become an authentic dialogue, and not a mere epistemological complement to the scientific discourse, it is essential that the dialogue be centred around questions which meet the demands and goals specific to these two disciplines.

The main goal of this workshop is to bring together internationally renowned physicists and philosophers to explore the various possible modes of collaborations enabled by the current status of the theories seeking the unification of quantum mechanics and gravity. It will focus on transversal questions, and more particularly on the principles and methods employed in quantum gravity. We shall try, as far as possible, not to confine the discussions to epistemological clarifications of the "foundations", but to show instead that the questions at stake might be potentially as important and general in their consequences as were those raised, at the beginning of the 20th century, by the theories of general relativity and quantum mechanics.

Indeed, quantum gravity reactivates long-standing questions about the relation between physical theories and empirical observations, the exact role (foundational or merely heuristic) of "principles", the identification of the basic objects or structures of a theory (problems of reduction and emergence), the mathematical characterisation of becoming and the meaning of time, the singularity of the object "universe", the stability of the laws of nature, etc.

The four days of conferences are organized around the following thematic units: the principles of quantum gravity, black holes, holographic correspondences, quantum cosmology, emergence of spacetime, the status of time in quantum gravity and quantum geometries.

This workshop also aims to provide students and young researchers with an overview of the major conceptual issues of this vast field of research.

Organizers:

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TUESDAY 24/10	*WEDNESDAY 25/10*
9h30 - 11h **Gabriele VENEZIANO** *Quantum Gravity or Gravity for the Quantum: String Theory's Lesson*	**9h30 - 11h** **Costas BACHAS** *Holographic Dualities and Quantum Gravity*
Coffee Break	Coffee Break
11h30 - 13h **Steven CARLIP** *Why We Need Quantum Gravity and Why We Don't Have It*	**11h30 - 13h** **Sebastian de HARO** *Dualities and Emergence*
Lunch	Lunch
14h30 - 16h **Carlo ROVELLI** *Physics and Philosophy of Quantum Gravity: What I Think We Have Understood and What We Do Not Know*	**14h30 - 16h** **Alain CONNES** *Why Four Dimensions and the Standard Model Coupled to Gravity - A Tentative Explanation From the New Geometric Paradigm of NCG*
Coffee Break	
16h30 - 18h **Michel BITBOL** *A Philosophy of Physics in the First Person*	

THURSDAY 27/10	*FRIDAY 28/10*
9h30 - 11h **Dennis DIEKS** *Physical and Experiential Time*	**9h30 - 11h** **Ted JACOBSON** *What Can Black Holes Teach Us About Quantum Gravity?*
Coffee Break	Coffee Break
11h30 - 13h **Yuval DOLEV** *Time, Experience and Quantum Gravity*	**11h30 - 13h** **Erik CURIEL** *Continuum Spacetime as the Limit of Discrete Structure*
Lunch	Lunch
14h30 - 16h **Gary HOROWITZ** *Spacetime in String Theory*	**14h30 - 16h** **Claus KIEFER** *Conceptual Issues in Quantum Cosmology*
Coffee Break	
16h30 - 18h **Tiziana VISTARINI** *Modality after String Theory*	

Tuesday October 25th, 9h30—11h

Gabriele VENEZIANO
(Theoretical Physics Department, CERN)

Quantum Gravity or Gravity for the Quantum: String Theory's Lesson

After recalling how non-relativistic quantum mechanics (QM) removes the singularities of its classical counterpart, I will turn to relativistic quantum mechanics and to its conventional formulation known as Quantum Field Theory (QFT).

Because of a combination of quantum and relativistic effects, QFTs typically lead to new singularities associated with ultraviolet (UV) divergences. Although theorists have become accustomed to (and have found a way to live with) them, such divergences may signal a new crisis in our description of microscopic phenomena. Furthermore, in the case of gravity there is no known way to deal with UV divergences without giving up predictivity. This is particularly unfortunate since Classical General Relativity (CGR) is plagued by its own singularities (e.g. the cosmological singularity and the one in a black-hole interior) and one would have hoped that QM helps to solve them. There are also conceptual problems with quantization in curved space times which could very well be at the origin of Hawking's information puzzle.

Since several decades, quantum string theory (QST) has been proposed as a possible (though only theoretical so far) solution to the above-mentioned problems. In the second part of my talk, I will try to explain how QST combines special relativity and quantum mechanics in a way that represents a truly Copernican revolution. Rather than attempting to quantize classical field theories (such as Maxwell's or Einstein's), QST starts from the quantum spectrum of strings moving in particularly simple (e.g. flat) space times. Such a spectrum includes a set of massless spinning states which implies, at sufficiently large distances, a QFT description of gravitational and non-gravitational phenomena together with short-distance modifications that cure the UV diseases of conventional QFTs. Finally, classical field theories, rather than representing the starting point of a problematic quantization procedure, are recovered in the appropriate limit of a fully quantum framework. The geometry of space-time of CGR is arguably the most amazing structure emerging from this revolutionary paradigm.

Tuesday October 25th, 11h30—13h

Steven CARLIP
(Department of Physics, University of California Davis)

Why We Need Quantum Gravity and Why We Don't Have It

It has been more than a century since Einstein first pointed out the need to incorporate quantum mechanics into general relativity. But despite the long, hard work of a great many very good physicists, the goal of a quantum theory of gravity still seems distant. In this talk I will give a personal perspective on what a theory of quantum gravity would mean, why it is (probably) necessary, and why it is so hard to find.

By "quantum gravity", what I will mean here is a quantum mechanical theory—with the usual apparatus of operators and states—that reduces to classical general relativity in some macroscopic limit. One might impose other requirements: for instance, quantum gravity should presumably offer a microscopic picture of black hole thermodynamics, and perhaps explain the value of the cosmological constant. (I have suggested another possible "universal" feature, short distance dimensional reduction, but this is far less certain.)

Most physicists take the existence of quantum gravity for granted. Apart from general considerations of the unity of physics—all other known fundamental interactions are quantum mechanical— there are a number of strong arguments: the possibility of using classical gravity to violate the uncertainty principle (a gravitational "Heisenberg microscope"), the difficulty of coupling quantum matter to classical gravity, the problem of making sense of conservation of combined classical and quantum energy. There are also hopes: quantum effects might eliminate singularities and perhaps explain the initial state of the Universe, and the inclusion of gravity might tame the divergences of quantum field theory. But while these arguments may be compelling, they are not conclusive; ultimately quantum gravity must be at least partly a question for observation and experiment.

For other fundamental interactions, a quantum theory is obtained by "quantizing" the classical theory, using some not very precisely defined algorithm. For gravity, such a procedure would presumably lead to a theory of quantum geometry. But there are cases in condensed matter physics in which macroscopic degrees of freedom "emerge" from very different microscopic degrees of freedom. Naive attempts to formulate a theory of emergent gravity quickly run into severe difficulties: it is exceedingly hard to build a theory with a single massless, pure spin 2, universally coupled excitation. But there are proposals, such as the AdS/CFT correspondence, that could arguably be said to describe an emergent spacetime, with gravity emerging as a byproduct.

Why, after all this effort, has quantum gravity remained out of reach? One obstacle, at least, is the very different starting points of quantum mechanics and general relativity. Standard quantum mechanics depends on the existence of a fixed background, used to define local observables, normalize wave functions, and determine a Hamiltonian. But in general relativity, spacetime is dynamical, and (presumably) must be described as a quantum state rather than a fixed background. This means, for instance, that a quantum theory of gravity can probably have no local observables and no unique local time evolution, and it is not even clear how to define normalized probabilities, making it very different from the conventional quantum field theories that we understand..

So where do we stand? While we do not yet have a quantum theory of gravity, we have a number of promising research programs. The most famous is string theory, with the associated AdS/CFT correspondence and the very interesting recent suggestions of a relationship between spacetime geometry and quantum information. Next in line is loop quantum gravity, with the related ideas of spin foams and group field theory. But there are also "traditional" quantum field theory approaches (e.g., asymptotic safety), lattice methods (e.g., causal dynamical triangulations), and discrete models (e.g., causal set theory). We also have simpler models such as lower-dimensional gravity that might offer clues. Each approach has strong advocates, and arguments sometimes become heated, but for now, perhaps, it is time to let a hundred flowers bloom.

Tuesday October 25th, 14h30 — 16h

Carlo ROVELLI

(Centre de Physique Théorique, Université Aix-Marseille)

Physics and Philosophy of Quantum Gravity: What I Think We have Understood and What We Do Not Know

A convincing empirically supported theory of quantum spacetime is still missing. But today we have a few coherent tentative theories in a not-too-unreasonable stage of completeness, as well as empirical results already disfavouring some alternatives, such as tentative theories violating Lorentz invariance at the Planck scale. The theories we have offer a remarkable picture of the physical world at the Planck scale, where continuous bulk space and time are absent. This is a challenge for philosophy and where philosophers can play a role: can we consistently think the world in a manner where the conventional structures of space and time are only emergent?

Wednesday October 26th, 9h30—11h

Costas BACHAS
(Département de physique, École Normale Supérieure)

Holographic Dualities and Quantum Gravity

Holographic dualities are twenty years old, and yet they are probably the latest truly revolutionary idea in theoretical physics. These dualities are mathematical equivalences that relate quantum gravity (QG), with asymptotically anti-de-Sitter boundary conditions, to ordinary quantum field theories (QFT) in one less dimension of spacetime.

Although the idea of holography is believed to hold more broadly, it has been tested extensively only when quantum gravity can be described by a weakly-coupled superstring theory. Indeed, holographic dualities were up to now mainly used to shed light on certain strongly-coupled QFTs whose equations can be mapped to the Einstein, or related, equations of semiclassical gravity.

In this talk, I will focus on efforts to use the duality arrow in the opposite way: What can one learn about the puzzles of quantum gravity, especially those related to quantum black holes and to the observed cosmological constant, by translating these puzzles in the more familiar language of ordinary quantum field theory?

Wednesday October 26th, 11h30 — 13h

Sebastian de HARO
(Faculty of Science, University of Amsterdam)

Dualities and Emergence

Dualities in string theory, and the associated ideas about the emergence of spacetime, have spawned a wave of work in the philosophy of spacetime and philosophy of science. There are four sets of related questions for both physicists and philosophers:

(1) How to best construe dualities conceptually? How does duality relate to other notions in the philosophy of science such as theoretical equivalence, intertranslatability, etc.? Are all string- and field-theoretic dualities to be treated on a par? Are string-theoretic dualities to be treated on a par with other cases of duality, such as position-momentum duality or Kramers-Wannier duality?

(2) Are string theory dualities, such as gauge/gravity duality, exact? Are there examples of exact dualities which illustrate a preferred conceptual framework for duality?

(3) Under what conditions do dualities amount to cases of physical equivalence?

(4) What is the relation between duality and emergence? What is emergence? Are the examples of emergence that one finds in string theory cases of ontological or epistemic emergence? Does spacetime emerge?

In this talk, I will present a conceptual framework for dualities and emergence, and show how it addresses *some* of the above questions. The framework starts with the following schema for dualities:

(a) A *bare theory* is a triple of structured sets of states, quantities, and dynamics, satisfying appropriate meshing conditions with the symmetries.

(b) A *model* is a representation of a bare theory, i.e. a homomorphism from the bare theory to a triple of structured sets. The model is characterised by its specific structure.

(c) An *interpretation* is a set of partial maps from the bare theory to a domain of application within a possible world, satisfying appropriate meshing conditions with the symmetries.

A *duality* is then an isomorphism between models. As such, it is a specific instance of theoretical equivalence. *Physical equivalence* is then defined as sameness of reference of the interpretation maps. I will argue that not all dualities lead to physical equivalence. I will argue that physical equivalence only obtains for 'internal interpretations', provided two conditions are satisfied. An *internal interpretation* is one that starts from the bare theory and nothing else, i.e. it does not interpret the specific structure of the models. The two conditions to be met then are:

(i) *Large domain*: the domain of applicability of the model coincides with the world described.

(ii) *Unextendability*: roughly, that the interpretation cannot be changed by coupling the theory to something else or by extending its domain, i.e. it is robust to small changes.

I will illustrate the schema in the case of bosonization (boson-fermion duality) and gauge/gravity duality.

Then I will present a framework for *approximative emergence*, which builds on the notions (a)-(c) above. Approximative emergence relates the emergent (or top) theory to the basic theory via an appropriate *approximative map,* which will provide the mechanism for ontological emergence.

Epistemic emergence then refers to cases of emergence in which the two interpreted theories, the basic and the top, give different theoretical descriptions of the world, there being novelty and robustness in the top theory's descriptions, relative to the basic theory. But also, the two theories describe the same sectors of reality (i.e. there is no novel reference). This can be summarised with the slogan: the interpretation and approximative maps commute.

Ontological emergence refers to cases of emergence in which there is novel reference, because the approximative emergence map refers to a different domain in the world. In other words, the interpretation and approximative maps do not commute.

I will illustrate the framework in an example from random matrix models, where a Riemann surface emerges out of a set of eigenvalues. Then I will comment on the connection between duality and emergence in general, and the extent to which emergence applies to gauge/gravity dualities.

Wednesday October 26th, 14h30 — 16h

Alain CONNES
(IHES)

Why Four Dimensions and the Standard Model Coupled to Gravity - A Tentative Explanation From the New Geometric Paradigm of NCG

This talk is not directly concerned with quantum gravity but it addresses a more basic related question which is to understand "why gravity coupled to the standard model". The starting point is an extension of Riemannian geometry beyond its classical domain which allows the needed flexibility in order to answer the query of Riemann in his inaugural lecture:

> *Nun scheinen aber die empirischen Begriffe, in welchen die räumlichen Massbestimmungen gegründet sind, der Begriff des festen Körpers und des Lichtstrahls, im Unendlichkleinen ihre Gültigkeit zu verlieren; es ist also sehr wohl denkbar, dass die Massverhältnisse des Raumes im Unendlichkleinen den Voraussetzungen der Geometrie nicht gemäss sind, und dies würde man in der That annehmen müssen, sobald sich dadurch die Erscheinungen auf einfachere Weise erklären liessen. Es muss also entweder das dem Raume zu Grunde liegende Wirkliche eine discrete Mannigfaltigkeit bilden, oder der Grund der Massverhältnisse ausserhalb, in darauf wirkenden bindenden Kräften, gesucht werden.*[1]

The Riemannian geometric paradigm is extended to the noncommutative world in an operator theoretic and spectral manner. A geometric space is encoded by its algebra of coordinates A and its "line element" which specifies the metric. The new geometric paradigm of spectral triples encodes the discrete and the continuum on the same stage which is Hilbert space. The Yukawa coupling matrix of the Standard Model provides the

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[1] "Now it seems that the empirical notions on which the metric determinations of Space are based, the concept of a solid body and of a light ray, lose their validity in the infinitely small; it is therefore quite conceivable that the metric relations of Space in the infinitely small do not conform to the hypotheses of geometry; and in fact, one ought to assume this as soon as it permits a simpler way of explaining phenomena. Therefore either the reality underlying Space must form a discrete manifold, or the basis for the metric relations must be sought outside it, in binding forces acting on it." (Riemann, Collected Papers, Springer, 1990, 272, translation by M. Spivak.)

inverse line element for the finite geometry which displays the fine structure of space-time detected by the particles and forces discovered so far. For a long time the structure of the finite geometry was introduced "by hand" following the trip inward bound in our understanding of matter and forces and adapting by a bottom up process the finite geometry to the particles and forces, with the perfect fitting of the Higgs phenomenon and the see-saw mechanism with the geometric interpretation. There was however no sign of an ending in this quest, nor any sensible justification for the presence of the noncommutative finite structure. This state of affairs changed recently in our joint work with A. Chamseddine and S. Mukhanov, with the simultaneous quantization of the fundamental class in K-homology and in K-theory. The K-homology fundamental class is represented by the Dirac operator. Representing the K-theory fundamental class, by requiring the use of the Feynman slash of the coordinates, explains the slight amount of non-commutativity of the finite algebra from Clifford algebras. From a purely geometric problem emerged the very same finite algebra which was the outcome of the bottom-up approach. We shall also discuss the crucial role of dimension 4 in our approach.

Thursday October 27th, 9h30—11h

Dennis DIEKS
(Institute for History and Foundations of Science, University of Utrecht)

Physical and Experiential Time

Time as directly experienced is a continuous flow, characterized by a shifting “now”. This direct phenomenological experience is often adduced as evidence, or at least as constituting a strong plausibility argument, for the objective existence of temporal passage and flow in physical reality: accordingly, in our experience we just latch on to something that independently exists outside of us.

However, within the conceptual framework of physics, it is notoriously difficult to give even a clear meaning to the intuition that time “flows”. Physics therefore standardly works with a “block universe” idea of time and space, in which there is no objective (observer-independent) distinction between past, present and future. But according to the adherents of the “dynamic” view of time, this only indicates that time as used in physics is a watered-down version of real phenomenological time. It is an abstraction that leaves essential temporal properties out of consideration.

In order to judge the validity of the arguments on both sides, we need to inquire into the links between physical and psychological time. One highly relevant claim is that the “static” block universe view is able to fully accommodate our direct experience. The central idea here is that the experienced flow and passage are “secondary qualities”, like the colors of objects that we experience. Although there exist objective physical differences in objects, corresponding to the differences in colors that we perceive, the standard view is that colors themselves are not objective physical properties of objects. Likewise, according to the “block theoretician”, the experience of a flow of time and passage is produced by our senses and our brain, without a direct and literal counterpart in physical reality.

We should take into account, however, that even if it is true that the block universe view is able to predict all our temporal experiences, this does not close the debate. Indeed, it might be that the dynamical notion of time still has the advantage, because it is able to provide a *better and simpler explanation* of our experience: according to the dynamical view we *simply record* what is actually there outside of us, namely the flow of time.

In the talk I will defend the position that this argument does not work. Contrary to what may appear to be the case, the dynamic view of physical time does *worse* than the static view in explaining our experience of time—or so I will argue. There are no known physiological mechanisms that could make it understandable that our senses respond to an inbuilt directionality or dynamics of time.

Additional light is cast on this debate by recent developments in physics, in particular in quantum gravity. Already in general relativity physical time loses its status of a fixed background against which physical processes evolve, but in a number of (tentative!) theories of quantum gravity the fundamental status of time appears to be further undermined. For example, in canonical quantum gravity and its variations we encounter the well-known "problem of time", and in string theory global time in the encompassing manifold seems to relinquish its fundamental status in favor of an internal string-time. This "disappearance of time" seems to call the idea of an objective physical time flow even further into question. Moreover, in many quantum gravity research programs continuous space and time are considered to be "emergent" from a deeper ontological level that is not spatiotemporal itself. This suggests that time is not needed at all for our description of nature, which in turn seems to spell doom for the notion of time flow.

However, there are also approaches to quantum gravity (in particular causal set theory) in which an asymmetric connection between events is built in from the beginning, which seems more friendly to the ideas of passage and becoming. Indeed, it has been argued that it is precisely in quantum gravity that the notions of time flow and becoming have finally been vindicated!

In the talk I will attempt to evaluate these arguments.

Thursday October 27th, 11h30—13h

Yuval DOLEV
(Department of Philosophy, Bar-Ilan University)

Time, Experience and Quantum Gravity

In this talk I will argue that physical time and psychological time are one and that the "physical time/psychological time" dichotomy is vacuous. Rather, there is one time, in which events occur, which has direction, and which passes, and which cannot be broken down into "experienced time" and "physical time".

I will further argue that temporal direction and passage are features of real time, objective, mind/experience independent time, but are not captured by physics. Direction, I will suggest, is notionally inextricable from passage, and passage in turn is given to us *solely* via its experiential manifestations. Indeed, passage does not figure in any way in physics, which is deaf and mute with respect to it (I discuss in this connection the groundlessness of the endeavor to square physics with passage, an endeavor taken up specifically in the context of relativity theory). Given that passage and direction are intertwined, it follows that physics does not, and cannot capture direction either, regardless of its laws being time reversal invariant (if they are). Experiential manifestations play a vital, constitutive role with respect to temporal direction as well. Succession, the fundamental temporal relationship figuring in physics, is underpinned by the notion of direction. Thus, the time of physics presupposes human time.

What does this mean for the philosophy of science, and of physics? Disalle describes a two-way interdependence between physics and philosophy: "philosophy is not an independent source of knowledge of space-time; our ability to conceive of or to reason about space has always depended on principles borrowed, explicitly or implicitly, from physics. But this is not to say that physics simply provides answers to philosophical questions from its own sources … Rather it says that [there are times] at which philosophical analysis has become an unavoidable task for physics itself". I reject this view and suggest physics and philosophy should not get in each other's way. The questions philosophy contends with are philosophical, and cannot be addressed scientifically. Scientific challenges are certainly not philosophical. Often philosophy and science are portrayed as engaged in a joint venture, with physicists grappling with philosophical issues, and philosophers doing their philosophy on the basis of new scientific discoveries. I think these descriptions are exaggerated. No doubt, mutual curiosity, and even inspiration exist (Locke's metaphysics was very much influenced by Newton's science). But the questions asked by each discipline are its own, and are ultimately addressed from within it.

As for time, I will suggest that the central arena for studying time is phenomenology, and that whatever physics may contribute to this study, must be assessed phenomenologically. To take an example, some theories of physics involve the discretization of space-time. Experienced time is inescapably continuous. An easy way to avoid conflict is to dismiss experience as vague, proximate and unreliable. I hold that this approach is untenable, and bound to lead to scientific claims that are indefensible. Experience provides structures that cannot simply be ignored. That is not to say that science cannot lead to new, and hitherto unimaginable experiences and ideas. Still, some constitutive features of reality that figure indispensably in experience—e.g., that time is directed and flows—cannot be surpassed.

Finally I consider the implications of this view for QG. QG generates questions about the origins of space and time, with conjectures to the effect that space and time emerge from more fundamental structures. I wish to question whether such hypotheses can be made coherent, given our experience-based understanding of time. If not, does this mean these conjectures must be abandoned? Or should ideas be contemplated even when they seem to conflict with the basic structures of experience and to go beyond what we can currently understand?

Thursday October 27th, 14h30—16h

Gary HOROWITZ
(Department of Physics, University of California Santa Barbara)

Spacetime in String Theory

I will give a brief overview of the nature of spacetime emerging from string theory. This is radically different from the familiar spacetime of Einstein's relativity. String theory is best understood in two main regimes: in a perturbative expansion around classical spacetimes, and for certain (anti-de Sitter) boundary conditions where a fully nonperturbative description is available. In both regimes spacetime has unusual properties.

At the perturbative level, the spacetime metric appears as "coupling constants" in a two dimensional quantum field theory. This has a number of profound consequences: Geometrically different spacetimes can be equivalent; some singularities in general relativity are not singularities in string theory; and the topology of space can change. I will give examples of each of these phenomena.

Nonperturbatively (with certain boundary conditions), spacetime is not fundamental but must be reconstructed from a holographic, dual theory. The dual theory is an ordinary quantum field theory in a lower dimensional space, so strings and spacetime are both emergent. I will describe some of the consequences of this holographic description of quantum gravity. One immediate consequence is that black hole evaporation is a unitary quantum process. Other consequences include the fact that spacetime topology can be ambiguous, one cannot send signals through the Cauchy horizon of a rotating or charged black hole, and certain cosmological singularities cannot become cosmological bounces. I will explain why these results follow from holography.

I will conclude by discussing a couple of ways that one can recover the spacetime geometry from the dual field theory in a classical limit. One approach is based on the notion of quantum entanglement in the dual theory. It has been shown that the entanglement entropy of a region of space in the dual theory is given by the area of certain extremal surfaces in spacetime. So geometric information can be recovered this way. A different

approach has recently been proposed based on "light-cone cuts". These are the intersection of the past or future of a point in spacetime with the boundary at infinity. I will show that one can determine these light-cone cuts just from the dual field theory, and one can reconstruct the conformal metric, i.e., the spacetime metric up to an overall rescaling, just from the location of these cuts. Under certain conditions, one can recover the conformal factor as well.

Thursday October 27th, 16h30—18h

Tiziana VISTARINI
(Department of Philosophy, University of Colorado Boulder)

Modality after String Theory

In one of my most recent works (Vistarini, 2017), I argue that quantum string theory is background independent. Indeed the theory does not posit any fundamental geometry and it admits emergent spacetime. This notion of emergence is a quite composite one. General relativistic spacetime emergence along with emergence of the extra dimensions are both admitted by the theory, although arising from different formal and physical features of the theory's articulation. Space and time are emergent in string theory since they are mechanical byproducts of more fundamental dynamics.

The topic of this talk starts from this claim of spacetime emergence and it makes an inquiry on some philosophical consequences it may have on modality. That is, what does the fundamental physical ontology of string theory say about the fate of modality?

It is widely held into the quantum gravity circles that endorsing Lewis ontology of modal realism is incompatible with endorsing the fundamental physical ontology of any quantum gravity theory, since they all deny the fundamental existence of space and time.

I argue that there isn't incompatibility as long as modal realism is metaphysically and formally revised. And it turns out that this revision, if made within the string theory formal articulation and dynamical content, can produce a metaphysical framework compatible with the non-fundamentality of spatiotemporal relations.

Briefly, Lewis' thesis of modal realism has a complex internal articulation branching out in several parts. He accepts a controversial ontology for the sake of what he considers to be some theoretical benefits, among which its application to modality.

By considering some features of Lewis' thesis (possible worlds internally unified by spatio-temporal relations, trans-worlds isolation, and so on), I attempt to understand what of this metaphysical framework can be preserved and revised in light of string theory, what instead should go.

Summarizing, my proposal branches out in the following way.

On the one side, I propose few ideas supporting a revision of modal realism without rejection. One, already developed in (Vistarini, 2017), consists in showing that the familiar logical relation of similarity among worlds can be revised in terms of a more rigorous notion of "closeness" arising from some non-spatiotemporal, topological techniques used in deformation theory.

Another revises the notions of logical and nomological possibilities characterizing the "Lewis pluriverse". Finally a third one proposes an interpretation of Lewis' use of the notion of fundamental which does not seem to conflict with the ways in which it is used in the quantum gravity debate about space and time.

On the other side, there is a feature of the Lewis metaphysical framework that works against my attempt of revision without rejection, namely Humean supervenience. Indeed, dualities of the strings dynamics undermine the main core of this crucial feature. My effort here is that of understanding how the "vast mosaic of local matters" can be maintained despite removing spatiotemporal relations.

This talk is part of a work in progress for an invited contribution to a miscellaneous volume invited contribution for the miscellaneous volume "Beyond Spacetime: The Philosophical Foundations of Quantum Gravity", Cambridge University Press.

Friday October 28th, 9h30 — 11h

Ted JACOBSON
(Center for Fundamental Physics, University of Maryland)

What Can Black Holes Teach Us About Quantum Gravity?

The key properties of a black hole are its causal horizon, the infinite redshift, and the curvature singularity. The challenge to understand these in quantum gravity focuses our attention on physical questions lying beyond the reach of effective field theory. (Primordial cosmology provides another avenue for guidance, but here I stay with black holes.) What lessons can we hope to learn? What have we learned so far? What is debatable? What seem like promising directions?

Microcausality is a cornerstone of quantum field theory, yet in GR causality is malleable, and observables are not local. So what role does causal structure play in quantum gravity? Is it transcended, e.g. by the non-locality of string theory, or by Lorentz violation as in Horava-Lifshitz gravity? Black hole thermodynamics augurs strongly against Lorentz violation, which would, it seems, allow violation of the second law. As for string theory, examination of (gauge dependent) string field commutators led to early doubts, but gauge/gravity duality so far suggests that bulk causality is regulated by boundary (CFT) causality, despite any bulk nonlocality that might be present. That is, perhaps local causality is replaced by a “holographic causality” quite generally.

Speaking of gauge/gravity duality, this is certainly a lesson from black holes for quantum gravity, on several levels. The discovery of this duality emerged from the effort to understand black hole entropy in string theory. There the redshift was the key ingredient. Supersymmetry played an essential role in the discovery, but it seems what was discovered is more general than that. In fact, the bulk/boundary relation connects to the profound consequences of diffeomorphism invariance, the governing property of gravity. And this lends support to the notion that this consequence of diffeomorphism invariance is robust, and should survive in quantum gravity.

The finiteness of Bekenstein-Hawking entropy is a beacon for quantum gravity. It shines brightly with a ring of truth. It seems to require some kind of cutoff on the horizon entanglement entropy of quantum fields, which diverges in semiclassical QFT. But what sort of cutoff could be consistent with low energy effective field theory (EFT)? How should the entanglement entropy of gauge fields and the gravitational field be defined? These questions touch on the UV completion of the theory, as well as the nature of observables in quantum gravity. Is there a well defined observable algebra exterior to a black hole horizon? And from whence do the outgoing black holes modes arise?

The success of counting black hole entropy microstates at weak coupling on D-branes is impressive, but what exactly does it teach us? It validates the belief that the SUSY counting of number of states at fixed charges is invariant under change of the coupling from weak to strong. And it supports with an example the expectation that any consistent theory of QG will admit a statistical account of a finite BH entropy. However (as far as I can tell) it doesn't tell us that QG must be string theory.

A key insight we have gained is that Bekenstein's generalized entropy, $S_{gen} = A/4\hbar G + S_{outside}$, is (or should be) invariant under joint renormalization group (RG) flow of the gravitational constant G and the outside entropy. With the EFT upper cutoff set at low energy, most of S_{gen} is in the area term. As the cutoff is raised, some shifts over to the outside entanglement entropy, with a compensating increase of G. Extrapolation of this trend leads to the conjecture that, when the upper cutoff is removed, S_{gen} is entirely entanglement entropy, and $1/G$ is zero. In that scenario, metric fluctuations are entirely unsuppressed in the deep UV.

The consistency of this RG flow may provide a constraint on viable theories. It seems to be in tension with the proposal of asymptotic safety for the gravitational field, because the existence of a UV fixed point for the field theory would entail the existence of an infinite number of local degrees of freedom that would contribute to $S_{outside}$, rendering the black hole entropy infinite. This is not definitive, however, since it is conceivable that quantum fluctuations of geometry could render all but a finite number of these irrelevant for the entropy.

And what should we make of the thermodynamics of black holes: the 0th, 1st, 2nd laws, the GSL? The compatibility of GR with these laws is striking. But in what sense, if any, does it mean gravity is thermodynamical?

A case can be made that the root of this compatibility can be found in the neighborhood of any point in any spacetime, in the sense that the classical Einstein equation can be inferred from the Clausius relation, causality, and area entropy of local causal horizons. Truth be told, the reasoning also posits local Minkowski metric structure, and, implicitly, general covariance. So the building blocks for GR are there from the beginning.

The real lesson, perhaps, is the link between the structure of the vacuum, and the dynamics of spacetime. Note that the thermodynamic system is not the whole system; rather it is the causal exterior. And the fluctuations and thermodynamic nature arise from the vacuum fluctuations. Subsystems of the vacuum must be consistent with thermodynamics, just as subsystems of anything must be. In that sense, it is not surprising. But what is surprising is that it leads immediately to the requirement that the causal structure of spacetime be dynamically responsive to the flux of energy, provided the horizon entropy is finite, and in a way that satisfies Einstein's equation. By contrast, a theory with infinite horizon entropy, like a conformal field theory, has a fixed causal structure, without dynamical gravity.

We should not conclude, however, that gravity is "only" thermodynamical. Whatever else can be said, GR makes sense as an effective QFT, which is unitary and reversible, properties that are not thermodynamic in nature. Nonetheless, can the thermodynamic description be taken to the next level, to a statistical description? It might be so, in view of the possible link between the Einstein equations and the maximization of entanglement entropy in small balls at fixed volume. But it is not yet clear how generally this entanglement maximization holds, and whether it is too local to be ultimately well-defined in quantum gravity.

Last, but not least, there is the black hole information paradox. This arises if (and only if) you buy into the notion that black hole evaporation, and more generally the black hole S-matrix, is unitary when viewed from the exterior alone. There are serious, thoughtful, and knowledgable people who don't buy into that notion, and I used to count myself among them. But there are good reasons to entertain the hypothesis; and once the genie is out of the bottle, the trouble begins. It's a good kind of trouble, because the discomfort demands a resolution, and one can reasonably hope that the resolution is attainable, and will deliver a deep lesson about quantum gravity.

The paradox is the apparent conflict between the exterior unitarity and the validity of local EFT near the horizon: the latter implies that Hawking quanta are entangled with partners behind the horizon, which are causally disconnected from the exterior. I'll sketch some of the reasoning that has been applied, critique some of that, and argue that the puzzle is generally not being posed in the correct way. The most important feature, diffeomorphism invariance, is being ignored in almost all of the literature.

Friday October 28th, 14h30—16h

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Conceptual Issues in Quantum Cosmology

Quantum cosmology is the application of quantum theory to the Universe as a whole. Such an application is required for consistency if one assumes the universal validity of quantum theory and the superposition principle (as we do here). Since gravity is the interaction that dominates at cosmic scales, we need a theory of quantum gravity to develop quantum cosmology. In my contribution, I discuss some of the most important conceptual issues arising in quantum cosmology. These include the problem of time, the role of boundary conditions, the quantum-to-classical transition, and the relevance for the interpretation of quantum theory.

In the first part, I draw some lessons from quantum mechanics. The superposition principle is identified as a key concept. It is well tested experimentally and also plays the central role in understanding the emergence of classical behaviour from quantum theory. Classical properties are acquired by the process of decoherence, which by now is well established conceptually and experimentally. Decoherence is the unavoidable and irreversible suppression of interference by entanglement formation with environmental (i.e. irrelevant) degrees of freedom. I describe the essential features of decoherence and assess its general role.

In the second part, I motivate the need for a quantum theory of gravity and concentrate on one particular approach that is especially useful for discussing conceptual issues—quantum geometrodynamics. Its central equation is the Wheeler-DeWitt equation for the "wave function of the universe". I emphasize that most of the conceptual issues also arise in other approaches to quantum gravity, such as loop quantum gravity, so there is no loss of generality in focusing attention to geometrodynamics. I explain the problem of time and show how the limit of quantum (field) theory in an external spacetime can be derived in a well defined approximation scheme.

In the third part, I apply geometrodynamics to cosmology. I show immediate consequences of the problem of time for choosing appropriate

boundary conditions. An explicit example is given. I also speculate about possibilities to avoid the singularities of the classical theory.

The fourth part is devoted to one of the most important conceptual theme —decoherence in quantum cosmology. I show how and to which extent the fundamental quantum variables such as the metric or inflaton fields can acquire classical behaviour to ensure the approximate validity of the classical spacetime picture. The standard concept of time is understood in this framework as a consequence of symmetry breaking. I also explain how primordial quantum fluctuations can decohere to provide the classical seeds needed for structure formation.

In my last part, I discuss how, at least in principle, the arrow of time, that is, the observed irreversible behaviour of our world, can emerge from the timeless nature of quantum cosmology. This is achieved by a natural boundary condition on the Wheeler-DeWitt equation.

More details and references can be found, for example, in my article "*Conceptual Problems in Quantum Gravity and Quantum Cosmology*", published in ISRN Math.Phys. 2013 (2013) 509316 (open access), also available on arXiv:1401.3578 [gr-qc].