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Edited by Jácome (Jay) Armas
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Introduction

Some books result from a breakthrough. This book results from an impasse: it would have not been conceived if there were overwhelming evidence – or agreement within the broader physics community – pinpointing a given theory, framework or model of quantum gravity. No obviously correct description of nature in this domain has emerged. What is to be made of this situation?

I emphasise the involvement of the broader physics community, in addition to those specialists dedicating their lives to the problem of quantum gravity, in order to keep the larger picture in view. After all, the signatures of gravitational effects in simple quantum systems have to be observed in laboratories, and the signatures of quantum effects in the large-scale structure of the universe have to be observed in the sky. Indeed, whatever theory of quantum gravity one devises, gravity must combine with all the other forces of nature in a way that is consistent with all known observations made at any scale between the Planck length and the entire observable universe, a total difference of roughly 61 orders of magnitude. The whole physical picture must hang together.

Ultimately, a theory of quantum gravity must be able to deliver such an all-encompassing framework that also incorporates the interaction between gravity and matter. Not surprisingly, the problem of quantum gravity is considered by many to be intrinsically intertwined with the problem of unification of all forces.

Any examination into this territory must recognise that even the basic concepts are up for debate. Different people have different notions of what is meant by a *theory of quantum gravity*. Perhaps it is not yet clear whether there should be a theory of quantum gravity at all.

Take the notion of *theory* itself. Is a theory a mathematical structure with an associated *set of fundamental principles* capable of specifying dynamical equations that describe the universe as well as predict the values of all constants of nature? Or do we understand it as a *framework* within which we can construct multiple *models*, one of which – say, the standard model of particle physics – will describe the universe? That is, are there many (billions of?) consistent cosmological histories, which we must narrow down (at least) to those compatible with human existence? Or, finally, do we understand a theory as a *method* that we can use, for instance, to quantise a given classical theory of gravity?

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Whether we view a theory as a set of fundamental principles, framework, model, method or more generally as an *approach*,[1] there is no table-top experiment or single cosmological observation that decisively confirms that gravity is a quantum field. The problem of finding a theory of quantum gravity partly rests on the lack of experimental set-ups able to probe deviations from standard (established) physics, as well as on the lack of precision within those set-ups.

Could gravity just be an effectively classical phenomenon? An entropic force caused by some underlying unknown microscopic constituents? Is spacetime itself an emergent structure at long distances and low energies? Questions such as these represent part of the debate around the quest for a theory of quantum gravity. The purpose of this introduction is to try to outline this debate – the set of open questions, related problems and different points of view – as well as to lay out and clarify the justified and unjustified criticisms directed towards those points of view.

The method of the remainder of the book is to present interviews with a select group of theoretical physicists and mathematicians who work on quantum gravity (and related subjects) about the quantum gravity debate, the state of the field, the impact of their own discoveries and the discoveries of others, their motivations to pursue these questions, and the benefit such research can bring to the scientific community and society as a whole.

Originally, I intended to provide a faithful and representative overview of the approaches in this area. This method would have led to an overwhelming majority of interviews within string theory, however. (A rough analysis of papers appearing between 2018 and 2020 on arXiv.org, either related to a given approach to quantum gravity or inspired by it, suggests that 85–90% of this research output is due to string theory.) Although my background is in string theory and I spend a considerable amount of time working in this area – as well as applying some of its lessons and tools to the contexts of hydrodynamics, astrophysical black holes, quantum matter, biomembranes and soft matter – I see value in exploring other approaches. Thus, I have chosen to give more room to a diversity of ideas at the expense of going into much depth in certain areas of string theory.

Nevertheless, I want to express clearly and respectfully that I do not think that the opinions presented here on this subject are necessarily more valuable than those of many of the theorists I did not interview, including the many string theorists who were excluded.

Moreover, I emphasise that the interviewees' positions and attitudes are not always widely shared across communities and do not always constitute the opinion of the majority. For instance, many think that the theories that they work on are not final theories but rather ways of providing clues about, and insights into, more fundamental formulations – an opinion not always shared by others in their field.

In my selection of interviewees, I focused mostly on senior theorists who were responsible for much foundational work. I also opted for the diversity of ideas and opinions within each of the approaches, including several theorists who may not brand themselves

[1] I use the word *approach* to refer broadly to any notion of theory (set of principles, framework, model, method or any other possibility).

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as proponents of any (theoretical) approach but who, I believe, have unique and interesting points of view on aspects of quantum gravity. Some approaches to quantum gravity are not directly covered in this book due to lack of space and time, but those approaches constitute smaller, or equally small, research programmes compared with the approaches that are directly covered here. I believe the editorial choices made here faithfully represent the debate and open up an array of useful questions.

Given the inherent nature of the subject matter, most of the discussions in the interviews are meant for specialists or experts, although some are suitable for readers with a general physics education and some are appropriate for those with only a popular science background.

The remainder of this introduction is concerned with summarising key aspects of the debate about quantum gravity and the issues motivating my choice of questions.

Since the advent of quantum mechanics and general relativity in the early 1900s, theorists have wondered about the quantum nature of gravity and the effect of gravity on quantum mechanics. In fact, how these two pillars of physics (quantum mechanics and general relativity) work together in theory and in practice has been the source of heated debate from their introduction, in particular between Niels Bohr and Albert Einstein. Already at that time, it became clear that the successful combination of the two theories, even if just by means of thought experiments, was crucial for the development of each theory, including understanding them as well-defined and consistent parts of physics. In the decades to follow, many theorists sought to combine quantum mechanics with special relativity, culminating in the framework of quantum field theory. This framework led to a stream of striking accomplishments, starting with the understanding of the electromagnetic and weak interactions and ending with the strong interactions, ultimately leading to the standard model of particle physics.

At different stages in this process, several theorists such as Richard Feynman and, in particular, Bryce DeWitt in the 1970s took the newly developed toolkit of quantum field theory (for instance, perturbation theory, renormalisation techniques and the gauge principle) and applied it to gravitational interactions. It became clear at that point that gravity, treating the spacetime metric as a fundamental field, even at the perturbative level, is not akin to all other interactions for which such methods and techniques were ideal. In particular, it turned out that gravity (without any other additional source of matter) is perturbatively non-renormalisable. This implies that as we take further and further perturbative corrections to graviton interaction processes, an infinite number of counterterms with an associated infinite number of free parameters need to be considered in order to obtain finite results. Gravity at increasingly high energies thus becomes, inevitably, non-predictive, and physics, as we know it, is lost.

Despite the lack of experimental confirmation, the opinion of the overwhelming majority of researchers, substantiated by multiple arguments that appeal to consistency, such as causality or puzzles related to the existence of black holes (for instance, singularities, information loss and thermodynamic properties), is that gravity must be inherently quantum, at least in a perturbative regime. This well-founded expectation has led to several ideas and

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suggestions about how to overcome the problem of non-renormalisability, all of which have been pursued to a certain (variable) extent, for instance:

- **New symmetries.** Gravity, as it stands, can be useful below a given energy scale but something else must complete gravity in the ultraviolet (high-energy) regime that renders it finite. This can entail that another mathematical language, framework or approach substitutes (or completes) gravitational interactions in the ultraviolet. Examples often involve new symmetry principles (for instance, conformal symmetry in various shades [worldsheet, spacetime, local, global, etc.], supersymmetry, E_{10} symmetry, non-commutative geometry, spacetime anisotropy and many others) or some topological completion.
- **Additional matter fields.** Even if gravity by itself is not predictive, it may become predictive when coupled to specific matter content (for instance, axions, scalars, supersymmetric particles and conformal matter, among others), which can contain a finite or infinite reservoir of particles or quantum states at high energies.
- **Other fundamental variables.** Taking the metric field as the fundamental field may not be the correct modus operandi. There are other formulations of gravity (for instance, Plebanski, Regge and higher-gauge formulations) and other potential fundamental variables (for instance, vielbeins and Ashtekar variables) or more general notions of geometry (for instance, non-commutative geometry) which, when appropriately quantised, may not lead to predictive physics in one way or another.
- **Modified infrared dynamics.** Although general relativity appears to be the correct description in the infrared (low-energy) regime, there exist various modifications of general relativity at low energies that are within current bounds set by observations (for instance, versions of higher-derivative theories and versions of modified gravity theories). Thus, perhaps the starting point of the quantisation procedure should be one of these infrared modifications and not conventional general relativity.
- **Non-perturbative renormalisability.** Gravity is perturbatively non-renormalisable, but it may be non-perturbatively renormalisable. Therefore, the formulation of the theory should be non-perturbative from the very beginning. Concrete ideas include the "magical" cancellation of divergences of all physical processes when summing over all perturbative orders; the theory suggests a minimal length scale in the configuration space which the path integral is integrating over; or there is an ultraviolet non-Gaussian fixed point characterised by a finite number of coefficients that determines all other coefficients arising from the process of renormalisation.
- **Spacetime discreteness.** It is a mistake to assume that the gravitational metric, and hence spacetime, is a continuum. Instead, spacetime is inherently discrete and thus a cut-off (of the order of the Planck length) is introduced in the theory by hand (for instance, discrete Regge calculus). A continuum spacetime should emerge at long distances. The discrete nature of spacetime may cure the ultraviolet and short-distance divergences.
- **Modifications of quantum mechanics.** The rules of quantum mechanics and the rules of general relativity may not be compatible with each other. A new mathematical framework is needed to modify the principles of quantum mechanics so as to accommodate

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both. Examples include modifications of quantum mechanics (for instance, deterministic versions) and different interpretations (for instance, hidden variable theories and Roger Penrose's gravitational objective reduction).

- **New formulations of quantum field theory.** The same type of logic as in the previous point applies to quantum field theory itself. Perhaps there are new formulations of quantum field theory (QFT) or gauge theory (for instance, axiomatic QFT, algebraic QFT and non-geometric formulations) that will more easily accommodate dynamical, and arbitrary, background geometries.
- **Dualities.** Gravity should not be directly quantised. Instead, it should emerge from some other (finite) fundamental theory. This is the case, for instance, when there are (holographic) dualities between theories without gravity and theories with gravity, implying that the very issue of non-renormalisability can be circumvented (for instance, the holographic ideas of Gerard 't Hooft and Leonard Susskind).

It should be said, first of all, that this list does not exhaust all possibilities for how to deal with some of the problems of quantum gravity and, second, that each of these ideas is not necessarily independent. Concrete proposals approaching the problem may in fact involve a combination of such mechanisms and ideas. I find that a rough classification of approaches is more useful in terms of what aspects of the above list they incorporate (or aim at incorporating) than standard classifications in terms of the type of quantisation procedure (for instance, canonical, covariant and path integral) and whether they are discrete, lattice-type approaches, or continuum. The reason for this preference is that there are several approaches where it is not clear exactly what they contain and some which can include several of these properties (for example, multiple quantisation procedures or lattice and continuum methods).

Based on limited knowledge, it is still useful to attempt to characterise the approaches directly covered within this book with the goal of aiding the reader in understanding some of the interviews. These approaches are as follows.

String theory. Introduces new symmetries such as supersymmetry; an infinite tower of massive particles which in standard versions amounts to the existence of extra dimensions; non-perturbative formulations; new geometric structures and variables; new QFT formulations and dualities such as the anti–de Sitter/conformal field theory (AdS/CFT) correspondence. As a matter of fact, it may include specific realisations of all the ideas in the above list in particular regimes, though not all these realisations are known at this point. Corners of string theory are formulated via a path integral (or covariant) quantisation of a two-dimensional worldsheet theory. It is incorrect, however, to claim that this is the general definition of the theory. Gravity is not quantised directly but emerges from the theory via interactions of closed strings at low energies. Usually included in string theory are other ideas such as E_{10} symmetry and twistor theory, though some think these ideas stand on their own. The former relates to maximal supersymmetric and supergravity theories but the exact theory that exhibits such symmetry is not yet known; it includes matter fields and may provide the required ultraviolet completion.

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Loop quantum gravity (LQG). Introduces new variables for dealing with gravity directly; is based on a non-perturbative formulation that suggests a minimal length scale in configuration space; provides examples of new QFTs, in particular topological QFTs with defects. The standard formulation is based on canonical quantisation of general relativity theory in four spacetime dimensions, which has two versions (one which requires the addition of matter) directly formulated in the continuum. Spin foam models are usually considered to be part of LQG, though the relationship between the two in four dimensions has not been fully established. Many view spin foam models as a path integral lattice approach within which a continuum limit (critical point) needs to be found after sending the lattice spacing to zero. In that limit, it is expected that some form of canonical LQG will be found. Others, however, view spin foam models as an inherently discrete approach.

Asymptotic safety. Also known as quantum Einstein gravity (QEG), requires the existence of an ultraviolet fixed point; uses renormalisation group techniques and can generate infrared modifications of gravity. In its most explored formulation, it takes the metric as the carrier field and a class of effective action functionals (truncations) that depends on diffeomorphism-invariant operators. It employs a continuum description. In principle, it can consider other action functionals, other carrier fields, other symmetries and matter fields but does not seem to require it.

Causal dynamical triangulations. A lattice approach which, in its usual formulation, takes general relativity with an additional positive cosmological constant as the bare action in the path integral; introduces new variables (piecewise flat manifolds) and a set of gluing rules that constrain configuration space in the path integral; its ultraviolet finiteness also rests on the possibility of finding an ultraviolet critical point and a continuum limit; it may generate infrared modifications.

Causal sets. Introduces a discrete length scale and takes causality (understood as time order) as a fundamental principle. Classically, it is based on a path integral whose bare action reduces to classical general relativity in some appropriate limit. It is not yet clear what the quantum theory is. It has suggested the study of some nonlocal QFTs and the need for a different interpretation of quantum mechanics.

Non-commutative geometry approach. Generalises the notion of Riemannian geometry to non-commutative geometry in terms of a non-commutative algebra, a Dirac operator and a Hilbert space; gravity, as well as matter, appears to emerge from it using (mostly) the algebra as an input. The theory is at first quantised level, and it is not yet clear how to perform second quantisation and address issues of renormalisability.

Hořava-Lifshitz gravity. Introduces spacetime anisotropy as a symmetry (that is, a Lifshitz-type symmetry in the ultraviolet that reduces to Lorentz symmetry in the infrared); there are several versions of the theory, some of which include additional matter fields;

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it can provide infrared modifications of gravity depending on how the coupling constants flow toward the infrared. There are some indications that the theory is renormalisable. It is not yet known exactly how to quantise the theory.

Other approaches. Other ideas include emergent gravity, which takes the holographic principle seriously and suggests different interpretations of infrared physics. In contrast, conformal gravity considers canonical gravity with conformal constraints while crystalline gravity introduces matter (defects) with a finite number of degrees of freedom that can be glued as to form spacetime. These latter three approaches remain, up to date, at the classical level.

Two- and three-dimensional models. Several theorists have worked on two- and three-dimensional toy models of quantum gravity within which it is possible to apply many quantisation procedures and study their effects. These models do not contain propagating degrees of freedom and so cannot describe the real world. However, many think that these models can give useful insights for tackling the four-dimensional (or higher) case. As such, these models are discussed throughout the interviews.

What do we expect from a theory of quantum gravity? A crude list of demands and expectations, which different theorists value in different degrees, includes:

- Ultraviolet and infrared finiteness
- A controlled classical limit
- Internal consistency and compatibility with standard physics
- Unification of all interactions
- A perturbative expansion around given backgrounds
- A non-perturbative definition of the theory
- A first-principle derivation of the dynamics
- A background-independent formulation (potentially with suitable boundary conditions)
- A solution space that includes our universe
- An understanding of the underlying fundamental degrees of freedom
- Well-defined physical observables
- The ability to perform computations, say, of the S-matrix
- A finite number of external parameters as input
- Suggestions of phenomenology[2] and dialogue with experiment
- Potential experimental tests and compatibility with observations
- Insights into neighbouring fields
- A microscopic understanding of black hole entropy
- A solution to the black hole information loss paradox
- A resolution of the big bang singularity and black hole singularities
- The theory incorporates the holographic principle
- The theory is outside the swampland.

[2] The word *phenomenology* refers to predictions, features or mechanisms that can potentially be used to interpret real world data.

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The failure to meet these expectations leads to potential criticisms. I turned these demands and expectations into questions directed at the interviewees:

- **Effective versus fundamental.** Is the theory an effective theory or a fundamental theory in certain cases or regimes? Is the theory pointing towards structures and principles that should then be used to construct the underlying theory?
- **Perturbative definition and the existence of our universe.** Is the theory perturbatively defined around any given background? Does the theory contain some background that describes our world? How many viable solutions are there?
- **Ability to compute.** Regardless of the properties the theory has, what can we actually compute? Scattering processes? The size of the universe? The shape of a star? The spectrum of some operator?
- **Ability to predict.** How many parameters need to be fixed by external input for the theory to be predictive? A few? Many? An infinite number?
- **Phenomenology.** Does the theory provide suggestive or concrete examples of phenomenology (for instance, particle physics models and cosmological models)?

These types of questions can be asked of any of the approaches to quantum gravity, and I did ask them in all cases in which the theory was sufficiently developed to give a proper answer.

There are also more specific criticisms of each of the approaches as well as specific questions that can highlight both their shortcomings and their advantages. Below are a few examples of such specific questions that I posed to the interviewees:

- **Questions about string theory.** What is string theory, that is, how do you define it? Is there any hope of finding a controlled cosmological solution that describes our universe? Is there hope of finding a non-perturbative definition of string theory in cosmological backgrounds? Is our universe governed by one of the supersymmetric string theories in ten dimensions or has the string theory that describes our universe not yet been found? Is it reasonable to think that anthropic principles should fix the vacuum we live in? What evidence is there for swampland conjectures? Is there any experiment that will verify string theory? Is there actually an ongoing dialogue between string theory and experiment? How well has string theory reproduced the Bekenstein-Hawking entropy of black holes from a microscopic calculation? Has it been proven that string theory is ultraviolet and infrared finite? If we do live in ten dimensions (measured abstractly in terms of field content), why are four of them large and six of them small? Are there holographic dualities for flat spacetime and cosmological spacetime? If the world is supersymmetric but we do not see superparticles at current accelerator scales, how and why did supersymmetry break?
- **Questions about the AdS/CFT correspondence.** Is AdS/CFT a non-perturbative and background-independent formulation? Isn't it just a conjecture or is there substantial proof? How well defined is the dictionary between bulk and boundary theories? Can we recover all bulk physics from the boundary theory? Is it a case of holography or

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photography? What is the quantum geometry in the bulk? Can you solve the black hole information paradox? What does an observer who falls into the black hole experience? What does physics look like at the Planck scale in the bulk? What happens if you scatter particles in the bulk at Planckian energies? Has it led to any predictions about strongly coupled systems? Are there concrete observables? Can you extract flat spacetime physics from it? Does it provide an example of emergent space and emergent time?

- **Questions about LQG.** Does LQG have a classical limit? Is the dynamics of LQG derived from first principles? LQG in the Hamiltonian formalism has two different versions (one which does not require matter and another that does), so are they equivalent? How can you formulate the theory directly in the continuum? Since LQG has a very large (infinite?) number of free parameters due to quantisation ambiguities, how can this be fixed in order for the theory to be predictive? Has the Hamiltonian constraint been solved? Is the standard Hamiltonian constraint correct? Has it been shown that LQG is generally covariant? How does LQG resolve the ultraviolet and infrared divergences? Is there any test of LQG? What are the LQG models for black hole entropy and why are the logarithmic corrections to the entropy in disagreement with semiclassical analyses? How faithful are the results and predictions of loop quantum cosmology? How does it resolve the big bang singularity?
- **Questions about spin foam models.** Spin foam models are portrayed as being part of LQG, but has this connection been formally established? Are spin foam models lattice approaches? Has a continuum limit been shown to exist? If there is a continuum limit, will it lead to the same theory as that of standard canonical LQG? What can you compute with it? How do you resolve quantisation ambiguities? Does it rely on asymptotic safety?
- **Questions about QEG.** Is there evidence that QEG has ultraviolet fixed points? What is the dimensionality of the ultraviolet critical surface? What would happen if you added more higher-curvature corrections? Is it possible to add any kind of matter and still find ultraviolet fixed points? Is there any suggestive phenomenology for particle physics and cosmological models? What is the infrared theory? And what is the picture that we find in the ultraviolet, that is, what is the theory at the Planck scale? Can we approach the renormalisation group flow trajectory near the Planck scale? Could you take different symmetries to begin with and still find fixed points? What is the relation between QEG and LQG and CDT?
- **Questions about CDT.** Is CDT generally covariant? Will the preferred foliation introduced in CDT lead to symmetry violations in the continuum limit? Has the existence of a continuum limit been demonstrated? How reliable are the numerical simulations near the fixed points? Is the continuum limit closer to general relativity or to Hořava-Lifshitz gravity? How big are the universes that can be simulated in a computer? Why is the starting action just the Einstein-Hilbert action with a positive cosmological constant? How does CDT justify the topological restrictions that are imposed in the path integral? Can CDT include matter, black holes, etc.? What can be computed with CDT? What is the theory at the Planck scale?

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- **Questions about causal sets.** How are causal sets defined? Does every spacetime have an associated causal set? How to determine which spacetime corresponds to a given causal set? What is the classical causal set theory? What evidence do we have for spacetime discreteness? How to grow a causal set? Is there any hope of finding the quantum theory? Have causal sets been used to predict the smallness of the cosmological constant? How can it make such predictions without being a quantum theory? Are there suggestions for phenomenology?
- **Questions about a non-commutative geometry approach.** How can we intuitively understand non-commutative geometry? Why should this be a better starting point for physics than Riemann geometry? What kind of input was needed in order to get the standard model coupled to gravity? Can you predict the magnitude of all masses and the strength of all interactions? How far are we from a quantum theory? What mathematical structures are needed in order to quantise the theory?
- **Questions about Hořava-Lifshitz gravity.** Has it been proven that Hořava-Lifshitz gravity is a renormalisable theory? How should one quantise the theory? Does it predict infrared modifications of general relativity compatible with observations? What is the concept of a black hole within Hořava-Lifshitz gravity? Should we understand it as being embedded in a larger theory such as string theory? What kind of phenomenology does it predict? What are the consequences of coupling the theory to matter?

The interviews also touch upon many other subjects, including interpretations of quantum mechanics, multiple cosmological models, particle physics models, the role of the QCD axion, the role of anyons, renormalisation, conformal symmetry breaking, black holes, two- and three-dimensional quantum gravity toy models, possible quantum gravity experiments, the large hadron collider (LHC), crystalline gravity, emergent gravity, E_{10} theories, conformal gravity, twistor theory, fluid dynamics, skyrmions, gauge theories and thermalisation processes. Indeed, there is no shortage of vital questions in physics.

By presenting these interviews I intend to address the concerns, doubts, misrepresentations and the misinformation in this critical area of study with the hope that it will lead to clarifications, dialogue and progress in the future. Overall my sense is that the many theoretical developments relating to quantum gravity discussed within these pages are as fascinating as they are in need of experimental testing.

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