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Quantum Gravity

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Abstract: These are some short notes on quantum gravity. I will try to review all relevant topics briefly. Perturbative string theory is the only UV finite quantum gravity theory we have (excluding toy models like SYK). Non-perturbative definitions exist for specific AdS compactifications via AdS/CFT and string field theory also gives some non-perturbative information. But non-perturbative string theory is not yet properly understood. Alternative approaches are very incomplete and inelegant compared to string theory. But I will also briefly discuss some of them. I will be continuously updating these notes when I learn new things. Which topic gets more importance will be biased based on what I am interested in. These notes are useful only to **revise** stuff that you already know, not for first time learning. Whenever many reviews are cited, assume that the first reference is the best. For frameworks that are already empirically verified (QM, GR, and QFT), check notes at ksr.onl/FP.

My current research area is section 8.2.

Please email me any mistakes you find.

Currently, these notes are in the beginning stage and are only useful to see the references cited under each section.

Contents

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1 Introduction

> Nevertheless, due to the inneratomic movement of electrons, atoms would have to radiate not only electromagnetic but also gravitational energy, if only in tiny amounts. As this is hardly true in nature, it appears that **quantum theory would have to modify** not only Maxwellian electrodynamics, but also the new theory of gravitation.
>
> *Albert Einstein* (1916) [1]

Gravity couples to the stress-energy tensor. So, gravity couples to everything. Except for gravity, we know that everything else in the physical world is fundamentally quantum in nature. It is probably not possible or at least inelegant to consistently couple classical gravity to quantum fields. So, we are compelled to quantize gravity.

Since it couples to everything, in principle, every calculation that we make to predict something about reality must include corrections coming from quantum gravity. For example, if you have a scalar field theory, we know how to solve the QFT if we neglect the scalar field interaction with gravity, but there will always be corrections due to the interaction between the scalar field and gravity. You can do semiclassical physics (QFT in curved spacetime), but there will still be quantum gravity corrections. But, in practice, quantum gravity effects are notoriously hard to detect in experiments. The Planck length is 10^{16} times smaller than the smallest scale that our species probed. In a loose sense, any approach to quantum gravity is a theory of everything since quantum gravity is ***necessary*** to understand anything exactly. But usually, the term theory of everything is reserved for theories like string theory where the theory is hoped to be ***sufficient*** to explain all physical phenomena.

We have figured out how to quantize fields with spin $0, \frac{1}{2}, 1$. But quantizing the spin 2 gravitational quantum field turned out to be hard or impossible due to the perturbative nonrenormalizability of gravity. It is unlikely that there is a nontrivial UV fixed point for gravity; see section 16. So, it seems highly likely that the framework of QFT is insufficient for quantum gravity, and we have... to go... even further beyond!

> I learned very early the difference between knowing the name of something and knowing something.
>
> *Richard Feynman*

When I started these notes, I knew the *names* of most topics related to quantum gravity. My goal now is to properly understand them instead of just knowing the names.

1.1 Problems

[15–19]
Some of the many problems that we encounter when we try to quantize gravity are:

Perturbative nonrenormalizability:

Unitarity of black hole evaporation:

Causality and chronology protection conjecture:

Singularities and cosmic censorship:

Problem of time:

Failure of classical spacetime: If we try to probe a distance smaller than the Planck scale, then due to the Heisenberg uncertainty principle, the momentum and energy will be so large that this region will collapse into a black hole. So, the classical spacetime that we understand well breaks down at the Planck scale. What is the nature of quantum spacetime from which the classical spacetime emerges? Is it noncommutative geometry 9.9?

Holographic description: Does the fact that black hole entropy scales like area really imply that quantum gravity must have a lower dimensional field theory description? Is holography limited to asymptotically AdS spacetimes (AdS/CFT)? Or is it a property of all spacetimes?

Framework: All approaches to quantum gravity indirectly use the framework of QFT or GR. For example, worldsheet string theory is $2D$ CFT, and holography is $D \geq 2$ CFT. Is there a more natural mathematical framework for quantum gravity instead of QFT?

> Quantum gravity is notoriously a subject where problems vastly outnumber results.
>
> *Sidney Coleman (1989)*

1.2 Expected properties

These are some expected properties of quantum gravity. Some things, like *no global symmetries*, *weak gravity conjecture*, can also be included here, but I will discuss them under the swampland conjectures in 6.5.

Unitarity:

No local observables: [21].

UV complete: [97]

IR complete: [22, 97, 183]. Although IR divergences are normally considered to be less serious than ultraviolet ones, they certainly cannot be ignored.

Holography: [23–25]. Historically, holography was first argued [26] based on black hole thermodynamics without invoking string theory.

1.3 History

[27–36]

I do not want to discuss history. But check the above references. There are many interesting historical facts like how string theory was originally developed to explain the strong force instead of quantum gravity.

1.4 QFT in curved spacetime

[37–55]

Even though Hawking radiation has not yet been experimentally observed, almost every reasonable physicist believes in its validity. So, this section could be, in principle, moved to my FP notes. But it is highly relevant to quantum gravity.

1.4.1 Unruh radiation in flat space

1.4.2 Hawking radiation

1.4.3 The information paradox

1.4.3.1 The small corrections theorem

[44–46]

1.4.3.2 AMPS firewall

1.5 GR as an EFT

[56–59]

Part I
String theory

References: [2, 3] are the standard references. [4, 5] are also very good and cover later understanding of non-perturbative and holographic stuff. Also see [6–14][196]

Why string theory? I will briefly mention some promising reasons. Check [60–62] for more.

1.

2 Conformal field theory

[63–70, 75]
The worldsheet descriptions of bosonic/superstring theories are 2D CFTs. $D > 2$ CFTs are the holographic duals of superstring theories with more than 3 noncompact dimensions. So, both cases are important.

2.1 $D \geq 3$

2.1.1 Conformal transformations

A conformal transformation is a specific combination of a general coordinate and a **Weyl transformation** that leaves the metric intact. Usually, this metric is the flat Minkowski metric.

Almost everywhere, people specify that conformal transformation is a type of coordinate transformation. **But it is not**. The first time I saw this definition was in [133] in my undergrad final year, and it resolved my longstanding confusion about this definition. Every physical theory (not only general relativity) has diffeomorphism invariance, and you can check the beginning of the General relativity chapter in my FP notes if you want to know why every physical theory from Newtonian mechanics has diffeomorphism invariance. If conformal transformation is just a subset of coordinate transformation, then conformal symmetry will be present in every theory, and that is nonsense. A **mere coordinate transformation** can never change distances, as ds^2 is invariant under coordinate transformations. So, you can never scale distances with them. But a **Weyl transformation changes the distances** because it directly changes the metric without changing the coordinates. Weyl symmetry **implies** conformal symmetry, but the converse is not true.

2.1.2 Representations of the conformal group

2.1.3 Radial quantization

2.2 $D = 2$

2.2.1 Conformal transformations

2.2.2 Primary fields

2.2.3 OPE

2.2.4 Ward identities

2.2.5 Free boson

2.2.6 Free fermion

2.2.7 The bc theory

2.2.8 The $\beta\gamma$ theory

2.2.9 CFT on the Disk

2.2.10 CFT on the Torus

2.2.11 Bosonization

2.2.12 Entanglement entropy

2.3 Bootstrap

2.3.1 Analytic

[71, 72]

2.3.2 Numerical

[73, 74]

2.4 Axiomatic CFT

[75–77][66]

3 Bosonic string theory

3.1 Classical

3.2 Quantize

For this part [9] is the best.

3.2.1 Canonical quantization

3.2.2 Light-cone quantization

3.2.3 Covariant path integral quantization

3.2.4 BRST quantization

3.3 Scattering amplitudes

3.3.1 Tree-level amplitudes

3.3.2 One-loop amplitudes

4 Supersymmetry

4.1 SUSY QM

[78, 79, 82, 196]

4.2 SUSY QFT

[80–86]

4.2.1 Superspace

[87]

4.2.2 Gauge theories

4.3 SUGRA

[88–94]

4.3.1 11D

[91, 92]

4.3.2 10D

4.3.3 4D

5 Superstring theory

There are no open strings in IIA, IIB in perturbation theory around the vacuum.
Type II does include open strings. However, they don't show up in the vacuum perturbation theory, they are only there in connection with non-perturbative effects like D-branes.

5.1 Classical

[7]

5.2 Type II string theories

5.3 Type I string theory

5.4 Heterotic string theories

5.5 Vertex operators

5.6 Scattering amplitudes

5.6.1 Tree-level amplitudes

5.6.2 One-loop amplitudes

5.6.3 UV finiteness

[97, 98]

5.7 String dualities

5.7.1 T-duality

5.7.2 S-duality

5.7.3 F-theory

[99]

6 String landscape

6.1 String compactifications

[100–106]

Freund–Rubin compactification

6.2 Nongeometric compactifications

[107–109]

6.3 String cosmology

[110–119]

6.3.1 de-Sitter vacua

[111, 112]

6.3.2 String inflation

[113, 114]

6.3.3 Brane cosmology

6.4 Particle phenomenology

[120–122]

The previous section was on the phenomenology of cosmology. Unlike other quantum gravity theories, string theory, being a ToE, must also answer questions of particle phenomenology.

6.4.1 Axiverse

[123, 124]

6.5 Swampland

[125–129]

7 D-branes

[5, 130, 131]

7.1 Effective actions

7.2 As BPS SUGRA solitons

7.3 D-branes moving and merging

7.4 Creation/Annihilation of D-branes

7.5 Multiple coincident D-branes

7.6 D-brane geometry

[258]

8 Holography

8.1 Stringy AdS/CFT

[5, 132–139]

8.1.1 Dictionary

8.1.2 Correlation functions

8.1.3 Finite temperature

8.1.4 Solitons

[140]

8.1.5 The pp wave correspondence

8.1.6 Different dimensions

8.1.6.1 AdS_3 compactifications

[141, 142]

8.1.7 Orbifolds and orientifolds

8.1.8 Integrability

[143]

8.1.9 Higher spin duality (tensionless limit)

[144–148]

8.1.10 Fluid/gravity correspondence

[149]

8.1.11 Nonrelativistic limit

[150, 151]

8.2 It from Qubit AdS/CFT

[152]

8.2.1 Holographic entanglement entropy

[152–157]

8.2.1.1 Classical gravity from entanglement

8.2.1.2 Quantum extremal surfaces

8.2.1.3 Derivation of RT, HRT, QES from gravity path integral

[152, 155]. Original articles are [158–160]

8.2.1.4 Holographic entropy cone

8.2.1.5 Bit threads

8.2.1.6 Islands

[152, 155]. Criticism about massive islands etc is discussed in [54, 161–164]

8.2.1.7 Quantum extremal surface perturbation theory

[165]

8.2.2 Tensor networks

[152, 166, 167]

8.2.3 Error correction

[166–168]

8.2.4 Chaos

[169–171]

8.2.5 Complexity

[152, 172, 173]

8.2.6 SYK

[175, 176]

8.2.7 JT

[174–176]

8.2.8 DSSYK

[177]

8.2.9 von Neumann algebras

[178–180] these are holography related. For math [181]

8.3 Flat space holography approaches

8.3.1 Celestial holography

[182–187]

8.3.2 Carrollian holography

[188–190]

8.4 de Sitter holography approaches

[191, 192]

8.4.1 dS/CFT

8.4.2 Static patch holography

8.4.3 $T\bar{T}$ deformation

[193]

9 Stringy maths (inspired from or related to strings)

[194, 195]

9.1 Mirror symmetry

[196–208]

9.2 Modular forms

[209][205]

9.3 Monstrous moonshine

[210–213]

9.4 Knot theory

[214, 215]

9.5 Geometric Langlands correspondence

[216–219]

9.6 K-theory

[220, 221]

9.7 p-adic strings

[222–225]

9.8 Higher structures

[226–233, 330]

9.8.1 Higher gauge theory

9.8.2 Higher category theory

9.9 Noncommutative geometry

[234–236]

9.9.1 Noncommutative algebraic geometry and mirror symmetry

[237][203]

9.9.2 Noncommutative quantum field theory

[238–258, 272–274]

10 M-theory

10.1 Membrane theory

[259–269][1]

10.2 Matrix theory

[270–276] [247, 248]

10.2.1 BFSS matrix model

10.2.1.1 BMN matrix model

[1]Fun fact: [259] was posted on arXiv on the same day I was born (23rd Jan 2002) just few hours after I was born.

10.2.2 IKKT matrix model

10.3 AdS/CFT approach

[277–281]

10.3.1 $AdS_4 \times S^7/\mathbb{Z}_k$ & ABJM CFT

10.4 Miscellaneous

[282–285]

11 String field theory

[14, 286–295]

11.1 Off-shell string theory

11.2 Bosonic string field theory

11.2.1 Open

11.2.2 Closed

11.2.3 Open-Closed

11.2.4 Background independence

11.3 Superstring field theory

11.4 Tachyon condensation

[296–300]

Doubt: Is there a holographic dual of bosonic string theory? The bosonic string is unstable non-perturbatively. So, it might not have a holographic dual. Sen's conjecture and instability of the D25-branes. But maybe there is still some unstable CFT with tachyons that is its dual? The R symmetry of the boundary theory will match to the symmetry of the compact dimensions. Since here we don't have R symmetry does that mean the bulk has no compactification? Does that mean the boundary theory is a 25-dimensional unstable CFT?

12 Miscellaneous

12.1 Black holes

[301–303]

12.1.1 Microscopic origin

12.1.2 Wormholes in the axiverse

[304, 305]

12.2 Chern-Simons theories

[306–309]

12.2.1 Superconformal Chern-Simons matter theories

[310]

12.2.2 Quantum Gravity in 2+1 Dimensions

[311–315]

12.3 Topological string theory

[316–318]

12.3.1 Twistor string theory

[352]

12.3.1.1 Amplituhedron

[319, 320]

12.4 More on scattering amplitudes

[321–324]

12.4.1 Double copy

[325]

12.5 Localization techniques

[326]

12.5.1 Gromov-Witten invariants

[327]

12.5.2 F-Theorem and F-Maximization

[328]

12.5.3 Localization and AdS/CFT

[329]

12.6 Generalized symmetries

[330–335]

12.7 Pure spinor formalism

[336–338]

12.8 Worldline formalism (∞ tension limit)

[339–342]

12.9 $2D$ string theory

[343, 344]

12.10 Liouville theory

[345]

12.11 Metastring theory and modular spacetime

[346]

Part II
Other approaches

13 Twistor theory

[347–353][7, 241]

13.1 Real slices and reality structures

13.2 $\mathbb{M}_{\mathbb{C}}$'s conformal structure = $\mathbb{PT}$'s complex structure

13.3 Penrose transform

13.4 Gauge theory

13.5 Ambitwistors and $d > 4$

[354]

13.6 Mini-Twistor theory

[355–359]

13.7 Miscellaneous

[360–362]

14 Canonical quantum gravity

[363, 364]

14.1 ADM formalism

[365]

14.2 Wheeler–DeWitt equation

15 Loop quantum gravity

[366–374]

15.1 Ashtekar variables

15.2 Quantum Riemannian geometry

15.3 Spin foams

15.4 Loop quantum cosmology

[375]

16 Weinberg's asymptotic safety

[376–378]
Also called nonperturbative renormalizability.

17 Causal set theory

[379, 380]

18 Causal fermion systems

[381, 382]

19 Causal dynamical triangulation

[383]

20 Group field theory

[384, 385]

21 Unimodular gravity

[386]

22 Hořava–Lifshitz gravity

[387]

A Miscellaneous math

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