Quantum Gravity & String Theory
A Status Report

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Typical article/talk on string theory begins with String Theory is the only known framework for a consistent theory of quantum gravity . . . and then deals with some exotic aspect of string theory which may or may not be related to quantum gravity per se.

Implicitly, such a statement implies the validity of at least 3 distinct statements:

1. Research on Quantum Gravity is relevant and interesting
2. Quantum Gravity is hard and requires some rather unconventional ideas
3. Quantum Gravity requires String Theory

While I agree with [1] and [2] (and try to keep an open mind regarding [3]), I believe that we owe it to the physics (or general scientific) community to occasionally explain or justify these statements in some more detail.

This TAM Meeting seems to provide an ideal opportunity for this.
Overview

I Quantum Gravity:
an introduction and some general comments

II String Theory as a Theory of Quantum Gravity:
a brief status report

- Sorry, no pictures, movies . . .
- Apologies to the experts in the audience for any (unavoidable) over-simplifications
- Part II based on an article with Stefan Theisen that appeared in the GRG Memorical Volume dedicated to John Archibald Wheeler († April 13 2008) the person who single-handedly kept Quantum Gravity research alive in the mid-20th century.
Quantum Gravity: History

- Quest for theory of **Quantum Gravity** is attempt to reconcile and unite the two pillars of 20th century physics,
  
  **Quantum Physics & General Relativity**

Separately these two theoretical frameworks are spectacularly successful (at their respective scales) but fundamentally they are very different.
The Two Main Players

Quantum Physics
- Central Object of Interest: wave functions (state) $\Psi(x)$
- Fundamental Equation: Schrödinger Equation
- Basic Principles and Insights:
  - Linearity, Superposition Principle
  - Heisenberg Uncertainty Relation
  - Probabilistic Interpretation

General Relativity
- Central Object of Interest: space-time metric (geometry) $g_{\alpha\beta}(x)$
- Fundamental Equation: Einstein Equation
- Basic Principles and Insights
  - Einstein Equivalence Principle
  - Gravity = Space-Time Curvature, Space-Time Geometry is Dynamical
  - General Covariance
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- First technical papers on Quantum Gravity: Rosenberg in the 1930s
- Nobel Laureates who have worked on the problem: Einstein, Bohr, Heisenberg, Dirac, Pauli, Salam, Schwinger, Weinberg, Feynman, Veltman, ‘t Hooft, Gross, Wilczek, . . .
- Outcome: plenty of insights - but no theory of quantum gravity
- Problem: not only technically hard but challenges basic ideas and assumptions about the nature of space and time!
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Quantum Gravity: Why the Fuss?
Or: why the “shut up and calculate” approach fails

- Standard approach to quantisation of interacting (non-linear) field theories: **Perturbation Theory**:
  - \( \Phi = \Phi_{cl} + g\Phi_q, \ g \ll 1 \)
  - \( \Rightarrow \) Perturbative (loop) expansion etc

- Applied to General Relativity (**Perturbative Quantum Gravity**)
  - \( g_{\alpha\beta} = \eta_{\alpha\beta} + \sqrt{G}h_{\alpha\beta} \)
  - Interpretation of GR as the theory of a massless interacting spin-2 field in Minkowski space-time
  - Turns out to be non-renormalisable: \( G = L_P^2 \) (\( \hbar = c = 1 \))
  - anticipated by Heisenberg (1938), established only in 1985 by Goroff and Sagnotti for pure gravity (2 loops)
  - for **Supergravity**: cf. talk by Hermann Nicolai

- Essentially means that the conventional perturbative approach to quantum gravity is dead (Weinberg and other proponents of asymptotic safety might disagree, cf. talk by Roberto Percacci)
Quantum Gravity: Why? Consistency

Adaptation of argument due to Heisenberg (de Witt): Interaction of classical EM / gravitational field with quantised particles / matter is inconsistent, e.g. something along the lines of (Eppley & Hannah)

- Classical gravitational measurement collapses quantum wave function ⇒ momentum is not conserved
- Classical gravitational measurement does not collapse the quantum wave function ⇒ signals can be sent faster than light

[Argument for GR not as watertight as for EM but still very compelling]

- ∃ major disagreement about details, but
- ∃ general consensus that some quantum theory of gravity is required.
Quantum Gravity: Why? Necessity

- Occurrence of Newton’s and Planck’s constants in the expression of the classical Bekenstein-Hawking or Black Hole entropy

\[ S_{BH} = \frac{A}{4L_P^2} \quad L_P^2 = \frac{\hbar G}{c^3} \]

shows that it can only be explained by a quantum theory of gravity.

- Proportionality of entropy to area rather than volume \(\Rightarrow\) degrees of freedom of a quantum theory of gravity very different from those of a local quantum field theory (holography)

- On dimensional grounds one expects combined effects of gravity and quantum physics to become relevant at the Planck scale:

\[ L_P \approx 10^{-33}\text{cm} \quad , \quad E_P \approx 10^{19}\text{GeV} \approx 10^{32}\text{K} \]

\(\Rightarrow\) very early universe (Big Bang), Black Hole singularities.
Quantum Gravity: Why? A Historical Analogy

The pre-quantum Era

- An equation without a theory:
  Planck’s Formula for Blackbody Radiation

- A serious clash between theory and reality:
  Stability of Atoms and Matter

The pre-quantum gravity Era (today)

- An equation without a theory:
  Bekenstein-Hawking Formula for Black Hole Entropy
  \[ S_{BH} = \frac{A}{4L_p^2} \approx 10^{80} - 10^{100} \]

- A serious clash between theory and reality:
  Stability of the Universe
  (how can a macroscopic universe arise from a theory with fundamental length scale the Planck length? the cosmological constant problem)
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Quantum gravity will do all kinds of nice things for us:

- lead to / require unification of all fundamental interactions
- explain Bekenstein-Hawking Black Hole entropy $S_{BH} = A/4G$
- explain cosmological constant / our universe
- solve global warming
- ... (add your favourite puzzle / question here)
Once one has (perhaps grudgingly) accepted that one needs a theory of quantum gravity,

- one faces a potentially very exciting and fruitful situation: a unification of not just two forces but two concepts as different as quantum mechanics and space-time geometry must almost invariably lead to something that is much more than just the sum of the two:

  - What is Quantum Space-Time Geometry?
  - What is the Fundamental Nature of Space and Time?
  - Why do Black Holes behave like Thermodynamics Objects?
  - How do we interpret a Wave Function of the Universe?

- and one is confronted with the major and fundamental question:

  Is Quantum Gravity the Quantisation of Einstein Gravity???
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Quantum Gravity: Conceptual Issues
Or: why the “shut up and calculate” approach fails again

Some Issues raised by the General Covariance of GR

- **General Covariance** is invariance under *coordinate transformations* (passive) or *moving space-time points* (active)
- Local Operators cannot be invariant unless they are constant, so presumably (?) Quantum Gravity Observables are non-local
- How to recover local space-time geometry in classical limit?
- Time-evolution $t \rightarrow t + \delta t$ is coordinate transformation $\Rightarrow$ generator (Hamiltonian) annihilates physical states: How to recover dynamics, time evolution?

Some Issues raised by the Interpretation of QM

How does one interpret a *Wave Function of the Universe* if there is neither an external observer nor something like an ensemble of quantum systems?
Is Quantum Gravity the Quantisation of Einstein Gravity?

This is not a trick question, and not an issue of terminology, but a fundamental issue that has firmly divided the quantum gravity community into two camps!

The underlying question is:

- **L**: Does General Relativity capture correctly the microscopic (fundamental) degrees of freedom of the gravitational field?
- **S**: Is General Relativity only an effective (low energy, "emergent") phenomenon arising at large distances from a more fundamental theory with different degrees of freedom?

Differences in consequences of believing hypothesis **L** or **S** are dramatic:
Visiting Camp L

If you believe L, then

- Your belief is shared by most quantum gravity researchers with a classical GR background.
- You will attempt to find a theory of quantum gravity via a non-perturbative quantisation of GR.
- Your reaction to the failure of perturbative quantisation of GR will be: I told you so! It makes no sense split a metric into a “background” and a “fluctuation”. There is no background!
- You will quote Penrose: *If we remove life from Einstein’s beautiful theory by steam-rollering it first to flatness and linearity, then we shall learn nothing from attempting to wave the magic wand of quantum theory over the resulting corpse!*
- You will most likely end up working in Loop Quantum Gravity (= non-perturbative canonical quantisation of GR).
Visiting Camp S

If you believe $S$, then

- your belief is shared by most quantum gravity researchers with a QFT background

- you are convinced that it is meaningless to quantise Einstein gravity directly (analogy: thermodynamics, collective phenomena in condensed matter or solid state physics)

- your reaction to the failure of perturbative quantisation of GR will be:
  
  I told you so! GR is only an effective theory, valid only below a certain energy scale, and should not be quantised as such!

- You will not quote anybody but start learning about CFT, SUSY, Algebraic Geometry, etc etc instead

- You will most likely end up working in String Theory
L vs. S: a personal assessment

- If I had more time, I would have liked to discuss in more detail the virtues and achievements of L vs. S
- Since I do not, I will just summarise the situation by the following picture:

The Little Kid may be more charming than the Sumo wrestler, but it is clear who has the better arguments . . .
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Part II:

- **The Past:** String Theory and Perturbative Quantum Gravity
- **The Present:** Non-Perturbative String Theory and Gravity
- **The Future:** Conceptual Challenges and Technical Problems

**Remarks:**

- Lightcone dividing research into Past, Present and Future not sharply defined, very appropriate for Quantum Gravity . . .
- Focus will not be so much on the success stories (which are reviewed in many places) but rather on what I consider to be currently unsatisfactory or open issues.
String Theory and Perturbative Quantum Gravity: Basics

String Theory provides a unifying framework for all elementary particles and their interactions

- gauge forces arise from massless excitations of open or closed strings
- inevitably and automatically includes gravity (through massless second-rank tensor excitation of the closed string)

Identification of this excitation with graviton is somewhat indirect (after all, gravity is emergent in string theory, like other forces)
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Method I:

- associate to each string mode a worldsheet (vertex) operator and calculate their 2d worldsheet correlation functions
- interpret the results as S-matrix elements of an effective field theory
- effective field theory = Einstein-Hilbert action (plus computable higher order stringy and quantum corrections)
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Method II:

- couple worldsheet theory to space-time metric,
  \[ S \sim \int d\tau \, d\sigma [\eta^{ab} \partial_a X^\alpha(\tau, \sigma) \partial_b X^\beta(\tau, \sigma) g_{\alpha\beta}(X(\tau, \sigma)) + \ldots ] \]
- require conformal invariance
- \( \beta \)-function equation = Einstein equation (plus computable & identical higher order corrections)
String Theory and Perturbative Quantum Gravity: Achievements

- string theory provides a (presumably order by order finite) consistent perturbative description of quantum gravity, avoiding the perturbative non-renormalisability of the field theory approach, and with correct low-energy limit.

- Theories with such properties do not grow on trees (indeed string theory is the only known approach to accomplish this!)

- accept additional structures introduced by string theory (“extra dimensions”, infinite towers of massive fields, supersymmetry) even though not clear if or why required for quantum gravity.

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Remarks:
superficially string theory apparently somewhat uneconomical description of quantum gravity, but actually extremely economical: reduces all the arbitrary field theory interaction vertices to a single simple string interaction
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Remarks:
it is precisely the infinite tower of massive fields (or the extended nature of the string) that is responsible for the good UV behaviour of the theory.
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Remarks:
"extra dimensions" just a simple geometric way of describing certain CFTs with a given central charge, in general no geometric interpretation and no extra dimensions, just some "worldsheet stuff" required by consistency.
String Theory and Perturbative Quantum Gravity: Shortcomings

This old (1980s) worldsheet picture of string theory is

- inherently perturbative
  (in an expansion in Newton’s or the string coupling constant)
- limited to a set of rules for computing on-shell scattering amplitudes
  in an on-shell background

If one wants to study situations where

- one expects quantum gravitational effects to become relevant
  (black holes, big bang),
- or if one wants to address conceptual issues of quantum gravity,

this is a double handicap:

- quantities can only be computed as formal power series in the string coupling,
- and one has to fix an on-shell background in advance.
Non-Perturbative String Theory: D-Branes, Dualities and AdS/CFT (1995 –)

- **D-Branes**: Non-perturbative sectors of closed string theory (gravity) described in terms of perturbative open string theory (gauge theory)!

- **Weak-Strong Coupling Dualities**: IIB S-duality \((g \rightarrow 1/g)\), IIA ↔ Heterotic, etc.

- **M-Theory and Unification of Perturbative String Theories**: Different known consistent string theories recognised as different perturbative expansions of one underlying theory

- **Gauge Theory – Gravity Duality**, in particular AdS/CFT: arising from the fact that D-branes can be equivalently described as gravitational objects in the (bulk) closed string theory, or in terms of their lower-dimensional worldvolume gauge theory (holography!)
D-Branes and Black Hole Microstates

Successful microscopic explanation of the Bekenstein-Hawking black hole entropy for a wide variety of black holes in terms of explicit counting of black hole (D-brane) microstates,

- including precise numerical factors
- with correct higher derivative corrections (Wald entropy)

Expectation that degrees of freedom responsible for the black hole entropy are not those of a local QFT is indeed realised in string theory
Non-Perturbative String Theory and Quantum Gravity Achievements

**AdS/CFT Correspondence / Duality**

Non-perturbative and holographic description of quantum gravity on asymptotically Anti-de-Sitter (AAdS) space-times in terms of a gauge theory on the conformal boundary of the AAdS space-time.

- Prominent Example: AAdS$_5$ and $\mathcal{N} = 4$ $SU(N)$ SYM in $D = 3 + 1$
- Has mostly been used to gain insight into strongly coupled gauge theories via classical gravity, but is more and more being used to gain insights into quantum gravity from the dual gauge theory

Currently the most powerful and popular tool we have to study quantum gravity questions within the context of string theory.
Non-Perturbative String Theory and Quantum Gravity
Shortcomings

- **D-Branes and Black Hole Microstates**
  - Successes are for the moment limited to (near) extremal black holes, Schwarzschild is the hardest case
  - No fundamental or a priori explanation why $S_{BH} \sim A$: Given charges (quantum numbers) $Q_a$ of the black hole, calculate separately $S_{BH} = S_{BH}(Q_a)$ and $A = A(Q_a)$ and then find that each and every time $S_{BH} \sim A$ (*blessing and problem*)
  - de Sitter entropy

- **AdS/CFT Correspondence / Duality**
  - In principle dual CFT should contain all information about formation, collision and evaporation of black holes. In practice any process localised in the bulk will be encoded in complicated non-local way in the boundary theory - code not yet completely deciphered.
    - Cf. talk by Albion Lawrence.
  - In particular, to my mind information loss “paradox” not yet completely resolved.
  - Other boundary conditions (asymptotically flat, de Sitter)?
Accounting for black hole entropy and understanding the presumably holographic nature of quantum gravity are cornerstones of research in quantum gravity.

⇒ accomplishments within string theory are encouraging and represent significant progress.

Nevertheless, current status of string theory as a theory of quantum gravity is still somewhat unsatisfactory, and there still remain a number of basic open conceptual and technical issues.
Conceptual Issues

- What are the fundamental symmetries of string theory? (What we have uncovered so far is presumably only the Tip of the Iceberg)
- What is string or quantum geometry? (Emergence and Redundance)
- What is the stringy counterpart of general covariance and the equivalence principle?
- ...
Technical (and conceptual?) Problems

Currently available technology seems to be not well suited to study time-dependent (non-susy) backgrounds like cosmological singularities; time-dependence gives rise to some rather basic problems:

- absence of Lightcone Gauge and No-ghost theorems,
- limited validity of Euclidean formulation
- questionable usefulness of standard on-shell S-Matrix formulation of string theory in a cosmological setting
- perturbative and non-perturbative instabilities of non-susy backgrounds

Promising approaches rely on non-perturbative formulations of string theory: AdS/CFT, M(atrix) Theory (cf. talk by Lorenzo Seri)
Conclusions

- String theory is a very promising (and fertile) framework for a consistent theory of quantum gravity.
- However, we still appear to be at a rather preliminary stage of our understanding of this theory.
- In particular a non-perturbative formulation of the theory and uncovering its symmetries are important open issues.

Far-reaching statements on either side of the string theory debate, proclaiming
- either the imminent demise of string theory
- or the ultimate unavoidability (and virtue) of some pseudo-scientific or pseudo-religious anthropic/multiverse scenario,
appear to be pre- (and quite im-) mature,
- and should not distract one from trying to better understand profound quantum gravitational issues to which string theory presumably holds the clue.
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Thank You for Your Attention!
and thanks to the University and People of Montenegro for their support!