String Theory and the Quest for Quantum Spacetime

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The Quest

Snapshots from a Himalayan Trek.
The Metaphor

- From Kanchenjunga to K2 ....

- It wasn’t always known that they are part of a single mountain range.
The Metaphor

- *It had to be painstakingly mapped out.*
The Metaphor

- Nowadays, we can literally see it all.
The Metaphor

- Understanding in Physics has come in much the same way.
- Detailed ground survey and the discovery of simple laws.
- Piecing together the terrain around nearby peaks: more general laws.
- Broadening the scope to see the connectedness between peaks into a vast Himalayan range.
The Laws of Physics

○ Embody our ability to discern regularities amidst complex behaviour.

○ Remarkably, capturable in precise mathematical language.

○ Seemingly able to continue to do so as we widen the scope of these laws.

○ Though sometimes to do so requires conceptual and mathematical reorientation.
Two Peaks

- Twentieth Century Theoretical Physics has stood on two pillars.
- These are General Relativity (GTR) and Quantum Field Theory (QFT).
- GTR has given us a successful theory of the cosmos and its evolution on the largest scales.
- QFT has brilliantly captured the physics at the smallest length scales that we can probe.
Gravity

- Gravity is the most ubiquitous force in nature.
- Newton’s law of gravitation the first “universal” law.
  \[ \vec{F} = \frac{G M_1 M_2}{r^2} \hat{r} \]
- Describes the motion of planets (and Mangalyaan!).
- However, it has a certain range of validity.
- Breaks down under two different sets of extreme circumstances
Limitations of Newton’s Law

- Not applicable when objects move very fast (e.g. pulsars).
- Nor when the density becomes large (e.g. at the centre of galaxies).
Einsteinian Gravity

- *Einstein succeeded in (partially) overcoming these limitations.*

- *His description of gravity applicable at high velocities (relativistic).*

- *Also for moderately high densities (e.g. neutron stars).*

- *Accomplished this not just by tweaking Newton’s Law a bit.*
Einsteinian Gravity

- Instead radically overhauled the very framework for describing gravity.
- Einstein tied up the description of gravity with the geometry of space and time!
- Spacetime no longer a passive stage for the drama of physical events.
- It becomes an active participant - responding to its contents.
Gravity and Geometry
Gravity and Geometry

- Einstein’s theory in a very different mathematical framework from Newton’s.
- In terms of a metric $g_{\mu \nu}(\vec{x}, t)$ - measure of distance and curvature of spacetime.
- Einstein’s equations determine the metric in terms of the matter/energy.
- Remarkably enough, reduces to Newton’s law for low densities and velocities.
Gravity and Geometry

- This picture of gravity in terms of geometry is a successful description all the way to the largest scales of the universe - million times the milky way.
Gravity in a Quantum World

- Physical reality is QM’cal - classical measurables have statistical outcomes.
- Is spacetime a statistically averaged notion?
- How can we sensibly talk of quantum fluctuations of the metric?
- How do we reconcile Einstein’s picture with Quantum Mechanics?
Limitations of Einstein’s Law

- Related to the breakdown of Einstein’s description as you enlarge its scope.
- Again under two sets of limiting circumstances.
  - At very short (“planckian”) distances and at ultra-high densities.
  - The equations themselves exhibit the breakdown - develop singularities.
Who cares about Quantum Gravity?

- Thus the need for a description that overcomes these limitations - A Quantum theory of Gravity.
- Need Qtm. Gravity to investigate the birth of the universe or understand black holes.
Quantum Gravity as a QFT?

- Superficially analogous situation in electrodynamics.
- Maxwell’s laws give a very good classical description.
- Breaks down at atomic scales or large electric/magnetic fields.
- However, a highly successful theory of Quantum Electrodynamics exists.
Limitations (Contd.)

- Might hope to quantise the gravitational field $g_{\mu\nu}(\vec{x}, t)$ in a similar way.
- Here we face the limitations of QFT.
- All attempts at a QFT like description of gravity seem to fail.
- Presumably because the gravitational field describes the geometry of spacetime itself.
- Quantising geometry is even more subtle!
The Reluctant Radical: String Theory

- String Theory originated as a “conservatively radical” modification of QFT.
- Quantum dynamics of extended objects.
- Delicately spun framework - highly constrained - more so than QFT.
- Showed early promise in addressing some of the difficulties QFT had w.r.t. gravity.
- But didn’t really address qtm. spacetime.
String Theory and Qtm. Spacetime

- Proposal by Maldacena for the quantum behaviour of a large class of spacetimes.

- QM’cally, (asymptotically) anti-deSitter spacetimes are described by a QFT!

- But in one lower dimension!!

- This QFT is not a quantisation of $g_{\mu\nu}(\vec{x}, t)$; but of fields like in electromagnetism.
Spacetime as a Hologram?

- *Notion of Qtm. Gravity being “holographic.*
- *Everything about Quantum AdS spacetime encoded in the QFT.*

The spacetime itself is encrypted in a somewhat mysterious way in the hologram QFT. Quantum fluctuations in the QFT must correspond to fluctuations of spacetime.
Black Holes and their Puzzles

- Formed from the intense gravitational pull of a dying star.
- Matter is compressed to a superdense point - described by a unique solution to Einstein’s equations.
Black Holes

- Remarkable theoretical laboratory for studying quantum effects in gravity.

- Hawking’s Discovery: Any QM’cal description of black holes will have to assign them a temperature and entropy.

\[ T = \frac{\hbar}{8\pi GM} \quad S = \frac{A}{4\hbar G} \]

- Suggests that they should have internal structure - conflicts with uniqueness.
Remarkably enough, the boundary QFT can describe the physics of black holes in AdS.

It is a state at finite temperature in the QFT!

Temperature is the Hawking Temperature of the Black Hole.

One obtains a description of the microstates that give the Bekenstein-Hawking Entropy of black holes.

\[ S_{BH} = \frac{A}{4\hbar G_N} \]
Quantum Spacetime

- Coming back to the original quest.... what have we learnt?
- Quantum Gravity is probably holographic in nature. Can thus understand B-H entropy microscopically.
- The notion of space and time are probably emergent in a classical limit - like water from atoms.
- But need to decode this hologram better.
- Is this how quantum spacetime behaves in all cases?
On the State of our Understanding

- In the meanwhile this connection has uncovered striking new facts about QFTs which are strongly interacting.

- It is the next best thing to having “experimental” evidence: make predictions about behaviour of theories which predate string theory - QFT and GTR. Highly nontrivial and falsifiable!

- Laying bare the underlying mechanism for this connection will give new insight into QFTs - potentially powerful in many real world contexts.

- Thus, the 21st century will see the twin peaks of 20th century finally linked together in a grand Himalayan panorama.
“In our acquisition of knowledge of the universe (whether mathematical or otherwise) that which renovates the quest is nothing more or less than innocence....It alone can unite humility with boldness so as to allow us to penetrate to the heart of things....This unique power is in no way the privilege given to `exceptional talents'... It is not these gifts, ..., that enable one to surmount the invisible yet formidable boundaries that encircle our universe. Only innocence can surmount them...”

— Alexandre Grothendieck
See you on the Trek!
Two Pictures

- How did this striking connection emerge?

- From two pictures within string theory for the same object - D-branes.

- In terms of open strings (gauge theory) as well as closed strings (gravity).

- Consistency demands duality.
Two Pictures (Contd.)

(3+1) Dim. Brane. w/ N=4 SYM Excitations

Open String Picture
- Only Yang-Mills Excitations

Closed String Picture
- Gravity and Other Stringy Excitations

Black hole geometry of 3-brane (transverse dimension shown)