

Duality and the nature of quantum space-time

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INTRODUCTION

Strings provide a working theory of quantum gravity existing in harmony with particle physics

Successes include computations of quantum graviton scattering, new models of beyond-standard-model particle physics based on branes, computation of black hole entropy

A powerful new discovery : Duality

- ▶ An unexpected equivalence between two systems, which a priori look completely unrelated, if not manifest opposites.
- ▶ Large and Small (T-duality)
- ▶ Gravitational and non-Gravitational. (Gauge-String duality)

Unification and Duality

- ▶ They are both powerful results of string theory. They allow us to calculate things we could not calculate before.
- ▶ Unification : We asked for it and found it. We kind of know why it had to be there.
- ▶ Duality : We didn't ask for it. We use it. We don't know what it really means.

Unification v/s Duality

- ▶ Unification has an illustrious history dating back to the days of Maxwell.
- ▶ Before Maxwell, we thought magnets attracting iron on the one hand and lightning on the other had nothing to do with each other
- ▶ After Maxwell : Magnets produce B -field. Electric discharge in lightning is caused by E -fields. The coupled equations of both allow fluctuating E, B -fields which transport energy travelling at the speed of light. In fact light is electromagnetic waves.

Unification v/s Duality

- ▶ Einstein tried to unify gravity with quantum physics.
- ▶ String Theory goes a long way.
- ▶ Computes graviton interaction probabilities.

Unification v/s Duality

- ▶ We think that asking the question of whether something is large or small has a unique answer.

- ▶ T-duality of string theory says : **Not always !!**

Unification v/s Duality

- ▶ We think, as physicists, we know whether we are dealing with gravity or not.
- ▶ In applications to the real world, gravity dominates at large distances. Non-gravitational forces dominate at small distances.
- ▶ Gauge-String duality says a theory of quantum gravity in 10 dimensions is equivalent to a generalized theory of photons in 4 dimensions !!

OUTLINE

- ▶ Large-small Duality (T-duality of strings)
- ▶ Gauge-String Duality
- ▶ What is this telling us ?
Something deep about space-time... We think.

T-duality

- ▶ Consider string theory in 10 dimensions.
- ▶ Let us say X^0, X^1, \dots, X^8 are infinite.
- ▶ But X^9 is finite.
- ▶ Further let us say : $X^9 = X^9 + 2\pi R$.

T-duality

- ▶ Equivalently, X^9 is a coordinate along a circle.
- ▶ The physical states include particles with different amounts of momentum along the circle.
- ▶ Any state in the spectrum has a definite momentum along X^9 .

T-duality

- ▶ Momentum is related to the waveform on the circle.
- ▶ Because the waveform is periodic, with periodicity $2\pi R$, the wavelength is quantized.
- ▶ There is a momentum quantum number n , and $p_n = \frac{n}{R}$

T-duality

- ▶ Because this is a string theory, the string can wind around the circle.
- ▶ It can wind multiple times.
- ▶ Any state has a winding number.

T-duality

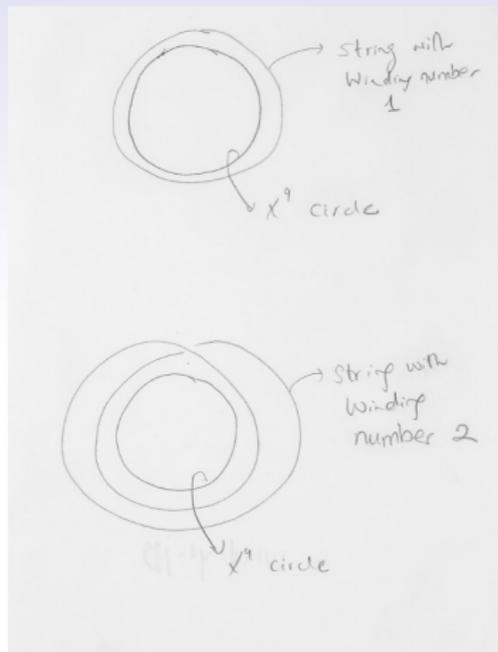


Figure: String Winding Number

T-duality

- ▶ Any state $\Psi(n, m; q)$ has a momentum quantum number n , a winding quantum number m and other quantum numbers q .
- ▶ The Energy of the state is $E(R, n, m; q)$.
- ▶ T-duality says that

$$E(R, n, m; q) = E\left(\frac{1}{R}, m, n; q\right)$$

- ▶ Physics on circle of radius R and $1/R$ are identical, as long as momentum and winding modes are exchanged !!

Gauge-String Duality

- ▶ The two-dimensional sphere S^2 is described by the equation

$$x_1^2 + x_2^2 + x_3^2 = 1$$

- ▶ The five-dimensional sphere S^5 is described by the equation

$$x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 + x_6^2 = 1$$

- ▶ Change some signs in the equation for S^5 and you get a space called anti-de-Sitter space AdS_5 .

Gauge-String Duality

- ▶ Consider string theory on a ten dimensional space, five of which are form S^5 and the remaining five of which form AdS_5 .
- ▶ This theory manifestly contains gravity and is a quantum theory.
- ▶ Gauge String Duality says : **It is in fact equivalent to a theory in 4 dimensions.**

Gauge-String Duality

- ▶ QCD is a theory of quarks and gluons, where there are 3 colours of quarks and $3 \times 3 = 9$ types of gluons.
- ▶ Colour is a generalization of charge. The gluons are generalizations of photons, i.e. light
- ▶ A further generalization is one where you have N colours.

Gauge-String Duality

- ▶ A theory of N -colour gluons is actually equivalent to String Theory on $AdS_5 \times S^5$, in the limit, of N going to infinity.
- ▶ A consequence of D-Brane physics, called the AdS/CFT correspondence or the Maldacena correspondence, and an example of Gauge-String Duality.

How can this be ?

Gauge-String Duality

- ▶ The S^5 part of the 10 D space is compact.
- ▶ We can Fourier transform the on the S^5 to write the theory in terms of the remaining non-compact space AdS_5 .
- ▶ Euclidean AdS_5 is a 5-ball, whose boundary is a 4-sphere.

Gauge-String Duality

- ▶ This AdS/CFT correspondence is a bulk-boundary correspondence.
- ▶ Gravity, Black Holes, gravitons live in the bulk.
- ▶ Gluons live on the boundary.
- ▶ All the physics of the bulk can be reproduced by the physics of the gluons.

Gauge-String Duality

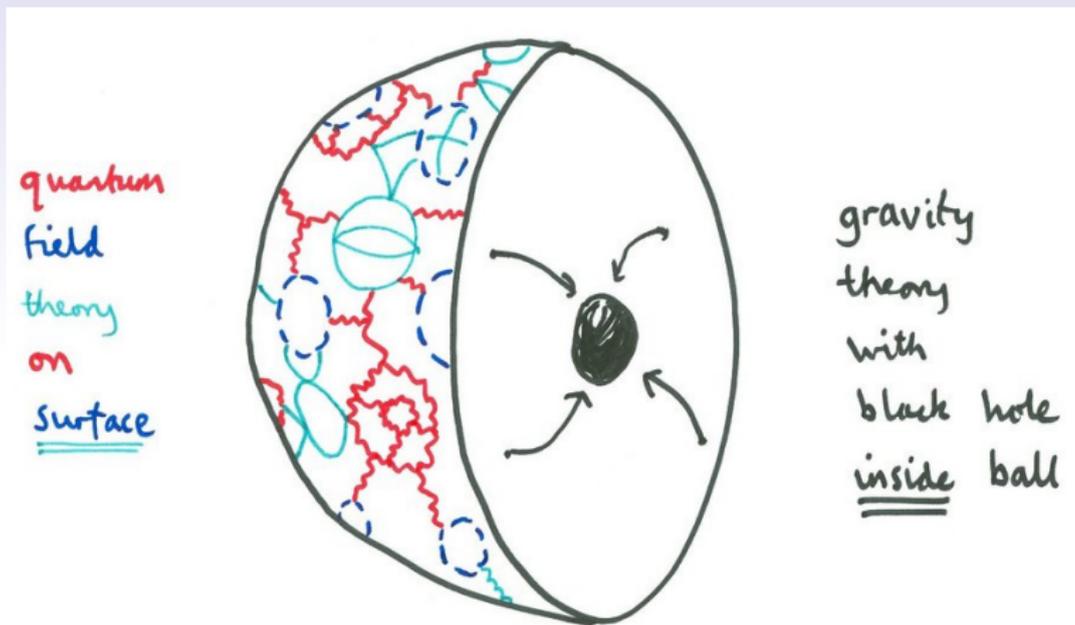


Figure: Bulk Boundary correspondence

What does it mean ? T-duality

- ▶ In ordinary QFT in 10 D spacetime which includes a circle, it is impossible to have an equivalence of large and small
- ▶ While string theory connects to 10D QFT, the QFT is a low-energy approximation. Going to higher and higher energy involves making the QFT more and more complicated.
- ▶ Large-Small duality means that the QFT way of thinking about spacetime physics using $\Phi(x, y, z, t)$ misses some crucial equivalences.

What does it mean ? T-duality

- ▶ If we find the right string theory which looks like the standard model below a TeV, SUSY theory around a TeV , more complicated SUSY theory at higher energy scale ...
- ▶ Then the full string theory is more than the sequence of QFTs ..
- ▶ It has qualitatively new features such as large-small equivalence in the extra dimensions which is not manifest in the sequence of QFTs

What does it mean ? Gauge-String duality

- ▶ The theory looks like a 5D theory of quantum gravity.
- ▶ Yet its physical degrees of freedom are 4D.
- ▶ So perhaps there is a way of thinking about the gravity where it is manifest that the fifth dimension is not real; so that we would not even begin to describe the bulk theory by $\Phi(x_1, x_2, x_3, x_4, t)$

What does it mean ? Gauge-String duality

- ▶ Perhaps there is a formulation of gravity where it is manifest that the theory is gravitational and four dimensional ?
- ▶ We have no idea what such a formulation might look like.
- ▶ Whatever the gravity field is doing in 4-directions determines what it is doing in the fifth ? A new type of space-time uncertainty ? Analogous to the Heisenberg uncertainty which taught us that x, p are redundant. Only one could be specified.

A new kind of space-time uncertainty ?

- ▶ There are hints from black hole physics that something new is needed.
- ▶ Hawking Radiation poses a paradox for the standard understanding of when quantum gravity effects can be ignored and QFT can be used as a low energy approximation.
- ▶ String Theory and duality tell us that a full theory of quantum gravity such as string theory can have non-localities very unlike our naive expectations based on ordinary quantum fields.

Some questions

- ▶ Implications of duality and associated non-localities for :
 - ▶ Black Holes
 - ▶ Early universe
 - ▶ Vacuum selection problem.