String Theory: Basic Facts and Recent Developments

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String theory: Basic Facts

1. Fundamental constituents of matter are different vibrational states of a string.

2. String theory is formulated consistent with the principles of

a. Quantum mechanics and

b. Special theory of relativity.

3. One of the vibrational states of such a string has the properties expected of a graviton, – the mediator of gravitational force.

$\rightarrow$ String theory automatically contains gravity.

4. The requirement of satisfying the laws of quantum mechanics and special theory of relativity also puts strong constraints on the theory.

a. Dimension of space = 9,   time=1   (instead of 3 + 1)

b. In (9+1) dimensions there are only five fully consistent string theories.

5. Often a string theory contains objects other than the fundamental strings, *e.g.* *p*-dimensional extended objects known as D-*p*-branes.

6. The problem of having six extra dimensions can be resolved using the idea of

Compactification

Take 6 of the 9 dimensions to describe a small compact space instead of infinite flat space.

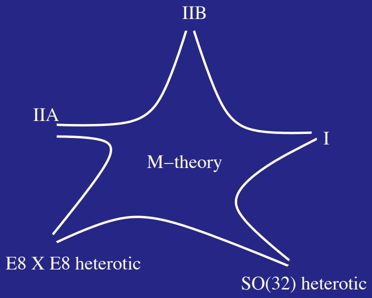
When the size of the compact space is smaller that the resolution of the most powerful microscope, the space will appear to be 3 dimensional.

7. There are many possible ways to compactify string theory.

These different compactifications correspond to different phases / vacua of string theory.

The apparent laws of nature *e.g.* spectrum and interactions of the elementary 'particles' depends on which phase of string theory we are in.

8. Duality: Often a given physical phase can be viewed in more that one ways, – as different compactifications of different string theories.



String theory is like a big room with five windows, with different objects in the room representing different phases and the five windows representing the five string theories.

9. AdS/CFT correspondence: Maldacena; $\cdots$

– an observation that some phases of string theory actually have dual descriptions as conventional field theories without gravity.

String theory on AdS space

$$ds^2 = \frac{dz^2 + \eta_{\mu\nu} dx^\mu dx^\nu}{z^2}$$

$\times$ a compact space

$$\Updownarrow$$

a conformally invariant quantum field theory living at the boundary $z = 0$.

10. Some phases of string theory look very similar to the theory that describes our world.

e.g. **besides gravity they also contain gauge interaction, chiral fermions etc.**

The main obstacle to connecting string theory to experiment is the existence of huge number of phases of string theory.

– string landscape

It is even conceivable that different parts of the universe are in different phases of string theory, and we happen to see one particular phase because we live in some particular region of the universe.

Unless we can identify precisely which phase describes the environment in which we live, we cannot make precise predictions which can be tested in experiment.

– still an unresolved problem.

Given this situation it would seem that until we can find the right phase of string theory which describes our world, there cannot be any further progress.

Despite this there has been significant progress in various directions, often by cleverly turning the landscape to our advantage.

Recent Developments

1. Conceptual issues

2. Developments within string theory

3. Exploring the landscape

4. Applied string theory

5. String motivated / induced developments in quantum field theory

I shall try to present few examples of each type.

1. Conceptual issues

Various theoretical issues, in particular those in quantum gravity, are common to either all or a wide variety of phases of string theory.

These issues can be addressed without knowing which particular phase of string theory describes our world.

Examples:

a. Gravity as an effective theory.

b. Black hole thermodynamics

a. Can gravity be an effective theory that arises out of some other basic degrees of freedom?

Proposal: The gravitational force may be regarded as the ‘entropic force’ – force obtained as the result of a system trying to maximize its entropy.

Verlinde

What could be the basic microscopic degrees of freedom whose statistical mechanical force generates gravity?

String theory provides a clue.

– open strings, – string with free ends.

This proposal is still in its infancy and needs to be explored further.

b. Understanding the origin of black hole thermodynamics.

For more than 30 years it has been known that black holes carry non-zero entropy.

Can we find a statistical interpretation of this entropy as $\ln \Omega$ where Ω is the number of quantum states of the system?

15 years ago Strominger and Vafa answered this in the affirmative for extremal black holes carrying large charges.

1. Does the agreement hold when the charges are finite?

2. Does this agreement hold for other quantities like the distribution of global quantum numbers among the quantum states?

Answer seems to be yes.

A.S.

Can we directly use classical (black hole) solutions in string theory to understand the microstates?

Mathur, $\cdots$

– needs developing techniques for quantizing the space of classical solutions in string theory.

de Boer, El-Shawk, Messamah, Van den Bleeken

2. Developments within string theory

Find new results in string theory which enhances our knowledge and understanding of the theory.

Example:

a. Theory of membranes in 11 dimensional supergravity

Bagger, Lambert; Gustavson, $\cdots$

Aharony, Bergman, Jafferis, Maldacena

This has now been understood not only in flat 11 dimensional space-time, but also for membranes in complicated background. Sparks

These theories are dual to string theory on AdS_4 times a compact space, – close cousin of the four dimensional de Sitter space in which we live.

b. Exact results for certain higher derivative corrections to the low energy effective action (including all loop and non-perturbative corrections) have been found

Green, Miller, Russo, Vanhove

c. Some exact classical solutions in open string field theory have been found.

Schnabl $+\cdots$

– describe new configurations of D-branes.

3. Exploring the landscape

In absence of a general principle, identifying the precise phase of string theory in which we live seems to be a difficult problem.

However it is still a fruitful exercise to see how close we can get to the phase in which we live.

– could give us a clue to where and how to look for the real world in the landscape, and how our part of the universe could have arrived there

Most well studied cases: F-theory models with flux

– a specific class of compactifications of type IIB string theory.

i) First construct type IIB on $\mathrm{AdS}_4 \times$ Calabi-Yau

ii) Lift AdS_4 to dS_4 by adding some supersymmetry breaking anti-branes

Kachru, Kallosh, Linde, Trivedi

It is important to study in detail the effect of the anti-branes.

Bena, Grana, Halmagyi

– may be more subtle than was previously thought.

Many other studies of type IIB / F-theory compactification have been carried out during the last few years yielding models closer to the observed world.

Beasley, Heckman, Vafa; $\cdots$

But it is also important to explore other possible ways of getting de Sitter vacua in string theory.

e.g. compactification of type IIA string theory.

Andriot, Goi, Minasian, Petrini

Another active area of research: string cosmology

Most studied case: Inflation via brane - anti-brane annihilation.

Inflationary phase: Slowly moving brane-antibrane system, separated along some compact directions

End of inflation: brane-antibrane annihilation via collision.

Main issue: How to get an extremely flat inflaton potential?

– highly sensitive to Planck scale physics

Still no completely natural mechanism

Baumann, Dymarsky, Kachru, Klebanov, McAllister

It is important to also explore other aspects of string cosmology.

Kounnas, Estes, Partouche

4. Applied string theory

String theory landscape includes many phases which do not describe the universe we live in.

However many of these phases may have phenomena similar to what we observe in our universe, and hence can be used to study these phenomena.

Examples:

a. Dynamics of strongly coupled gauge theories

Policastro, Son, Starinets; Sakai, Sugimoto; $\cdots$

b. Superconductivity **Gubser; Hartnoll, Herzog, Horowitz**

– do not require us to construct a phase which at $\sim$ TeV scale is described by the standard model.

Basic tool: AdS/CFT correspondence

We consider an appropriate gravitational background with asymptotic AdS geometry

By AdS/CFT correspondence this describes a conformal field theory living on the boundary of AdS.

By choosing the gravitational background appropriately one can try to ensure that the CFT at the boundary describes the physics we are interested in.

e .g. superconductivity requires a U(1) gauge symmetry that is unbroken near the boundary of AdS space but is broken in the interior by non-vanishing background value of a charged field.

Some results found using this approach

1. For a wide variety of strongly coupled conformally invariant gauge theories with AdS dual, the finite temperature low energy dynamics is controlled by hydrodynamic equations with universal coefficients.

Policastro, Son, Starinets

Bhattacharyya, Hubeny, Minwalla, Rangamani

2. Using dual AdS description one can find examples of quantum systems in 2+1 dimensions with non Fermi liquid behaviour.

Liu, McGreevy, Vegh; $\cdots$

In ICHEP10: Niarchos, Wallon, Skenderis

5. String motivated developments in quantum field theory

Examples:

a. Exact results for anomalous dimensions of operators in $\mathcal{N} = 4$ super Yang-Mills theories in the planar limit.

$\cdots$; Gromov, Kazakov, Vieira

b. Exact results for all tree amplitudes and many constraints on loop amplitudes in $\mathcal{N} = 4$ supersymmetric Yang-Mills theories.

c. New results on $\mathcal{N} = 2$ supersymmetric Yang-Mills theories.

Gaiotto; $\cdots$

– many new models and exact results for low energy effective action, Wilson line expectation values etc.

d. Finiteness of $\mathcal{N} = 8$ supergravity?

Talks at ICHEP10

Korchemsky: Tree level scattering amplitudes in $\mathcal{N} = 4$ supersymmetric Yang-Mills theory have not only the usual conformal symmetry but also dual superconformal symmetry acting on momentum space

– strong constraints on amplitudes.

Rychkov: Crossing symmetry of 4D conformal field theories can be used to put bounds on anomalous dimensions and operator product expansion coefficients.

– relevant for constraining technicolour and unparticle models.

Johansson: Simple rules for constructing gravity amplitudes from Yang-Mills amplitudes.

Vanhove: Used these rules to argue that the cancellation of ultraviolet divergence of $\mathcal{N} = 8$ supergravity will stop at 7 loops unless there are some 'accidental' cancelations.

Alternative theories of gravity at ICHEP10

Barrau: Loop quantum gravity and its application to cosmology for homogeneous universe.

Ward: Asymptotically safe gravity after resummation of Feynman graphs.

Conclusion

String theory has made progress in diverse directions.

1. Formal

2. Applied

The history of the subject shows that often the development in one leads to development in the other.

e.g. string theory and quantum field theory

Thus it is important to keep an open mind and try to make progress in whatever direction one can.