Search for a Unified Theory

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One of the basic questions that has been around almost since the beginning of civilization is:

What are the basic constituents of matter and what are their properties?

The aim of this talk is to summarize our current understanding of this subject and attempts to go beyond.

Modern understanding of the ultimate constituents of matter

Molecules

$\downarrow$

Atoms

$\downarrow$

Nucleus Electrons

$\downarrow$

Protons Neutrons Electrons

$\downarrow$

Quarks Gluons Electrons

$\cup$

Zoo of elementary particles

These elementary particles interact via various kinds of forces.

1. **Gravitational**
2. **Electromagnetic**
3. **Strong**
4. **Weak**

These forces give rise to complicated interaction between elementary particles.

$\rightarrow$ **measured by studying how the elementary particles scatter off each other.**

It turns out that the effect of gravitational force between elementary particles is negligible compared to the other forces.

To see this one can compare the electrostatic force between two protons with the gravitational force between two protons at rest.

Result:

$$\frac{\text{Grav. Force}}{\text{Elec. Force}} = \frac{Gm_p^2/r^2}{e_p^2/r^2} \sim 10^{-36}$$

G: Newton's gravitational constant (6.67×10^{-8} cm^3/gm sec^2)

m_p: proton mass (1.67×10^{-24} gm)

e_p: proton charge (4.8×10^{-10} e.s.u.)

Similarly all other forces are also much larger than the gravitational force.

For developing a theory of elementary particles and their forces, we must remember two important points:

1. In typical experiments elementary particles move very fast.

   Hence we need to use special theory of relativity.

2. The elementary particles are very small.

   Hence we need to describe them using quantum mechanics.

There is a mathematical theory, known as the standard model, which describes all the elementary particles and their forces if we leave out gravity.

This theory is based on the principles of quantum mechanics and special theory of relativity.

In principle this theory can be used to calculate the result of any experiment that we wish to perform involving elementary particles.

So far the standard model has been extremely successful in explaining almost all observed experimental data.

List of elementary particles according to the 'standard model':

QUARKS

u^1, u^2, u^3 d^1, d^2, d^3 c^1, c^2, c^3

s^1, s^2, s^3 t^1, t^2, t^3 b^1, b^2, b^3

LEPTONS

(e, ν_e) (μ, ν_μ), (τ, ν_τ)

MEDIATORS

gluons: $g_1, \dots g_8$ Photon: γ

W^+, W^-, Z

HIGGS ϕ

Despite these successes, the standard model cannot be the final story.

First of all there are some experimental results which do not agree with the predictions of the standard model

Example: Mass of the neutrinoes

However these can be easily explained by a minor modification of the standard model without giving up any of the basic principles.

There is a more serious reason why standard model is not complete.

It does not contain one important force that we observe in nature, namely, the

GRAVITATIONAL FORCE

In all present day experiments gravitational force between elementary particles is extremely small and beyond measurement.

But any complete theory must account for all forces, however small.

Can we modify the standard model so as to include gravity?

The standard model is based on the principles of special theory of relativity and quantum mechanics.

$\rightarrow$ we need to first make the theory of gravity consistent with the principles of

1. special theory of relativity

2. quantum mechanics.

The first step – making gravity consistent with special theory of relativity – was carried out by Einstein in 1915.

$\rightarrow$ general theory of relativity.

The second step, – combining this with quantum mechanics – turns out to be extremely difficult.

String theory provides a possible way out of this problem.

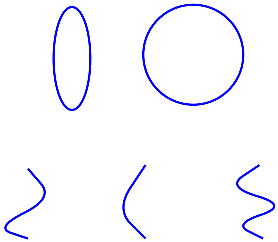
The rest of this talk will be the story of

String theory

- **Why do we need it?** $\surd$
- **What is it?**
- **What has it achieved so far?**
- **What has it not achieved so far?**

String Theory

Different elementary 'particles' are different vibrational states of a string.



Typical size of a string $\sim 10^{-33}$ cm

This is much smaller than the length scale that can be probed by any present day experiment

($\sim 10^{-17}$ cm.)

Thus to a present day experimentalist the states of the string will appear to be particle like objects.

We need to formulate a theory of strings consistent with the principles of

1. Quantum mechanics.

2. Special theory of relativity.

It turns out that as a consequence of these two requirements strings automatically exert gravitational force on each other.

– string theory is automatically a quantum theory of gravity!

However string theory is so tightly constrained that we cannot adjust it to suit our needs.

In particular we cannot demand that

the dimension of space is what we observe in nature (i.e. 3),

or that

different vibrational states of the string behave like the elementary particles we observe in nature.

We have to take what string theory gives us.

First of all one finds that there are <u>five</u> consistent string theories.

They differ from each other in the way the string vibrates.

Furthermore one finds that in each of these five string theories the dimension of space is

9

$\rightarrow$ **requires 9 coordinates to describe a point in space instead of the usual 3 coordinates.**

This does not describe what we see in nature.

This however is not the end of the story.

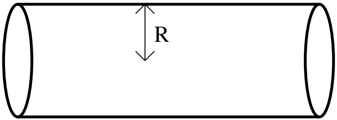
The intrinsically 9 dimensional theory can be made to appear as a 3 dimensional theory by using an old idea known as

Compactification

I shall try to explain this idea in the context of an imaginary world which has only two dimensions.

Consider a 2 dimensional world, with 2-dimensional people living in it.

Take the two space coordinates to describe the surface of an infinitely long cylinder of radius R instead of an infinite plane.



If R is very large (larger than the range of the most powerful telescope) then the two dimensional space will appear to be infinite in both directions.

Now consider the opposite situation where R is very small.

The world looks one dimensional as $R \rightarrow 0$.

As long as R is smaller than the resolution of the most powerful microscope, the world will appear to be one dimensional.

The same idea works in making a 9 dimensional space look 3 dimensional.

Take 6 of the 9 space directions to be small, describing a compact space K.

When the size of K is sufficiently small, the space will appear to be 3 dimensional.

Mathematical consistency puts strong restriction on what kind of spaces K we can use for compactification.

Nevertheless there are many different spaces K which can be used for compactification.

Thus even if we begin with a specific string theory, upon compactification there are more possibilities.

These different possibilities may be regarded as different <u>phases</u> of the underlying string theory.

An analogy: The single theory, describing the H_2O molecules and the force between them has different phases in the form of ice, water and steam.

Similarly a string theory has many many phases, characterized by many many different choices of K.

Just as the environment inside ice, water and steam are very different, similarly the 3-dimensional environment for different choices of the compact space K will be very different.

Even the ‘fundamental constants of nature’ like the number of elementary particles and their masses and charges will appear to be different in different phases.

For some choices of K the 3-dimensional environment is very similar to the nature that we observe.

$\rightarrow$ has elementary 'particles' and forces similar to what we observe in nature.

Thus besides solving the problem of formulating the quantum theory of gravity, string theory also offers the possibility of combining this with a theory of elementary particles and their forces.

From what we have described so far, it would seem that there are altogether five consistent string theories, each with many different phases.

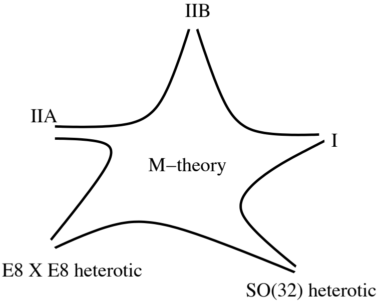
This was our understanding of the subject till the early 1990’s.

However subsequent research has shown that the five different string theories are not really different, but they all give different descriptions of the same underlying theory.

This theory has been given the name

M-theory

Different phases of M-theory can be schematically represented as different points inside a room with five windows.



The five windows are the five string theories.

Through each window we see only a small part of the room.

If there is no overlap between the different parts we see through different windows, then we would not know that we are looking into the same room.

$\rightarrow$ **describes the situation in the early 1990's.**

However once we begin seeing deep enough into the room through each window, we may glimpse some objects through more than one window.

We may then realize that all the windows open into the same room.

$\rightarrow$ **describes the development since mid 1990's.**

One of the main directions of research in string/M theory involves attempts to open up new windows into this room.

The most famous example of such a window is AdS/CFT correspondence. Maldacena

– some phases of M-theory may be described by quantum theories of point particles!

Another example: 10+1 dimensional supergravity

– a particular phase of M-theory may be described by a theory in 10 space dimensions.

What has string theory not achieved yet?

- Finding a phase of string theory that has exactly the elementary particles we observe in nature remains an open problem.

  It is generally believed that the phases we have discovered so far are only a tip of the iceberg and there are many more phases yet to be found.

- We must also explain why nature exists in one particular phase and not in any other phase.

Both issues are currently under active investigation by many researchers.

I shall end this talk by describing a speculative solution of the second issue.

According to this speculation, no single phase of M-theory is special.

Different parts of the universe exist in different phases, and we see a particular phase of M-theory because we happen to live in a particular region.

Analogy: We can have a big reservoir of H_2O molecules with different parts of the reservoir existing in different phases – some part as ice, some as water and some as steam.

For the reservoir of H_2O molecules the system will eventually come to thermal equilibrium, and all parts of the system will be in the same phase.

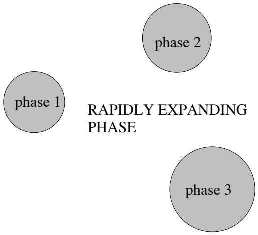
To prevent this we need some driving mechanism, e.g. some heating and cooling systems in different parts of the H_2O reservoir.

What is the mechanism that prevents our universe from coming to thermal equilibrium?

Answer: force of gravity!

Many phases of M-theory have the property that they expand rapidly according to the laws of general theory of relativity.

This rapid expansion separates the different parts in different phases very quickly, preventing the system from coming to thermal equilibrium.



As the universe expands more and more space is created making room for new phases to form.

Since this process continues for infinite time, it is possible that every phase of M-theory will be realized in some region of the universe.

Thus no phase of M-theory gets a special role in the universe as a whole, although in any given region one phase will appear to be special.

The side stories

What I have described so far is the main story of string theory.

However like the great epics, string theory also has many side stories

– possible application of string theory to solve problems in other related fields.

1. Understanding black hole entropy

2. String theory approach to solving problems in quantum field theory (theory of point particles).

3. String theory applications to Mathematics.

All these make string theory a rich subject to study and explore.

Summary

String theory is an attempt to formulate a theory of nature that would explain the existence and various properties of all the elementary particles and their forces.

It is based on the idea that different elementary particles are different vibrational states of a string.

String theory provides us with a consistent quantum theory of gravity, and possibly of other forces as well.

Although initially it was thought that we have five consistent string theories, each existing in many different phases, we now know that they describe different phases of the same theory, – called the M-theory.

However, finding the phase of M-theory that describes the world around us remains a challenging problem for the future.