# SEARCH FOR A UNIFIED THEORY

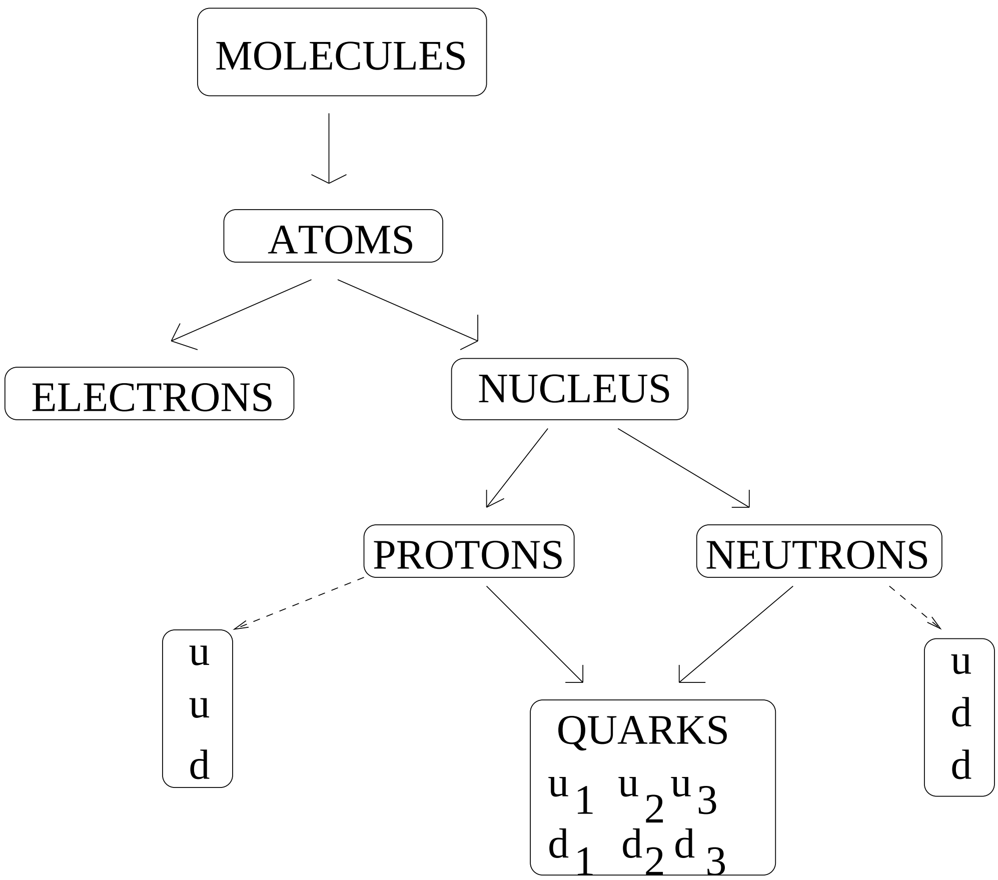
An attempt to understand the

elementary constituents of matter

and the

forces (interactions) operating between them

## Modern understanding of the ultimate constituents of matter



These elementary particles **interact** via various kinds of forces.

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

It turns out that in studying the physics of elementary particles, we can ignore the effect of gravitational force.

For example, one can compare the electrostatic force between two protons with the gravitational force between two protons at rest.

Result:

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

G: Newton's Constant ($6.67 \times 10^{-8}$ c.g.s.)

$m_p$: proton mass ($1.67 \times 10^{-24}$ gm)

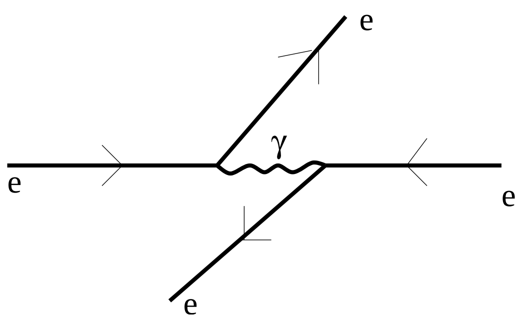
$e_p$: proton charge ($4.8 \times 10^{-10}$ e.s.u.)

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

In quantum theory all forces are mediated via the exchange of mediator particles.

- Electromagnetic force is mediated by a particle known as the photon ($\gamma$)
- Strong force is mediated by eight different particles known as gluons ($g_1, \ldots g_8$)
- Weak force is mediated by three particles, denoted by $W^+$, $W^-$ and $Z$.

Example: Scattering of two electrons via electromagnetic interaction



We must add the mediator particles to our list of elementary particles.

Besides quarks, electrons and mediators, there are also other elementary particles which are produced by cosmic rays, radioactive decays, collision of high energy particles, etc.

They must also be added to the list.

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

This model, in principle, can be used to predict the result of any experiment that we wish to perform involving these constituents of matter.

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

Particle content of the standard model:

## QUARKS:

$u^1, u^2, u^3$ $\quad$ $d^1, d^2, d^3$ $\quad$ $c^1, c^2, c^3$

$s^1, s^2, s^3$ $\quad$ $t^1, t^2, t^3$ $\quad$ $b^1, b^2, b^3$

## LEPTONS

$(e, \nu_e)$ $\quad$ $(\mu, \nu_\mu)$, $\quad$ $(\tau, \nu_\tau)$

## GAUGE BOSONS

gluons: $g_1, \ldots g_8$ $\quad$ Photon: $\gamma$

$W^\pm$, $\quad$ $Z$

## HIGGS $\phi$

## Theoretical framework behind the standard model

- Quantum mechanics
- Special theory of relativity
- Laws of electromagnetism and their generalization to strong and weak forces

This framework in known as gauge theory.

Despite its enormous success, the standard model does not give a complete description of the elementary constituents of matter and their interactions.

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

Gravitational force

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

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

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

There is a mathematically consistent classical theory of gravity, consistent with the principles of relativity.

This theory is known as

General theory of Relativity

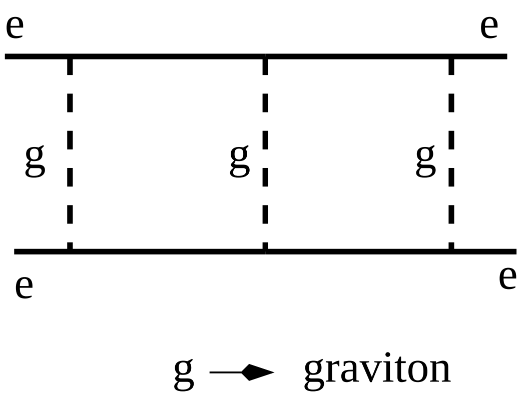
This is a classical theory.

Why can't we quantise it and combine it with the standard model?

Naive quantization

→ gravity is mediated by a new kind of elementary particle, called graviton.

But in this theory if we try to calculate the probability of two electrons to scatter via the exchange of multiple gravitons, the answer turns out to be infinite!

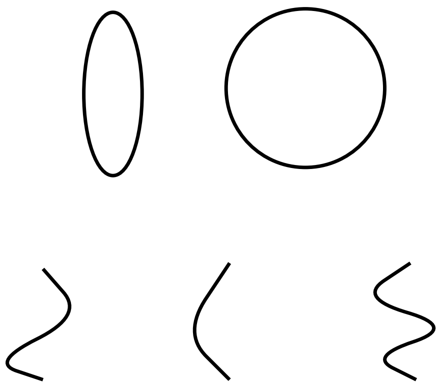



In actual practice, this probability is extremely small.

Thus the naive quantization method fails.

# 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

($\sim 10^{-16}$ cm.)

Thus to the present day experimentalists the elementary string states will appear to be point-like.

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

1. Quantum mechanics.

2. Special theory of relativity.

$\rightarrow$ strong constraints on the type of string theory we could have.

1. Dimension of space = 9

   (instead of 3)

2. Only five distinct possible string theories:

   Type I, Type IIA, Type IIB,

   $E_8 \times E_8$ heterotic, SO(32) heterotic

These five string theories differ from each other in the type of vibrations which the string performs.

Having 9 space dimensions instead of 3 seems to be a serious problem.

If we leave aside this problem for a moment, then string theory provides us with some good things.

- One of the vibrational states of string theory describes a graviton, – the mediator of gravitational interaction.

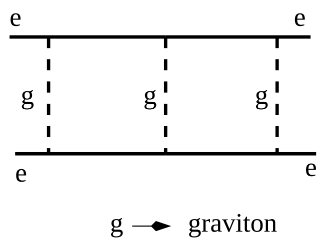
  Thus string theory automatically contains gravity!!!

- Furthermore, string theory calculations do not suffer from any infinities of the type we encounter while trying to directly quantize general theory of relativity!

→ A finite quantum theory of gravity!!!

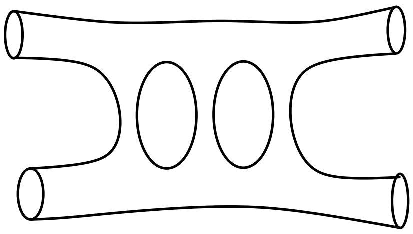
Origin of finiteness of string theory:

Consider the earlier divergent diagram




Divergences appear when interaction points come close to each other.

In string theory this is replaced by:



There are no interaction points!

→ Leads to the study of Riemann surfaces and their moduli spaces.

Let us now return to the issue about the dimension of space.

Consistency of string theory demands that we can formulate the theory only in 9 dimensions.

How can string theory be relevant for describing nature, which seems to have only 3 space dimension??

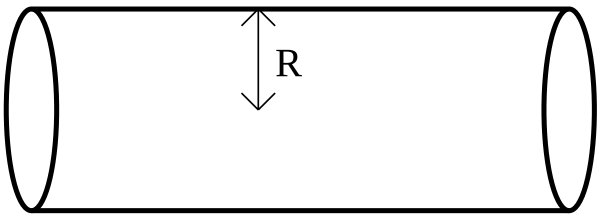
The answer to this question is provided by an old idea known as

Compactification

Compactification by an example:

Consider a 2 dimensional world.

Take the two space coordinates to describe the surface of a 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.

On the other hand, if $R$ is within the visible range, then the two dimensional creatures will start seeing infinite number of images of each object, separated by an interval of $2\pi R$.

Take R to be even smaller.

The world looks one dimensional as R$\to$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 like 3 dimensional.

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

Full space: $R^3 \times K$

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

The 3-dimensional theory gotten this way will depend on the choice of the compact space K, as well as which of the five string theories we start from.

Thus beginning with any of the five string theories we can get a whole variety of theories by making appropriate choice of the compact space $K$.

Different choices of the compact space $K$ for a given string theory can be regarded as different phases of the same theory.

(Just like ice, water and steam are different phases of the same underlying theory of $H_2O$ molecules)

For a special class of compact six dimensional spaces, known as Calabi-Yau spaces, the 3 dimensional theory has properties very similar to the ones we observe in nature.

- Gravitational interaction

- Gauge interactions

  $\rightarrow$ responsible for electromagnetic, strong and weak forces.

- 'Particles' with properties very similar to quarks and electrons

etc.

Unfortunately, we have not yet found a compact space which gives results in complete quantitative agreement with the observed universe.

Efforts are still on to find such a model.

One of the questions which plagued the early days of string theory is:

Why are there five consistent string theories?

How does nature choose one out of these five theories for its description?

This problem was resolved by the discovery of duality symmetry.

# Duality

Duality is an equivalence relation between different compactifications of different string theories.

A dual pair of theories look different but actually describe the same physical theory.

In other words, the same physical theory may have multiple descriptions as different string theories with different choices of compact spaces.

Also under duality, a particle which looks elementary in one description may appear to be composite in a dual description.

Thus elementarity of a particle loses its absolute meaning.

Examples of String Dualities:

- In 9 dimension,

  SO(32) heterotic $\leftrightarrow$ type I

- In 5 dimension,

  Heterotic string theory compactified on a four dimensional torus, denoted by $T^4$

  $\updownarrow$

  type IIA string theory compactified on a different four dimensional compact space, known as K3.

Thus using duality symmetry one can obtain complicated topological and geometrical information about K3 by suitable computations on $T^4$.

Mirror symmetry: A special case of duality

Type IIA theory on Calabi-Yau space $\mathcal{M}$

$$\Updownarrow$$

Type IIB theory on Calabi-Yau space $\mathcal{W}$

This allows us top calculate non-trivial properties of $\mathcal{M}$ in terms of simpler computation on $\mathcal{W}$ and vice versa.

Using the various known chain of dualities one can now argue that all 5 string theories are different ways of describing a single theory.

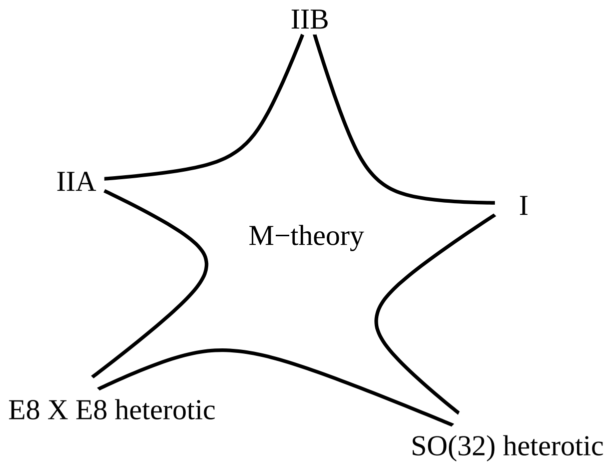
This theory is known as

M-theory

Inequivalent compactifications correspond to different phases of M-theory.

(Just like ice, water and steam are different phases of the same material)

A schematic picture of the phases of M-theory.




$\rightarrow$ a room with five windows

Different points in this room represent different phases of M-theory.

The five windows represent five different types of string theory

String theorists: people trying to peep into the room through these 5 windows

Before the discovery of duality we did not realize that we are looking into the same room through these five windows.

After the discovery of duality our vision improved and we started getting glimpses of some region of the room from more than one window.

This led to the realization that we are actually looking into the same room.

However most of the room is still unexplored, and presumably the universe we live in correspond to one of these unexplored points in the room.

Thus the problem of connecting string theory to nature reduces to:

1. Demonstrating that there is a phase of M-theory that describes exactly the nature that we observe.

2. Explaining why nature exists in this 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 some recent speculations on the second issue:

'how does nature choose one phase out of many?'

M-theory has certain metastable (supercooled) phases with the property that if any region of the universe is in that phase, it expands rapidly as a consequence of the laws of general theory of relativity.

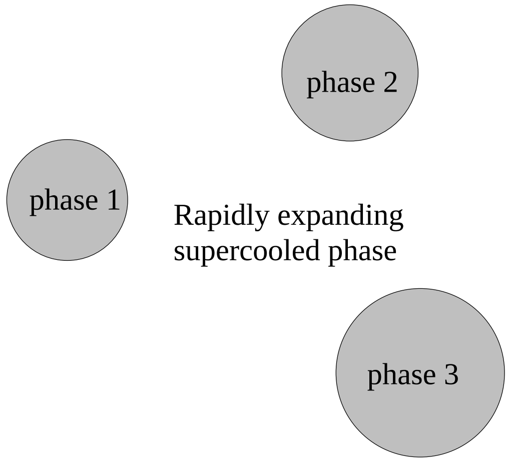
(de Sitter phase)

During this expansion parts of the universe make transition into more stable phases through nucleation of bubbles.

Inside different bubbles we may have different stable phases of M-theory.

In an ordinary fluid these different bubbles will expand and collide, and eventually the most stable phase will fill up the whole region.

However in the present situation, because of the rapid expansion of the universe the bubble walls do not collide even if they expand at the speed of light.




Since the rapidly expanding supercooled phase exists for infinite time, it is possible that every phase of M-theory will be realized inside one or more of these bubbles.

In this picture, no single phase of M-theory is prefered by nature.

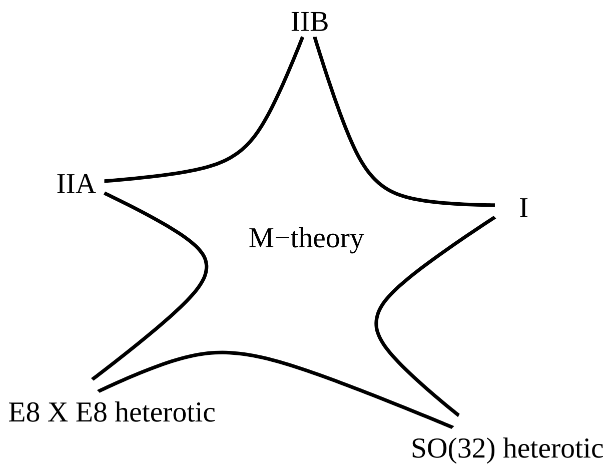
The world that we see around us exists in a particular phase simply because we happen to live in this part of the world.

If we had lived in another part of the world we would see a different phase.

Of course, in most of the phases of M-theory life as we know would be impossible, and so nobody would be there to observe these phases.

But that is another matter!

# CONCLUSION




Most of the phases of M-theory are still to be found, and presumably one of these unexplored points in the phase space describes the universe in which we live.

Discovering this point will require improving our vision through the existing windows and also possibly opening new hidden windows into this room.

This is a challenging problem for the present as well as future generation of string theorists.