What is String theory ?

Sanjaye Ramgoolam

Queen Mary, University of London

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OUTLINE : What is String Theory ?

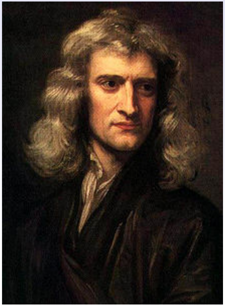
- Four fundamental forces in Physics.
- The mathematical description of each force unifies diverse physical phenomena.
- String theory attempts, with some success, to unify all four forces.
- What is String theory ? How does it unify forces ?
- Good theories are capable of surprises.
- The surprises of string theory : extra dimensions, dualities.
- Research Avenues : The link between theory and experiment.

Basic Questions of Physics :

What is the world made of ?

What are the constituents (building blocks) of matter ?

What causes motion or changes in motion ?



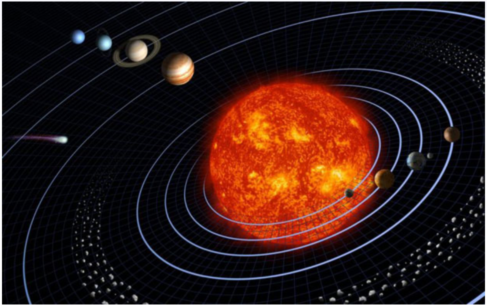
Newton's second Law :

$$F = ma$$

What are the forces that exist in nature ?

Force of Gravity

Among these forces : The force of gravity
which causes apples to fall off trees and planets to go round the sun.



Universality of gravitational force

The force of gravity is universal :

$$F = \frac{Gm_1 m_2}{r^2}$$

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Any two physical bodies, e.g two people who hate each other, will attract via gravity according to the same equation.

Universality and Unification

Gravity, this most familiar of forces, shows unification in action.

Diverse phenomena – apples, planets – are governed by the same equation.

Electromagnetism

Another unification arises in the physics of electricity and magnetism.

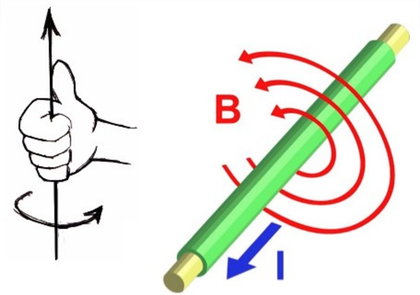
Static electricity is due to separation of positive and negative charges. These charges produce electric force fields $E(\vec{x}, t)$.

Magnets produce magnetic force fields $\vec{B}(\vec{x}, t)$.

Electromagnetism

Electricity and magnetism are related.

The motion of charges is electrical current. Currents produce magnetic fields.



Maxwell's equations of Electromagnetism

Maxwell wrote the equations obeyed by electric and magnetic fields $E(\vec{x}, t), B(\vec{x}, t)$ which shows how they are related.

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Unification to prediction : Light as electromagnetic waves

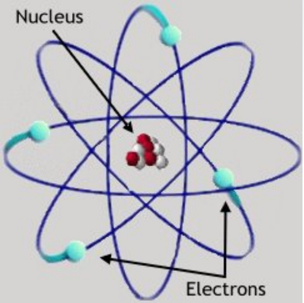
These electromagnetic forces are described by Maxwell equations.

They predict the existence of light and electromagnetic waves

Yet other phenomena within our experience, but brought within the fold of the same set of equations.

Strong Force

We encounter additional forces when we try to understand the atoms that make up matter.



Strong force keeps the proton and neutron inside the nucleus.

Also the quarks and gluons inside the protons and neutrons.

The fourth force

Weak force Responsible for radioactive beta decay of nuclei.

Atomic Physics is Quantum Physics

Studying the interior of the Atom, aside from revealing the microscopic constituents, e.g protons, neutrons, electrons, quarks etc.

requires a radical rethink of the classical physics of Newton and Maxwell equations.

Heisenberg Uncertainty Principle and a fundamental role of probability.

Uncertainties in Measurements

Positions and velocities are always measured with some finite precision.

$$x \sim x \pm \Delta x$$
$$v \sim v \pm \Delta v$$

e.g $x = 10.00 \pm 0.05\mathrm{cm}$.

In classical physics, there is no obstacle to making these uncertainties as small as we like.

Quantum Uncertainty

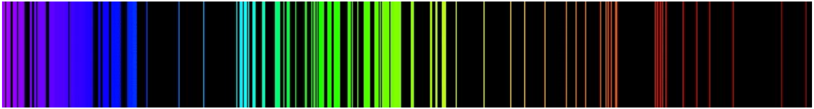
But in Quantum Physics, the Uncertainty Principle says that these uncertainties have to be bigger than some small quantity determined by the universal Planck constant

$$\Delta x \Delta v \geq \frac{h}{4\pi m}$$

The maths of quantum physics relates this universal uncertainty to observable properties such as the quantization of the energy levels in atoms.

Uncertainty and Observables

In turn related to observables such as distinctive colors (emission spectra) associated with different types of atoms.



Particles and Forces

We have a spectrum of particles and a list of forces.

Forces are described by fields.

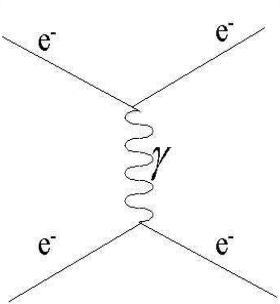
Particles are subject to quantum uncertainties in position and velocities.

But Quantum Physics requires further uncertainties (e.g in particle number), which lead to a fusion of the concepts of particle and force, through the theory of quantum fields

Particles and Forces

In Quantum Field Theory, each type of force is mediated by a force carrier.

The electric repulsion of two electrons is mediated by the exchange of photons (particles of light).



Forces and Particles

Electromagnetic Force : Photon

Strong Force : Gluon

Weak Force : W and Z bosons

Quantum Field Theory (QFT)

The equations of QFT, developed in the mod-twentieth century, incorporate the principles of quantum mechanics as well as special relativity.

Special relativity says that no particle can travel faster than light.

Dirac used QFT to predict the existence of anti-electrons before they were discovered experimentally.

Gravity

To understand the small scales of atomic and nuclear physics, we had to extend classical physics and go to quantum physics.

To understand the gravity effects of very massive bodies (e.g. stars, galaxies, black holes) and the structure of the universe over very large distance scales, we need Einstein's General Relativity.

QFT combines special relativity and quantum mechanics very effectively, adding general relativity to this mix does not really work.

The mysteries of the graviton

QFT works very well to calculate the quantum effects due to electro-magnetic, weak and strong force.

But QFT methods fail to systematically calculate quantum effects for gravity – Naive application of QFT methods lead to non-sensical infinities.

These quantum effects are important in the Early Universe, at times close to the Big Bang and for understanding black holes.

String Theory

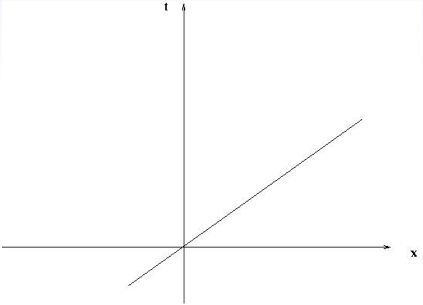
String Theory manages to compute quantum interactions of gravitons with each other and with other particles.

All particles, including graviton, come from one object – a string.

Point-like objects (particles), which are viewed as fundamental in QFT, are now different excitations of a string.

Towards strings : The worldlines of particles

In relativity, it is extremely useful to describe the motion of particle with space-time diagram depicting the worldline of the particle.



In String Theory, particles are replaced by strings or one-dimensional objects.

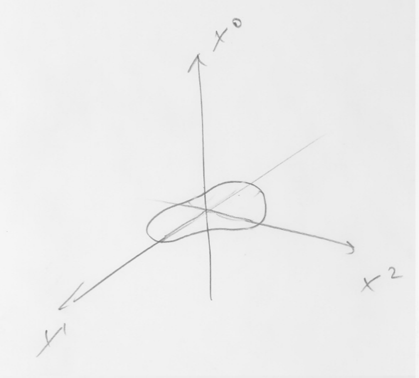


Figure: String in Space-time

The string worldsheet

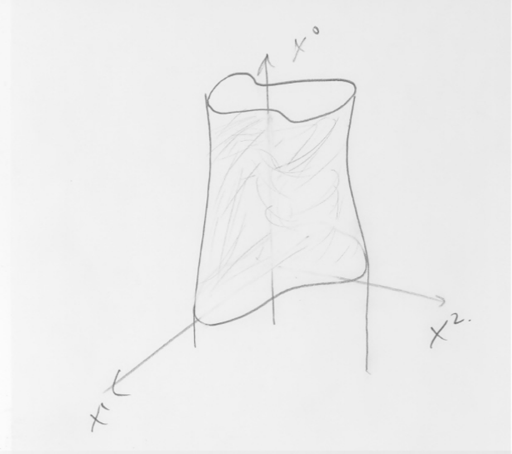


Figure: String worldsheet in Space-time

Particles from strings

Unlike ordinary strings, the fundamental string is not made of atoms

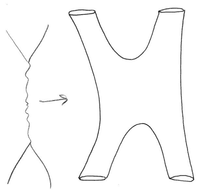
Rather the fundamental constituents quarks, electrons, gravitons etc. are all different vibrations of the string.

Different vibrations have different energies.

Different energies are related to different masses ($E = mc^2$). These different masses are those of different particles.

Particle Interactions from string diagrams

Feynman diagram becomes a string diagram.



Quantum Fields on the Worldsheet

The worldsheet parametrized by (τ, σ) propagates in spacetime $X^0, X^1, X^2 \cdots$

The quantum physics of strings is described by quantum fields on the worldsheet $X^0(\sigma,\tau), X^1(\sigma,\tau), \cdots, X^D(\sigma,\tau)$.

Analogy
$\vec{E}(t, x_1, x_2, x_3) \leftrightarrow \vec{X}(t, \sigma)$

Dimensions of space-time in String Theory

String theory contains a surprise about the dimensionality of space.

Any point in space can be specified, by giving the displacement from the chosen origin of coordinates, in three directions i.e x_1, x_2, x_3 which are needed to specify a force field $\vec{E}(t, x_1, x_2, x_3)$ for example.

We say that space is three dimensional.

A line is one-dimensional. A surface is two-dimensional. They can exist within three-dimensional space.

Dimensions of space-time in String Theory

In string theory, we can consider any number D of space-time dimensions $X^0, X^1, X^2, \cdots, X^D$.

It turns out that, in the simplest string theories, compatible with relativity and quantum mechanics in $(x^0, x^1, \cdots, x^D)$:

Only one value of D works !!

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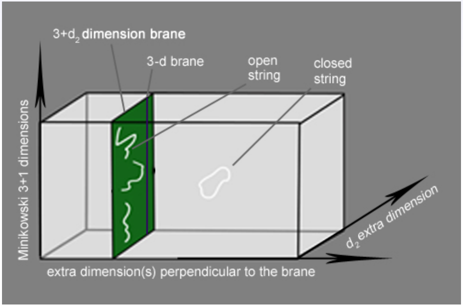
Only one value of D works !!

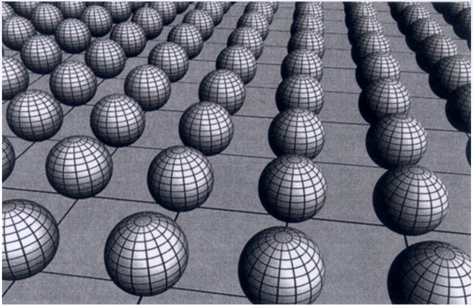
$$D = 9$$

String theory contains “branes” where open strings can end.

We can build something that looks like the real world (of 3 space dimensions) using branes in string theory.



Alternatively, the extra dimensions can be small



These different possibilities have different implications for what sort of zoo of particles will extend the list of known quarks, etc. when we do particle physics experiments at very high energies, such as those at CERN.