Quantum Gravity

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PART I
Classical gravity
What is Gravity?

• We all had encounters with gravity in our daily lives

• Gravity is an extremely important factor in shaping our Universe

• Still: a most mysterious force .....
A quick history of gravity

• Aristotle: There is no motion without cause! (Force)

• Vitruvius: Gravity not dependent on weight rather on substance! (Acceleration)

• Brahmagupta: Earth is spherical and attract things! (Uniformity)
Scientific method

Gravity— no exception!

Standard scientific method endless cycle of explaining results of experiments through new theories:

Data <-> Theory <-> Better data <-> New theory...

Experiment/Observations

Ideas
Observations and new theory

• Tycho Bache: Direct observations of orbital anomalies for planets

• Question: Heliocentric system?

• Difficult questions and challenge to “accepted” truths...

• Kepler: Through careful analysis of Tycho Brahe’s results: laid the ground for Newton’s work through his laws for the motion of planets in the solar system.
Kepler's work

- The orbits of the planets are ellipses.
- A line drawn from a planet to the sun sweeps out equal areas in equal intervals of time.
- The square of the Planets orbital period ($T$) is proportional to the cube of its average Distance ($D$) from the Sun.

$$T^2 \sim D^3$$
**Newton**

Gravity attraction: between matter.

**Newton:** gravity fundamental force, same force on apple as for the moon.

New way of thinking...

**Birth of modern physics:** Newton’s theory confirmed by numerous observations and experiments.
Newton’s work

- Gives a direct way to compute the effects of gravity
  
  \[ \text{Force} = \text{mass} \times \text{acceleration} \]

- Explains a number of observations from theoretical reasons, derives Kepler's law!

- Introduces the important notion: A universal force (a new concept)
Inertia
Einstein’s theories

• The concept of universal forces in Nature is inspiration for Maxwell who combines Electric and Magnetic forces as one force of Nature.

• The theory of Electromagnetism is problematic to combine with Newtonian mechanics, but leads Einstein on the track to formulate special relativity...
Einstein’s general theory

- Derived from the principles of special relativity but introducing new concepts

- Basic equation is the Einstein equation:

  Curvature is connected to the energy-density

  Leads to the notion of curvature of space!

- Gravity is a result of attraction between densities of energy, curvature of space is given by solving the Einstein equation.
Experimentel verification

Einstein predicts: Bending of light

• Light bends around massive objects
• Deflection can be measured
• Gives clear justification to Einstein’s theory!

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.
Einstein predicts: Perihelion distortion

- Planet orbits are generally a little distorted from their Newtonian form (ellipses).
- This is due to the Newtonian mechanics neglect of energy as a source of gravity.
- Can be measured rather precisely.
Experimentel verification

• Gravitational time dilatation:

• Time goes little slower on the surface of a massive object, this can be observed as a small time delay!

• Plays a crucial role for GPS systems

• Gives a gravitational redshift for light
Einstein’s theory

• A beautiful theory based on one equation, explaining all theories before and giving important new theoretical results

• Everything we know about gravity is in correlation with the general theory of relativity

• Deterministic theory like Newton’s theory: given initial conditions everything is known in future!
PART II

Deterministic vs. Non-deterministic
Deterministic vs. Non-deterministic

In order to understand how this question becomes important in theoretical physics – one has to understand **matter better**

Eventually this question comes down is matter really **dividable forever** or does smallest quantities appear at some scale.

**Birth:** *Quantum mechanics*
History of atoms

Idea: matter containing undividable particles (atoms)

Close to modern knowledge of atoms constituting matter

Philosophical work: no direct experiments to establish if theory is correct...
In the middle ages, alchemy, Aristotle's elements - based on basic observations (data)

Lavoisier: creator of modern chemistry (against the phlogiston theory)

Idea: elements constitute matter and interact through chemistry -> idea of a periodic table of elements
1913 Atoms and Nuclei

Properties of atoms and nuclei

Spectral lines

A very hard and small nucleus

Challenge: To understand of the concept of interactions at the quantum level.
Niels Bohr's model for the atom

Creative new solution to problem of stability and explanation of spectra:

- Fixed energy levels between shells
- Quantum jumps between shells: light (photon) emission

Increasing energy of orbits
Amplitudes

Fundamental object in quantum mechanics

Matter described as waves/amplitudes

Squaring the amplitude gives quantum probability
Amplitudes and probability
Quantum Mechanics

Unique importance for physics

Completely new concepts

Complimentary interpretation

Extremely successful:
Match of theory to experiment with unseen high precision

The quantum path forward for Theoretic Physics even today

Position and momentum cannot be measured at the same time
Distinct break between quantum and classical physics – Wave properties hold for single particles
Deterministic vs. Non-deterministic

Classical interaction

Have to integrate/sum over all paths

Feynman path integral
Particle wave duality

Absolutely crucial in Quantum Mechanics

- Particle properties are as real as wave properties. It is the same fundamental manifestation of matter.

- What we have grasp is that this is fundamental break with classical mechanics where all variables can be measured at the same time to all times

- Problem: Quantum gravity? What framework?
PART III
Modern Particle Physics
Concerned with a large number of topics ranging from the sub-nuclear scales to the cosmological...
Some current goals and ongoing investigations:

New physics

- New particles and symmetries
  (esp. Supersymmetry)
- Understanding “Dark matter”
- Extra dimensions of spacetime?

Masses of neutrinos

- Anti-symmetry of matter

Quantum gravity

- Unification of forces
From the atom to the nucleus

atom $\sim 10^{-8}$ cm

nucleus $\sim 10^{-12}$ cm
From the atom to the proton

- Electron: \( <10^{-16}\text{ cm} \)
- Proton (neutron): \( \sim 10^{-13}\text{ cm} \)
- Nucleus: \( \sim 10^{-12}\text{ cm} \)
- Atom: \( \sim 10^{-8}\text{ cm} \)
From the atom to the quark

atom $\sim 10^{-8}$ cm

nucleus $\sim 10^{-12}$ cm

proton (neutron) $\sim 10^{-13}$ cm

electron < $10^{-16}$ cm

quark < $10^{-16}$ cm
Nucleus

Atom: Nucleus and Electrons, held together by Electromagnetic forces.

Nucleus: Protons and Neutrons held together by much stronger nuclear forces.

Possible: in many cases to reuse solutions from atomic physics
Nuclear forces

Weak nuclear interactions
- Force particle: W and Z bosons
- Neutrons decay into Protons: new particle: neutrino

Strong nuclear interactions
- Force particle: gluon
- Quarks interacts via gluons
- New concept: Asymptotic freedom
Standard Model of particle physics: Bosons, leptons and quarks - gravity?
Three generations for matter:

<table>
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<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
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<tbody>
<tr>
<td>$\nu_L$ lightest neutrino*</td>
<td>$(0-0.13) \times 10^{-9}$</td>
<td>0</td>
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<td>e electron</td>
<td>0.000511</td>
<td>-1</td>
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<td>$\nu_M$ middle neutrino*</td>
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<td>0</td>
</tr>
<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_H$ heaviest neutrino*</td>
<td>$(0.04-0.14) \times 10^{-9}$</td>
<td>0</td>
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<tr>
<td>$s$</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$</td>
<td>4.2</td>
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Amazing cookbook for all matter

**Leptons** spin = 1/2

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**Quarks** spin = 1/2

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<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ down</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$ charm</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ strange</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
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<td>173</td>
<td>2/3</td>
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2x Hydrogen
Bubble chamber
LHC CERN
Large Hadron Collider

LHC 'event'

Proton

Jets

...
**Discovery** – center for particle physics, is researching the fundamental building blocks of matter and forces. This is done partly through collisions between protons and atomic nuclei at very high energy in the LHC accelerator at CERN and partly by observing the afterglow of the birth of the universe with ESA’s Planck satellite.
Detektorer
Electronic detectors
Electronic detectors

ATLAS EXPERIMENT

Run Number: 167776, Event Number: 134650167
Date: 2010-10-28 11:02:58 CEST

Snapshot of a proton collision directly from the ATLAS experiment
Higgs partikel
So where is the graviton in all this??
Grand-unified theory

Forces of nature: merge at high energies

Does not include gravity. Still an open problem

Need completely new ideas about space and time??
Dark matter and antimatter

What is Dark matter?

Universe: Expanding forever

- 73% Dark energy
- 23% Dark matter
- 3.6% Intergalactic gas
- 0.4% Stars, etc.

Why more matter than antimatter in universe?

Fundamental antisymmetry??..Current tests

Masses of neutrinos?
PART IV

Quantum gravity as a Particle Theory
How to think of gravity as a quantum theory

- Gravity is mediating the attraction of matter
- We know other theories:
  - Electromagnetism: Photons
  - Strong interactions: Gluons
Graviton

- Graviton should be emitted from all matter not 'charged' like photons
- It should be an attractive force, not mixed repulsive / attractive like electro-magnetism
- The optimal candidate particle is a spin-2 particle (photons are spin-1)
Einstein-Hilbert

- Einstein equation can be derived from a classical action theory
- The offers a starting point for particle physics.
- Idea is to proceed as if the theory was one we know well like electromagnetism or strong interactions
Amplitudes and Feynman diagrams

In particle physics: amplitudes from diagrams

Feynman diagrams

Example
Amplitudes and Feynman diagrams

In particle physics: amplitudes from diagrams

Feynman diagrams

Example
Amplitudes and Feynman diagrams

In particle physics: amplitudes from diagrams

Feynman diagrams

Example

Vertex

Propagator
Amplitudes and Feynman diagrams

- Feynman’s method not flawless
- Diagrammatic expansion: huge permutational problem!
  - Scalar field theory: constant vertex (i.e. 1 term)
  - Gluons: momentum dependent vertex (i.e. 3 terms)
  - Gravitons: momentum dependent vertex (i.e. 100 terms)
- Naïve basic 4pt diagram count (graviton exchange):
  
  $100 \times 100 \text{ i.e. } 10^4 \text{ terms} + \text{index contractions (i.e. 36 pr diagram)}$

  Number of diagrams: $(4!) 10^5 \text{ terms i.e. } 10^6 \text{ index contractions}$

  n-point: $(n!) \text{ i.e. more atoms in your brain!}$

Too much clutter.....
Topologies of amplitudes

- Feynman diagrams have different topologies:
  - Tree diagrams:
  - One-loop diagrams:
  - Multi-loop diagrams:
Amplitude cookbook!

1. Unitarity: Fuse tree amplitudes into loops

2. Recursion: Extend trees and loops into more complicated amplitudes

\[ A(0) = - \sum_{\alpha} \text{Res}_{z=z_{\alpha}} \frac{A(z)}{z} \]

3. String theory: Complete the picture and link concepts
Research

\[ i \frac{\langle j k \rangle^4}{\langle 1 2 \rangle \langle 2 3 \rangle \cdots \langle n 1 \rangle} \]
Research

Amplitudes$^2 \sim \text{Probability}$
Research

Gravity

Highly creative and experimental.

\[ R_{\mu \nu} = 0 \]

\[ \sum (s_{12} + s_{1M} + s_{123})^2 \sim 0 \]

'Vanishing' relations!!!
Quantum gravity from particle physics

Reproduces Einstein's result plus quantum effects!

Using only particle theory plus computational tricks!
Quantum gravity from particle physics

- Solves part of the problem: how to combine particle physics and general relativity

- There is a framework where it is possible to compute in quantum mechanical valid way.

- Very high-energy limit: still a problem, here new non-perturbative effects are needed + it appears fundamental obstacles hinders valid computations. String theory??
Extensions of the Standard Model

- Big changes in concepts of standard model difficult
- Extra symmetry?
- Super-symmetry exciting possibility
- Solves many issues...
- Funny new dimensions with anti commuting variables: $X Y = - Y X$ (Grassman)
Supersymmetry

**Problem:** forces of nature seems to not meet in a point if we try to reach unification scales (with supersymmetry they do...)

![Graph showing unification of interactions helped by SUSY](image-url)
Supersymmetry

New model(s), couplings, fields
Quantum gravity?
String theory

- Natural quantum gravity
- Particles as vibrations on strings
- M-theory in 10 Dimensions
- From creative point of view: Natural idea: extend the concept of interaction point into a interaction surface...
If we are **creative** we can understand particles in 4D as shadows of particles living in higher dimensions.
Quantum gravity visions going ahead

Still many things we do not know..

But we are making progress all the time.

We are seeing deep connections in quantum mechanics – between gauge and gravity theories.

Developments no one would have believed of a few years ago.

Very exciting times in physics ahead!
Every great and deep difficulty bears in itself its own solution. It forces us to change our thinking in order to find it.

Niels Bohr

Learn from yesterday, live for today, hope for tomorrow. The important thing is not to stop questioning

Albert Einstein
Tak fordi De lyttede med