Lecture 2 - The current state of fundamental physics

1) Einstein & General Relativity
   • Gravity as Spacetime Curvature
   • Gravitational Radiation, LIGO & LISA
   • Cosmology & the Expanding Universe
   • Dark Energy & the Cosmological Constant
   • Black Holes

2) The Standard Model of Particle Physics
   • The Four Forces of Nature
   • Quarks, Leptons & Gauge Bosons
   • LHC & the Search for the Higgs Boson
General Relativity is Einstein’s theory of gravity (1915)

NEWTON ALREADY GAVE US A THEORY OF GRAVITY. WHY DID WE NEED A NEW ONE?

Newtonian gravity is inconsistent with the principle of causality in Special Relativity - that nothing can move faster than the speed of light

Newton’s inverse square law requires action at a distance - if one object moves, the other one knows about it instantaneously due to the change in the gravitational force, no matter how big their separation is.
Making gravity consistent with special relativity required a major revision of how we think of space & time.

Einstein’s thinking started with a simple principle, now known as the **Equivalence Principle**.

All things fall in the same way. If you drop a bowling ball, it falls in the same way as a pea….

This happens because the “inertial” mass that enters Newton’s law of motion, F=ma, is the same as the “gravitational” mass that enters the gravitational force law.

David Kastor

COSMOS to HUMANITY, Spring 2008

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The equivalence suggested to Einstein that the path an object follows is a property of space itself, rather than having anything to do with the specific properties of the object.

- We know that in the absence of any forces, objects follow straight lines, and we also know that straight lines are the shortest possible paths……
- Perhaps gravity is a manifestation of objects in free fall following the shortest possible paths, known as geodesics, in *curved spacetimes*

It is difficult to visualize curved *spacetimes*, but the surface of a sphere is a simple curved *space*. Geodesics are great circles that pass through both poles. We see that they can pull apart and then meet up again…. 
Spacetime curvature is in turn created by concentrations of matter. For example, the Sun curves spacetime in the vicinity of the Solar System and the elliptical orbits of the Planets are geodesics…. The predictions of the detailed mathematical theory of General Relativity reproduce those of Newtonian gravity in the large separation limit.

The first significant test of General Relativity was resolving a small discrepancy in the orbit of Mercury, the innermost planet, for which the relativistic corrections to the Newtonian orbit are largest.
Like Special Relativity, the physical implications of General Relativity turned out to be huge……

1) Gravitational Radiation
2) Cosmology and the Expanding Universe
3) Gravitational Collapse and Black Holes
Gravity Waves

In General Relativity, disturbances in the gravitational field (i.e. spacetime curvature) propagate at the speed of light as gravitational radiation, also known as gravity waves. Thus, GR solves the original action at a distance problem of Newtonian gravity.

Light is produced by moving around electric charges. Gravity waves are produced by moving *anything* around. When you wave your hand, you make gravity waves.

The catch is that gravity is very weak. It takes a lot of mass, e.g. the sun or the earth, to generate substantial spacetime curvature. Likewise, it takes moving around very big masses to generate gravity waves that we can hope to measure.

In Fact, gravity waves have not yet been detected. The first detectors, really gravity wave telescopes, with enough sensitivity have only recently been built.
The LIGO Project (Laser Interferometer Gravitational-Wave Observatory) will begin a new field of gravity wave astronomy.

The biggest sources of Gravity Waves for LIGO will be collisions between black holes. A pair of black holes orbiting each other lose energy through gravity waves and gradually spiral together. LIGO will be able to detect the last few catastrophic minutes of this process…..
Gravitational waves cause the length of one 2.5 mile long arm to decrease very slightly, while the length other arm increases.

To be able to detect gravity waves, LIGO must be able to measure changes in length of order 1 part in $10^{16}$ - about 1/10 the size of a proton - quite a technical feat.

LISA, a proposed space based gravity wave detector would detect gravity waves from supermassive black hole mergers, and a gravitational analogue of the CMB.
Cosmology & the Expanding Universe

Einstein asked the question, what curved spacetime describes our Universe on very large scales? Making the approximation that matter is spread out uniformly, he found that our Universe cannot be static. It must be either expanding, or contracting.

This seemed horribly wrong to Einstein. He found a way to fix it by adding a new element to his theory - a cosmological constant - a background energy density with negative pressure. This allowed a static (but unstable) Universe.

In 1929, the astronomer Edwin Hubble discovered that, in fact, the universe is expanding. Einstein famously described the cosmological constant as his “greatest blunder”.
Ironically, over the past decade cosmologists have come to believe that the cosmological constant may exist.

70% of the matter in the universe appears to be of an unknown form - termed Dark Energy.

Unlike any kind of ordinary matter (or even what cosmologists call dark matter), dark energy causes the expansion of the universe to accelerate.
If the universe is expanding now, then sometime in the past it was very, very small. It was discovered in 1965 that back in this early time it was also very hot…. Two radio astronomers, Penzias and Wilson found that the Universe is filled with microwave radiation with a blackbody spectrum of temperature 2.7K.

Together these led to the picture of the origin of the universe in a hot Big Bang! As the universe has expanded it has cooled off...
Understanding the very early history of the universe involves both gravity and particle physics.

At very high temperature matter gets broken up into its smallest bits...
**Black Holes**

A black hole is literally a region from which light cannot escape.

General Relativity predicts that black holes can form by **gravitational collapse**. Once a star has burned up its supply of nuclear fuel, it can no longer support itself against its own weight and it collapses.

It will reach a critical density at which an explosive re-ignition of burning occurs, called a **supernova**.

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*David Kastor*  
*COSMOS to HUMANITY, Spring 2008*  
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If the remnant left behind by the supernova is massive enough, it will be a black hole. (If not it will be a Neutron star)

More generally, if anything is compressed within its Schwarzschild radius, then a black hole will form.

\[ R_s = \frac{2Gm}{c^2} = \left( \frac{m}{m_{\text{sun}}} \right) \times 3\text{km} \]

The boundary of a black hole is called the event horizon. When something passes through the event horizon, it can no longer communicate in any way with the world outside. Surprisingly, if you fell into a large black hole, you wouldn’t know when you had passed through the event horizon.

The radius of the sun is actually about 700,000 km.
The real dramatic stuff comes at the center of the black hole, where the spacetime curvature becomes infinity. As you approach the center, you are torn apart by tidal forces. The gravitational pull on your feet becomes enormously more than that on your head….

For many years, it was questioned whether, or not, black holes existed and should be taken seriously.

There is now a wealth of evidence that supermassive black holes exist at the centers of many, or perhaps most galaxies and that they are responsible for many dramatic galactic phenomena…
The Standard Model of Particle Physics

Warm up for this topic by breaking things into small bits.
• everything is made of molecules
• molecules are made of atoms
• atoms are made of **electrons** and nuclei
• nuclei are made of protons and neutrons
• protons and neutrons are made of **quarks**

As far as we know **electrons** and **quarks** are not made of anything smaller. We call them **fundamental particles**.

The standard model of particle physics describes how these and the other known fundamental particles **quantum mechanica]ly** interact with each other.
The four forces of nature

- Gravity (Einstein)
- Electromagnetism (Maxwell)
- Strong force
- Weak force

The Strong force is responsible for binding protons & neutrons together into nuclei and binding quarks together into protons & neutrons.

The weak force is responsible for certain radioactive decays, such as the beta decay of the neutron.

\[ n \rightarrow p^+ + e^- + \bar{\nu}_e \]
Our experience with the microscopic world tells us that all physics should be quantum mechanical, but General Relativity and Electromagnetism are classical theories.

Leaving gravity aside for the moment, the path to the Standard Model begins with “quantizing” Electromagnetism. (1940’s)

Quantization was formally a straightforward process, but when physicists tried to do calculations with the resulting theory the answer to every question was always the same - infinity! Even a simple quantity like the energy density of empty space turned out to be infinite.

**Feynman, Schwinger and Tomanaga** won the Nobel Prize in 1965 for making sense of this situation by inventing a technique called renormalization for extracting physical answers from the theory of Quantum Electrodynamics (QED)
The mathematical language of the Standard Model is called **Quantum Field Theory**, in particular a class of theories called **Nonabelian Gauge Theories**, which are generalizations of QED.

The usual physicist’s abbreviation for the standard model looks like

\[ SU(3) \times SU(2) \times U(1) \]

These symbols are names for certain mathematical objects called groups. Roughly speaking, the group U(1) is associated with QED, the group SU(2) is associated with the Weak force, and SU(3) is associated with the Strong force.
A very little bit of group theory

One simple example of a group, are the symmetries of a triangle. You can rotate the triangle, or flip it. This is called a discrete group.

Another simple group is the symmetries of the circle. This is a continuous group and is called U(1)

The group SU(2) is basically the group of rotations of 3 dimensional space. The group SU(3) is more challenging to describe.
\[ SU(3) \times SU(2) \times U(1) \]

Note: Gravity is still left out....
Full Particle Content of the Standard Model

A highly accurate view of a Neutron, 2 down quarks & 1 up quark

A Proton is, 2 up quarks & 1 down quark
**Quark Confinement:** Quarks, which interact via the strong force, never exist singly. They are always bound either in quark anti-quark pairs called **mesons**, or in triplet combinations, like the proton and the neutron, called **baryons**.

If a pair of quarks is moving apart, the color force between them increases with distance.

Either the quarks are pulled back together, or the force lines snap creating a quark/anti-quark pair.

In this picture the force lines snap and color neutral mesons move apart.
Let’s go back and look at our proto/anti-proton collision from lecture 1
There is one missing piece of the Standard Model - the Higgs Boson.

The Higgs mechanism is an intricate part of the Standard Model that gives rise to particle masses. It also produces one extra particle known as the Higgs Boson, which has not been found to date.

The Large Hadron Collider at CERN is designed to find the Higgs. Particle physicists are also looking to the LHC for clues of what physics lives beyond the standard model.
# Standard Model of Fundamental Particles and Interactions

The **Standard Model** summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the “Standard Model.”

## Fermions

<table>
<thead>
<tr>
<th>Leptons</th>
<th>spin = 1/2</th>
</tr>
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<tbody>
<tr>
<td>Flavor</td>
<td>Mass (GeV/c^2)</td>
</tr>
<tr>
<td>ν_e</td>
<td>&lt;1.0⋅10^{-6}</td>
</tr>
<tr>
<td>e^-</td>
<td>0.000511</td>
</tr>
<tr>
<td>ν_μ</td>
<td>&lt;0.0002</td>
</tr>
<tr>
<td>μ^-</td>
<td>0.106</td>
</tr>
<tr>
<td>ν_τ</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>τ^-</td>
<td>1.7771</td>
</tr>
</tbody>
</table>

Spin is the intrinsic angular momentum of particles. Spin is given in units of ℏ, which is the quantum unit of angular momentum, where ℏ = h/2π = 6.626⋅10^{-34} J⋅s. Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.602⋅10^{-19} C.

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The energy unit of particle physics is the electron volt (eV). The energy gained by one electron in crossing a potential difference of one volt. **Mesons** are given in GeV/c^2 + m, where 1 GeV = 1.602⋅10^{-19} J and the mass of the proton is 0.938 GeV/c^2 = 1.672⋅10^{-27} kg.

## Bosons

<table>
<thead>
<tr>
<th>Unified Electroweak</th>
<th>spin = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Mass (GeV/c^2)</td>
</tr>
<tr>
<td>γ</td>
<td>0</td>
</tr>
<tr>
<td>W^-</td>
<td>80.4</td>
</tr>
<tr>
<td>W^+</td>
<td>80.4</td>
</tr>
<tr>
<td>Z^0</td>
<td>91.187</td>
</tr>
</tbody>
</table>

Color Charge: Each quark has one of three types of “color-changing,” also called “color charge.” These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electricity and magnetism are described by electromagnetic force, the color force is described by a force-carrying particle: the gluon.

## Properties of the Interactions

### Gravitational

- **Particles experiencing:** All
- **Particles mediating:** Graviton
- **Strength (relative to electromagnetism):** 10^{-18} m

### Electromagnetic (Electroweak)

- **Particles experiencing:** All Quarks, Leptons
- **Particles mediating:** Electromagnetic charge
- **Strength (relative to electromagnetism):** 10^{-4} m

### Strong

- **Particles experiencing:** Quarks, Gluons
- **Particles mediating:** Gluons
- **Strength (relative to electromagnetism):** 10^{-2} m

## Mesons

<table>
<thead>
<tr>
<th>Mesons</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>π^+</td>
<td>+1</td>
</tr>
<tr>
<td>K^-</td>
<td>-1</td>
</tr>
<tr>
<td>ρ^+</td>
<td>+1</td>
</tr>
<tr>
<td>B^0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Residual Strong Interaction**

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electric interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

**Matter and Antimatter**

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (e.g., e becomes e̅). Particles and antiparticles have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z, γ, and ω) are not antiparticles.

**Figures**

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.