There is another form of temptation even more fraught with danger. This is the disease of curiosity. . . . It is this which drives us on to try to discover the secrets of nature, those secrets which are beyond our understanding, which can avail us nothing, and which men should not wish to learn. . . . In this immense forest, full of pitfalls and perils, I have drawn myself back, and pulled myself away from these thorns. In the midst of all these things which float unceasingly around me in my everyday life, I am never surprised at any of them, and never captivated by my genuine desire to study them. . . . I no longer dream of the stars.

ST. AUGUSTINE
Confessions

AD 397-398 1st western autobiography
Higgs
Peter Higgs

Waiting 44 years for particle physicists to discover his Boson
The Wait is Almost Over
Bose-Einstein Statistics

Bose  

Einstein
Fermi and Dirac
Fermions and Bosons

Higgs checks in the Boson Inn
The Essence

Higgs field breaks the electroweak symmetry

- Early universe
- Particles and fields
  - Forces
  - Force carriers
- Spontaneous symmetry breaking
Long History

• Even earlier but let’s start with Greeks
• Greeks invented the word atom—not divisible
• Aristotle says everything composed of earth, water, air, fire, ether
• Reductionist thinking still here today
• John Dalton (father of chemistry) used the idea of atoms (1766-1844).
• Thomson, Rutherford, Chadwick discovered electron, proton, neutron
Some More Work Needed

Important to look for deviations from your model

Develop a model and get data to look for deviations is a way to make progress in science

"OF COURSE THE ELEMENTS ARE EARTH, WATER, FIRE AND AIR. BUT WHAT ABOUT CHROMIUM? SURELY YOU CAN'T IGNORE CHROMIUM."
Composition of Atom

Each element is an atom made up of a central nucleus and shells of electrons. The number of the element corresponds to the number of electrons in the outer shell. Inside the nucleus there are an equal number of protons. And there are also many neutrons. Are electrons, protons, and neutrons the new “elements”??
Periodic Table

- The Periodic Table brought order among the elements
- Why is it called periodic? Because the patterns repeat
- Why do the patterns repeat?
- Yes, there is order, But is this really simple or elegant?
- Why are there so many elements? > 100
- Because there is an underlying structure; The underlying order is simpler
Proton is Not Elementary Mr. Watson
Electron, Proton, Photon

- J.J. Thomson discovered electron in 1897 and thus showed atoms are “tomos” or divisible & measured electric charge = (-1) and electron e/m
- Rutherford measured size of proton, charge = (+1) and proton mass
- Einstein’s photoelectric effect was quantization of EM radiation $E=hf$ (photons)
- Atoms can emit (create) photons and absorb (destroy) photons
- Photons have zero rest mass and zero charge
Introduction to Particle Physics

• Fundamental particles are not permanent entities
• Particle are created and destroyed
• Particles & interactions = subject of particle physics
• Classified into several categories based on conservation laws and symmetries
• Recent connection between shortest distance scale physics and early universe or cosmology
• Particle physics is based upon well developed mathematical description—quantum field theory
• Experimentally based science
Four Fundamental Forces In Nature

Why are they so different?
The Four Forces In Nature

Gravity Force
- Graviton?
- Solar systems
- Galaxies

Strong force
- Quarks
- Gluons (8)
- Mesons
- Baryons
- Nuclei

Electromagnetic force
- Hydrogen atom
- Water molecule
- Oxygen atom
- Protons and Neutrons
- Electron
- Oxygen atom

Weak force
- Bosons (W, Z)
- Neutron decay
- Beta decay
- Neutrino interactions
- Burning of the sun
Particles as Force Mediators

- Classical picture for repulsion is exchanging two heavy balls between two people on ice skates
- Attraction would be trying to grab the ball out of the other person's hands
- Real description needs quantum mechanics and development of a potential
- Two electrons repel one another by exchanging a photon
- Impulse of photon can have either sign in QFT
- Electromagnetic interaction mediated by photons
- A photon that exists for a period of time like this is called a virtual photon.
Feynman Graph

Solid line for particle

Primitive vertex

A line which begins and ends in the diagram represents a "virtual particle". In this case it is a virtual photon.

Feynman diagram for like charge repulsion

Time

Space
Feynman Graphs

**Electromagnetic**

**Weak**

**Strong Interaction**
**Force Summary**

<table>
<thead>
<tr>
<th>Carried By</th>
<th>Gravity (not yet observed)</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on</td>
<td>All</td>
<td>Quarks and Leptons</td>
<td>Quarks and Charged Leptons and $W^+ W^-$</td>
<td>Quarks and Gluons</td>
</tr>
</tbody>
</table>

- Carried By: Graviton (not yet observed)
- Acts on: All
- Weak (Electroweak): $W^+ W^- Z^0$
- Electromagnetic: Photon
- Strong: Gluon

Standard Model combines electroweak and strong
"All we need are the facts, ma'am."

Particle physics asks:
What is the universe made of and how does it work?

Universe is made of matter particles held together with force carriers:

Matter Fields:
3 generations of quarks and leptons

Force Carriers:
12 fundamental gauge fields
8 gluons, $W^+$, $W^-$, $Z$, photon
(3 gauge couplings, $g_1, g_2, g_3$)

Plus much more we do not know!
High Temperature All Forces Same
3. Do all the forces become one?

As the universe cooled down that single force split into the four we know today: gravity, electromagnetism, the strong and weak nuclear forces.

We believe that there was just one force after the Big Bang.

Similar mathematical laws describe three of the forces but not gravity.

At the TeV scale electromagnetism and weak forces unified.

Strong interaction thought to be unified at GUT scale.

Gravity unifies at Planck Scale.
Hubble Deep Field (10 day exposure) (12 billion years ago)
The Physicists’ View

The Big Bang Theory

1. The cosmos goes through a superfast “inflation,” expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second.

2. Post-inflation, the universe is a seething, hot soup of electrons, quarks, neutrons, and other particles.

3. A rapidly cooling cosmos permits quarks to clump into protons and neutrons.

4. Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog.

5. Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine.

6. Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars.

7. As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets.
Symmetry in Art
What is Spontaneous Symmetry Breaking? from Steam to Snow

Steam

Hot!
Perfect
Symmetry

Ice

Cold!
Broken
Symmetry

Another example is iron, which below some critical temperature, becomes magnetic because the magnetic moments align. Above that temperature, spins not aligned, which is a state of greater symmetry.
What is a Particle?

Disturbance in an energy field
What is a Field?

• Temperature field (scalar field)
• Higgs is a scalar field
• Defined everywhere in space
• One number at every point

• Wind field (vector field)
• Magnetic field (vector field)
Spontaneous Symmetry Breaking(1)

• Ferromagnetism above the Curie temperature is spatially invariant and there is no magnetic field in space.
• Below the Curie temperature the symmetry is spontaneously broken and there is a magnetic field created in space.
• This is called a phase transition.
Spontaneous Symmetry Breaking (2)

• In electroweak symmetry breaking there is a phase transition at the electroweak temperature
• The universe cooled below this temperature about a picosecond after the big bang
• Above this temperature, there was no Higgs field
• Below this temperature there was a Higgs field
• The electroweak symmetry breaks into electromagnetic and weak fields (same as rotational symmetry broken in ferromagnetism example)

• The W & Z (carriers of weak force) “eat” some of the Higgs field and gain mass (short range force)
• The photon (carrier of electromagnetic force) is massless (long range force)
Higgs Field

A scalar field that fills the entire universe

Particles traveling through the universe interact with this field & become massive

Importantly, the W and Z bosons receive mass but not the photon
Origin of Mass:
There might be something (new particle?!) in the universe
that gives mass to particles

Nothing in the universe

Something in the universe

**Higgs Particles:**
Coupling strength to Higgs
is proportional to mass

Electron

Z,W Boson

Top Quark
Higgs Mechanism (1)

Politicians (field points) at a party talking about politics
thanks to David Miller (University College London) and CERN
Higgs Mechanism (2)

Important politician enters the room and all cluster around her and she “gains mass”
Rumour whispered at one end of room of politicians
As rumour moves through room, people cluster around the Higgs Boson (2) particle.
The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons

Higgs particles are spin-0 bosons.
The Higgs is neither matter nor force;
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

The Higgs field is thought to fill the entire universe.
Could give a handle on dark energy(scalar field)?

If discovered, the Higgs is a very powerful probe of new physics.

ATLAS will discover the Higgs.
ILC will use the Higgs as a window viewing the unknown.
THE END