What are we?
Where do we come from?
Where are we going?

The aim of particle physics:
What is matter in the Universe made of?
Evolution of the Universe

What happened then?

What will happen in the future?

What is the universe made of?

Big Bang

Today

13.8 Billion Years

10^{28} \text{ cm}
Gauguin’s Questions in the Language of Particle Physics

- What is matter made of?
  - Why do things weigh?
- What is the origin of matter?
- What is the dark matter that fills the Universe?
- How does the Universe evolve?
- Why is the Universe so big and old?
- What is the future of the Universe?

Our job is to ask - and answer - these questions.
Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology
Electricity and Magnetism

- **Electricity:**
  - Named using the Greek word for amber
  - Fish, lightning, …
  - Static electricity and electric currents

- **Magnetism:**
  - Named for the region of Greece where lodestones were found
  - Used for navigation from 12th century

The first fundamental forces to be unified
James Clerk Maxwell

- Professor at King’s 1860 – 1865
- The first colour photograph
- **Unified theory of electricity and magnetism**
- Predicted electromagnetic waves
- Identified light as due to these waves
- Calculated the velocity of light
- ...

One scientific epoch ended and another began with James Clerk Maxwell - *Albert Einstein*
Electromagnetic Waves

- Proposed by Maxwell
- Discovered by Hertz

- A lot to answer for ….
- Nobody knows where fundamental physics may lead

Gravitational waves?
The First Elementary Particle

- Discovered by J.J. Thomson in 1897

- **The electron** – the basis of the electronic industry
- Old-style TV sets used beams of electrons
Photon: the Particle of Light

• Quantum hypothesis introduced by Planck: 
  \[ E = hf \]

• Physical reality postulated by Einstein to explain photoelectric effect

• Motivation for his Nobel Prize
From Cosmic Rays to Accelerators

Discovered a century ago …

… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail
The Discovery of Antimatter

- Existence predicted by Dirac
- The antiparticle of the electron (the positron) was discovered in cosmic rays by Anderson
- The same mass as the electron, opposite electric charge
- Used in medical diagnosis (PET scanners)
Experiments at Accelerators

Collisions take place inside large detectors that observe and measure the particles produced.

Large accelerators are based on the same principles as old TV sets. Accelerate and direct particle beams using electric and magnetic fields.
The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg

Tested by experiments at CERN

Perfect agreement between theory and experiments in all laboratories
The ‘Standard Model’ = Cosmic DNA

The matter particles

Where does mass come from?

The fundamental interactions

Gravitation electromagnetism weak nuclear force strong nuclear force
Weak Interactions

Radioactivity due to weak interactions (β decay)

W boson - carrier of weak interaction
postulated by Yukawa

Discovered at CERN in 1983 by Carlo Rubbia et al

Why is it as heavy as a nucleus?
Why do Things Weigh?

Newton:  
Weight proportional to Mass

Einstein:  
Energy related to Mass

Neither explained origin of Mass

Where do the masses come from?

Are masses due to Higgs boson? (the physicists’ Holy Grail)
Think of a Snowfield

Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

The LHC discovered
the snowflake:
The Higgs Boson

Hiker sinks deep,
moves very slowly:
Particle with large mass
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.
To answer Gauguin’s questions:

The Large Hadron Collider at CERN
The Large Hadron Collider (LHC)

Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

To answer these questions:

Primary targets:
• Origin of mass
• Nature of Dark Matter
• Primordial Plasma
• Matter vs Antimatter
Vacuum similar to interplanetary space: the pressure in the beam-pipes will be ten times lower than on the Moon.
LHC 1.9 degrees above absolute zero = -271 C
Outer space 2.7 degrees above zero = -270 C
ALICE: Primordial cosmic plasma

ATLAS: Higgs and dark matter

CMS: Higgs and dark matter

LHCb: Matter-antimatter difference
2012: The discovery of the Higgs Boson

Mass Higgsteria
A Simulated Higgs Event @ LHC
Interesting Events
July 4th 2012
The discovery of a new particle
The Particle Higgsaw Puzzle

Did the LHC find the missing piece?
Is it the right shape?
Is it the right size?
It Walks and Quacks like a Higgs

• Do couplings scale ~ mass? With scale = v?

\[ \lambda_f = \sqrt{2} \left( \frac{m_f}{M} \right)^{1+\epsilon}, \quad g_V = 2 \left( \frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}} \right) \]

• Blue dashed line = Standard Model
Standard Model Particles: Years from Proposal to Discovery

Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON

Source: The Economist
Today we believe that “Beyond any reasonable doubt, it is a Higgs boson.” [1]


Without Higgs …

… there would be no atoms
  – massless electrons would escape at the speed of light

… there would be no heavy nuclei

… weak interactions would not be weak
  – Life would be impossible: everything would be radioactive

Its existence is a big deal!
• « Empty » space is unstable
• Dark matter
• Origin of matter
• Sizes of masses
• Masses of neutrinos
• Inflation
• Quantum gravity
• …

The Standard Model
Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark

Mass of top 173 quark

Mass of Higgs boson

Unstable

World average

Need new Physics?

Stable

0
Should it have Collapsed already?

Fluctuate over barrier in the early Universe?

Tunnel through barrier now?

Quantum fluctuations

We are here

Not if infinite barrier: Supersymmetry?

The Big Crunch
The Dark Matter Hypothesis

• Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
• The galaxies move too quickly
• The observations require a stronger gravitational field than provided by the visible matter
• Dark matter?
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- Further strong evidence for dark matter
Rotation Curves

- In the Solar System
  - The velocities decrease with distance from Sun
  - Mass lumped at centre

- In galaxies
  - The velocities do not decrease with distance
  - Dark matter spread out
What is the Dark Matter in the Universe?

Astronomers say that most of the matter in the Universe is invisible. Dark Matter is made of unknown particles. We are searching for them at the LHC.
Classic Dark Matter Signature

Missing transverse energy carried away by dark matter particles
Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory
General Interest in Antimatter Physics

Physicists cannot make enough for Star Trek or Dan Brown!
How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:
- same mass
- opposite internal properties:
  - electric charge, …

Discovered in cosmic rays
Studied using accelerators
Used in PET scanners

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers
Unify the Fundamental Interactions: Einstein’s Dream …

… but he never succeeded

Unification via extra dimensions of space?
Would vanish instantly.

Eat up the entire Earth?

Will LHC experiments create black holes?

Cosmic rays have not harmed us!
The LHC is the world’s most powerful microscope …

… and also a telescope addressing Gauguin’s questions
Michael Faraday

- Invented the electric motor
- Discovered induction

Einstein’s study had pictures of Newton, Faraday and Maxwell
Inside Matter

All matter is made of the same constituents

What are they?
What forces between them?
Maxwell’s Equations

- Prototype for describing particle interactions: unified electricity & magnetism
- Basis for Einstein’s theories of relativity

\[
\begin{align*}
\nabla \cdot E &= 0 \\
\nabla \times E &= -\frac{\partial B}{\partial t} \\
\nabla \cdot B &= 0 \\
\nabla \times B &= \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}
\end{align*}
\]

Electric charge
Magnetic charge?

There is every probability that you will soon be able to tax it!
Fraday to William Gladstone, then Chancellor of the Exchequer, when he asked about the practical worth of electricity
The Hottest Place in the Galaxy

Particle collisions create (within a tiny volume) temperatures a billion times higher than in the heart of the Sun.
Evolvution of the Universe

13.8 Billion Years

Today

Big Bang

10^{28} \text{ cm}

Matter and dark matter originated here

Only particle physics can tell us how
Formation of atoms
Formation of nuclei
Formation of protons & neutrons
Appearance of mass?
Appearance of dark matter?
Appearance of matter?

300,000 years
3 minutes
1 micro-second
1 pico-second
Is this the Higgs Boson?

No Higgs here!