Back to basics

The three fundamental units $G$, $c$, $\hbar$ are sufficient to describe all the quantities that appear in physics. They are connected to three fundamental concepts:

- $G$ is related to gravity (Newton, general relativity).
- $c$ is related to relativity (Maxwell, Einstein).
- $\hbar$ is related to quantum physics (Planck).

- Gravity and relativity are combined by general relativity.
- Gravity and quantum physics have not yet been combined.
- Relativity and quantum physics are combined by quantum field theory, our next topic.
Quantum field theory

What’s the problem?

- Relativity was derived from Maxwell’s equations for electric and magnetic fields.
- Quantum physics dealt with photons, electrons, atoms, and other particles.
- Apply quantum physics to fields.
Infinity times infinity

- A field extends over an infinite number of points.
- A particle exists only at a single point.
- Thus, a field is like an infinite number of particles.

This was true in classical physics. Now we want to extend the analogy to quantum physics. A quantum field should be like an infinite number of quantum particles. Each of those is a wave packet (Lect. 23), which again contains an infinite number of points.
The manybody problem

- Dealing with infinite numbers of particles is often called the manybody problem.

- The infinite number of particles in quantum field theory is related to the appearance of virtual particles. These are short-lived particles which pop up out of nowhere and live such a short time $\Delta t$ that the energy uncertainty $\Delta E = \hbar/4\pi \Delta t$ is as large as their energy (Lect. 23, Slide 9). They get away with violating energy conservation because of the uncertainty relation: They vanish before they can be caught cheating.

- Although we can’t catch virtual particles, their effects can be measured with great accuracy (Lect. 34, Slide 9).
Dealing with infinity

- In **solids** one deals with $10^{24}$ electrons (Lect. 26). This problem is solved by increasing the number of particles to infinity. A crystal is divided into an infinite number of **unit cells**, each containing only a few particles.

- There are similar approaches in quantum field theory. **Lattice quantum chromodynamics** uses the same trick for calculating the strong interaction between quarks and gluons **inside the proton**.

- Still, **infinities are a constant annoyance** in quantum field theory. They need to be eliminated by subtracting infinite quantities from each other, such as the infinite negative charge of virtual electrons from the infinite positive charge of virtual positrons.
Fields and forces

Each force is related to a field by:

\[
\text{Force} = \text{Charge} \cdot \text{Field}
\]

For example, the electric force is given by the electric charge times the electric field.

We know of four fundamental forces:

Electromagnetic, weak, strong, gravity
Quantum electrodynamics (QED) describes the electromagnetic force.

Quantum electrodynamics involves electrons and photons.

Richard Feynman

electron in → electron out

electron in → photon out → electron out
Feynman diagrams are world lines in space-time. (Lect. 15, Slides 9,10)

They can be assembled like LEGO pieces from a basic building block which describes emission or absorption of a photon by an electron:
Combining building blocks

- This basic building block diagram cannot conserve both energy and momentum.
- At least two building blocks are required for that.
- This diagram describes the **electromagnetic force**:

Electric repulsion between two electrons via emission and absorption of a photon.
Rotating a leg of a diagram = going backward in time

What is an electron going backwards? A positron!
Antiparticles: The positron

- The positron is a particle similar to the electron with the same mass but opposite charge.
- Every particle has such an antiparticle. Some are identical to their antiparticle, for example the photon.
- A positron can be compared to a hole in a semiconductor, which is an electron missing from an occupied band (Lect. 26, Slide 10).
- When an electron moves to the left to fill a hole next to it, the hole moves in the opposite direction:

![Diagram](image)
Rotate a diagram by $90^\circ$

= interchange space and time

electron-electron scattering

electron-positron scattering

A new physical process
Particle - antiparticle annihilation

electron - positron annihilation into two photons
Particle-antiparticle pairs

- Electron and positron can annihilate and create two photons.
- In reverse, two photons can create an electron-positron pair.

**Energy conservation** together with \( E = mc^2 \) gives:

Energy of the two photons

\[
\text{mass of the electron-positron pair } \times c^2 = 1 \text{ MeV}
\]
Why two photons?

- Because of momentum conservation.
- Use the center-of-mass reference frame, where the total momentum is zero.
- If only one photon went out, its momentum would not be zero, because a photon cannot sit still ($p = h/\lambda$, de Broglie).
Making antiparticles

- Gamma photons enter from below into a bubble chamber containing $H_2$.
- Electron-positron pairs are created, like electron-hole pairs in a solar cell.
- Electrons and positrons curve towards opposite sides in a magnetic field.
The penguin diagram

The result of a bet between a theorist (John Ellis) and an experimentalist. The loser had to incorporate the word ‘penguin’ into his next publication.

John Ellis, chief theorist at CERN.