The Higgs Boson

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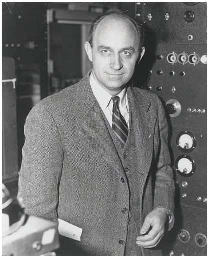
Everything, in Two Categories

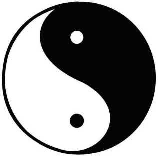
Physicists divide everything that makes up the universe into two categories: fermions and bosons.



Enrico Fermi

Satyendra Nath Bose

[Images from Wikimedia Commons]

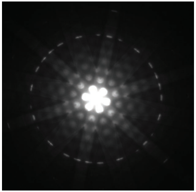


Like yin and yang, the differences between these two possibilities will help us to understand their similarities.

Category 1: Fermions

Fermions are what we usually think of as “matter”: electrons are fermions, as are protons and neutrons. (Protons and neutrons are made up of quarks, which are also fermions.) Fermions:

- Fermions obey the Pauli exclusion principle: two fermions cannot occupy the same state. This property is what makes them act like matter, and is also the reason for chemistry.
- Since multiple fermions cannot occupy the same state, we most often encounter them one at a time. So we usually see them behave like particles, even though they can also act like waves (e.g. interference in an electron microscope).



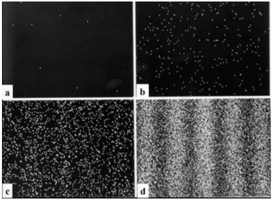
[Image: Wikimedia Commons]

- A fermion has (typically) two spin states, often chosen as “spin up” and “spin down.”

Category 2: Bosons

Bosons are what we usually think of as "waves": The most familiar boson is the photon, which makes up light.

- Bosons do not obey the Pauli exclusion principle: bosons like to be in the same state, as in a laser beam.
- Since many bosons can occupy the same state, we most often encounter many of them at once. So we usually see them behave like waves, even though they can also act like particles (you can see an individual photon).

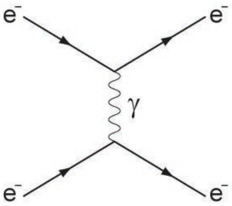


[Image: Hitachi.com]

- Most bosons are described by vectors. For example, light is made up of electric fields **E** and magnetic fields **B**.
- A photon has two polarization states. We'd expect three (for the three directions of space), but photons are transverse — they cannot be polarized along the direction they are moving.

Interactions

We can think of bosons as "force carriers": Fermions interact via the electromagnetic force by exchanging photons. For example, the interaction that yields the repulsive force between two electrons (Coulomb's law):



[Image from SLAC Today]

Each force has an associated charge, which gets introduced at each vertex of the diagram and gives the strength of the interaction.

Known force carriers:

- Photons, which carry the electromagnetic force.
- W and Z bosons, which carry the weak force.
- Gluons, which carry the strong force.
- Gravitons, which carry the gravitational force (we think!).

All the Fermions (as far as we know)

- The electron, which can be turned into a neutrino (and vice versa) by the weak interactions. Neutrinos have no electric charge, and mostly fly right through everything.
- The up and down quarks, which can be turned into each other by the weak interactions; each type of quark comes in one of three "color" charges, which govern its interactions by the strong force.

Protons and Neutrons

A proton contains two up quarks and one down quark, and a neutron contains one up quark and two down quarks (both in combinations with zero net color charge).

- For each fermion listed so far, there are two more particles that are the same in every respect, except with larger rest masses. "Who ordered that?"
- Every fermion has a corresponding antiparticle, with the same mass and opposite charge.

Particle Summary

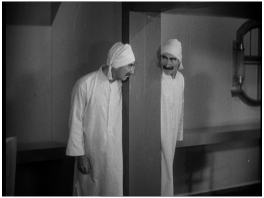
particle	electric charge?	weak charge?	strong charge?	(rest) mass?	type?
electron, muon, tau	YES	YES	NO	YES	fermion
neutrino (e, μ, τ)	NO	YES	NO	YES	fermion
quarks (6 "flavors," 3 "colors")	YES	YES	YES	YES	fermion
photon (E&M force)	NO	NO	NO	NO	boson
W^+, W^- (weak force)	YES	YES	NO	YES	boson
Z^0 (weak force)	NO	YES	NO	YES	boson
gluon (strong force, 8 "colors")	NO	NO	YES	NO	boson
graviton (gravity)	NO	NO	NO	NO	boson

Note: Everything has energy, so everything interacts via gravity.

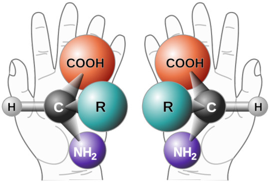
The photon is the only force carrier that does not also carry the associated charge (for example, gravitons have energy).

The Problem(s)

- The forces we observe in nature can all be described by a beautiful mathematical structure known as "gauge symmetry," which in turn is rooted in differential geometry. But gauge symmetry requires that the force carriers be massless — which is true for the photon, gluon, and graviton, but not for the $W^{\pm}$ and Z.
- It gets worse. The weak nuclear force is chiral — it is not symmetric under reflection in a mirror:



[Image from *Duck Soup*]



[Image from Wikipedia]

[Image from cuisine-saine.fr]

Chiral interactions require massless fermions. But all the fermions have nonzero masses.

What Does Mirror Symmetry Have to Do With Mass?

Let the helicity of a football be the direction it spins as it comes toward you — or, equivalently, the opposite of the direction the ball spins as it moves away from you.

[Image from Middlebury.edu]

Imagine a world where footballs with opposite helicity would fly differently.

But that's a contradiction with relativity: If I run down the field faster than the football, I see the ball moving away from me, not toward me. From my point of view, helicity is reversed!

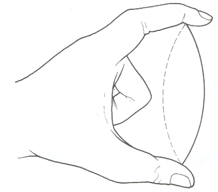
[Image from Middlebury.edu]

A massless particle moves at the speed of light, so you can't outrun it. . .

A Remarkable Solution

Our understanding of fundamental forces relies on maintaining gauge symmetry, but for particles to have mass that symmetry must be broken.

How do you break and not break a symmetry at the same time?



[Image from Griffiths, *Introduction to Elementary Particles*]

A brilliant insight

You can break the symmetry "spontaneously": The system is symmetric, but the ground state is not. Instead, the set of all ground states is symmetric.

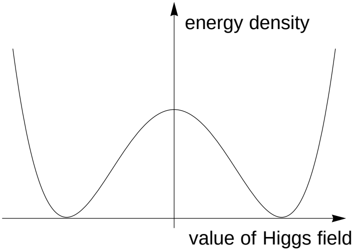
[Image from National High Magnetic Field Laboratory]

The system still has symmetry, but it's hidden.

A Remarkable Solution

What does spontaneous symmetry breaking look like for gauge symmetry? It requires a scalar boson, described by a number at each point in space instead of a vector.

- Still a boson (can have many in the same state).
- Doesn't have a polarization (so the math is simpler).
- Because it's a scalar, it can be nonzero without selecting a preferred direction in space. We can have a universe where empty space is filled with Higgs!



Particle or Field?

Just as electric and magnetic fields describe a collection of photons, the Higgs field describes a collection of Higgs particles.

The Origin of Mass

All around us, the Higgs field in its lowest energy state, which is not the state where its value is zero.

- By filling empty space, the Higgs offers a solution to the paradox: Particles are intrinsically massless, but some (including the Higgs itself) acquire masses through their interactions with the Higgs. Particle masses are really just the particle getting "bogged down" in Higgs field!
- The mass of a particle is proportional to the strength of its interaction with the Higgs.
- Correctly predicts intricate relationships between masses and charges.
- This mechanism also explains superconductivity: Inside of a superconductor, the photon effectively becomes massive, due to its interactions with a background condensate of paired electrons.

At the high temperatures just after the Big Bang, the Higgs field wasn't in its lowest energy state — instead it fluctuated symmetrically around zero.

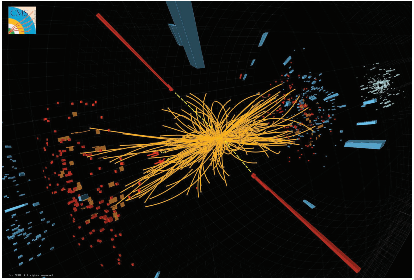
Looking for the Higgs Boson

If space is filled with Higgs field, shouldn't it be easy to find?

Yes and no. We already see the effects of the Higgs through the masses of elementary particles. But to see the Higgs itself, we need to create disturbances from its usual value in empty space.

That's what happens inside the Large Hadron Collider (LHC).

These disturbances decay rapidly (in about the time it takes light to travel across an atomic nucleus), but we can look for the telltale signs they leave behind.



[Image from CMS Collaboration]

Just as a photon is the fundamental unit of light, a Higgs particle is the fundamental unit of these ripples in the Higgs field.

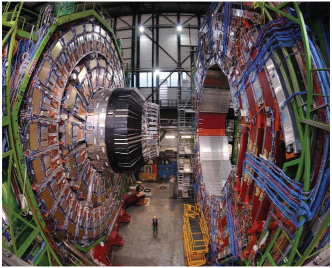
Finding the Higgs Boson

The LHC produces Higgs particles by colliding protons at 99.9999991% of the speed of light.

99.99999999% of the collisions produce stuff we already understand, so filter those out and look for the 0.00000001% in which a Higgs particle is produced.

> "Like smashing two Swiss watches together to figure out how they work."
> — Richard Feynman

Use



[Image from CMS Collaboration]

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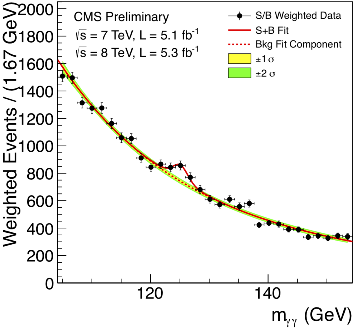

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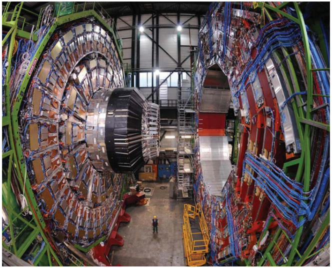

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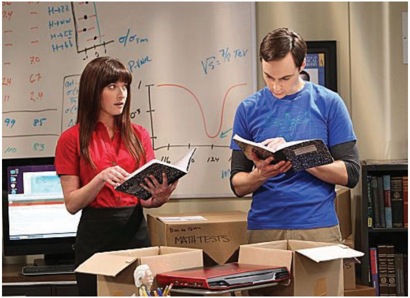

[Image from *The Big Bang Theory*]

What's Next?

The various pieces of Standard Model seem to be begging to be assembled into a more fundamental theory. What can guide us?

- Gauge symmetry (spontaneously broken) unifying all the forces?
- Symmetries (also spontaneously broken) relating bosons and fermions?
- Dark matter (an unknown weakly interacting particle) and dark energy (energy of empty space)?
- A better theory of the graviton, putting gravity on an equal footing with other forces quantum-mechanically?
- The idea that there are many parallel universes with different laws of physics, and ours is just the one in which it's possible for us to exist?

We are still waiting for our next clue. . .