The Standard Model

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A quick look

These are the ingredients you would need to make up the universe minus a few details.
Is this the Standard Model?

- Yes....and No, the Standard Model is more than just a list of particles, but what is it?
Inquiring minds want to know…

“Mommy…

…why don’t ants get hurt when they fall from really high up?”

…why, when I throw this ball up while in the car, doesn’t it fly to the back?”

…why do cars on the street look like they’re floating on a hot day?”

…why does the sky look red when the sun sets?”

…what makes a rainbow?”

…why do grandma’s eyes look bigger behind her glasses? 

…why do geese fly in V’s?”
Famous Inquiring Minds...

Galileo Galilei:
“Maybe the Church was wrong...
We can understand nature by observing the universe!”

Born: Modern Science
Niels Bohr: “If we assume that the electrons orbit the nucleus, does it explain what we see?”

Born: The Bohr Model of the Atom
Famous Inquiring Minds Continued

Albert Einstein: “Maybe, though Newton’s ideas seem to work in the everyday world, they are actually approximations of something else that works in all conditions!”

Born: Special and General Relativity
Particle Probes

By using particles we know about as probes, we can find information about objects that we aren’t familiar with.
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Collisions

Colliding things helps break them apart to see what’s inside
By throwing particles together at high energies, we can find information about them.

Particle Accelerators like Brookhaven (NY) or Fermilab (IL) accelerate particles until they have a lot of kinetic energy, then slam them together to see what happens.
Particle Physicists…

- Form hypothesis to explain the behavior of little pieces of matter
- Use particle accelerators and other tools to test the validity of their hypothesis
- This result (so far) is the Standard Model
Let’s look at what it is...

- Description of the fundamental particles
- Description of three of the fundamental forces
  - Strong
  - Weak
  - Electromagnetic
- Union of weak & electromagnetic as the electroweak force
- Conservation laws, e.g. matter-energy, momentum, charge, etc...
A complete theory
Description of gravity
Explanation of heavy generations of leptons and quarks
Unification of strong and electroweak forces
Definitive explanation on the origins of mass
But what does all this mean?

What are quarks and leptons?
What are the force carriers?
What do they do?
And how do we get from weird sounding particles to the world around us?

We’ll need some tools and then we can dive in
Our Toolbox

Concepts and Methods

- Spin
  - Bosons
  - Fermions
- Quantization
- Antimatter
- Conservation Laws
- Feynman Diagrams
  - Real Particles
  - Virtual particles
Spin

- Analogous to spinning top, but nothing is really “spinning”
- Has nothing to do with motion in space…
- Intrinsic Property of all Fundamental particles (very mathematical)
- Can be integer (boson) or odd half-integer (fermions)
- Conserved quantity
Bosons and Fermions

Bosons have integer spin

- Examples: Photon, W, Z, gluon, He-4 nuclei, Oxygen 16
- Multiple particles can be in the same state, at the same time, in the same place.

Fermions have odd half-integer spin

- Examples: Electron (all leptons for that matter), quarks, He-3
- Pauli Exclusion principle – one particle per quantum configuration
Quantization

- Energy, charge, spin, matter, etc. come in quantized amounts

- Einstein (1905) – light quantized, thus the photon

Possible Conclusion?

- Force carriers — quantization of a force
Antimatter

- Every particle has an antiparticle.
- Same except opposite charge, color, and "strangeness."
- Particle and its antiparticle annihilate upon contact into pure energy.
- Problem of why more matter than antimatter in the universe.
The Wild World of Conservation Laws

• **Symmetries** exist in the equations of the Standard Model – **theorem**: for each symmetry there exists a conservation law

Most of us are familiar with a few:

• Energy, Momentum, Charge

And some a little less familiar:

• Color, Spin, Baryon number, Lepton number

These limit what is possible, and what is not possible
Feynman Diagrams

Embodies Quantum Theory in Simple Diagrams

- “Wonderfully clear yet powerful technique!” (Paul A. Tipler, 1969)
- Arrow going forward in time means particle
- Arrow going backwards in time means antiparticle
- Dashed line means this particle is its own antiparticle (no arrow)
More on Feynman Diagrams

- Arrangements limited by conservation laws....
  i.e. cannot replace the photon with an electron

- Electrons in this case represent real particles
- Photon in this case is a virtual particle
So what are Real and Virtual Particles?

Real particles
- Can be observed directly or indirectly in experiment
- Satisfy the relativity equation
  \[ E^2 = p^2c^2 + m^2c^4 \]

Virtual particles
- Cannot be observed directly, represent intermediate stage of a process
- \( E^2 \neq p^2c^2 + m^2c^4 \) !!!
- Allowed by Heisenberg’s Uncertainty principle
  \[ \Delta p \Delta x \geq \hbar/2 \text{ or } \Delta E \Delta t \geq \hbar/2 \]
The Four (or Three) Fundamental Forces

Gravity

Strong Force

Electroweak

Electromagnetism

Weak Force
Gravity

- Attractive force between any objects with mass or energy
- Outside of the Standard Model, described by **General Relativity**
- Infinite Range, weakest of the forces, dominates astronomical scales
- **Graviton** predicted as force carrier
Electromagnetism

- Mediated by photon exchange
- Described by QED
- Infinite Range: acts on astronomical and atomic scales, responsible for chemical properties
- Attractive or repulsive force that acts upon objects with electric charge
Electromagnetic forces...

hold electrons in their orbits around positive nuclei to form neutral atoms....

... and hold neutral atoms to other neutral atoms to form molecules!
What about the nucleus?

The nucleus of an atom is protons and neutrons.... Why don’t electromagnetic forces push the protons apart?

The strong force holds them together!! Ok... what’s that?
Strong Force

- Strongest force, but **quarks** are only particles that it affects
- Quarks and gluons have **color charge**
- Force mediated by **gluons**
- Attractive; limited range; “rubber band force”

So how does color work?
**Color**

- Three types of color charge, Red, Green, Blue and associated anti-color

- And....
Color cont...

Color has to be “neutral” for quarks to combine
- A color and anticolor cancel each other out (“neutral”)
- Red, Green, and Blue make “neutral” or “white”
- Confinement!!!
- Possible combos
  - mesons: quark-antiquark pair
  - baryons:
    - Three quarks, different colors
      (e.g. protons, neutrons)
    - Three antiquarks, different anticolors
      (e.g. anti-protons, antineutrons)
Quarks Unite!

- **Quarks** exchange massive amounts of gluons creating a color field.
- Each gluon exchange and absorption changes the color of a quark.
The nucleus is held together by what we call the Residual Strong Force that the quarks in each proton or neutron feel.
Weak Force

- Responsible for decays of massive quarks and leptons into lighter particles
- Cause of $\beta$ – decay and fusion in the sun
- Short range force mediated by the massive $W^+$, $W^-$, and $Z^0$ bosons
- Only way of particles of one generation to change into another.
Weak Force in Action

A down quark decays into an up quark, an electron and an anti-electron neutrino via a $W$ boson.
Electroweak force

- Weak and electromagnetic forces unified into the electroweak force
- This theory predicted the $W^+$, $W^-$, and $Z^0$ bosons, relates them to the photon
- Requires another particle called the Higgs boson which gives particles mass

So why do physicists think these two forces are related?
Differences between Weak & EM force

• Range of EM = ∞
  Range of Weak = atomic scale

• Photon is massless
  Ws, Z are MASSIVE

• EM conserves parity
  Weak violates parity

• EM is a strong force
  Weak force is... err... well... weak
Not so Different

- $W^+$, $W^-$, $Z^0$ and photon are very similar except for huge mass difference.
- $W^+$, $W^-$, $Z^0$ predicted by this theory and found.
- $W$ and $Z$ bosons act very similar to the photon at higher energies and short distances.
Why do EM & Weak Force look so different?

- Electroweak symmetry breaking...
- Broken by what we call the Higgs Mechanism
- Mechanism explains why $W^+$, $W^-$, and $Z^0$ have mass, while the photon does not.

- Higgs Boson
Those are the Forces and Their Carriers
But what about the other particles?
Quarks

- Affected by
  - strong force
  - weak force
  - electromagnetism
  - gravity

- Fractional charge
- Fermions: spin 1/2
- Three generations differing only by mass
Leptons

- Affected by weak force
- Affected by electromagnetism
- Affected by gravity

- Charged Leptons – electron, muon, and tau
- Corresponding Neutrinos
  - no charge
  - tiny mass

- Fermions: have spin 1/2
- Three generations differing only by mass
Unsolved Mysteries

- Gravity?
- Why three generations?
- Standard Model can’t predict a particle’s mass, oops, Higgs?
- Matter/Anti-Matter asymmetry
- Dark Matter

These are some of the kinks in the Standard Model
The Horizon

- Supersymmetry
- String Theory
- Extra Dimensions
- Dark Matter
- Dark Energy
- Grand Unified Theories