CHAPTER 7
THE FORCES

In the previous chapter we discussed fermions, the building blocks of matter. In this chapter we consider Nature's mortar and trowel -- the forces through which the fermions interact.

In common usage the term "force" means a "push" or "pull." Physicists use "interaction", a more general term, to describe the forces between particles. Particles interact with fields. The interaction changes the particle's momentum or its energy, or the interaction may change the kind of particle. The term "interaction" also describes the decay of an isolated particle, such as beta decay of a neutron.

In Ch.1, we described how physicists developed the idea of a field to explain action at a distance. In Ch.5, we discussed the quantum nature of matter and energy. Current theory blends these concepts: fields, and therefore the forces, are quantized. While classical field theory successfully describes the macroscopic behavior of electromagnetism and gravity ("macroscopic" in that we feel these forces directly, on the human scale), we require a quantum field theory to understand the forces, especially the strong force and the weak force, at the scale of the fundamental particles.

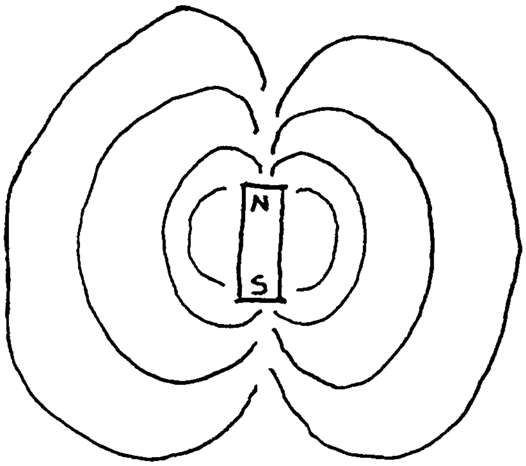
In the following pages, we will discuss electromagnetism and gravity as fields. Then we will outline the principles of quantum field theory in order to describe the four forces at the scale of particles. We will invoke quantum field theory to explain why the forces differ in range and why the relative strength of the forces depends on distance between particles. Finally, we will present evidence that the forces are, in fact, inter-related.

FIELDS: ELECTROMAGNETISM

As discussed in Ch.1, electricity and magnetism are manifestations of the same underlying force: a moving electric charge induces a magnetic field, and a changing magnetic field produces an electric current.

The electromagnetic force is only one-hundredth as strong as the strong force. (Note: we will compare the relative strengths of the four forces as they would affect two quarks positioned 10^{-13} cm apart. Relative strengths vary with distance, for reasons we will discuss at the end of the chapter.) The electromagnetic force affects all electrically charged particles. It has infinite range, although its strength decreases as $1/R^2$ (where R is the distance between two charges). The electromagnetic force determines the structure of atoms and molecules. It keeps us from falling through the floor, and it provides the chemical energy that powers rockets and bird wings.

The concept of a field serves well to describe the gross features of electromagnetism. In fact, we can visualize the electromagnetic field: Place a bar magnet flat on a table, and lay a stiff sheet of paper on it. Sprinkle fine iron filings on the paper. As the filings fall, they orient themselves along curved lines linking the north and south poles of the magnet -- the lines of the magnetic field, which permeates space around the magnet.



Magnetic field

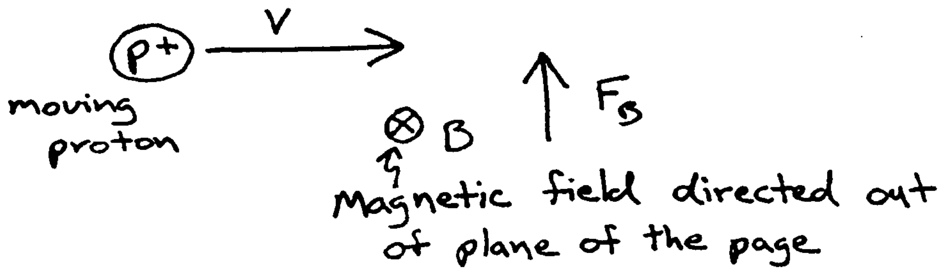
The electric force on a stationary charged particle is F = qE, where E is the local electric field, and q is the particle's electric charge. The local field is determined by the distribution of other electric charges. In the simplest case, the force exerted by one electron on another, the field E = q/R^2, and the force F = q^2/R^2.

$e^- \leftarrow R \rightarrow *$ ↙ Electric field at a point in space near an isolated charge = $E = q/R^2$

$e^- \leftarrow R \rightarrow e^-$ Force of one electric charge separated from another charge by distance R

$$F = q^2/R^2 = qE$$

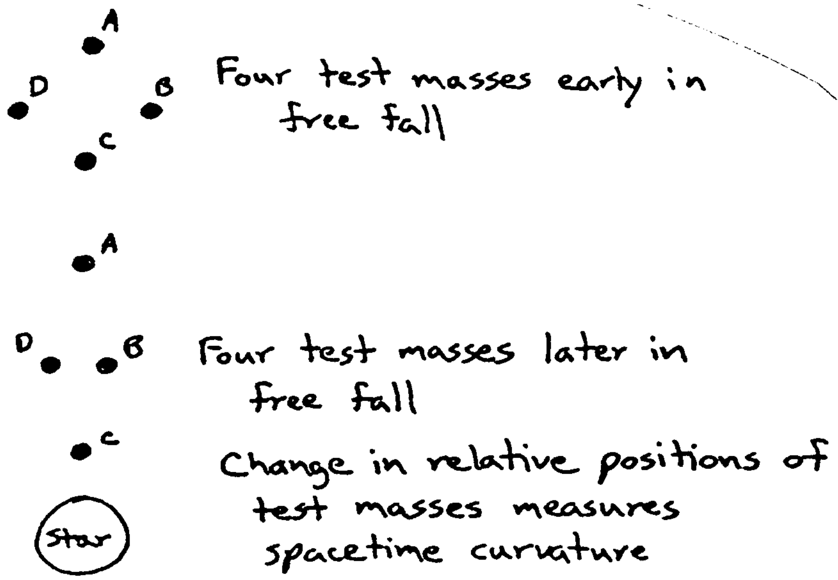
An electric charge moving through superimposed electric and magnetic fields experiences a force F = q(E + v/c X B), where v is the particle's velocity, c is the speed of light, and B is the local magnetic field. The "cross product," X, indicates that the magnetic component of the force is perpendicular both to the velocity and to the magnetic field.



FIELDS: GRAVITY

The gravitational force affects all particles, bosons as well as fermions. Gravity bends the paths of photons as well as the paths of stars. On the scale of the particles gravitational effects are negligible (about 10^-38 the strength of the strong force), but the gravitational force is cumulative: the force of gravity increases as mass increases. At the scale of stars, it sometimes overwhelms the other forces: gravity crushes the cores of the most massive stars when they die, and tidal forces near black holes can rip apart atomic nuclei.

We can describe the force of gravity in Newtonian terms: F = -GMm/R^2, where M and m are two masses, R is the distance separating their centers of mass, and G is the gravitational constant (see Ch.1.). We can calculate the gravitational field more precisely using Einstein's metric, and we can measure the field (the curvature of spacetime) with test masses, as described in Ch.3.



Gravity is unique among the forces in that it is "monopolar:" it is always attractive -- always "pull" and never "push." While the other forces involve opposite charges (e.g. positive and negative electric charges) gravity has only one "charge," mass. There is no "anti-gravity."

Only attractive, never repulsive, the force of gravity is cumulative -- it increases with increasing mass -- and it is self-augmenting. A large mass accumulates more mass by gravitational attraction, which produces a stronger gravitational force (greater spacetime curvature), which attracts more mass . . .

Gravity is unique, also, in that its measure, spacetime curvature, determines the very grid we use to plot the effects of all the other forces. In a way, the other forces are superimposed on the fabric of spacetime.

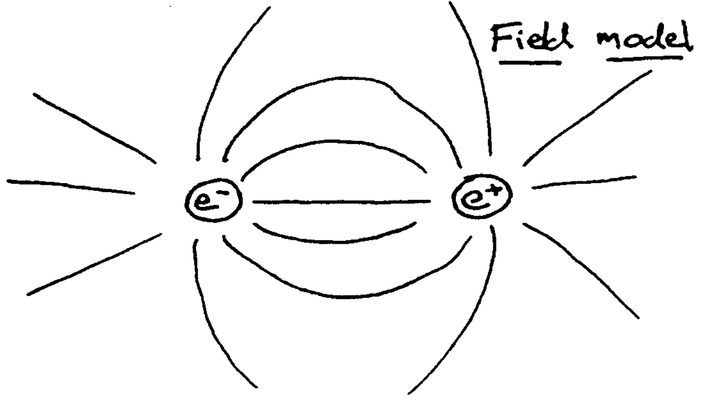
QUANTIZED FIELDS: UNDERSTANDING FORCES AT THE SCALE OF PARTICLES

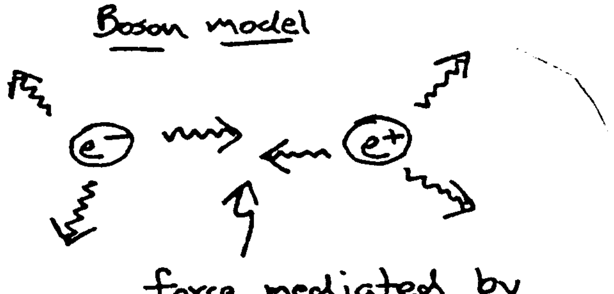
The concept of a field serves well for electromagnetism and gravity, but quantum mechanics demands a new model of the forces at the scale of particles: the fields themselves must be quantized.

As we discussed in Ch.5, mass and energy are quantized: they come in packets. By extrapolation, since the forces transfer momentum ($p = mv = h/\lambda$) and energy ($E = hf$), the forces must be quantized, and therefore the fields that transmit the forces must be quantized.

The field quanta ("packages" of field) are called "bosons," and there are bosons associated with each of the forces. The photon is the field quantum of the electromagnetic force; the graviton is the (hypothetical) field quantum of gravity; vector bosons are the field quanta of the weak force; and gluons are the field quanta of the strong force. All the bosons have been detected in accelerator experiments except the graviton.

In terms of field quanta, the electromagnetic force results from an exchange of photons between charged particles, and the gravitational force results from an exchange of gravitons.





force mediated by virtual photon exchange between charged particles

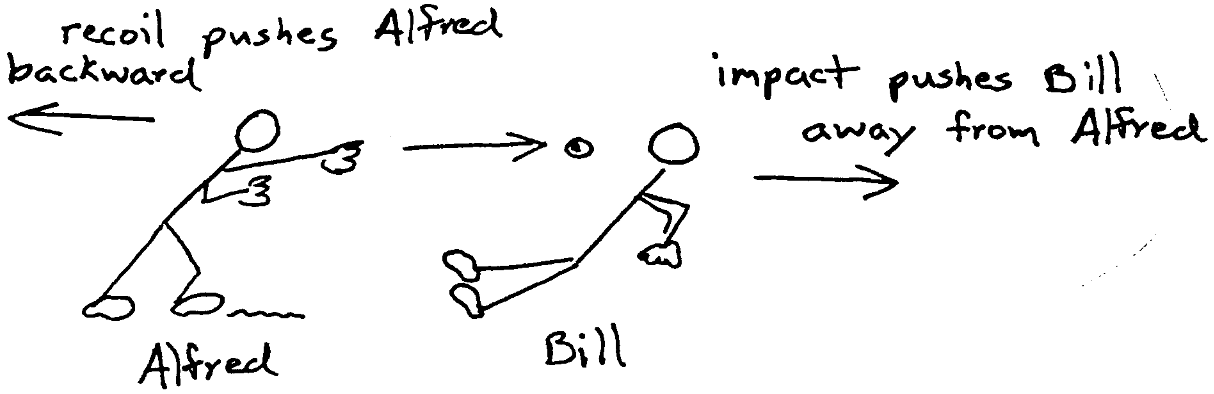
Bosons

FORCE	RANGE	STRENGTH AT 10^{-13} CENTIMETER IN COMPARISON WITH STRONG FORCE	CARRIER	MASS AT REST (GeV/c^2)	SPIN	ELECTRIC CHARGE	REMARKS
GRAVITY	INFINITE	10^{-38}	GRAVITON	0	2	0	CONJECTURED
ELECTROMAGNETISM	INFINITE	10^{-2}	PHOTON	0	1	0	OBSERVED DIRECTLY
WEAK	LESS THAN 10^{-16} CENTIMETER	10^{-13}	INTERMEDIATE BOSONS. W^+	81	1	+1	OBSERVED DIRECTLY
			W^-	81	1	−1	OBSERVED DIRECTLY
			Z^0	93	1	0	OBSERVED DIRECTLY
STRONG	LESS THAN 10^{-13} CENTIMETER	1	GLUONS	0	1	0	PERMANENTLY CONFINED

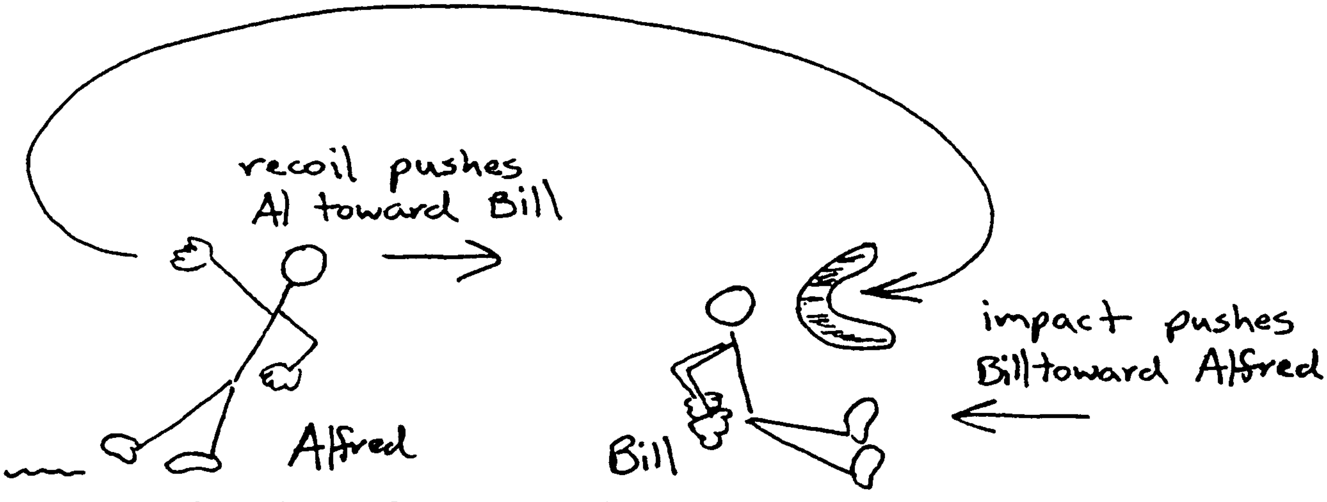
from Quigg, Sci. Am, 4/85

A MODEL OF BOSON EXCHANGE

It is difficult to visualize how particles can mediate forces: boson-mediated interactions are best described abstractly in the mathematics of quantum field theory. There is an everyday analogy to boson exchange, however. Imagine two people on slippery ice throwing snowballs at each other. The recoil of each throw pushes A away from B, and the impact of the snowball pushes B away from A.



Now imagine them throwing boomerangs. The recoil of the throw pushes A toward B, and the impact of the boomerang pushes B toward A.



In this (grossly oversimplified) model, the people represent fermions, and the snowballs and boomerangs represent bosons.

THE WEAK FORCE

While we experience electromagnetism and gravitation directly, the weak force works at the smallest scales, beyond our senses. Furthermore, while electromagnetism and gravitation conform to our notions of forces as "push and pull," the primary effect of the weak interaction is more subtle. It changes fermion flavor.

The weak force affects all fermions -- leptons and quarks, charged and uncharged. It is the weakest of the four forces -- only about a billionth the strength of the strong force -- and its effective range is quite short -- 10^-16 cm., about one-thousandth the diameter of a proton.

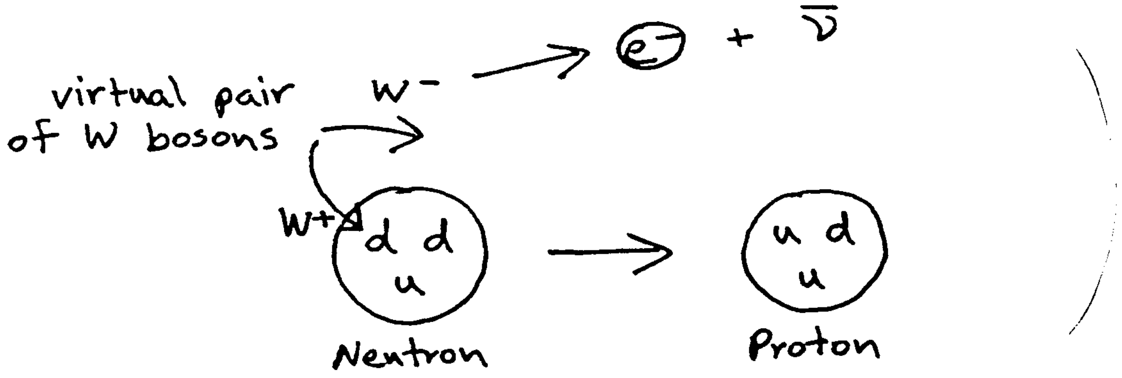
Neutron decay provides the most common example of the weak force at work. In gross terms, an isolated neutron decays to a proton, an electron, and an anti-neutrino:

$$N \longrightarrow p^+ + e^- + \bar{\nu}$$

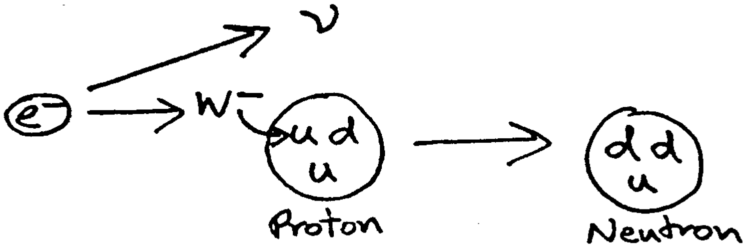
Neutron decays to proton, electron, and anti-neutrino

In detail, the weak force is mediated by field quanta called "intermediate vector bosons" -- the W+, W-, and Z particles. The vector bosons are unique among the field quanta in that they have large masses (the other bosons are, theoretically, massless), and the W's carry two kinds of charge -- an electric charge and a weak charge. (The Z carries only weak charge.) The vector bosons were discovered at energies of 81 GeV (W's) and 93 GeV (Z) by Carlo Rubbia and his team in a brilliant series of experiments at CERN (the European accelerator center). They had been predicted, theoretically, by Steven Weinberg and Abdus Salam.

In neutron decay, a virtual W+ converts one of the neutron's down quarks into an up quark, and its partner W- disintegrates into an electron and an anti-neutrino.



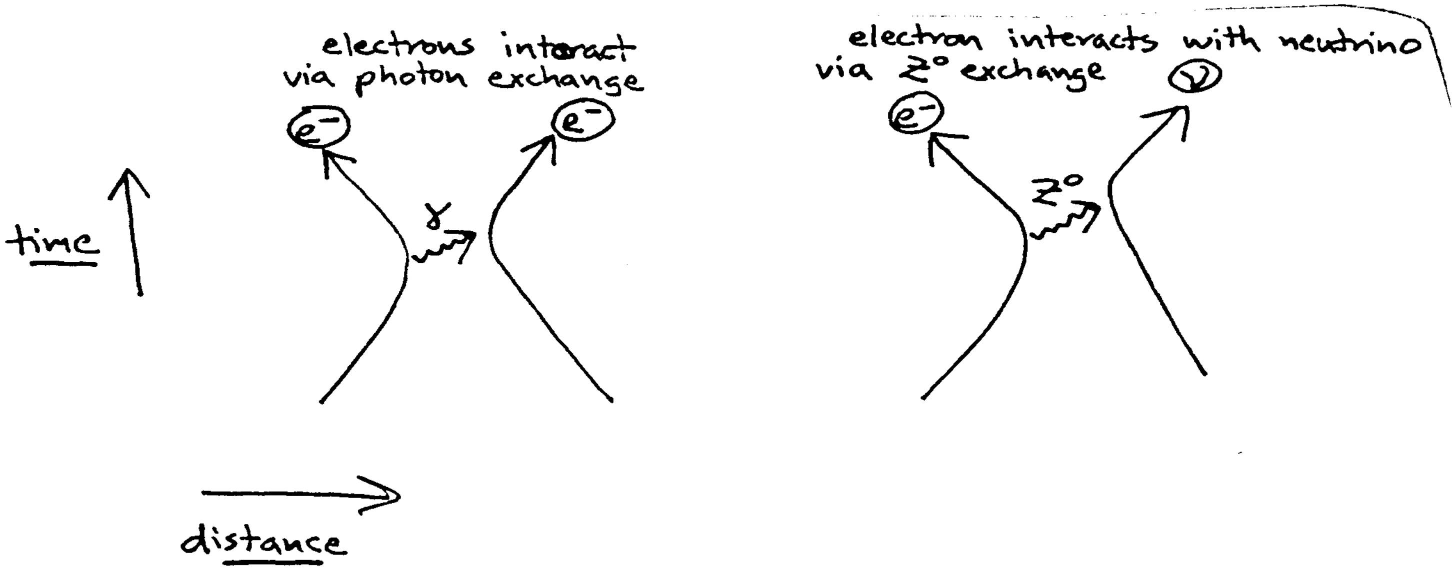
The reverse reaction occurs during core collapse in a supernova. When the supernova progenitor collapses on its iron core, the overwhelming force of gravity "squeezes" electrons inside protons, leaving a residue of neutrons.



$e^- + p^+ \rightarrow N + \nu$

electron interacts with Proton (via W⁻) to produce Neutron and neutrino

Rather than changing particle flavor, the neutral Z particle mediates weak scattering events (events in which particles responsive to the weak force recoil from each other) called "neutral current" interactions. In these events, the Z plays a role similar to the photon's role in electromagnetic scattering.

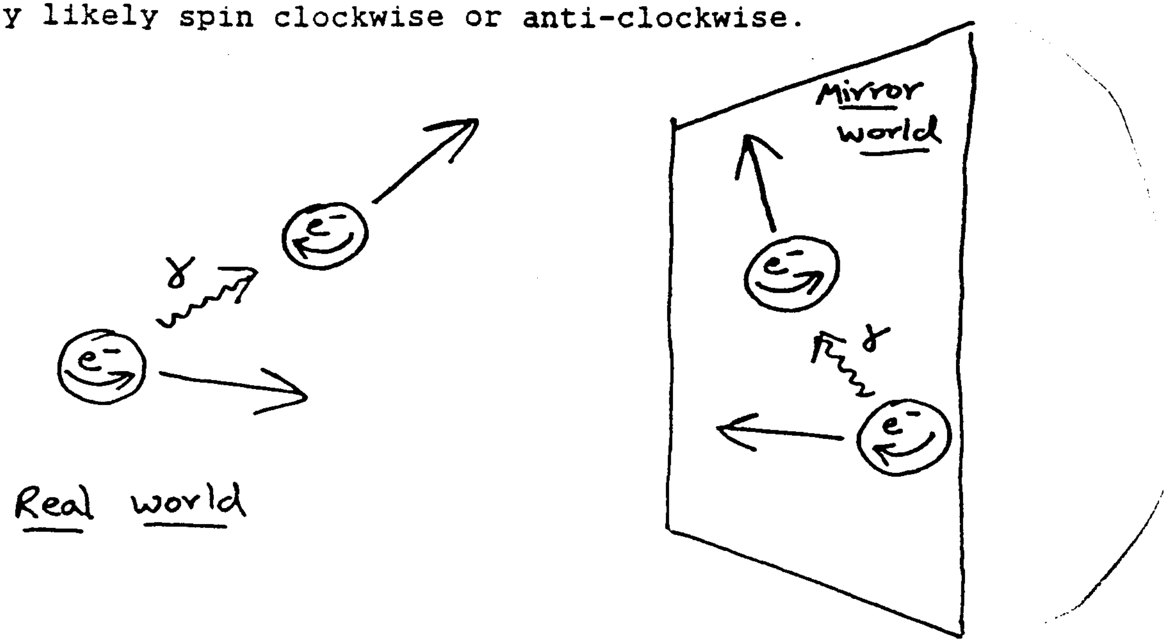

electrons interact via photon exchange

electron interacts with neutrino via Z° exchange

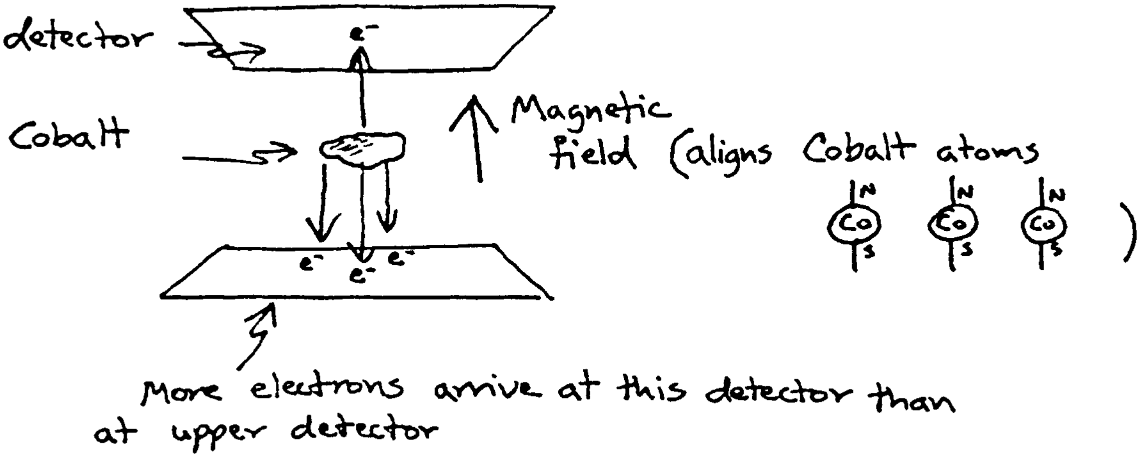
PARITY VIOLATION IN WEAK INTERACTIONS

Unlike other particle interactions, the weak interaction preferentially produces particles with left-handed spin -- i.e. the weak force violates "parity".

"Parity" refers to mirror symmetry. Prior to the discovery of weak parity violation, physicists believed Nature had no preferred direction and that particle interactions in a mirror world would be indistinguishable from interactions in the real world. Too, they assumed Nature had no preferred handedness and that particles would equally likely spin clockwise or anti-clockwise.

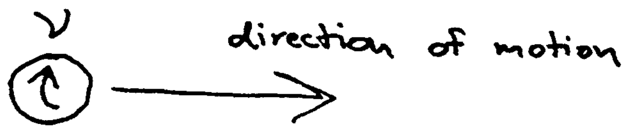


The discovery of parity violation in weak interactions shook the foundations of physics. Parity violation was predicted theoretically by C.N. Yang and T.D. Lee and verified experimentally in 1957 by M. Wu. Madam Wu found that radioactive cobalt nuclei eject beta particles (electrons) preferentially with left-handed spin.



Parity violation has been observed in other processes involving the weak interaction. Neutrinos, for example, always spin left, and anti-neutrinos always spin right. The

K particle preferentially decays to positron and pi minus (the negative pion) rather than to electron and pi plus.



neutrinos have left-handed spin

$$\textcircled{K^0} \longrightarrow \pi^- + e^+$$

Kaon preferentially decays to pi minus and positron

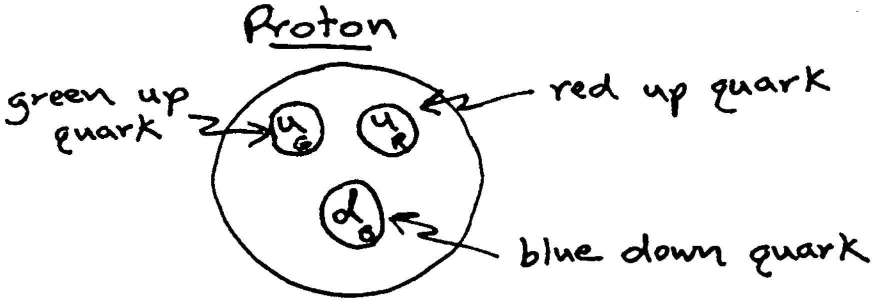
THE STRONG FORCE

As its name implies, the strong force is the strongest of the four forces, but its grasp extends only about 10^-13 cm., roughly the diameter of a proton. While the weak force affects both leptons and quarks, the strong force affects only quarks and hadrons, those particles composed of quarks. The strong force holds quarks inside hadrons and mesons, and it binds the hadrons in atomic nuclei. While the weak force changes fermion "flavor," the strong force changes quark "color."

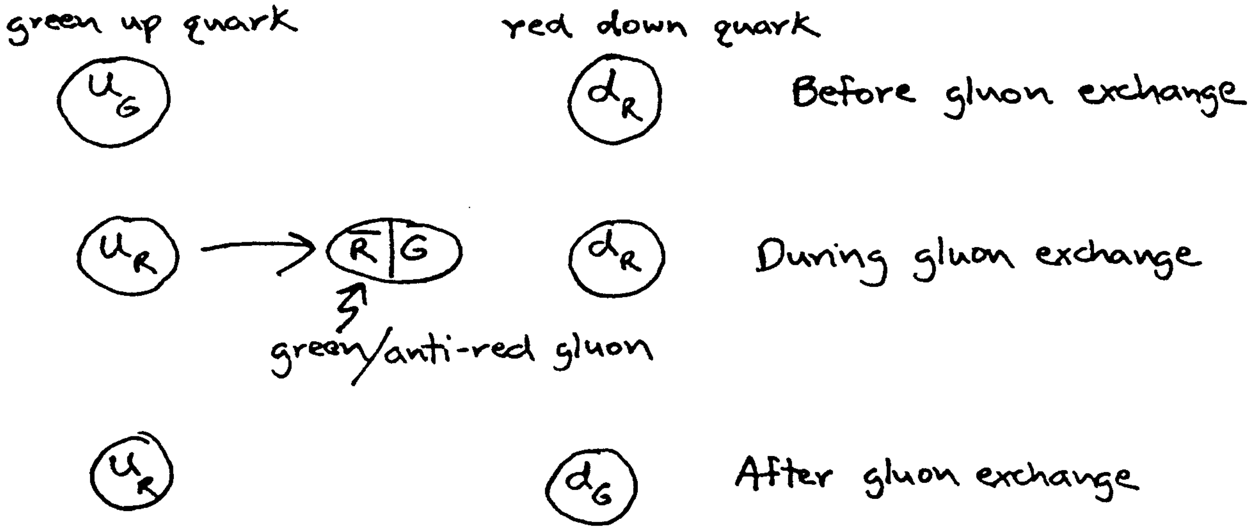
Quarks carry electric charge, and they also carry color charge -- red, blue, or green. Anti-quarks carry anti-colors -- cyan, magenta, or yellow. The terms "red," "green," and "blue," of course, are whimsical. If we could see quarks under a microscope (we can't -- they are far too small) we wouldn't see brightly colored little spheres. Colors provide handy labels to describe the otherwise abstract behavior of the strong force: individual quarks behave as if they carry one of three strong charges. The three colors label those charges, for easy reference.

In fact, the terms "positive" and "negative," used to describe electric charge, are arbitrary, too -- chosen historically to describe interactions between electrons and protons. Electric charges might just as well have been designated "chocolate" and "vanilla," so long as the scientific community agreed chocolate always repels chocolate, and chocolate attracts vanilla. What _is_ charge, really? We don't know.

Quantum chromodynamics (QCD), the theory of quark interaction discovered in the 1960's by Murray Gell-Mann, Yuval Ne'eman, George Zweig, and others, indicates quarks interact according to two basic rules: 1) the net electric charge in a hadron must be an integer (e.g. -1, 0, or +1), and 2) the net color charge of a hadron must be "white", i.e. of the three quarks confined in a proton or neutron, one must be red, one green, and one blue. Inside a meson, one quark must carry the anti-color of the other.

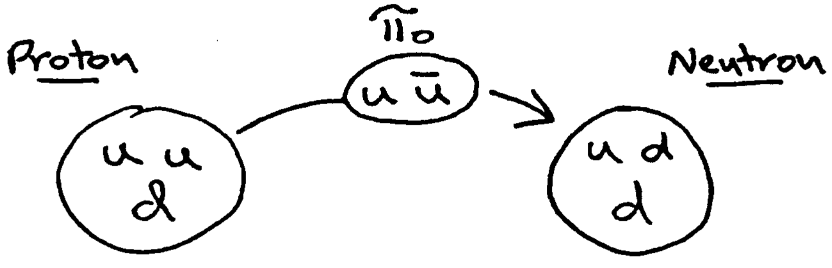


Just as electrically charged particles interact via photon exchange, quarks exchange bosons called "gluons," and it's the gluons that bind quarks in hadrons. Unlike the photon, which is uncharged, gluons themselves carry color charge: in fact, each gluon carries a color and an anti-color. Gluon exchange between two quarks interchanges the colors of the quarks.



Color charge "leaks out" of individual hadrons and binds quarks in other, nearby neutrons and protons. In fact the nucleus behaves like an amalgum of quarks linked by gluon exchange: There is evidence the quarks are organized into different energy levels, like the electrons surrounding the nucleus.

The color "leakage" which binds protons and neutrons in a nucleus manifests itself in the form of pions, a kind of "second level" carrier of the strong force. Pions behave like dollops of glue (gluons accompany the pion's quark and anti-quark) which stick nucleons together.

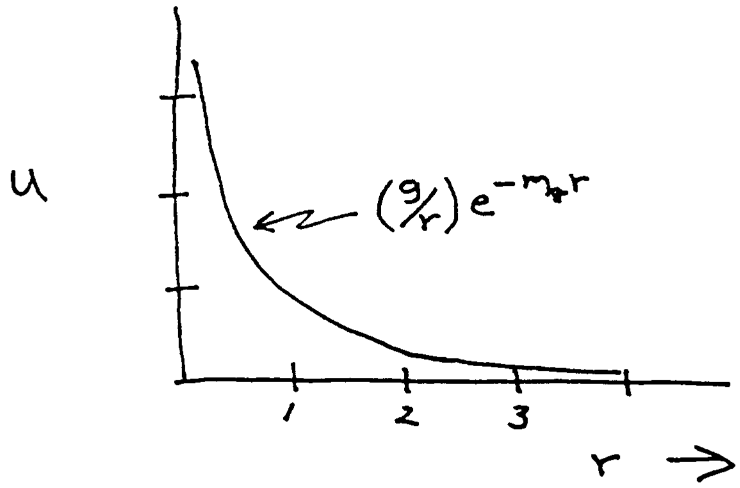


Nuclear binding mediated by exchange of π^0

We can describe the gross features of nuclear binding with a semi-classical equation: strong potential = $U_s = (g/r)e^{-m_\pi r}$ *

where g is the value of the color charge, r is the distance separating nucleons, and m_π is the mass of a pion. Note that the force in this description decreases exponentially with distance.

*



As long as the diameter of the nucleus is less than the reach of the strong force, the nucleus holds together. If the perimeter outdistances the gluon links, electromagnetic repulsion overcomes the color charge, and the nucleus ejects part of its mass (and charge).

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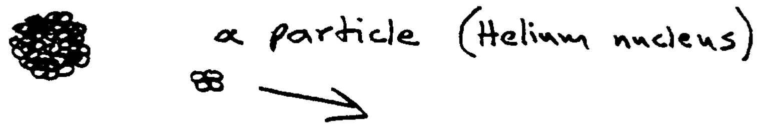
* From Berkeley *Physics*, V. 4

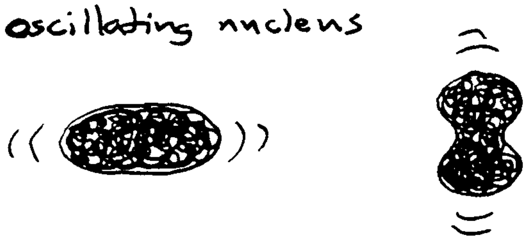


Alpha decay of U^{238}

The interplay between the electromagnetic force and the strong force explains nuclear fission (see Ch.2), and we can understand the energy released by fission in similar terms. Think of the nucleus as a compressed spring: the strong force binds like charges in a confined space like two hands compressing a coil spring. There is energy stored in the electric field within the nucleus just as there is energy stored in a spring, and we can think of this energy as the origin of the extra mass per nucleon associated with large nuclei.

Large nuclei are never at rest. They oscillate like water droplets, sometimes spherical, sometimes obloid. If a nucleus becomes so distorted -- because of random oscillations or gyrating from collision with an incoming neutron -- its diameter may exceed the reach of the strong force, and the coiled energy of the electromagnetic "spring" blasts the nucleus apart.

oscillating nucleus



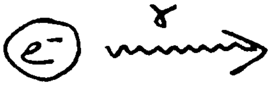
incoming neutron adds enough extra energy to split nucleus

RANGE

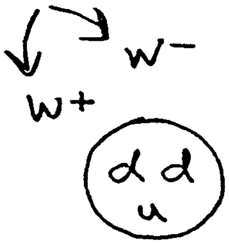
We can exploit quantum field theory to understand the relative ranges and strengths of the four forces. Boson mass determines the range of a force, and the interplay of virtual fermions and virtual bosons with real particles determines force strength.

For gravitation, electromagnetism, and the weak force, the range of the force is inversely proportional to the mass of the boson that mediates it. Electromagnetism and gravity, mediated by the massless photon and the graviton, respectively, have an infinite range. The weak force, mediated by the vector bosons with masses on the order a thousand times greater than the proton, is felt only over a range of about 10^-16 cm.

We can understand the relation of boson mass to range in terms of the uncertainty principle, $\Delta E \Delta t$ >= h (see Ch.5). Massive virtual bosons (large mass = large ΔE) must interact in a short time interval, therefore within a short distance. Virtual particles of zero rest mass, such as the photon, have an infinite Δt, hence an infinite range.



photon, because it has 0 rest mass, has infinite range

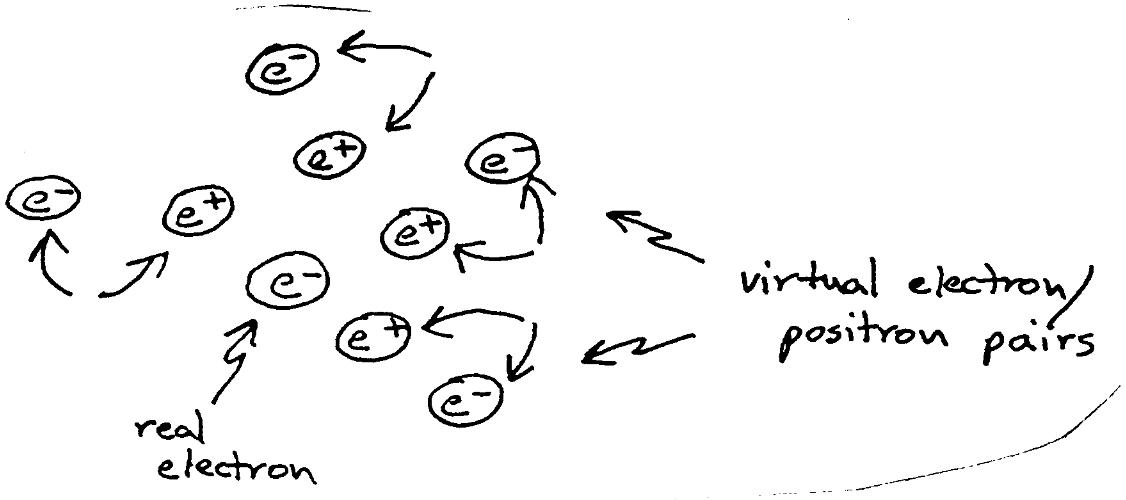


W bosons, which have large mass, must interact within a very short time (and distance) or they will annihilate

The strong force apparently violates this relation of mass to range. Gluons, theoretically, are massless, but the strong force obtains only over a range of about 10^-13 cm. As we will discuss below, the range of the strong force is limited because gluons themselves carry color.

SHIELDING

Virtual particles profoundly affect the forces between fermions, especially in the electromagnetic and strong interactions. The space around an electron, for instance, seethes with virtual positrons and electrons, and these virtual particles effectively mask the electron's "bare" negative charge: virtual positrons are attracted to the "real" electron, and virtual electrons are repelled. The distribution of virtual particles creates a dielectric (electrical insulator) that screens the bare charge of the electron: from a distance, the measured charge is less than the bare charge.



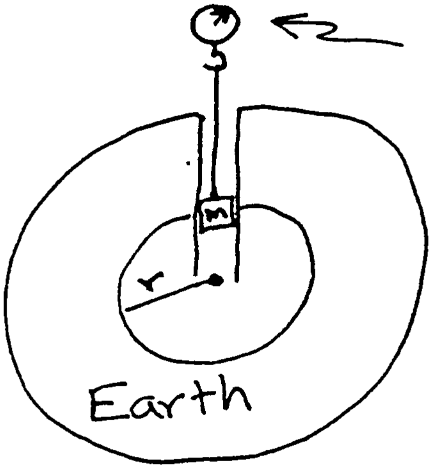
The color field surrounding quarks is more complicated, because gluons themselves carry color. Virtual quarks surround a confined quark, just as virtual electrons and positrons surround an electron. But virtual gluons accompany the virtual quarks, and virtual gluons effectively increase the color force at increasing distance.

(bar over letter indicates anti-color, e.g. $\bar{B}$ = anti-blue)

This up green quark is attracted to all the starred gluons (4 of the 6 possible gluons) and repelled by the un-starred gluons (2 of 6)

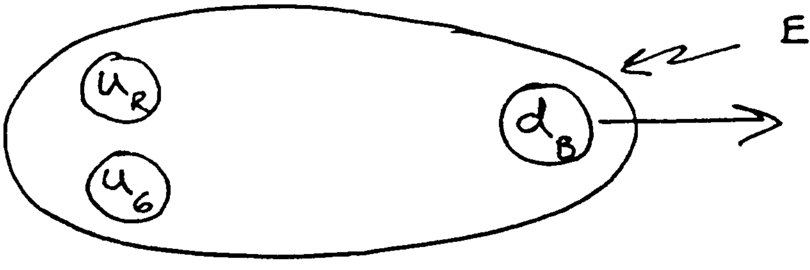
Quark B is attracted by two thirds of the virtual gluons surrounding quark A and repelled by only 1/3 of them. If quark B approaches A closely, it feels only the color force contained within the small volume immediately surrounding A, while at increasing distance, it feels A's color force augmented by all the gluons inside the larger volume.

We can model this "anti-shielding" with an analogy: Imagine drilling a hole to the center of the Earth and reeling a test mass down the hole, weighing the mass at different distances from the center. At the Earth's surface, the mass feels the full "pull" of the Earth's gravitational field. At the Earth's center, the mass is "weightless:" the Earth pulls on it equally in all directions. In between, the test mass feels a gravitational force proportional to the mass of the Earth inside that radius.



Force on test mass, m, is proportional to the mass of the rock (magma) inside radius r

Because of anti-shielding, quarks behave as if they are held together by rubber bands: close to each other, quarks move around freely (a condition called "asymptotic freedom"), but the farther they move apart, the more the bands restrain them ("confinement"). The bands provided by the color force cannot break, except at exceedingly high energy -- energy enough to create new quarks that replace the sundered partners. In such conditions, free quarks cannot exist.



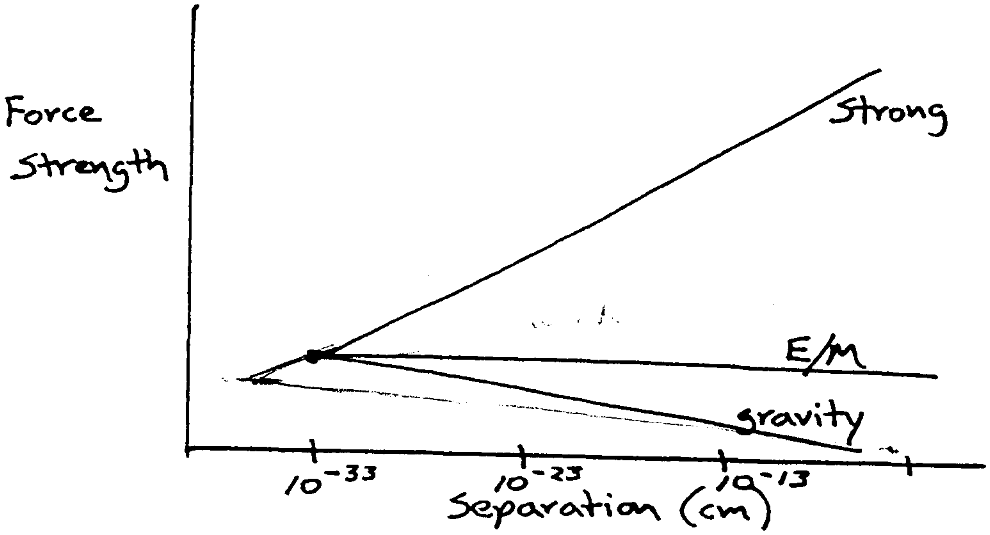
Energy required to separate this quark from its partners would produce new quarks

UNIFYING THE FORCES

Particle physicists generally ignore gravity: dealing with such small masses as the particles, the force of gravity is negligible.

On the other hand, if particles approach each other very closely (within about 10^-33 cm), the gravitational interaction becomes significant. (By F = GMm/R^2, the gravitational force increases exponentially as R diminishes.)

Here's a curious rub: when particles are pushed close together, as they are in particle accelerators, all four forces approximate each other in strength. The electromagnetic force perceived by a charged particle, for instance, increases as it penetrates the cloud of virtual particles surrounding the bare charge of an electron. The force of gravity increases (by 1/R^2) as particles approach, and the strong force weakens, since color bonds loosen when quarks are near each other.



To drive particles close together (as in accelerators) requires large kinetic energies, so the difference in strength varies inversely as the kinetic energies of the interacting particles: at high interaction energies, the forces approximate each other in strength, at low interaction energies the strengths diverge.

This relationship between the strengths of the forces provides another hint of underlying unity in physics, which we shall explore in more detail in the next chapter.

SUMMARY

There are four known forces through which particles interact: electromagnetism, gravitation, the strong force, and the weak force. We model gravity and electromagnetism as macroscopic fields, but at the scale of particles, interactions must be described in terms of field quanta.

Interactions include exchanges of energy or momentum between particles, changes in particle identity, and the decay of isolated particles.

The weak force changes particle "flavor," as in converting a down quark to an up quark in neutron decay. Weakly interacting particles may also scatter in neutral current interactions. The weak force is carried by vector bosons -- the W-, W+, and Z.

Gluons carry the strong force (color force). The strong force binds quarks inside hadrons, and it "spills out" of individual hadrons to hold groups of them in atomic nuclei.

Virtual boson production, by the uncertainty mechanism, helps explain the range of the different forces. "Shielding" and "anti-shielding" affect the relative strengths of the forces. We find that at higher energies (shorter interaction distances) the forces approach each other in strength.

DEMONSTRATIONS
CHAPTER 7

1. Electrostatics:

Experiment with wool felt, silk, a graphite rod, a glass rod, and silvered styrofoam spheres to analyze the electric force. For example, hang the silvered spheres from fine thread and touch them with a glass rod that has been rubbed vigorously with the wool felt. Hold the rod close to the spheres. Then pull the rod away and bring the felt near the spheres. Compare the effects of the other materials.

From your observations, how many kinds of electric charge are there? What can you say about the range of the electric force? Can you outline the electric field? Is there an electric field present in the absence of electric charge?

2. Magnetic field:

Place a notebook size piece of paper over a bar magnet on a flat surface. Sprinkle iron filings over the paper. (You can collect iron filings yourself by stirring through sand with a magnet.)

Bring a second magnet close to the first, north pole to north pole underneath the paper. What happens to the structure of the magnetic field? Approximate south pole to north pole. What happens to the structure of the field now?

3. Transferring momentum via fields:

Hang a bar magnet by a fine thread, balanced at its center of mass. Bring a second magnet close to the hanging magnet, north pole to north pole (or south to south). What happens to the hanging magnet?

If the magnets are strong enough, the outside magnet affects the motion of the hanging magnet without physically touching. How is the momentum of the outside magnet transferred to the hanging magnet?

Imagine that the magnets are separated by a considerable distance, say one minute of light-travel time, and that they were strong enough to affect each other noticeably over that distance. If you accelerated the outside magnet briefly, what would you expect to happen to the hanging magnet? What's going on during the interval that you accelerate the outside magnet and the time when the hanging magnet responds?

4. Photoelectric effect as an example of boson-fermion interaction:

In Ch.5 we discussed the photoelectric effect as an example of the quantum nature of energy. It also illustrates the interaction of bosons and fermions. You will need a photoelectric demonstration apparatus.

With a simple apparatus, turning on a nearby light causes electrons "boil" off a cathode, and a current meter measures the arrival of electrons at the detector.

In terms of particle interactions, which bosons are interacting with the electrons (fermions)? What is the origin of those bosons? Can you measure the force being exerted by the bosons on the electrons?

5. <u>An analogy for the balance between forces in a nucleus:</u>

Compress two or three elastic balls (such as tennis balls or racket balls) with a stout rubber band, or bind them with string.

What happens to the balls when you cut the confining band? Using this system as a model for the interplay between the electromagnetic force and the strong nuclear force in an atomic nucleus, what part of the model mimics the electromagnetic force and what part mimics the strong force? What force actually causes tennis balls to resist compression and rubber bands to resist distension?

Real rubber bands pull back with more force as they are stretched until they are so distended that the inter-molecular bonds in the rubber begin to weaken, the rubber band resists further distension with <u>less</u> force, and it eventually snaps. Compare this behavior with the behavior of the strong force in larger and larger nuclei.

6. Rubber band analogy of asymptotic freedom:

Loop a stout rubber band over your thumbs. What force do you feel if you approximate your thumbs? What happens to the magnitude of the force as you try to separate your thumbs to greater distance? Compare this model to asymptotic freedom of quarks and quark confinement.

7. Spring model of asymptotic freedom:

Spread springs or rubber bands radially around a crochet hoop or other large rim, and hook them in the center to a finger ring or baby's teething ring. The elastic bands should be relatively relaxed when the central ring is in its equilibrium position.

What happens to the force on the central ring as you try to displace it from its equilibrium position? Compare this model to quark confinement and asymptotic freedom in an atomic nucleus.

8. An analogy of the dependence of force range on boson mass:

Suppose you were trying to exert a force on a charging lion to stop its attack. For defense you have a bow and arrow (small mass), a spear (medium mass), and a boulder (large mass). Over what range can you exert a force on the lion with each of the above? Compare this analogy with the dependence of force range on boson mass.

9. Shielding a magnetic field:

Place a strong bar magnet on a flat surface, and probe its magnetic field with a small compass or with iron filings (as in demonstration 2 above).

Next, distribute smaller bar magnets around the larger one with the poles aligned north poles to south pole as illustrated below, and probe the magnetic field once again.

What changes do you find in the structure of the magnetic under these conditions? What changes do you note in the apparent strength of the magnetic field?

10. Electromagnetic induction:

Find (or construct) a coil of copper wire with an interior diameter large enough to admit a bar magnet. Attach the ends of the wire to a current meter.

What happens to the current reading when you push the magnet north pole first into the coil? What happens when you push the magnet south pole first into the coil?

Next, construct an electromagnet by wrapping copper wire around a nail. Attach the ends of the wire to a small (no more than 3 amp) current source. You should be able to pick up light metal objects such as paper clips with your electromagnet.

On the basis of these projects, what can you say about the relation between electricity and magnetism? If magnetism results from circulating electric currents, what do you suppose is happening at the atomic scale in a bar magnet to produce the magnetic field?

11. Parity:

Stand a mirror on a flat surface. (The larger the mirror -- 1 foot square or more -- the better.) Roll a ball from left to right toward the mirror. What direction does the ball appear to be rolling as seen in the mirror?

Collide two bumper cars in front of the mirror. Do you notice any difference in the collision as seen in the mirror?

Next, spin a patterned beach ball clockwise on its axis in front of the mirror. What direction does the ball appear to be spinning as seen in the mirror?

12. Modelling forces as boson exchange:

Sit yourself and a friend on rolling carts (or skateboards, if you can balance carefully). Toss a medicine ball or basketball back and forth. What happens, and why? Express your analysis in terms of the conservation laws.