A Field Day:
Some Physics You May Find Useful

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Why Physics?

We take physical measurements to make inferences about physical entities (brain, behaviour…)
… don’t break the chain of inference

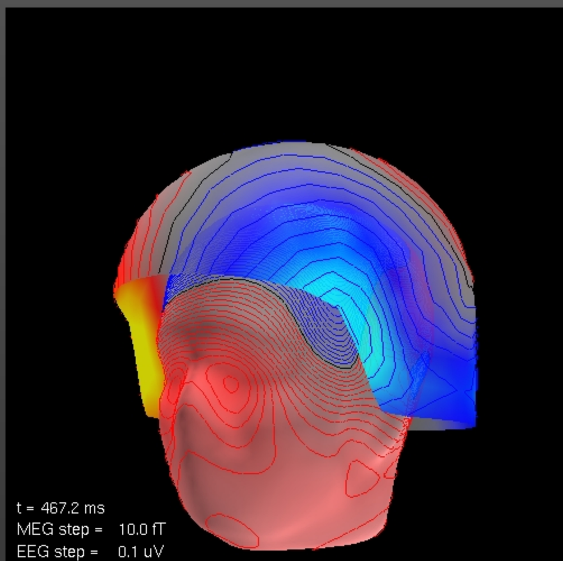
We need to communicate in an interdisciplinary environment

Health & Safety

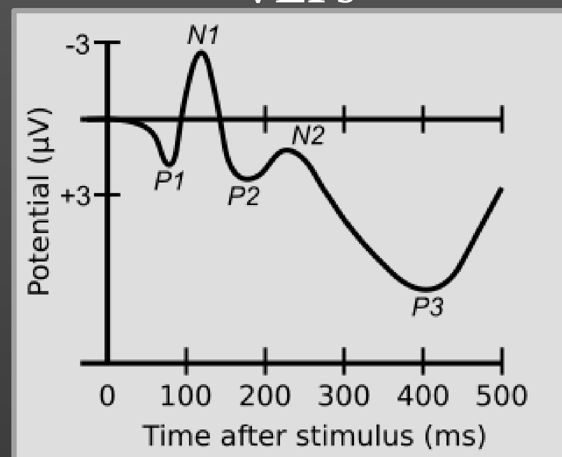
The Pitfalls of Interdisciplinary Research

We are interested in cognitive/brain functions –
based on evidence from physical measurements

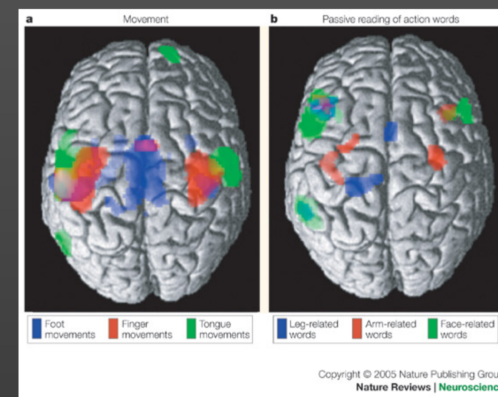
Keep track of the inferential chain from measurement to conclusion



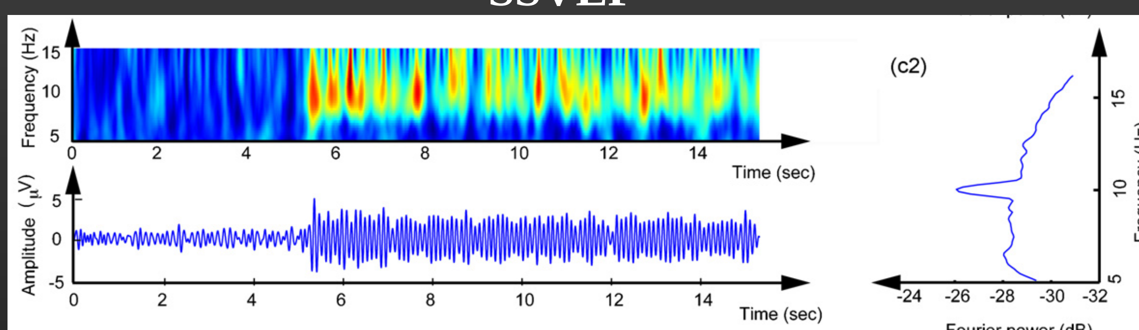
VEPs



http://en.wikipedia.org/wiki/Visual_N1



SSVEP



Vialatte et al., Progr Neurobiol 2010

Newton's Laws of Motion

http://creativecan.com/2012/04/macbook-stickers/

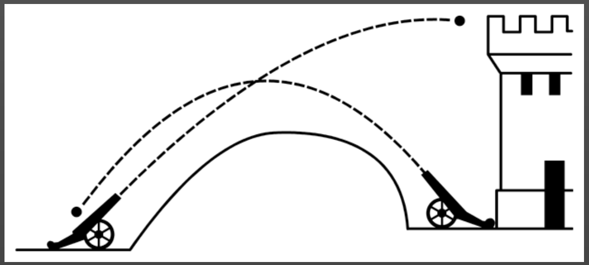
1) An object only changes its velocity in reaction to an external force
2) F = m*a: The net force acting on an object is proportional to its mass and its acceleration (=> a = F/m)
3) If one body exerts a force on a second body, the second body exerts a force of the same magnitude on the first body ("actio et reactio")

N.B.: We use the term "Weight" wrong. It should refer to the force on mass under gravitation, i.e. be measured in Newtons (e.g. our weight is different on the moon, but mass isn't).

Newton's Laws of Motion

Newton decomposed a multitude of seemingly different and complex phenomena into a few basic measurable entities and quantitative relationships

Dropping stones, moving vehicles, canon balls, planets…



Car: 1000 kg
Acceleration: to 100 km/h in 10 s

$\Rightarrow$ F = a*m = (100 km/h / 10 s) * 1000 kg = 100 (1000 m)/(10*3600 s^2) * 1000 kg ~ 2779 kg*m/s^2 = 2789 N(ewton)

1 N is the force of gravity at the Earth's surface on a mass of about 102 g

The "Potential"

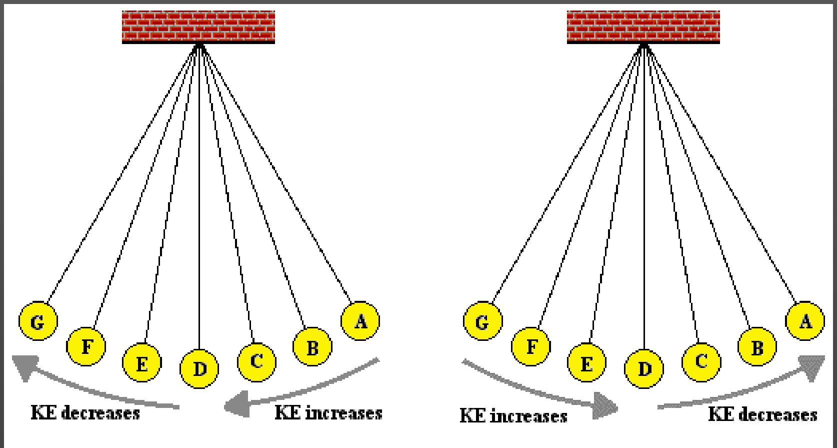
A potential is only defined between two states/locations

"Gravitational Potential":
Energy required to move an object of unit mass to a reference location.

For example:
"How much energy can I gain by dropping my shoe from the roof?"
only makes sense if I specify how far it can fall – to the balcony? To the ground? To sea level? To the middle of earth?

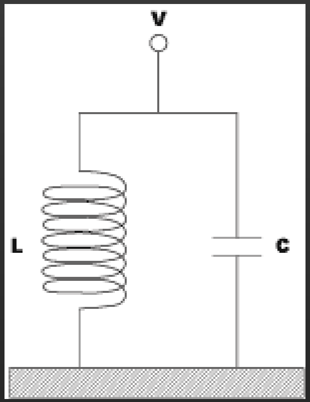
The "Potential", "Potential Energy"

The Pendulum:
Conversion of potential energy into kinetic energy and vice versa



http://www.physicsclassroom.com/class/waves/u10l0c.cfm

Electric oscillator:
Conversion of voltage into current and vice versa



Energy and Power

1 food calorie, i.e. 1kcal (kilocalori, usually just called “calorie”) is equivalent to the amount of energy needed to…

- heat 1l of water by one degree Celsius
- lift a chocolate bar to ~4.2km, or a tomato can to about 1km, or me to about 5m
- run a 1000W hair dryer for ~4.2 seconds

A pint of beer has about 200 kcal…

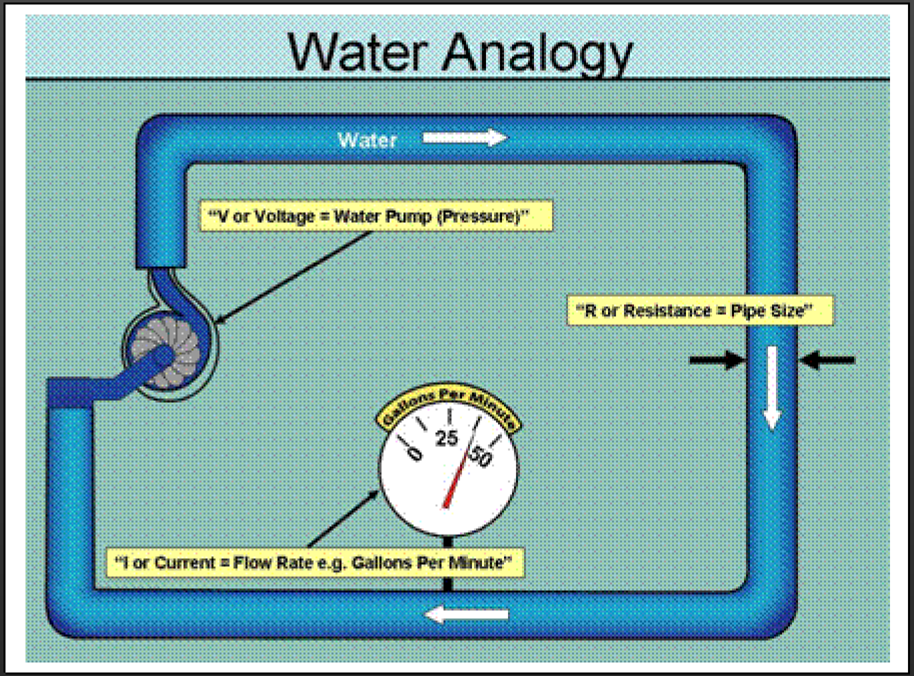
“Power”: Energy per time

You can release or absorb the same amount of energy quickly or slowly - the rate of the release or absorption is the “power”

Electricity: Voltage and Current

Voltage:
Difference in electric potential between two points
or
Energy required to move an electric unit charge between two points
(1V = 1 “Joule per Coulomb” = 1 J/C)

Hydraulic Analogy:
Pressure ~ Voltage, Flow ~ Current



http://apps.americanbar.org/lpm/lpt/articles/tch05071.shtml

Electricity: Ohm's Law

For a given voltage, the current depends on the **resistance** of the conductor:

$$I = U / R$$

("Ohm's Law")

(I: current (Ampere), U: voltage (Volt), R: resistance (Ohm, "Ω"))

If you can measure the voltage and the current, you can get the resistance:

$$R = U / I$$

Sometimes it is more convenient to talk about "**Conductance**":

$$G = 1 / R$$

(G: conductance (Siemens))

Resistance often depends on the frequency of voltage/current. For alternating currents, the conductor can affect amplitude and phase of the current. More general:

"Impedance"

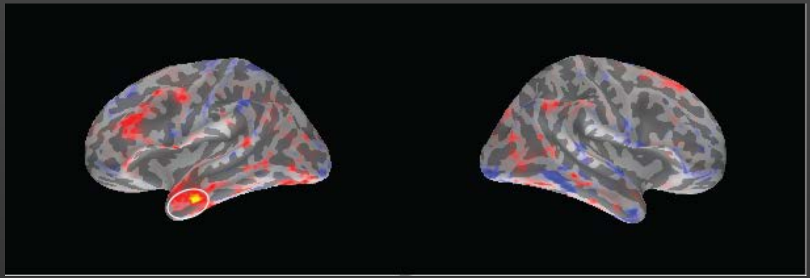
Current Flow in the Head

Conductances, currents etc. can vary with location (e.g. in different brain tissues)

They are often expressed as densities (per length, per area, per volume), e.g.

“resistance per unit length”
(Ohms per m etc.)

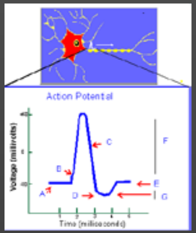
“current per unit area”
(A/m^2, pA/cm^2 etc.)



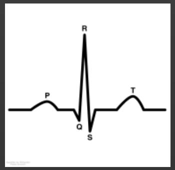
Examples of Voltages, Currents, Resistance

Household Batteries
~ 1-12 V

Membrane Potentials
~ 70 mV



ECG
~ 1mV

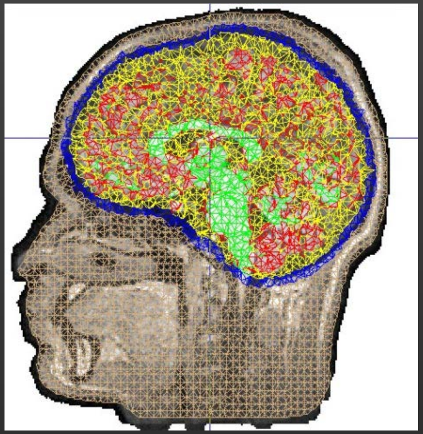


ERPs
~ 1-10 µV

Copper (resistivity 17nΩ*m)
Wire (10m, 1 mm²)
~ 0.2 Ω ~ 5 S

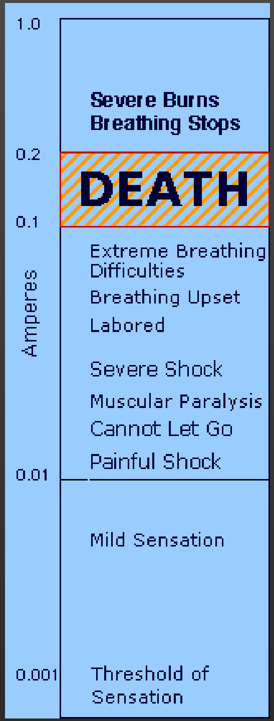
Skull ~ 70 Ωm

Brain+scalp ~ 1 Ωm



http://www.sourcesignal.com/mrviewer.html

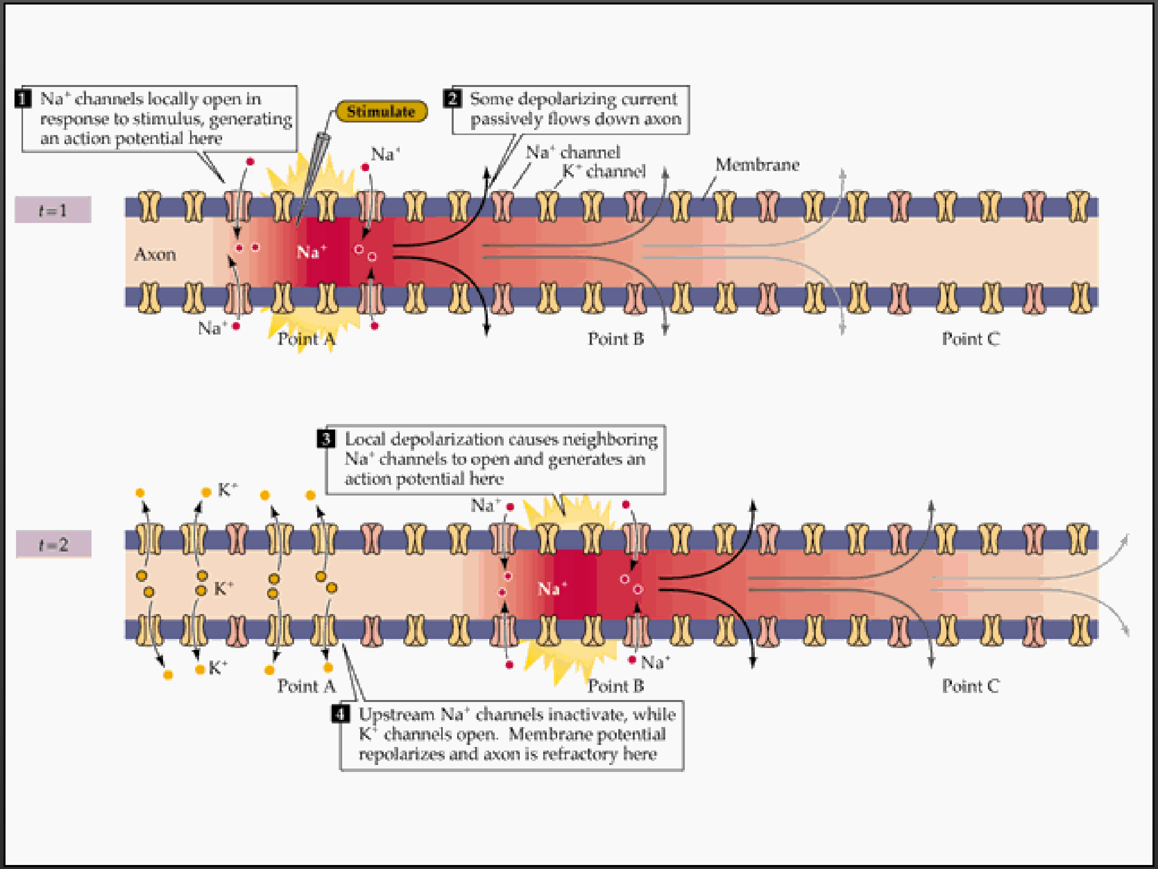
Voltage 1V ->
Current 5A
(short circuit)



http://www.physics.ohio-state.edu/~p616/safety/fatal_current.html

Nerves Are Not "Wires"

Action potentials are caused by active cellular mechanisms, not passive "Ohmic" currents



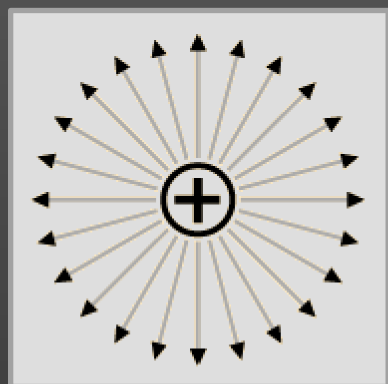
http://www.arts.uwaterloo.ca/~bfleming/psych261/lec4se21.htm

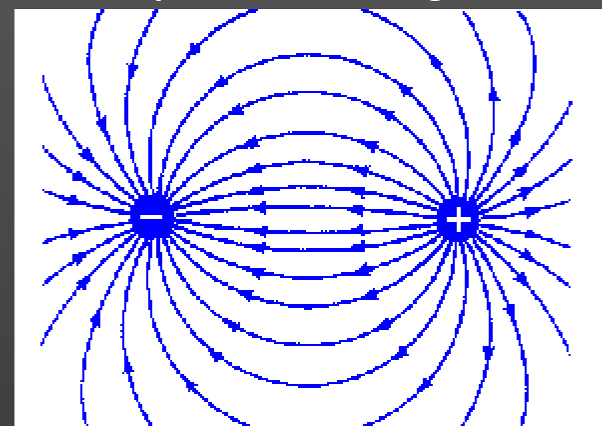
Electric Fields

Charges can act on each other without a conducting medium between them

⇒ Electric field

⇒ Electric field lines: The path along which a positive charge would travel





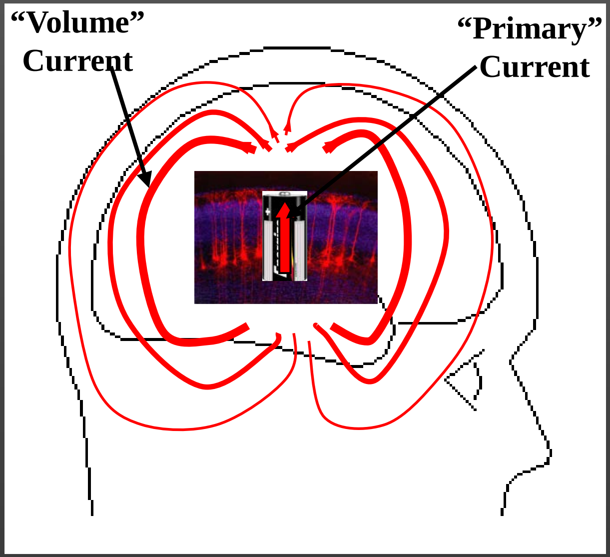
When a conductor is placed into an electric field, charges move along field lines

⇒ Current density: $J = \sigma E$ *(conductivity * electric field strength)*

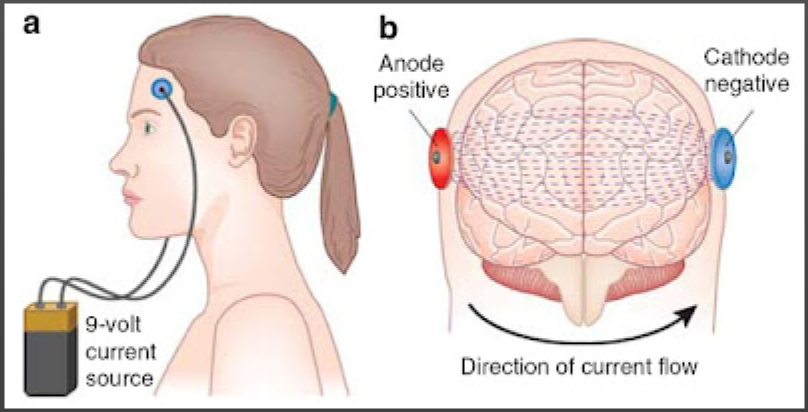
http://labman.phys.utk.edu/phys222core/modules/m1/Electric%20field.htm

Example: Current Flow in the Head

EEG/MEG
"Volume Conduction"



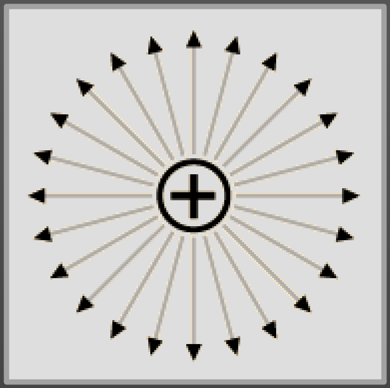
tDCS
Transcracial direct current stimulation



http://neurocritic.blogspot.co.uk/2012/04/tdcs-symposium-stimulates-giant-brain.html

Coulomb's Law

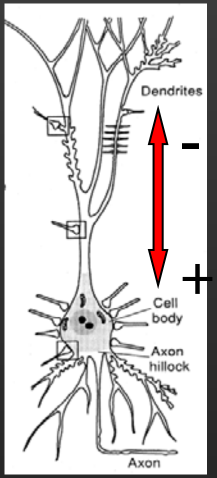
For a single charge: Electric field decreases with squared distance (in vacuum)

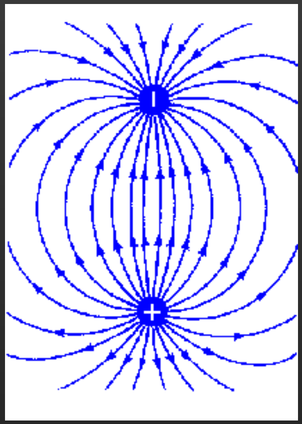


$$E(r) = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$$

For a "dipole": Electric field decreases ~ with cubic distance (in vacuum)

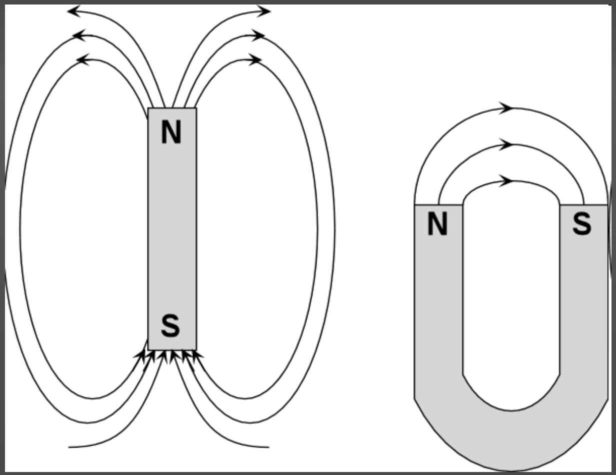
http://en.wikipedia.org/wiki/Electric_dipole_moment

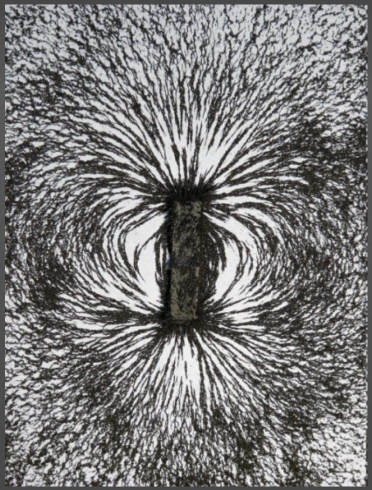




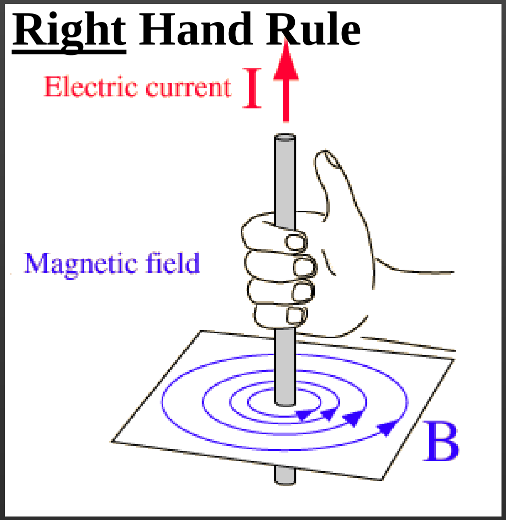
Magnetic Fields

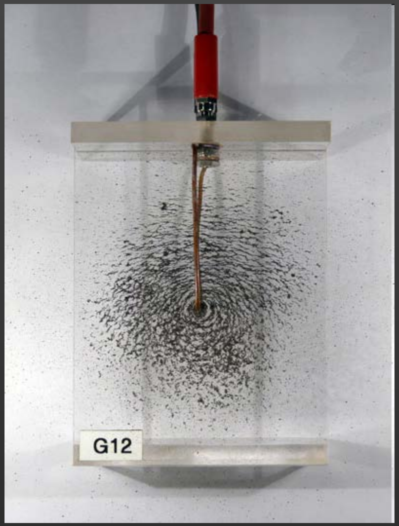
Bar magnets

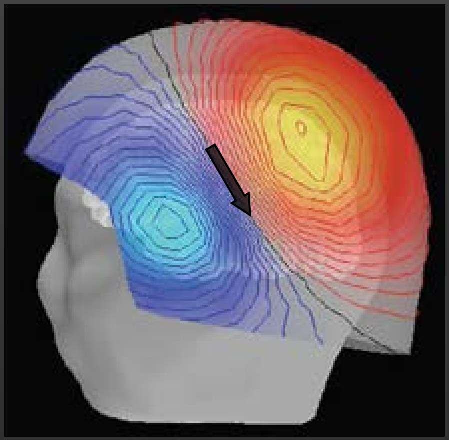




Currents







There are no “magnetic monopoles”, field lines are always closed

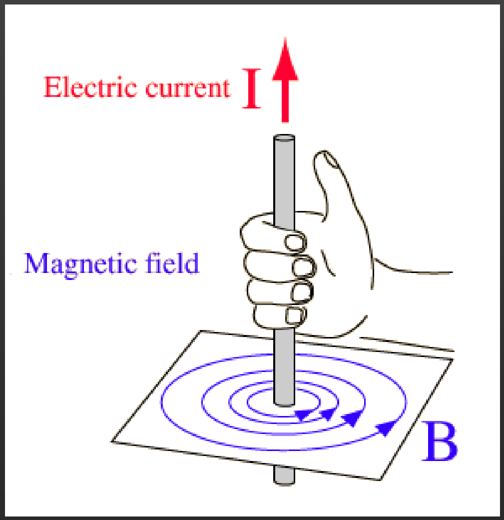
Magnetic Fields

The Biot-Savart Law to compute the magnetic field of a current (in vacuum):

$$B(r) = \frac{\mu_0}{4\pi} \frac{dI \times \hat{r}}{r^2}$$

The magnetic field strength decreases with squared distance to current

The magnetic field direction is perpendicular to the current flow

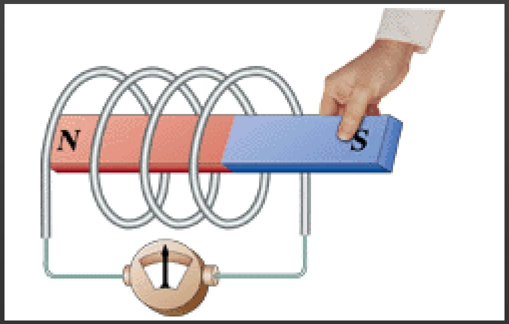


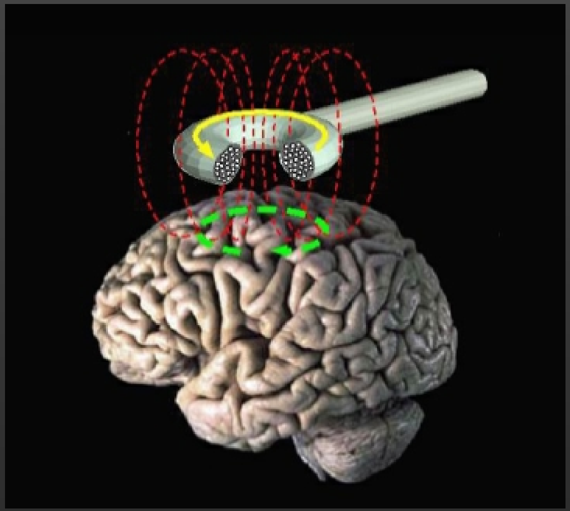
Magnetic Induction

Faraday's Law of Induction:
The induced current in the coil is proportional to the rate of magnetic flux change inside the coil

$$I \sim \frac{d\varphi_B}{dt}$$

TMS pulse duration ~ 100 μs, ~ 1T
Induced currents ~ mA





Eddy Currents

A changing magnetic field induces an electric current in a conductor ("Eddy Current")

Moving the conductor (e.g. the body) can change the magnetic field around it

The induced electric current may produce heat

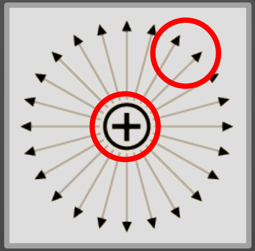
An electric current in a magnetic field receives a force

(Watch: http://www.youtube.com/watch?v=SPCIRklX2bs)

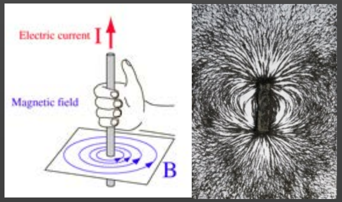
Maxwell's Equations (Classical Electrodynamics)

They describe mathematically how electric and magnetic fields are generated and altered by each other and by electric charges and currents

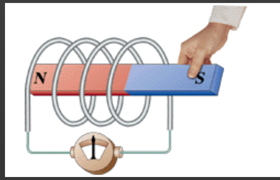
1) *The summed electric flux around a close surface is proportional to the total electric charge enclosed within this surface* (Gauss's Law)



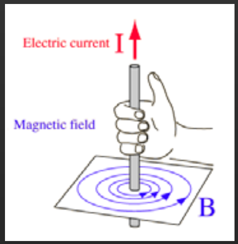
2) *Magnetic field lines are closed* (Gauss's Law for magnetism) *(no "magnetic monopoles")*



3) *Changing magnetic fields produce an electric field proportional to the rate of change* (Faraday's Law of Induction)

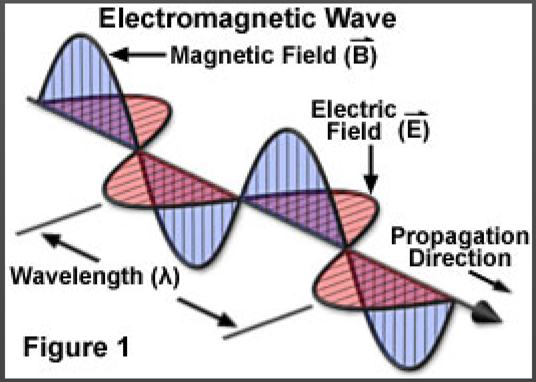


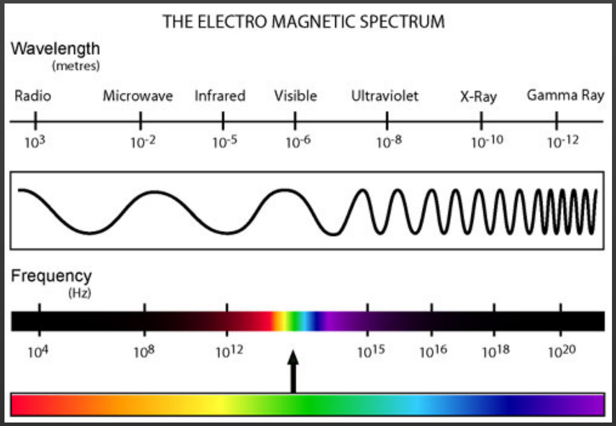
4) *Magnetic fields can be caused by currents and changing electric fields* (Ampere's Law)



Electromagnetic Waves

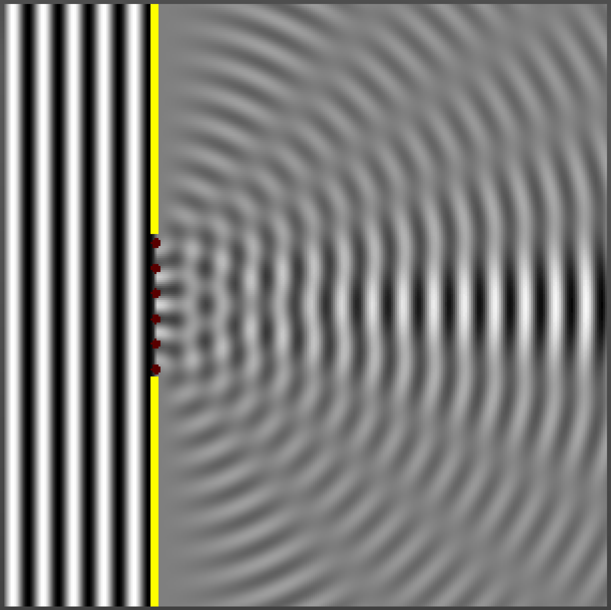
Temporally changing electric and magnetic fields induce each other

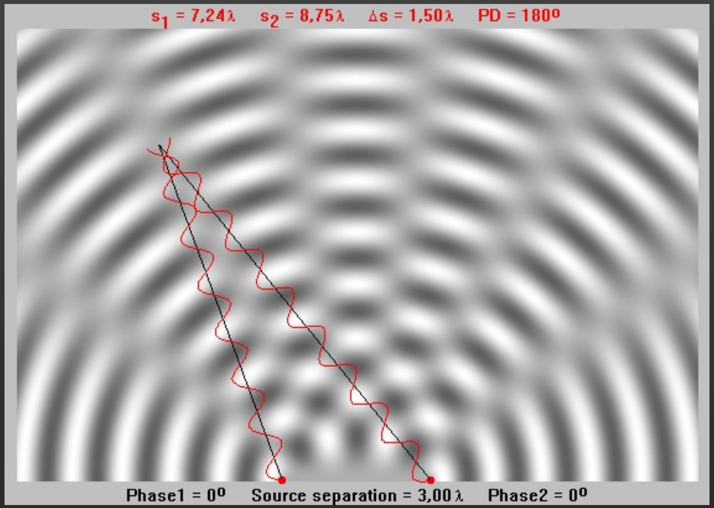




The energy of an electromagnetic wave decreases with distance squared

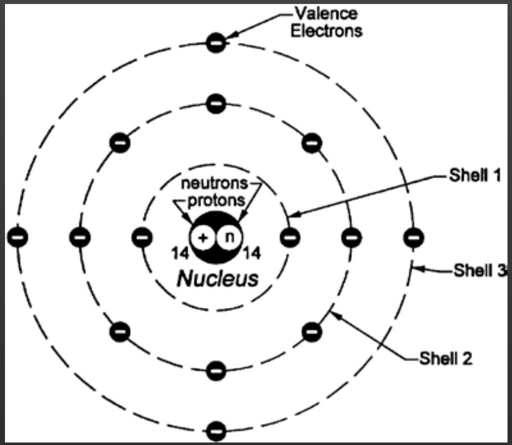
Properties of (Any) Waves: Difraction and Interference



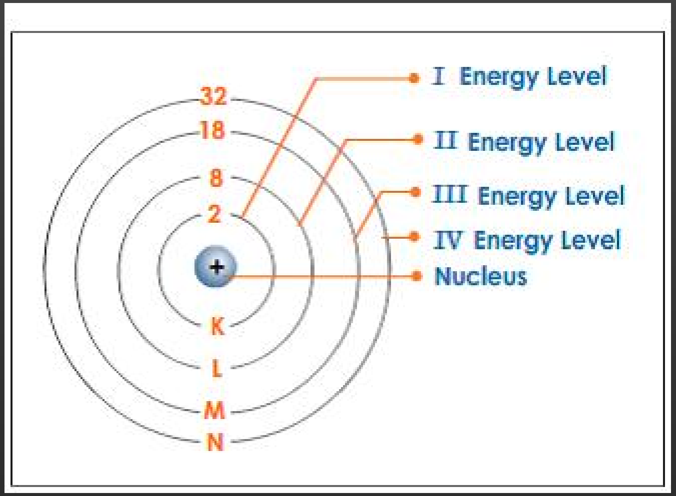


Atoms

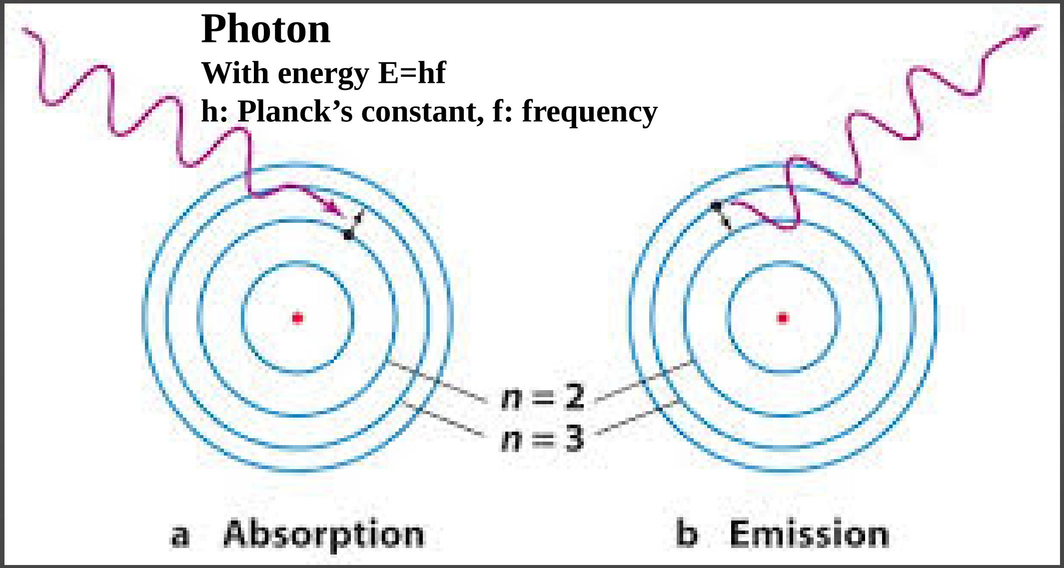
Electron "orbits" are associated with different energy levels



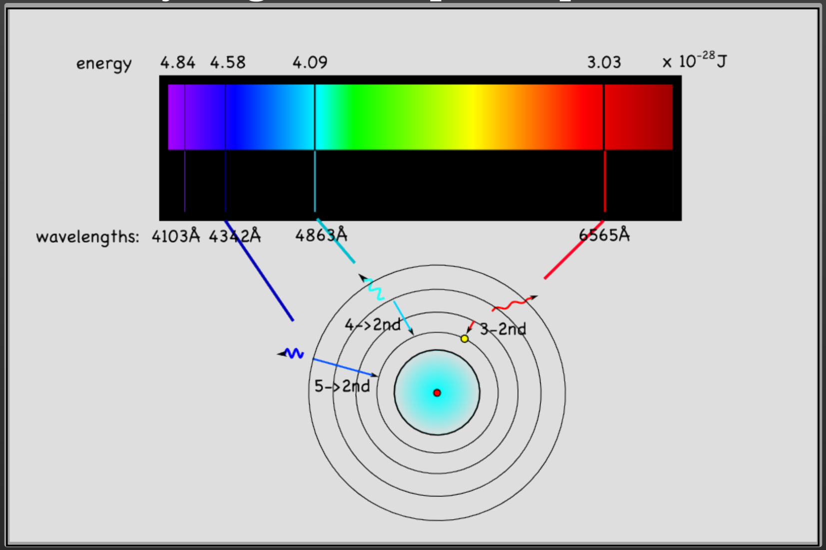
"Atomic number": 14



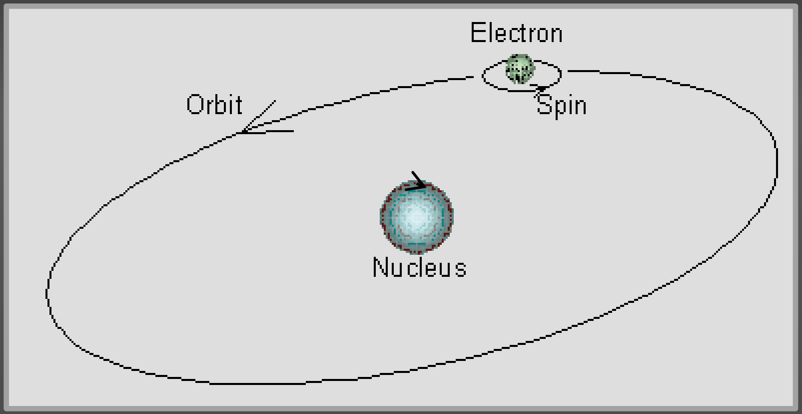
Atoms and Electromagnetic Waves



Hydrogen Absorption Spectrum



Atomic Spin



"Atomic Spin" is a purely quantum physical phenomenon
Sort of corresponds to rotation of a particle around its own axis

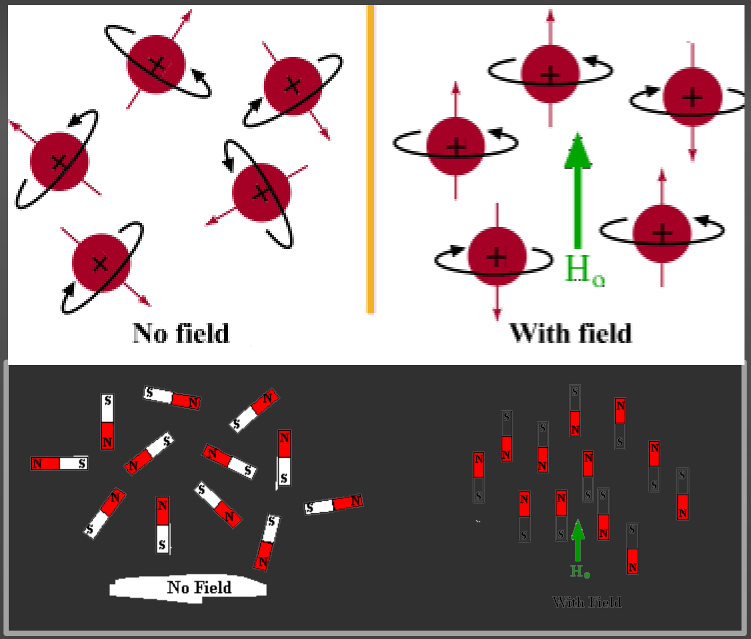
In Bohr's classical atomic model, electrons orbit around the nucleus
$\Rightarrow$ A moving charge acts like a current, producing a magnetic field
$\Rightarrow$ Related to magnetism

Spin exists for many particles, including electrons and protons

Spins can be in two states: "up" and "down"

There are rules about how spins within one orbit are aligned to each other

Atomic Spin



Spins align to an external magnetic field

Principle of nuclear Nuclear Magnetic Resonance:

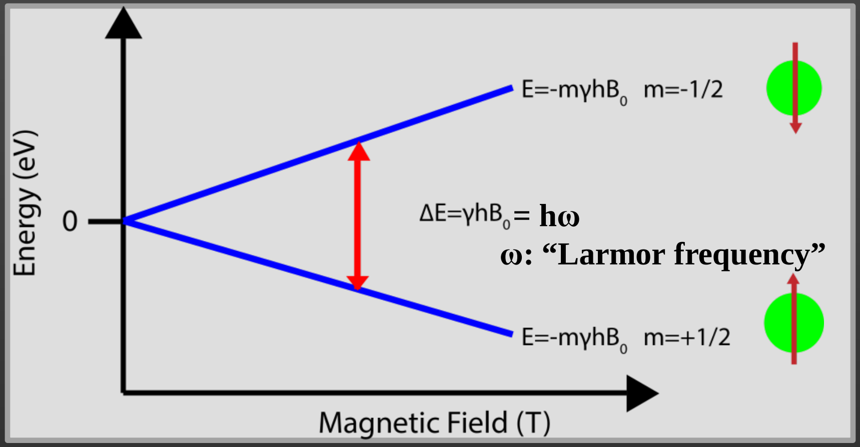
1) Align nuclear spins in a constant magnetic field
2) Perturb alignment of spins using a short electro-magnetic pulse
3) See what happens

Atomic Spin

Without a magnetic field, the two spin states (“up” and “down”) have the same energy

In a magnetic field, these states “degenerate”: parallel spins have lower energy than anti-parallel spins

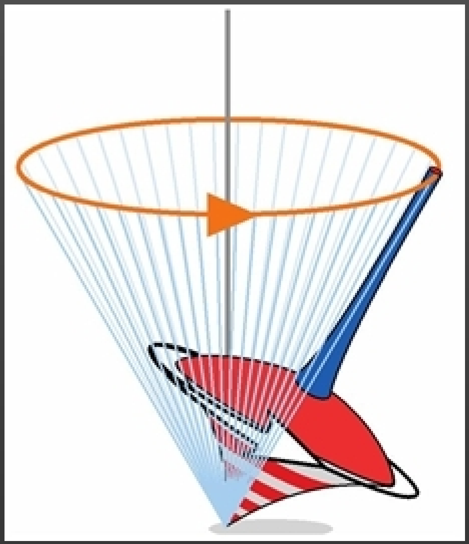
The difference between these two states depends on magnetic field strength

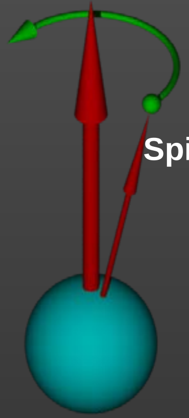


http://chemwiki.ucdavis.edu/Physical_Chemistry/Spectroscopy/Magnetic_Resonance_Spectroscopies/Nuclear_Magnetic_Resonance/Nuclear_Magnetic_Resonance_II

Magnetic “Resonance”

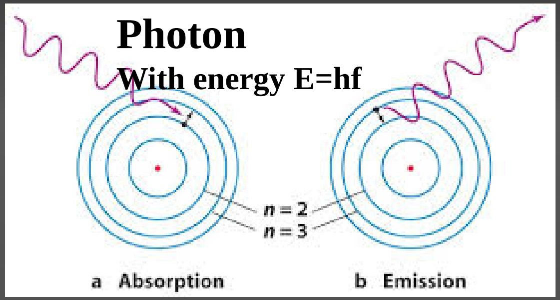
Spins can be thought of as “precessing” around the direction of the magnetic field





http://en.wikipedia.org/wiki/Larmor_precession

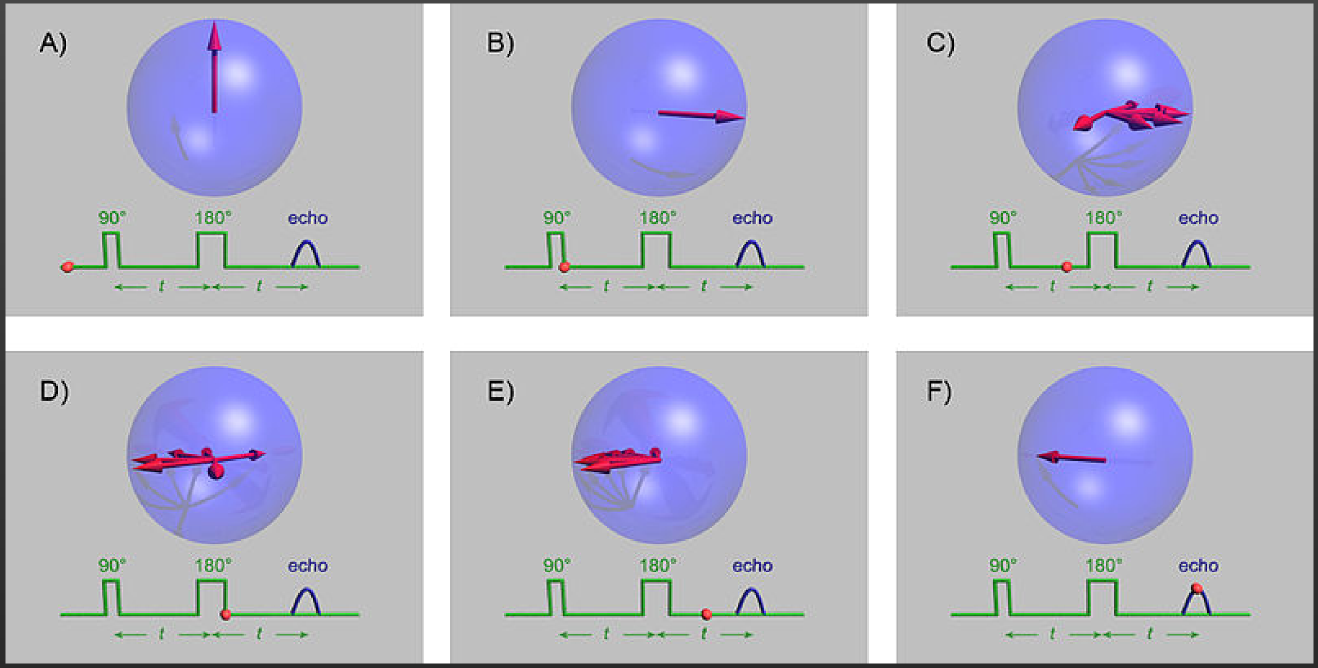
Principle of Spin Echo Imaging



Atomic energy states can be changed by absorption of photons

The difference in energy is proportional to the frequency of photons:
Electron orbits ~ Light and x-ray (> 100 THz)

(f)MRI: Radio frequency (RF) pulses change spin precession
Static magnetic field: 3T, RF frequency: 123 MHz
UHF radio: ~300 MHz, Mobile phones: ~1GHz, Microwave: ~2 GHz



http://en.wikipedia.org/wiki/Spin_echo