Conceptual RF and Microwave Engineering

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1. Introduction

2. Overview and Definitions

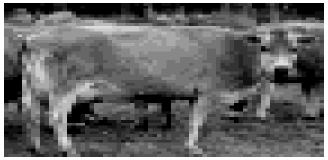
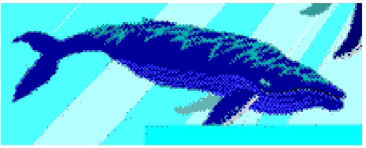
3. Electricity and Magnetism

Length Scale

- Some length scales

10^{-18} *meters*	Classical radius of proton
10^{-12} *meters*	Classical radius electron”orbit”about an atomic nucleus
10^{-10} *meters*	Spacing of atoms in solid copper
10^{-9} *meters*	Molecular mean free path in the atmosphere
10^{-7} *meters*	Radius of virus
10^{-6} *meters*	Typical size of a cell

Length Scale

10^{-4} *meters*	(1 micron). Typical size of dust	
10^{-3} *meters*	Unraveled human DNA strand	
10^{0} *meters*	Size of a small cow	
10^{+1} *meters*	Size of a whale	
10^{+4} *meters*	Radius of Eugene, Oregon	
10^{+6} *meters*	Radius of Earth	
10^{+8} *meters*	Radius of Sun	

Length Scale

10^{+11}	*meters*	Distance Earth to Sun
10^{+17}	*meters*	Distance to the nearest star
10^{+22}	*meters*	Distance to M31
10^{+24}	*meters*	Distance to Coma cluster of galaxies
10^{+26}	*meters*	Distance to the Horizon

Time Scale

10^{-24} *seconds*	Typical lifetime of strong interaction resonance
10^{-13} *seconds*	Period of vibration of an atom in a solid
10^{-5} *seconds*	Time it takes for light to travel 1 kilometer
10^{+1} *seconds*	Donovan Bailey, 1996 Atlanta Olympics 100 meters event 9.84 sec.
10^{+5} *seconds*	Earth rotation time
10^{+7} *seconds*	Earth orbital time
10^{+15} *seconds*	Orbital time of the Sun about the Galaxy
10^{+17} *seconds*	Age of the Earth

RF Overview

- Historical review
- What are the Characteristics of Modern RF and Microwave?
- Examples

Historical Review

1844: Samuel Morse's telegraph line becomes operative

It turned out that pulses on lines would be deformed and reflected on long lines.

End of 19th century:

Lord Kelvin and Oliver Heaviside find an explanation:

Electromagnetic pulses propagate as waves on lines

1886-1888:

Heinrich Hertz succeeds in generating electromagnetic waves in free space. He gives a mathematical deduction based on James Clarke Maxwell's equation.

Modern RF and Microwave

Is based on the discovery that all electromagnetic signals propagate as waves, either as waves guided by lines, or as non-guided waves..

Waves are generated if electric and magnetic fields are varying so fast that coupling between these types of fields cannot be neglected.

Therefore:

RF& Microwave theory deals with transport of information and/or power through fast varying electromagnetic fields.

Electromagnetic Waves

- Electromagnetic waves are produced by accelerating charges.
- The fields of the wave are self-supporting-the electric field induces magnetic field and the magnetic field induces electric field.
- Both radio waves and light waves are electromagnetic waves.
- Their main difference is in their frequency.
- Radio waves are created by the acceleration of the electrons in a radio antenna, and light waves are created by oscillations of the electrons within atoms.
- The electromagnetic wave has two components: the electric radiation field and the magnetic radiation field.

Electromagnetic Waves

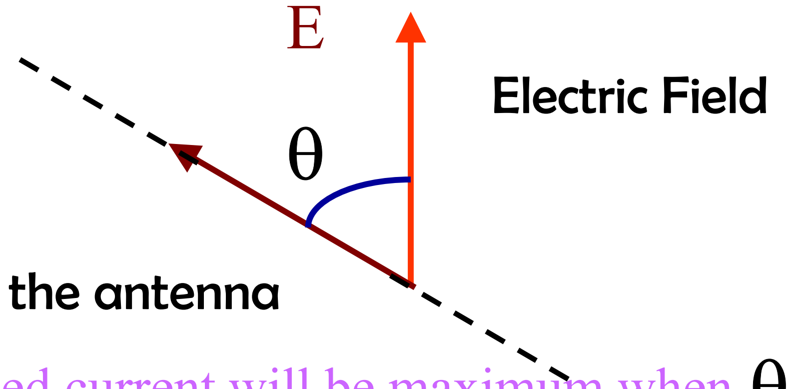
Radio receiver

One type of a antenna for a radio receiver consists of a short piece of straight wire;when the electric field of the radio wave strikes this wire it makes current flow along it, which are detected and amplified by a receiver.

Suppose the electric field of the radio wave is vertical. What must be the orientation of the wire for max sensitivity?

The electric field of the radio wave will exert a force on the electrons in the antenna. However, only the components of the electric field along the the direction of the antenna will contribute to the current induced in the antenna.

$$E_{antenna} = E_{wave} \cos\theta$$



Orientation of the antenna

Therefore the magnitude of the induced current will be maximum when $\theta = 0$ deg

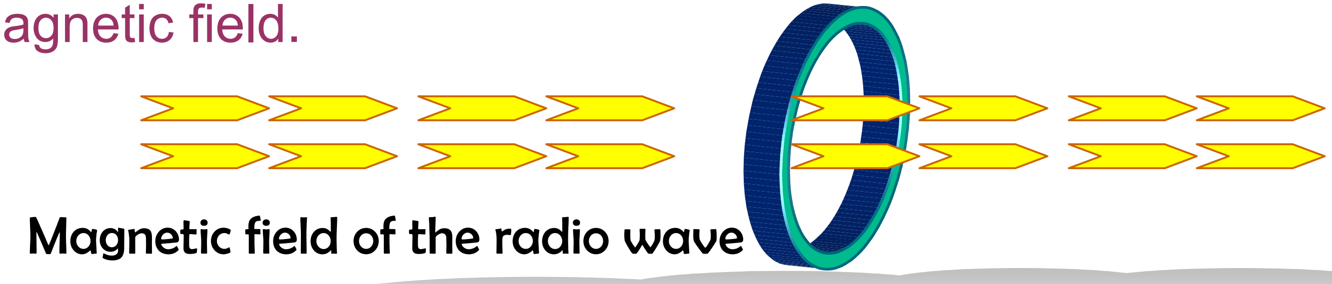
Electromagnetic Waves

Radio receiver

Another type of a antenna for a radio receiver consists of a circular loop; when the magnetic field of the radio wave strikes this loop it induced current around it.

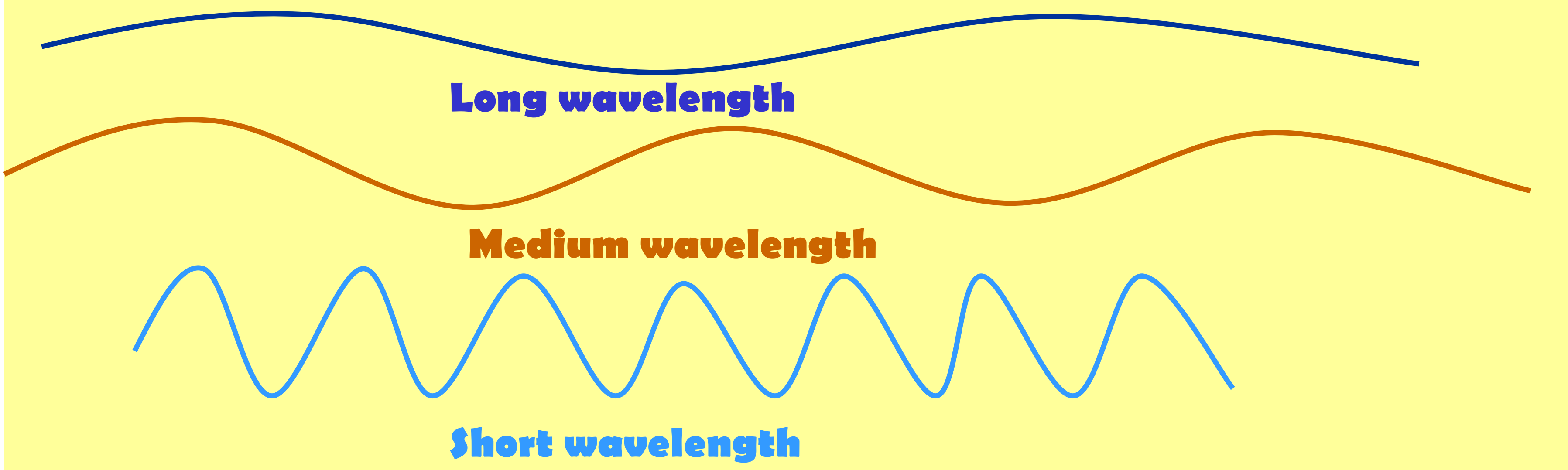
Suppose the magnetic field of the radio wave is horizontal. What must be the orientation of the loop for max sensitivity?

A changing magnetic field induces an emf in a conducting loop (Faraday's law of induction). The induced emf is proportional to the magnetic flux intercepted by the surface spanned by the loop. In order to maximize the the induced current, we have to maximize the induced emf, and therefore maximize the magnetic fluc intercepted by the loop. This can be achieved of the loop located perpendicular to the direction of the magnetic field.



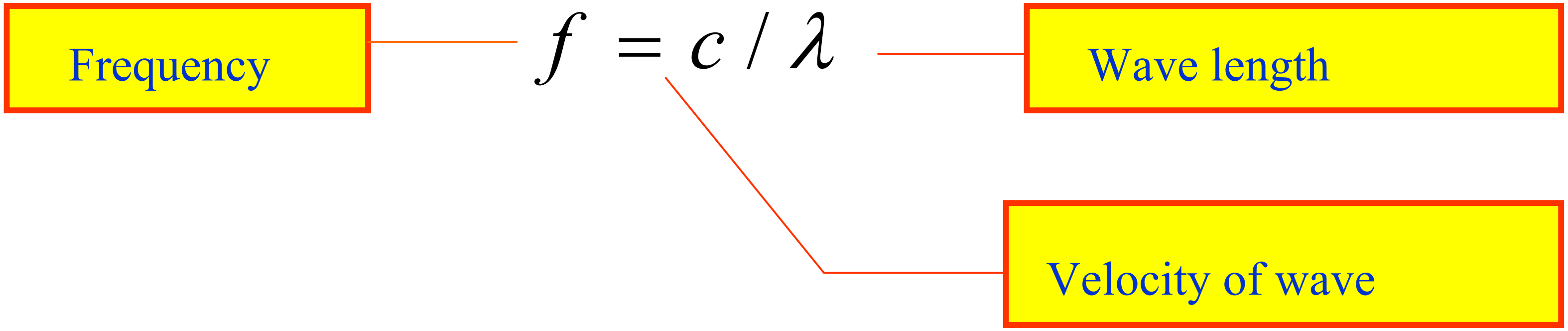
Electromagnetic Waves

Radio Waves and **TV waves** have wavelengths ranging from a few centimeters to 10^5meters. **Microwaves** have wavelength as short as millimeter. These waves can be generated by oscillating charges in an antenna. Waves with wavelength less than a millimeter can not be generated by oscillating currents in an antenna. Instead, they are generated by electrons oscillating within molecules and atoms. This type of motion produces **infrared, visible, and ultraviolet light, and x-rays**. The corresponding wavelengths range from 10^{-3} m to 10^{-11} m (visible light has wavelengths between 7x 10^{-7} m and 7x 10^{-7} m). Protons and neutrons moving in a nucleus emit **gamma rays** which have a wavelength between 10^{-11} m and 10^{-16} m.



Modern RF and Microwave

Relation between wave length and frequency (only valid for harmonic time dependence):



$$f = c / \lambda$$

Frequency

Wave length

Velocity of wave

Examples

1 MHz (wave-length in free air $l \approx 300$ m).

- This is a typical frequency used for radio-broadcast.
- Wave-range: medium-wave

- Broadcast uses wave-properties for propagation.

⇒ 1MHz is RF

- On an IC-chip (3 cm x 3 cm), wave-effects will be negligible at that frequency

⇒ 1MHz is LF

Examples

10 GHz (wave-length in free air: $l \approx 3$ cm).

(wave-length in GaAs: $l \approx 1$ cm).

This is a typical frequency used for radio-relay systems.

- Wave-range: microwave

  ⇒ 10 GHz is RF

- On an IC-chip (3 cm x 3 cm), wave-effects will not always be negligible at that frequency

  ⇒ 10 GHz is sometimes RF

Examples

50 Hz (wave-length in free air: $l \approx 3000$ km).

This is a typical frequency used for power supply.

- Wave-range: extremely low frequency

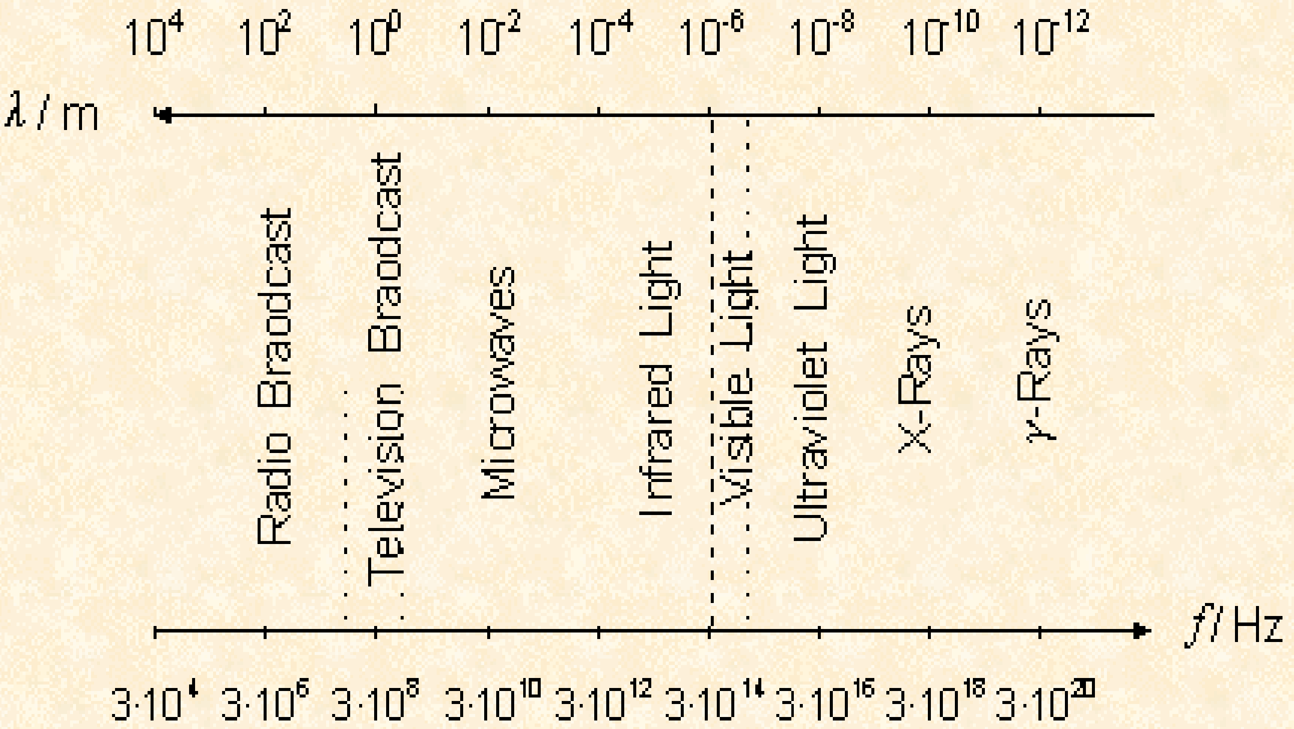
  In a building with height 300 m: wave-properties are negligible.

  ⇒ 50 Hz is LF

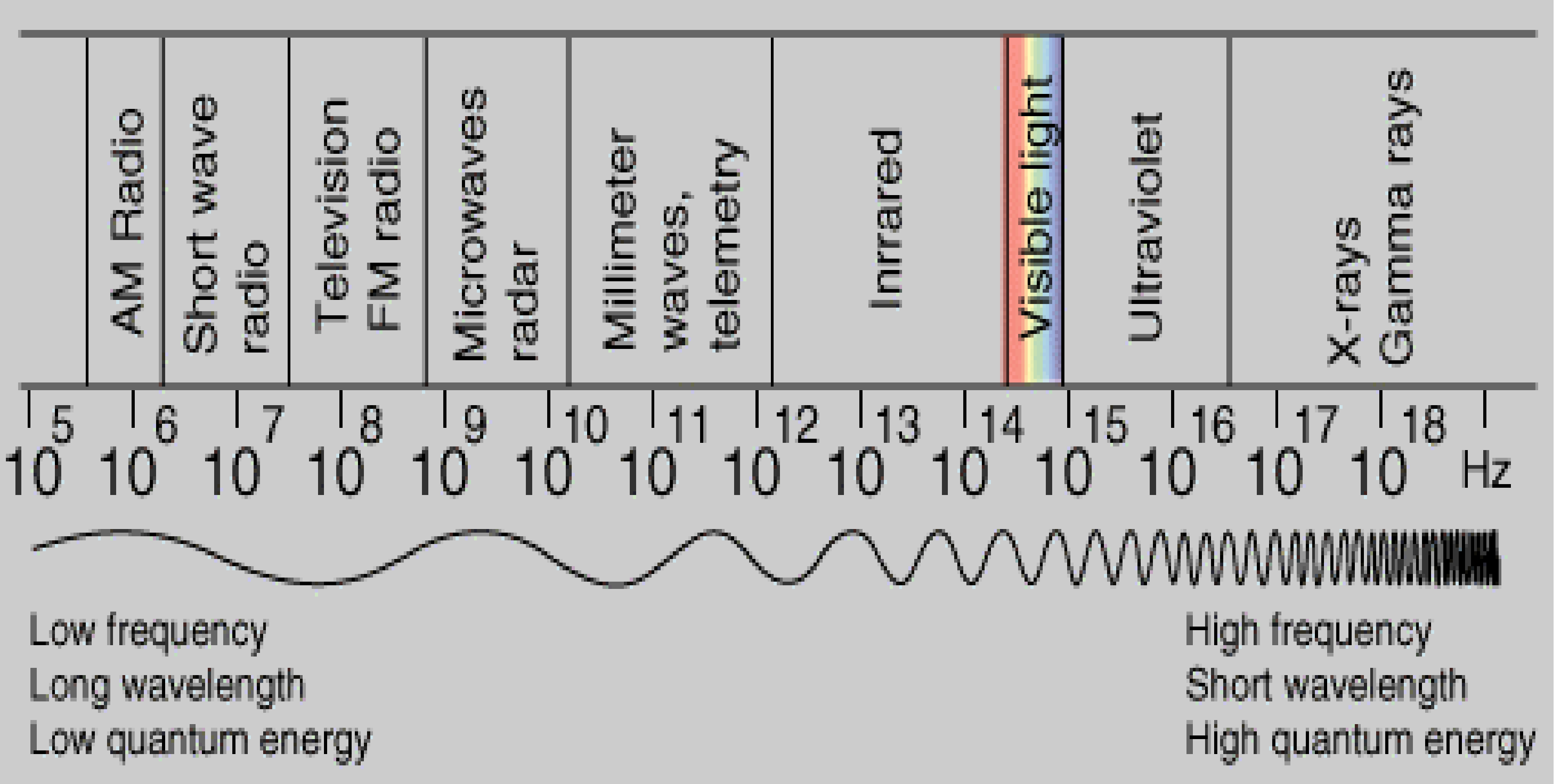
- In a net of power-suppliers that is arranged on a continent, wave-properties could play a role:

⇒ 50 Hz is then RF

Frequency Ranges and Wave Lengths (Scientific)



Electromagnetic Spectrum

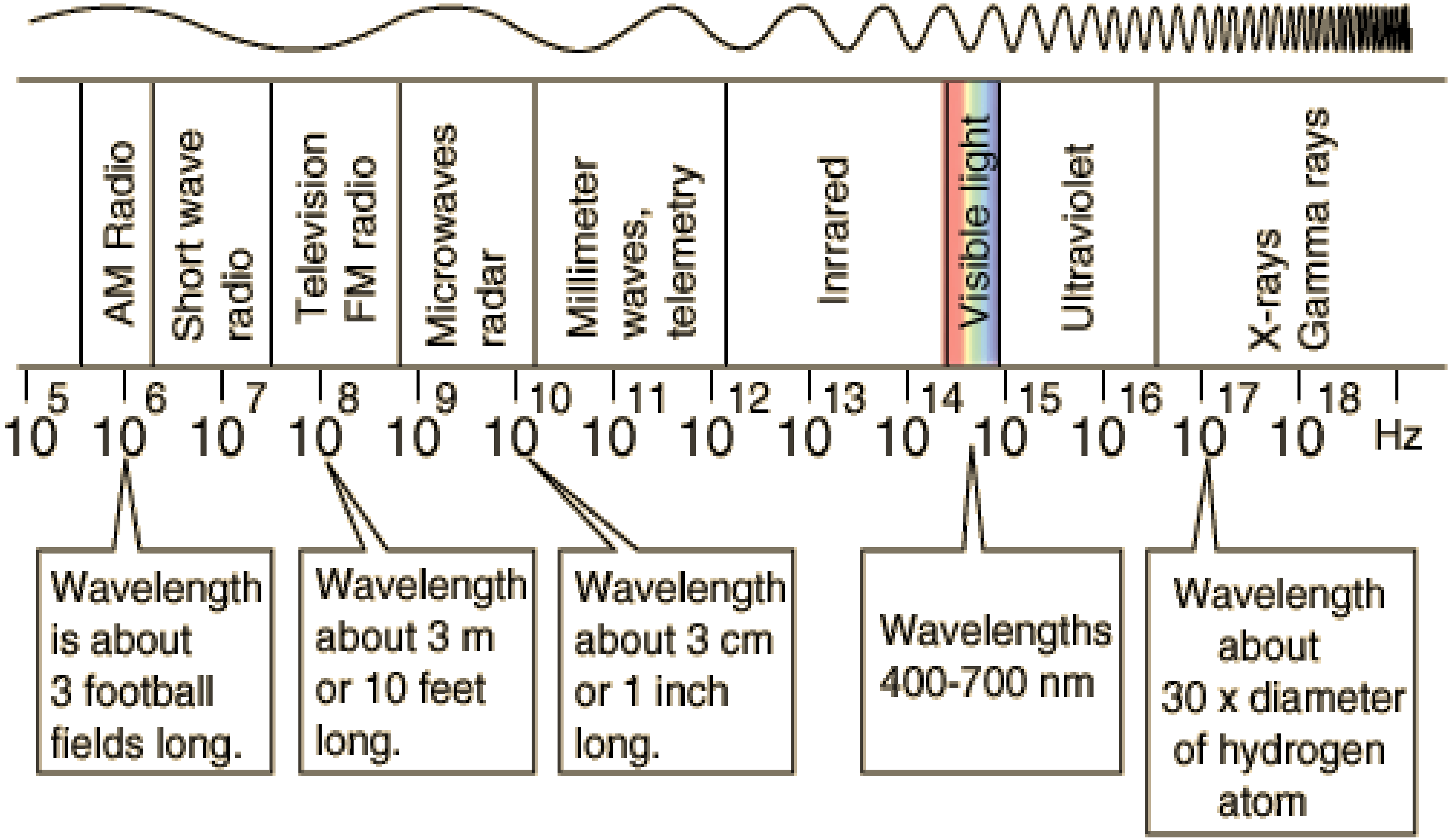


$$\nu = f\lambda$$

$c \equiv$ 299,702,458 m/s

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}}$$

Electromagnetic Spectrum -- Scale



Wavelength is about 3 football fields long.

Wavelength about 3 m or 10 feet long.

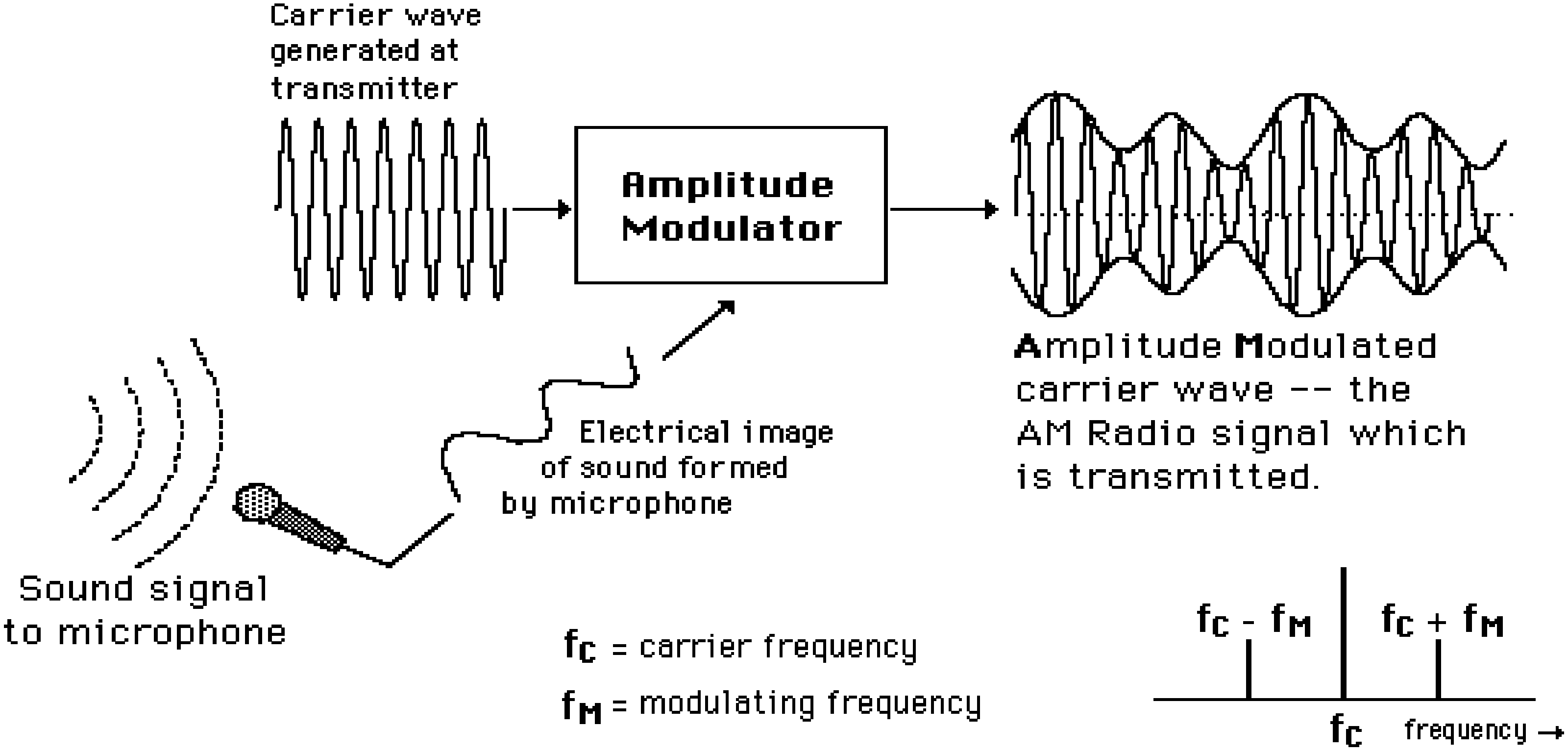
Wavelength about 3 cm or 1 inch long.

Wavelengths 400-700 nm

Wavelength about 30 x diameter of hydrogen atom

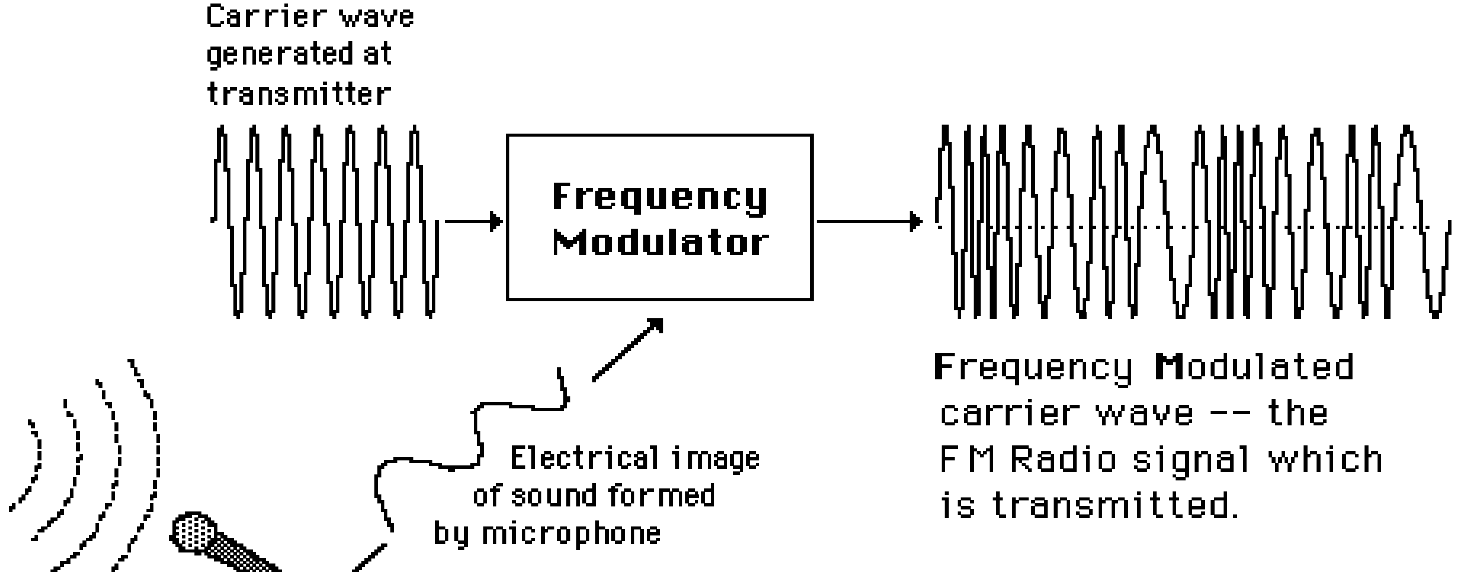
AM Radio Band

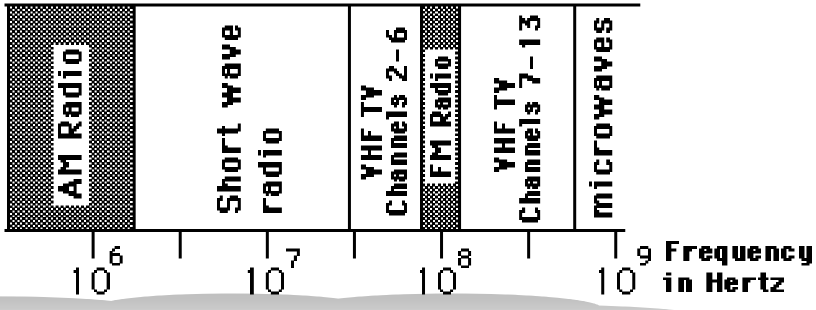
The Amplitude Modulated (AM) radio carrier frequencies are in the frequency range 535-1605 kHz. The frequencies 30-535 kHz are used for maritime communication and navigation and for aircraft navigation. Carrier frequencies of 540 to 1600 kHz are assigned at 10 kHz interval.



FM Radio Band

FM radio uses the electrical images of a sound source to modulate the frequency of a carrier wave. At the receiver end in the detection process, that image is stripped back off the carrier and turned back into sound.





Short Wave

The frequencies from the top of the AM band to the bottom of the VHF television band are generally called the"short wave" range, a historical term. The range from 1605 kHz to 54 MHz has multiple communication used.

1605 kHz – 30 MHz

Amateur radio, government radio, international short-wave broadcast, fixed and mobile communications.

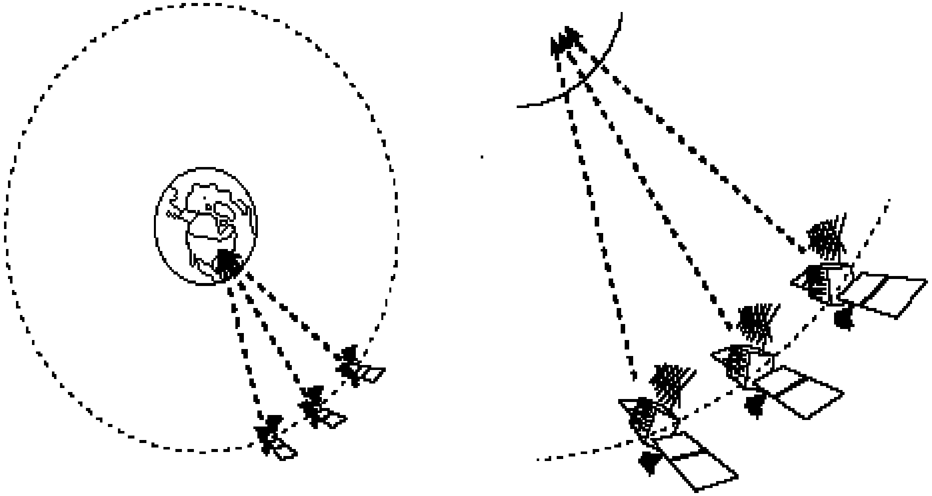
30 – 50 MHz

Government and non-government, fixed and mobile. Includes police,fire,forestry, highway, and railroad services

50 – 54 MHz Amateur

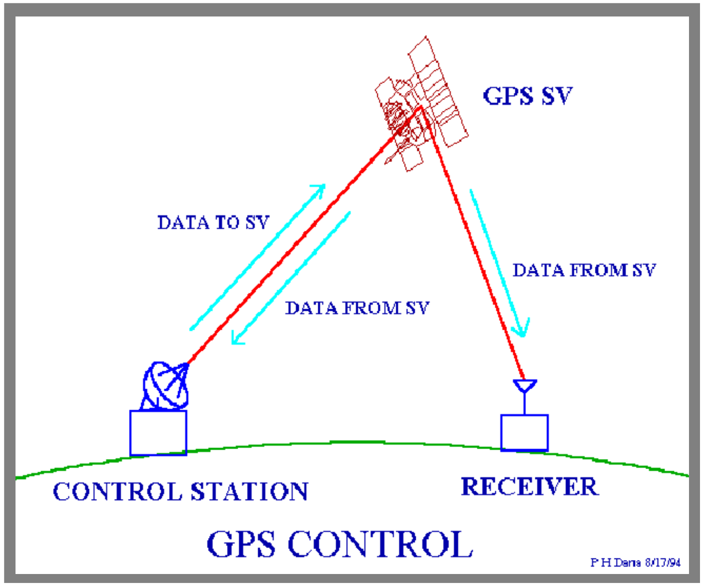
L-Band for Satellite

The range 390-1550 MHz in the ultrahigh radio frequency range is designated as L-Band and is used for the variety of satellite communication purposes. For example, the GPS used two carrier frequencies in this band for broadcasting navigation data.



What is GPS?

- The GPS System is divided into 3 segments
  - Satellite Segment
  - Ground Segment
  - User Segment

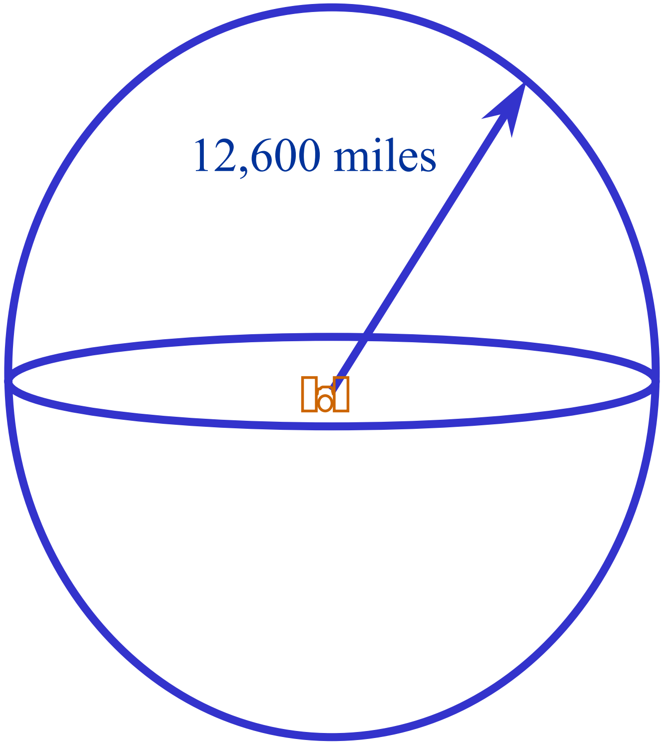


Trilateration

- The basis of GPS is "trilateration" from satellites.
- To "trilaterate," a GPS receiver measures distance using the travel time of radio signals.
- To measure travel time, GPS needs very accurate timing which it achieves with some tricks

Trilateration

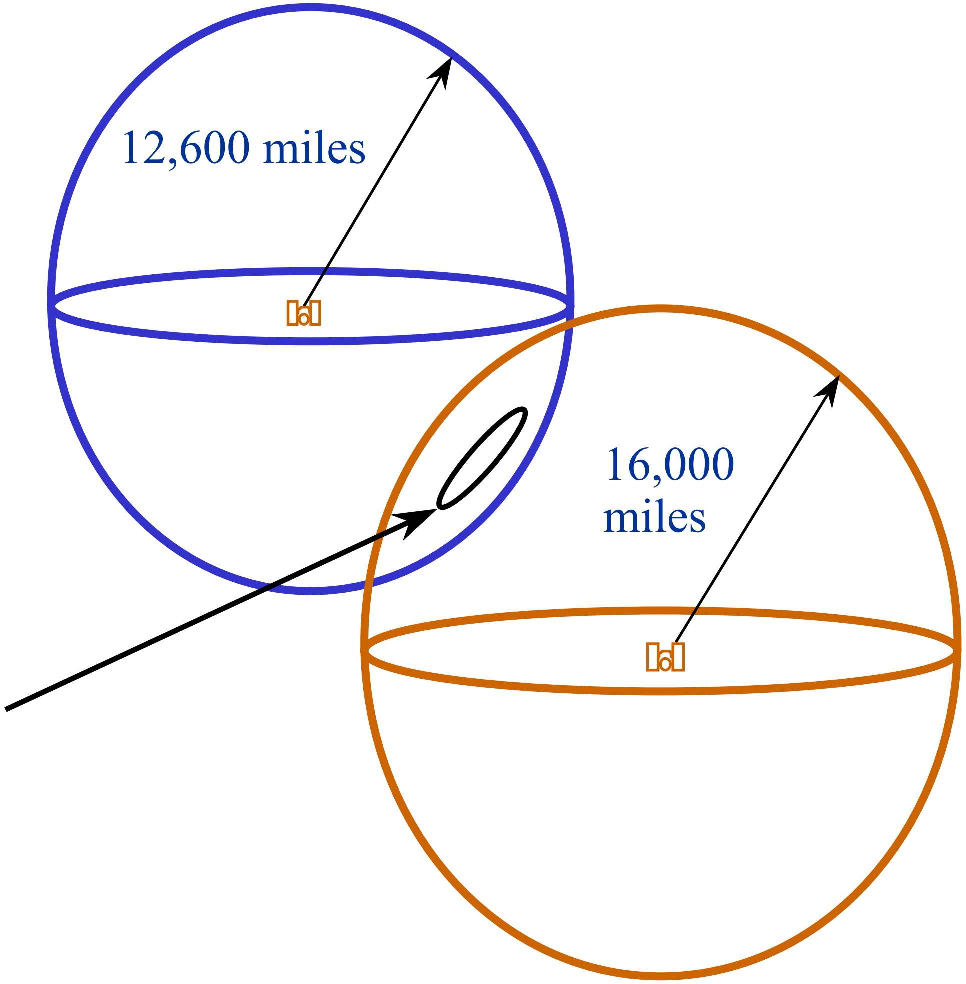
Knowing that we're 12,600 miles from a particular satellite narrows down all the possible locations we could be in the whole universe to the surface of a sphere that is centered on this satellite and has a radius of 12,600 miles.



We're somewhere on the surface of this Sphere

Trilateration

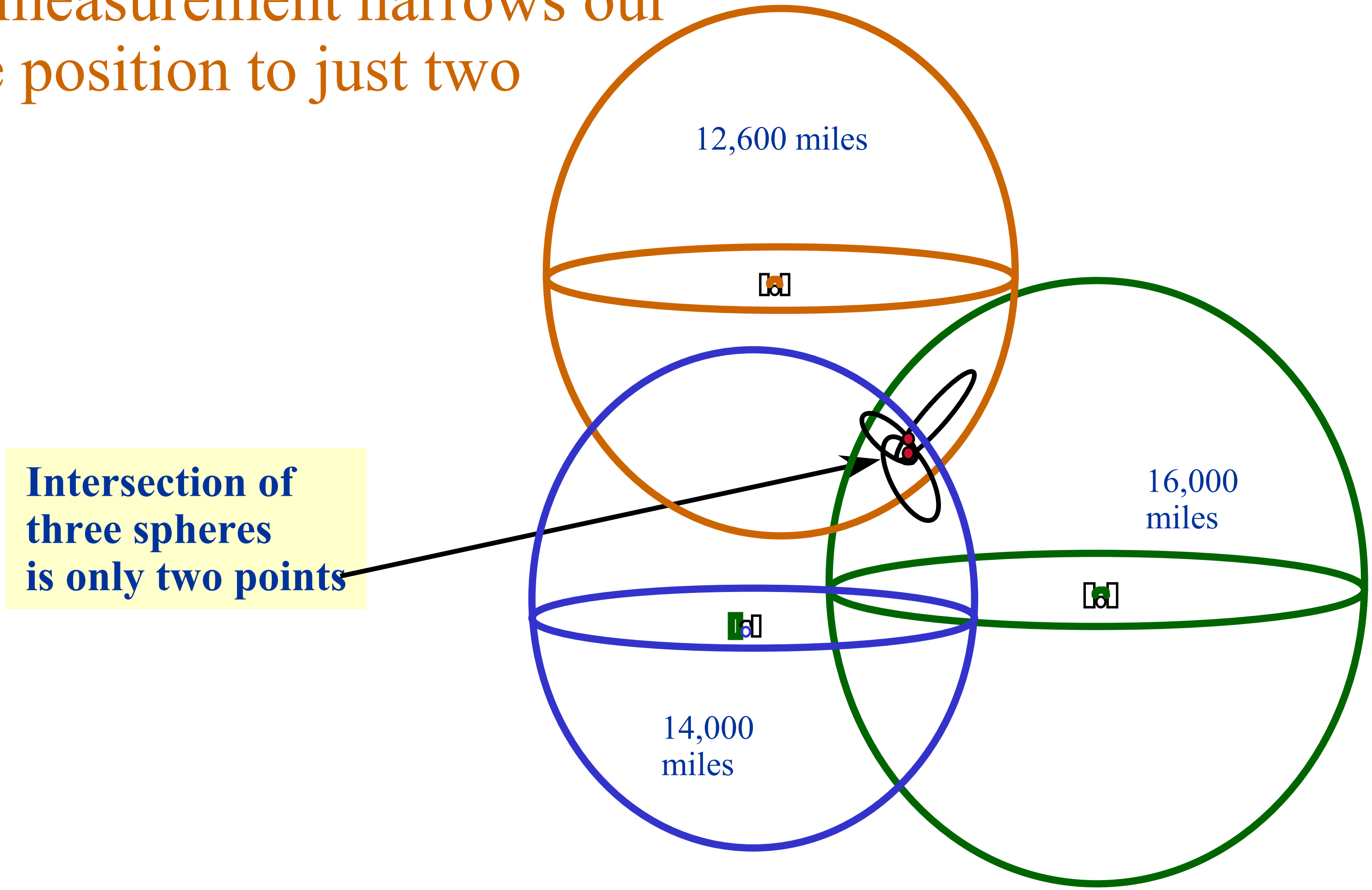
A second measurement narrows our position down to the intersection of two spheres - an imaginary circle



The intersection of two spheres is a circle

Trilateration

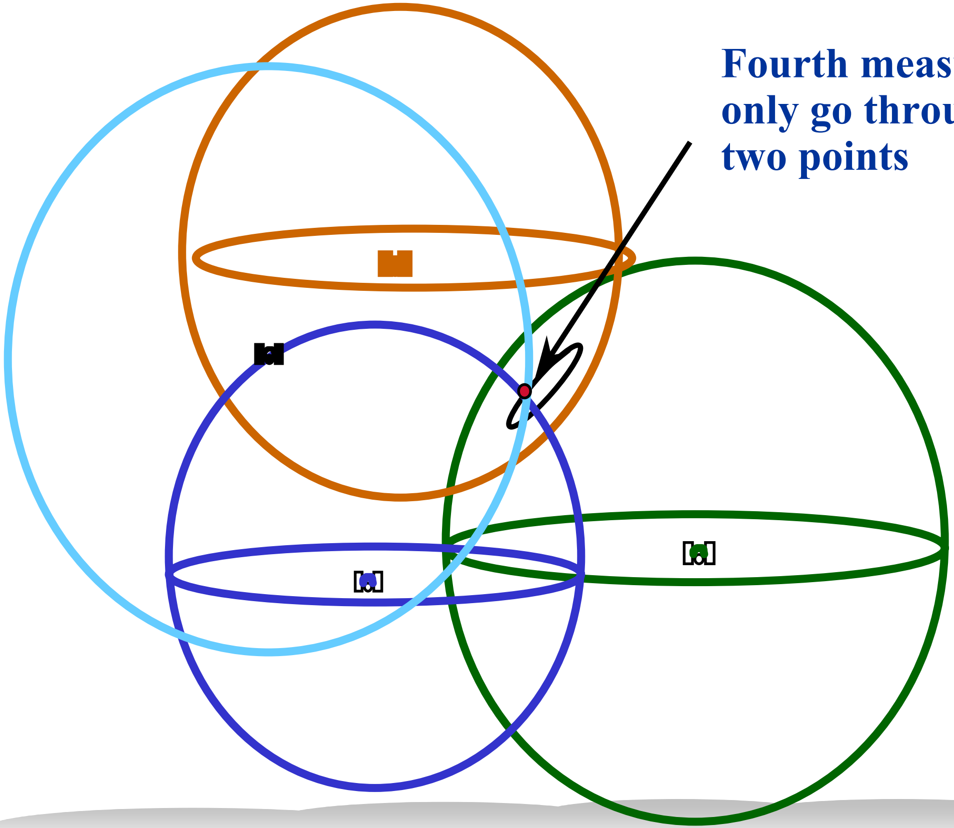
A third measurement narrows our possible position to just two points



Intersection of three spheres is only two points

Trilateration

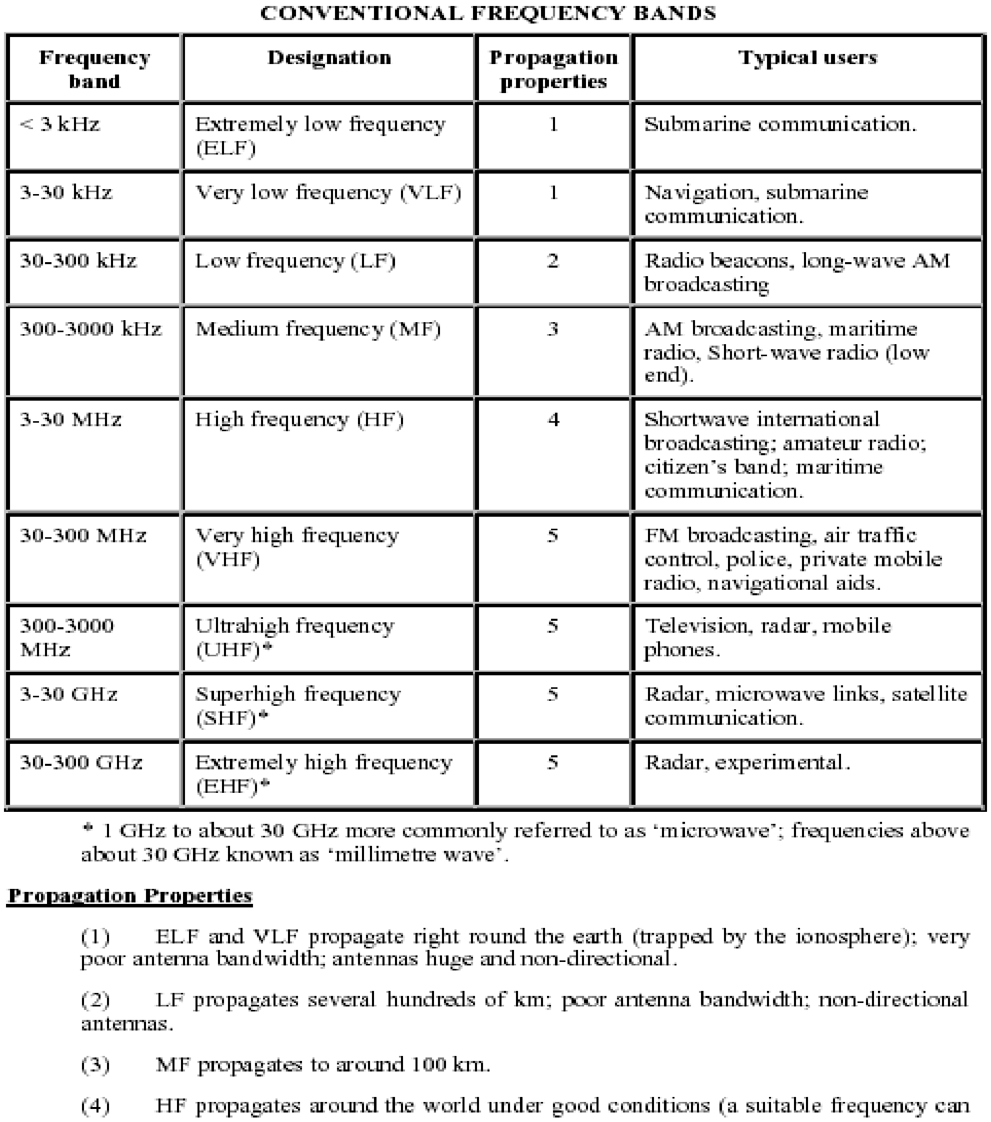
Fourth measurement will decide between two points



Fourth measurement will only go through one of the two points

Microwave and Radar

While there are some radar bands from 1300 to 1600 MHz, most microwave applications fall in the range 3000 to 30,000 MHz (3 –30 GHz). Current microwave ovens operate at a nominal frequency of of 2450 MHz, a band assigned by FCC. There are also some amateur and radio navigation uses of the 3-30 GHz range.



CONVENTIONAL FREQUENCY BANDS

Frequency band	Designation	Propagation properties	Typical users
< 3 kHz	Extremely low frequency (ELF)	1	Submarine communication.
3-30 kHz	Very low frequency (VLF)	1	Navigation, submarine communication.
30-300 kHz	Low frequency (LF)	2	Radio beacons, long-wave AM broadcasting
300-3000 kHz	Medium frequency (MF)	3	AM broadcasting, maritime radio, Short-wave radio (low end).
3-30 MHz	High frequency (HF)	4	Shortwave international broadcasting; amateur radio; citizen's band; maritime communication.
30-300 MHz	Very high frequency (VHF)	5	FM broadcasting, air traffic control, police, private mobile radio, navigational aids.
300-3000 MHz	Ultrahigh frequency (UHF)*	5	Television, radar, mobile phones.
3-30 GHz	Superhigh frequency (SHF)*	5	Radar, microwave links, satellite communication.
30-300 GHz	Extremely high frequency (EHF)*	5	Radar, experimental.

* 1 GHz to about 30 GHz more commonly referred to as 'microwave'; frequencies above about 30 GHz known as 'millimetre wave'.

Propagation Properties

(1) ELF and VLF propagate right round the earth (trapped by the ionosphere); very poor antenna bandwidth; antennas huge and non-directional.

(2) LF propagates several hundreds of km; poor antenna bandwidth; non-directional antennas.

(3) MF propagates to around 100 km.

(4) HF propagates around the world under good conditions (a suitable frequency can

Basic Electricity and Magnetism

Formulas:

$$F = \kappa \frac{q_1 q_2}{r^2} \qquad E = \frac{F}{q_0}$$

$$e = 1.60 \times 10^{-19}\, C$$

$$\kappa = \frac{1}{4\pi\varepsilon_0} = 8.988 \times 10^{9}\ Nm^2 / C^2$$

$$\varepsilon_0 = 8.85 \times 10^{-12}\ C^2 / (Nm^2)$$

Electric Charges

The Greek philosopher Thales observed that if a person rubbed amber with wool or fur, then the amber would attract small pieces of a leaf or cloth. Our word “electricity” comes from the Greek elektron- which means “amber”.

There are two kinds of charges. Benjamin Franklin named then positive and negative and defined the charge on the rubbed glass rod to be positive.

Like charges repel and unlike charges attract. We do not create or destroy charge, just transfer it. In accelerators it can be created in pairs so that the total charge is always the same. So if a charged object touches an uncharged object, some of the extra charges from the charged object transfers to the uncharged object. But the total charge stays the same.

Coulomb's Law

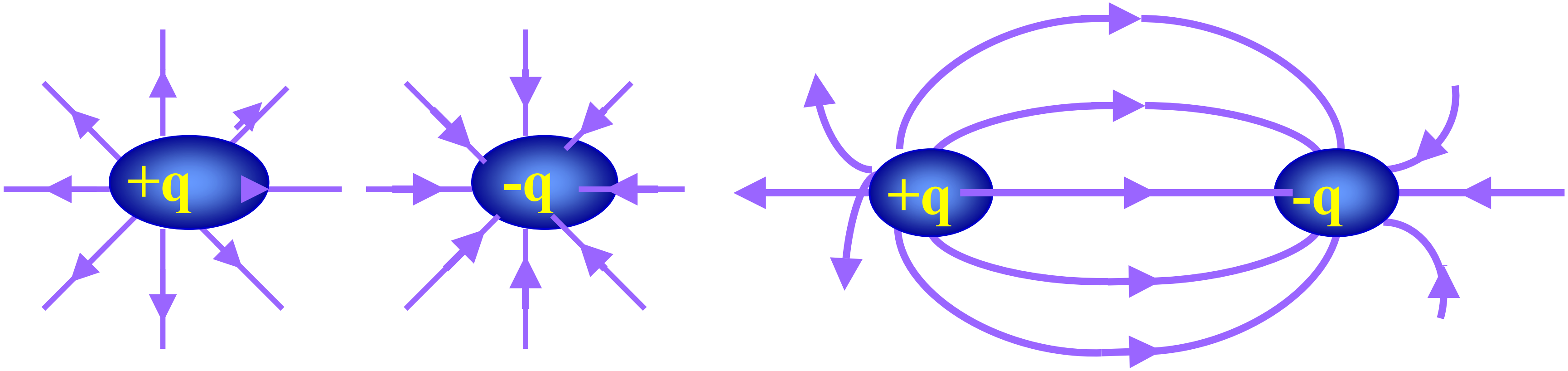
We want to know how strong the attraction or repulsion is between charged objects. This is given by Coulomb's Law that gives the strength of force between two charged objects.

$$F = \kappa \frac{q_1 q_2}{r^2}$$

Meaning: If you double the charge on one object, the force doubles. If you double the distance, the force decreases by a factor of four.

Electric Field

An electric field is a vector quantity meaning it has a magnitude and a direction. The direction is defined as the direction of the electrical force that would be exerted on a small positive test charge. A field leads to a force on a charged object.

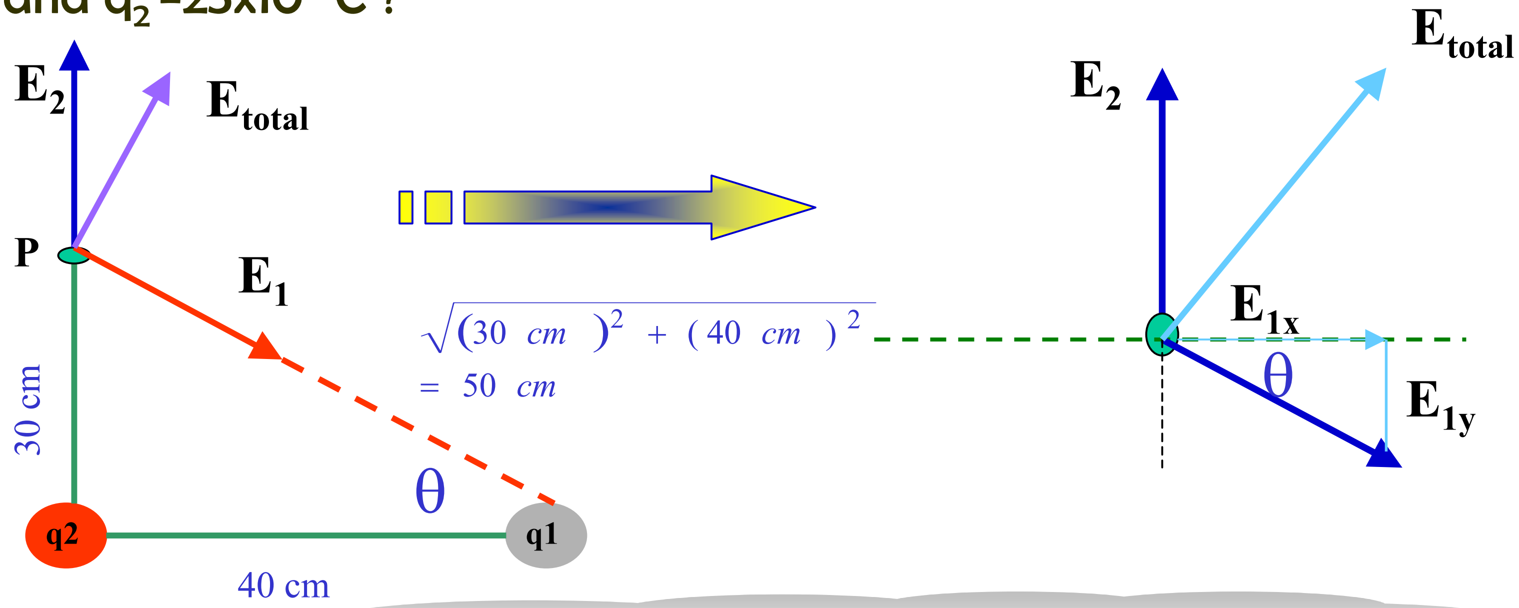


Force from Electric Field

Electric fields can exist due to a variety of sources. There may be a small charge nearby, or from a capacitor nearby. If a charge is placed in an electric field, it then feels a force. How big is the force ? It depends on the size of the field and on the size of the charge (*F=Eq*) . Both the force and the field are vectors.

Example

What is the total electric field 30 cm above charge q_2 if $q_1=-25\times10^{-6}$C and $q_2=25\times10^{-6}$C ?



$$\sqrt{(30\ cm)^2 + (40\ cm)^2} = 50\ cm$$

Force from Electric Field

The angle that E_1 makes with the x-axis is cos θ=40 cm/50 cm⇒ θ=36.9 deg.

Electric field from q_1:

$$E_1 = \kappa q_1 / r^2 = \frac{(9.0\times 10^9\,Nm^2/C^2)(25\times 10^{-6}\,C)}{(0.5m)^2} = 9.0\times 10^5\,N/C$$

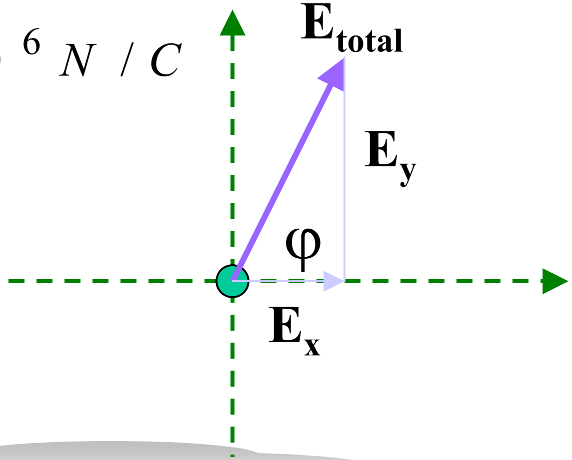
Electric field from q_2:

$$E_2 = \kappa q_2 / r^2 = \frac{(9.0\times 10^9\,Nm^2/C^2)(25\times 10^{-6}\,C)}{(0.3m)^2} = 2.5\times 10^5\,N/C$$

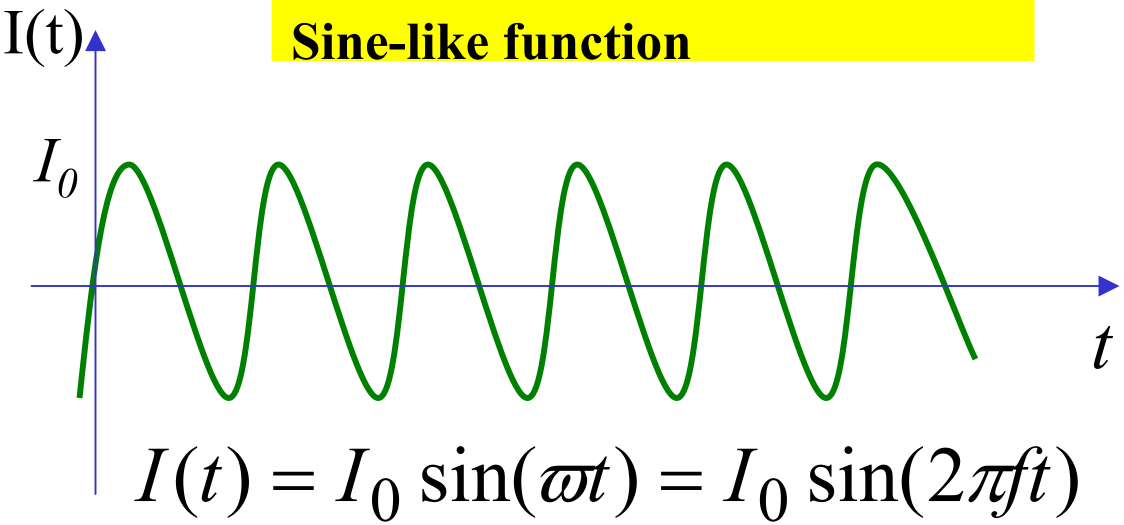
$$E_x = E_{1x} = E_1\cos(36.9^\circ) = 7.2\times 10^5\,N/C$$

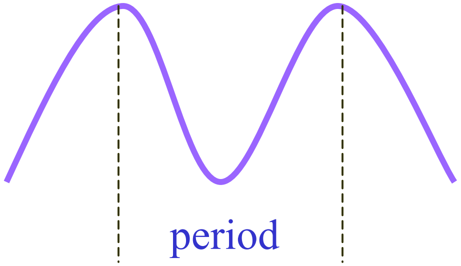
$$E_y = E_2 - E_{1y} = E_2 - E_1\sin(36.9^\circ) = 2.0\times 10^6\,N/C$$

$$E_{total} = \sqrt{E_x^2 + E_y^2} = 2.1\times 10^6\,N/C$$



Alternating Current and Voltage


Sine-like function

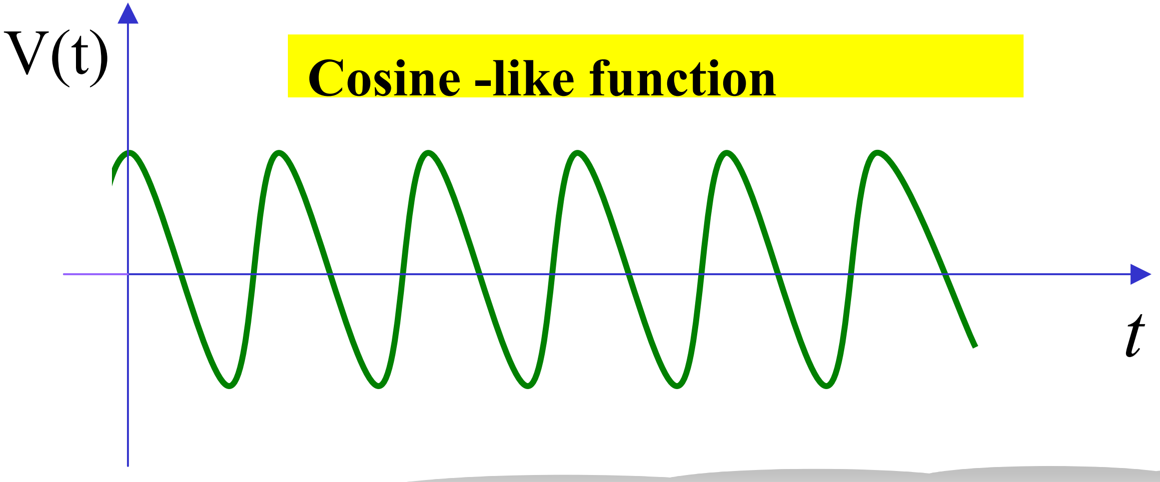


$$I(t) = I_0 \sin(\varpi t) = I_0 \sin(2\pi f t)$$

$$V(t) = V_0 \cos(\varpi t) = V_0 \cos(2\pi f t)$$

$$\omega = 2\pi f$$

$$f = c / \lambda$$


Cosine -like function

$$I_{RMS} = I_0 / \sqrt{2}$$

$$V_{RMS} = V_0 / \sqrt{2}$$

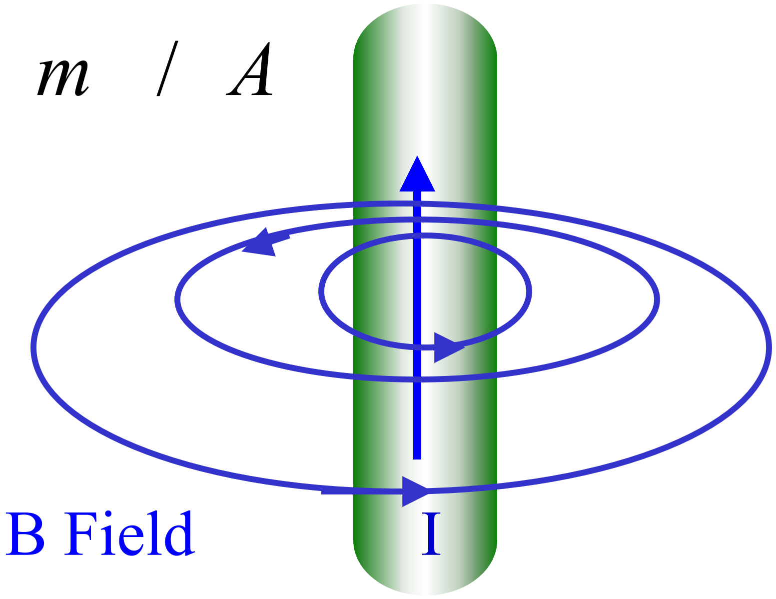
Magnetic field of a wire

The field goes in a circle around the wire. The direction is given by the right hand rule.

The magnitude is given by

$$B = \mu_0 \frac{I}{2\pi r}$$

$$\mu_0 = 4\pi \times 10^{-7}\, T \cdot m / A$$



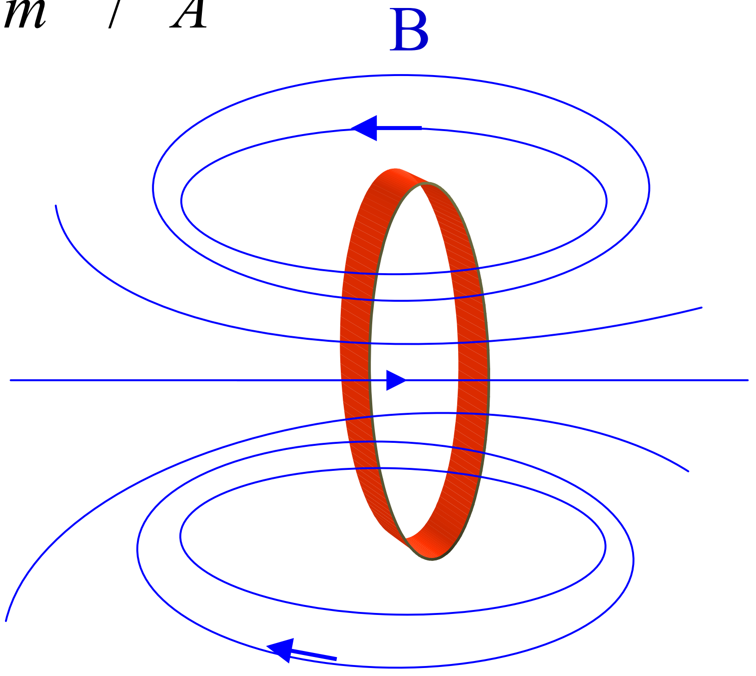
Magnetic field of a wire loop

$$B = N\mu_0 \frac{I}{2R}$$

$$\mu_0 = 4\pi \times 10^{-7}\ T \cdot m / A$$

N is no. of turns, I=current,

R=radius of wire



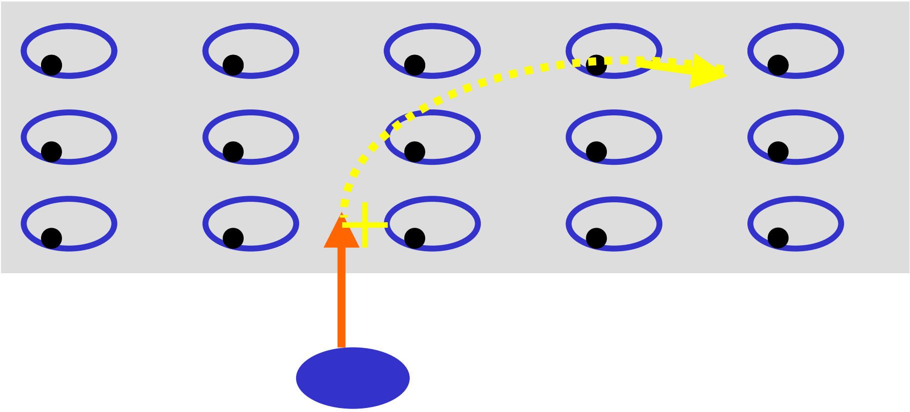
Motion of a charged particle

The motion of a charged particle in a magnetic field would be a circle. To keep this motion there must be a force causing centripetal acceleration. That is the magnetic force.

$F=mv^2/r = qvB\sin\theta$. Here $\theta=90$ so $\sin\theta=1$

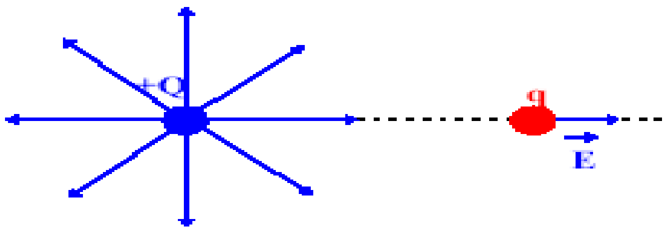
$F=mv^2/r = qvB$ $\quad$ $mv/r=Bq$, or $r=mv/Bq$

NOTE: the radius is given by the particle's mass, the magnetic field, the charge and the velocity.



Fields

The Electric Field



The charge Q produces an electric field which in turn produces a force on the charge q. The force on q is expressed as two terms:

$$F = K\,qQ/r^2 = q\,(KQ/r^2) = q\,E$$

The electric field at the point q due to Q is simply the force per unit positive charge at the point q:

$$E = F/q \qquad\qquad E = KQ/r^2$$

The units of E are Newtons per Coulomb (units = N/C).

The electric field is a physical object which can carry both momentum and energy. It is the mediator (or carrier) of the electric force. The electric field is massless.

The Electric Field is a Vector Field:

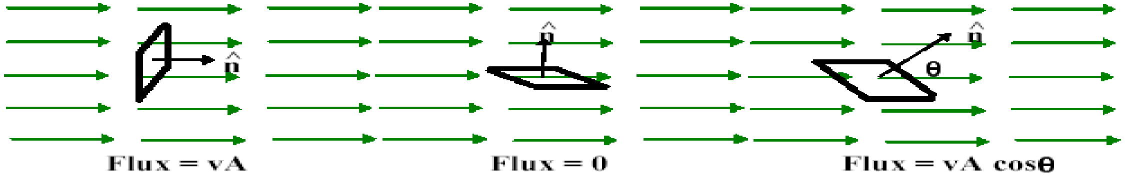
Electric Field of a Point Charge

$$\boxed{\vec{E} = \frac{KQ}{r^2}\hat{r}}$$

Fields

Flux of a Vector Field

Fluid Flow:



Consider the fluid with a vector $\vec{v}$ which describes the velocity of the fluid at every point in space and a square with area $A = L^2$ and normal $\hat{n}$. **The flux is the volume of fluid passing through the square area per unit time.**

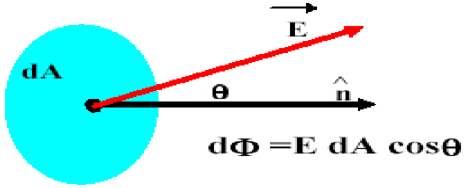
Generalize to the Electric Field:

Electric flux through the infinitesimal area dA is equal to

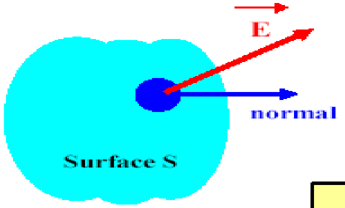
$$d\Phi = \vec{E} \cdot d\vec{A}$$

where

$$d\vec{A} = A\hat{n}$$



Total Electric Flux through a Closed Surface:



$$\Phi_E = \oint_S \vec{E} \cdot d\vec{A}$$

Electric Flux

Surface Integral!

Electrical Potential Energy

Electrostatic Force: $F = K\, q_1 q_2 / r^2$

Electric Potential Energy: $EPE = U$ (Units = Joules)

Kinetic Energy: $KE = \frac{1}{2} m v^2$ (Units = Joules)

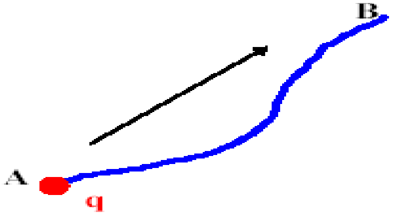
Total Energy: $E = KE + U$ (Units = Joules)

Work Energy Theorem: (work done on the system)

$$W = E_B - E_A = (KE_B - KE_A) + (U_B - U_A)$$

Energy Conservation: $E_A = E_B$ (if no external work done on system)

Electric Potential Difference $\Delta V = \Delta U / q$:



Work done (**against the electric force**) per unit charge in going from A to B (**without changing the kinetic energy**).

$$\Delta V = W_{AB}/q = \Delta U/q = U_B/q - U_A/q$$

(Units = Volts 1V = 1 J / 1 C)

Electric Potential $V = U/q$: $U = qV$

Units for the Electric Field (Volts/meter):

$$N/C = Nm/(Cm) = J/(Cm) = V/m$$

Energy Unit (electron-volt): One electron-volt is the amount of kinetic energy gained by an electron when it drops through one Volt potential difference

$$1\ eV = (1.6\mathrm{x}10^{-19}\ C)(1\ V) = 1.6\mathrm{x}10^{-19}\ Joules$$

1 MeV = 10^6 eV 1 GeV=1,000 MeV 1 TeV=1,000 GeV

Conductivity

Free Charged Particle:

For a free charged particle in an electric field,

$$\vec{F} = m\vec{a} = q\vec{E} \quad \text{and thus} \quad \vec{a} = \frac{q}{m}\vec{E}\ .$$

The **acceleration is proportional to the electric field strength E** and the **velocity of the particle increases with time!**

Charged Particle in a Conductor:

However, for a charged particle in a conductor the **average velocity is proportional to the electric field** strength **E** and since $\vec{J} = nq\vec{v}_{ave}$ we have

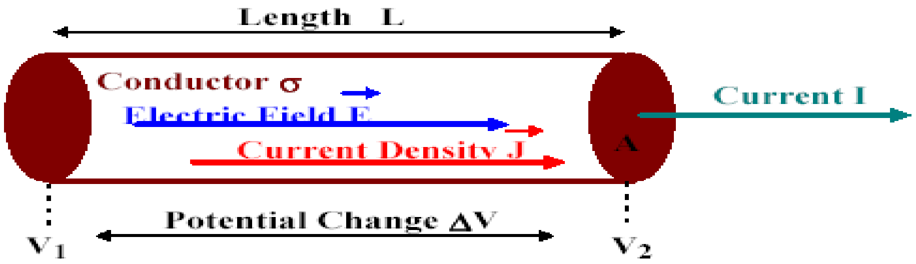
$$\vec{J} = \sigma\vec{E}\ ,$$

where **σ** is the **conductivity** of the material and is a property of the conductor. **The resistivity ρ = 1/σ.**

Ohm's Law:

$$\vec{J} = \sigma\vec{E}$$

$$I = JA = \sigma EA$$

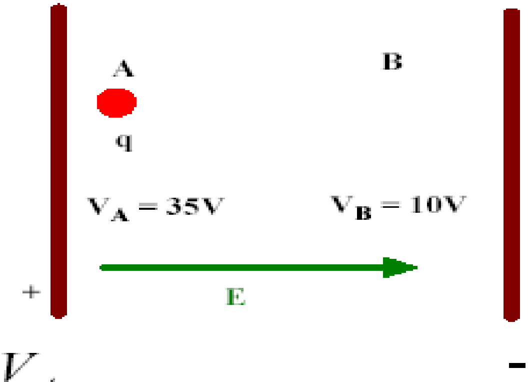


$$\Delta V = EL = \frac{I}{\sigma A}L = \left(\frac{L}{\sigma A}\right)I = RI$$

ΔV = IR (Ohm's Law) **R = L/(σA) = ρL/A (Resistance)**

Units for R are Ohms 1Ω = 1V/1A

Accelerating Charged Particle



Example Problem: A particle with mass **M** and charge **q** starts from rest the point **A**. What is its speed at the point **B** if V_A=35V and V_B=10V (M = 1.8x10^{-5}kg, q = 3x10^{-5}C)?

Solution:

The total energy of the particle at **A** and **B** is

$$E_A = KE_A + U_A = 0 + qV_A$$

$$E_B = KE_B + U_B = \frac{1}{2}Mv_B^2 + qV_B \, .$$

Setting **$E_A = E_B$ (energy conservation)** yields

$$\frac{1}{2}Mv_B^2 = q(V_A - V_B)$$

(Note: the particle gains an amount of kinetic energy equal to its charge, q, time the change in the electric potential.)

Solving for the particle speed gives

$$v_B = \sqrt{\frac{2q(V_A - V_B)}{M}}$$

(Note: positive particles fall from high potential to low potential $V_A > V_B$, while negative particles travel from low potential to high potential, $V_B > V_A$.)

Plugging in the numbers gives

$$v_B = \sqrt{\frac{2(3\times10^{-5}C)(25V)}{1.8\times10^{-5}kg}} = 9.1m/s \, .$$