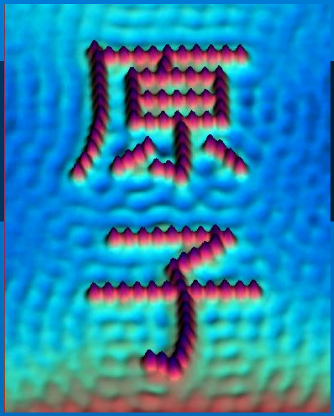
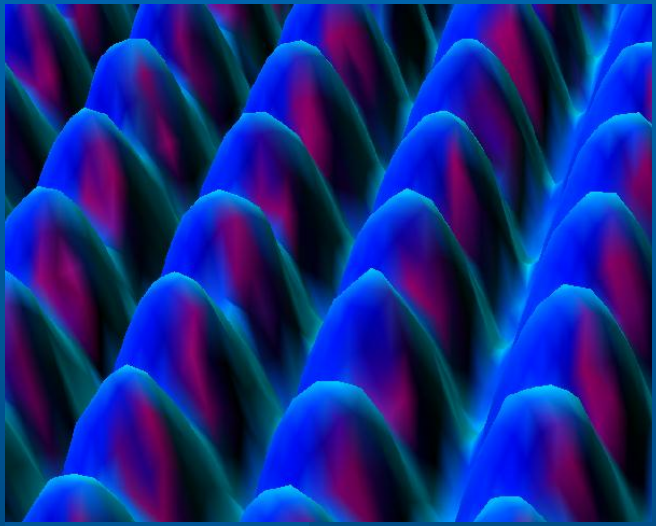
EM Fundamentals

Antenna Detection
UCSF-QB3
Lucas Carvajal

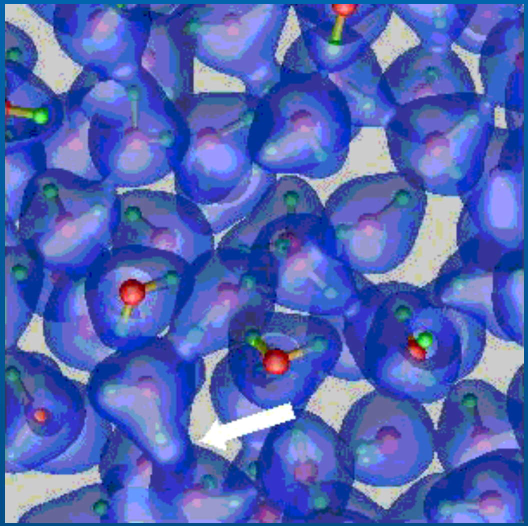
Introduction



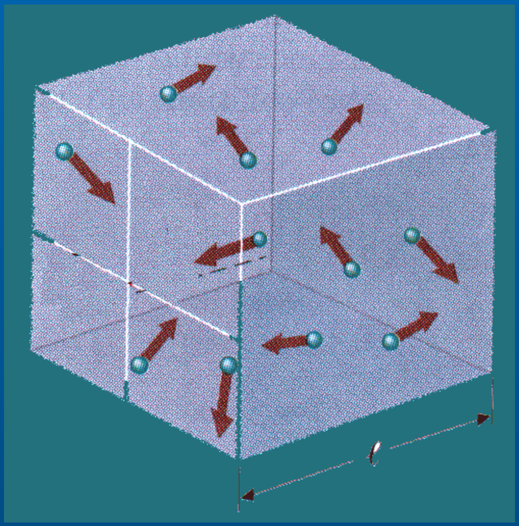
- Everything is made out of atoms (there is about 100 kinds only)



Nickel (STM)



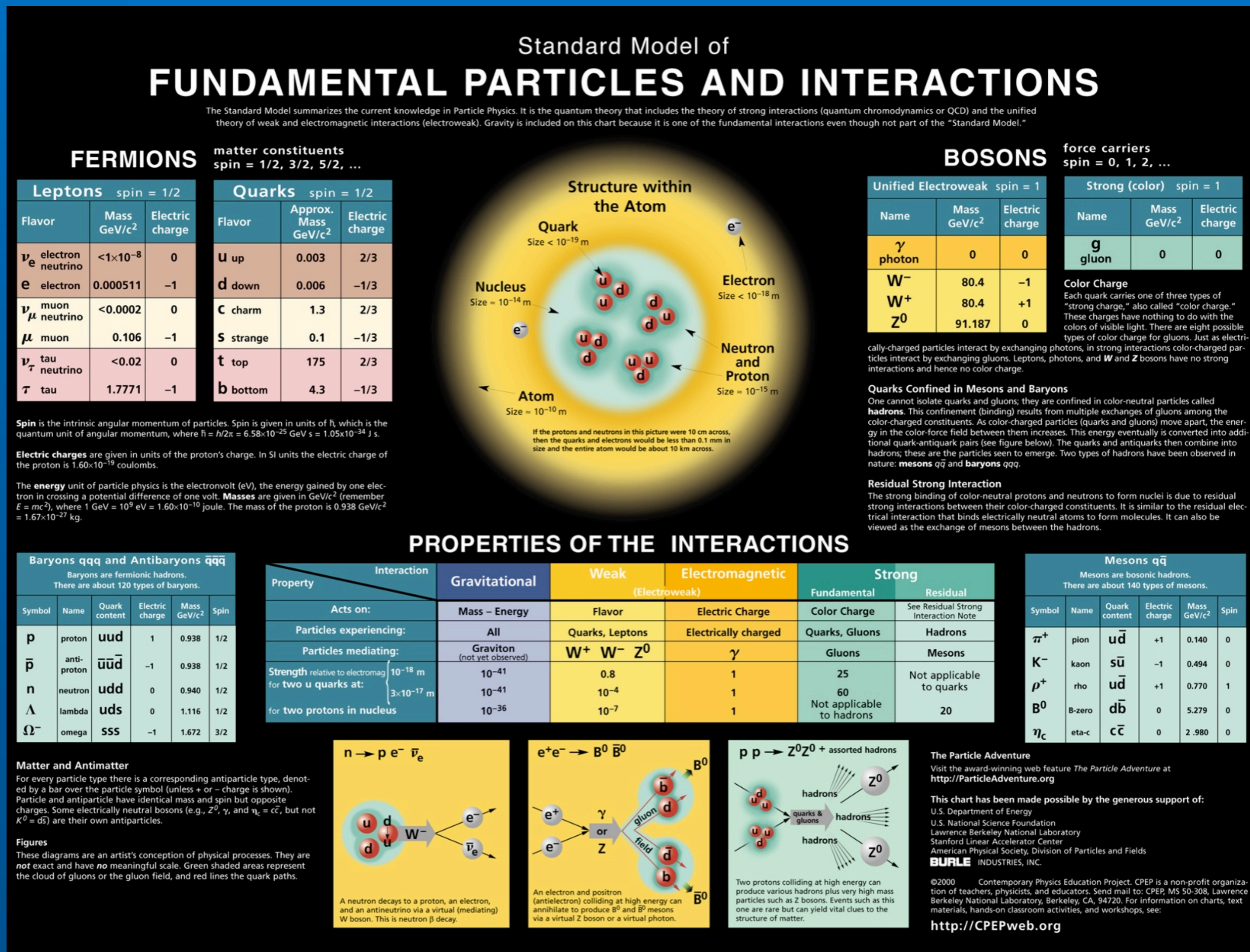
Water



Gas

Plasma

Atomic (standard) MODEL



Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and *W* and *Z* bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \to p\, e^-\, \bar{\nu}_e$
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

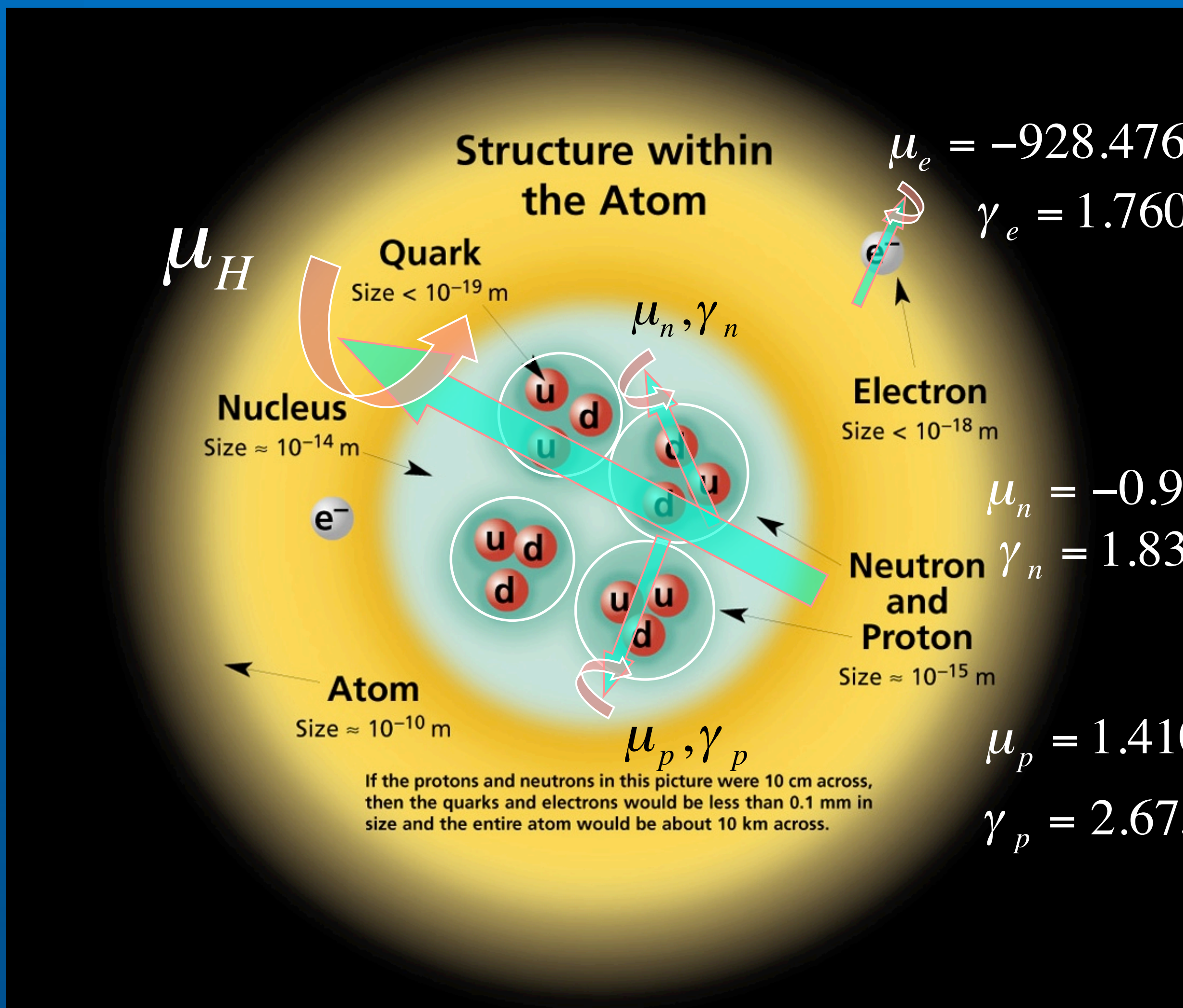
$e^+e^- \to B^0\,\bar{B}^0$
An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \to Z^0 Z^0$ + assorted hadrons
Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

Magnetic moments



$$\mu_e = -928.476 \times 10^{-26} J/T$$

$$\gamma_e = 1.760 \times 10^{11} s^{-1}T^{-1}$$

$$\mu_n = -0.966 \times 10^{-26} J/T$$

$$\gamma_n = 1.832 \times 10^{8} s^{-1}T^{-1}$$

$$\mu_p = 1.410 \times 10^{-26} J/T$$

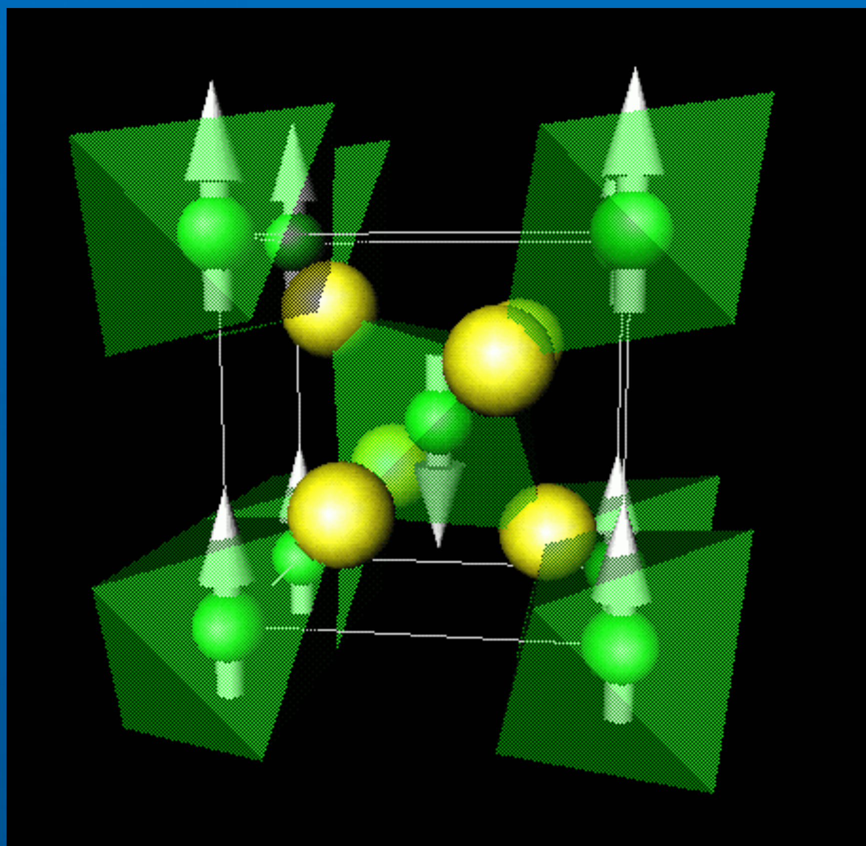
$$\gamma_p = 2.675 \times 10^{8} s^{-1}T^{-1}$$

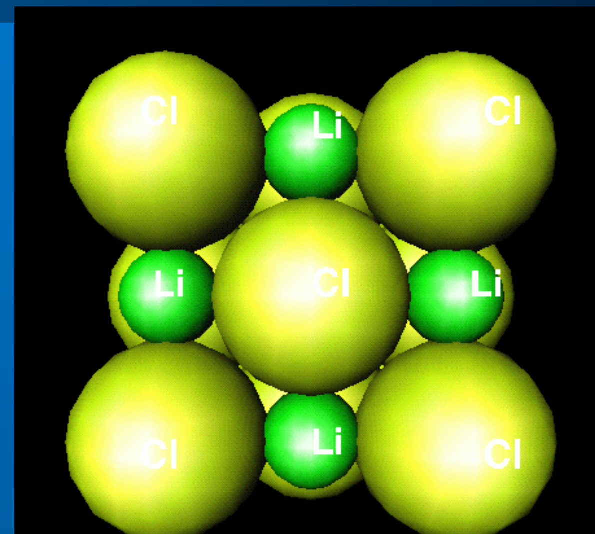
Atomic structure defines matter' s properties

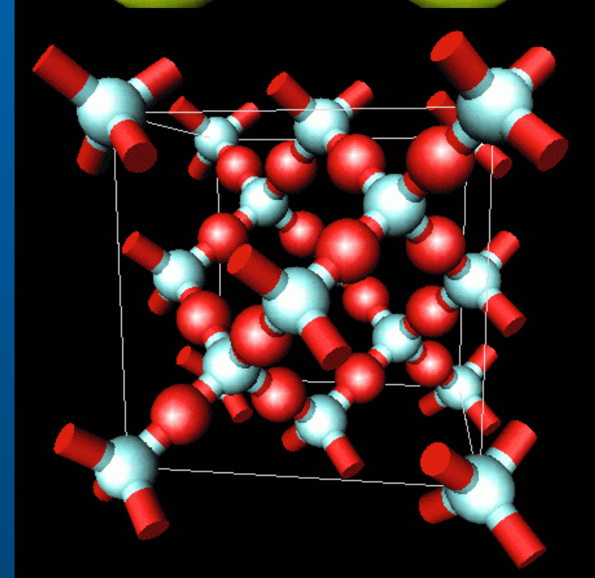
Group**

Period	1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 vIIIA 8A
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.47	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57 La* 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 190.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.5	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac~ (227)	104 Rf (257)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 --- ()	111 --- ()	112 --- ()		114 --- ()		116 --- ()		118 --- ()

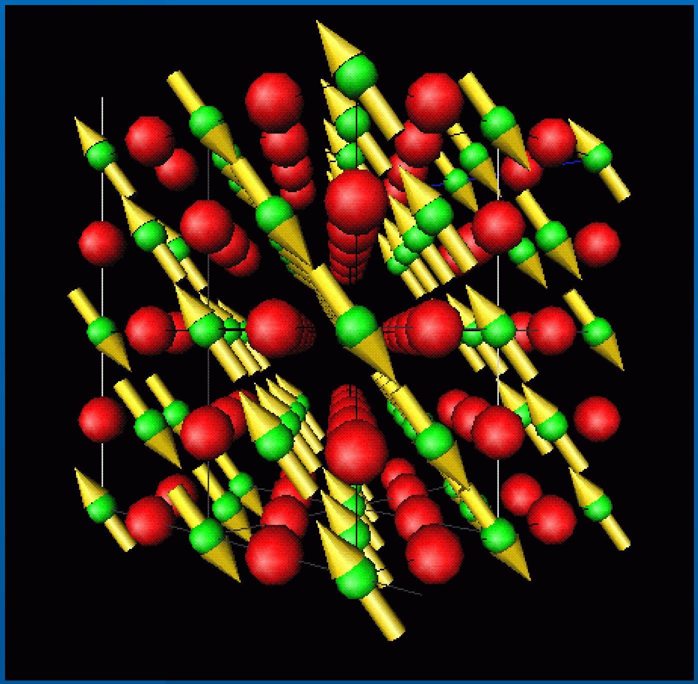
Solid state lattices







Magnetic anti-magnetic materials



Anti-ferromagnet
Manganese oxide
MnO

Macroscopic properties

Macroscopic properties of matter

- Macroscopic = Avogadro’s number of things. 6.023x10^23

- Physical properties include such things as: color, brittleness, malleability, ductility, electrical conductivity, density, magnetism, hardness, atomic number, specific heat, heat of vaporization, heat of fusion, crystalline configuration, melting temperature, boiling temperature, heat conductivity, vapor pressure, or tendency to dissolve in various liquids. These are only a few of the possible measurable physical properties.

More properties

- Chemical properties include: whether a material will react with another material, the rate of reaction with that material, the amount of heat produced by the reaction with the material, at what temperature it will react, in what proportion it reacts, and the valence of elements.

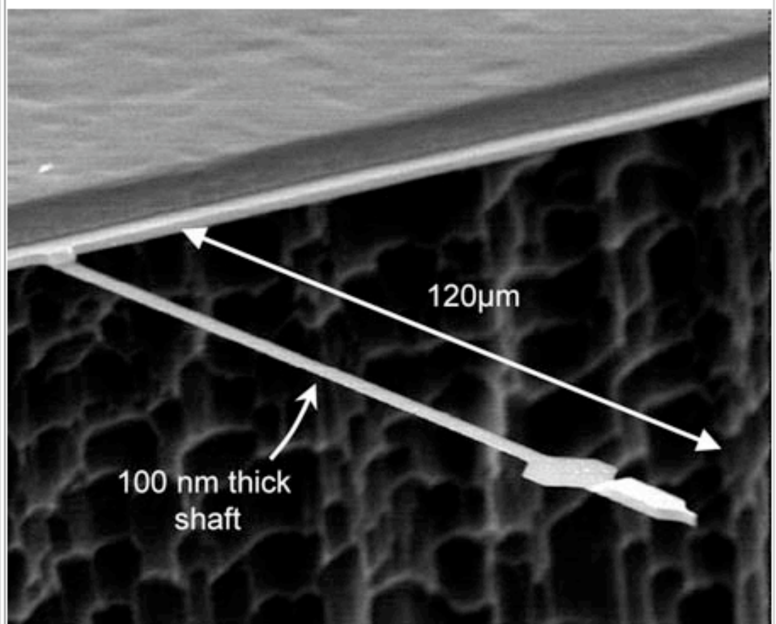
- ELECTRICAL PROPERTIES
  - Conductor - electrons free to move around
  - Insulator - electrons bound tight to nucleus
  - Resistance - opposition to e-flow, power dissipation
  - Capacitance - property to store charge
  - Inductance - electromagnetic inertia

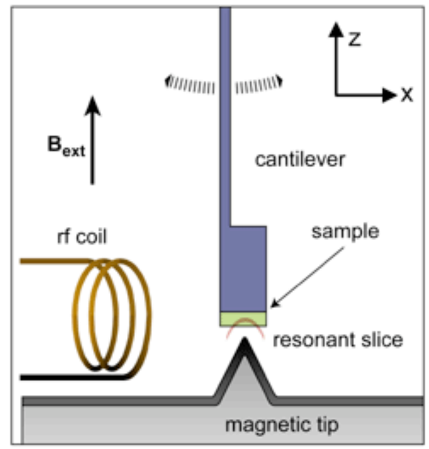
Interactions of EM and Matter

- Magnetic Resonance Imaging is the Visualization of the interaction of electro-magnetic fields with matter at FM frequencies which are interpreted in a clinical forum
- In general Spectroscopy = the study of the interaction of electro-magnetic fields with matter
- The fundamental probe for the study of electromagnetic fields is the loop antenna or coil.

  This probe needs to operate correctly at very high power or minuscule electromagnetic power levels with the same accuracy for transmit or receive.

A tiny probe for 90nm MRI

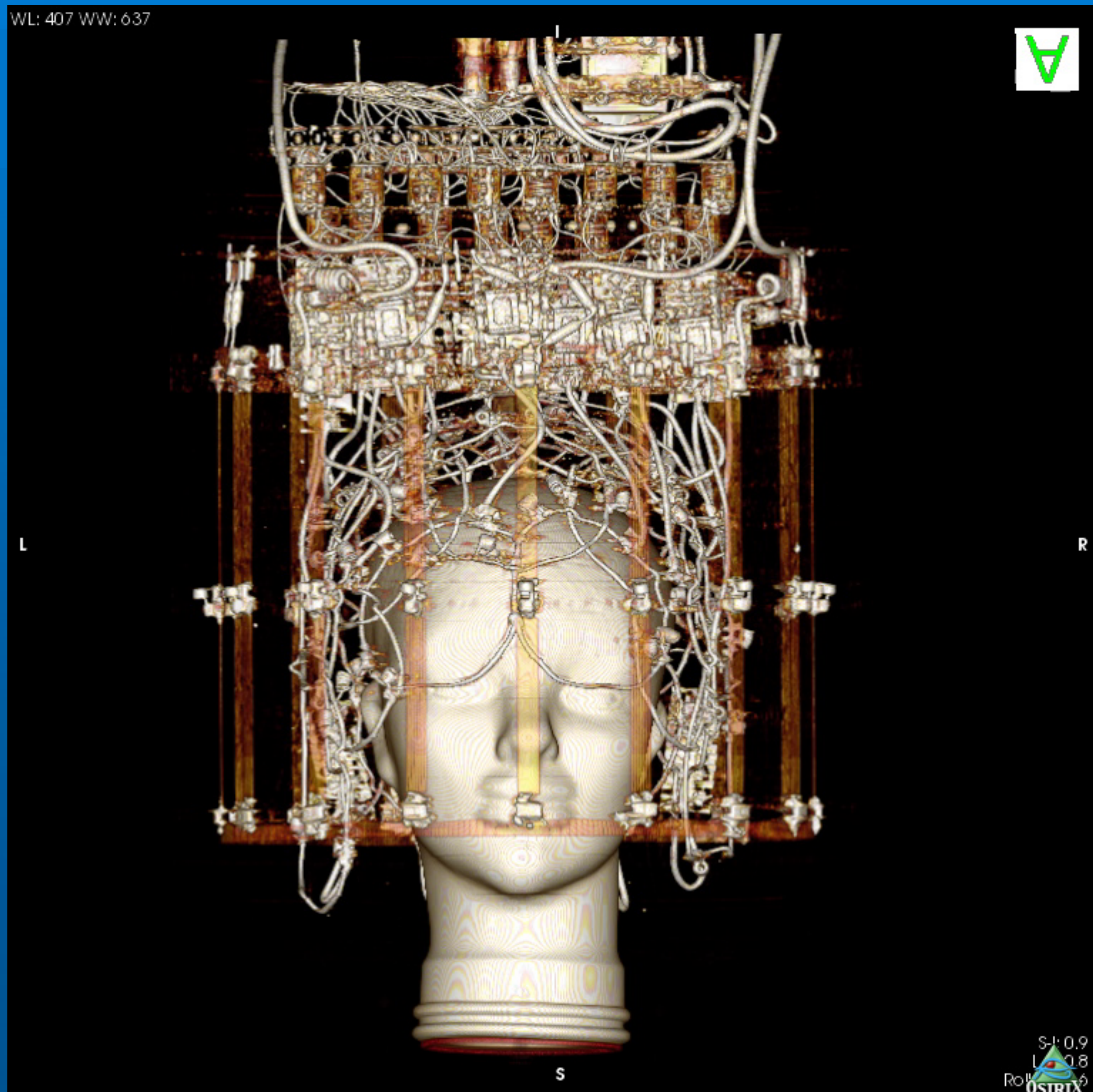




(1) Tiny volumes in a sample (green) are imaged through the resonant interaction of nuclei in that volume with both RF waves (coil to left) and a sharp magnetic tip beneath. This causes the cantilever to change its oscillation frequency. (2) Picture of the cantilever.

Reported by:

500 m Dish for Radio Astronomy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Basic Electro statics

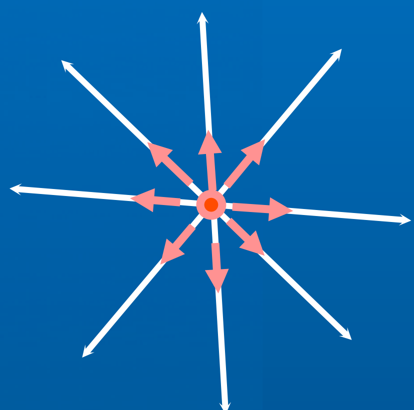
- All matter is made of atoms
- All atoms have charges

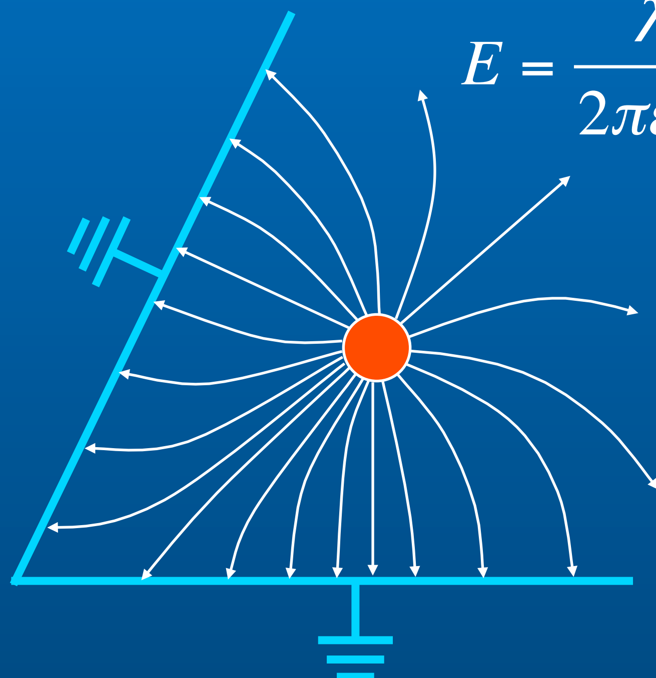
Electric field

$$E(r) = \frac{1}{4\pi\varepsilon_0}\int_{V'} \frac{\rho(r')\hat{R}}{R^2}\,d\tau'$$

E=Newton/Coulomb

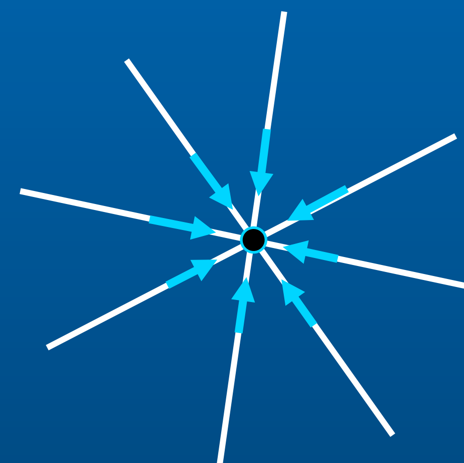
Source of electric flux lines (E) is CHARGE





$$E = \frac{\lambda}{2\pi\varepsilon_0 r}\hat{r}$$

$$F = qE$$



Line density = electric field strength

$$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$$

Permittivity $\varepsilon_0 = 8.85\times10^{-12}(\text{coulomb})^2/\text{Nm}^2$

Permittivity of Free Space

- ε_0 is a measurement-system constant introduced and defined as a result of international agreement
- Defined as $\varepsilon_0 \equiv \dfrac{1}{\mu_0 c_0^2}$ $\quad\quad \varepsilon_0 \approx 8.854 \times 10^{-12}\ \text{F/m}$
- permittivity relates to a material's ability to transmit (or "permit") an electric field.

Permeability of free space

- In electromagnetism, permeability μ_0 is a measure of resistance encountered when forming a magnetic field in vacuum
- and has the exact (defined) value $\mu_0 = 4\pi x 10^{-7}\ NxA^{-2}$ due to the definition of what is an ampere.

Quantifying Impedance

- The intrinsic impedance of an EM wave is the ratio of of the transverse components of the electric and magnetic fields

$$Z = \frac{|E|}{|H|}$$

What is the Z of free space?

- For free space vacuum (outer space) the intrinsic impedance is given by

$$Z = \sqrt{\frac{i\omega\mu}{\sigma + i\omega\varepsilon}}, \text{ since the conductivity } \sigma = 0$$

$$Z = \sqrt{\frac{\mu_0}{\varepsilon_0}} = \sqrt{\frac{4\pi \times 10^{-7}}{8.854 \times 10^{-12}}} \approx 120\pi \approx 377\Omega$$

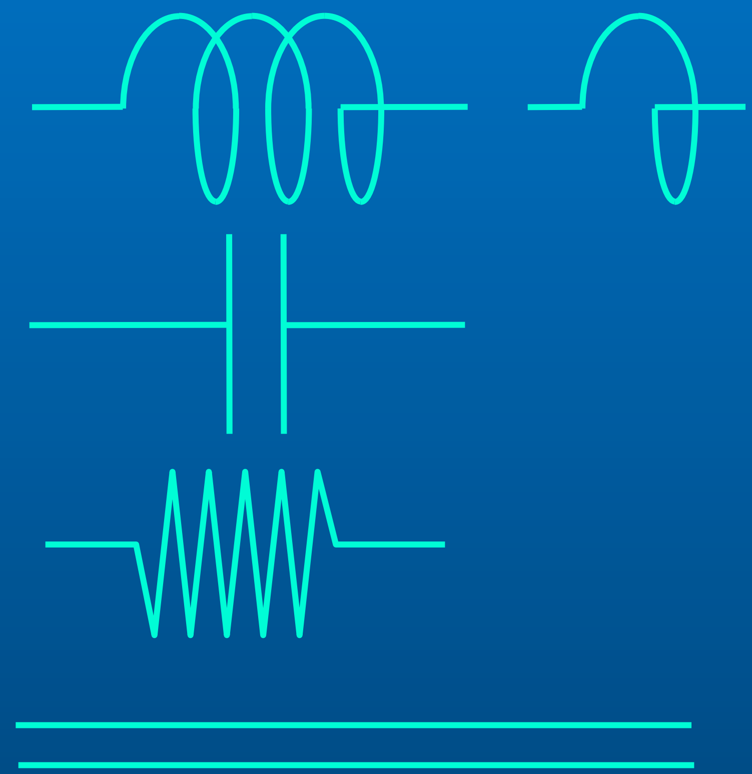
$$c_0 = \frac{Z}{\mu_0} = 2.998 \times 10^{8} \text{ m/s}$$

Basic concepts to harness EM

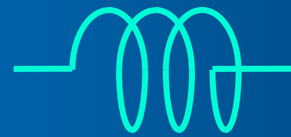
I. Lumped element components
II. The RF receiver Chain

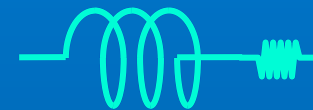
Physical components

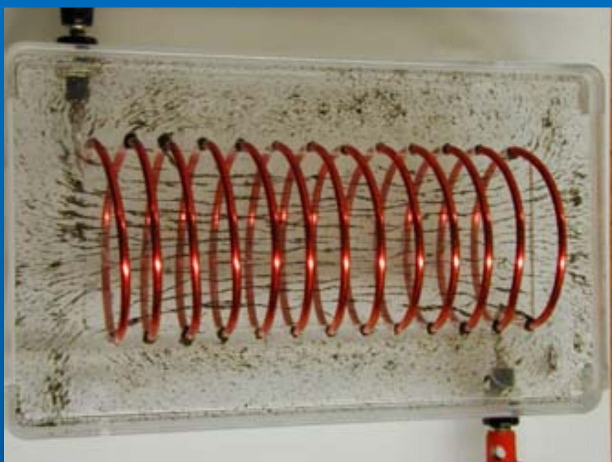
- Inductor
- Capacitor
- Resistor
- Conductor

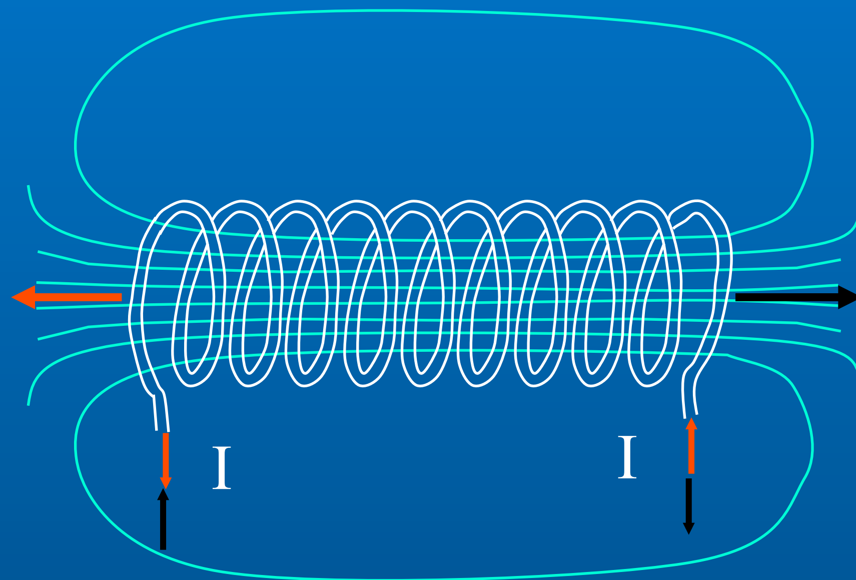


Inductor









$$B = \mu_0 N l$$

Stores energy as a magnetic field

$$L = \frac{\mu_0 N^2 A}{l} \qquad Energy = \frac{1}{2} L I^2 \qquad X_L = \omega L$$

Reactance is a measure of how well a circuit stores or releases energy

Permeability $\mu_0 = 4\pi \times 10^{-7}$ N/amp^2 or henry/m

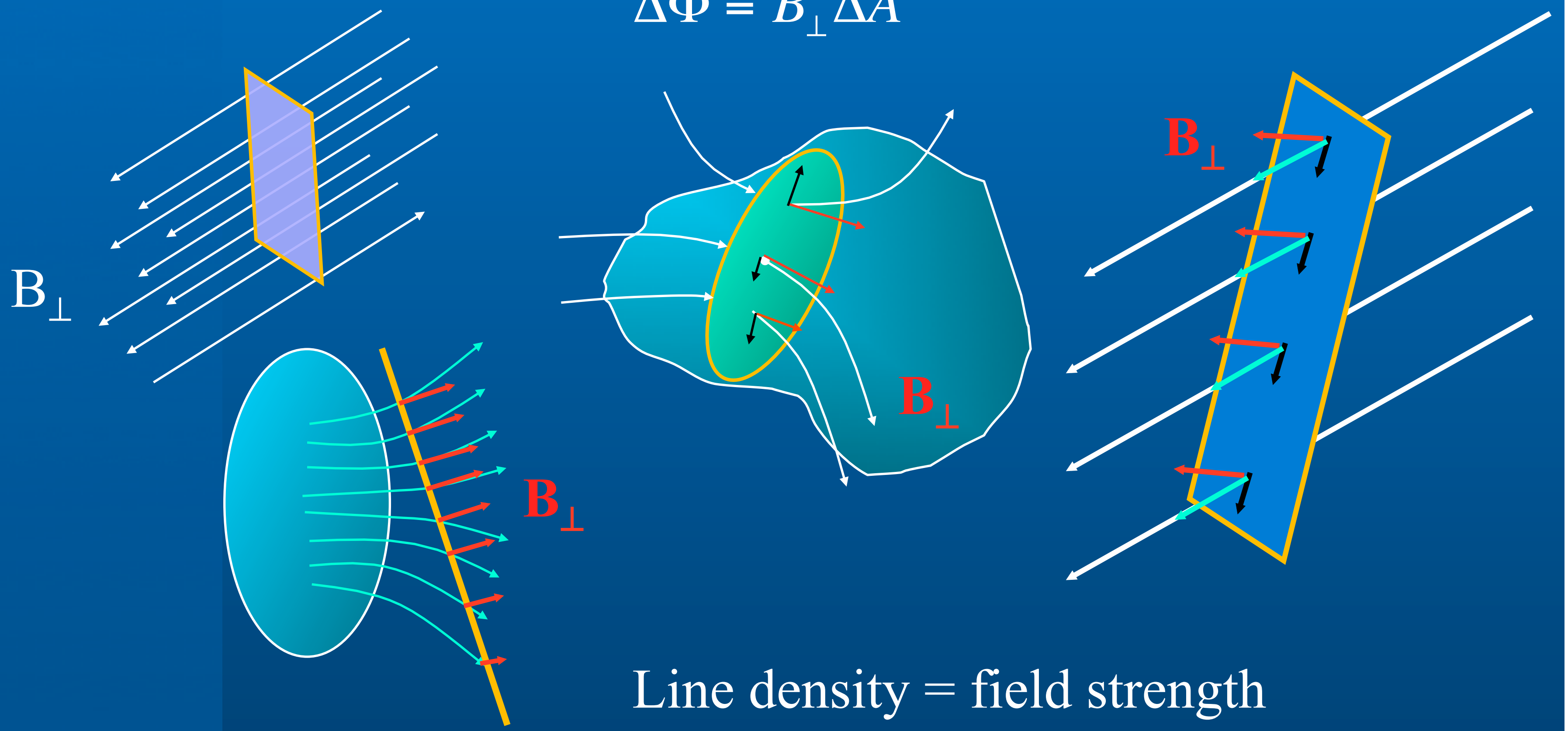
Magnetic Flux

$$\Phi = B_{\perp} A$$

B=weber/m^2

Source of magnetic flux lines (B) are always CURRENTS

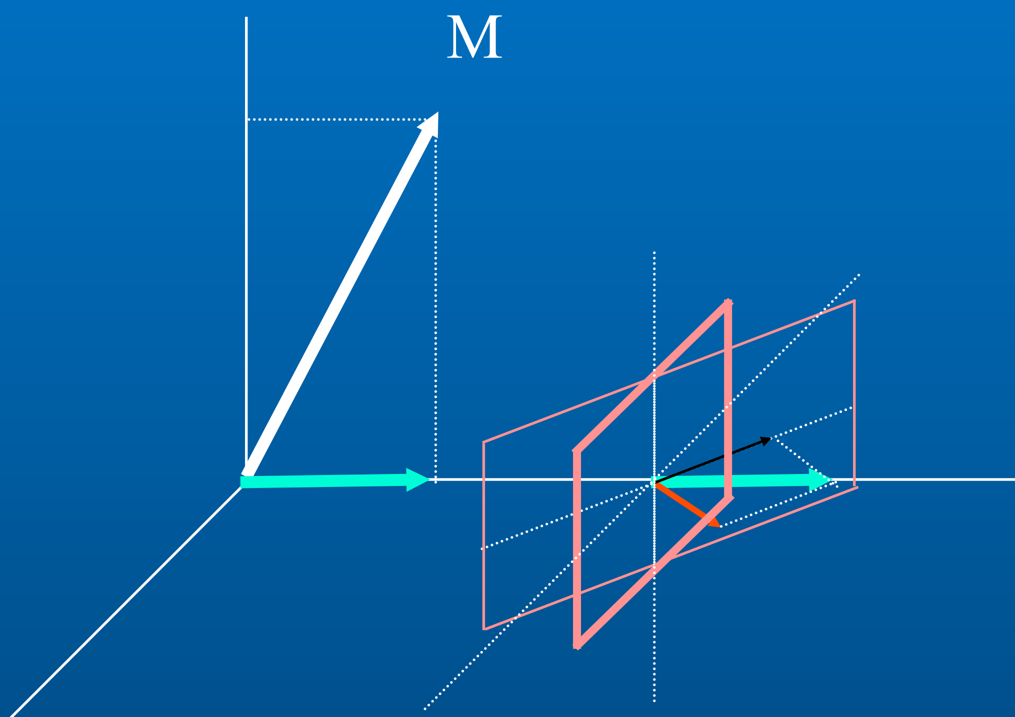
$$\Delta\Phi = B_{\perp} \Delta A$$



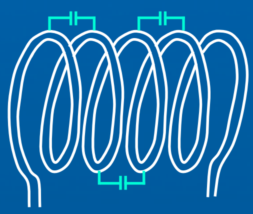
Line density = field strength

The only observable component of the field is the one transvers (perpendicular) to the detector

Detection orientation matters



Characteristics of inductors

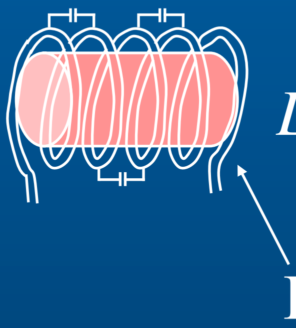


Wire length has certain self inductance

Inductors can be chokes to RF waves,
they look as OPEN circuits (infinite resistance)

Any inductor has some capacitance between turns
Therefore they are an LC circuit and self resonate

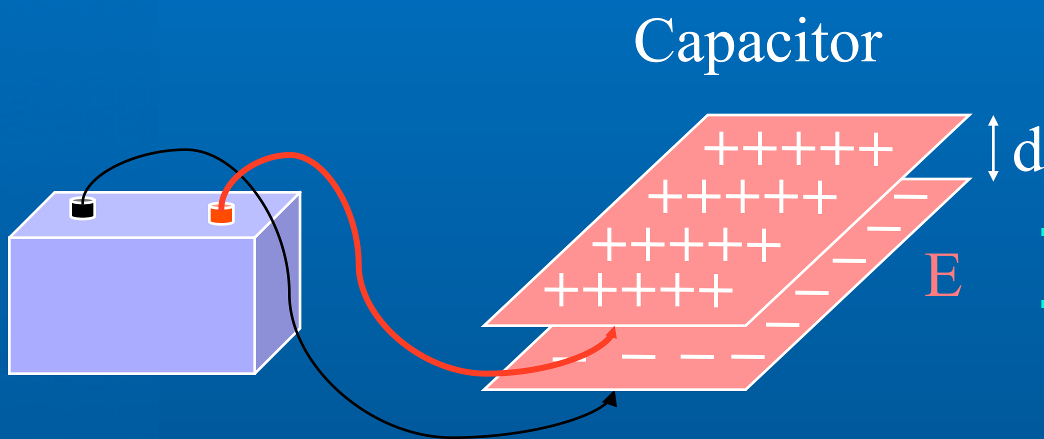
Change inductance with material
of high permeability μ.

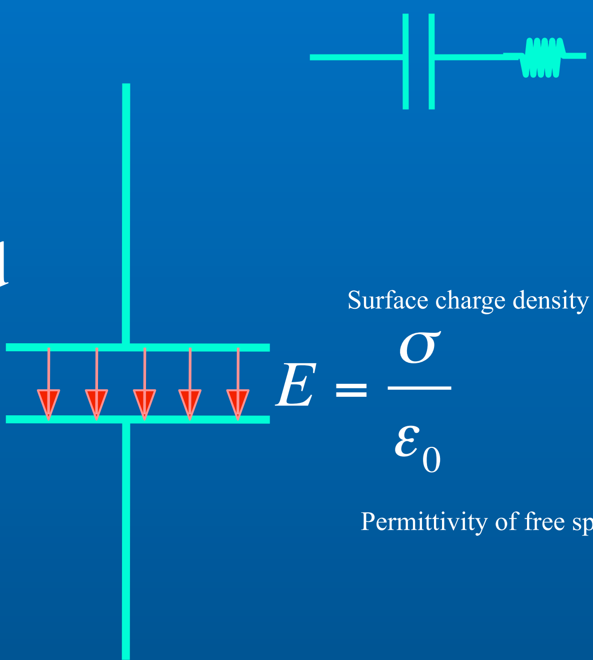


$$L = \frac{\mu N^2 A}{l}$$

Changes magnetic field $B = \mu N l$

Capacitor





$$E = \frac{\sigma}{\varepsilon_0}$$

Capacitor stores energy as Electric Field

$$C = \frac{\varepsilon A}{d} \qquad Energy = \frac{1}{2}CV^2 \qquad X_C = \frac{1}{\omega C}$$

Reactance is a measure of how well a circuit stores or releases energy

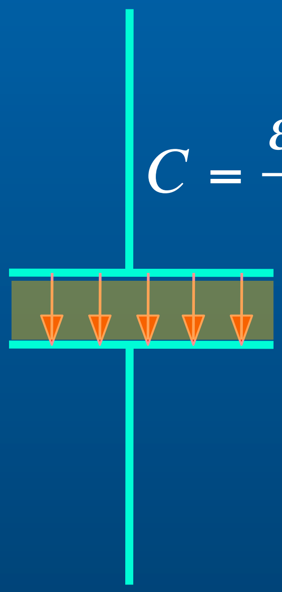
Characteristics of capacitors

To RF they look like short circuits

They are continuous direct current (DC) blocks

Capacitors have certain inductance
So they are also self resonant!

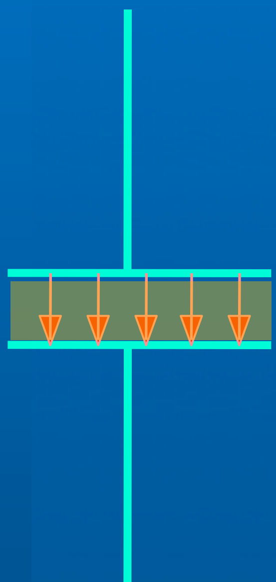
$$C = \frac{\varepsilon A}{d}$$

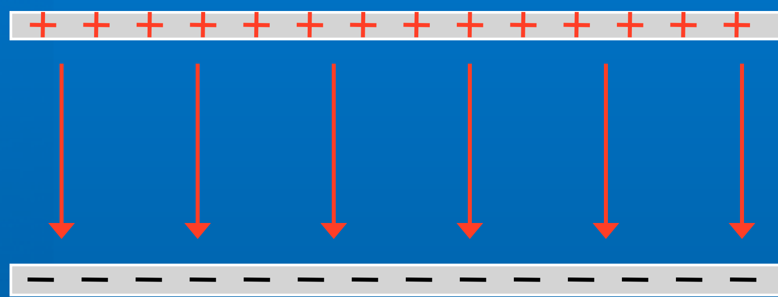


Change capacitance with material permittivity ε

Changes the electric field. $E = \frac{\sigma}{\varepsilon}$

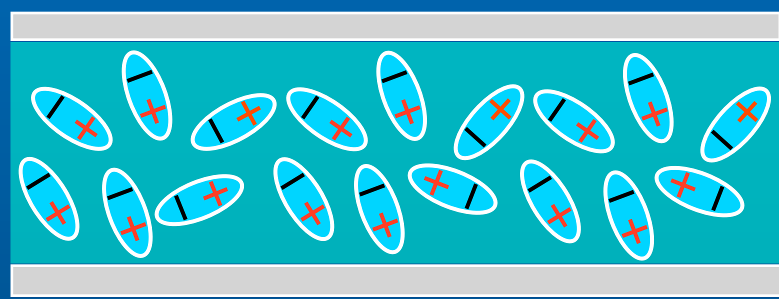
Polarization



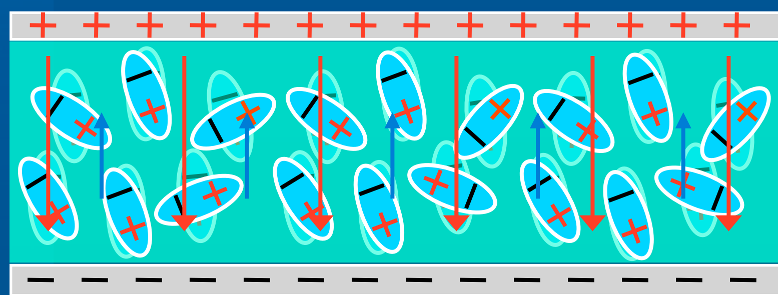


$$E = \frac{\sigma}{\varepsilon_0} = \frac{V}{d} \qquad C = \frac{\varepsilon_0 A}{d}$$

unpolarized



polarized



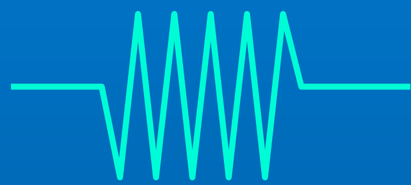
$$E_{eff} = E - E_{polarized} = \frac{\sigma}{k\varepsilon_0}$$

$$C = \frac{k\varepsilon_0 A}{d}$$

Polarization

$$F = qE$$

Resistor



Electrical Symbol

Intrinsic property $R = \rho \frac{l}{A}$ $\rho = resistivity$

Doped conductor with carbon or iron impeding electron flow causing dissipation of energy.

Energy loss $P = I^2 R = VI$

Mean power $P = \left(\frac{I_{max}}{\sqrt{2}}\right)^2 R = \frac{I_{max}{}^2 R}{2}$

Per unit cycle $P = \frac{I_{max}{}^2 R}{2} \times \frac{1}{f}$

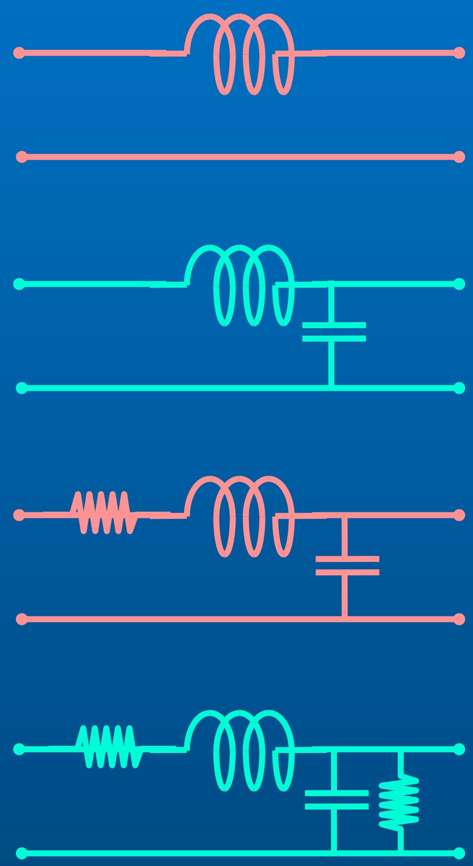
Conductor characteristics

Any conductor behaves as a small inductor (L)

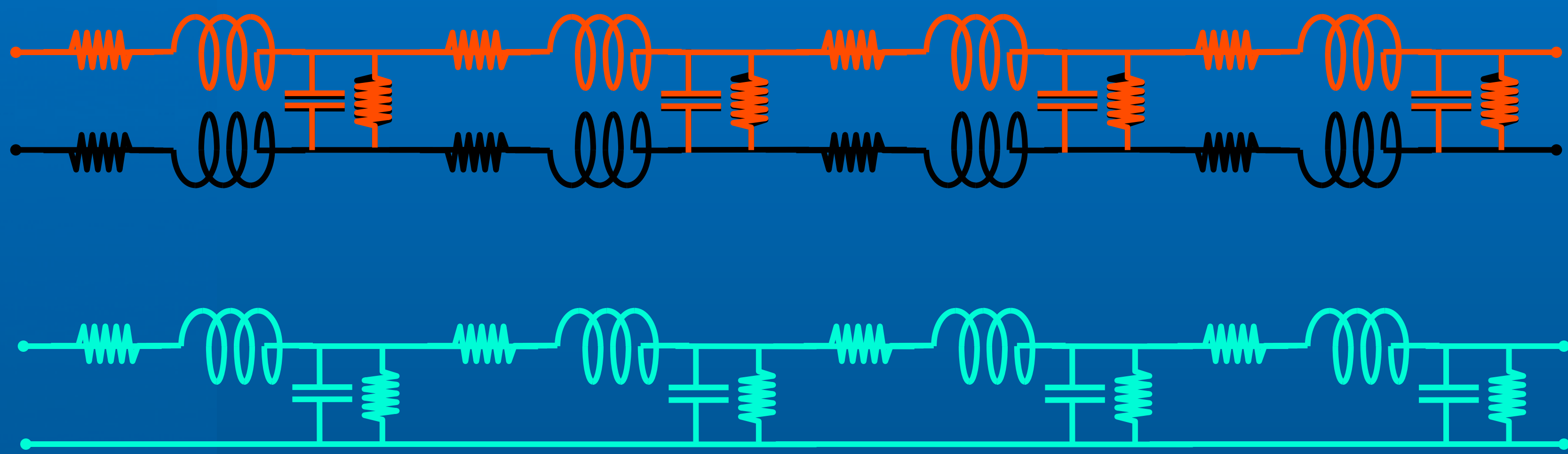
Has a small amount of distributed capacitance

It is not perfect, has small resistance (R)

It may have a some leakage, conductance (G)

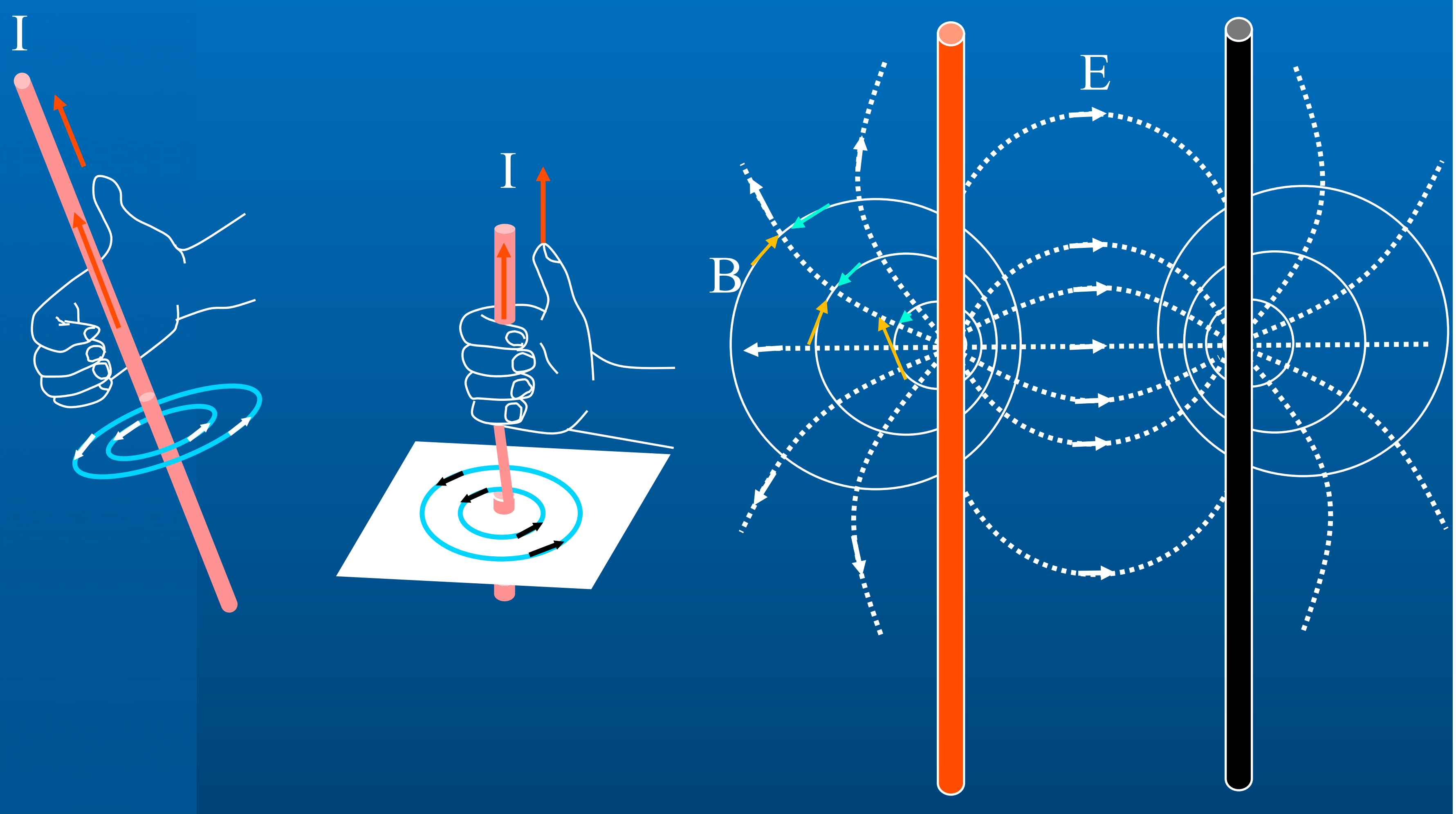


Conductor is a network

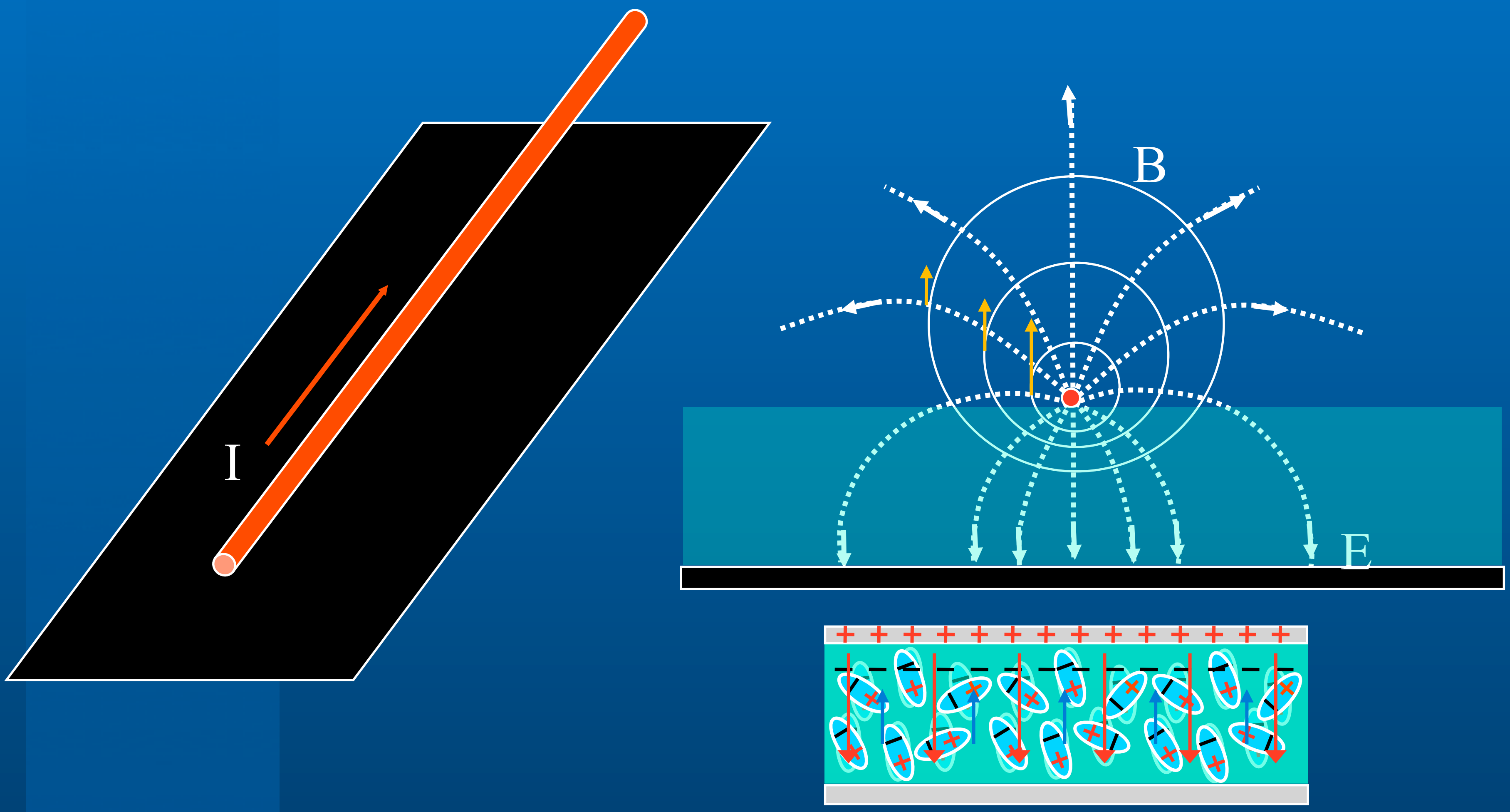


$$Z_0 = \frac{V}{I}$$

Conductors



Conductor next infinite g plate

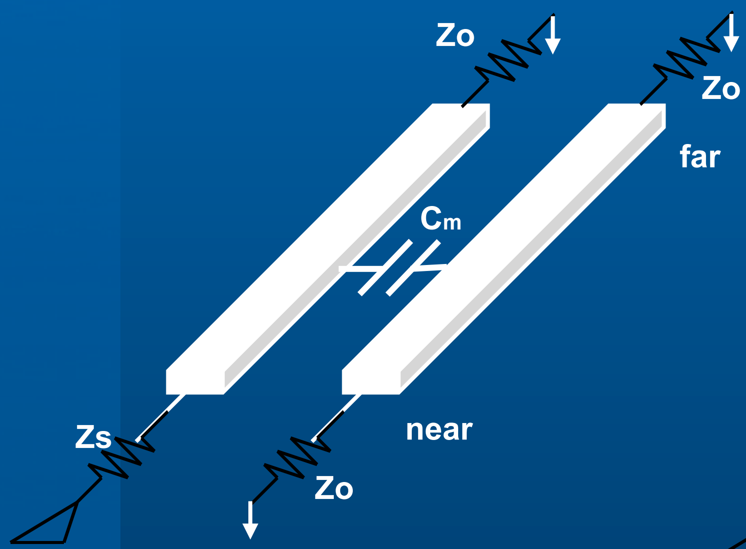


Mechanism of Cross Talk E and B

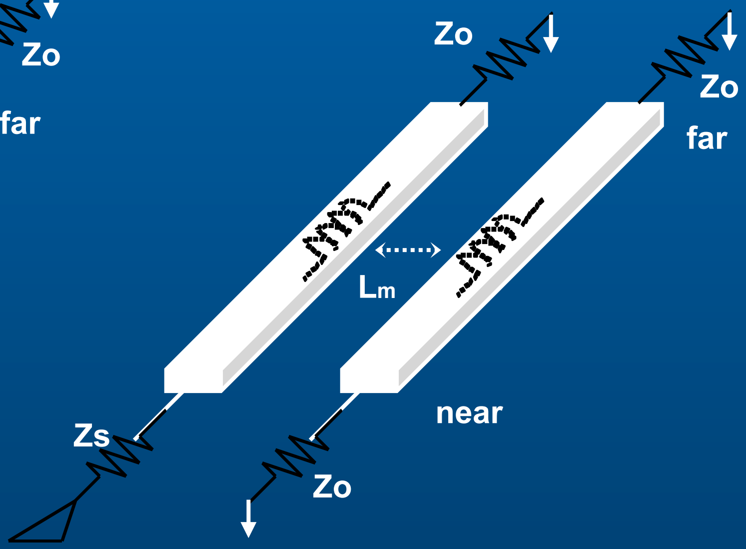
- Cross talk is the coupling of energy from one line to another via

- Mutual Capacitance (Electric Field)
- Mutual Inductance (Magnetic Field)

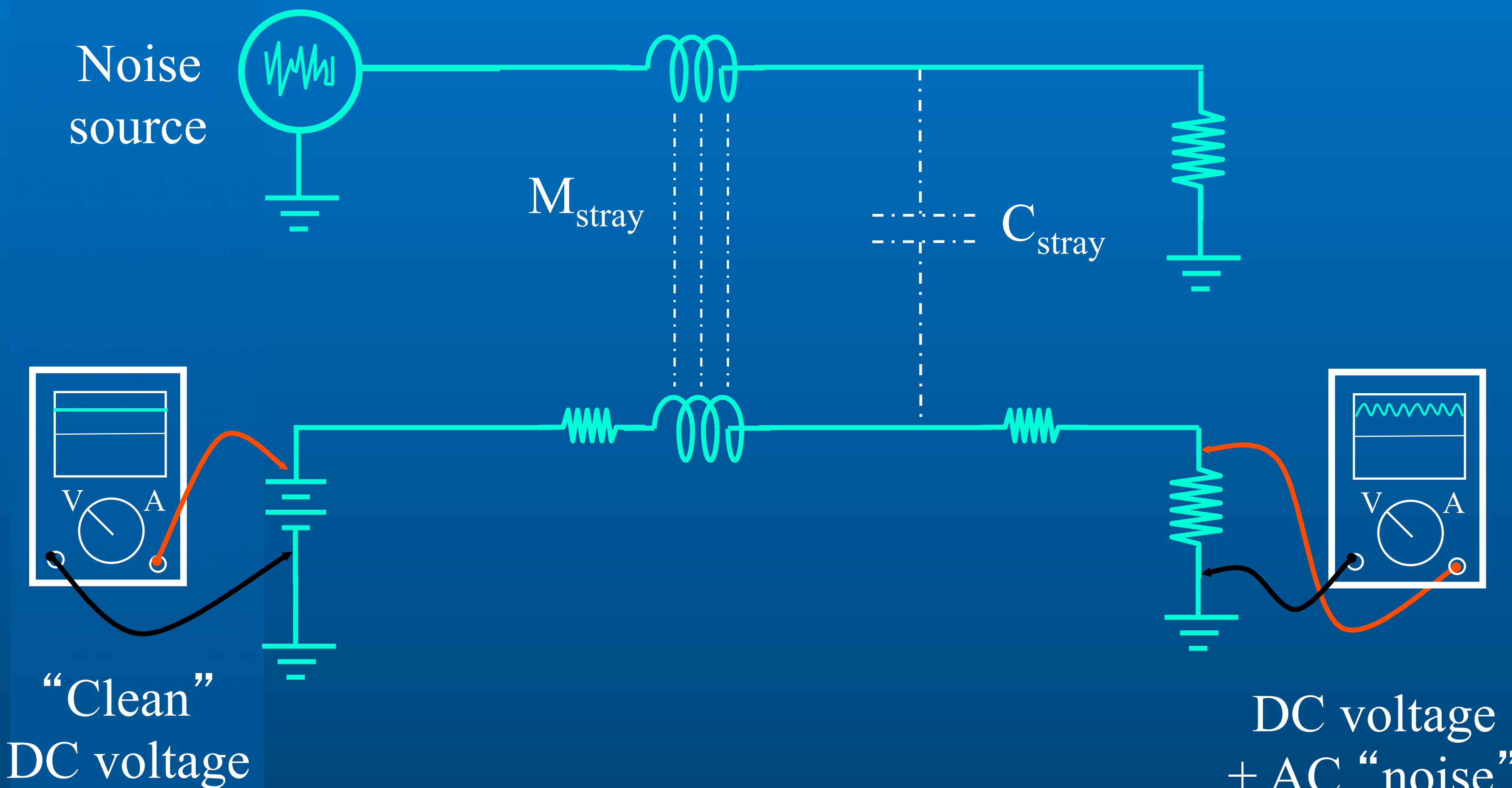
Mutual Capacitance, C_m



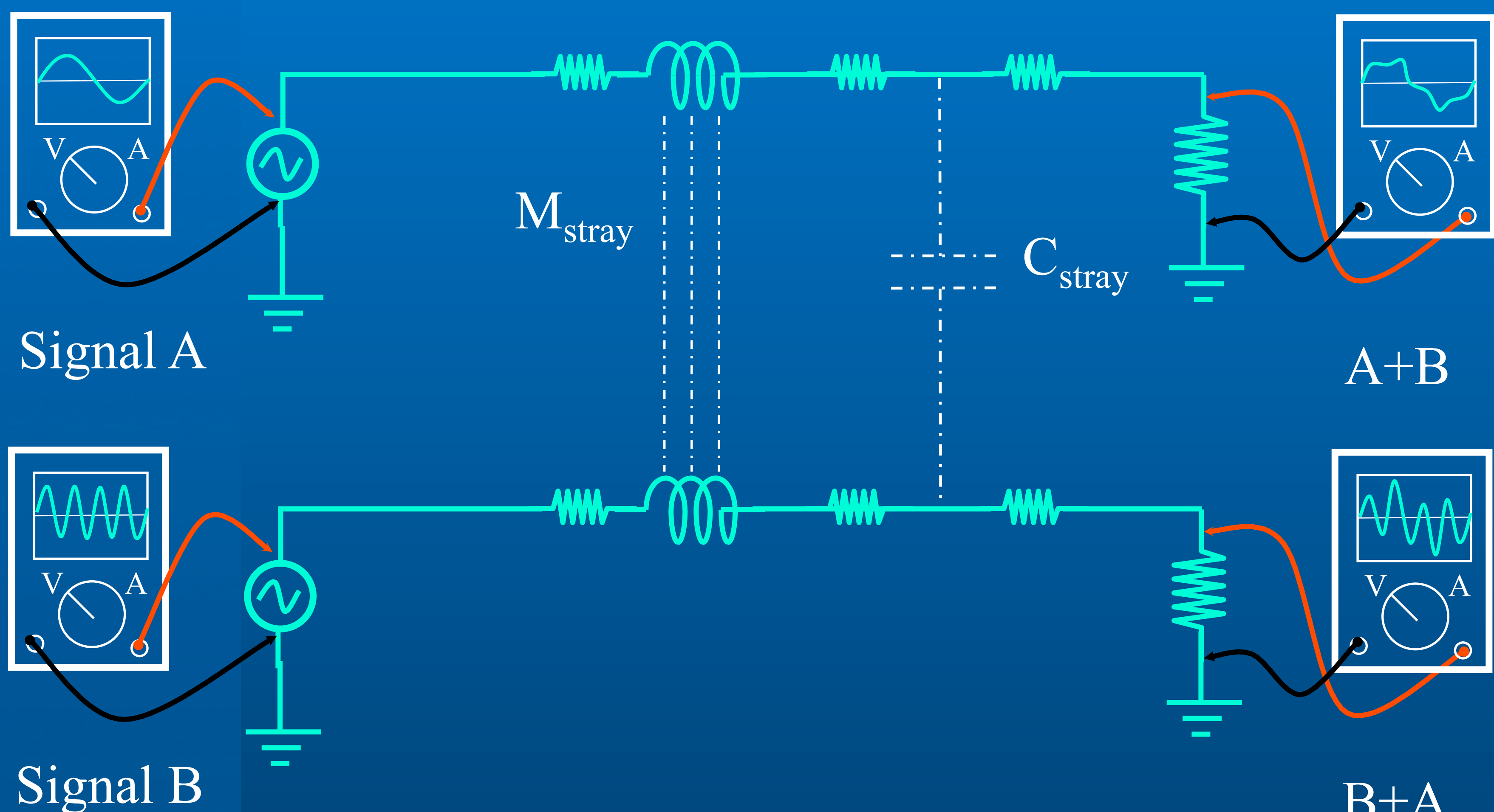
Mutual Inductance, L_m



Stray inductance and capacitance

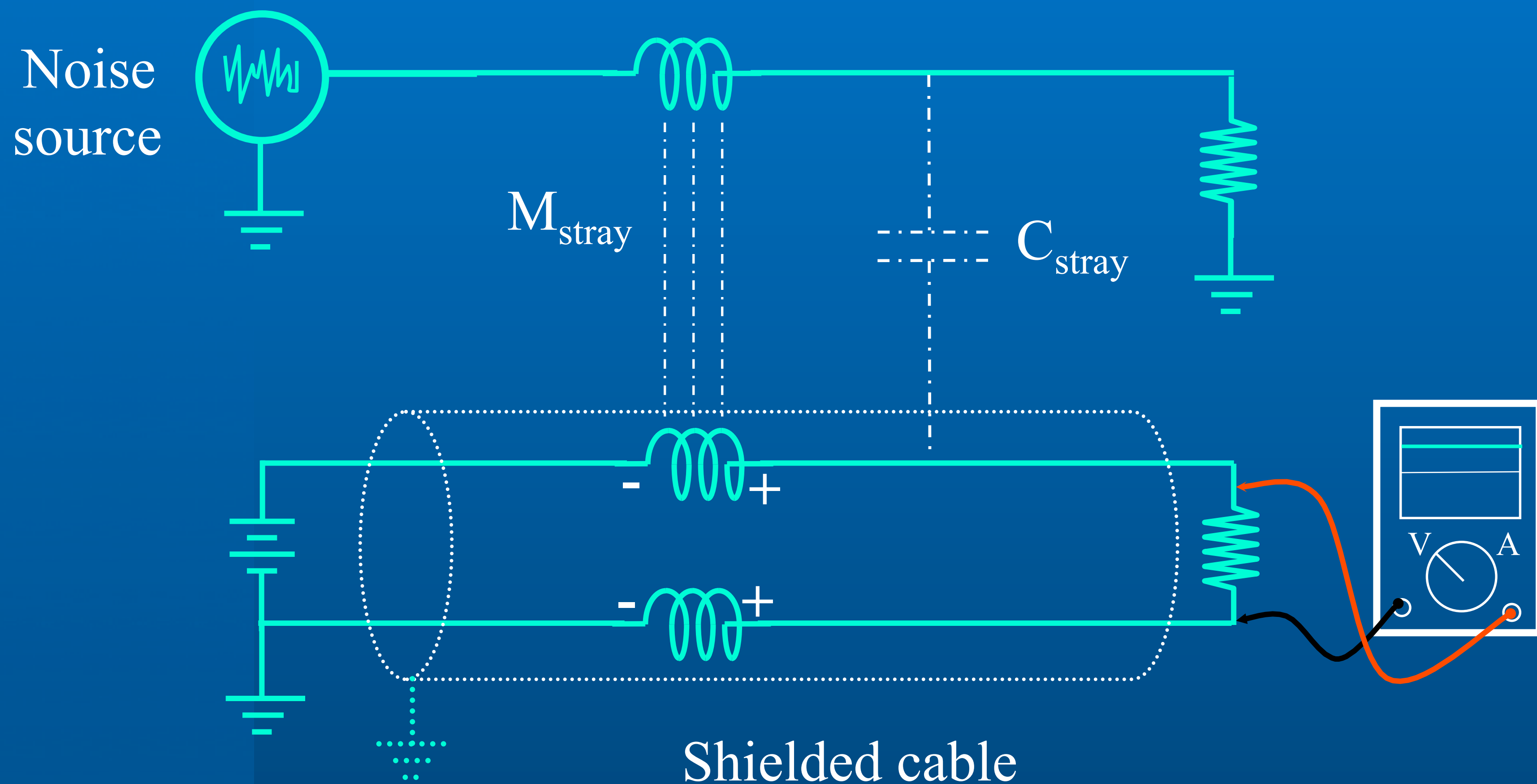


AC signal coupling

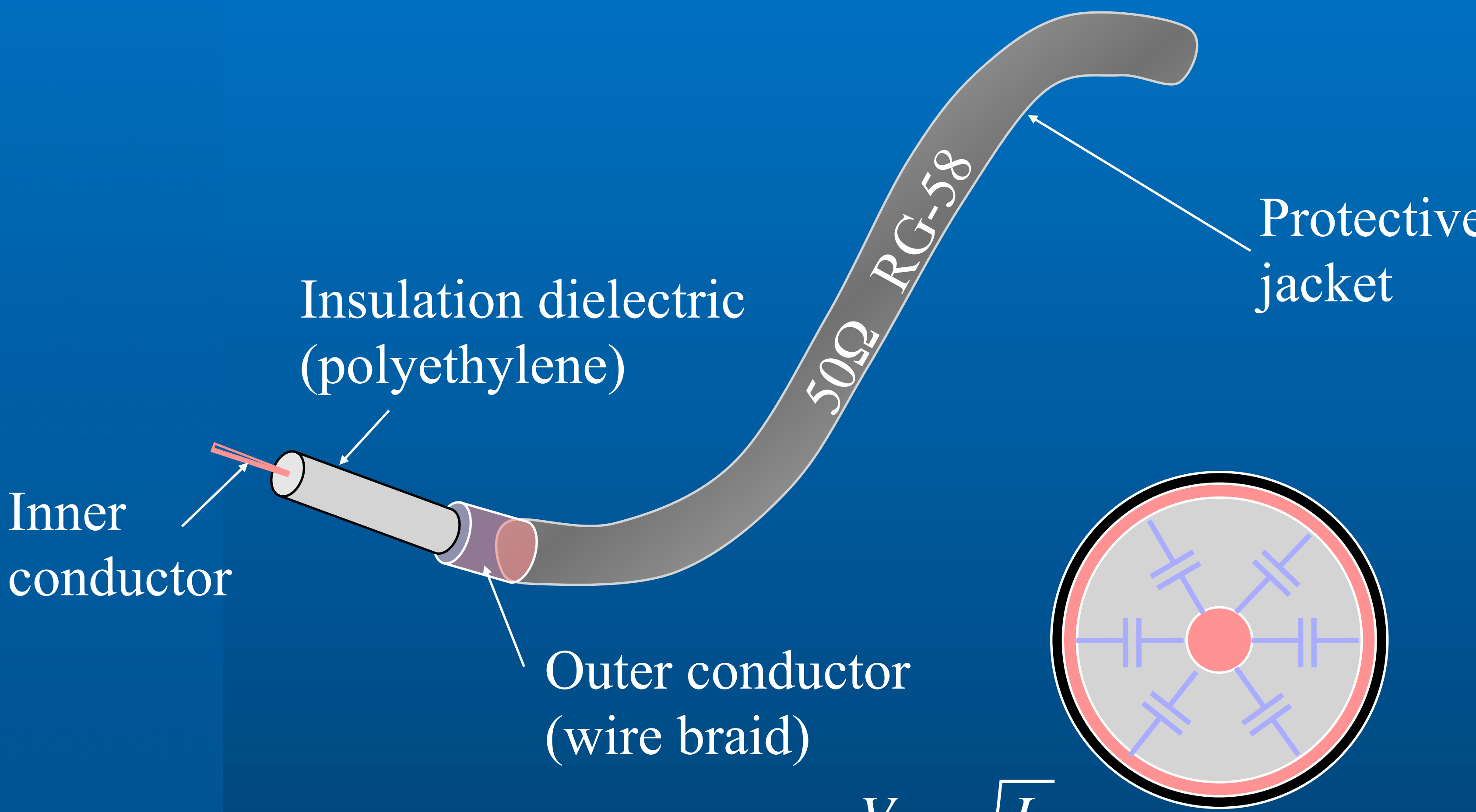


Usually accidental and undesired

Shield conductor

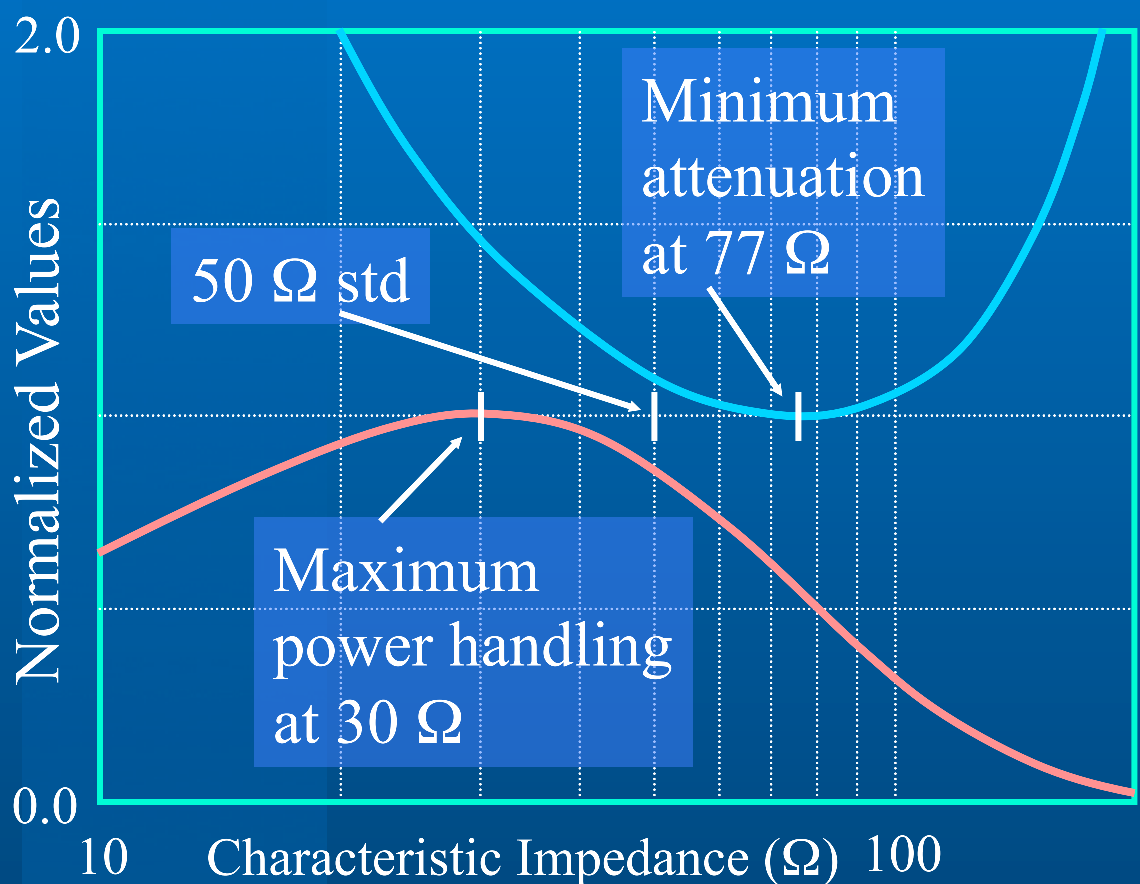


Coax is transmission line

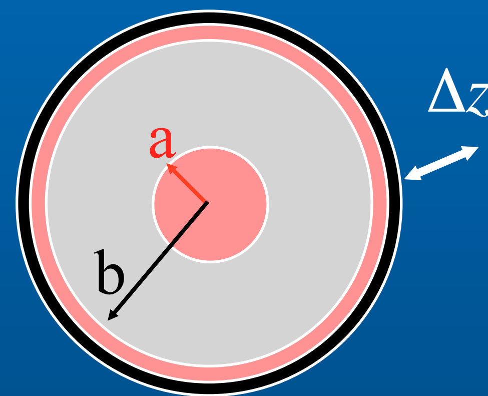


$$Z_0 = \frac{V}{I} = \sqrt{\frac{L}{C}}$$

Characteristic impedance Z=50Ω



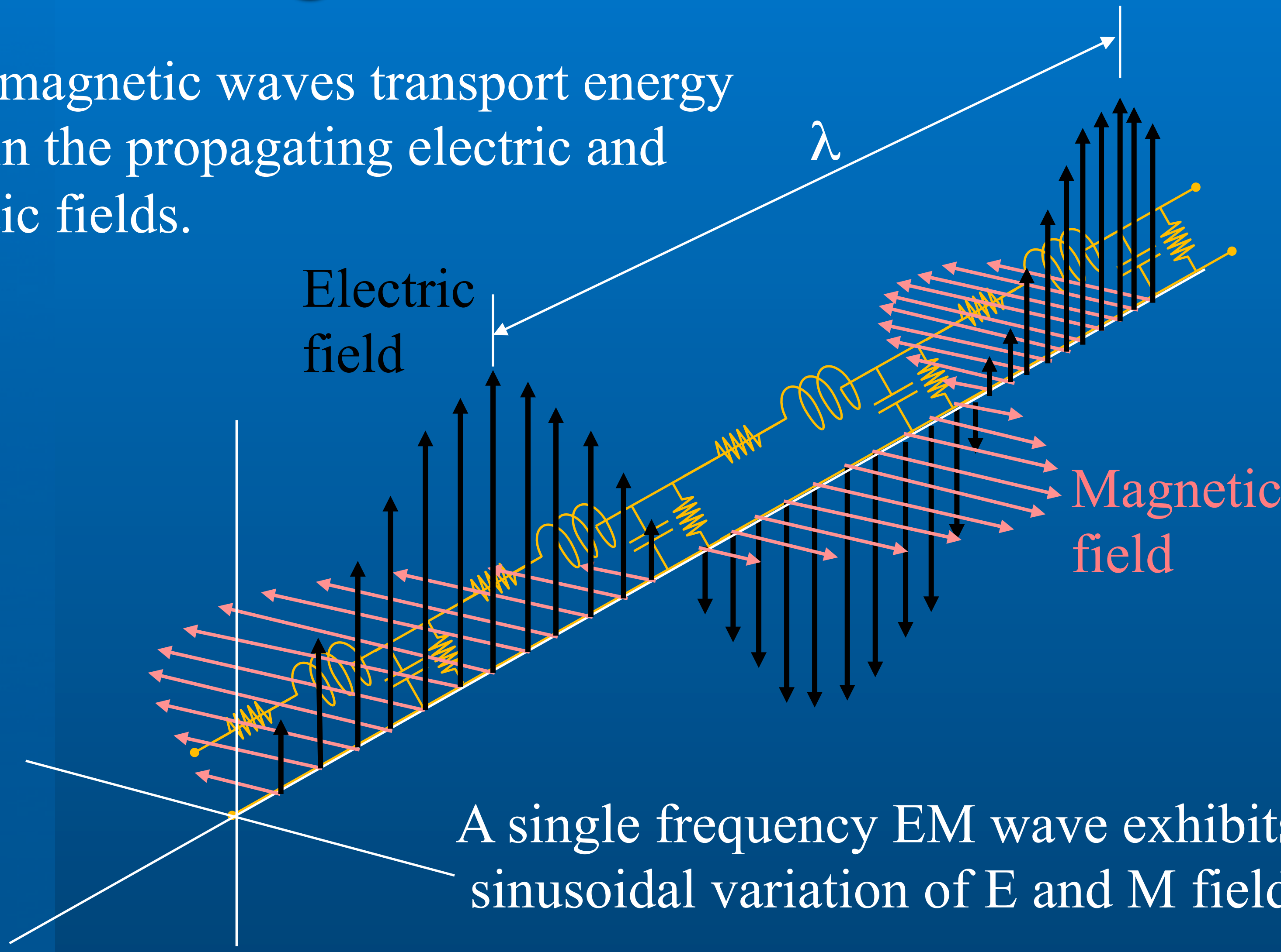
Optimum line dimensions for lowest attenuation and best power handling



$$L = \frac{\mu}{2\pi}\ln(b/a) \qquad C = \frac{2\pi\varepsilon}{\ln(b/a)} \qquad Z_0 = \sqrt{\frac{L}{C}} = \frac{\eta}{2\pi}\ln\left(\frac{b}{a}\right)$$

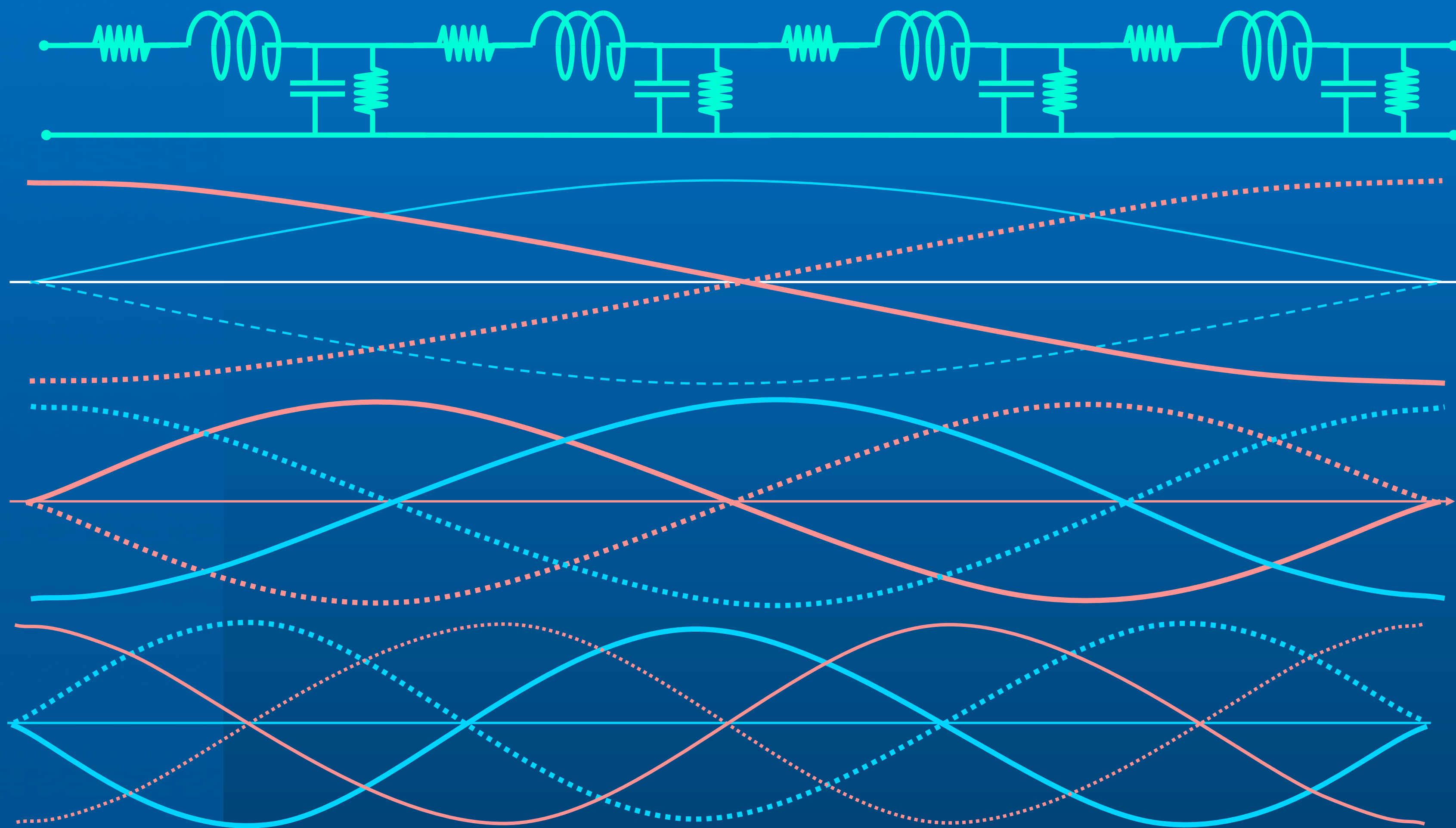
Electromagnetic waves

Electromagnetic waves transport energy stored in the propagating electric and magnetic fields.



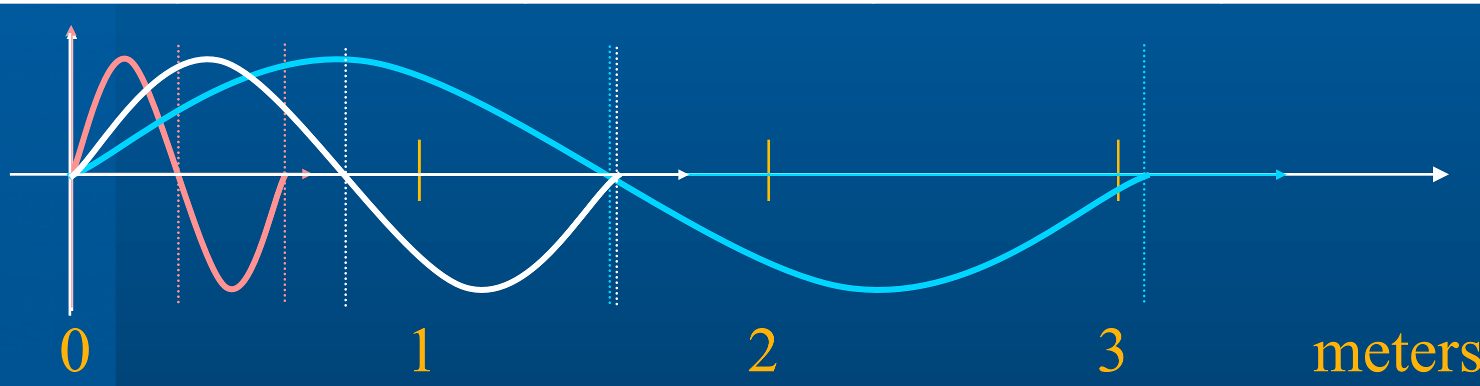
A single frequency EM wave exhibits sinusoidal variation of E and M fields.

RF standing waves in a conductor



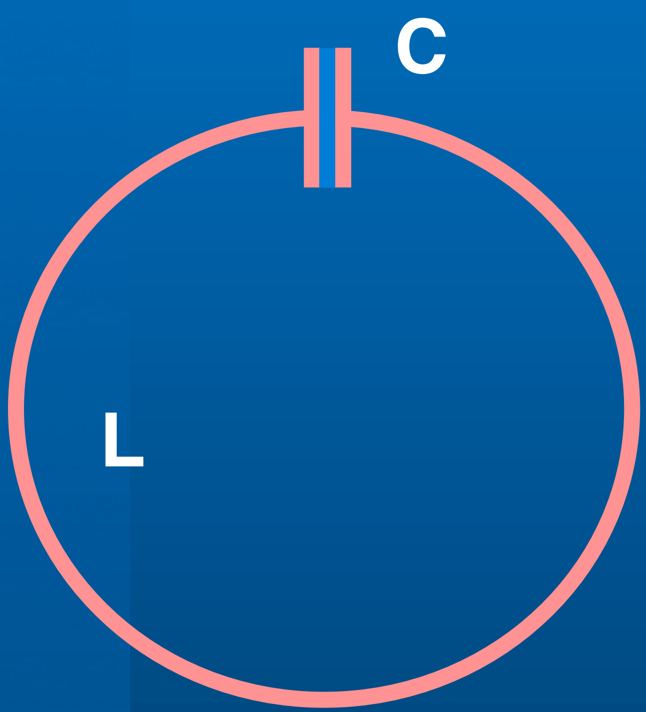
Wavelengths

Freq MHz	Vacuum λ meters	Coaxial λ	Coaxial λ/2	λ/10 cm
64	4.68	3.09	1.54	30.9
128	2.34	1.54	0.77	15.4
300	1.00	0.66	0.33	6.6



Velocity of propagation is decreased in conductors

So what do we use to measure EM fields?



The basic detection unit: a loop

Voltage Generation

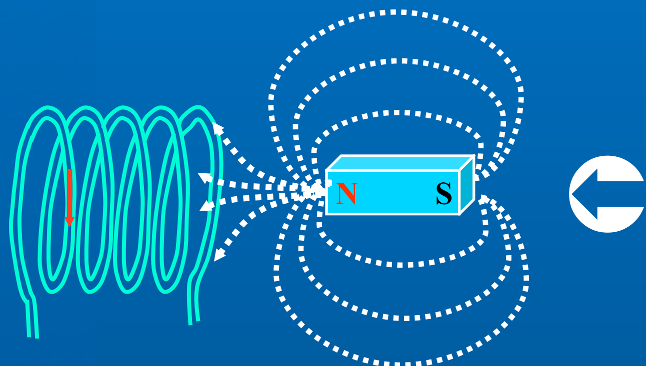
$$Voltage = -N\frac{\Delta(BA)}{\Delta t}$$

$\Delta B / \Delta t = 0.4T / s$

$A = 0.002m^2$

$N = 5$

Move magnet



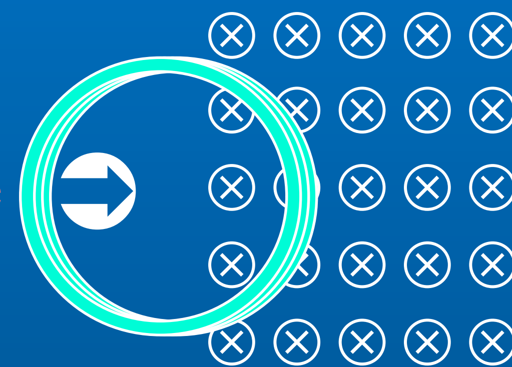
$$V_{gen} = -5 \times 0.002 \times 0.4 = -0.004V$$

$B = 0.2T$

$\Delta A / \Delta t = 0.2m^2 / s$

$N = 3$

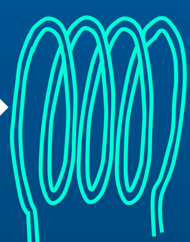
Change area



$$V_{gen} = -3 \times 0.2 \times 0.2 = -0.12V$$

Change magnetic flux constantly

$$\frac{\Delta(BA)}{\Delta t} = 4Tm^2 / s \Rightarrow$$



$N = 4$

$$V_{gen} = -16V$$

$$\frac{\Delta(BA)}{\Delta t} = 4Tm^2 / s \Rightarrow$$

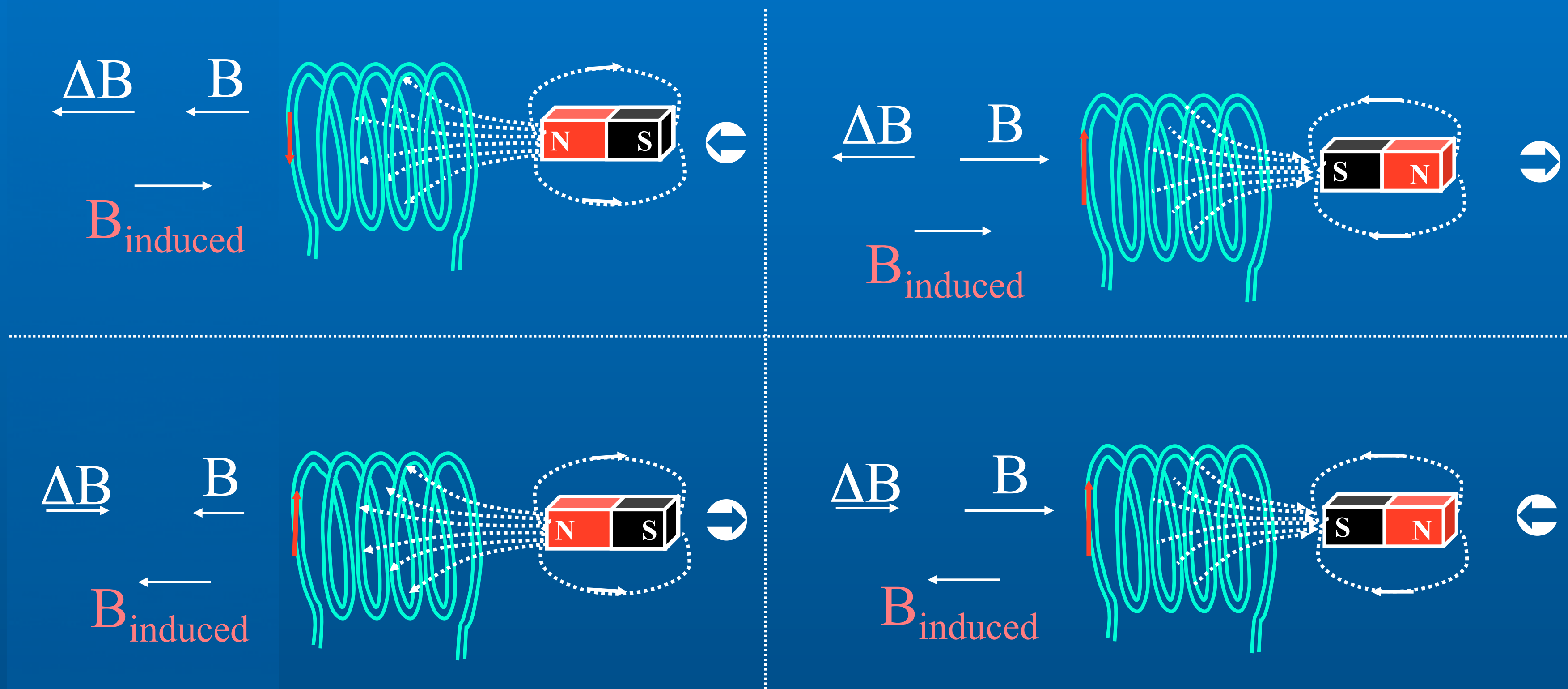
$N = 2$

$$V_{gen} = -8V$$

EMF is generated due to change in magnetic FLUX

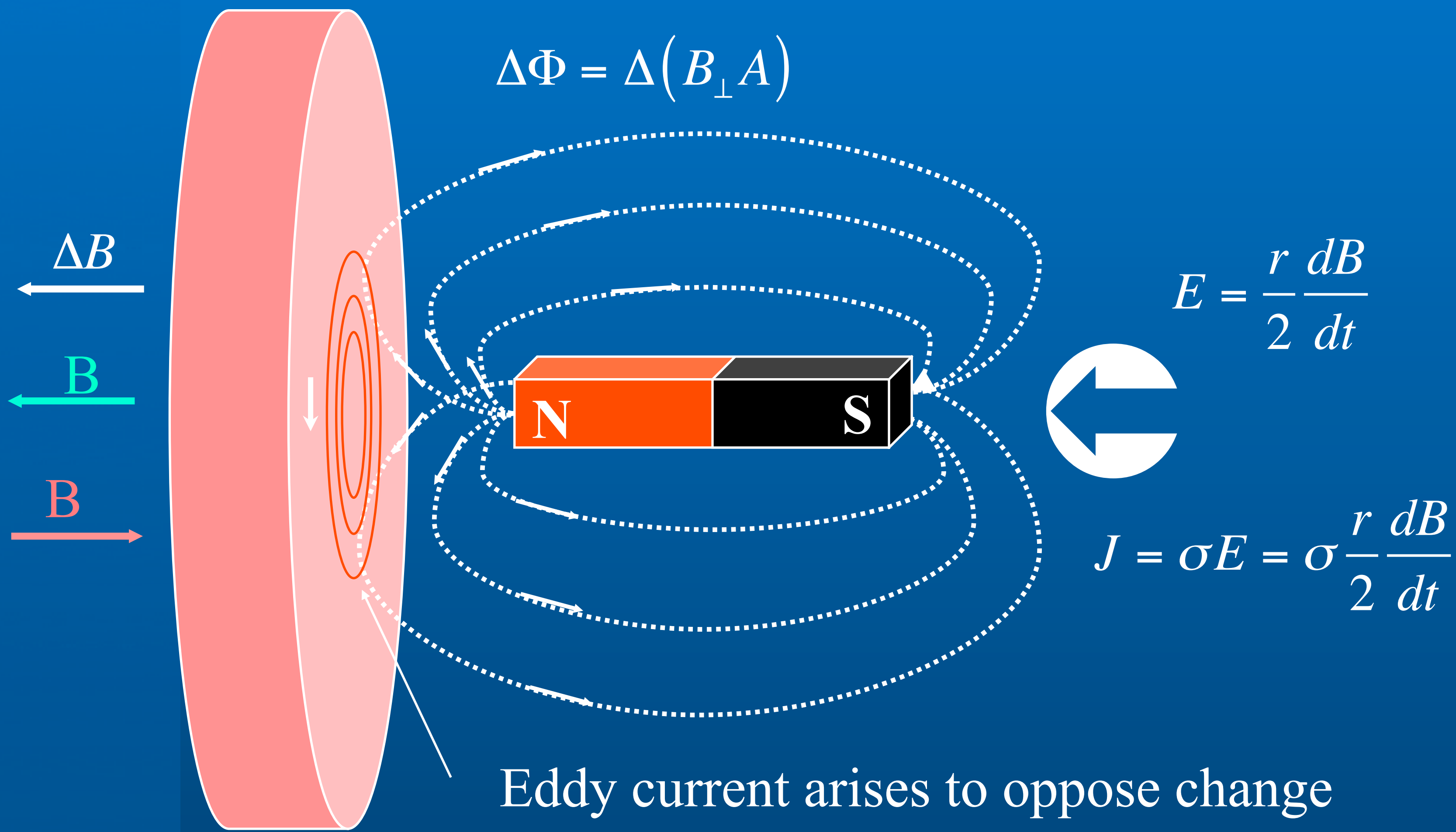
Excursion to EDDY currents

Field Induction



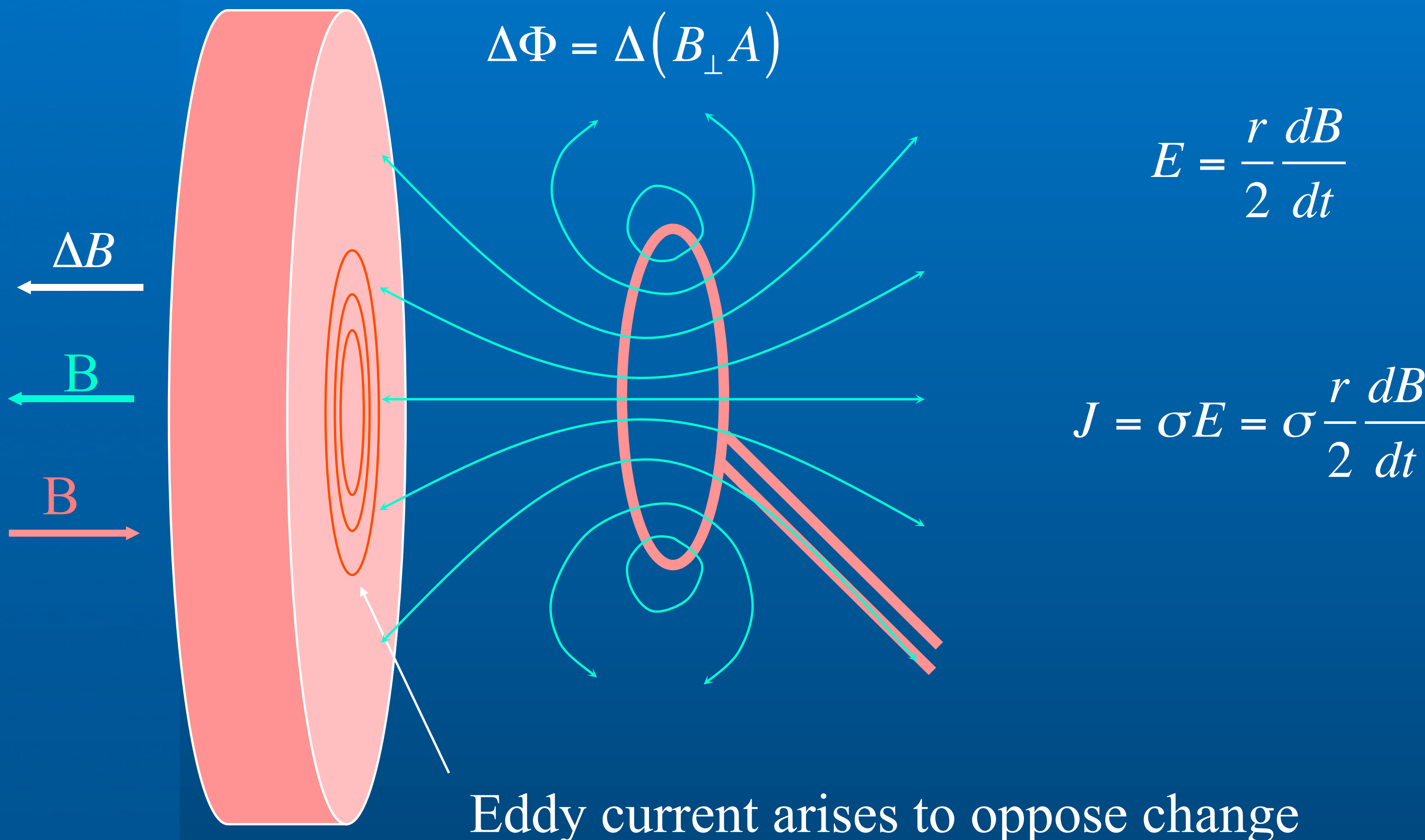
The induced magnetic field always acts to keep the magnetic flux in the loop constant (Lenz' Law).

Eddy currents due to flux change



Eddy current arises to oppose change

RF flux change: eddy currents



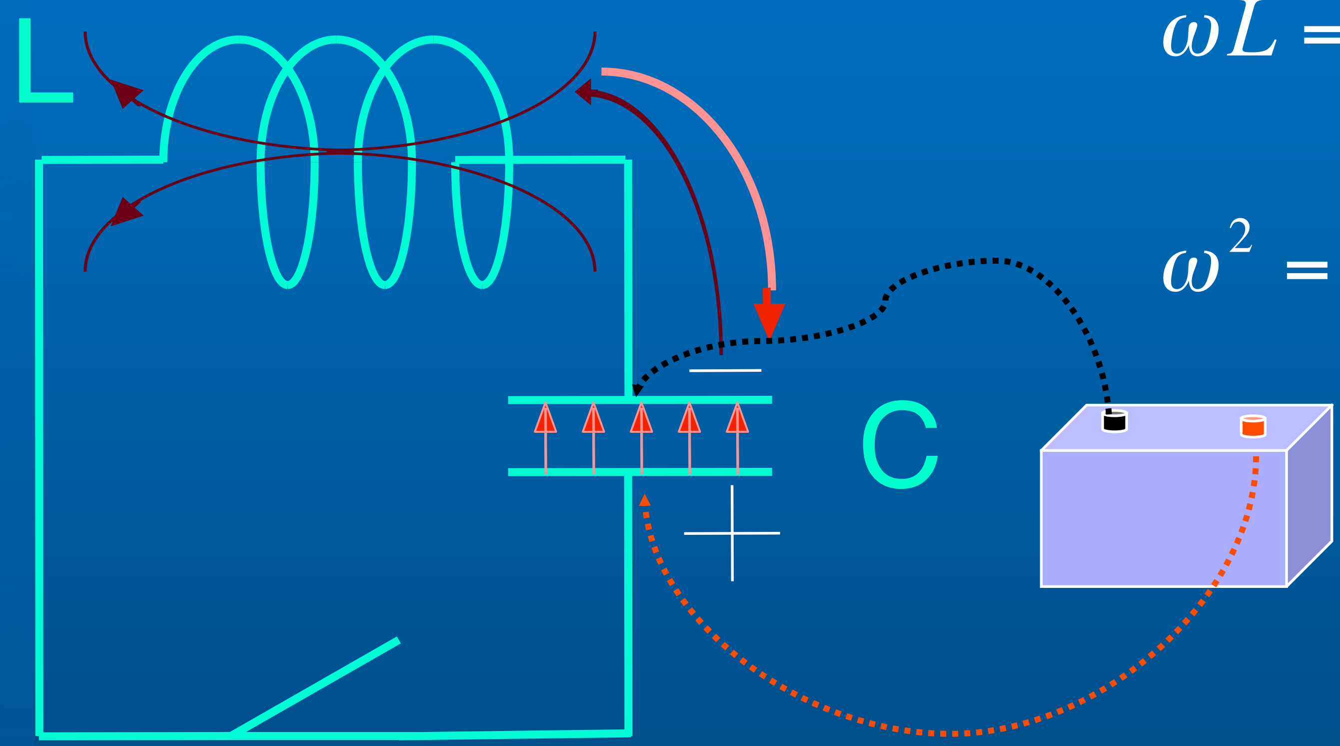
Eddy Currents

F=q(v x B)

Physics demo: NCSU

Back to our detection unit: the loop

Natural electrical oscillator



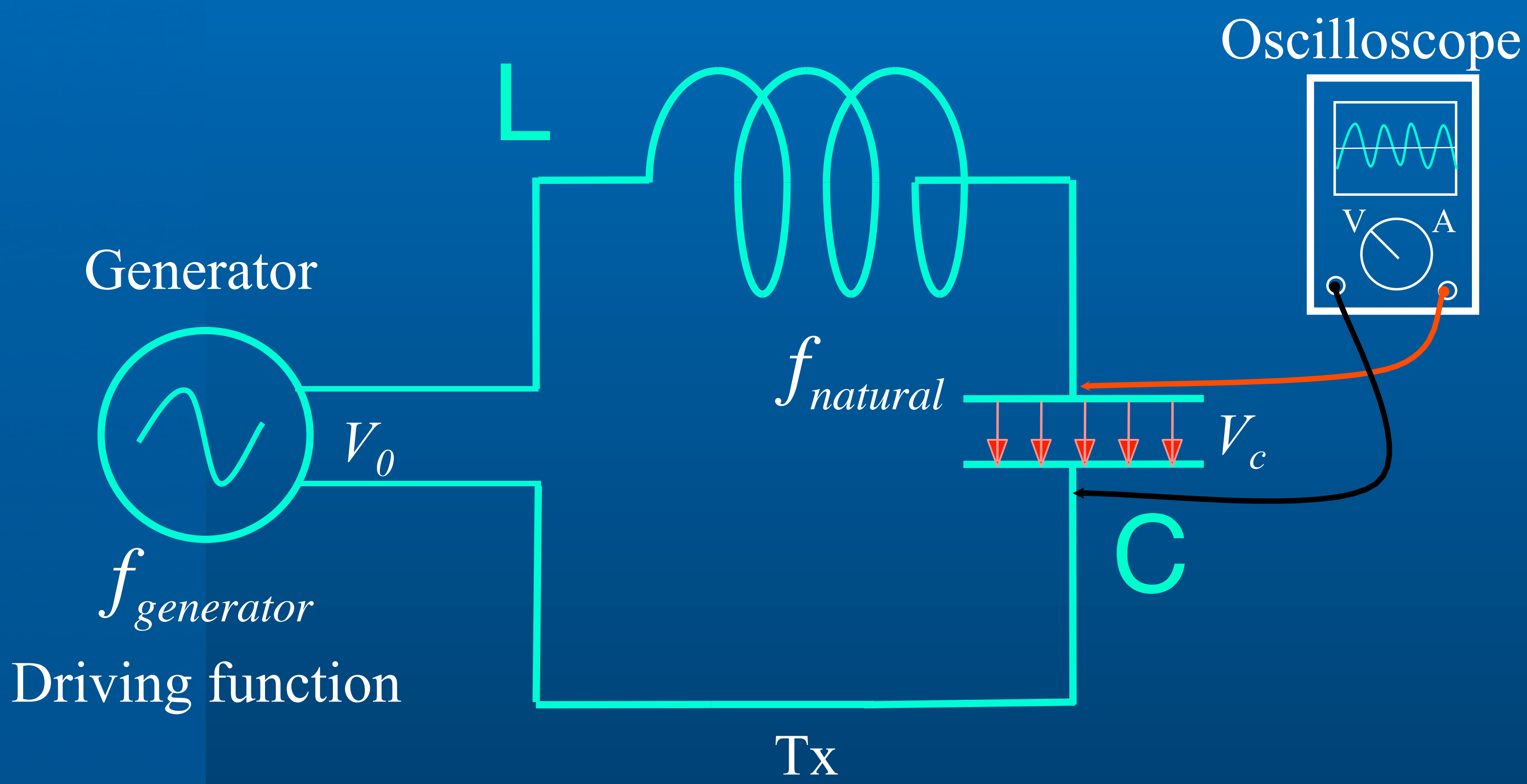
$$\omega L = \frac{1}{\omega C}$$

$$\omega^2 = \frac{1}{LC}$$

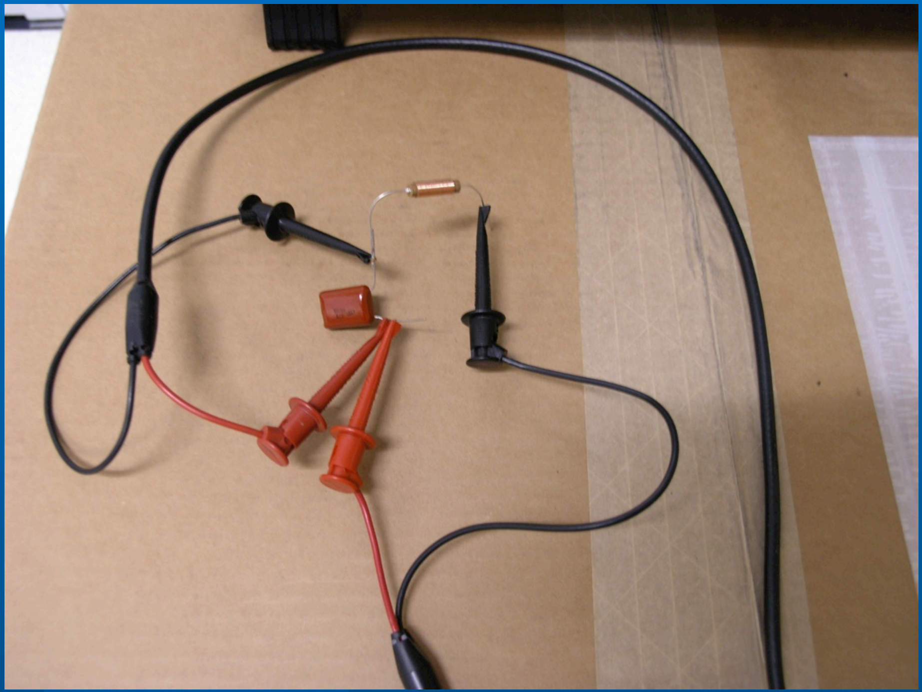
Natural Oscillation occurs at frequency $f_{natural} = \dfrac{1}{2\pi\sqrt{LC}}$

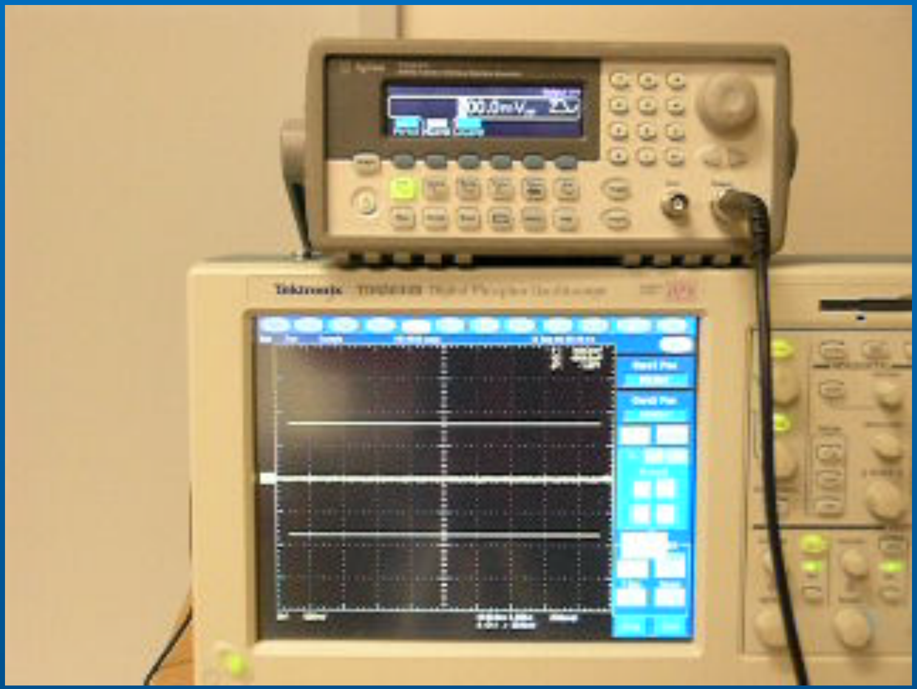
Resonance is a condition $f_{natural} = f_{generator}$

Resonance occurs when the generator exactly matches the natural frequency of oscillation of the LC circuit



Observing LC resonance and Q

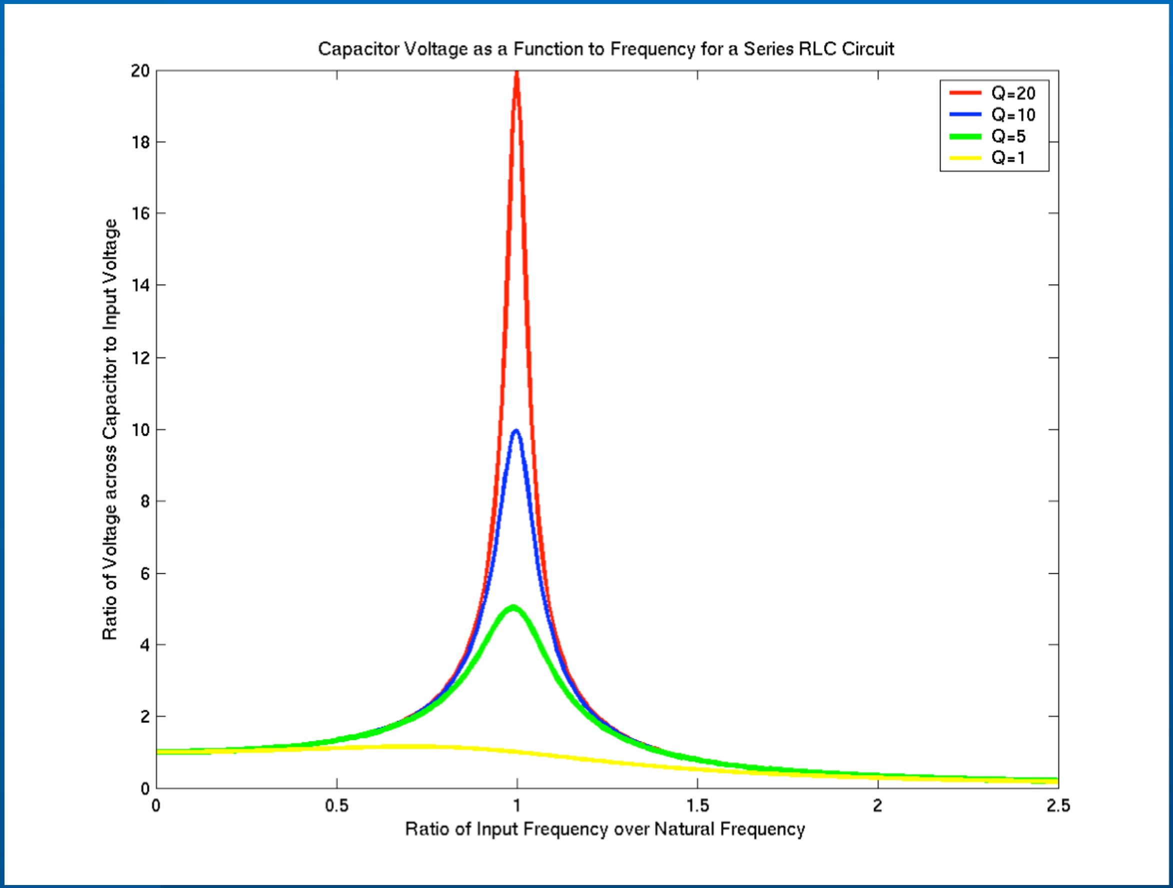




$$V_0 = 0.5V \qquad Vc = 2V$$

Q measures amplification

At the resonant condition a LC circuit is an AMPLIFIER and is SELECTIVE on the frequencies it amplifies.



$$Q \equiv \frac{1}{R}\sqrt{\frac{L}{C}}$$

$$Q \equiv \frac{V_c(\omega)}{V_0}$$

More than a single loop

Coupled inductors

Coupling is quantified by property called mutual inductance

$$\Phi_{1\to 2} = M_{2\to 1} I_1$$

$$\Phi_{1\to 2} = \Phi_{2\to 1}$$

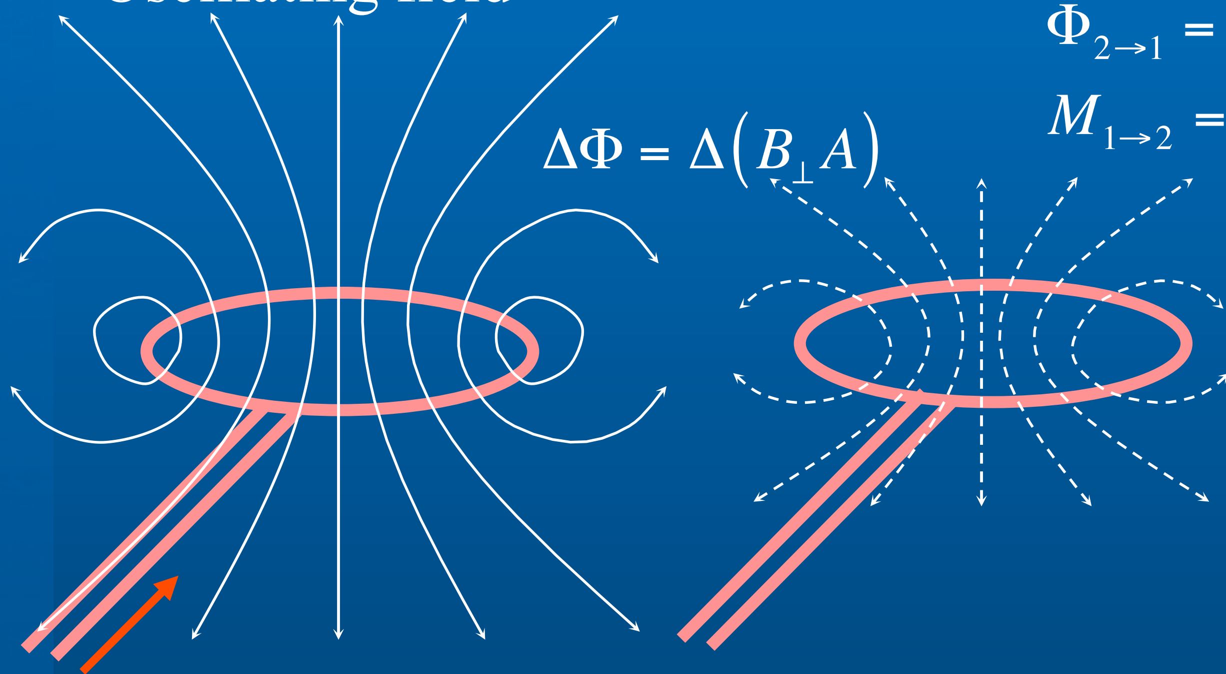
$$\Phi_{2\to 1} = M_{1\to 2} I_2$$

$$M_{1\to 2} = M_{2\to 1} = M$$

Oscillating field $= \Delta\Phi$

$$\Delta\Phi = \Delta\left(B_{\perp} A\right)$$

Coil #1

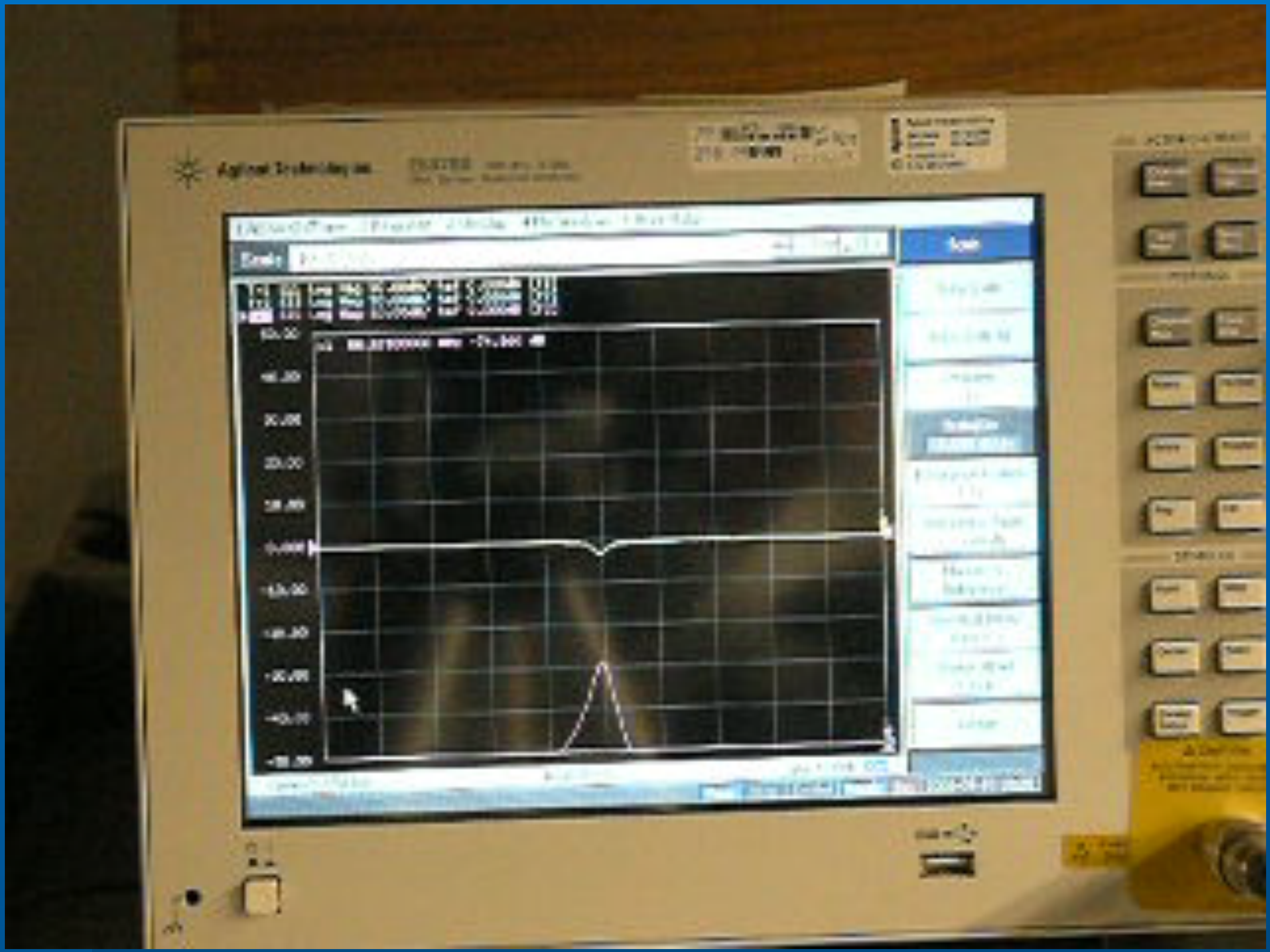


Coil #2

Change in flux in #1 induces an emf in #2

$$V_{2\to 1} = -\frac{\Delta\Phi_{2\to 1}}{\Delta t} = -M_{1\to 2}\frac{dI}{dt}$$

Mutual inductance



Magnetic coupling cross-talk

Coefficient of coupling

$$k = \frac{M}{\sqrt{L_1 L_2}} = \frac{\omega M}{\sqrt{X_1 X_2}}$$

k > 0.5 close-coupled

k < 0.5 loosely-coupled

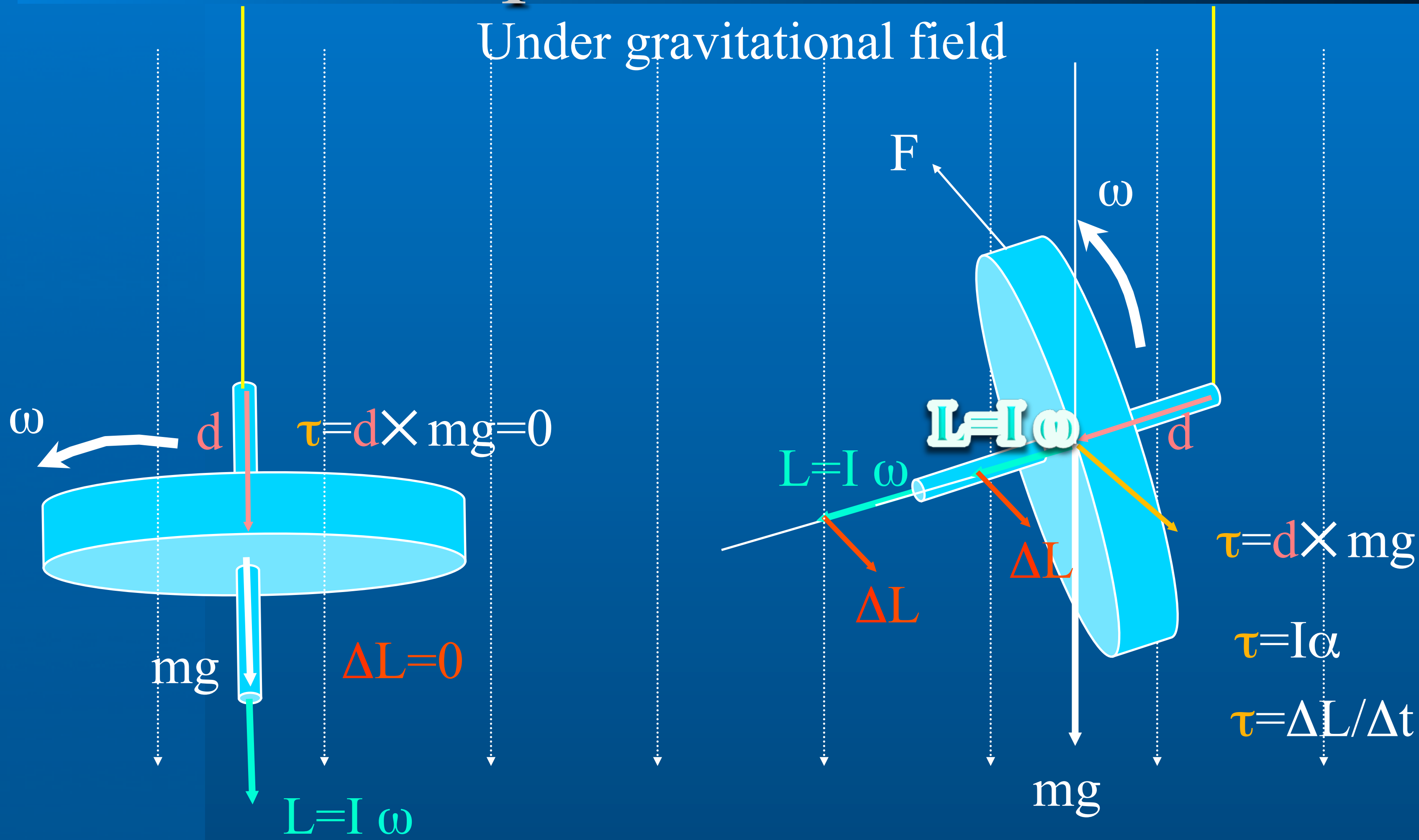
Where does nuclear magnetic resonance come from?

1st there is PRECESSION a natural oscillation when matter is immersed in a constant magnetic field

2nd We match that natural oscillation with and RF field at exactly the same frequency of precession; thus we meet the condition for resonance

Mechanical precession

Under gravitational field

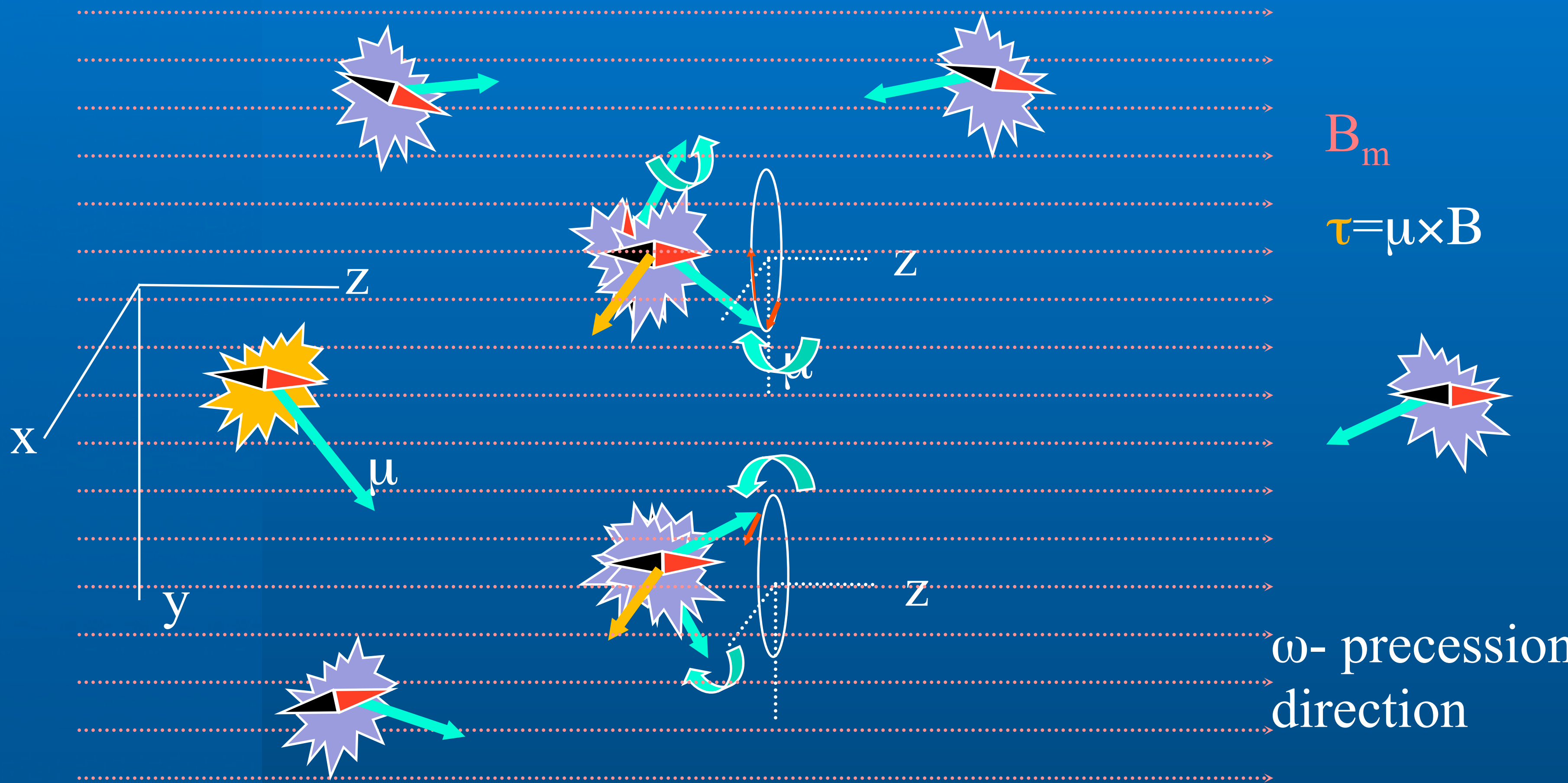


Torque is perpendicular to angular momentum.
So, the change ΔL is perpendicular to L

ω- precession direction

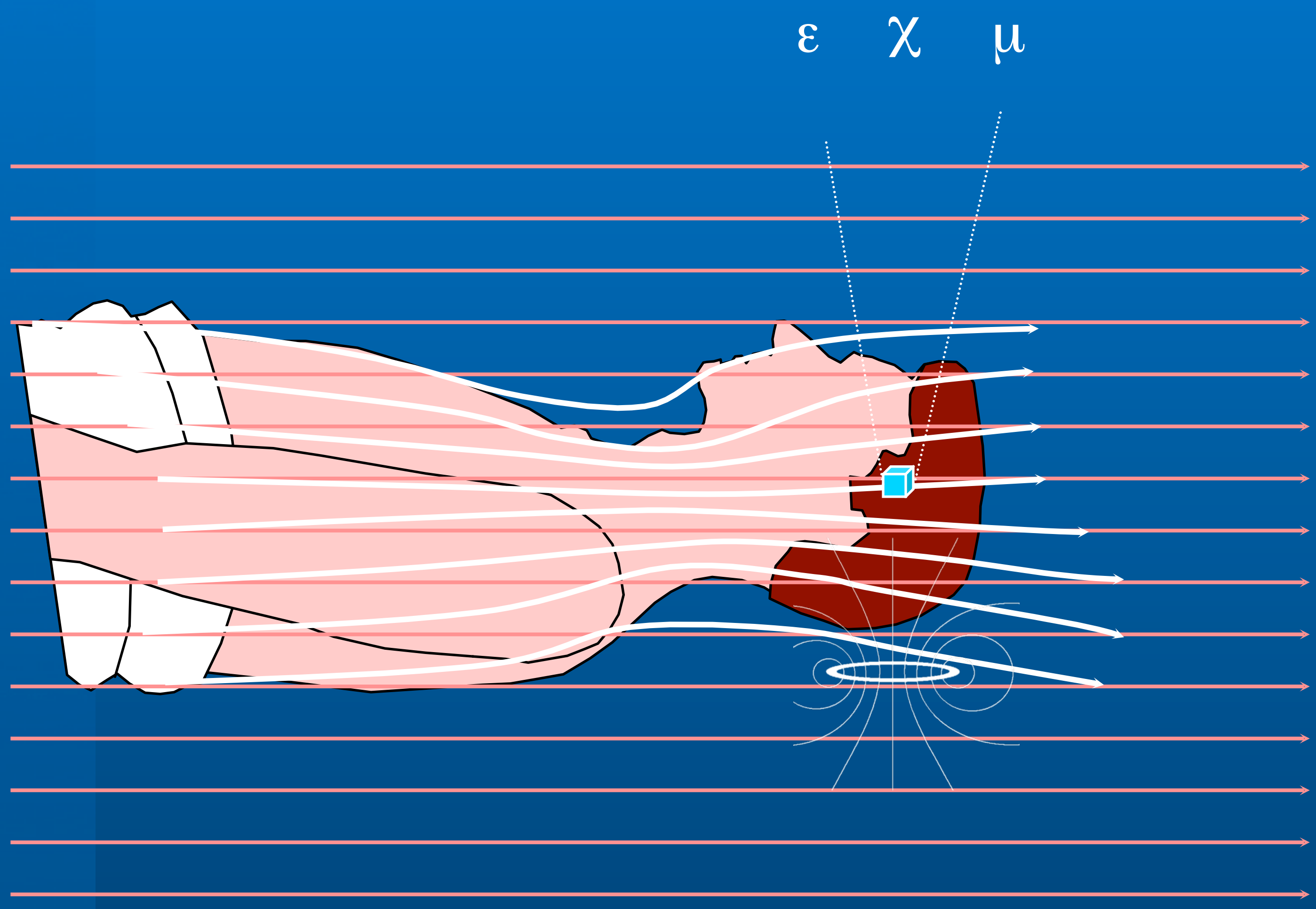
Precession

Momentum, B, τ ⇨ precession



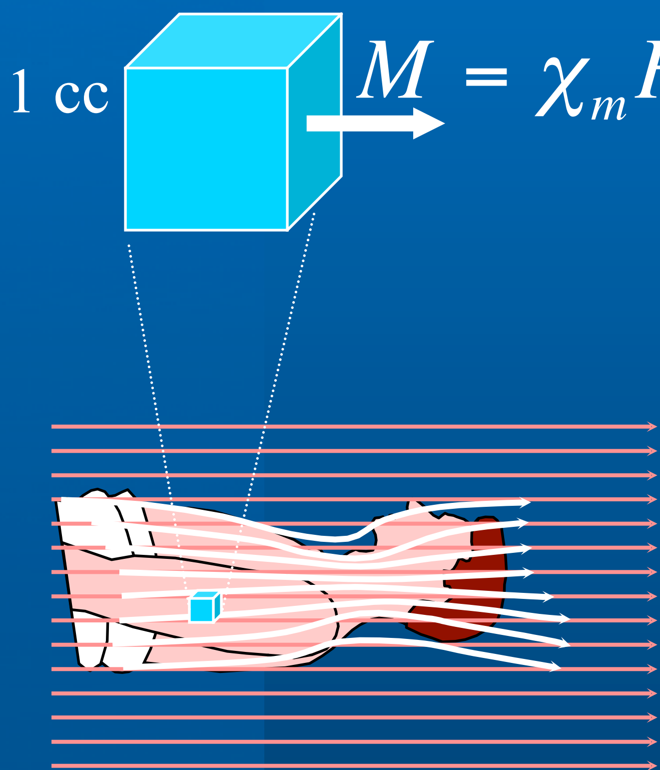
Torque is perpendicular to angular momentum.
So, the change ΔL is perpendicular to L

Body inside static Magnetic field



Body gets magnetized

How big is this MACROSCOPIC bulk magnetization M?
If H=10000 gauss=1T at standard conditions T=291K



$$M = \chi_m H$$

$$\chi_m = \frac{(j+1)}{3j}\left(\frac{N\mu^2}{kT}\right) \quad j = \frac{1}{2}$$

$N=6.7\times10^{22}$ hydrogen-atoms/1cc

$$\mu = 1.4 \times 10^{-23} c.g.s.$$

$$k = 1.38 \times 10^{-16} erg / \mathrm{deg}$$

$$\chi = 3.4 \times 10^{-10}$$

$$M = 3.4 \times 10^{-6} gauss$$

Nuclear Induction: F.Block 1946

Nuclear induction of $M = 3.4 \times 10^{-6} gauss$?

Probably not. But what we are measuring is the Nuclear induction B=4πM.

The flux thru N turns of a receiver of a sample of cross sectional area A is:

$$\Phi = NA \frac{\Delta B}{\Delta t}$$

$$V = -N \frac{\Delta\Phi}{\Delta t} = -NA \frac{d(B)}{dt} = \pm NA 4\pi M \omega \cos \omega t$$

With N=10 turns, A=area of 1cc sample and $\omega = 2.66 \times 10^8$:

$$V = \pm 10 \times 10^{-4} \times 4\pi \times 3.4 \times 10^{-10} \times 2.66 \times 10^8$$

$$\boxed{V = 1.1 \times 10^{-3} Volts}$$

This is for: $N = 6.7 \times 10^{22}$ hydrogen-atoms !

RF Receive Chain

So we can observe a signal

Now we are ready to look at the receiver chain