DEPARTMENT OF
ELECTRICAL &
COMPUTER ENGINEERING

ENEE381

Instructor: T. M. Antonsen Jr.antonsen@umd.edu

Course Outline

Topic	Textbook Sections
Review of EM fields	
Magnetic induction	7.1, 7.2
Displacement current	7.3
Maxwell's equations	7.3
Constituative relations	7.3
Boundary condition	7.3
Conservation Laws	
Charge	8.1
Energy	8.1
Momentum	8.2

Topic	Textbook Sections
Plane wave solution of Maxwell's equations	
Waves in 1D	9.1
Sinusoidal fields/phasors	9.1
Electromagnetic waves	9.2
Power flow	9.2
Boundary conditions	9.2
Waves in media	9.3
Waves incident on discontinuities	9.3
Dispersion and absorption	9.4

Course Outline (2)

Guided Waves

Modes and Cut-off frequencies	9.5
Planar waveguides	9.5
Hollow rectangular wave guides	9.5
Dielectric wave guides	9.5

Relation between field and circuit theory (Supplemental)

Transmission lines (Supplemental

Wave Equation
Reflection of waves
Pulses and transients
Reflection of sinusoidal waves
Standing waves
Smith Chart
Dispersive Lines
Networks

Resonators (Supplemental)

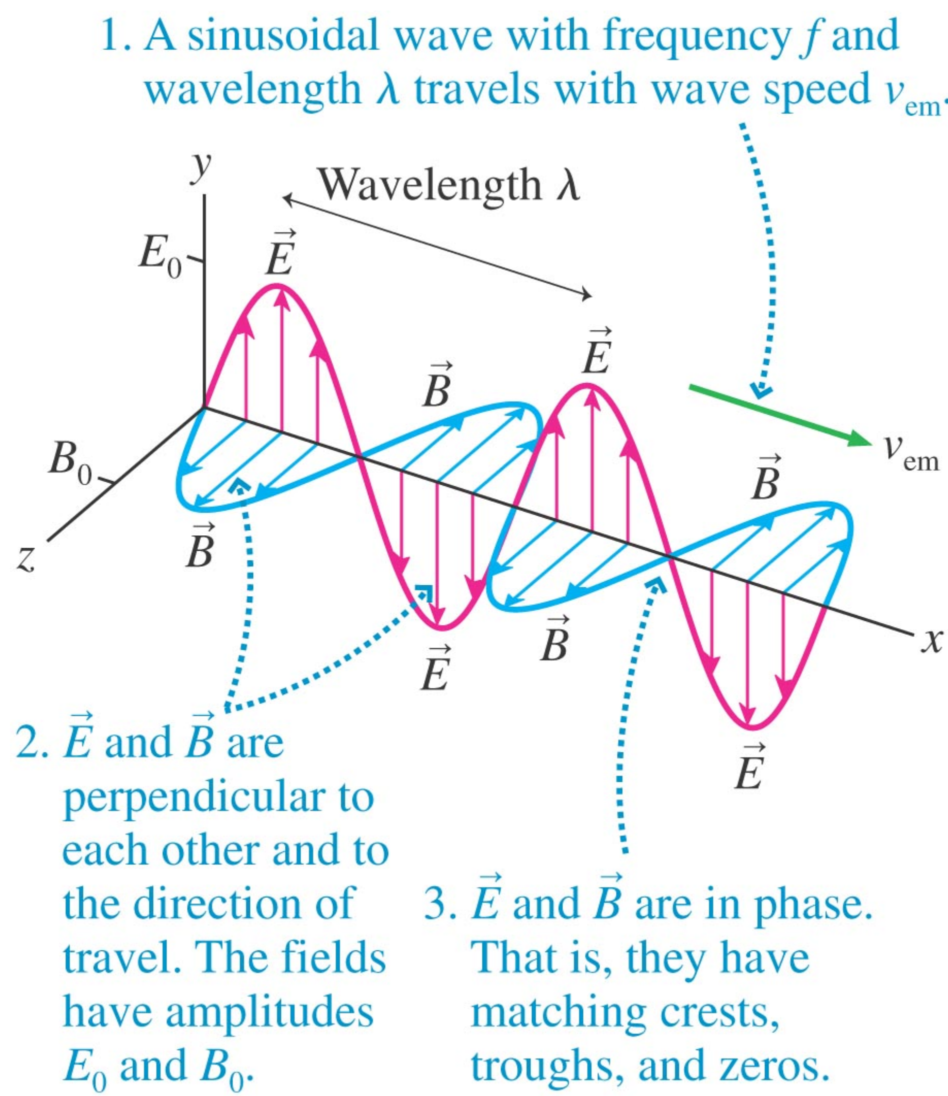
Radiation

Potentials and fields	10.1, 10.2
Basics	11.1
Dipole antennas	11.1
Radiation from fixed currents	11.1
Radiation be moving charges	11.2

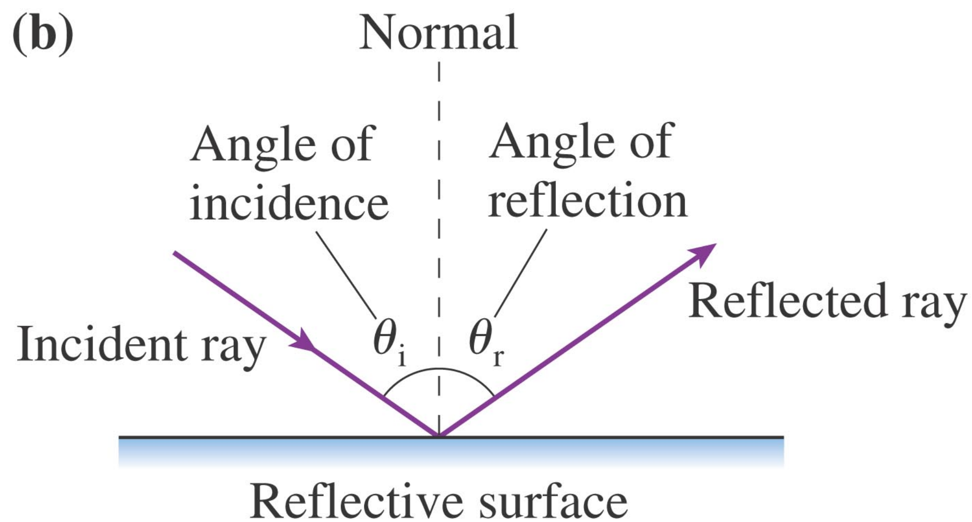
Overview

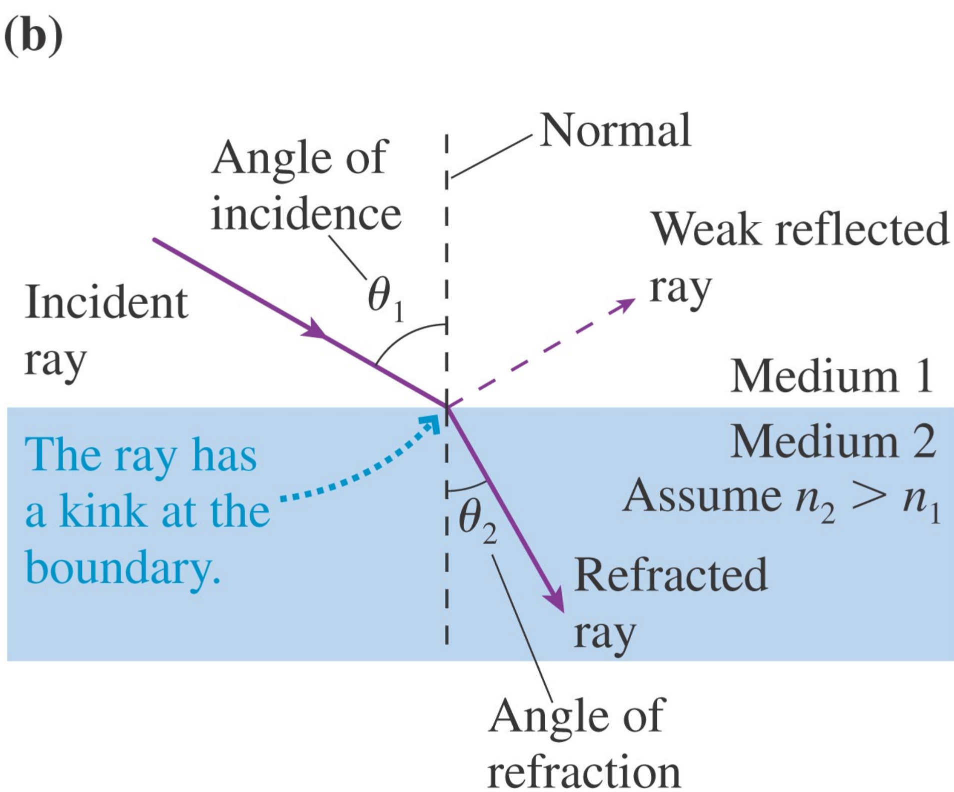
The goal of the course is to:
Introduce the phenomena of wave of wave propagation
Develop an understanding of the properties of Electromagnetic waves
Learn how to solve problems involving wave propagation

Propagation
Attenuation
Polarization
Reflection
Refraction
Dispersion
Diffraction
Interference



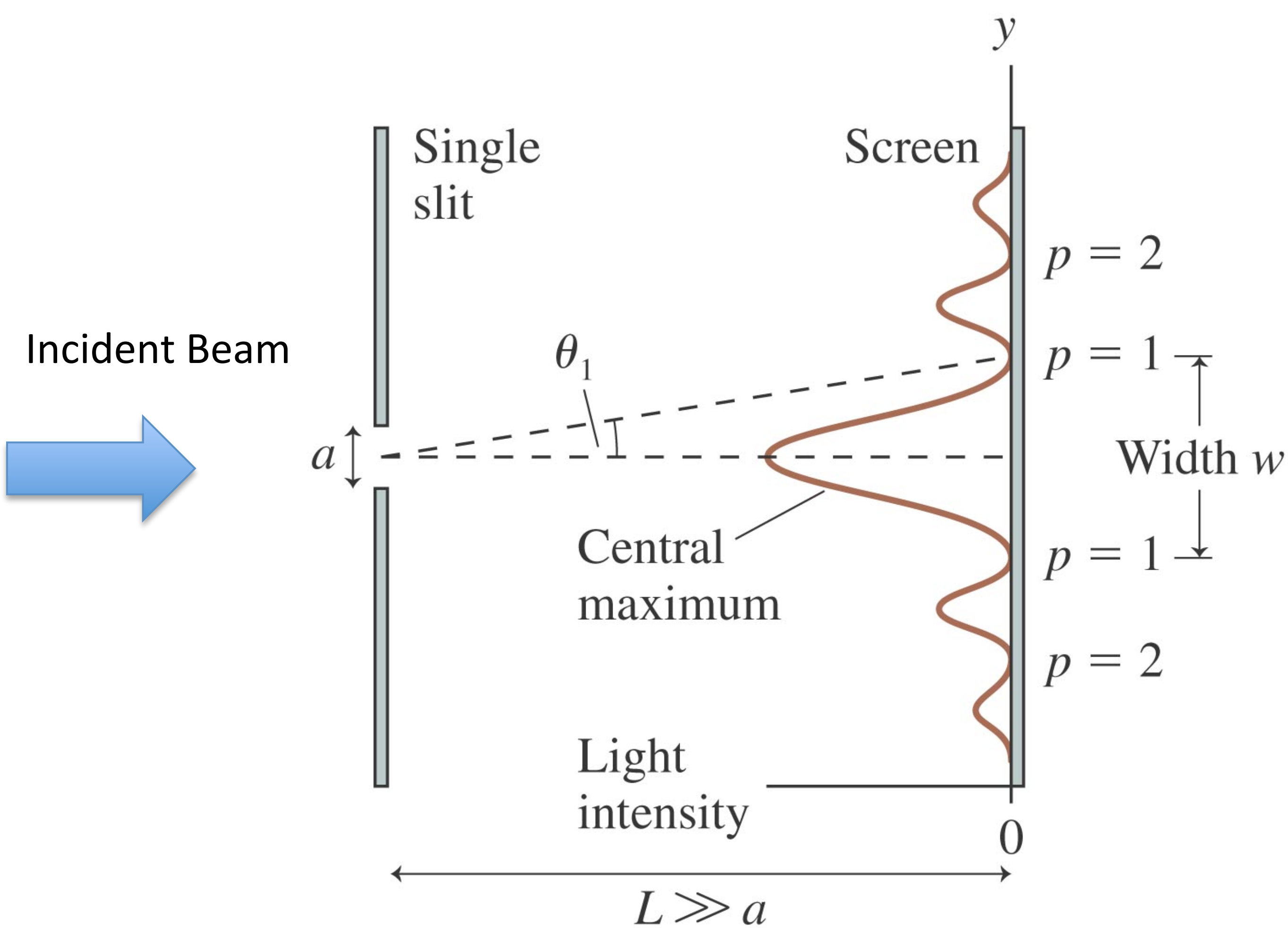
Reflection and Refraction





Diffraction and Interference

Incident Beam



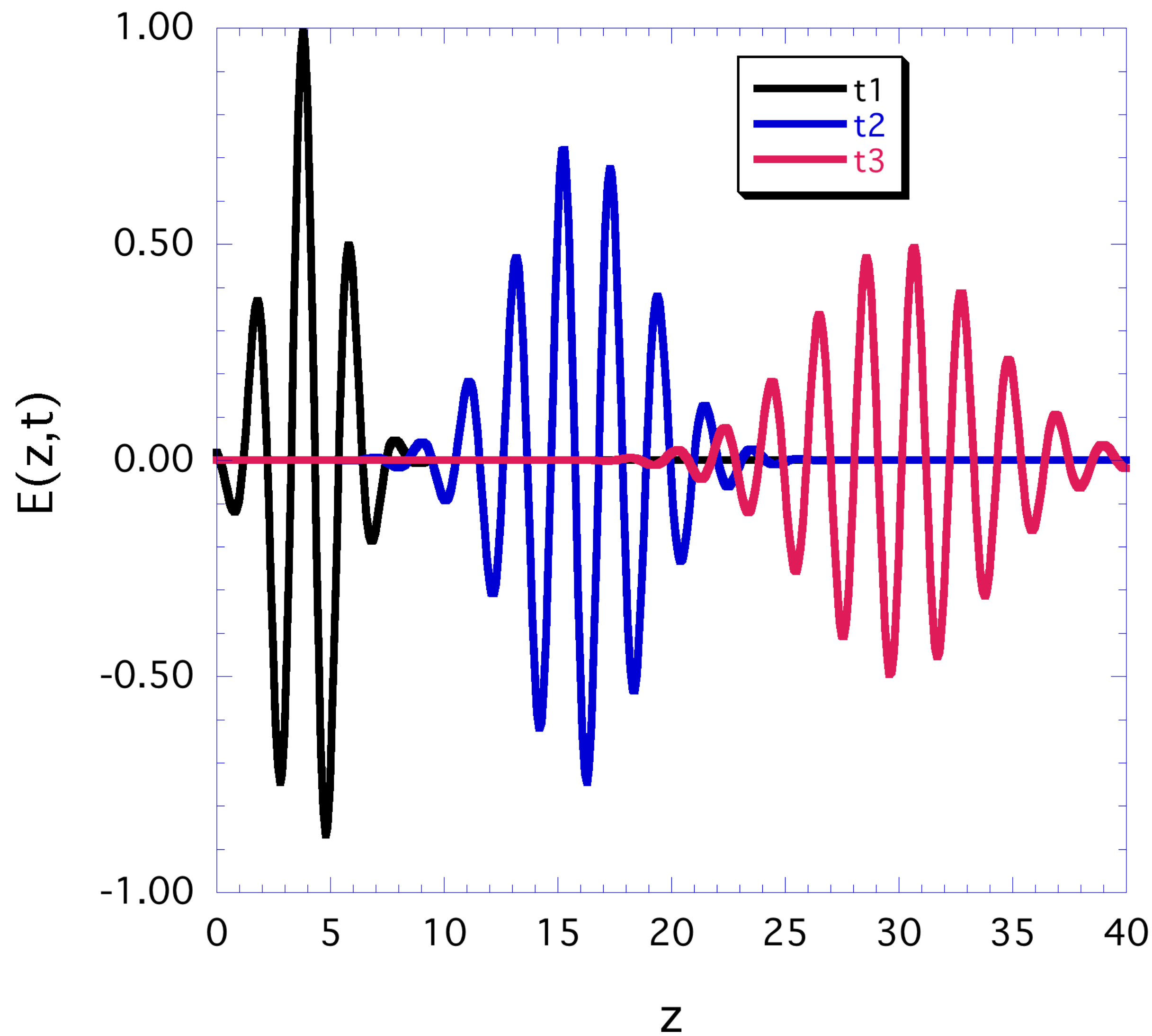
Dispersion and Attenuation

Pulses contain a spectrum of frequencies.

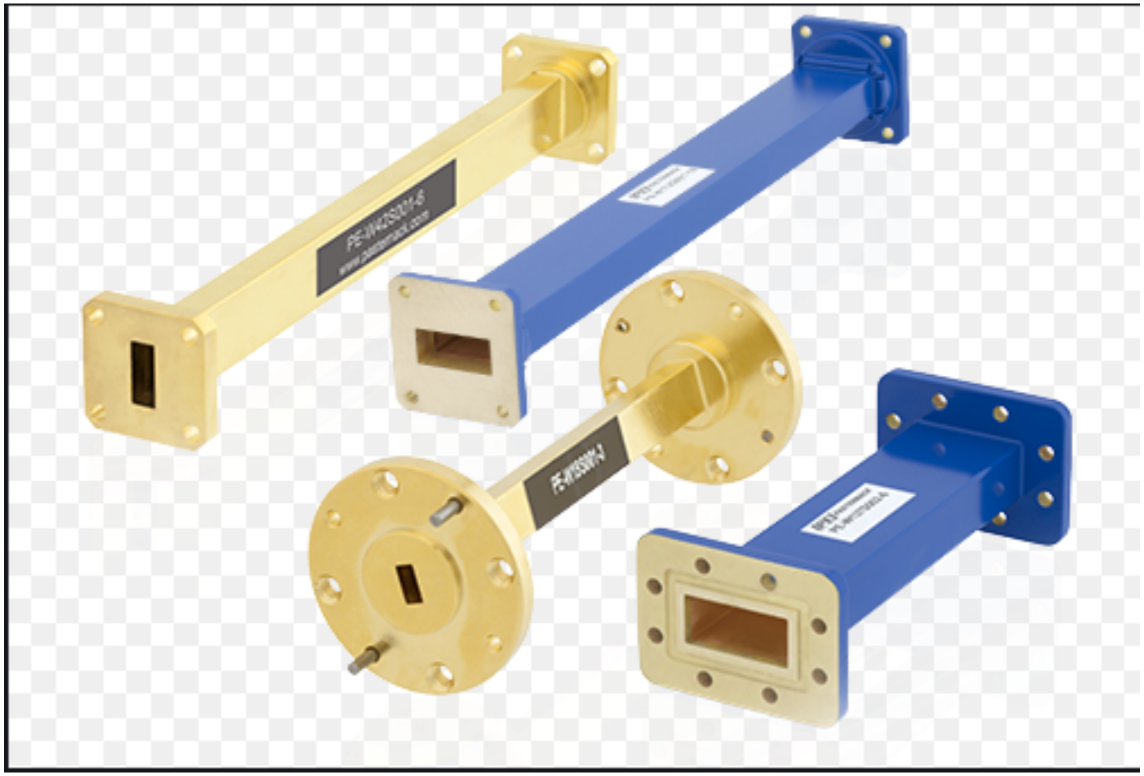
In dispersive media different frequency components propagate with different speeds.

Pulses spread out.

Losses lead to attenuation



Guided Waves



Pasternak Enterprizes
https://www.pasternack.com/

A bundle of optical fibers

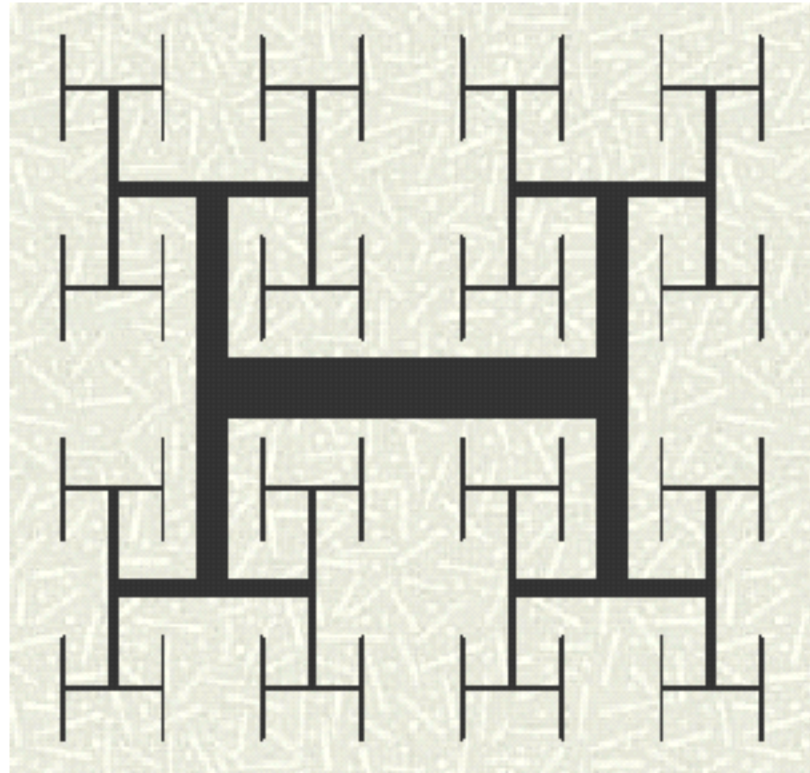
Wikipedia

Clock Distribution Network
H-Tree

System of transmission lines

Each chip is the same distance from the clock

Line widths halve at each junction to reduce reflections



Courtesy Prof. Bruce Jacob

Efficient Power Plane Modeling Using the Finite Difference Frequency Domain Method

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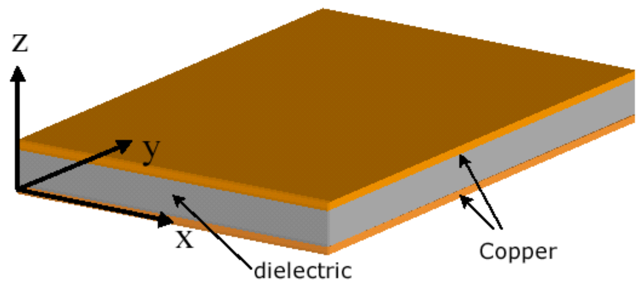
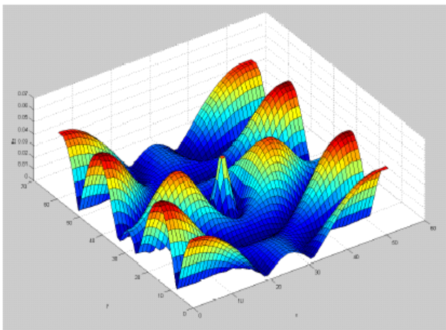
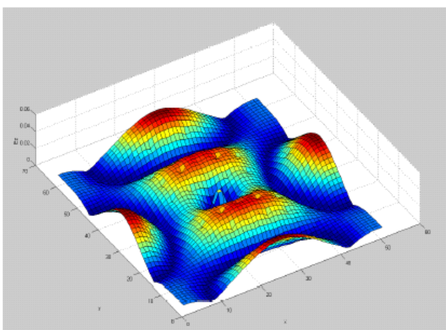


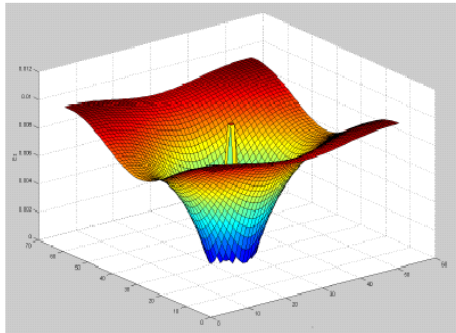


(a)

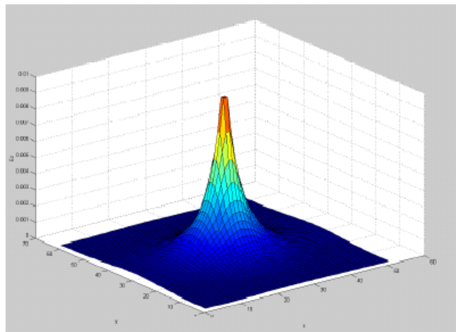


(b)

Fig. 6. Electric Field Distribution for the 25.4cm x 30.48cm board at 1GHz. (a) Without capacitors. (b) With 99 uniformly distributed capacitors of L=2nH, R= 50mΩ and C=10nF.



(a)



(b)

Fig. 5. Electric Field Distribution for the 25.4cm x 30.48cm board at 200MHz. (a) Without capacitors. (b) With 99 uniformly distributed capacitors of L=2nH, R= 50mΩ mOhm and C=10nF.

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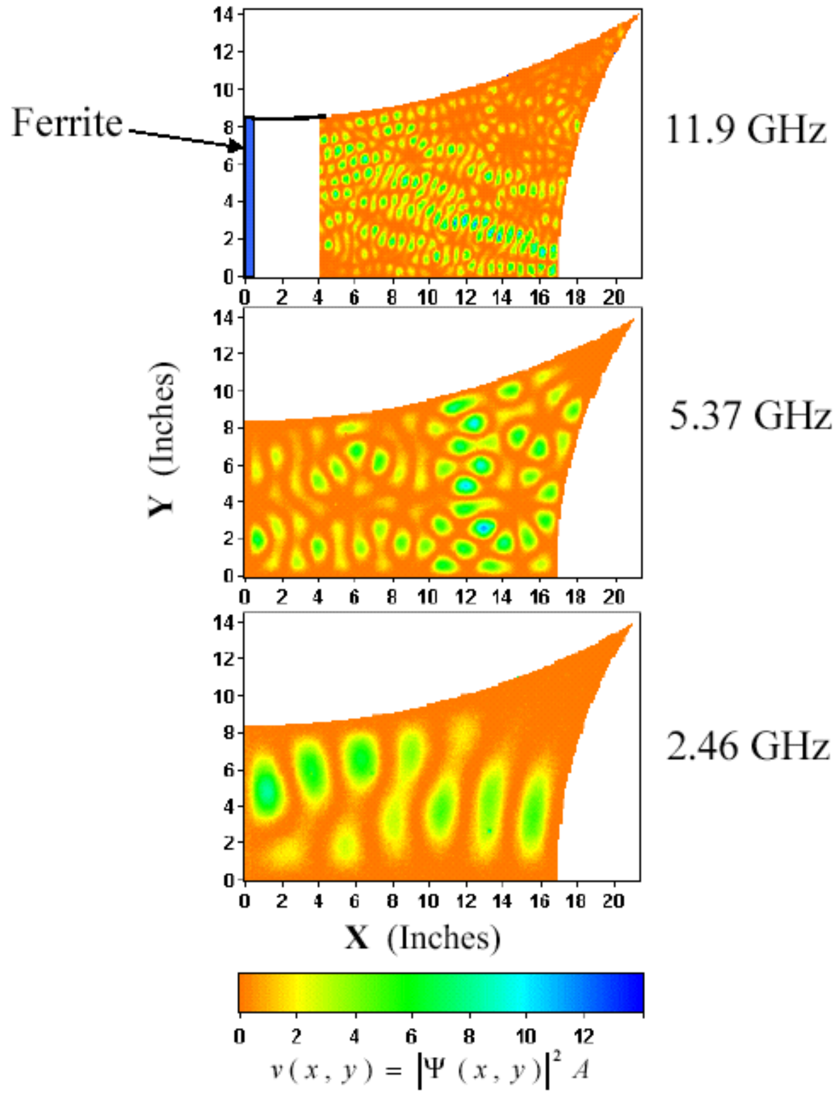
Eigenfunctions

Quarter bow-tie cavity

A magnetized ferrite (top Fig.) breaks time-reversal symmetry for the microwaves

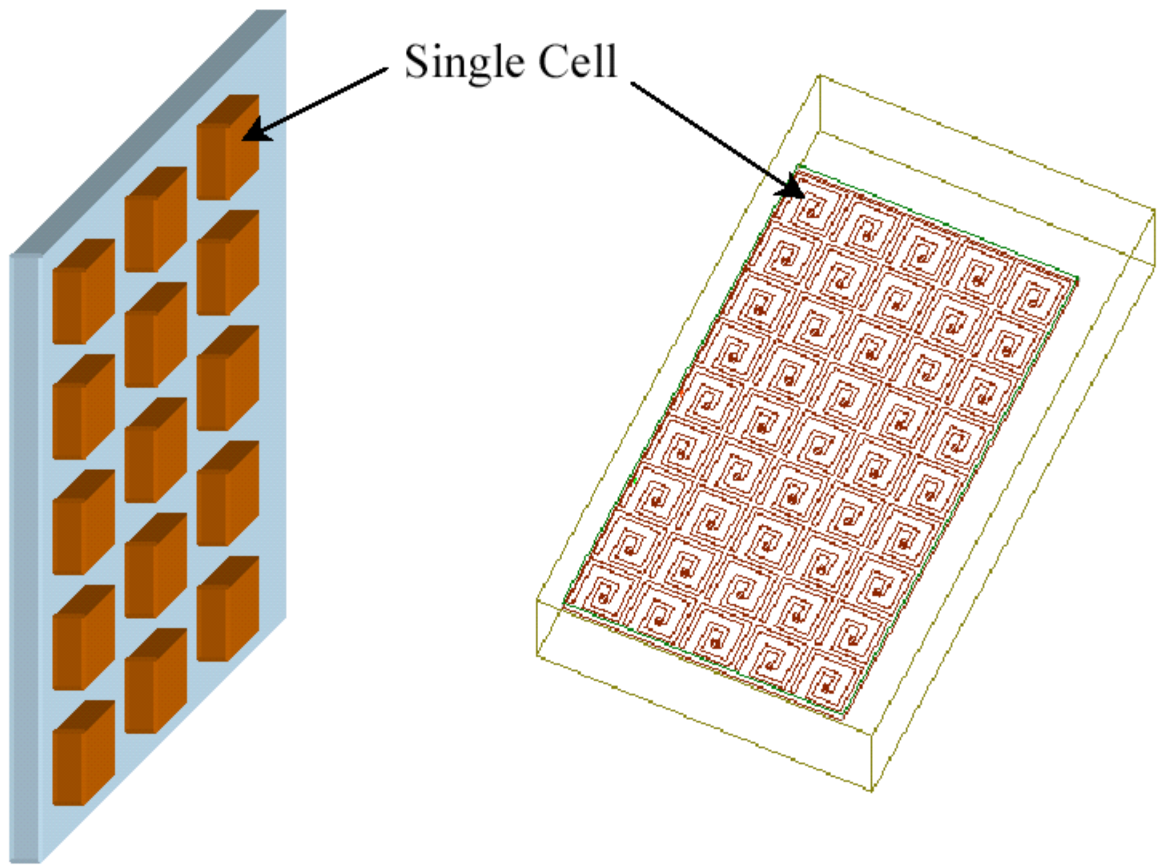
Steven M. Anlage



EM Noise Mitigation in Electronic Circuit Boards and Enclosures

Omar M. Ramahi, Lin Li, Xin Wu, Vijaya Chebolu, Vinay Subramanian,
Telesphor Kamgaing, Tom Antonsen, Ed Ott, and Steve Anlage
A. James Clark School of Engineering
University of Maryland, College Park

Electromagnetic Band Gap Structures

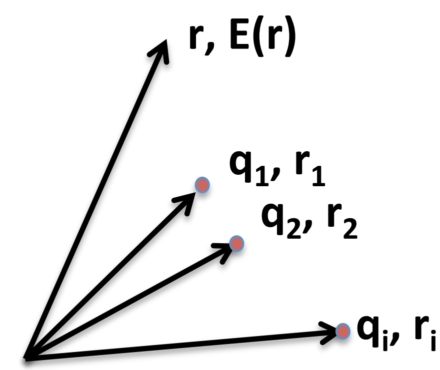


Radiation and Antennas

Review of Static Fields

Static: not changing in time
For us: changing sufficiently slowly

Start with Coulomb's Law for the electric field



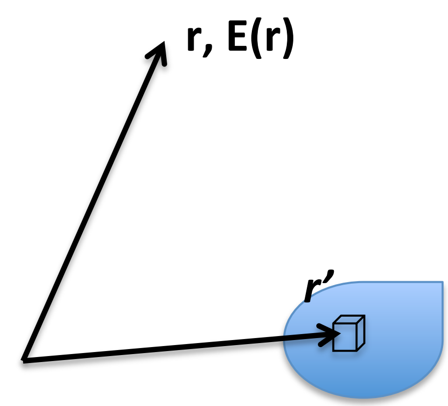
Point Charges

$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0} \sum_{charges-i} \frac{q_i\left(\mathbf{r}-\mathbf{r}_i\right)}{\left|\mathbf{r}-\mathbf{r}_i\right|^3}$$

Force on charge q $\quad \mathbf{F} = q\mathbf{E}(\mathbf{r})$

Continuous charge distributions

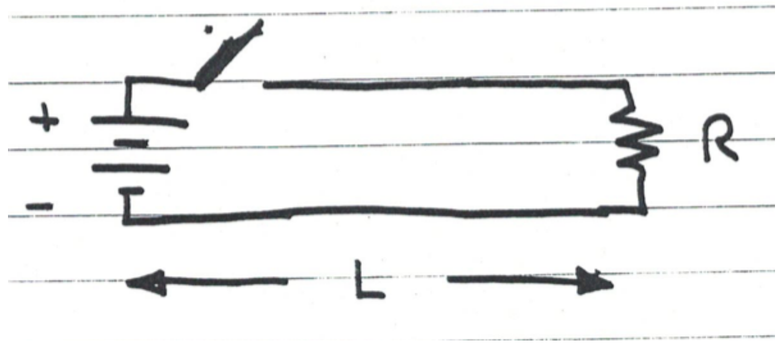
$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0} \int_V \frac{\rho(\mathbf{r}')\left(\mathbf{r}-\mathbf{r}'\right)}{\left|\mathbf{r}-\mathbf{r}'\right|^3} d^3r'$$



$$dq' = d^3r'\,\rho(\mathbf{r}')$$

Electrostatic or not?

Circuit vs Transmission line?
When the switch is closed
how long until current flows
in R?



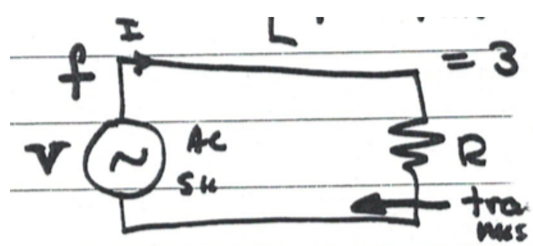
$$\Delta t = L / c$$

L=1m, c = 3 x10^8 m/s

$$\Delta t = 3.3 \times 10^{-9} s \quad = 3.3 ns$$

How long until current reaches steady state? Depends on reflections.

AC source, What load does source see?



If L < < wavelength = c/f then R
However, once L = wavelength/4
load is transformed.

Some Examples

Comcast signal: 55.25 **MHz** to 553 **MHz**

Wavelength at 553 MHz = 0.54 m

Verizon 5G signal: 28 GHz

Wavelength at 28 GHz = 0.01 m

Infrared laser: 3×10^{14} Hz

Wavelength = 1 micron = 10^{-6} m

Bohr Radius = 5.29×10^{-11} m << 1 micron wavelength

Laser field in atom is electrostatic

Fork in microwave oven: f = 2 GHz

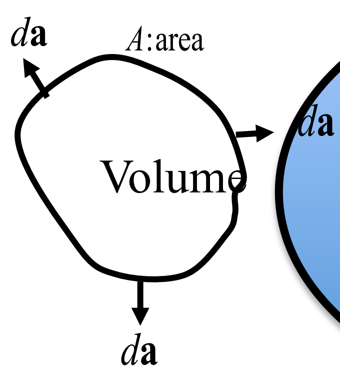
Wavelength = 0.15 m >> fork prong

Three ways to say the same thing

Coulomb's Law:

$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0}\int_V \frac{\rho(\mathbf{r}')(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3} d^3r'$$

Gauss' Law:



$$\oint_S \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q_{in}}{\varepsilon_0} = \frac{1}{\varepsilon_0}\int_V \rho d^3r$$

$$\oint_{loop} \vec{\mathbf{E}} \cdot d\vec{\mathbf{l}} = 0$$

Poisson Equation:

$$\nabla \cdot \vec{\mathbf{E}} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \vec{\mathbf{E}} = 0$$

Integral Relations

Gauss' Law:

$$\oint_S \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q_{in}}{\varepsilon_0} = \frac{1}{\varepsilon_0} \int_V \rho d^3 r$$

Electrostatic Field:

$$\oint_{loop} \vec{\mathbf{E}} \cdot d\vec{\mathbf{l}} = 0$$

$$\vec{\mathbf{E}} = -\nabla \Phi$$

Comments:

Always true, but only useful in determining E from rho if symmetry is present.

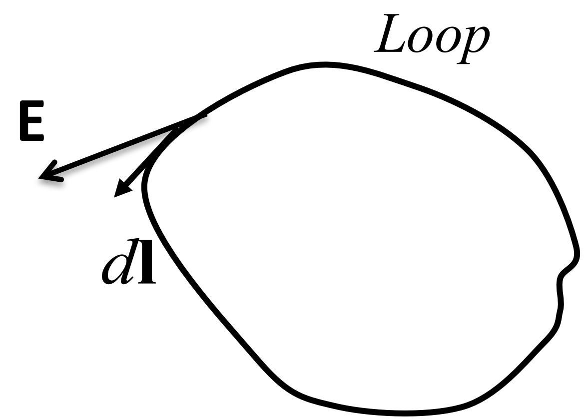
Second condition, E.dl, only true for electrostatic fields.

Integral Relations

Electrostatic Field:

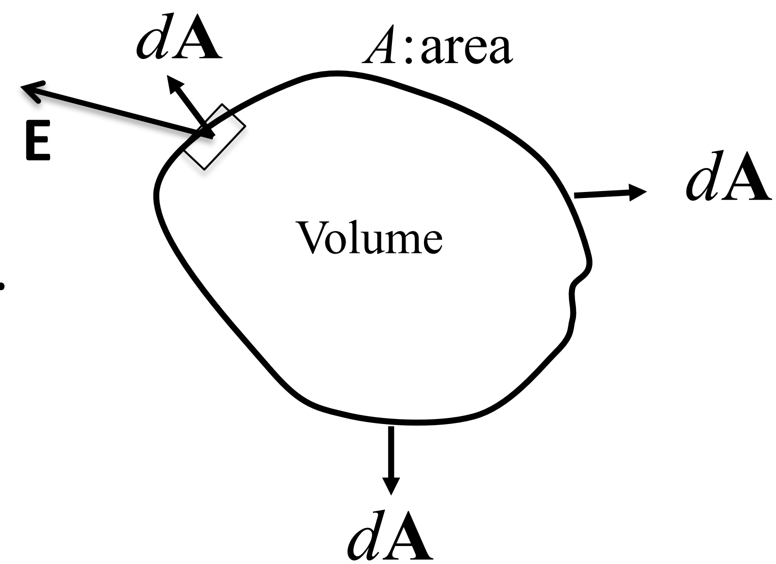
$$\oint_{loop} \vec{\mathbf{E}} \cdot d\vec{\mathbf{l}} = 0$$

$$\vec{\mathbf{E}} = -\nabla\Phi$$



Gauss' Law:

$$\oint_S \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q_{in}}{\varepsilon_0} = \frac{1}{\varepsilon_0}\int_V \rho d^3 r$$

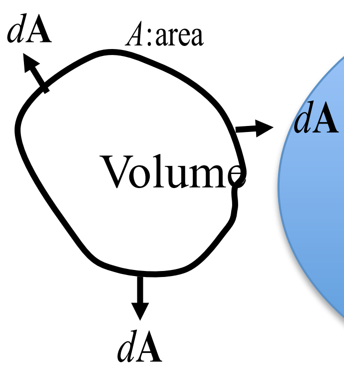


Three ways to say the same thing

Coulomb's Law:

$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\varepsilon_0}\int_V \frac{\rho(\mathbf{r}')\left(\mathbf{r}-\mathbf{r}'\right)}{\left|\mathbf{r}-\mathbf{r}'\right|^3} d^3r'$$

Gauss' Law:



$$\oint_S \vec{\mathbf{E}}\cdot d\vec{\mathbf{A}} = \frac{Q_{in}}{\varepsilon_0} = \frac{1}{\varepsilon_0}\int_V \rho d^3r$$

$$\oint_{loop} \vec{\mathbf{E}}\cdot d\vec{\mathbf{l}} = 0$$

Poisson Equation:

$$\nabla\cdot\vec{\mathbf{E}} = \frac{\rho}{\varepsilon_0}$$

$$\nabla\times\vec{\mathbf{E}} = 0$$

Differential Equation

Poisson Equation:

$$\nabla \cdot \vec{\mathbf{E}} = \frac{\rho}{\varepsilon_0}$$

Electrostatic Field:

$$\nabla \times \vec{\mathbf{E}} = 0$$

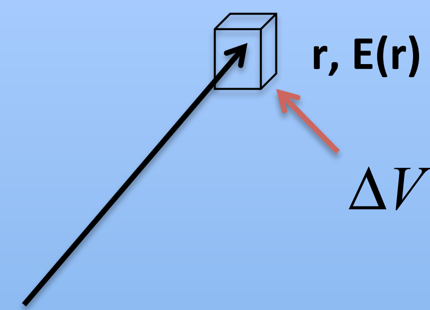
Comments:

Always true
Only can solve analytically in special cases.

Numerical Solutions in software programs

Definition of Divergence

$$\nabla \cdot \mathbf{E} \triangleq Lim_{\Delta V \to 0} \frac{1}{\Delta V} \oint_A \mathbf{E} \cdot d\mathbf{a}$$



Definition of derivative

$$\frac{dE(x)}{dx} \equiv Lim_{\Delta x \to 0} \frac{1}{\Delta x} \left(E(x + \Delta x) - E(x) \right)$$

In Cartesian Coordinates

$$\nabla \cdot \mathbf{E} = \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z}$$

Pick a small volume located at ***r***.

Integrate E.dA over the surface of that volume.

Divide by the volume.

Take the limit of the volume going to zero

That is the divergence of E at r.

Definition of Curl

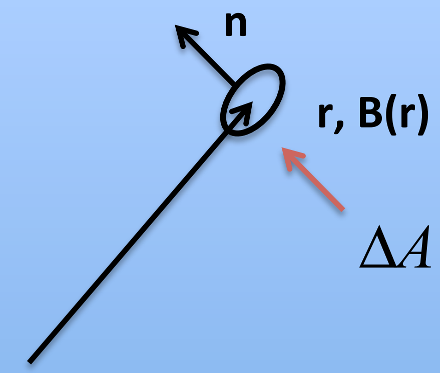
$$\left(\nabla\times\mathbf{B}\right) \triangleq Lim_{\Delta A\to 0}\frac{\vec{\mathbf{n}}}{\Delta A}\oint_C \mathbf{B}\cdot d\mathbf{l}$$

Cartesian Coordinates

$$\left(\nabla\times\mathbf{B}\right)_x = \frac{\partial}{\partial y}B_z - \frac{\partial}{\partial z}B_y$$

$$\left(\nabla\times\mathbf{B}\right)_y = \frac{\partial}{\partial z}B_x - \frac{\partial}{\partial x}B_z$$

$$\left(\nabla\times\mathbf{B}\right)_z = \frac{\partial}{\partial x}B_y - \frac{\partial}{\partial y}B_x$$



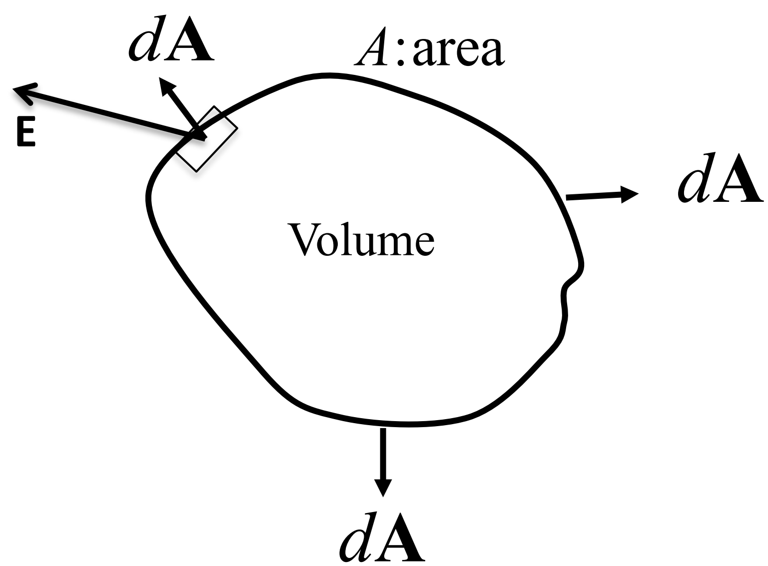
Pick a small loop of area ΔA located at ***r***.
Integrate B.dl around that loop
n is a unit vector normal to the area in a direction given by the RHR relative to dl

Divide by the area.
Take the limit of the area going to zero
That is the curl of B at r.

Divergence Theorem

For any E

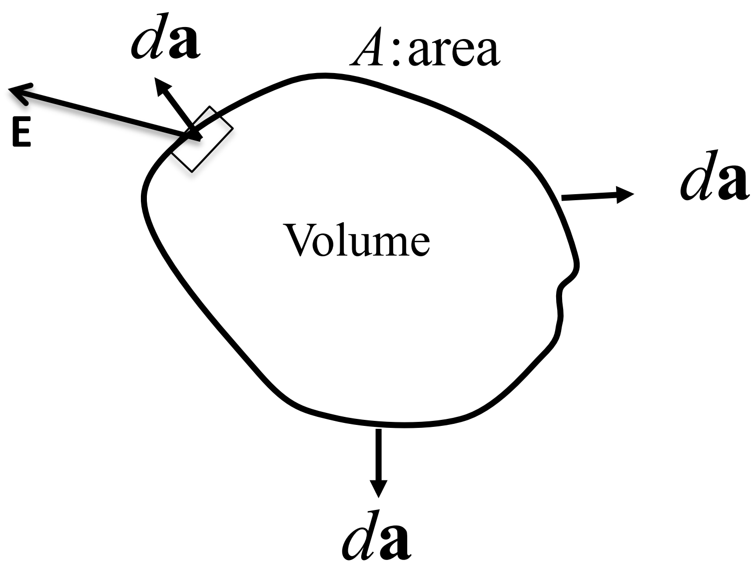
$$\int_V \nabla\cdot\mathbf{E}\,d^3r = \oint_A \mathbf{E}\cdot d\mathbf{A}$$



Divergence Theorem

For any E

$$\int_V \nabla \cdot \mathbf{E} d^3 r = \oint_A \mathbf{E} \cdot d\mathbf{a}$$



Fundamental rule of calculus

$$\int_b^a dx \frac{dE(x)}{dx} = E(a) - E(b)$$

The integral of the derivative is determined by the values of the function at the end points.

Magnetostatics

Biot-Savart Law:

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int_V \frac{\mathbf{J}(\mathbf{r}')\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}d^3r'$$

Ampere’s Law:

$$\oint_{loop}\vec{\mathbf{B}}\cdot d\vec{\mathbf{S}} = \mu_0 I_{enclosed}$$

$$= \mu_0 \oint_S \vec{\mathbf{J}}\cdot d\vec{\mathbf{A}}$$

Gauss’ Law:

$$\oint_S \vec{\mathbf{B}}\cdot d\vec{\mathbf{A}} = 0$$

$$\nabla\times\vec{\mathbf{B}} = \mu_0\vec{\mathbf{J}}$$

$$\nabla\cdot\vec{\mathbf{B}} = 0$$

Integral Relations

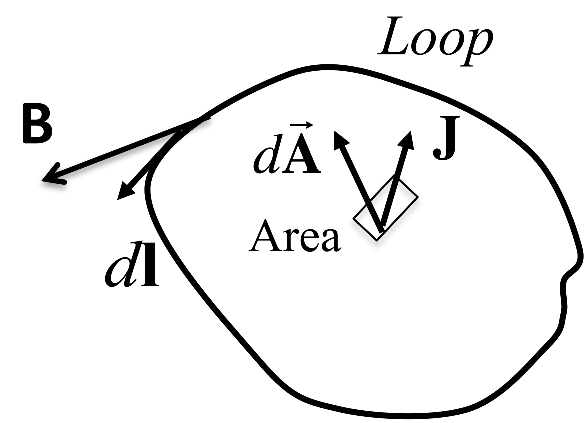
Ampere's Law:

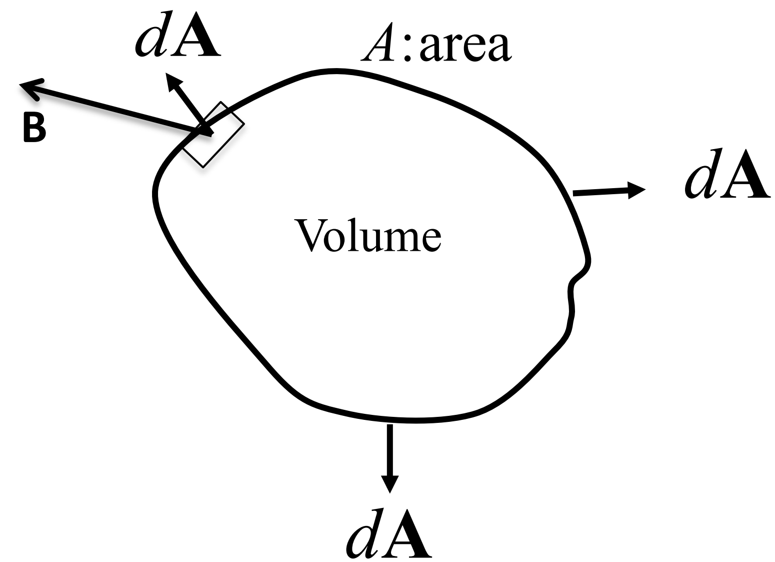
$$\oint_{loop} \vec{\mathbf{B}} \cdot d\vec{\mathbf{l}} = \mu_0 I_{enclosed}$$

$$= \mu_0 \oint_S \vec{\mathbf{J}} \cdot d\vec{\mathbf{A}}$$

Gauss' Law:

$$\oint_S \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$$





Differential Relations

Ampere's Law:

$$\nabla \times \vec{\mathbf{B}} = \mu_0 \vec{\mathbf{J}}$$

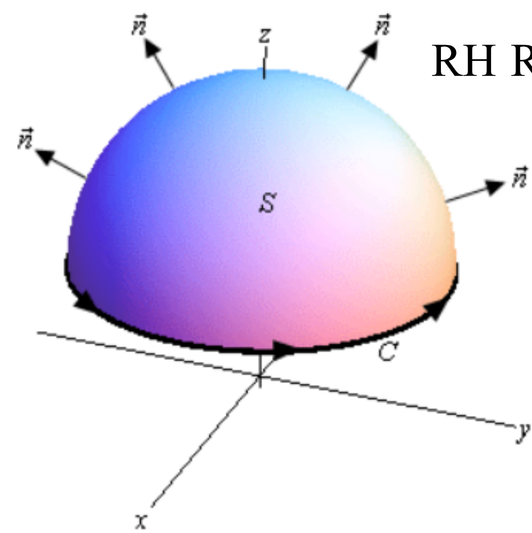
Gauss' Law:

$$\nabla \cdot \vec{\mathbf{B}} = 0$$

Stokes' Theorem

$$\int_S (\nabla \times \mathbf{B}) \cdot d\mathbf{A} = \oint_C \mathbf{B} \cdot d\mathbf{l}$$

$$d\mathbf{a} = da\,\hat{\mathbf{n}}$$



Holds for any B(x) and curve C and any surface that has curve C for its perimeter.

A consequence:

If $\nabla \times \mathbf{B} = 0$ Everywhere

Then $\oint_C \mathbf{B} \cdot d\mathbf{l} = 0$ For any loop

and $\mathbf{B} = \nabla \psi$

MKS-SI Units

E	Volts/meter
Q	Coulombs
B	Tesla
I	Amperes

$$\oint_S \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q_{in}}{\varepsilon_0} \qquad \left[\varepsilon_0\right]$$ = Volts-Meters/Coulombs

$$\left[\varepsilon_0\right] = 8.8542 \times 10^{-12} \quad \text{Farads/meter}$$

Force on a moving charge q

$$\vec{\mathbf{F}} = q\left(\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}}\right)$$

[B] = Volts-seconds/meter^2

Ampere's Law

$$\oint_{loop} \vec{\mathbf{B}} \cdot d\vec{\mathbf{l}} = \mu_0 I_{enclosed}$$

[B.dl] = Volts-seconds/meter = Amperes $\left[\mu_0\right]$

$$\mu_0 = 4\pi \times 10^{-7} \quad \text{Volt-seconds/Ampere-meters} \quad = \quad \text{Henry's/meter}$$

What to remember:

$$1/\sqrt{\varepsilon_0 \mu_0} = c = 3 \times 10^8 \quad \text{m/s} \qquad \sqrt{\mu_0 / \varepsilon_0} \quad = 377 \text{ Ohms} = \text{impedance of free space}$$

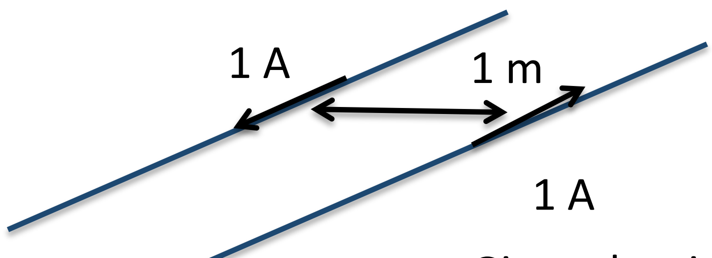
Why such funny numbers?

$$\varepsilon_0 = 8.8542 \times 10^{-12} \quad \text{Farads/meter}$$

$$\mu_0 = 4\pi \times 10^{-7} \quad \text{Henry's/meter}$$

The size of the Ampere is set by the requirement that two infinitely long parallel wires separated by 1 meter and each carrying 1 Ampere of current feel a force of

$$\mu_0 = 4\pi \times 10^{-7} \quad \text{Newtons/meter}$$



Given the size of an Ampere and the unit of time, 1 second, the unit of charge is defined,

1 Coulomb = 1 Ampere X 1 second

Statics to Dynamics

Integrals over closed surfaces

Poisson: $\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = Q / \varepsilon_0$

Gauss' Law: $\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$

Integrals around closed loops

Faraday's Law:

$$\oint_{loop} \vec{\mathbf{E}} \cdot d\vec{\mathbf{l}} = -\int_S d\vec{\mathbf{A}} \cdot \frac{\partial \vec{\mathbf{B}}}{\partial t}$$

Ampere's Law:

$$\oint_{Loop} \vec{\mathbf{B}}(\vec{\mathbf{r}}) \cdot d\vec{\mathbf{l}} = \mu_0 \int_S d\vec{\mathbf{A}} \cdot \left[\vec{\mathbf{J}} + \varepsilon_0 \frac{\partial \vec{\mathbf{E}}}{\partial t} \right]$$