INTRODUCTION TO MICROWAVE

LECTURE 3

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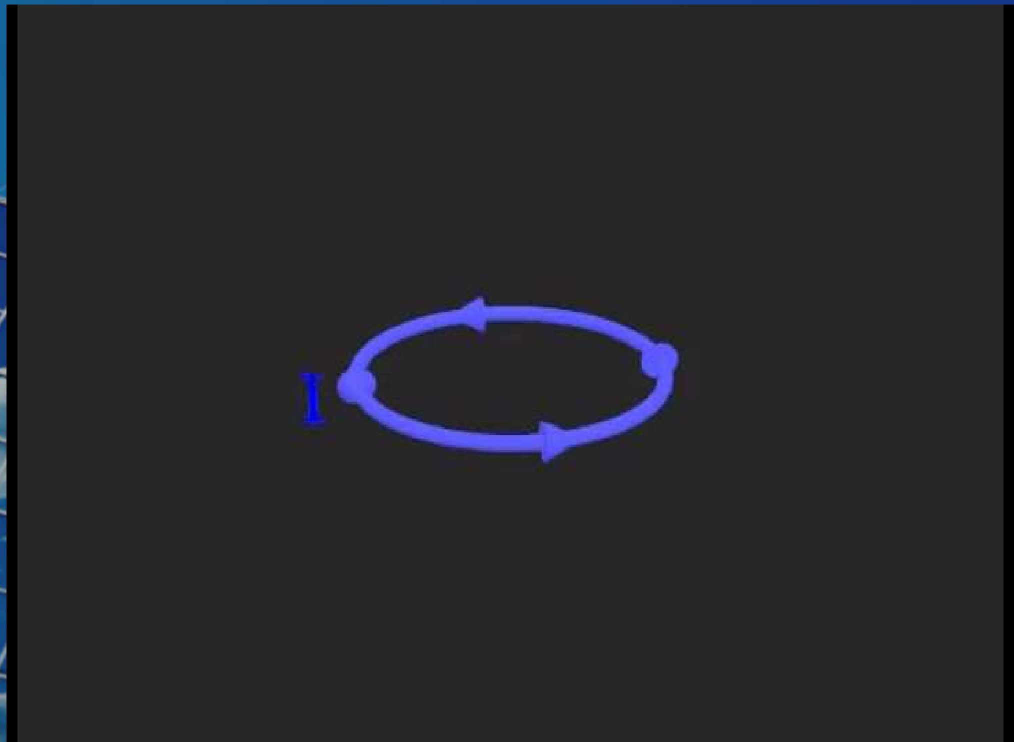
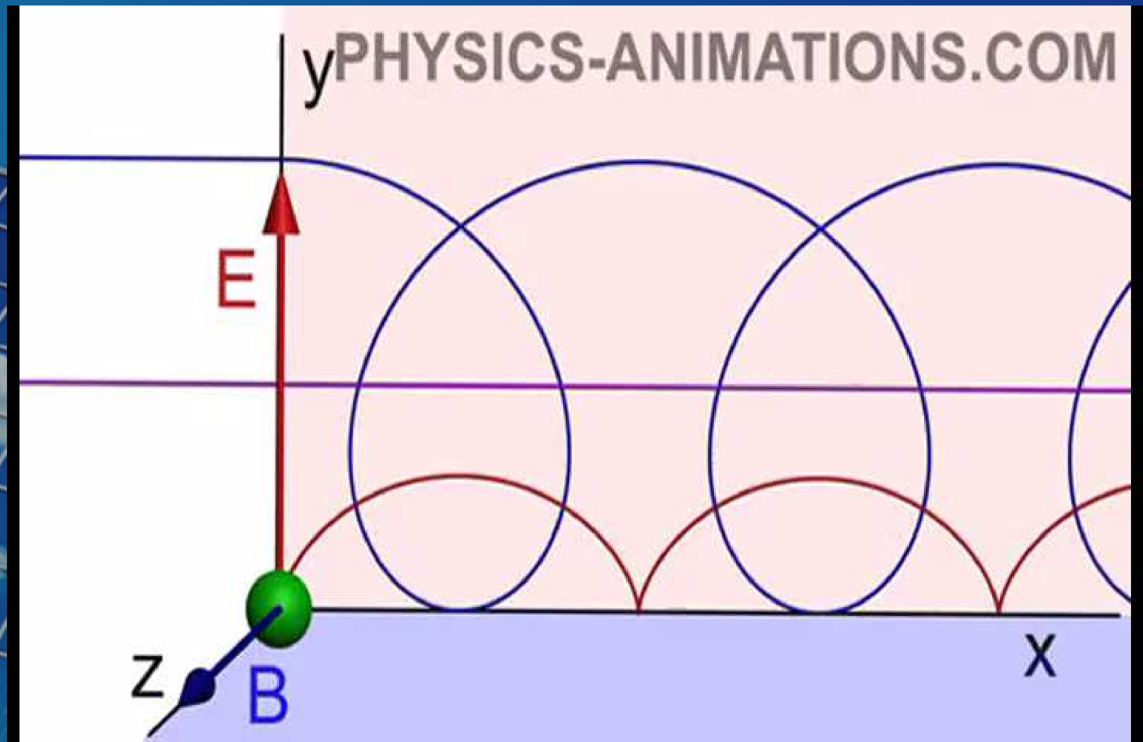
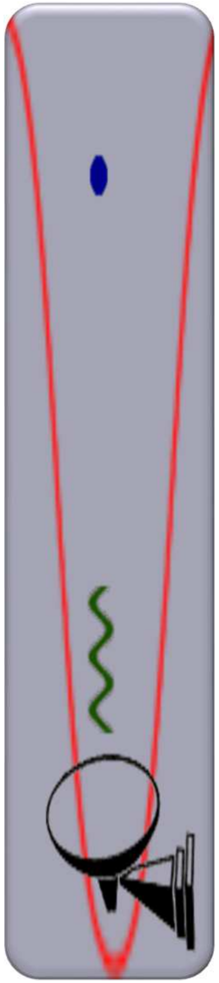
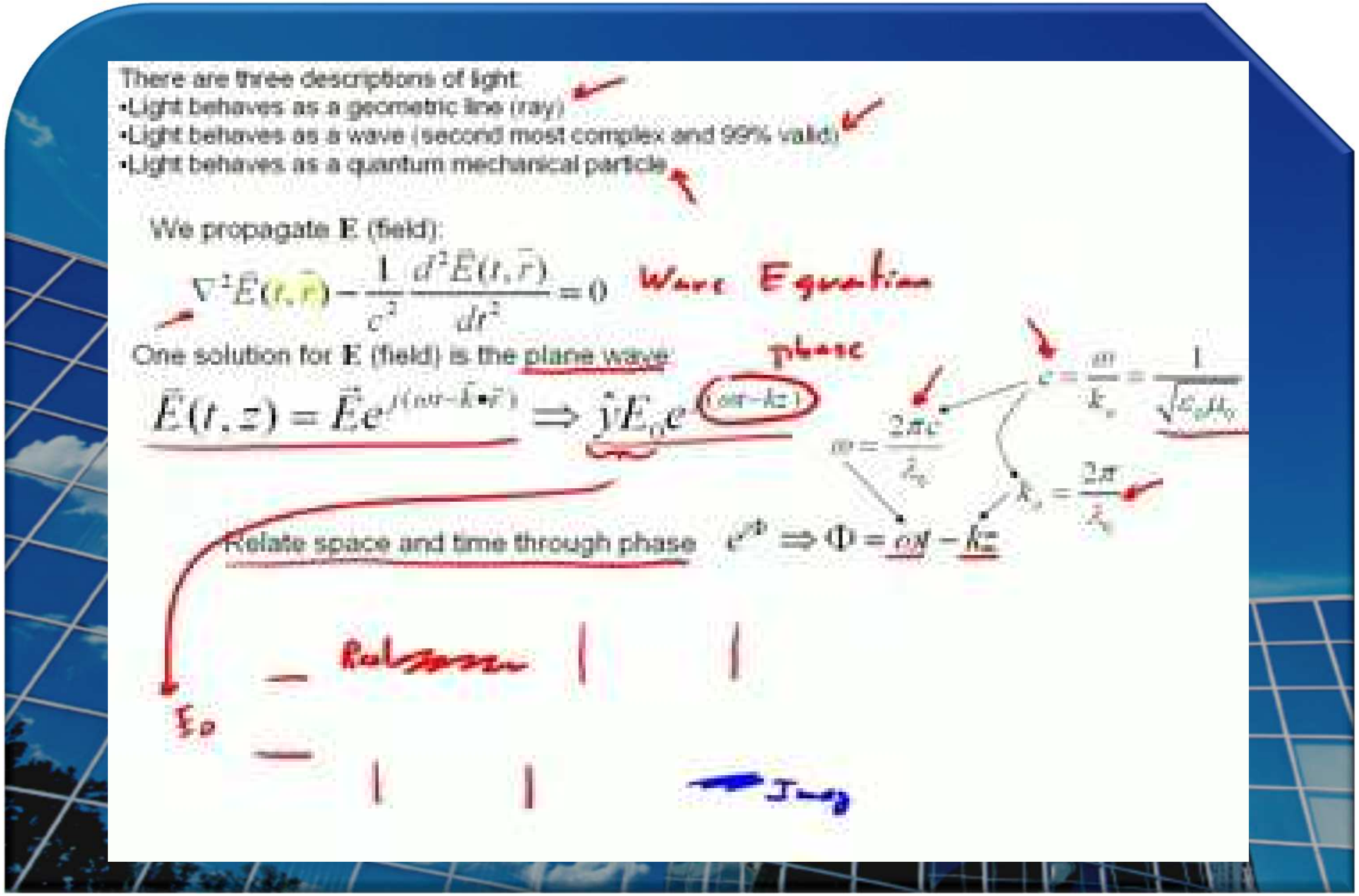
RIGHT HAND RULE



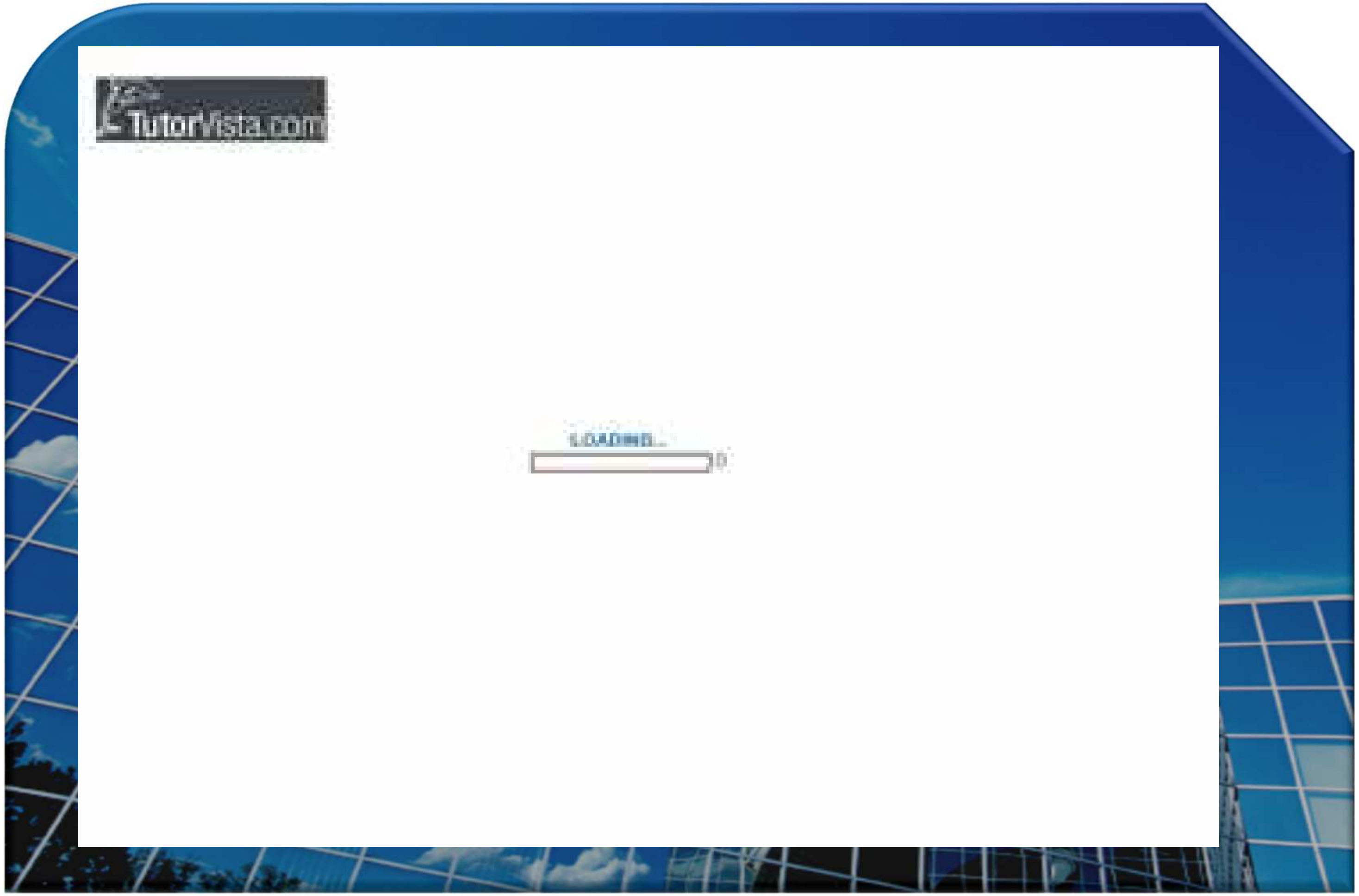
ELECTROMAGENTIC WAVE PROPOGATION

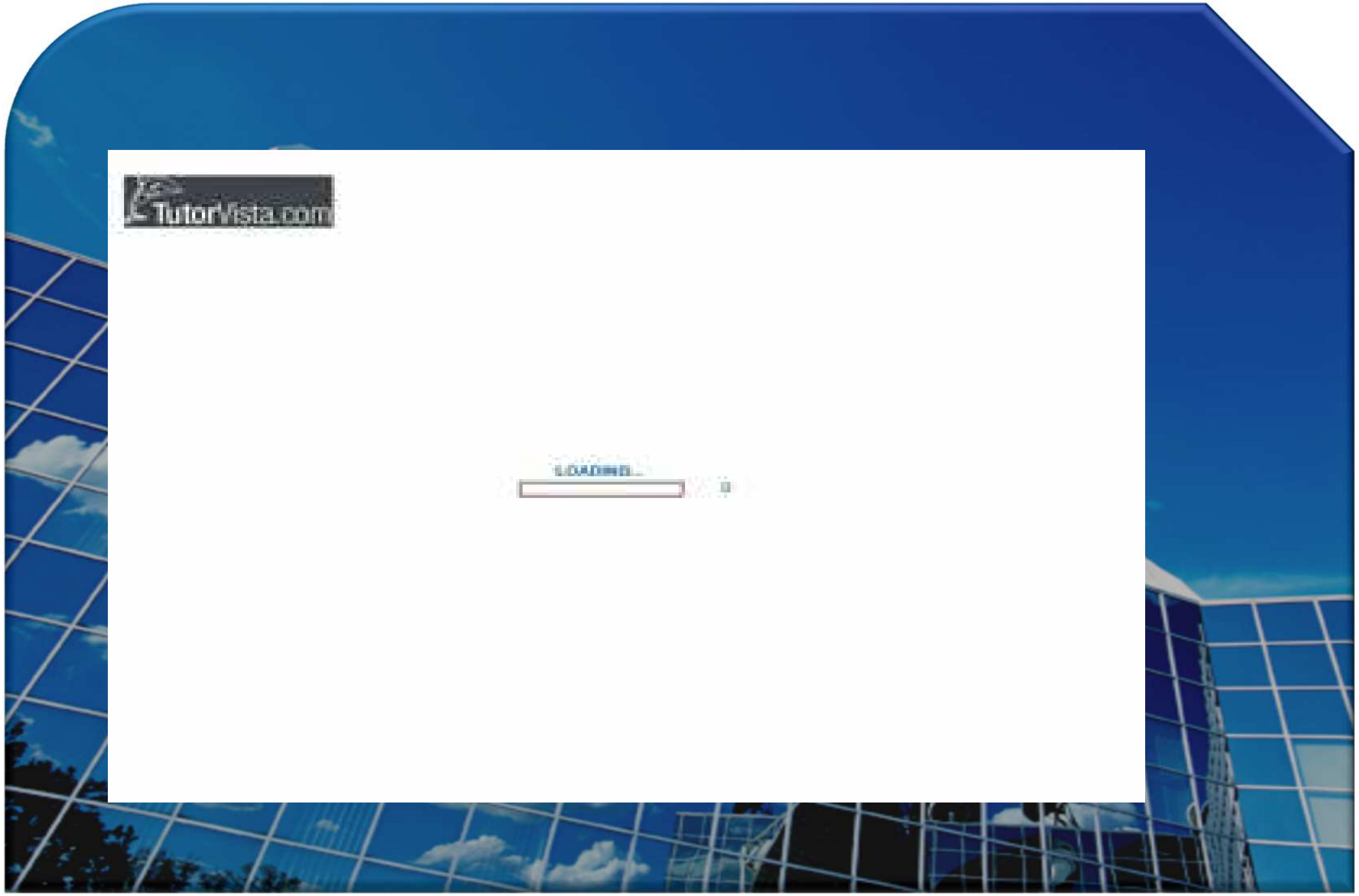





There are three descriptions of light:
•Light behaves as a geometric line (ray)
•Light behaves as a wave (second most complex and 99% valid)
•Light behaves as a quantum mechanical particle
We propagate E (field):
$\nabla^2 \vec{E}(t,\vec{r}) - \frac{1}{c^2}\frac{d^2\vec{E}(t,\vec{r})}{dt^2} = 0$
Wave Equation
One solution for E (field) is the plane wave:
phase
$\vec{E}(t,z) = \vec{E}e^{j(\omega t - \vec{k}\bullet\vec{r})} \Rightarrow \hat{j}E_o e^{j(\omega t - kz)}$
$c = \frac{\omega}{k_o} = \frac{1}{\sqrt{\varepsilon_o \mu_o}}$
$\omega = \frac{2\pi c}{\lambda_o}$
$k_o = \frac{2\pi}{\lambda_o}$
Relate space and time through phase
$e^{j\Phi} \Rightarrow \Phi = \omega t - kz$
Real
E_o
Imag

Faraday

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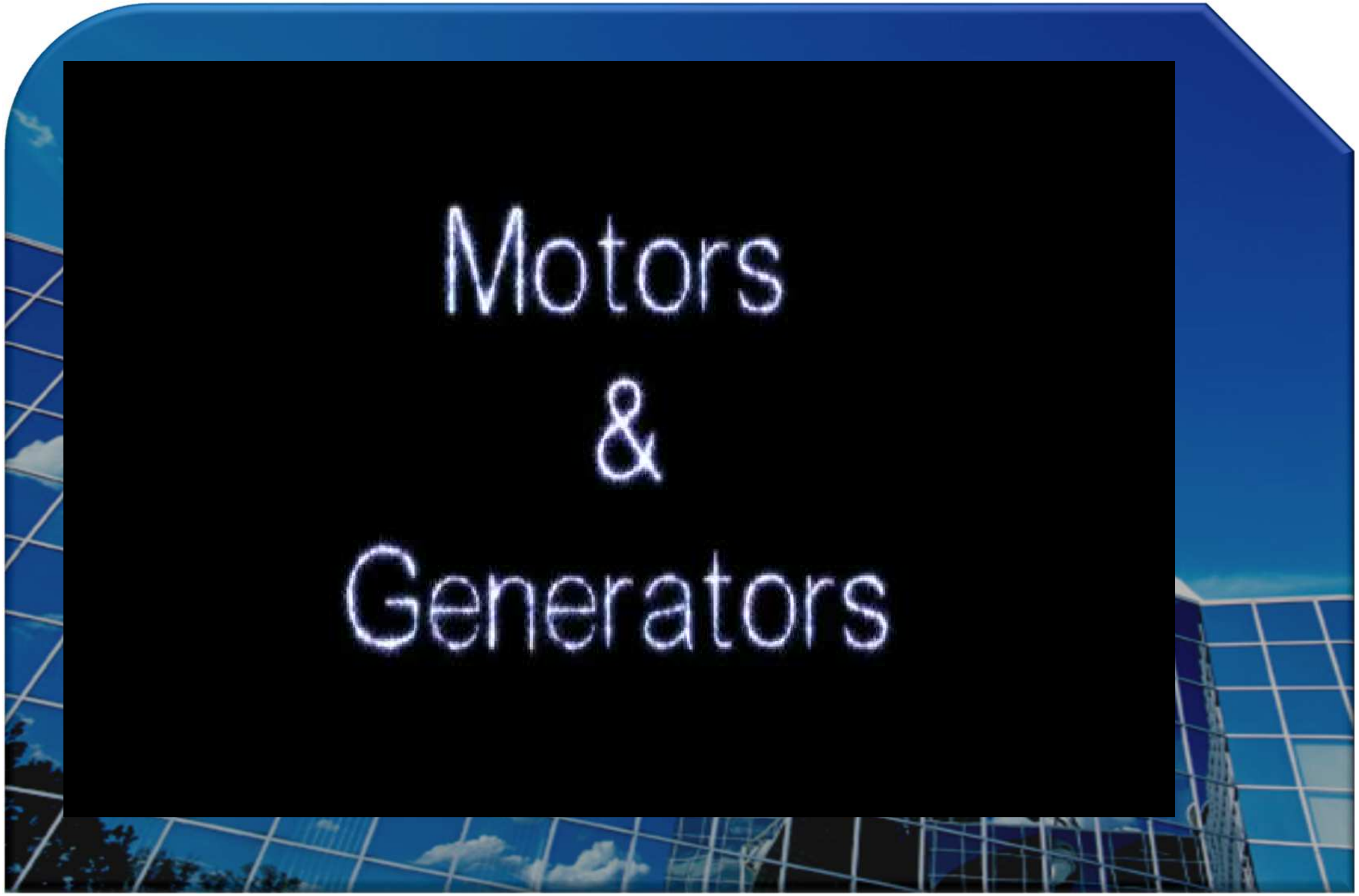
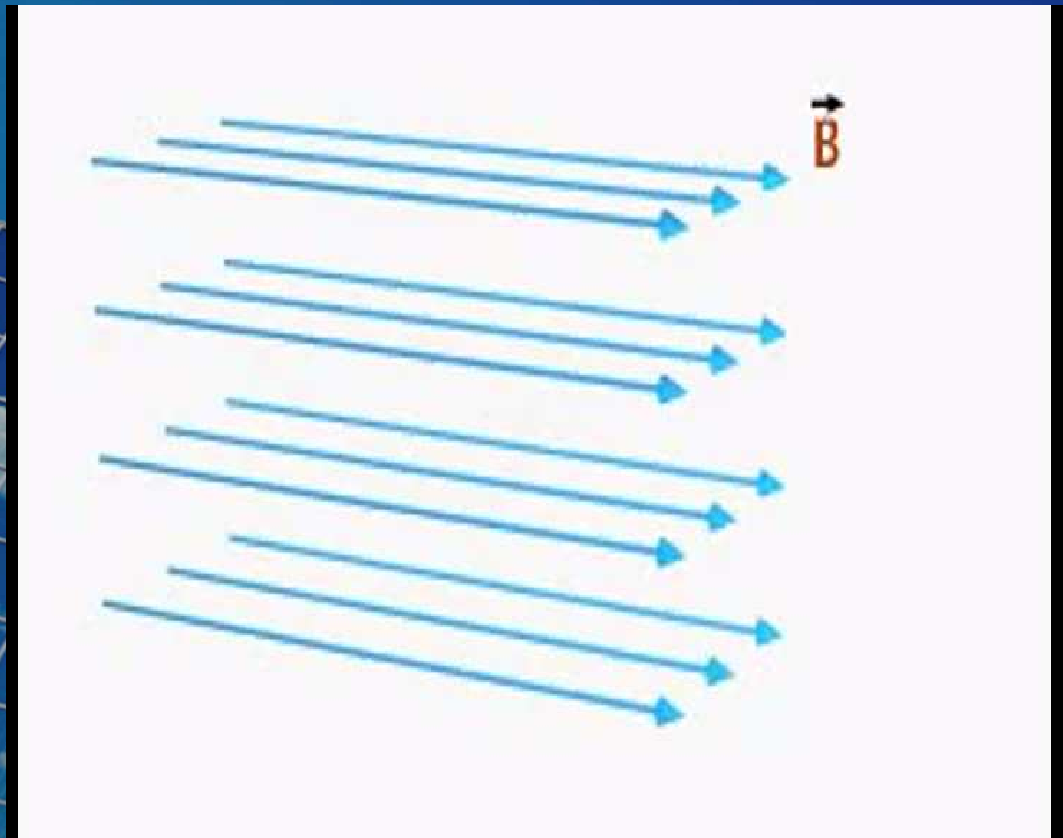
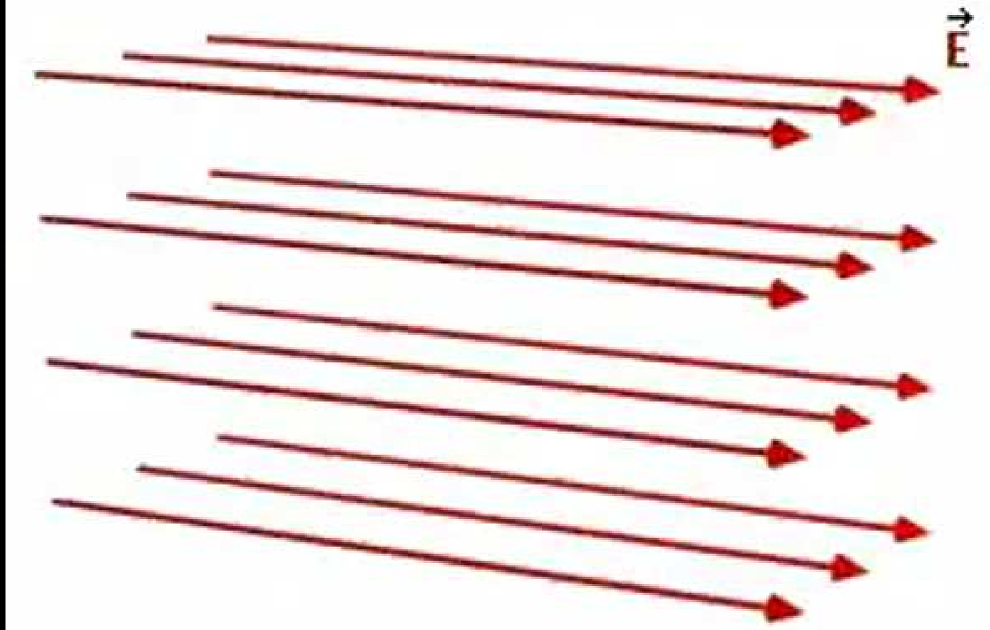
SIMPLE EXAMPLE OF HOW EM WORKS



MAGNETIC FLUX



ELECTRIC FLUX



MAXWELL'S EQUATIONS

are four differential equations summarizing nature of electricity and magnetism: (formulated by James Clerk Maxwell around 1860):

$\vec{\nabla} \cdot \vec{D} = \rho$	Gauss's Law
$\vec{\nabla} \cdot \vec{B} = 0$	Gauss's Law for Magnetism
$\vec{\nabla} \times \vec{E} = -\dfrac{\partial \vec{B}}{\partial t}$	Faraday's Law
$\vec{\nabla} \times \vec{H} = \vec{J} + \dfrac{\partial \vec{D}}{\partial t}$	Ampere's Law

MAXWELL'S EQUATIONS

(1) Electric charges generate electric fields.

(2) Magnetic field lines are closed loops; there are no magnetic monopoles.

(3) Currents and changing electric fields produce magnetic fields.

(4) Changing magnetic fields produce electric fields.

From Maxwell's equations one can derive another equation which has the form of a "*wave equation*".

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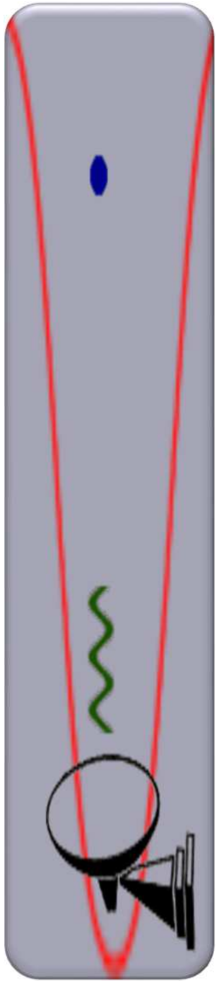
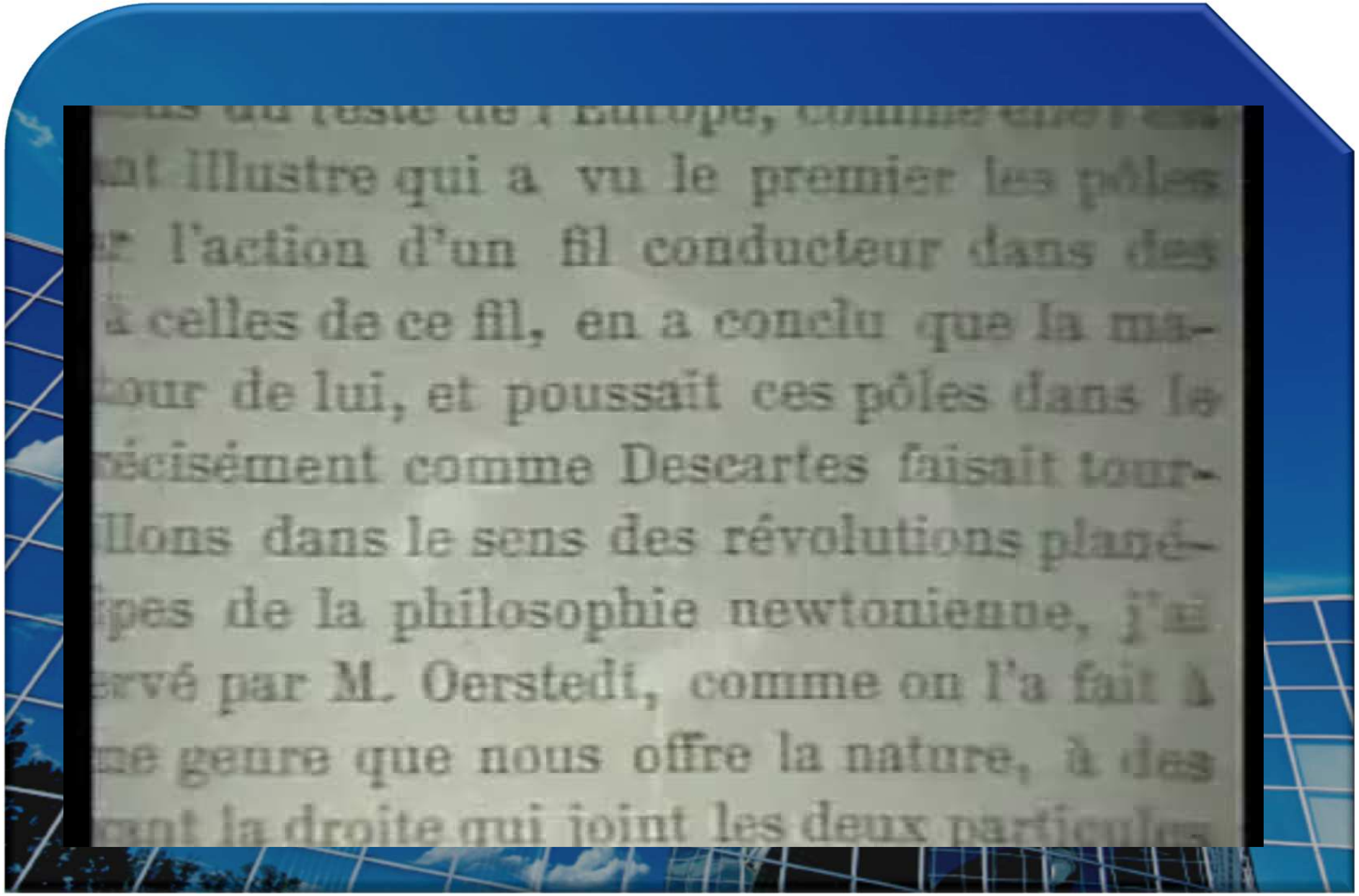
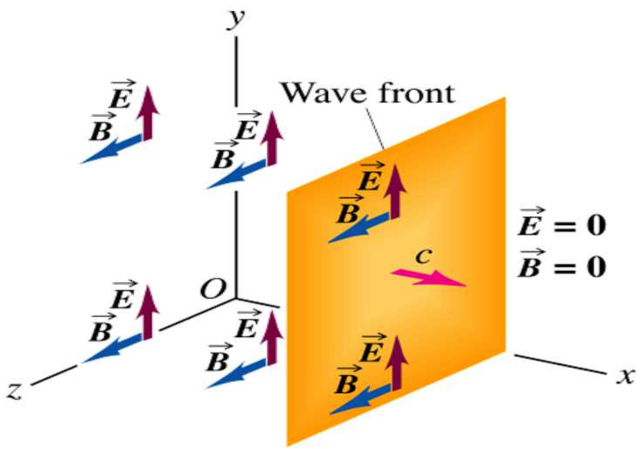
ELECTROMAGENTIC





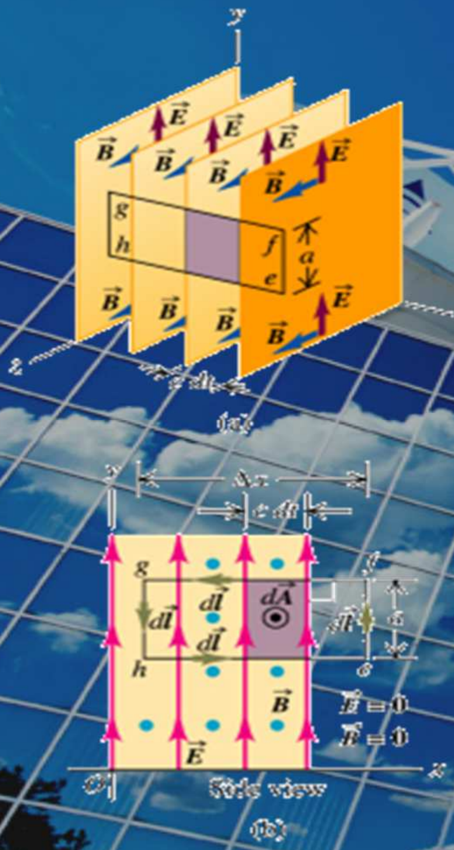
ant illustre qui a vu le premier les pôles
r l'action d'un fil conducteur dans des
à celles de ce fil, en a conclu que la ma-
tour de lui, et poussait ces pôles dans le
récisément comme Descartes faisait tour-
illons dans le sens des révolutions plané-
ipes de la philosophie newtonienne, j'ai
ervé par M. Oerstedt, comme on l'a fait à
me genre que nous offre la nature, à des
ant la droite qui joint les deux particules

Faraday's law to a plane wave



An electromagnetic wave front.
The plane representing the wave front (yellow) moves to the right with speed c.

The **E** and **B** fields are uniform over the region behind the wave front but are zero everywhere in front of it.



$\int E \cdot dl = - d\Phi_B / dt$

1. $\int E \cdot dl = -Ea$ (cos 90° = 0)

2. In time dt the wave front moves to the right a distance $c\,dt$. The magnetic flux through the rectangle in the xy-plane increases by an amount $d\Phi_B$ equal to the flux through the shaded rectangle in the xy-plane with area ac dt, that is,

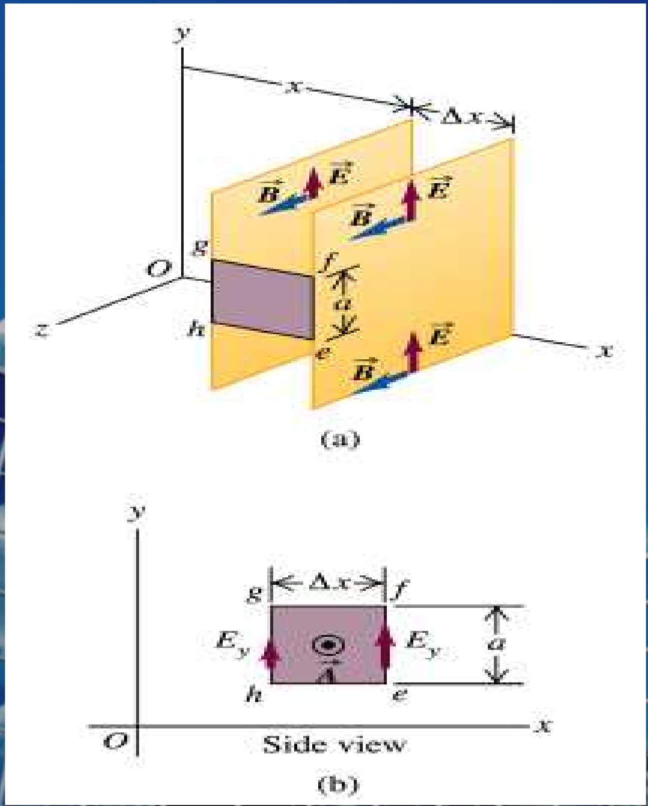
   $d\Phi_B = Bac\ dt$. So

   $-d\Phi_B / dt = -Bac$ and

   $E = Bc$

Faraday's law to a plane wave

Faraday's Law applied to a rectangle with height *a* and width D*x* parallel to the *xy*-plane.



Ampere's law to a plane wave

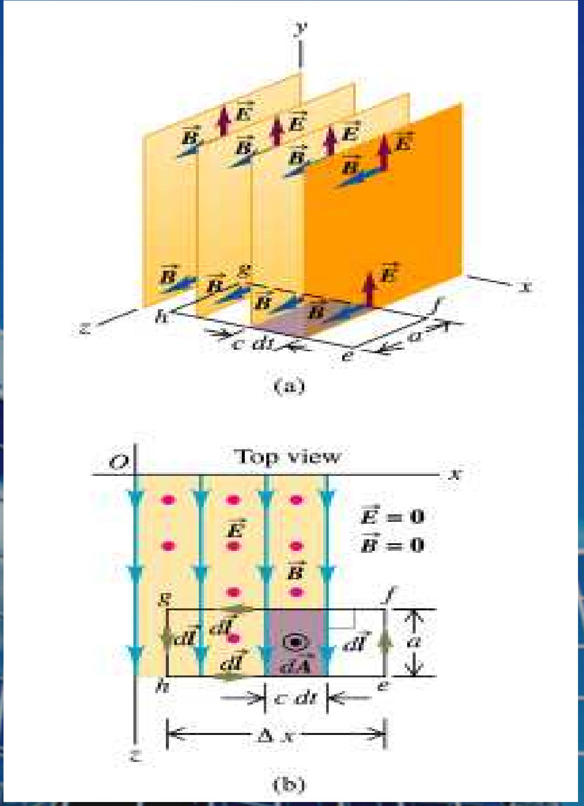
$\int B \cdot dl = \mu_o \varepsilon_o \, d\Phi_E / dt$

1. $\int B \cdot dl = Ba$ (cos 90° = 0)

2. In time *dt* the wave front moves to the right a distance *c dt*. The electric flux through the rectangle in the *xz*-plane increases by an amount $d\Phi_E$ equal to *E* times the area *ac dt* of the shaded rectangle, that is,
$d\Phi_E = Eac\,dt$. Thus
$d\Phi_E / dt = Eac$.
$Ba = \mu_o \varepsilon_o Eac \rightarrow B = \mu_o \varepsilon_o Ec$

and from $E = Bc$ and $B = \mu_o \varepsilon_o Ec$
We must have $c = 1 / (\mu_o \varepsilon_o)^{1/2}$

$c = 3.00\ (10)^8$ m/sec



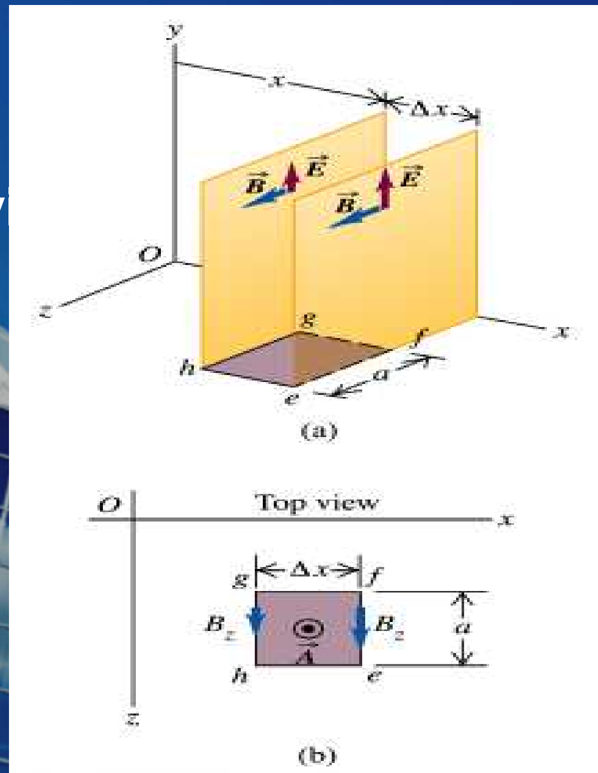
Ampere's law to a plane wave

Ampere's Law applied to a rectangle wi

height *a* and width

D*x* parallel to the

***xz*-plane.**



Guass Law

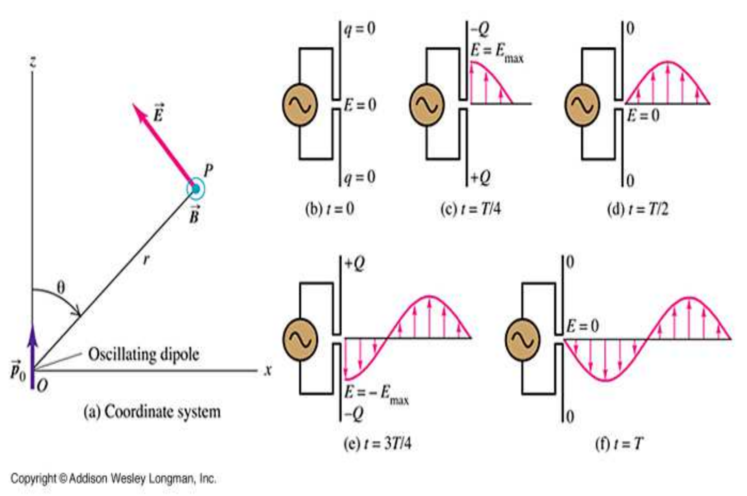
Gauss's law (electrical):

- The total electric flux through any closed surface equals the net charge inside that surface divided by ε_o
- This relates an electric field to the charge distribution that creates it

$$\oint_S \mathbf{E} \cdot d\mathbf{A} = \frac{q}{\varepsilon_o}$$

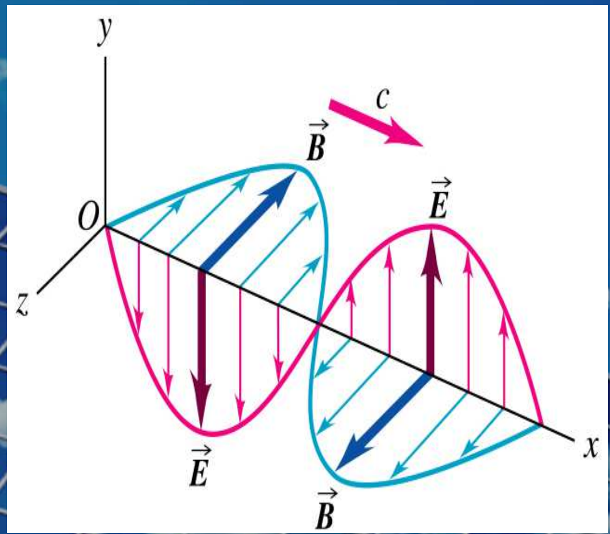
- Gauss's law (magnetism):
- The total magnetic flux through any closed surface is zero
- This says the number of field lines that enter a closed volume must equal the number that leave that volume
- This implies the magnetic field lines cannot begin or end at any point
- Isolated magnetic monopoles

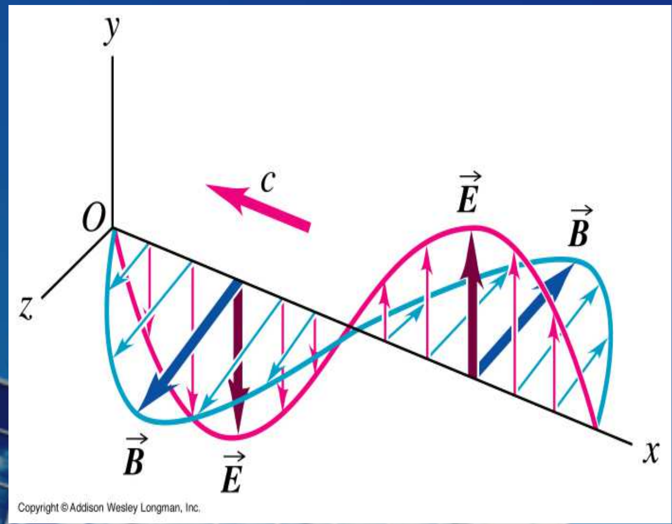
$$\oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$



•One cycle in the production of an electro-magnetic wave by an oscillating electric dipole antenna.

•The red arrows represent the *E* field. (*B* not shown.)





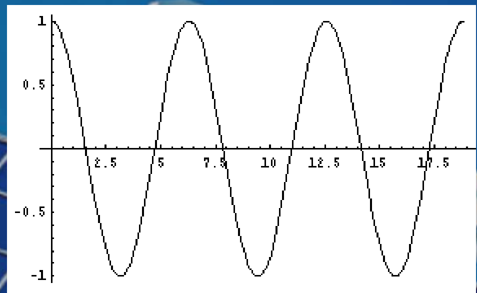
- Representation of the electric and magnetic fields in a propagating wave. One wavelength is shown at time $t = 0$.

- Propagation direction is E x B.

Harmonic Plane Waves

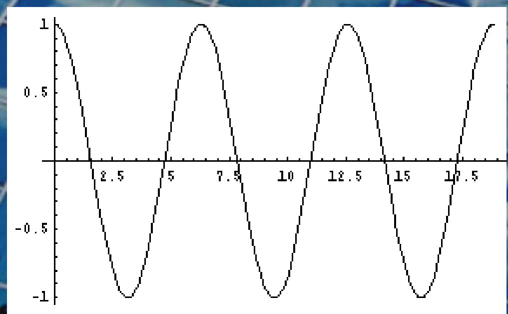
At t = 0

$\vec{E}$



At x = 0

$\vec{E}$



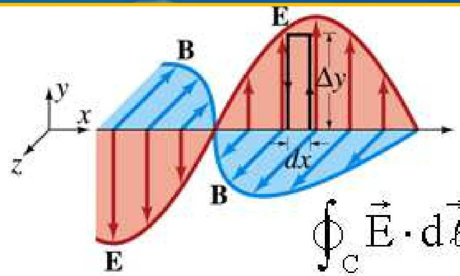
λ = spatial period or wavelength

phase velocity

$$v = \frac{\lambda}{T} = f\lambda = \frac{2\pi}{T}\frac{\lambda}{2\pi} = \frac{\omega}{k}$$

T = temporal period

Applying Faraday to radiation



$$\oint_C \vec{E} \cdot d\vec{\ell} = -\frac{d\Phi_B}{dt}$$

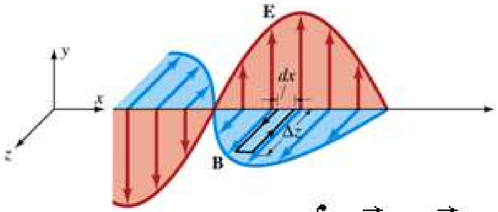
$$\oint_C \vec{E} \cdot d\vec{\ell} = (E + dE)\Delta y - E\Delta y = dE\Delta y$$

$$\frac{d\Phi_B}{dt} = \frac{dB}{dt} dx\Delta y$$

$$dE\Delta y = -\frac{dB}{dt} dx\Delta y$$

$$\frac{dE}{dx} = -\frac{dB}{dt}$$

Applying Ampere to radiation



$$\oint_C \vec{B}\cdot d\vec{\ell} = \mu_o \varepsilon_o \frac{d\Phi_E}{dt}$$

$$\oint_C \vec{B}\cdot d\vec{\ell} = B\Delta z - (B + dB)\Delta z = -dB\Delta z$$

$$\frac{d\Phi_E}{dt} = \frac{dE}{dt} dx\Delta z$$

$$-dB\Delta z = \mu_o \varepsilon_o \frac{dE}{dt} dx\Delta z$$

$$\frac{dB}{dx} = -\mu_o \varepsilon_o \frac{dE}{dt}$$

Fields are functions of both position (x) and time (t)

$$\frac{dE}{dx} = -\frac{dB}{dt}$$

$$\frac{dB}{dx} = -\mu_\circ \varepsilon_\circ \frac{dE}{dt}$$

Partial derivatives are appropriate

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

$$\frac{\partial B}{\partial x} = -\mu_\circ \varepsilon_\circ \frac{\partial E}{\partial t}$$

$$\frac{\partial^2 E}{\partial x^2} = -\frac{\partial}{\partial x}\frac{\partial B}{\partial t}$$

$$\frac{\partial}{\partial t}\frac{\partial B}{\partial x} = -\mu_\circ \varepsilon_\circ \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 E}{\partial x^2} = \mu_\circ \varepsilon_\circ \frac{\partial^2 E}{\partial t^2}$$

This is a wave equation!

The Trial Solution

The simplest solution to the partial differential equations is a sinusoidal wave:

$E = E_{max} \cos (kx - \omega t)$

$B = B_{max} \cos (kx - \omega t)$

The angular wave number is $k = 2\pi/\lambda$

λ is the wavelength

The angular frequency is $\omega = 2\pi f$

f is the wave frequency

The Trial Solution

$$E = E_y = E_o \sin(kx - \omega t)$$

$$\frac{\partial^2 E}{\partial x^2} = \mu_o \varepsilon_o \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 E}{\partial x^2} = -k^2 E_o \sin(kx - \omega t) \qquad \frac{\partial^2 E}{\partial t^2} = -\omega^2 E_o \sin(kx - \omega t)$$

$$-k^2 E_o \sin(kx - \omega t) = -\mu_o \varepsilon_o \omega^2 E_o \sin(kx - \omega t)$$

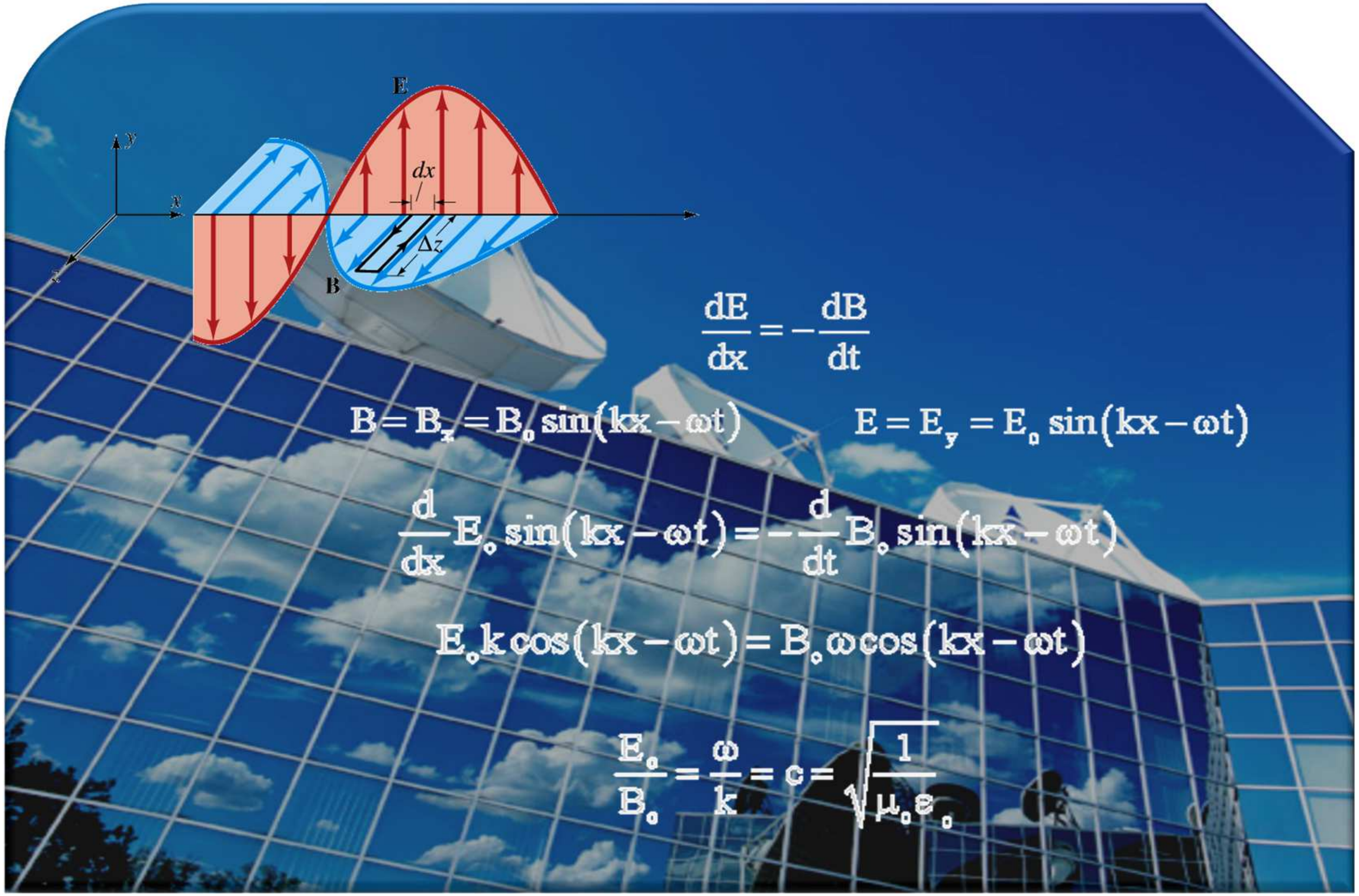
$$\frac{\omega^2}{k^2} = \frac{1}{\mu_o \varepsilon_o}$$

The speed of light

$$v = \frac{\lambda}{T} = f\lambda = \frac{2\pi}{T}\frac{\lambda}{2\pi} = \frac{\omega}{k}$$

$$v = c = \frac{\omega}{k} = \sqrt{\frac{1}{\mu_o \varepsilon_o}}$$

Another look



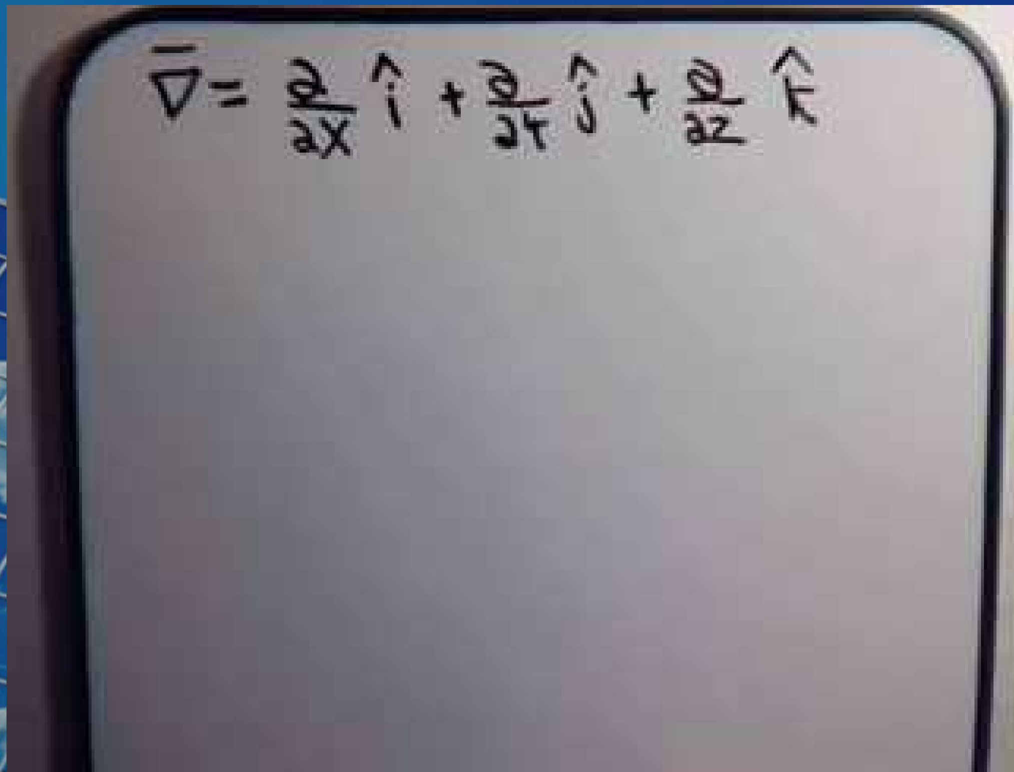
$$\frac{dE}{dx} = -\frac{dB}{dt}$$

$$B = B_z = B_0 \sin(kx - \omega t) \qquad E = E_y = E_0 \sin(kx - \omega t)$$

$$\frac{d}{dx} E_0 \sin(kx - \omega t) = -\frac{d}{dt} B_0 \sin(kx - \omega t)$$

$$E_0 k \cos(kx - \omega t) = B_0 \omega \cos(kx - \omega t)$$

$$\frac{E_0}{B_0} = \frac{\omega}{k} = c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}}$$


$\bar{\nabla} = \frac{\partial}{\partial x}\hat{i} + \frac{\partial}{\partial y}\hat{j} + \frac{\partial}{\partial z}\hat{k}$