Capítulo 7:

Ecuaciones de Maxwell y Ondas Electromagnéticas

Hasta ahora:

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_o}$$ Ley de Gauss

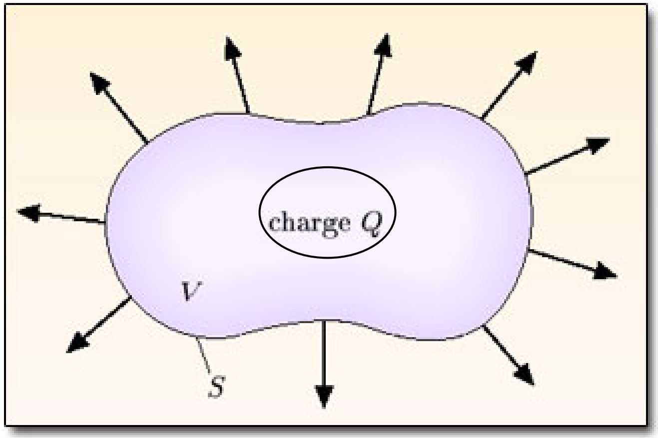
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$ Ley de Faraday-Henry

$$\nabla \cdot \vec{B} = 0$$ Ley de Gauss para el magnetismo

$$\nabla \mathbf{x} \vec{\mathbf{B}} = \mu_0 \vec{\mathbf{J}}$$ Ley de Ampere

Veremos que la Ley de Ampere presenta problemas

Principio de conservación de la carga



$$-\frac{\partial}{\partial t}\int_V \rho\, dV = \int_S \mathbf{J}\cdot \mathbf{dS} = I = -\frac{\partial Q}{\partial t}$$

Usando el teorema de la divergencia:

$$\boxed{\nabla \cdot \vec{J} = -\frac{\partial \rho}{\partial t}}$$

Ecuación de continuidad de la carga

Ley de Ampere-Maxwell

James Clerk Maxwell (1831-1879)

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j}$$

Ley de Ampere

$$\underbrace{\vec{\nabla} \cdot \left(\vec{\nabla} \times \vec{B} \right)}_{=0} = \mu_0 \vec{\nabla} \cdot \vec{j} \quad \Longrightarrow \quad \nabla \cdot \vec{j} = 0$$

Maxwell propuso un termino adicional:

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

$$\vec{\nabla} \cdot \left(\vec{\nabla} \times \vec{B} \right) = \mu_0 \vec{\nabla} \cdot \vec{j} + \mu_0 \epsilon_0 \frac{\partial}{\partial t} \left(\vec{\nabla} \cdot \vec{E} \right) \quad = 0$$

Usando la Ley de Gauss

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0} \quad \Longrightarrow \quad \nabla \cdot \vec{J} = -\frac{\partial \rho}{\partial t}$$

Ley de Ampere-Maxwell en forma diferencial

$$\boxed{\vec{\nabla} \times \vec{B} = \mu_0 \vec{\jmath} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}}$$

Ley de Ampere-Maxwell en forma integral

$$\boxed{\oint_C \vec{B} \cdot d\vec{s} = \mu_0 \int_S \vec{\jmath} \cdot \vec{n} \cdot dS + \mu_0 \epsilon_0 \frac{d}{dt} \int_S \vec{E} \cdot \vec{n} \cdot dS}$$

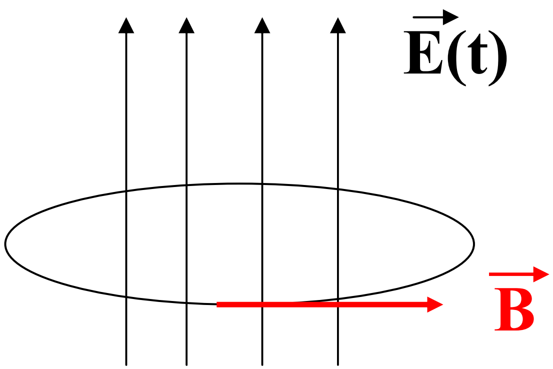
Los campos magnéticos son producidos por corrientes eléctricas y por campos eléctricos variables.

En ausencia de corrientes:

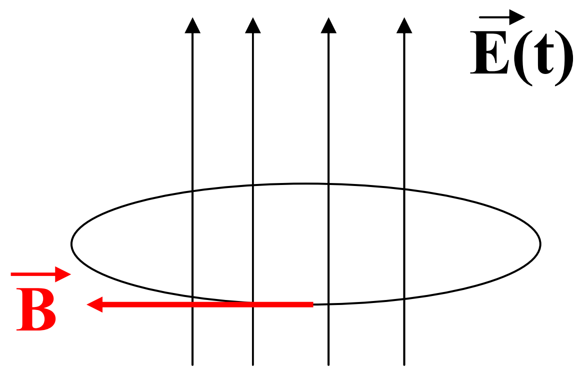
$$\oint \vec{\mathbf{B}} \cdot d\,\vec{\mathbf{s}} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$

Comentar similitudes y diferencias con la Ley de Faraday

$$\oint \vec{\mathbf{E}} \cdot d\,\vec{\mathbf{s}} = -\frac{d\Phi_B}{dt}$$

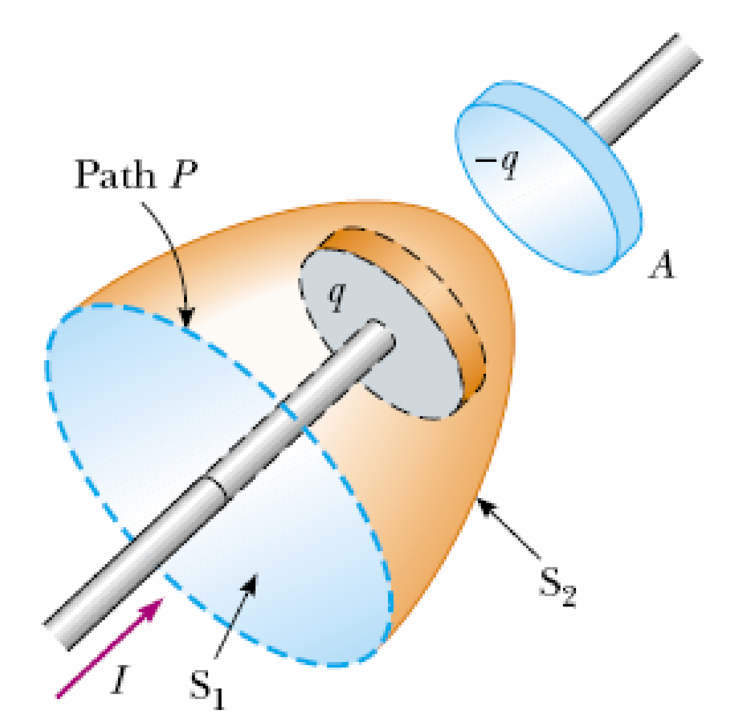


E aumenta



E disminuye

Ejemplo de la necesidad del nuevo término



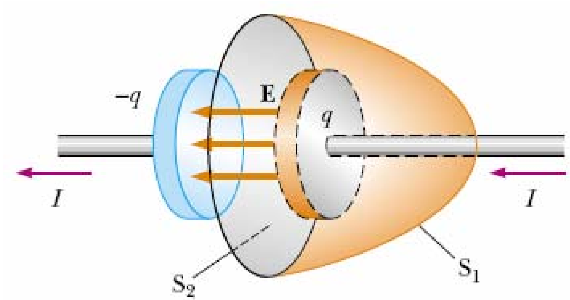
Usando Ley de Ampere:

S_1: $$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I$$

S_2: $$\oint \mathbf{B} \cdot d\mathbf{s} = 0$$

Esta contradicción la resuelve el nuevo término:

$I \neq 0$ ⟶ Capacitor se esta cargando ⟶ q(t) ⟶ E(t)

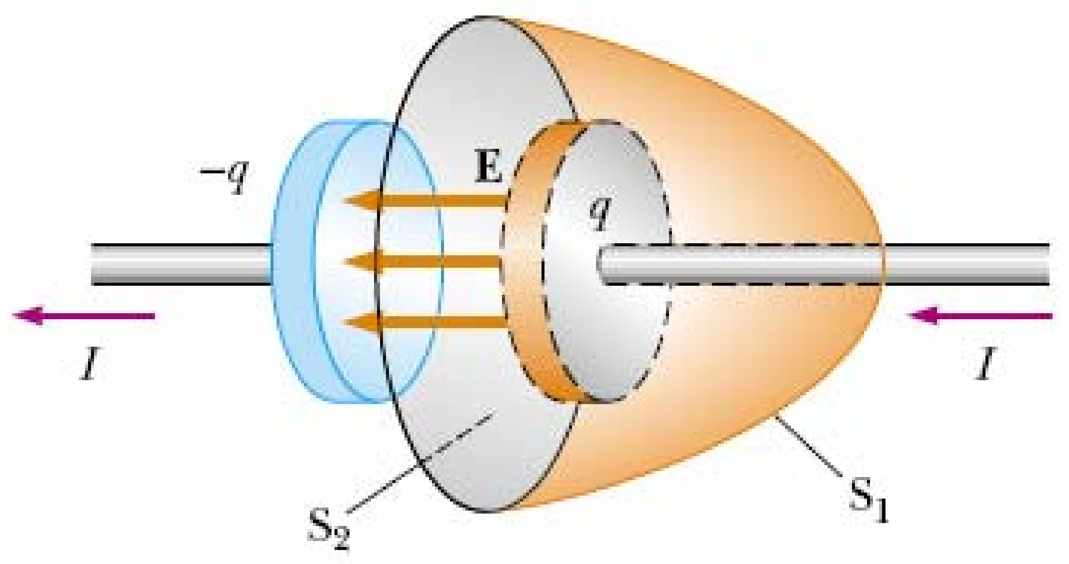


Por razones históricas, se denomina

$$I_d \equiv \epsilon_0 \frac{d\Phi_E}{dt}$$

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0(I + I_d) = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

corriente de desplazamiento



S_1:

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I$$

S_2:

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I_d$$

$$\Phi_E = \int \mathbf{E} \cdot d\mathbf{A}$$

$$\Phi_E = EA = \frac{q}{\epsilon_0}$$

$$I_d = \epsilon_0 \frac{d\Phi_E}{dt} = \frac{dq}{dt}$$

Ecuaciones de Maxwell

Ley	Forma diferencial	Forma integral
Gauss	$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\epsilon_0}$	$\oint_S \vec{E}\cdot d\vec{s}=\frac{q}{\epsilon_0}$
Gauss para B	$\vec{\nabla}\cdot\vec{B}=0$	$\oint_S \vec{B}\cdot d\vec{s}=0$
Faraday-Henry	$\vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$	$\oint_C \vec{E}\cdot d\vec{l}=-\frac{d}{dt}\int_S \vec{B}\cdot d\vec{s}$
Ampere-Maxwell	$\vec{\nabla}\times\vec{B}=\mu_0\vec{j}+\mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t}$	$\oint_C \vec{B}\cdot d\vec{l}=\mu_0\int_S \vec{j}\cdot\vec{n}\cdot ds+\mu_0\epsilon_0\frac{d}{dt}\int_S \vec{E}\cdot\vec{n}\cdot ds$

Fuerza de Lorentz $\mathbf{F}=q\mathbf{E}+q\mathbf{v}\times\mathbf{B}$

Aquí tenemos el electromagnetismo!!!!

Física Clásica

Maxwell's equations

I. $\nabla \cdot \boldsymbol{E} = \dfrac{\rho}{\epsilon_0}$ (Flux of $\boldsymbol{E}$ through a closed surface) $=$ (Charge inside)$/\epsilon_0$

II. $\nabla \times \boldsymbol{E} = -\dfrac{\partial \boldsymbol{B}}{\partial t}$ (Line integral of $\boldsymbol{E}$ around a loop) $= -\dfrac{d}{dt}$ (Flux of $\boldsymbol{B}$ through the loop)

III. $\nabla \cdot \boldsymbol{B} = 0$ (Flux of $\boldsymbol{B}$ through a closed surface) $= 0$

IV. $c^2 \nabla \times \boldsymbol{B} = \dfrac{\boldsymbol{j}}{\epsilon_0} + \dfrac{\partial \boldsymbol{E}}{\partial t}$ c^2(Integral of $\boldsymbol{B}$ around a loop) $=$ (Current through the loop)$/\epsilon_0$

$+\dfrac{\partial}{\partial t}$ (Flux of $\boldsymbol{E}$ through the loop)

Conservation of charge

$\nabla \cdot \boldsymbol{j} = -\dfrac{\partial \rho}{\partial t}$ (Flux of current through a closed surface) $= -\dfrac{\partial}{\partial t}$ (Charge inside)

Force law

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Law of motion

$\dfrac{d}{dt}(\boldsymbol{p}) = \boldsymbol{F}$, where $\boldsymbol{p} = \dfrac{m\boldsymbol{v}}{\sqrt{1 - v^2/c^2}}$ (Newton's law, with Einstein's modification)

Gravitation

$$\boldsymbol{F} = -G\,\frac{m_1 m_2}{r^2}\,\boldsymbol{e}_r$$

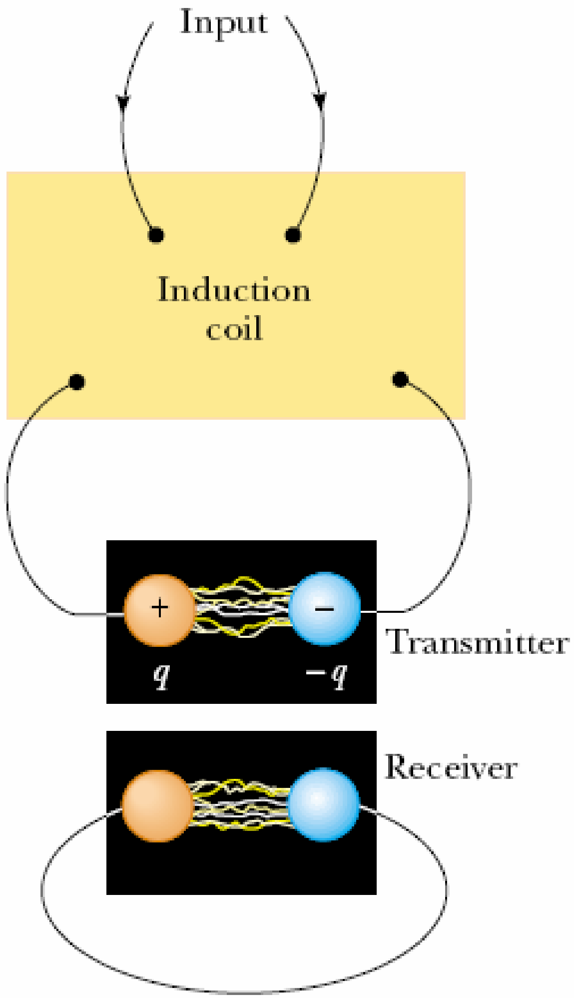
Gran descubrimiento!!! → Ondas electromagnéticas

$$E(t) \longrightarrow B(t) \longrightarrow E(t) \longrightarrow B(t) \longrightarrow E(t) \longrightarrow B(t)$$

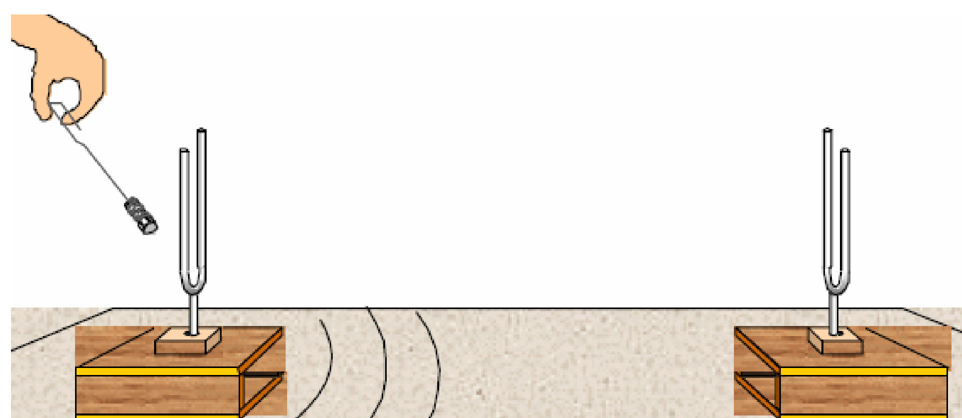
Maxwell predijo en forma teórica la existencia de ondas de E y B (ondas electromagnéticas)

generó y detectó ondas electromagnéticas

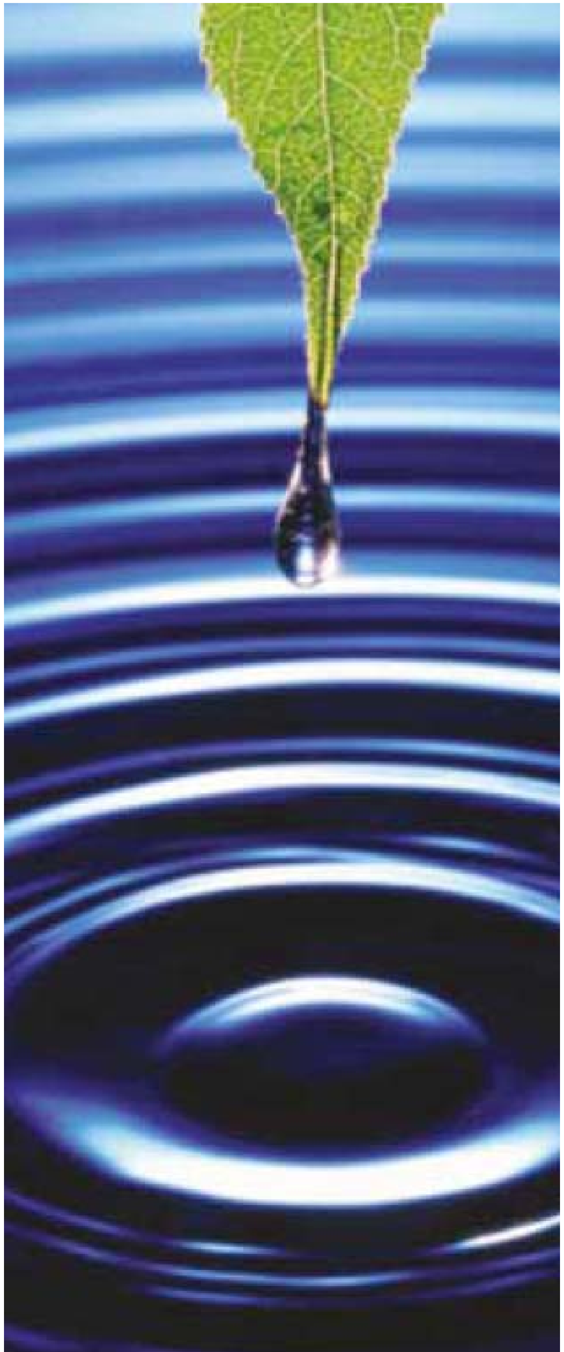
Heinrich Hertz (1857-1894)



Análogo mecánico



Movimiento Ondulatorio



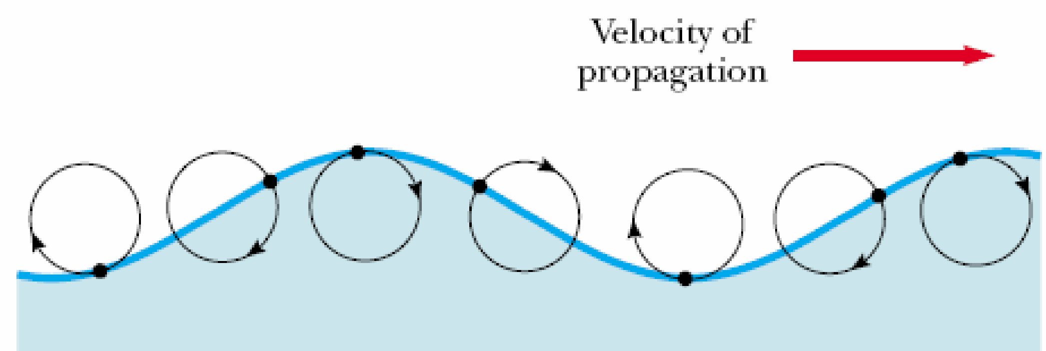
Características comunes

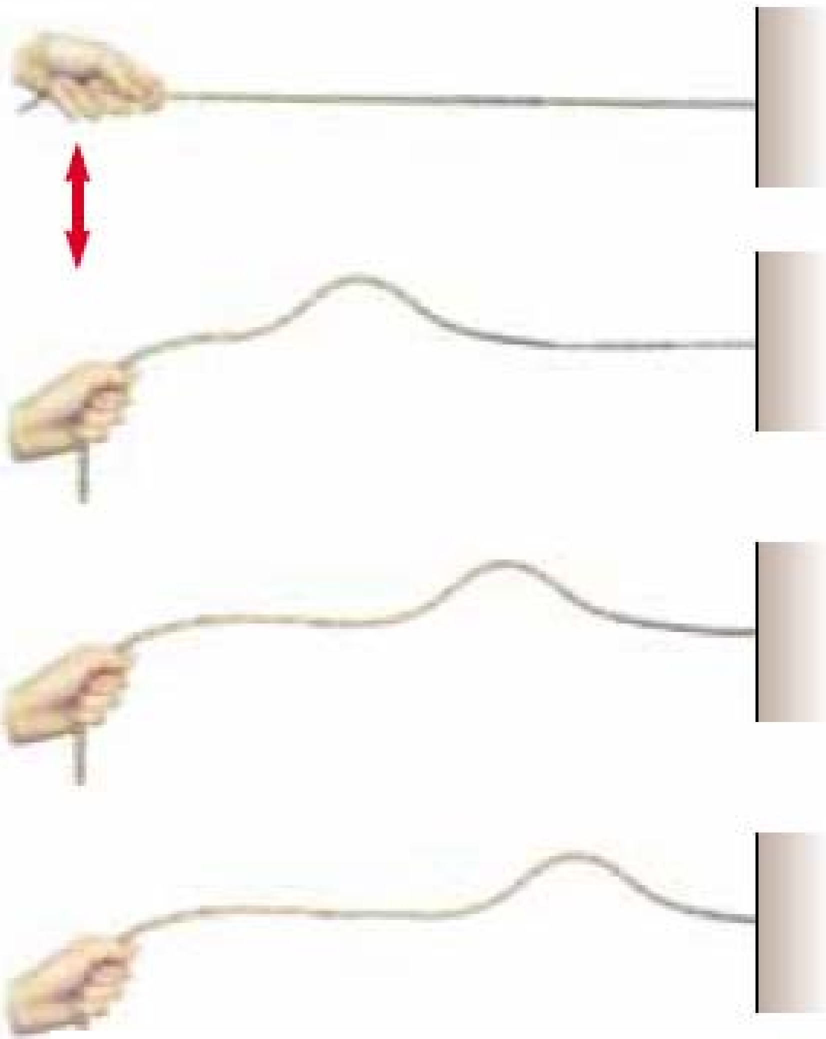
1- estado inicial de equilibrio

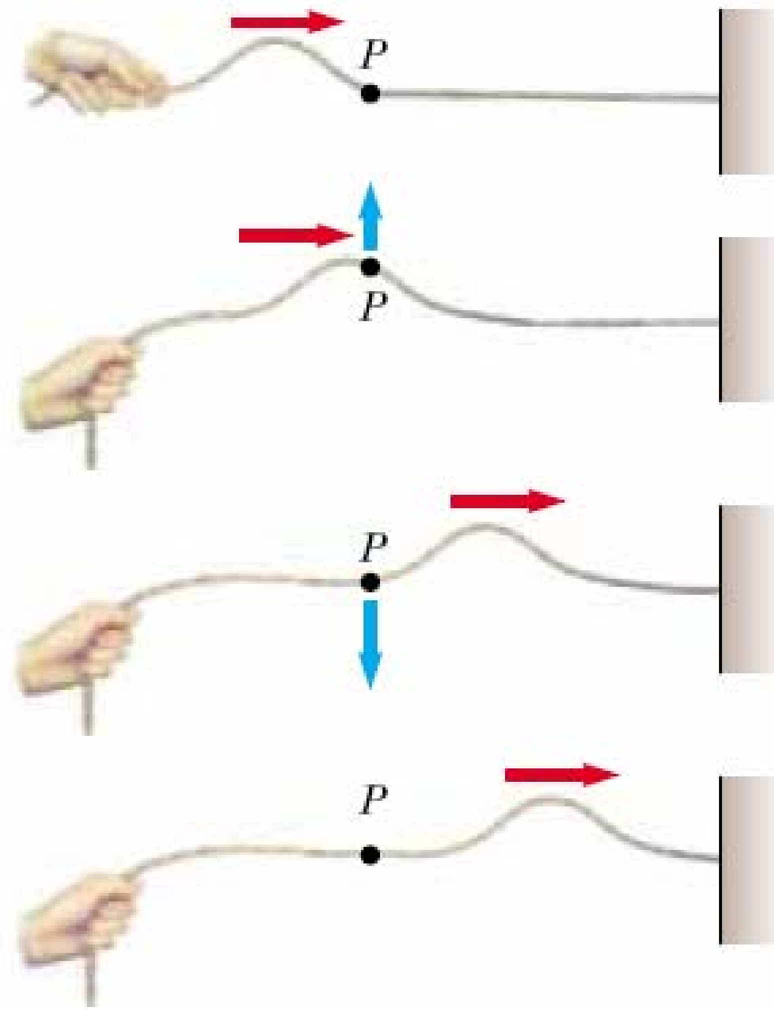
2- perturbación en un punto del espacio

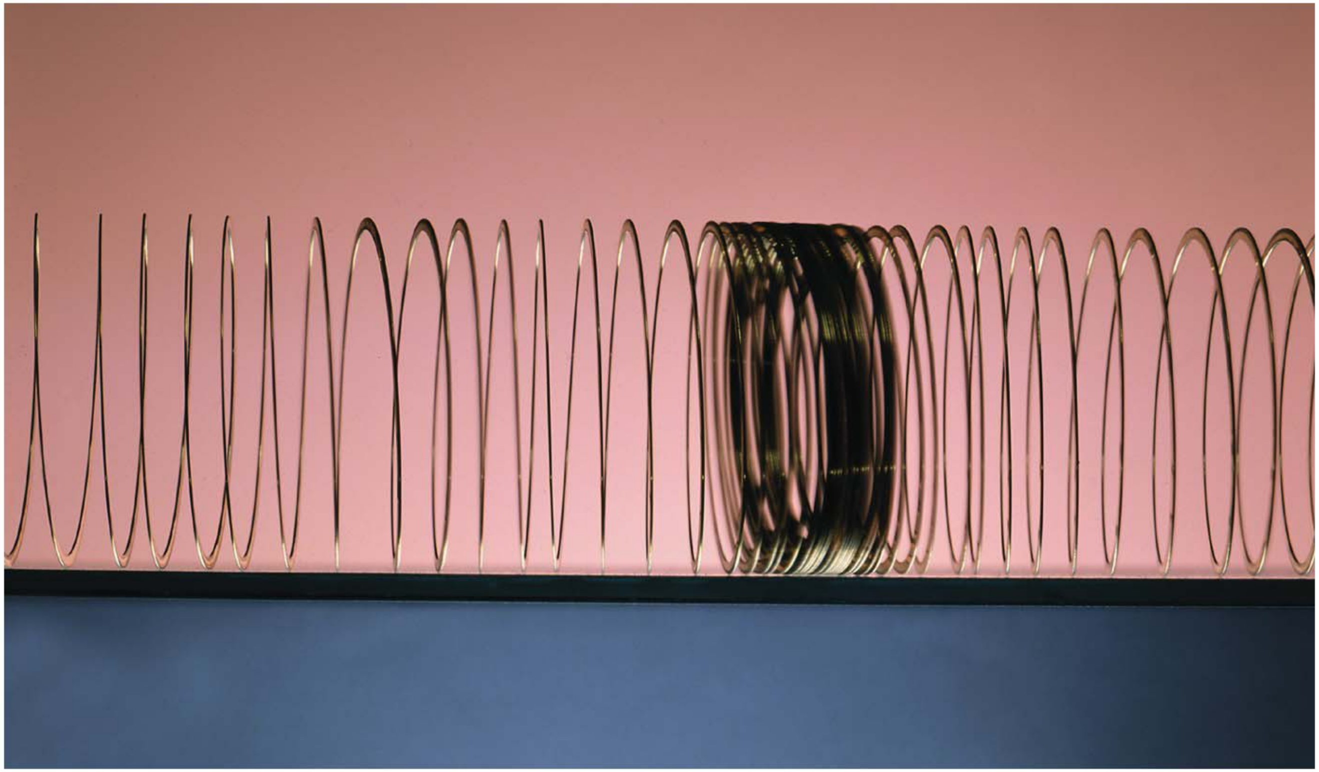
3- propagación de la perturbación con velocidad v

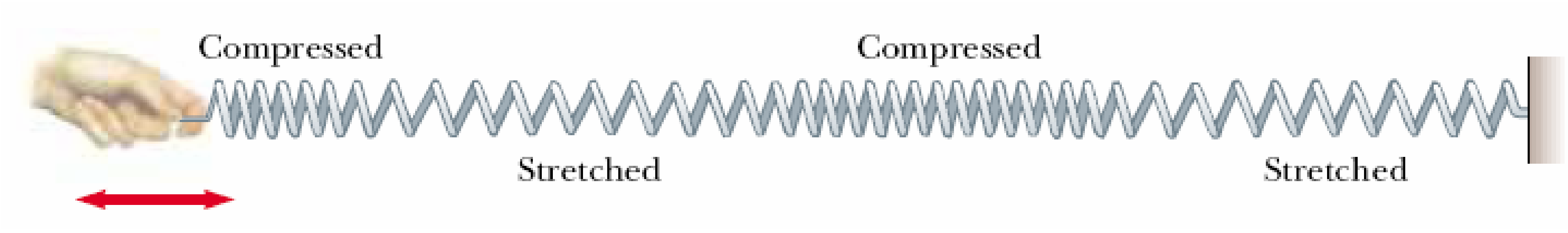
4- oscilación del medio perturbado alrededor de la posición de equilibrio



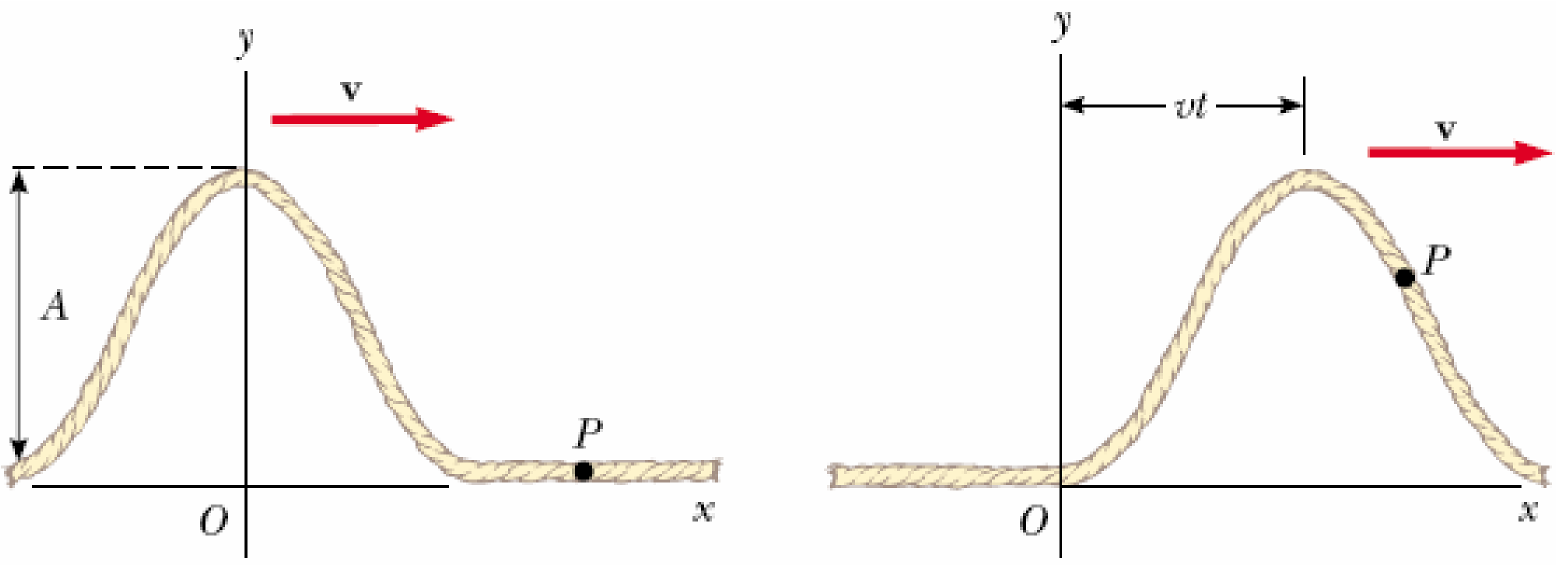



P
P
P
P




Compressed
Compressed
Stretched
Stretched

Descripción matemática de la propagación



(a) Pulse at $t = 0$

(b) Pulse at time t

$$y(x, t) = f(x - vt)$$

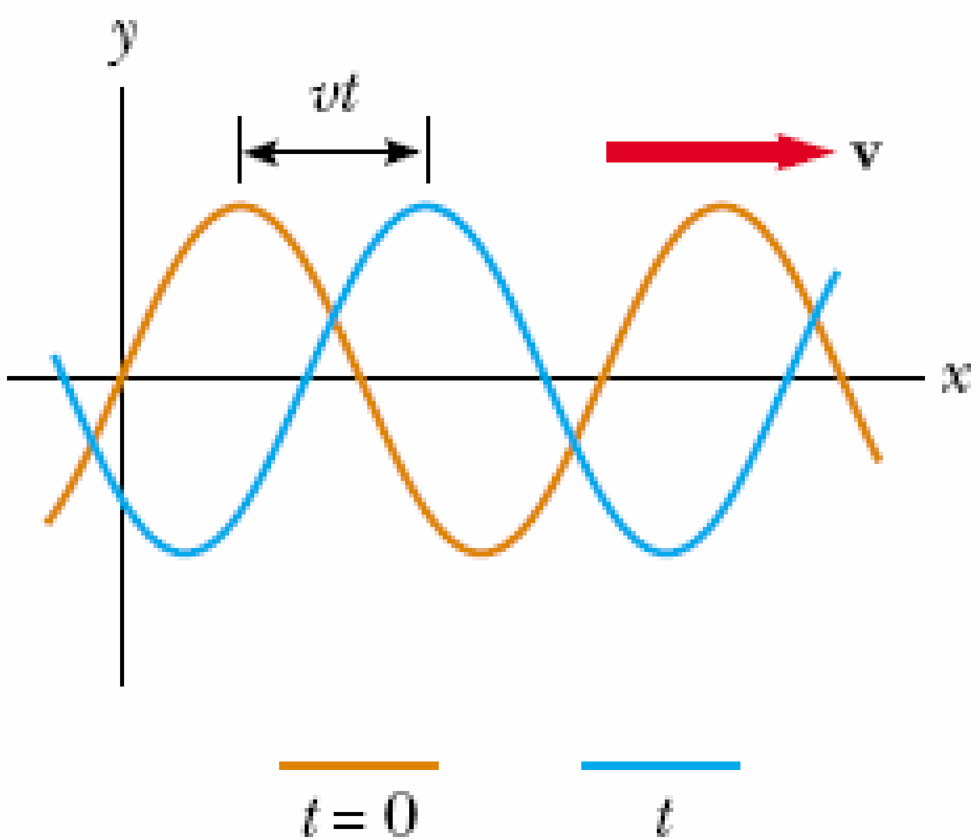
$$y(x, t) = f(x + vt)$$

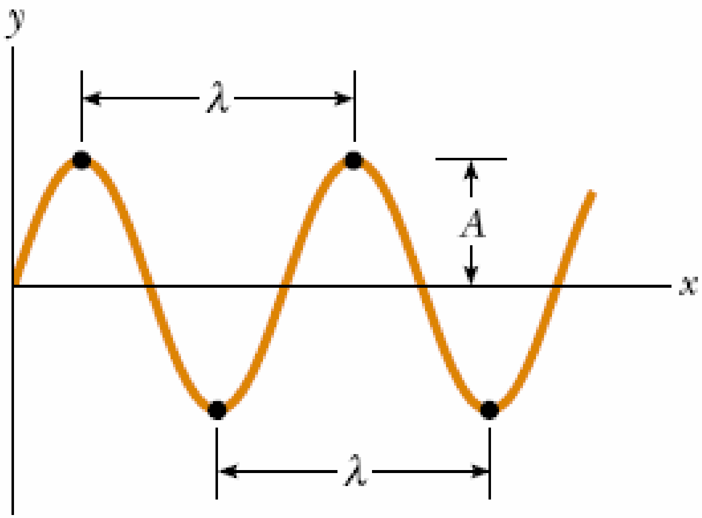
Describe una situación física que viaja o se propaga

Caso especialmente interesante:

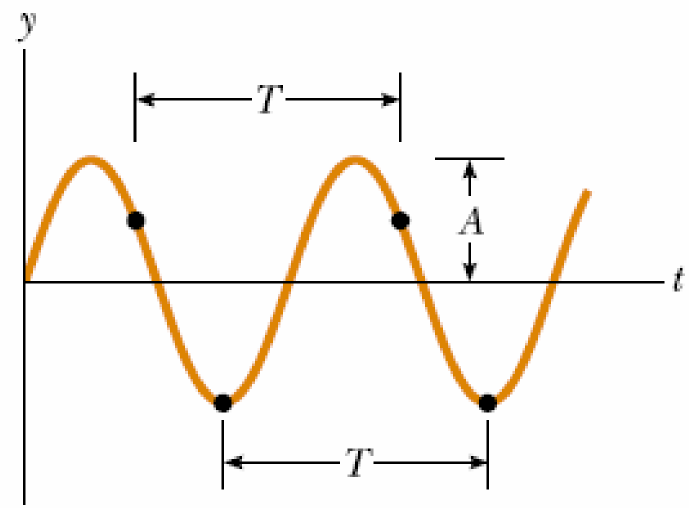
$$y(x, t) = A \sin\left[\frac{2\pi}{\lambda}(x - vt)\right]$$

onda sinusoidal o armónica





longitud de onda



periodo

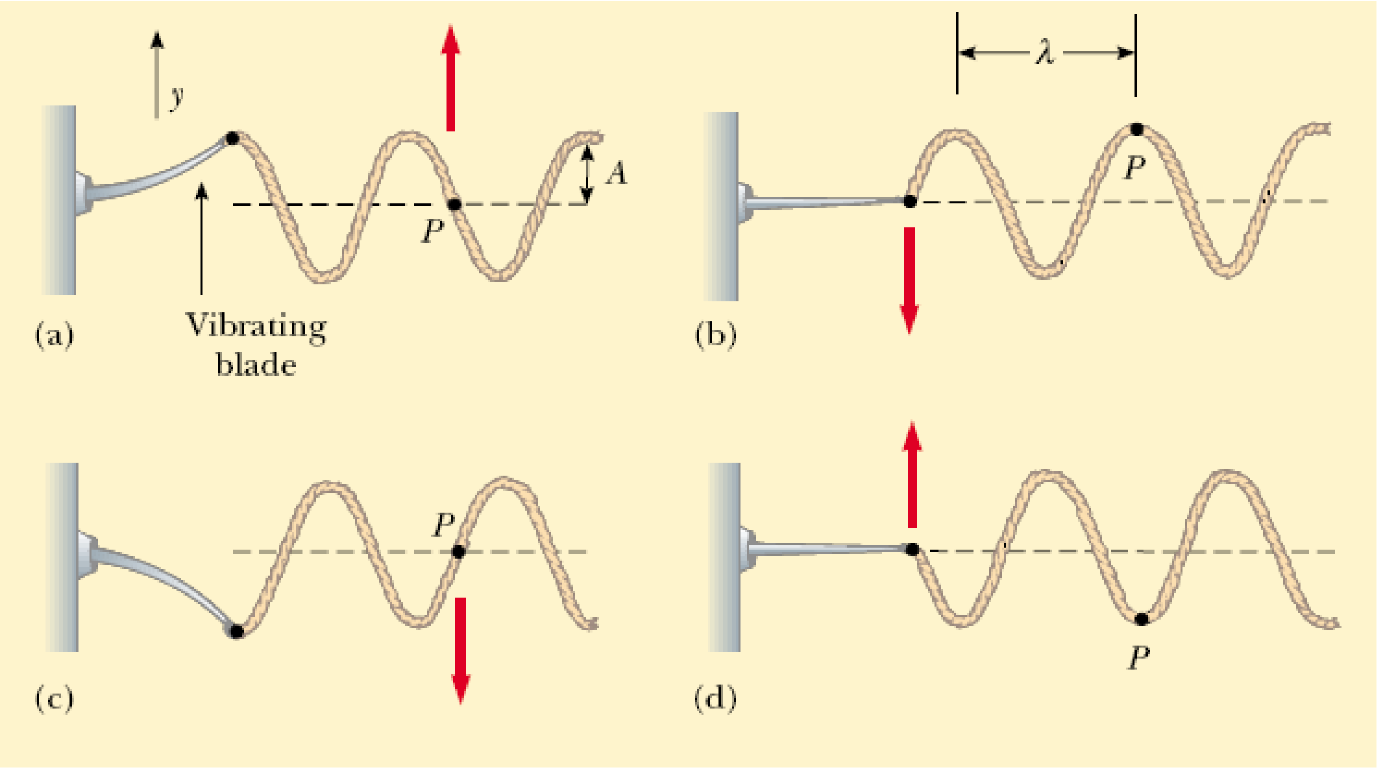
$$k \equiv \frac{2\pi}{\lambda}$$ nº de onda

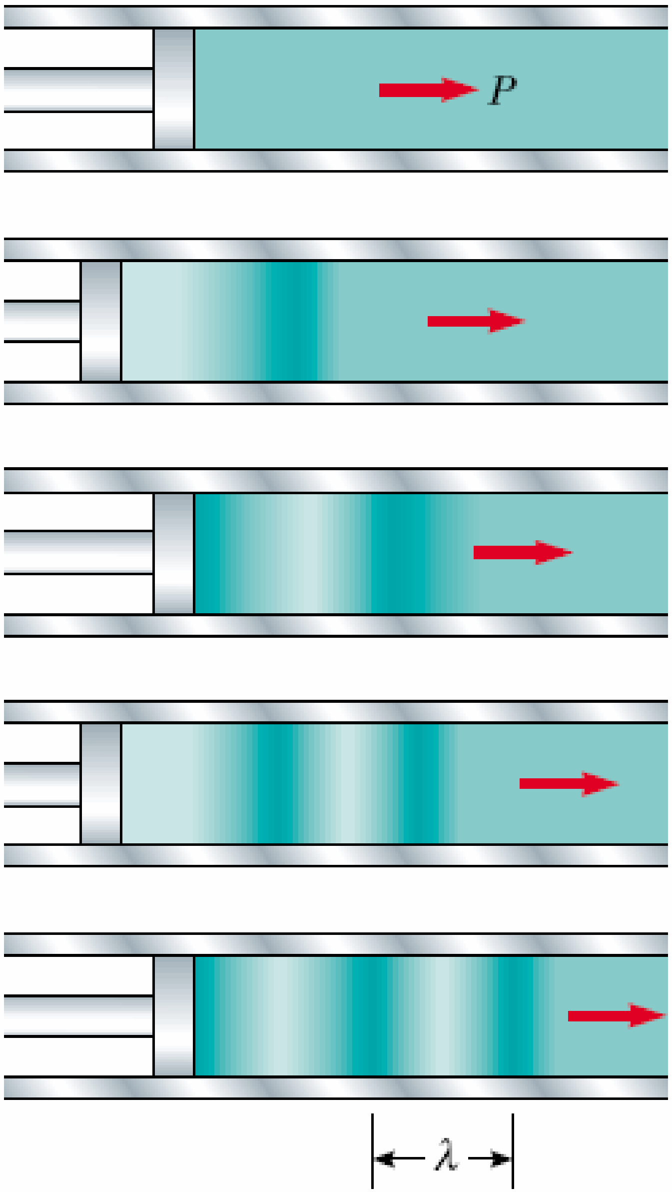
$$f = \frac{1}{T}$$ frecuencia

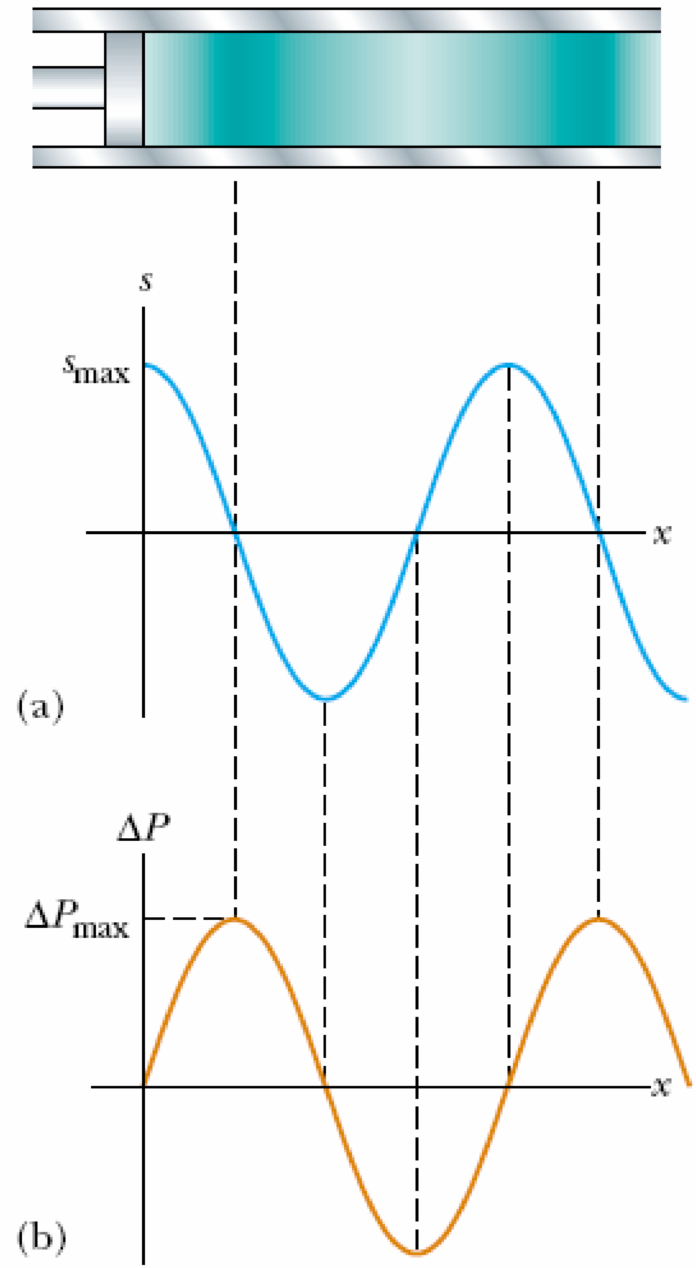
$$\omega \equiv \frac{2\pi}{T}$$ frecuencia angular

$$y(x, t) = A \sin\left[\frac{2\pi}{\lambda}(x - vt)\right] \Longrightarrow y = A \sin(kx - \omega t)$$

donde $v = \dfrac{\omega}{k}$ $\qquad v = \dfrac{\lambda}{T}$ $\qquad v = \lambda f$







$$\Delta P = \Delta P_{\max} \sin(kx - \omega t)$$

Ecuación diferencial del movimiento oscilatorio

supongamos $\psi(x \pm vt)$ **llamamos** $x' = x \pm vt$ $\longrightarrow$ $\partial x' / \partial x = 1$, $\partial x' / \partial t = \pm v$

$$\frac{\partial \psi(x')}{\partial x} = \frac{\partial \psi}{\partial x'}\frac{\partial x'}{\partial x} = \frac{\partial \psi}{\partial x'} \longrightarrow \frac{\partial^2 \psi}{\partial x^2} = \frac{\partial}{\partial x}\left(\frac{\partial \psi}{\partial x'}\right) = \frac{\partial^2 \psi}{\partial x'^2}\frac{\partial x'}{\partial x} = \frac{\partial^2 \psi}{\partial x'^2}$$

$$\frac{\partial \psi}{\partial t} = \frac{\partial \psi}{\partial x'}\frac{\partial x'}{\partial t} = \pm v \frac{\partial \psi}{\partial x'} \longrightarrow \frac{\partial^2 \psi}{\partial t^2} = \frac{\partial}{\partial t}\left(\pm v \frac{\partial \psi}{\partial x'}\right) = \pm v \frac{\partial^2 \psi}{\partial x'^2}\frac{\partial x'}{\partial t} = v^2 \frac{\partial^2 \psi}{\partial x'^2}$$

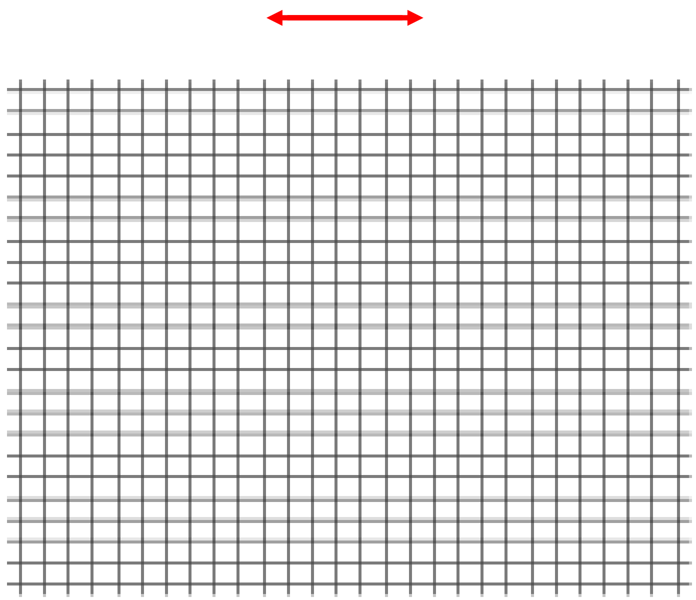
$$\frac{\partial^2 \psi}{\partial x'^2} = \boxed{\frac{\partial^2 \psi}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 \psi}{\partial t^2}}$$

ecuación de onda

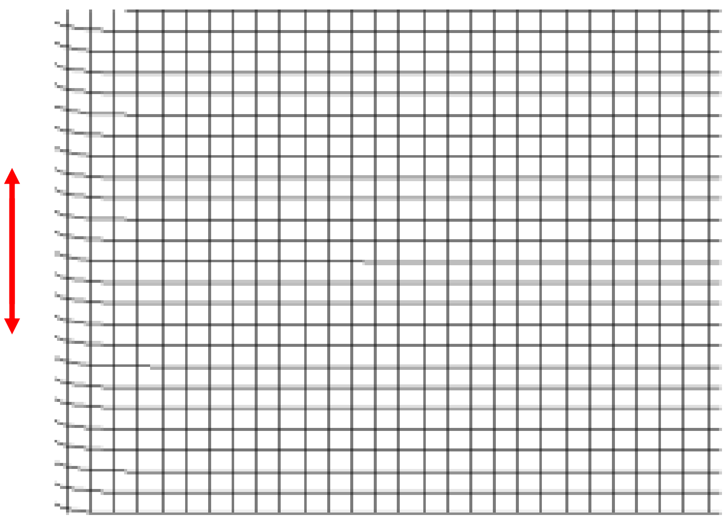
Si $\psi_1(x,t)$ **y** $\psi_2(x,t)$ **son solución** $\longrightarrow$ $\psi_1(x,t) \pm \psi_2(x,t)$ **es solución**

dirección de propagación de la onda

perturbación

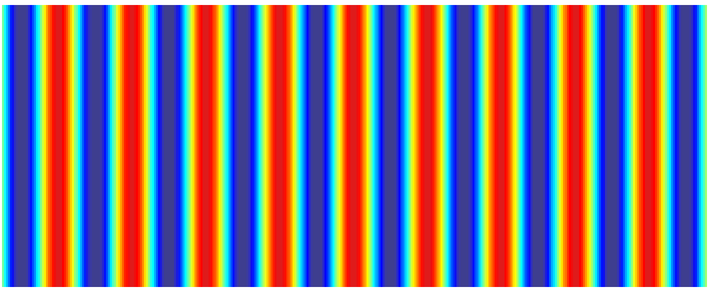


onda longitudinal

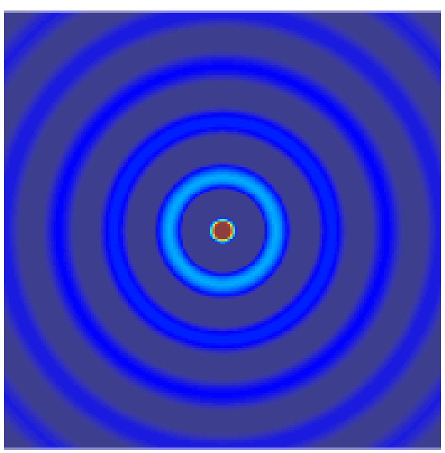


onda transversal

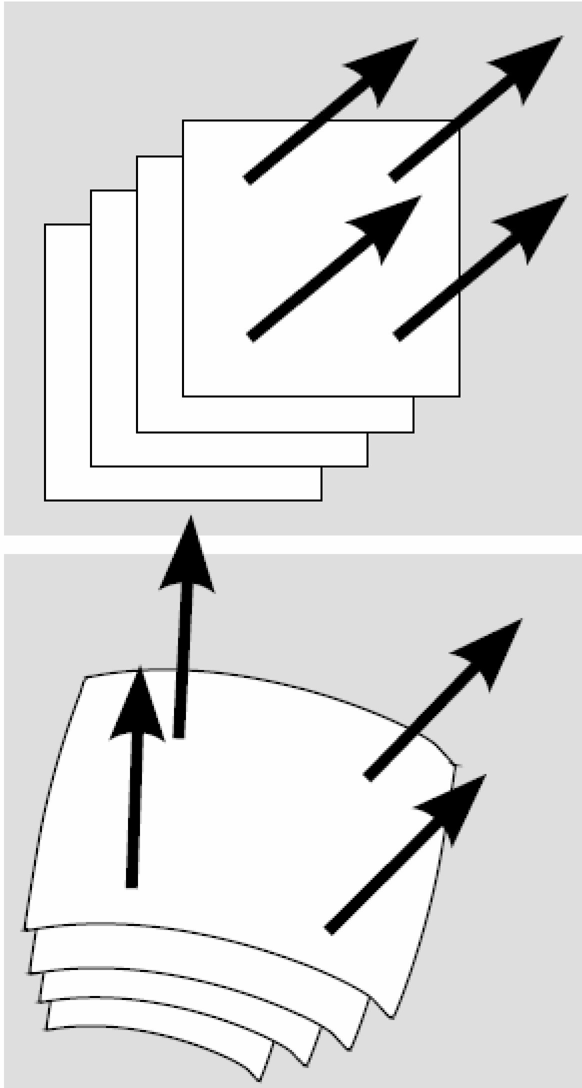
Frente de onda: lugar del espacio donde la perturbación toma el mismo valor en un dado instante de tiempo.



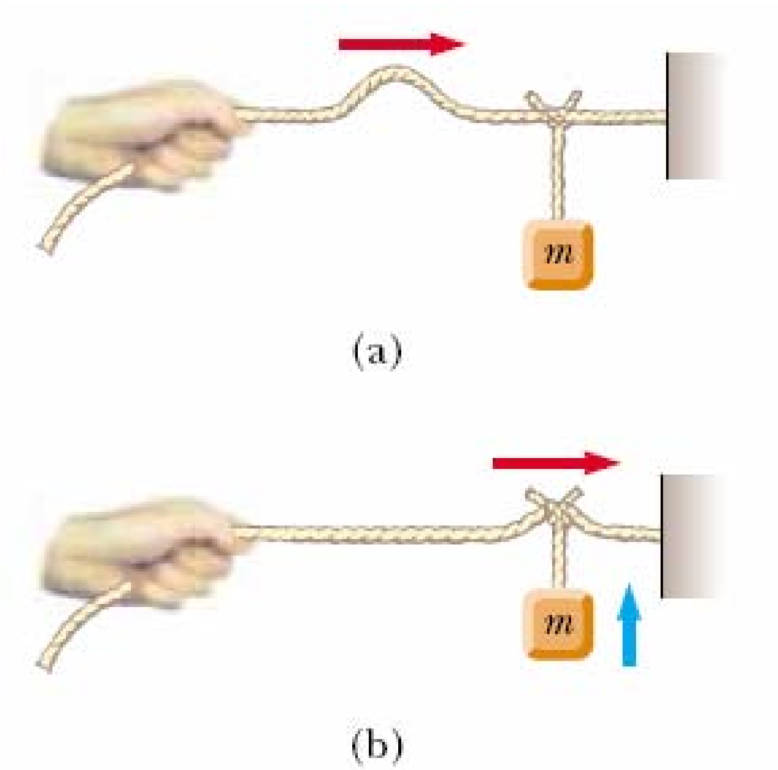
onda plana



onda esférica



Que se propaga en un movimiento ondulatorio?

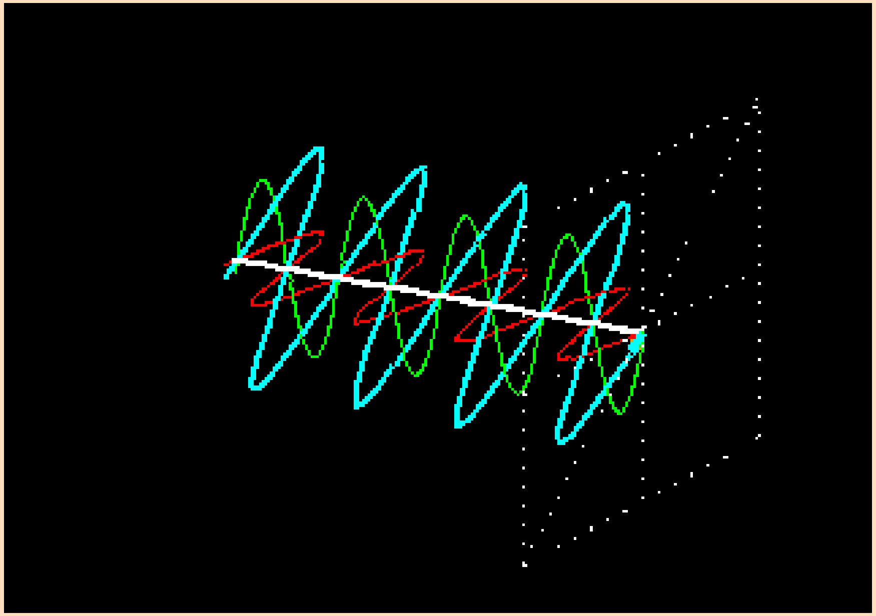


Respuesta general:

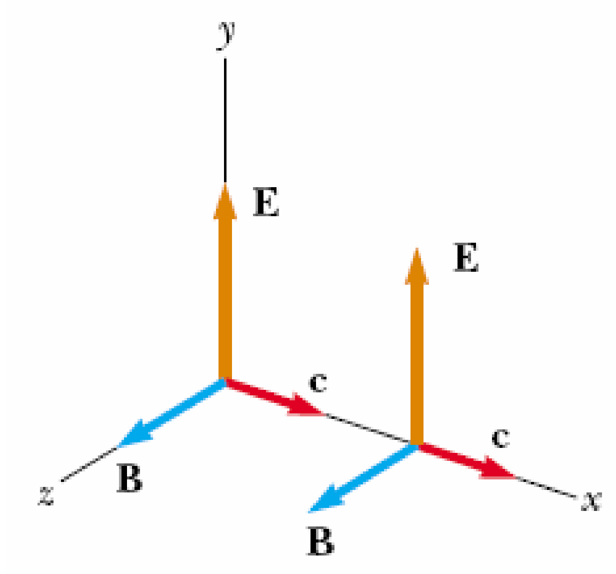
una condición física generada en algún lugar y que se transmite a otra regiones

En un mov. ondulatorio se propaga momento y energía

Ondas Electromagnéticas Planas



Ecuaciones de Maxwell en el vacio (j=0, ρ=0) $\Longrightarrow$ **Ondas EM**



Suponemos:

$$\vec{E} = (0, E, 0)$$

$$\vec{B} = (0, 0, B)$$

1- $\nabla \cdot \vec{E} = 0 \longrightarrow \dfrac{\partial E_x}{\partial x} + \dfrac{\partial E_y}{\partial y} + \dfrac{\partial E_z}{\partial z} = 0$

$$\frac{\partial E}{\partial y} = 0 \longrightarrow E \neq E\,(y)$$

$$2\text{-}\quad \nabla \cdot \vec{B} = 0 \longrightarrow \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0$$

$$\frac{\partial B}{\partial z} = 0 \longrightarrow B \neq B\,(z)$$

$$3\text{-}\quad \nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} \longrightarrow \nabla \times \vec{E} = \begin{vmatrix} \vec{\mu}_x & \vec{\mu}_y & \vec{\mu}_z \\ \partial x & \partial y & \partial z \\ 0 & E & 0 \end{vmatrix}$$

$$\left(\frac{-\partial E}{\partial z},\ 0,\ \frac{\partial E}{\partial x} \right) = \left(0,\ 0,\ \frac{-\partial B}{\partial t} \right)$$

$$E \neq E\,(z) \qquad \frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

$$4-\ \nabla \times \vec{B} = \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \longrightarrow \nabla \times \vec{B} = \begin{vmatrix} \vec{\mu}_x & \vec{\mu}_y & \vec{\mu}_z \\ \partial x & \partial y & \partial z \\ 0 & 0 & B \end{vmatrix}$$

$$\left(\frac{\partial B}{\partial y}, \frac{-\partial B}{\partial x}, 0 \right) = \mu_0 \varepsilon_0 \left(0, \frac{\partial E}{\partial t}, 0 \right)$$

$$B \neq B(y) \qquad \frac{-\partial B}{\partial x} = \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$

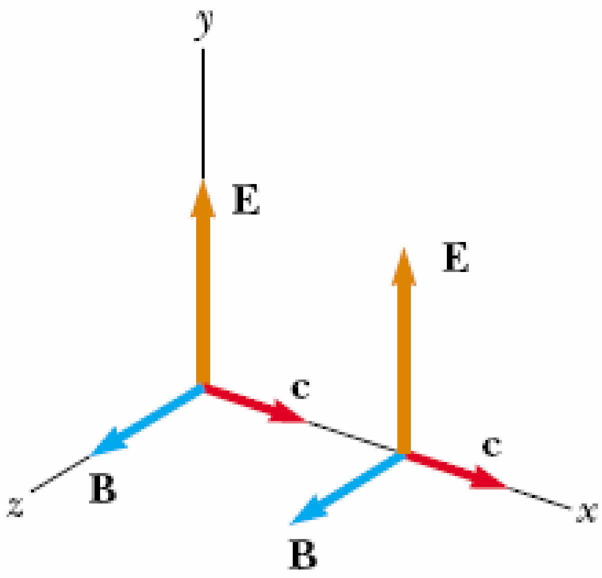
$$E \neq E(y,z)$$

$$B \neq B(y,z)$$

$$\Longrightarrow$$

$$E = E(x,t)$$

$$B = B(x,t)$$



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

$$\frac{\partial B}{\partial x} = -\mu_0 \epsilon_0 \frac{\partial E}{\partial t}$$

$$\frac{\partial^2 E}{\partial x^2} = -\frac{\partial}{\partial x}\left(\frac{\partial B}{\partial t}\right) = -\frac{\partial}{\partial t}\left(\frac{\partial B}{\partial x}\right) = -\frac{\partial}{\partial t}\left(-\mu_0 \epsilon_0 \frac{\partial E}{\partial t}\right)$$

$$\boxed{\frac{\partial^2 E}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2}}$$

$$\boxed{\frac{\partial^2 B}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 B}{\partial t^2}}$$

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 B}{\partial t^2}$$

$\Longrightarrow$

Velocidad de la onda

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

Pero: $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{T \cdot m/A}$ $\quad \epsilon_0 = 8.854\,19 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2}$

$$\boxed{c = 2.997\,92 \times 10^8\ \mathrm{m/s.}}$$

Velocidad de la luz en el vacio !!!!!

Caso particular: onda armónica

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

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

$$\frac{\omega}{k} = \frac{2\pi f}{2\pi/\lambda} = \lambda f = c$$

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m/s}}{f}$$

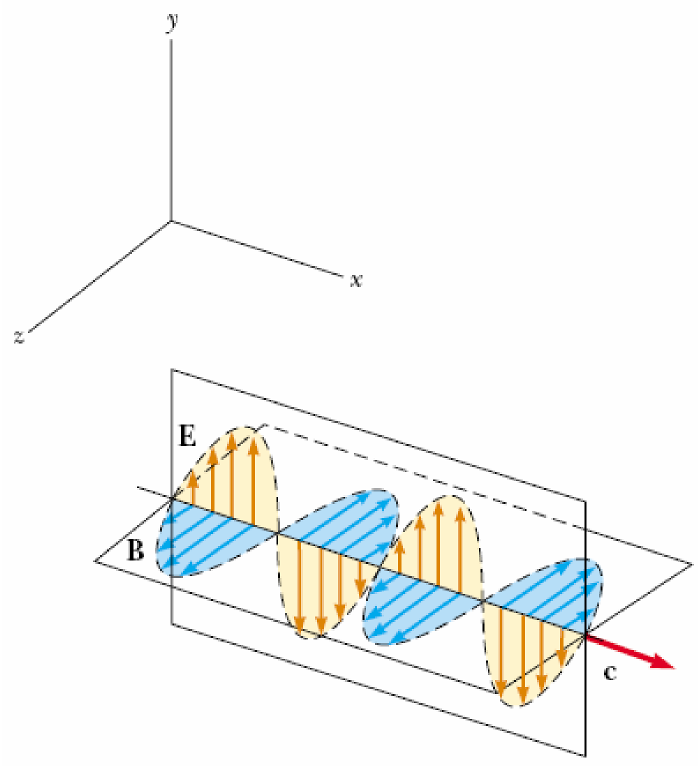
$$\frac{\partial E}{\partial x} = -kE_{\max} \sin(kx - \omega t)$$

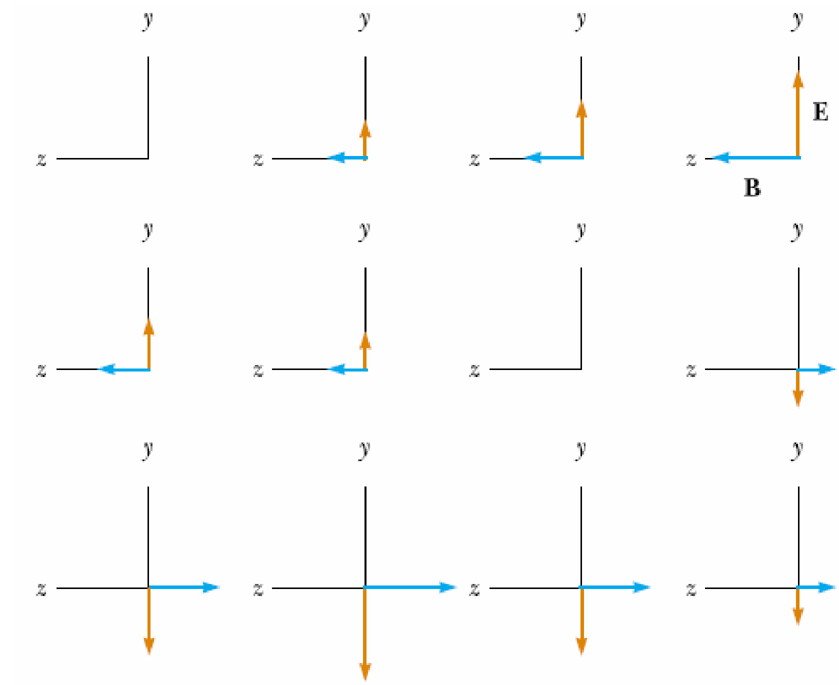
$$\frac{\partial B}{\partial t} = \omega B_{\max} \sin(kx - \omega t)$$

$$\Rightarrow \quad kE_{\max} = \omega B_{\max}$$

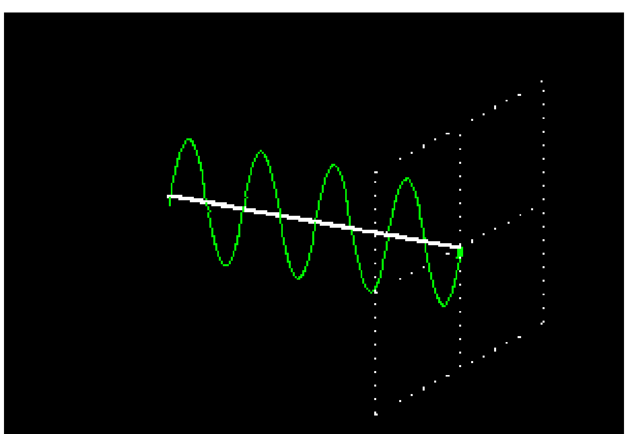
$$\frac{E_{\max}}{B_{\max}} = \frac{\omega}{k} = c$$

$$\boxed{\frac{E_{\max}}{B_{\max}} = \frac{E}{B} = c}$$

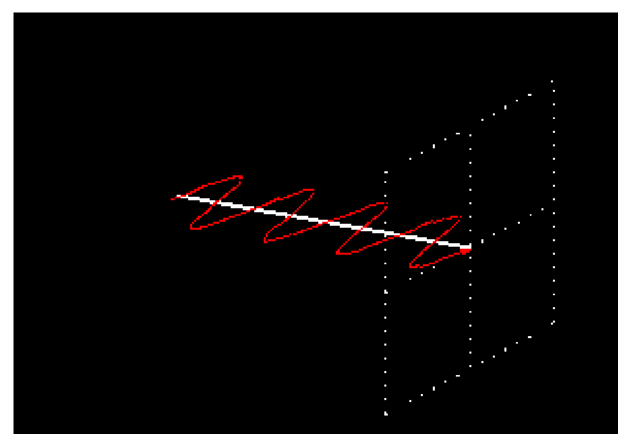


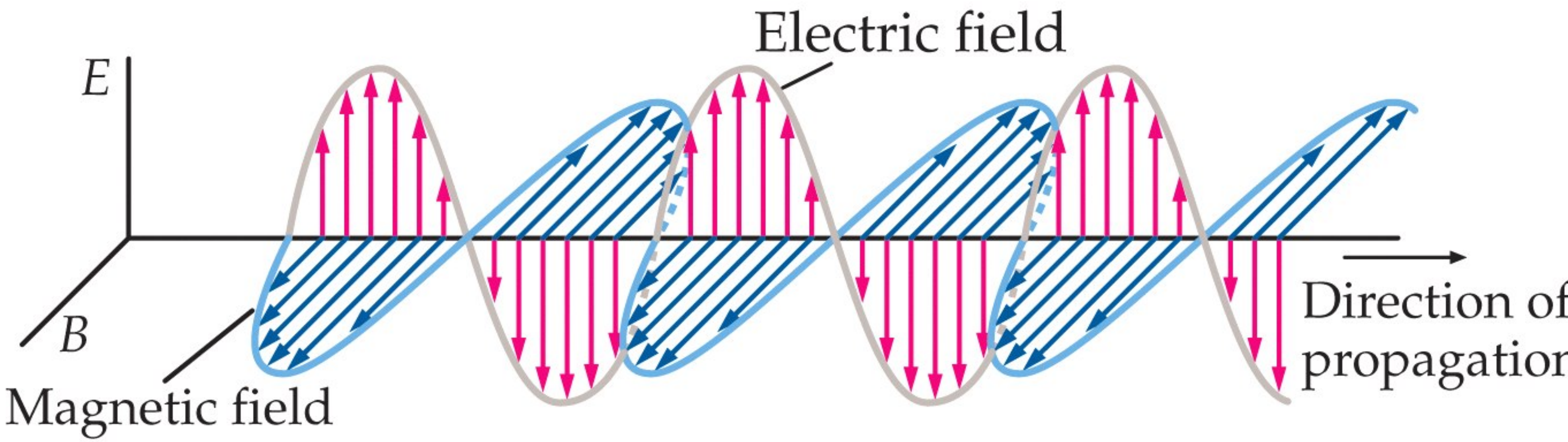


E

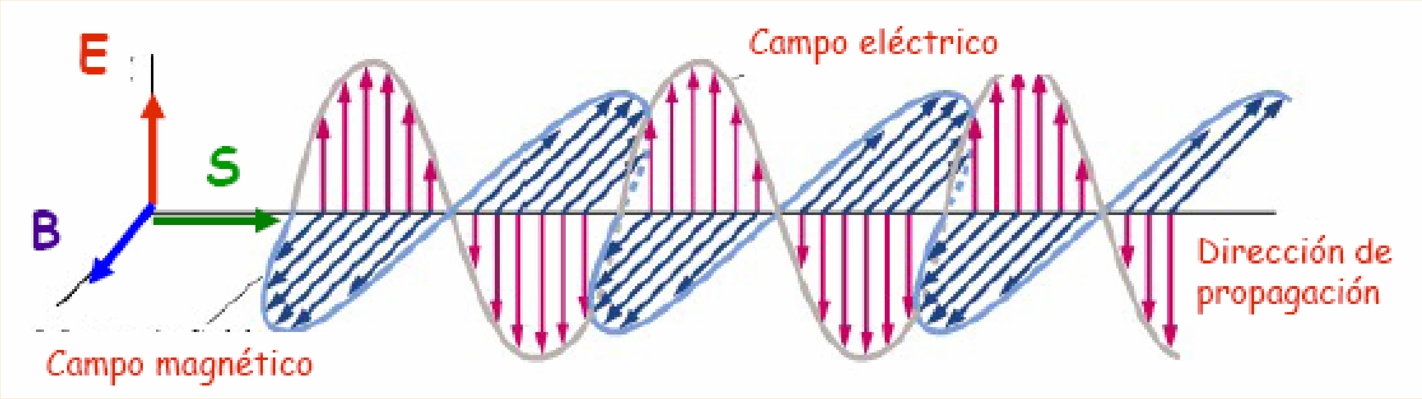


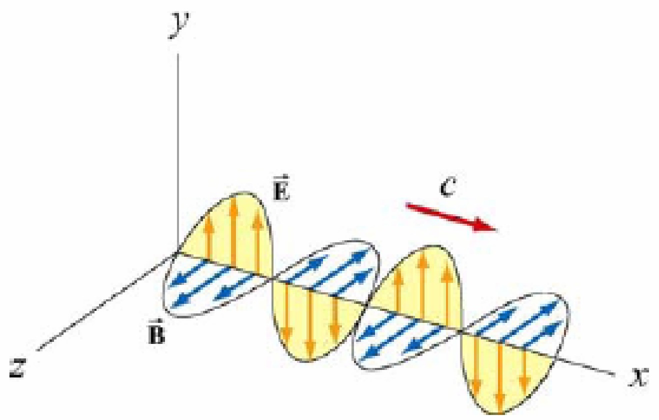
B




Electric field
E
B
Magnetic field
Direction of
propagation

Energía y Momento Transportados por Ondas Electromagnéticas





$$u_E = \frac{1}{2}\epsilon_0 E^2$$ **densidad de energía eléctrica**

$$u_B = \frac{B^2}{2\mu_0}$$ **densidad de energía magnética**

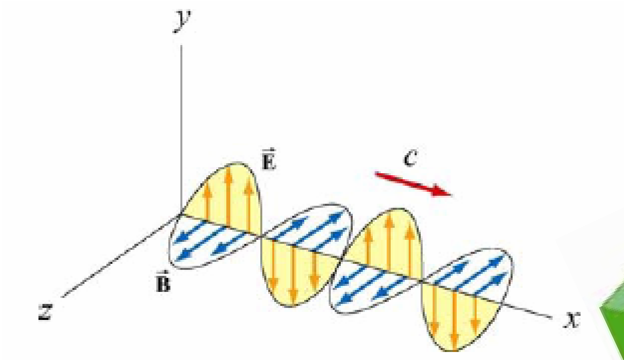
pero $B = E/c$ **donde** $c = 1/\sqrt{\epsilon_0\mu_0}$,

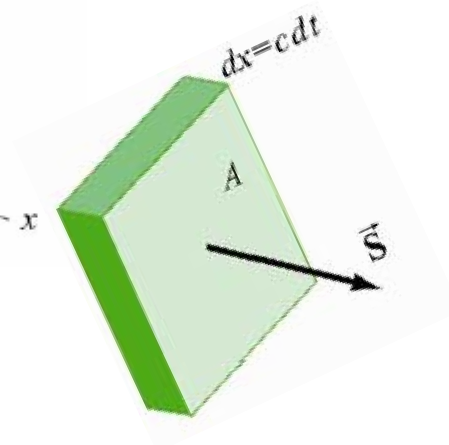
$$u_B = \frac{(E/c)^2}{2\mu_0} = \frac{\epsilon_0\mu_0}{2\mu_0}E^2 = \frac{1}{2}\epsilon_0 E^2$$

$$u_B = u_E = \frac{1}{2}\epsilon_0 E^2 = \frac{B^2}{2\mu_0}$$

$$\boxed{u = u_E + u_B = \epsilon_0 E^2 = \frac{B^2}{\mu_0}}$$

densidad de energía de la onda EM





$dx = c\,dt$

$$dU = uA\,dx = (u_E + u_B)A\,dx = \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{B^2}{\mu_0} \right) A\,dx$$

$$S = \frac{dU}{A\,dt} = \frac{c}{2}\left(\varepsilon_0 E^2 + \frac{B^2}{\mu_0} \right)$$

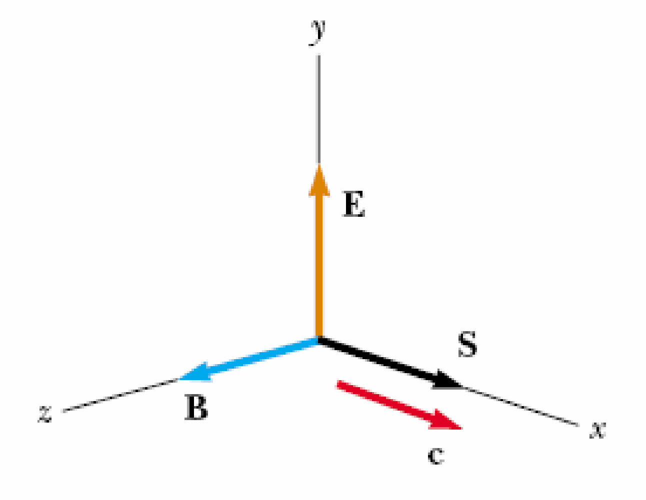
energía por unidad de área y unidad de tiempo

$[S] = \mathrm{W/m^2}$

$$S = \frac{c}{2}\left(\varepsilon_0 E^2 + \frac{B^2}{\mu_0} \right) = \frac{cB^2}{\mu_0} = c\varepsilon_0 E^2 = \frac{EB}{\mu_0}$$

Se define el vector de Poynting:

$$\vec{\mathbf{S}} \equiv \frac{1}{\mu_0} \vec{\mathbf{E}} \times \vec{\mathbf{B}}$$



$$S = \frac{EB}{\mu_0}$$

$$S = \frac{E^2}{\mu_0 c} = \frac{c}{\mu_0} B^2$$

Se define la intensidad de una onda EM:

$$\boxed{I = \langle S \rangle = \frac{E_0 B_0}{\mu_0} \langle \cos^2(kx - \omega t) \rangle = \frac{E_0 B_0}{2\mu_0} = \frac{E_0^2}{2c\mu_0} = \frac{cB_0^2}{2\mu_0}}$$

donde hemos utilizado: $\langle \cos^2(kx - \omega t) \rangle = \dfrac{1}{2}$

En general, la energía que atraviesa una superficie por unidad de tiempo es:

$$\frac{dU}{dt} = \iint \vec{\mathbf{S}} \cdot d\vec{\mathbf{A}}$$

La densidad de energía promedio de la onda EM es:

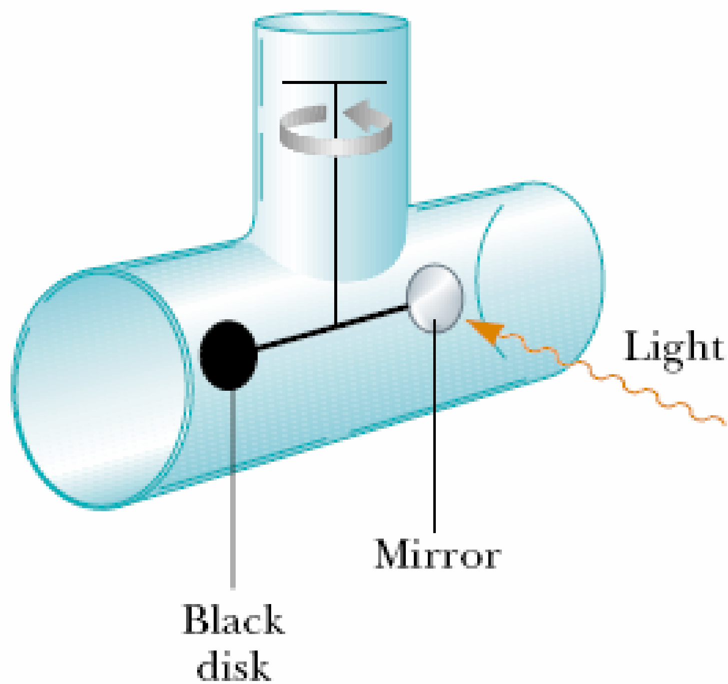
$$\langle u \rangle = \langle u_E + u_B \rangle = \varepsilon_0 \langle E^2 \rangle = \frac{\varepsilon_0}{2} E_0^2$$

$$= \frac{1}{\mu_0} \langle B^2 \rangle = \frac{B_0^2}{2\mu_0}$$

La intensidad y la densidad de energía promedio de la onda EM se vinculan de la siguinte manera:

$$\boxed{I = \langle S \rangle = c \langle u \rangle}$$

onda EM también transporta momento ⇒ ejerce una *presión de radiación* sobre una superficie (absorción o reflexión)



Asumimos incidencia normal. Maxwell mostró que si la onda es completamente reflejada por la superficie, la transferencia de momento esta relacionada con la energía reflejada

$$\Delta p = \frac{2\Delta U}{c}$$

Si la onda es completamente absorbida

$$\Delta p = \frac{\Delta U}{c}$$

Para el caso de absorción, la presión de radiación promedio (fuerza por unidad de área) es dada por:

$$P = \frac{\langle F \rangle}{A} = \frac{1}{A}\left\langle \frac{dp}{dt} \right\rangle = \frac{1}{Ac}\left\langle \frac{dU}{dt} \right\rangle$$

$$\left\langle \frac{dU}{dt} \right\rangle = \langle S \rangle A = IA$$

$$\boxed{P = \frac{I}{c}}$$

Absorción

$$\boxed{P = \frac{2I}{c}}$$

Reflexión

Ej.: bombita de luz de 60 W a una distancia de 1 m

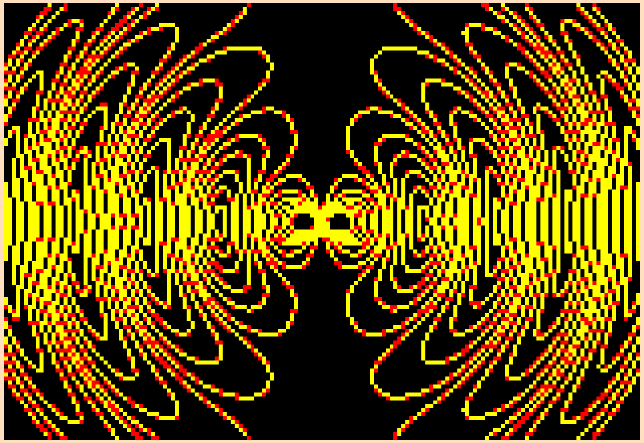
I(r) = Pot / 4 π r^2 = 4.77 W/m^2

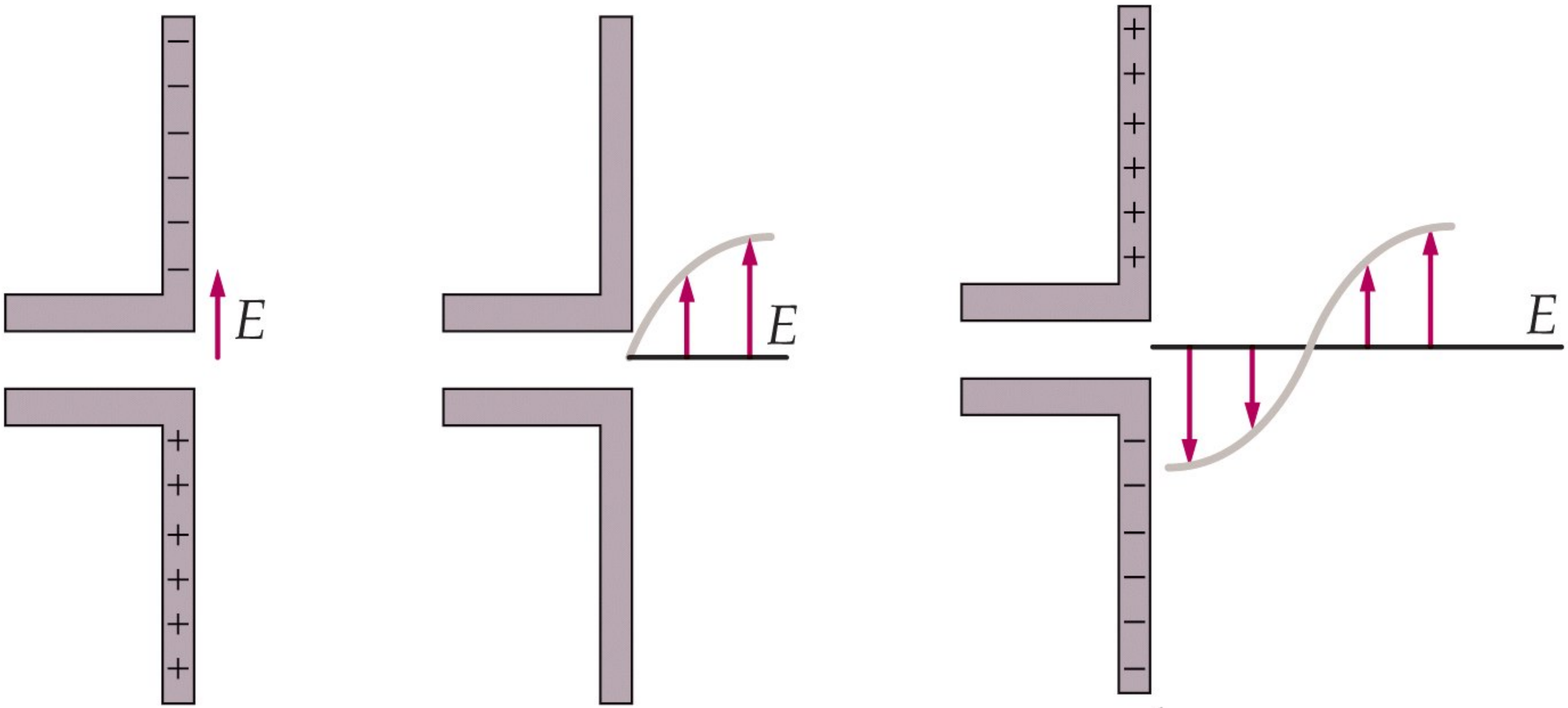
P = I / c = 15.8 10^{-9} Pa

Fuerza sobre mi mano (20 cm x 10 cm)

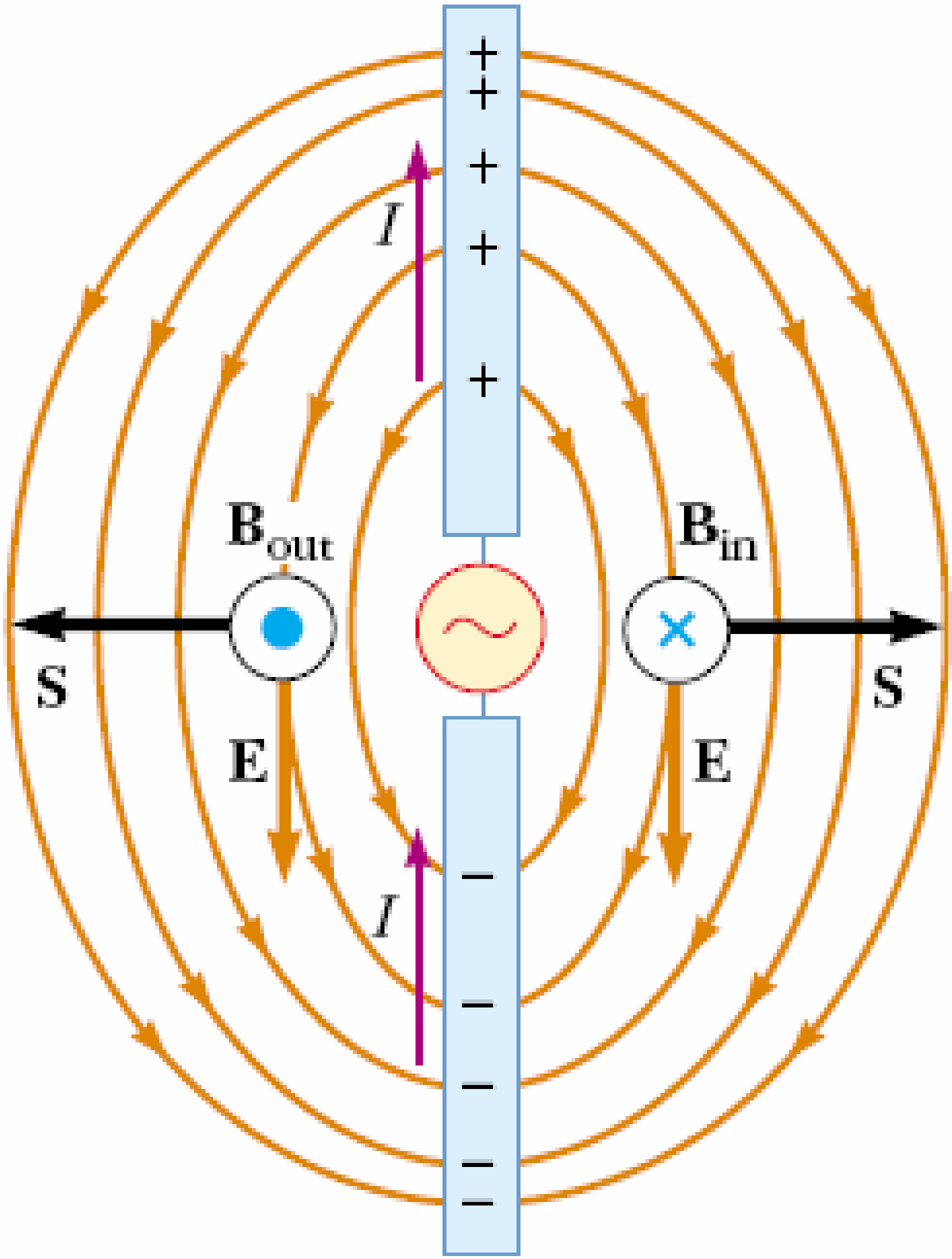
F= 3 10^{-8} N

Producción y Recepción de Ondas Electromagnéticas

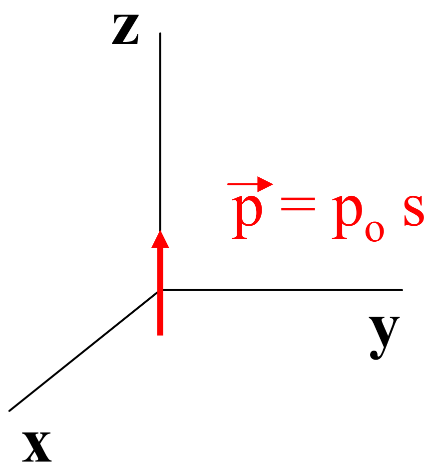




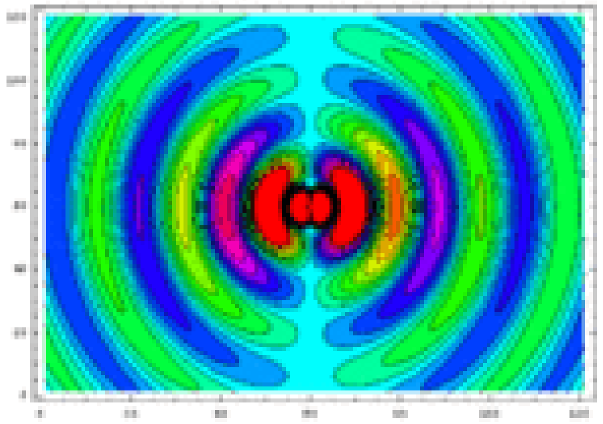
$t = 0$ $t = \frac{1}{4}T$ $t = \frac{1}{2}T$



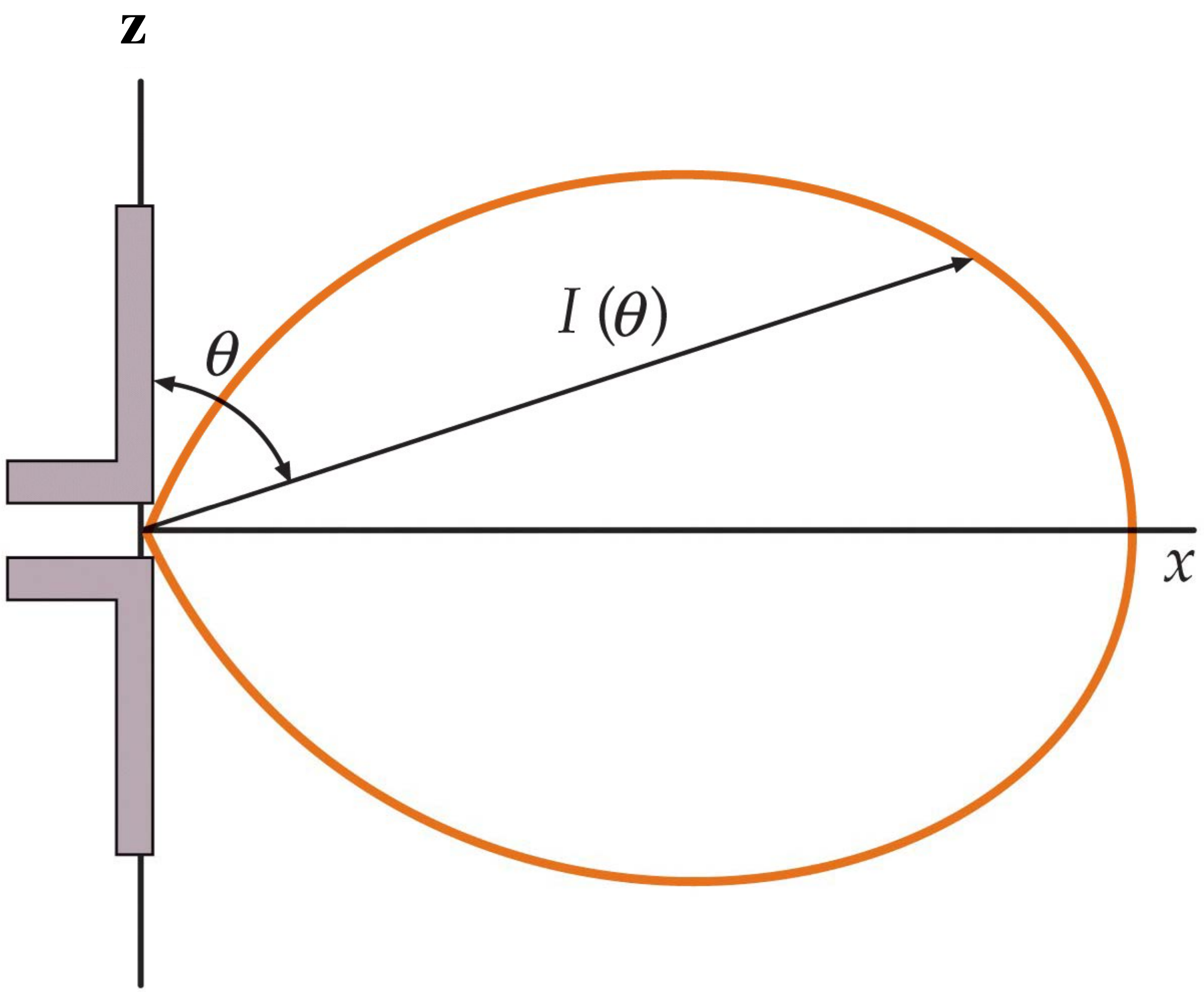
El movimiento de cargas en esta antena se puede representar mediante un ***dipolo eléctrico oscilante***

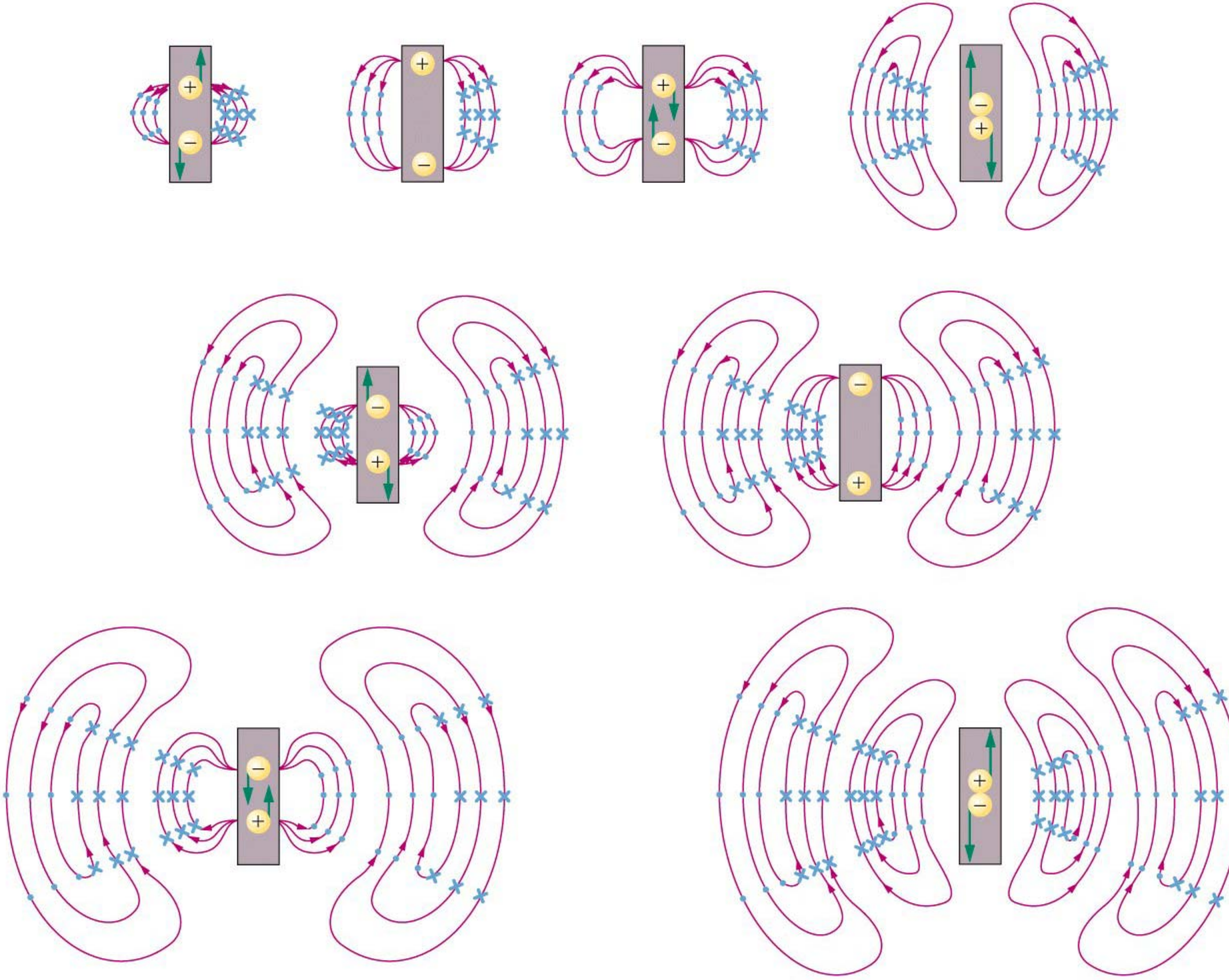


$$\vec{p} = p_o \text{ sen } \omega t \, \vec{\mu}_z$$

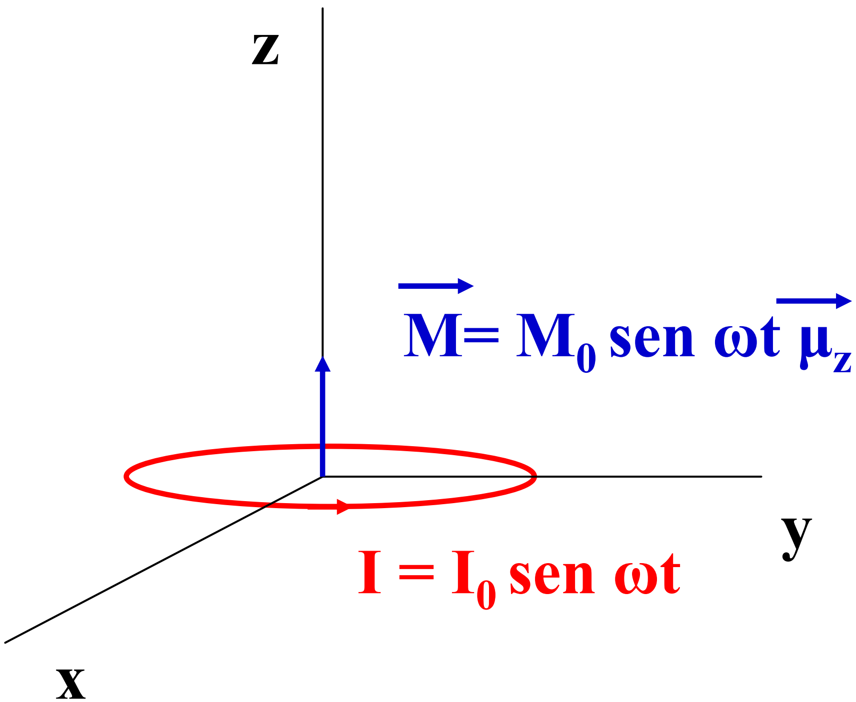


Se puede mostrar que $\boxed{I \;\alpha\; \dfrac{sen^2\theta}{r^2}}$

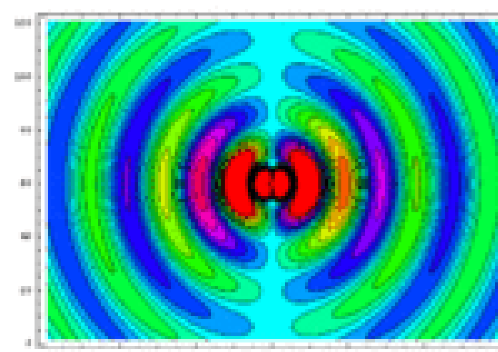




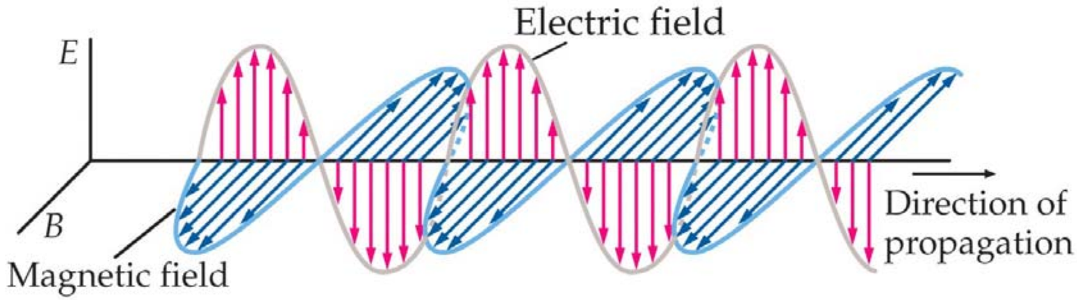
Dipolo magnético oscilante



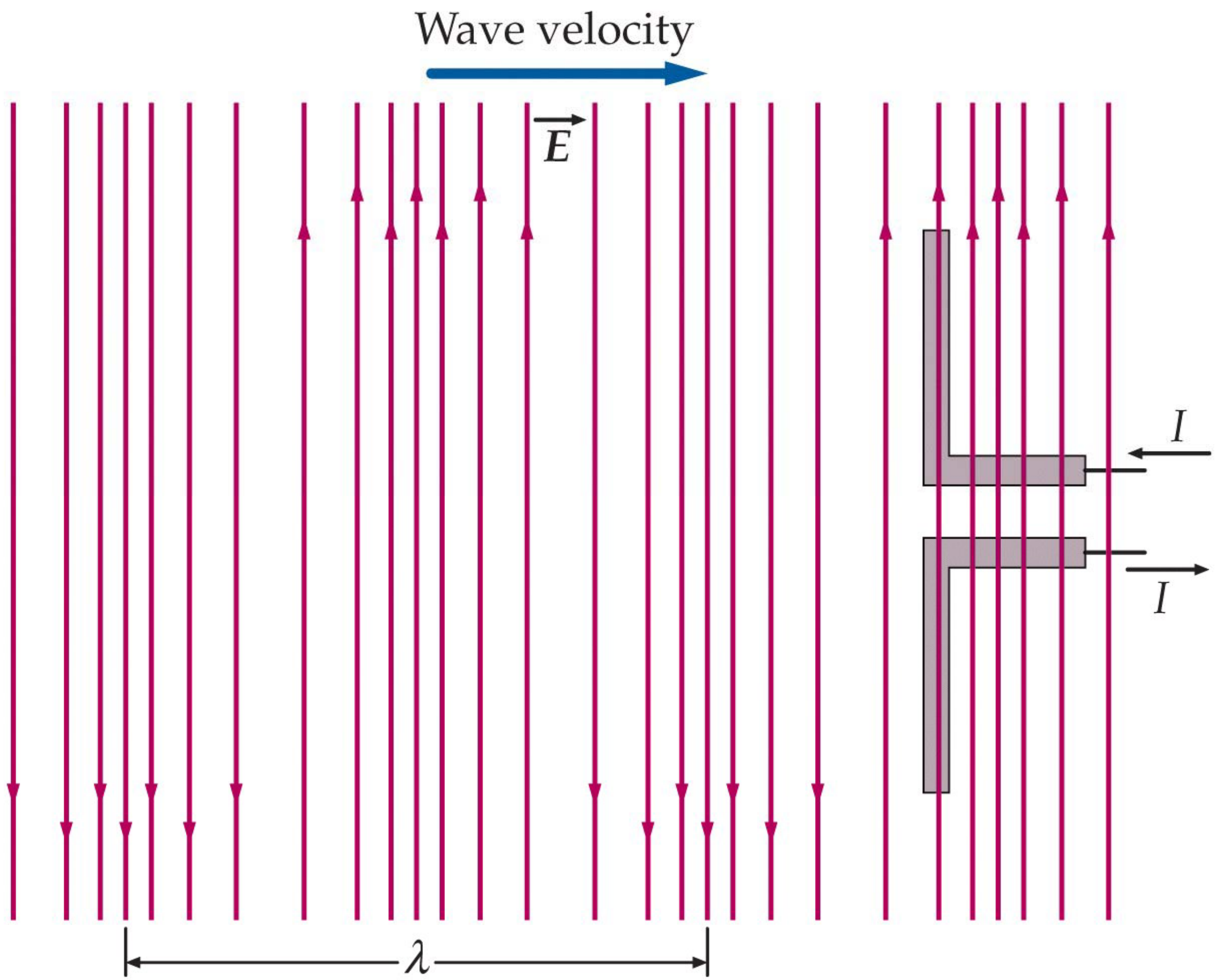
$$\boxed{I \ \alpha \ \frac{\text{sen}^2\theta}{r^2}}$$



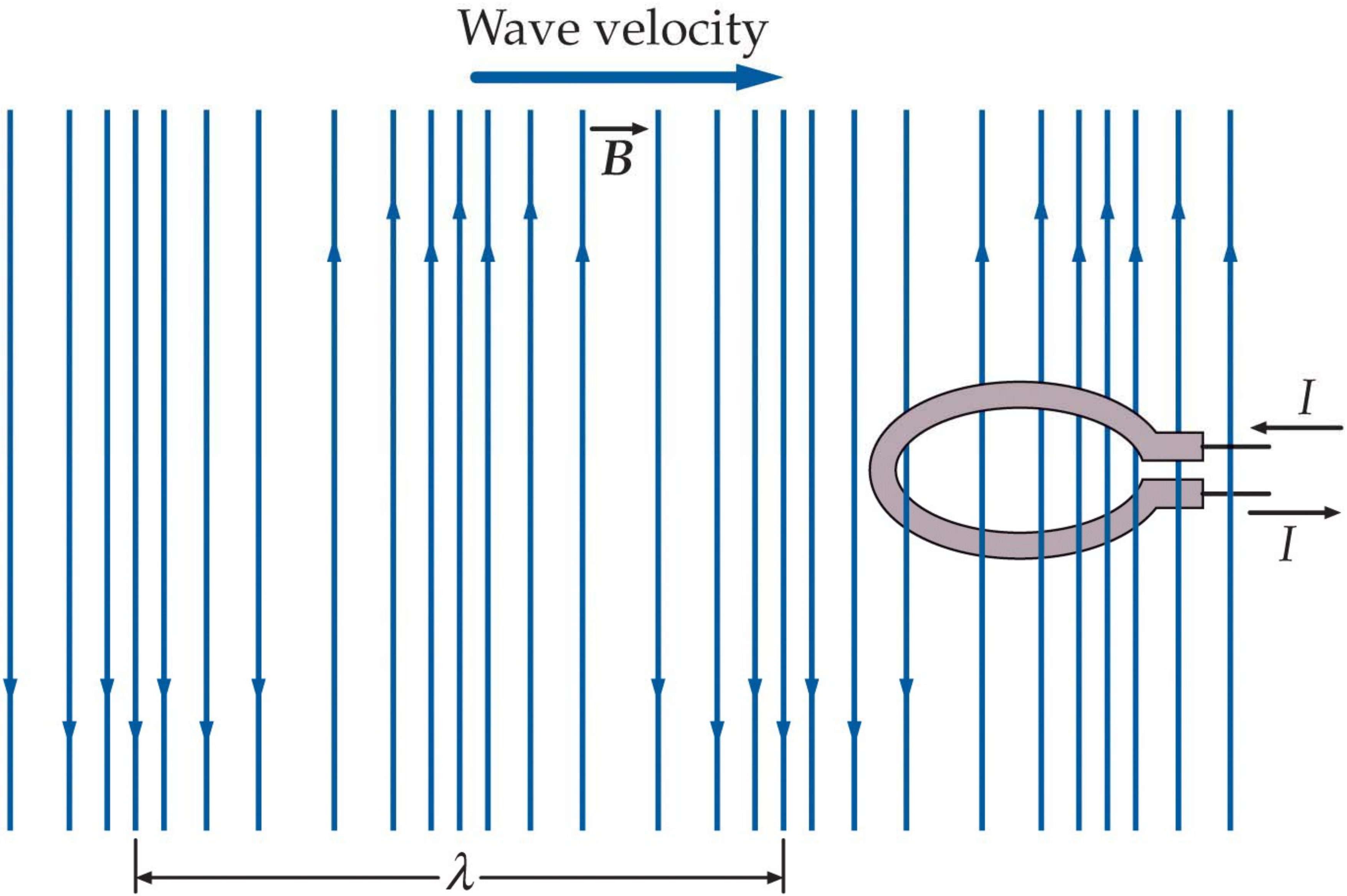
Recepción



Electric field
E
B
Magnetic field
Direction of propagation



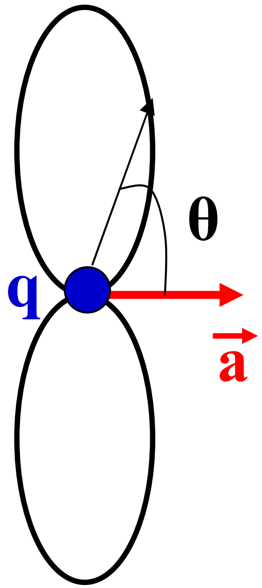
Wave velocity
$\vec{E}$
I
I
λ



Wave velocity
$\vec{B}$
I
I
λ

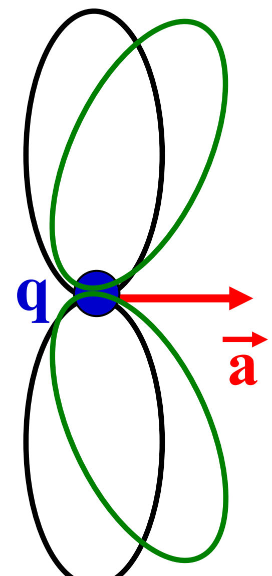
Radiación de una carga acelerada

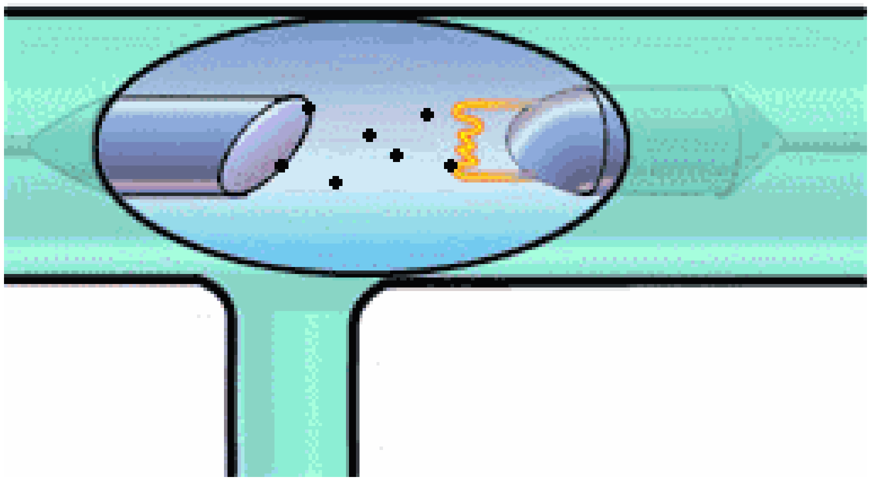
Una carga acelerada irradia energía electromagnética



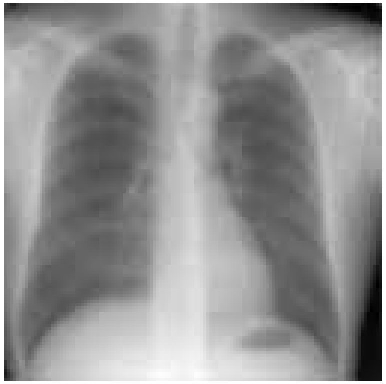
$$I = \frac{q^2 \; a^2 \qquad \mathrm{sen}^2\theta}{16\, \pi^2\, c^3\, \varepsilon_0 \quad r^2}$$

v << c



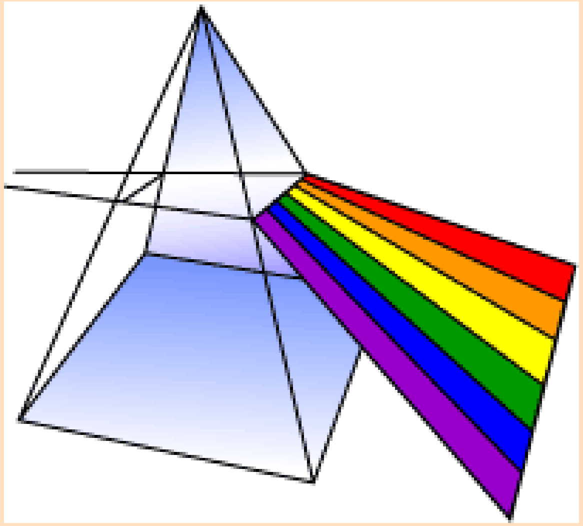


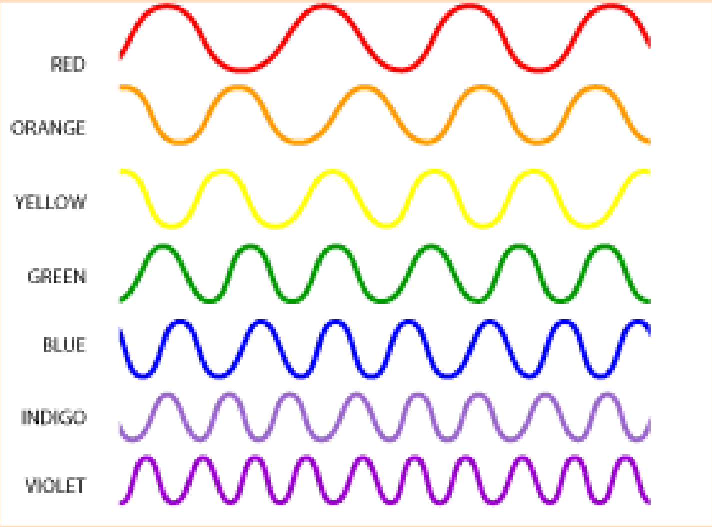
Radiación de frenado
Generación de Rayos X

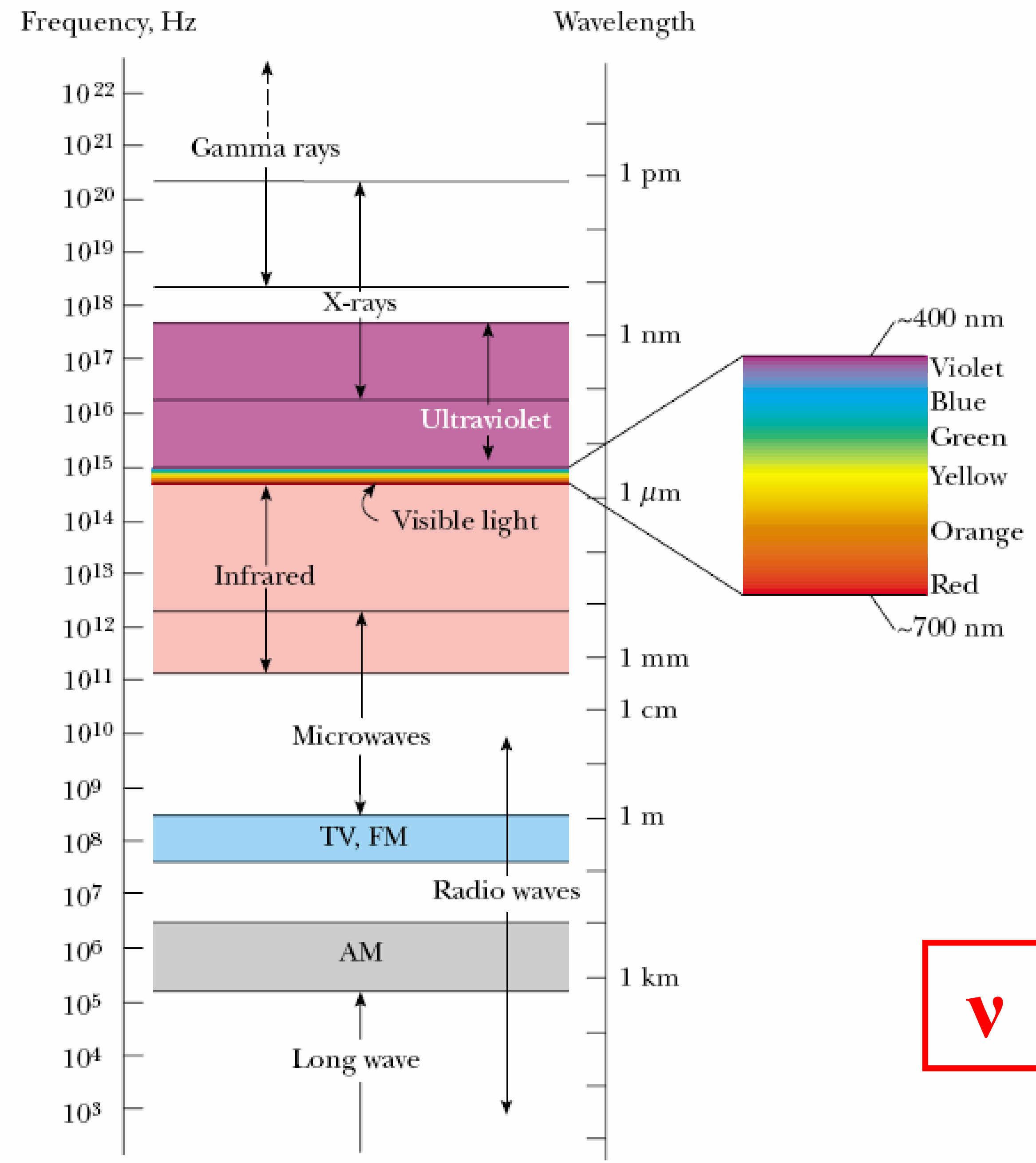


Radiación Sincrotrónica

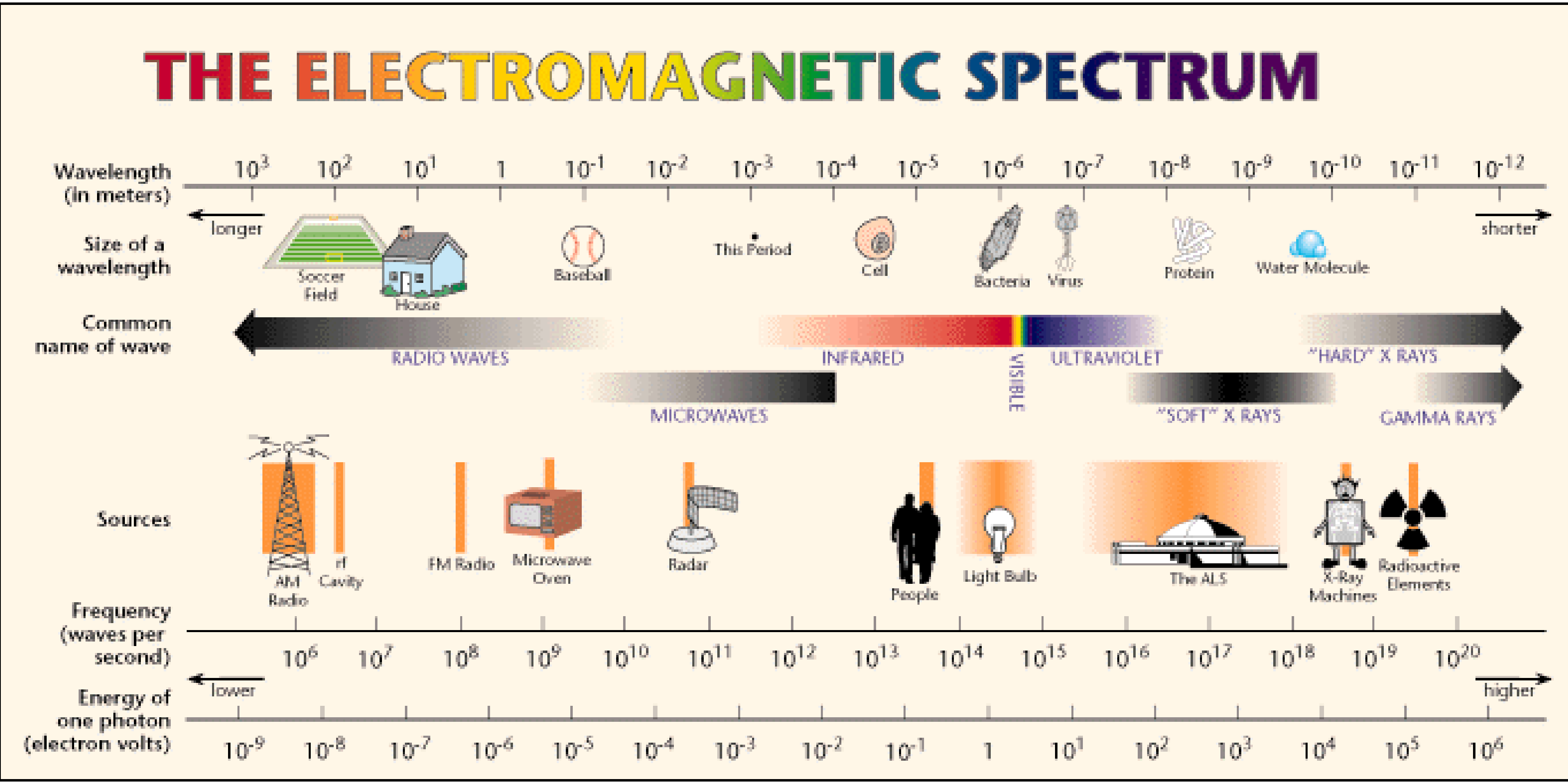
El Espectro Electromagnético







$$\boxed{\nu \ \lambda = c}$$


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6