PHY250

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Digipen

Fall 2020

Introduction

- Changing Magnetic Field $\rightarrow$ Changing Electric Field

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Electromagnetic Wave: Wave of Electric and Magnetic Field

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Electromagnetic Wave: Wave of Electric and Magnetic Field

Changing Electric Field $\rightarrow$ Changing Magnetic Field$\rightarrow$ Changing Electric Field

The light is an electromagnetic wave that can propagate through space.

Introduction

To describe an electromagnetic wave we have to know first:

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- what is an Electric Field?

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- what is an Electric Field?
- what is a Magnetic Field?

Electric Field

Force between two point charged particles:

Electric Field

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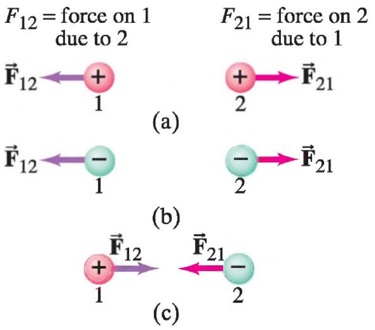

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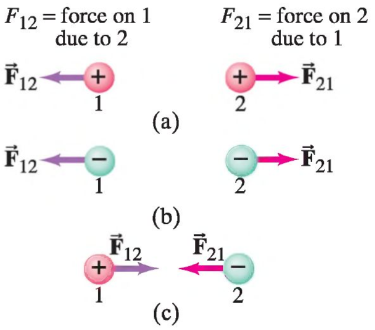

$$\vec{F_{12}} = \frac{1}{4\pi\epsilon_0}\frac{Q_1 Q_2}{r_{12}^2}\hat{r}_{12} \qquad (1)$$

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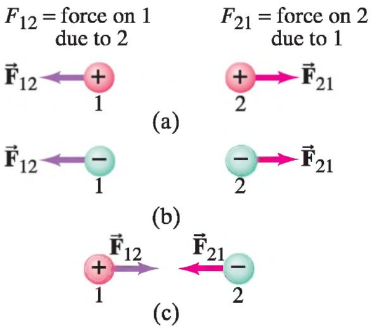

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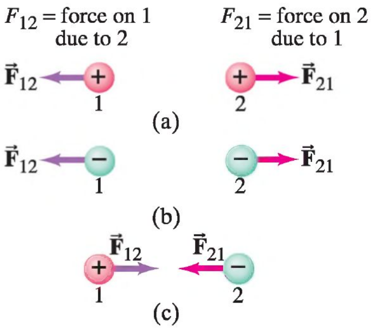

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Where ϵ_0 is the permitivity of free space,

$$\epsilon_0 = 8.85 \times 10^{-12}\frac{C^2}{Nm^2} \qquad (2)$$

Electric Field

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charge $\propto n \cdot e$, n integer, it is quantized.

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$\vec{F} \rightarrow$ Force on a small positive test particle q.

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Then, the electric field generated by a charge Q is:

$$E = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2} \tag{6}$$

Electric Field

Electric Field of more than one particle:

Electric Field

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Superposition principle.

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Superposition principle.

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$$\vec{E} = \int d\vec{E} \tag{10}$$

$$E_x = \int dE cos\theta, \quad E_y = \int dE sin\theta \tag{11}$$

Electric Potential

Work made by a constant force:

$$w = F \cdot d = qEd \tag{12}$$

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Potential Energy:

$$\Delta U = -w = -qEd \tag{13}$$

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Definition of Electric Potential: Volt

$$V = \frac{U}{q} \tag{14}$$

Electric Potential

$$\Delta V = \frac{\Delta U}{q} = -\frac{w}{q} = -Ed \tag{15}$$

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Unit:

$$[V] = \frac{J}{C} \qquad (16)$$

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In general,

$$\Delta V = -\int \vec{E} \cdot d\vec{\ell} \tag{17}$$

Electric Flux

Flux of a constant field through an area:

Electric Flux

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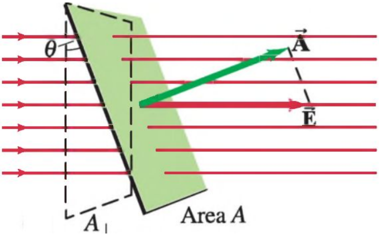

$$\Phi_E = E \cdot A cos\theta = \vec{E} \cdot \vec{A}$$

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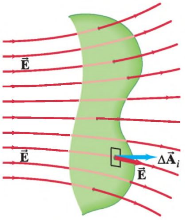

General case,

Electric Flux

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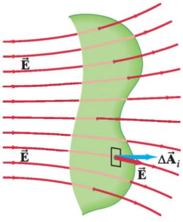

General case,

$$d\Phi_E = \vec{E} \cdot \vec{A} \rightarrow \Phi_E = \int \vec{E} \cdot \vec{A}$$

Electric Flux

Electric flux through a closed surface.

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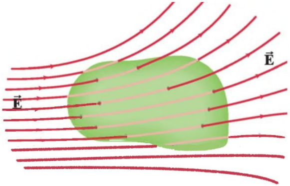

General case,

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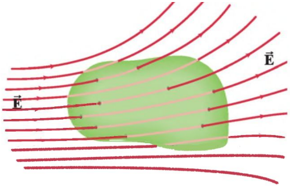

General case,

$$\oint \vec{E} \cdot \vec{A} = 0$$

Gaus Law

Gaus Law: Relates the Electric Flux with the total charge enclosed inside a closed surface.

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$$\oint \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0} \quad (18)$$

Basically, this law says that if the flux crossing a closed surface is different from zero, then it is generated by a charge inside the surface.

Gaus Law

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Consider a point charge enclosed into an sphere,

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$$\oint \vec{E} \cdot d\vec{A} = E4\pi r^2 \rightarrow E = \frac{1}{4\pi r^2}\frac{Q}{\epsilon_0} \tag{19}$$

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Coulomb $\rightarrow$ Gaus

$$\oint \vec{E} \cdot d\vec{A} = \oint \frac{1}{4\pi\epsilon_0} \frac{Q}{r^2} dA = \frac{Q}{4\pi r^2} 4\pi r^2 = \frac{Q}{\epsilon_0} \tag{20}$$

Electric Current

Electric Current: is generated by charge in motion.

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Units:

$$[I] = \frac{C}{s} = A, \quad Ampere$$

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The Electric current in a wire is proportional to the electric potential:

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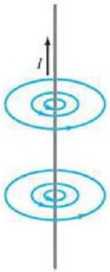
Units:

$$[R] = \frac{V}{A} = \Omega, \quad Ohm \tag{23}$$

Magnetic Field

Sources of Magnetic Fields: Ampere's Law



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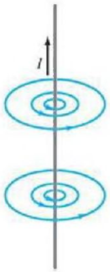

The magnetic field generated by a straight wire is circular

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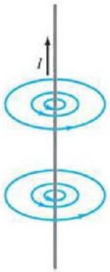

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{enclosed}$$

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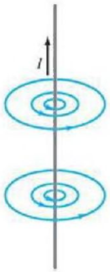

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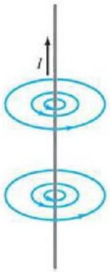


$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{enclosed}$$

$$\oint B d\ell = B 2\pi r = \mu_0 I$$

$$\rightarrow = B = \frac{\mu_0 I}{2\pi r} \qquad (24)$$

The magnetic field generated by a straight wire is circular

Magnetic Field

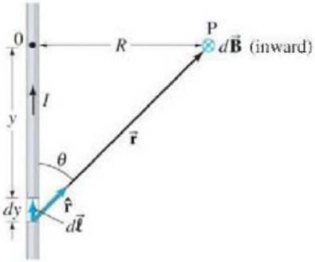
The unit of the magnetic field is Tesla,

$$[B] = \frac{N}{Am} \tag{25}$$

The constant μ_0 is the **Vacuum Magnetic Permeability**.

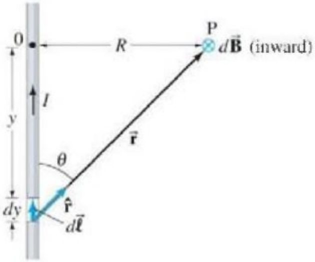
$$\mu_0 = 4\pi \times 10^{-7} \frac{T}{mA} \tag{26}$$

Biot-Savat Law



$$d\vec{B} = \frac{\mu_0}{4\pi} I \frac{d\vec{\ell} \times \hat{r}}{r^2} \qquad (27)$$

Biot-Savat Law



$$d\vec{B} = \frac{\mu_0}{4\pi} I \frac{d\vec{\ell} \times \hat{r}}{r^2} \tag{27}$$

$$\rightarrow \vec{B} = \int \frac{\mu_0}{4\pi} I \frac{d\vec{\ell} \times \hat{r}}{r^2} \tag{28}$$

Force due to a Magnetic Field

Force on a current due to a magnetic Field:

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$$\vec{F} = I\vec{\ell} \times \vec{B} \tag{29}$$

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Force on a point charge due to a magnetic Field:

Force due to a Magnetic Field

Force on a current due to a magnetic Field:

$$\vec{F} = I\vec{\ell} \times \vec{B} \tag{29}$$

Force on a point charge due to a magnetic Field:

$$\vec{F} = q\vec{v} \times \vec{B} \tag{30}$$

Force due to a Magnetic Field

Total force due to an electric and magnetic field:

Force due to a Magnetic Field

Total force due to an electric and magnetic field:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \rightarrow Lorentz\ \ Equation \tag{31}$$

Example: Magnet

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In some materials called **Ferromagnetic**, the angular momentum of electrons are aligned so that they create a resultant macroscopic magnetic field.

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Iron - Cobalt - Nickel

When the electric and magnetic fields are static, the are separate entities. But when they are changing, we can not treat them separately

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$\rightarrow$ **Maxwell Equations**

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$\rightarrow$ **Maxwell Equations**

A changing magnetic field generates a changing electric field that generates a changing magnetic field.

When the electric and magnetic fields are static, the are separate entities. But when they are changing, we can not treat them separately

$\rightarrow$ **Maxwell Equations**

A changing magnetic field generates a changing electric field that generates a changing magnetic field.

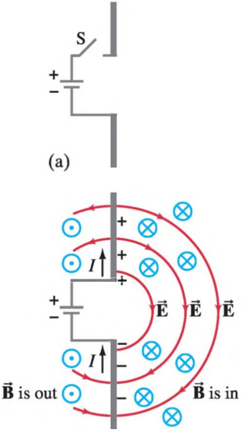
$\rightarrow$ **Wave traveling in the espace**

Maxwell Equations

TABLE E–1 Maxwell's Equations in Free Space†

Integral form	Differential form
$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = \frac{Q}{\epsilon_0}$	$\vec{\nabla} \cdot \vec{\mathbf{E}} = \frac{\rho}{\epsilon_0}$
$\oint \vec{\mathbf{B}} \cdot d\vec{\mathbf{A}} = 0$	$\vec{\nabla} \cdot \vec{\mathbf{B}} = 0$
$\oint \vec{\mathbf{E}} \cdot d\vec{\boldsymbol{\ell}} = -\frac{d\Phi_B}{dt}$	$\vec{\nabla} \times \vec{\mathbf{E}} = -\frac{\partial \vec{\mathbf{B}}}{\partial t}$
$\oint \vec{\mathbf{B}} \cdot d\vec{\boldsymbol{\ell}} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$	$\vec{\nabla} \times \vec{\mathbf{B}} = \mu_0 \vec{\mathbf{j}} + \mu_0 \epsilon_0 \frac{\partial \vec{\mathbf{E}}}{\partial t}$

† $\vec{\nabla}$ stands for the *del operator* $\vec{\nabla} = \hat{\mathbf{i}}\frac{\partial}{\partial x} + \hat{\mathbf{j}}\frac{\partial}{\partial y} + \hat{\mathbf{k}}\frac{\partial}{\partial z}$ in Cartesian coordinates.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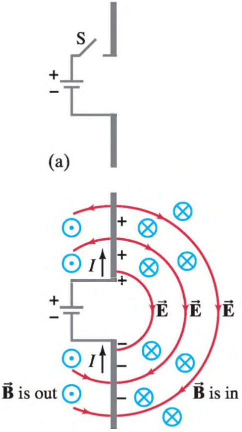
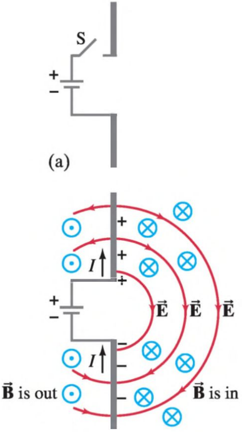
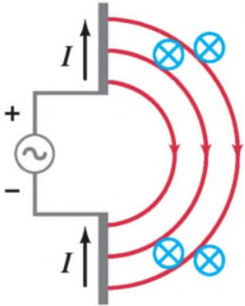
I
$\vec{B}$ is out
$\vec{B}$ is in



- We connect two rod to a battery → Electric Field



- We connect two rod to a battery $\rightarrow$ Electric Field
- The charge is re-distributed $\rightarrow$ Magnetic field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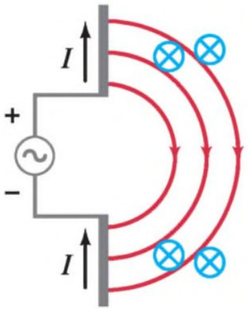
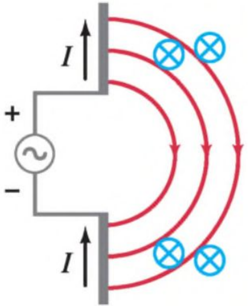
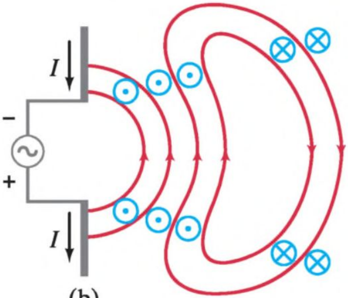


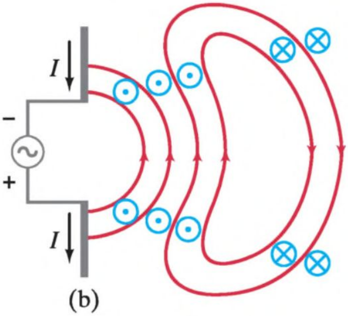
- sinusoidal voltage $\rightarrow$ Alternating Current



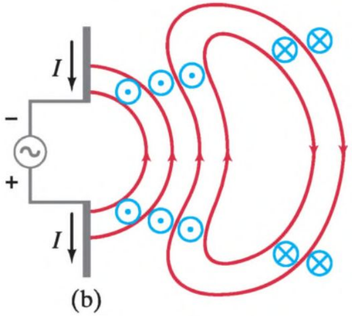
- sinusoidal voltage $\rightarrow$ Alternating Current
- $\rightarrow$ variable Electric and Magnetic Fields.



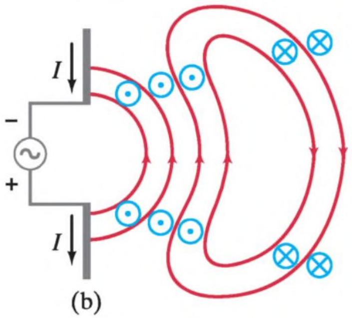
(b)



- Old Field lines fold back to connect to some of the new lines → closed loops



- Old Field lines fold back to connect to some of the new lines $\rightarrow$ closed loops
- The old field don't suddenly disappear



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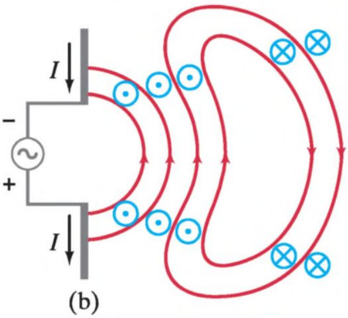
- changing EF → changing MF → changing EF ...→ so on



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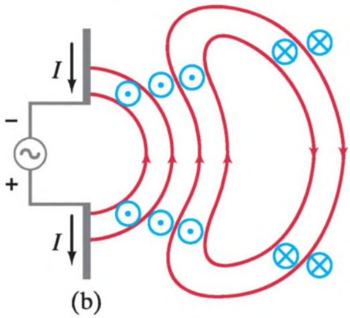
- This combination of changing EF and MF moving outward is self supporting, no longer depending on the antenna.



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- The old field don't suddenly disappear
- changing EF → changing MF → changing EF ...→ so on
- This combination of changing EF and MF moving outward is self supporting, no longer depending on the antenna.
- They are on their way to distant points.

Characteristics of Electromagnetic Waves

- The field not far the antenna (*Near Field*) is complicated.

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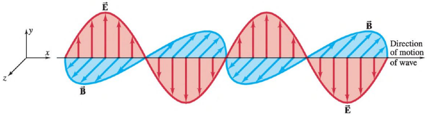

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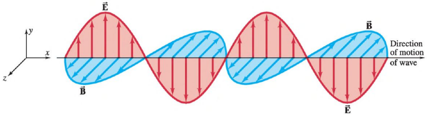

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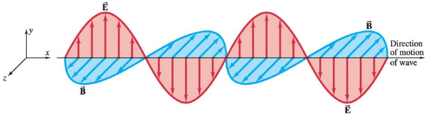

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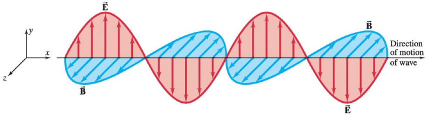

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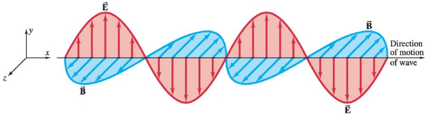

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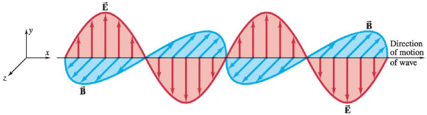

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Mathematical Description

The Maxwell equation take the form:

$$\oint \vec{\mathbf{E}} \cdot d\vec{\mathbf{A}} = 0$$

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

$$\oint \vec{\mathbf{E}} \cdot d\vec{\boldsymbol{\ell}} = -\frac{d\Phi_B}{dt}$$

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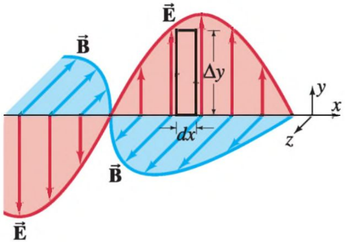
$$k = \frac{2\pi}{\lambda}, \quad \omega = 2\pi f, \quad f\lambda = \frac{\omega}{k} = v$$

Speed of light



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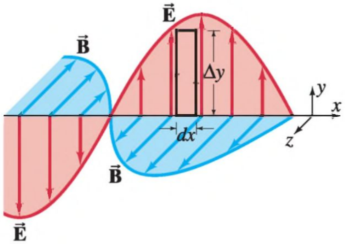

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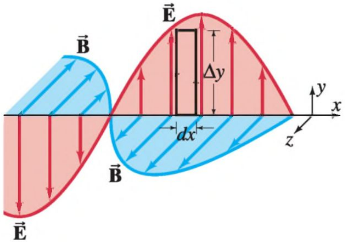

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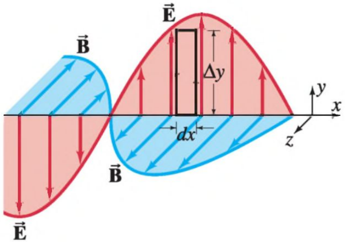

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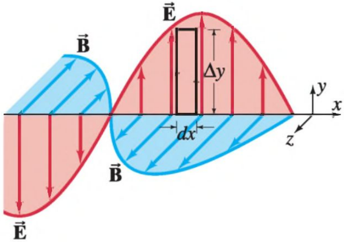

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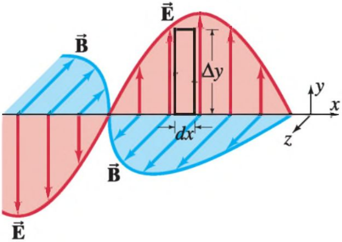

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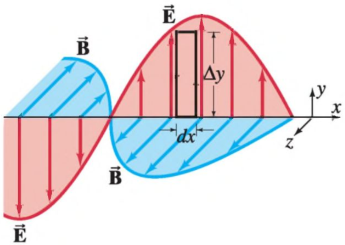

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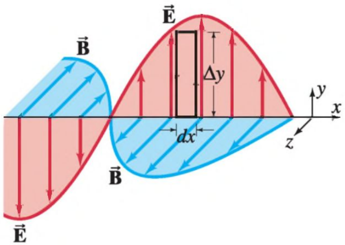

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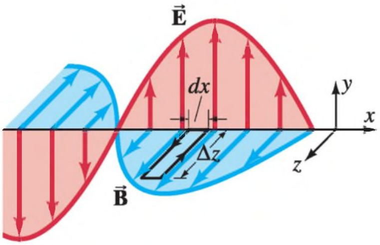

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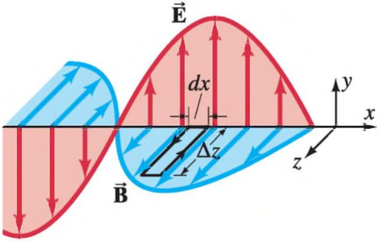

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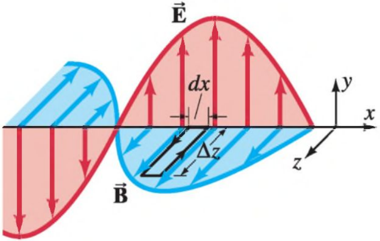

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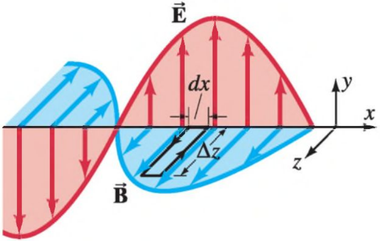

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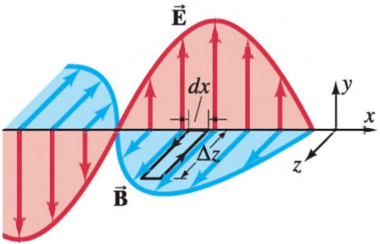

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Speed of light

Then, the velocity of propagation of the wave is,

$$v^2 = \frac{1}{\epsilon_0 \mu_0} \rightarrow v = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = c \tag{36}$$

c is the speed of light,

$$c = 3 \times 10^8 \ m/s \tag{37}$$

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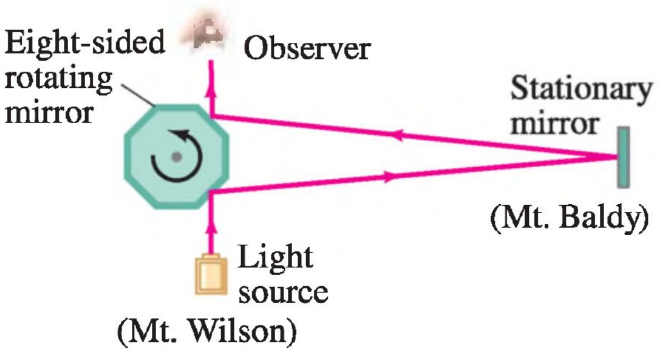
Measuring the speed of light

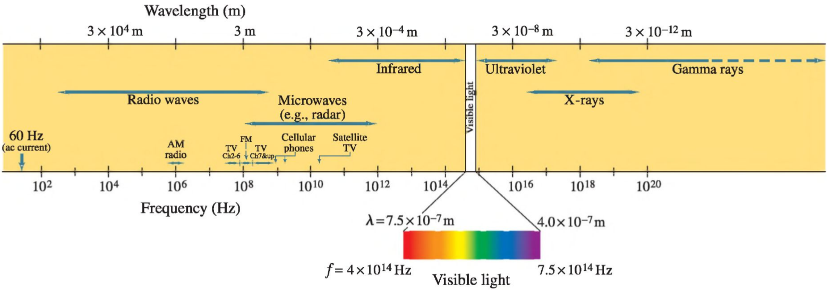
Michelson's Experiment



Electromagnetic spectrum

The frequency of light is related with its speed thought the expression,

$$c = f\lambda$$



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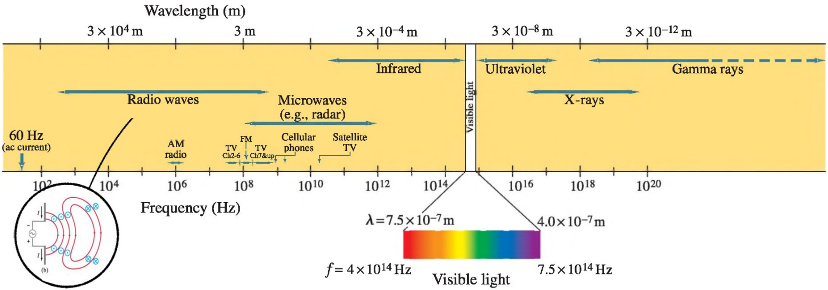

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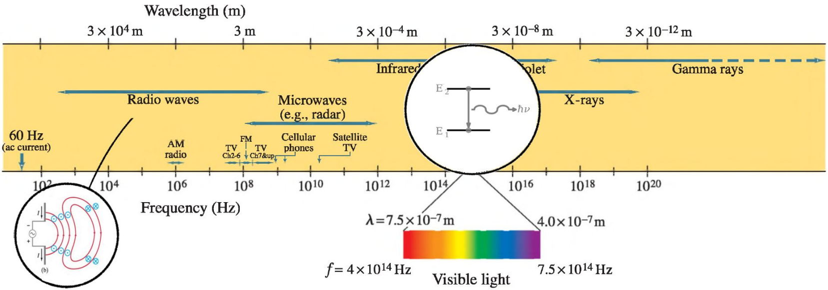

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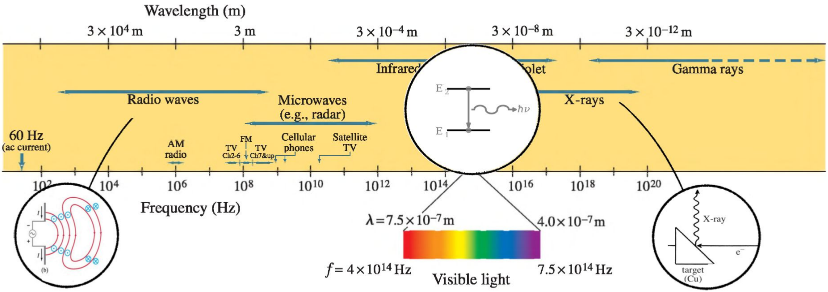

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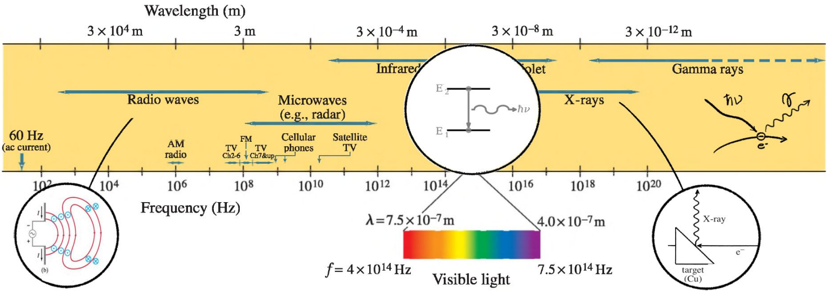


Electromagnetic spectrum

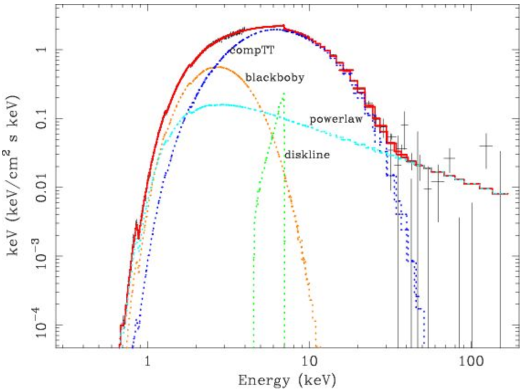
Example:

BB radiation $\rightarrow I \propto \frac{1}{e^{\frac{\hbar\nu}{kT}}-1}$

Synchrotron radiation $\rightarrow \nu^{\alpha}$ Power Law

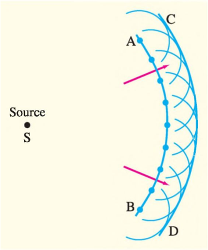
Electromagnetic spectrum

Application: knowing what process are occurring in an Astrophysical Object.



Huygens' principle

Every point on a wave front can be considered as a source o f tiny wavelets that spread out in the forward direction at the speed o f the wave itself The new wave front is the envelope o f all the wavelets— that is, the tangent to all o f them.



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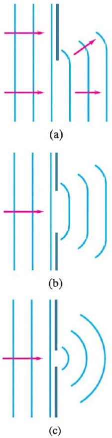

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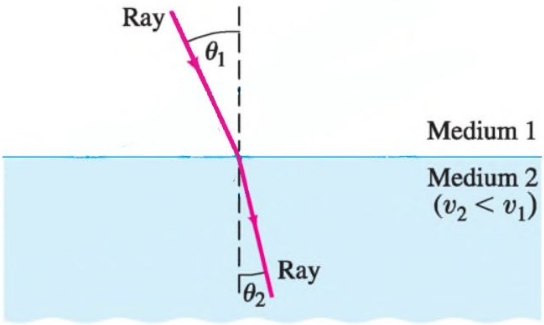

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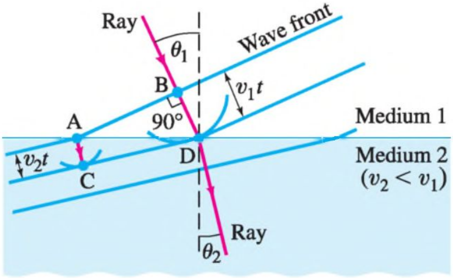

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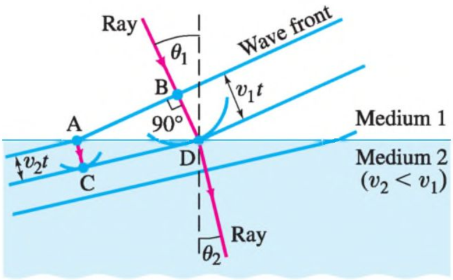

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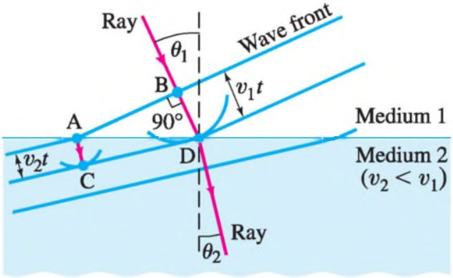

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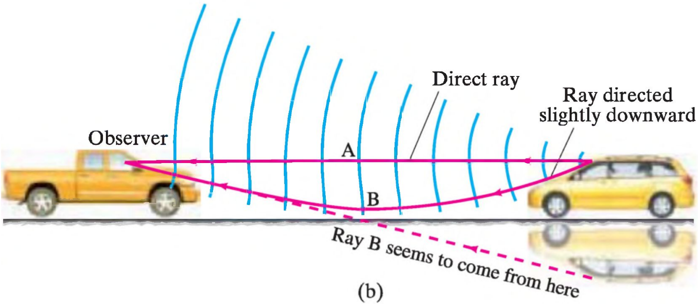
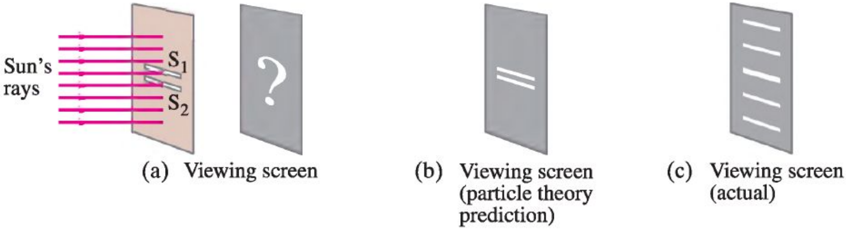
Refraction

Example: Mirages



(b)

Interference: Youn's double-slit Experiment



If light consists of tiny particles, we might expect to see two bright lines on a screen placed behind the slits as in (b). But instead a series of bright lines are seen, as in (c). Young was able to explain this result as a wave-interference phenomenon.

Interference: Youn's double-slit Experiment

To understand why, we consider:

Interference: Youn's double-slit Experiment

To understand why, we consider:

- plane waves

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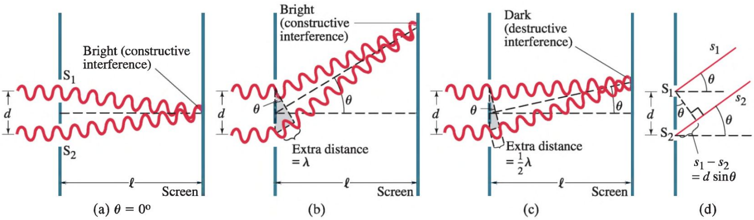
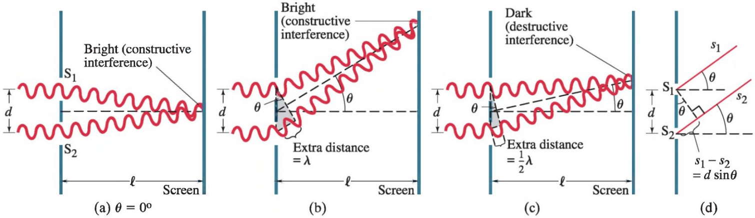
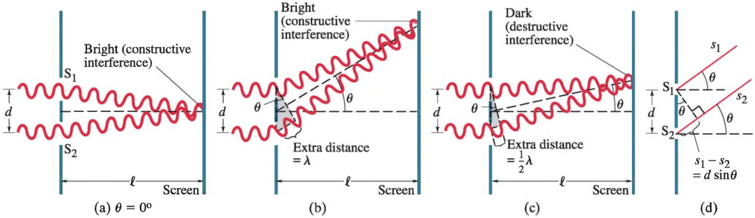


Interference: Youn's double-slit Experiment

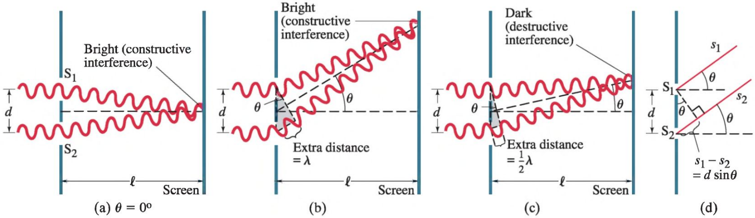


Interference: Youn's double-slit Experiment



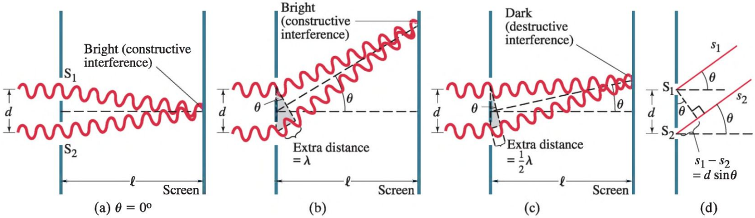
- Constructive interference $\rightarrow$ the path of 2 rays differs in $n\lambda$, n integer.

Interference: Youn's double-slit Experiment



- Constructive interference → the path of 2 rays differs in $n\lambda$, n integer.
- Destructive interference → the path of 2 rays differs in $(2n+1)\lambda/2$, n integer.

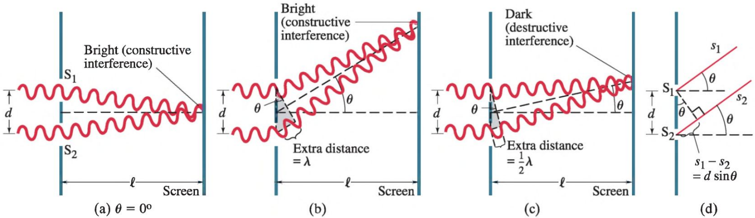
Interference: Youn's double-slit Experiment



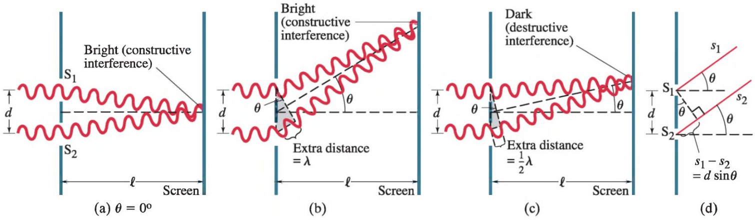
- Constructive interference → the path of 2 rays differs in $n\lambda$, n integer.
- Destructive interference → the path of 2 rays differs in $(2n+1)\lambda/2$, n integer.

Thus, there will be a series of bright and dark lines (or fringes) on the viewing screen.

Interference: Youn's double-slit Experiment

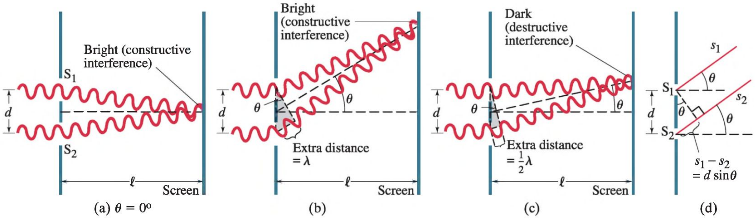


Interference: Youn's double-slit Experiment



Where the bright lines fall?

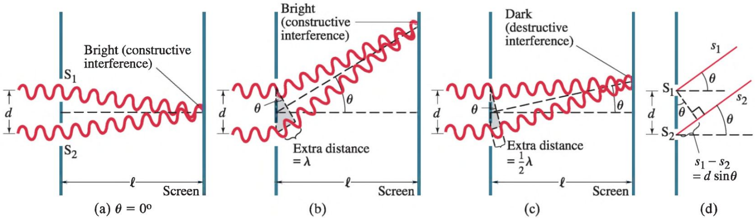
Interference: Youn's double-slit Experiment



Where the bright lines fall?

- $d << \ell$

Interference: Youn's double-slit Experiment



Where the bright lines fall?

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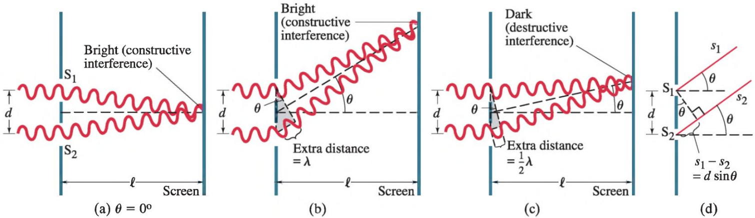
- The rays are essentially parallel.

Interference: Youn's double-slit Experiment



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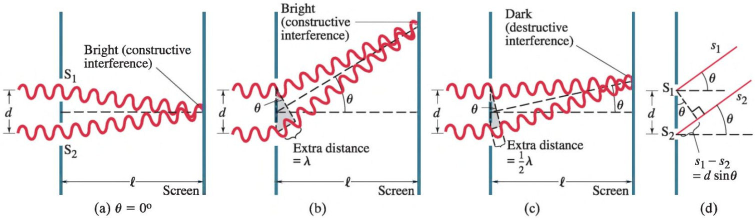
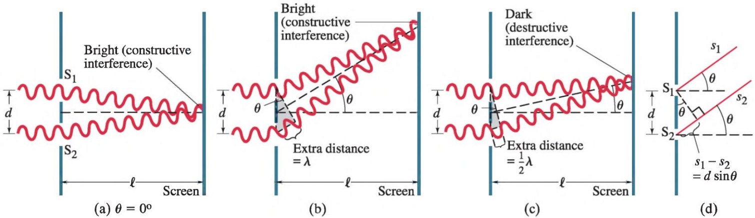


Where the bright lines fall?

- $d << \ell$
- The rays are essentially parallel.
- θ is the angle they make with the horizontal.
- The extra distance traveled by the lower ray is $d sin\theta$

Interference: Youn's double-slit Experiment



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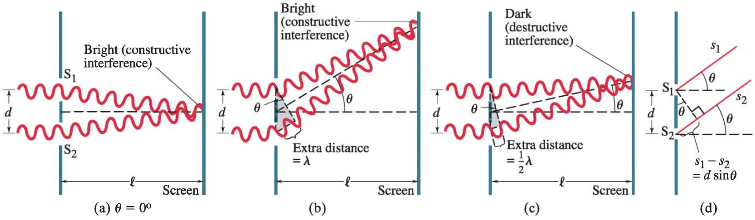

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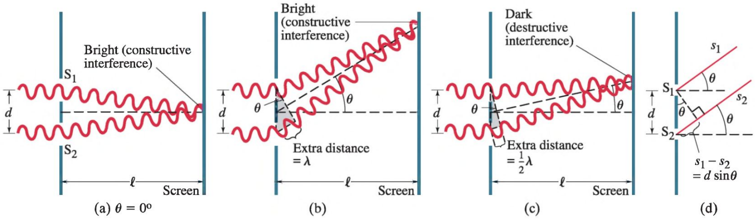

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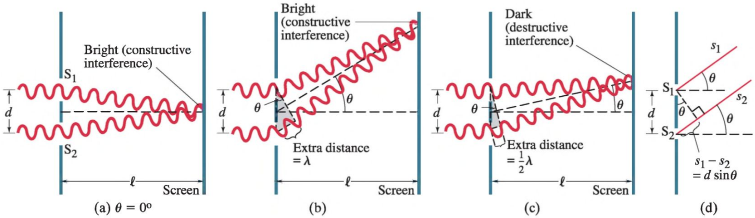
Constructive interference:

Interference: Youn's double-slit Experiment

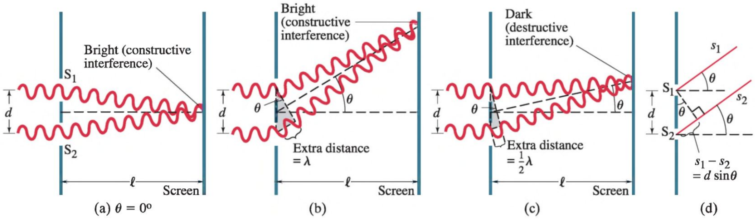


Where the bright lines fall?

Constructive interference:

$$sin\theta = \frac{n\lambda}{d} = \frac{X}{\ell} \tag{44}$$

Interference: Youn's double-slit Experiment

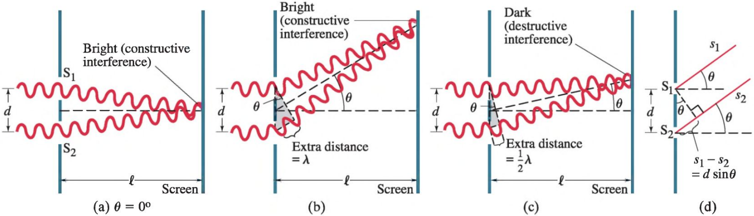


Where the bright lines fall?

Constructive interference:

$$sin\theta = \frac{n\lambda}{d} = \frac{X}{\ell} \rightarrow X = \ell\frac{n\lambda}{d} \quad (45)$$

Interference: Youn's double-slit Experiment



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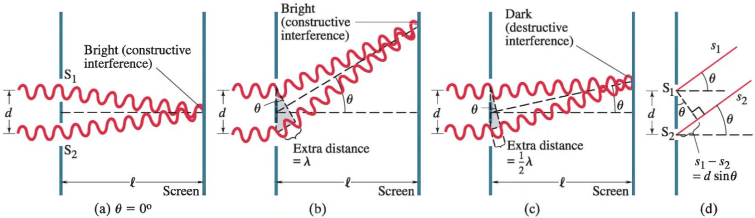
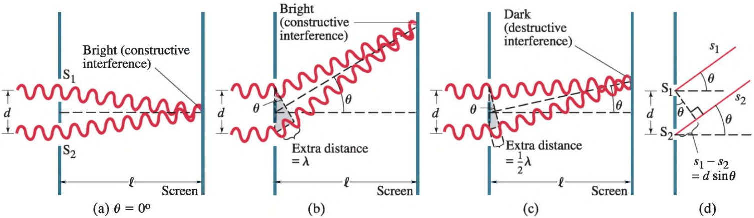


Destructive interference:

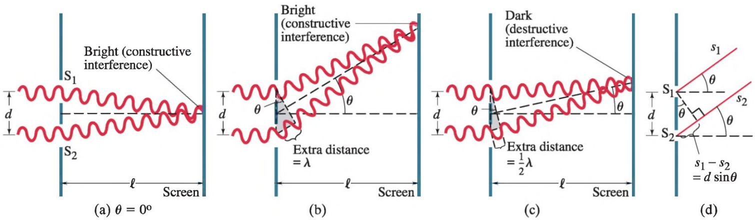
Interference: Youn's double-slit Experiment



Destructive interference:

$$sin\theta = \frac{(2n+1)\lambda}{d} = \frac{X}{\ell} \qquad (46)$$

Interference: Youn's double-slit Experiment



Where the bright lines fall?

Destructive interference:

$$sin\theta = \frac{(2n+1)\lambda}{d} = \frac{X}{\ell} \rightarrow X = \ell\frac{(2n+1)\lambda}{d} \quad (47)$$

Interference: Youn's double-slit Experiment

Conceptual Example:

(a) Will there be an infinite number of points on the viewing screen where constructive and destructive interference occur, or only a finite number of points?

Interference: Youn's double-slit Experiment

Conceptual Example:

(a) Will there be an infinite number of points on the viewing screen where constructive and destructive interference occur, or only a finite number of points?

(b) Are neighboring points of constructive interference uniformly spaced, or is the spacing between neighboring points of constructive interference not uniform?

Interference: Youn's double-slit Experiment

Conceptual Example:

(a) The maximum value of n is the integer closest in value but smaller than d/X.

Interference: Youn's double-slit Experiment

Conceptual Example:

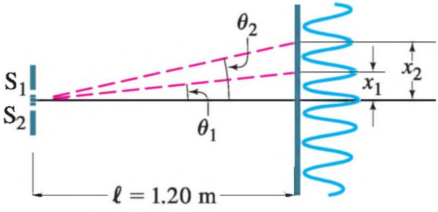
(a) The maximum value of n is the integer closest in value but smaller than d/X.

(b) For small values of θ the spacing is nearly uniform. For non-small values $\rightarrow$ the spacing gets larger as θ gets larger.

Interference: Youn's double-slit Experiment

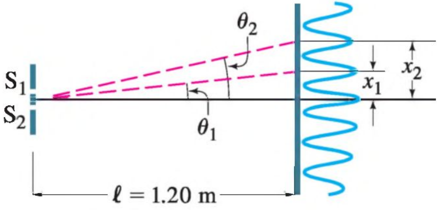
Example:

A screen containing two slits 0.100 *mm* apart is 1.20 *m* from the viewing screen. Light of wavelength $A = 500$ *nm* falls on the slits from a distant source. Approximately how far apart will adjacent bright interference fringes be on the screen?



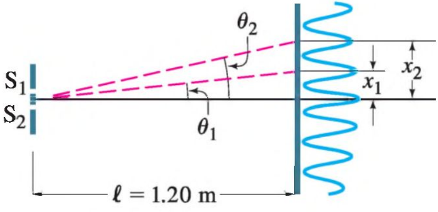
Interference: Youn's double-slit Experiment

Example:



Interference: Youn's double-slit Experiment

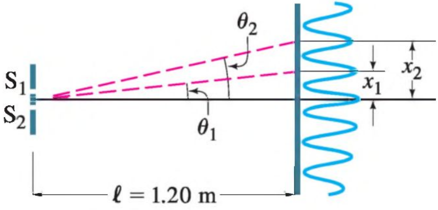
Example:



$$sin\theta_1 = \frac{m\lambda}{d} = \frac{(1)(500 \times 10^{-9}\ m)}{1.00 \times 10^{-4}\ m} = 5.00 \times 10^{-3} \qquad (48)$$

Interference: Youn's double-slit Experiment

Example:



$$sin\theta_1 = \frac{m\lambda}{d} = \frac{(1)(500 \times 10^{-9}\ m)}{1.00 \times 10^{-4}\ m} = 5.00 \times 10^{-3} \qquad (48)$$

$\theta << 1 \rightarrow sin\theta \sim \theta$ and $x_1/\ell = tan\theta_1 \sim \theta_1$

Interference: Youn's double-slit Experiment

Example:

then,

$$x_1 \sim \ell\theta_1 = (1.20\ m)(5.00 \times 10^{-3}) = 6.00\ mm \tag{49}$$

Interference: Youn's double-slit Experiment

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Interference: Youn's double-slit Experiment

Example:

then,

$$x_1 \sim \ell\theta_1 = (1.20\ m)(5.00 \times 10^{-3}) = 6.00\ mm \tag{49}$$

$$x_2 \sim \ell\theta_2 = \ell\frac{2\lambda}{d} = 12.00\ mm \tag{50}$$

Thus the lower order fringes are 6.00 mm apart.

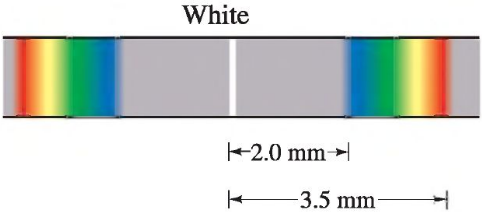
Interference: Youn's double-slit Experiment

Conceptual Example:

(a) What happens to the interference pattern, if the incident light (500 nm) is replaced by light of wavelength 700 nm? (b) What happens instead if the wavelength stays at 500 nm but the slits are moved farther apart?

Interference: Youn's double-slit Experiment

Except for the zeroth-order fringe at the center, the position of the fringes depends on wavelength.



Intensity in the Interference Pattern

- $E_\theta = E_1 + E_2$

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- $E_1 = E_{10} sin \omega t$

Intensity in the Interference Pattern

- $E_\theta = E_1 + E_2$
- $E_1 = E_{10} sin \omega t$
- $E_2 = E_{20} sin(\omega t + \delta)$, $\frac{\delta}{2\pi} = \frac{dsin\theta}{\lambda}$

We can work with this expression and prove that:

$$\frac{I_\theta}{I_0} = \frac{E_{\theta 0}^2}{(2E_0)^2} = cos^2 \frac{\delta}{2} \qquad (51)$$

Intensity in the Interference Pattern

$$I_\theta = I_0 cos^2\left(\frac{\pi d sin\theta}{\lambda}\right) \tag{52}$$

Intensity in the Interference Pattern

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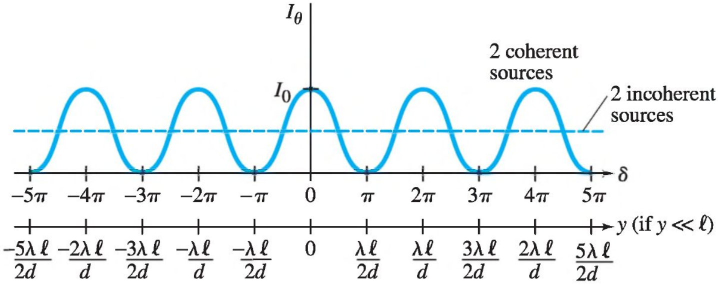
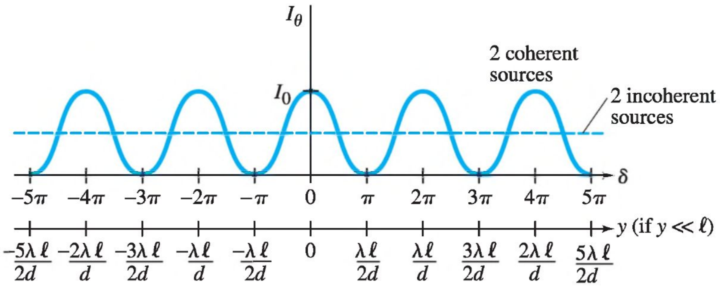
small θ, $sin\theta = \frac{y}{\ell}$

$$I_\theta = I_0 \left[cos\left(\frac{\pi d}{\lambda \ell} y\right)\right]^2 \tag{53}$$

Intensity in the Interference Pattern

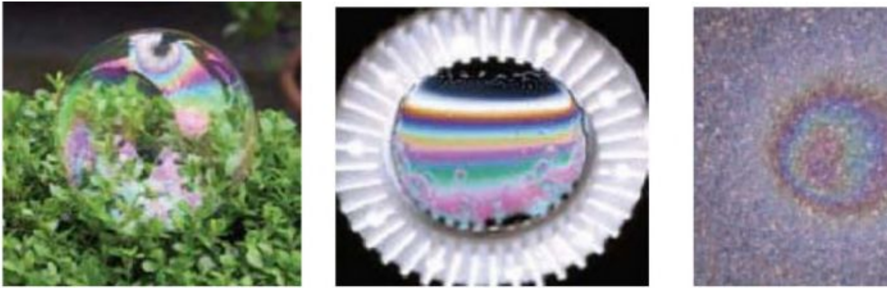


Intensity in the Interference Pattern



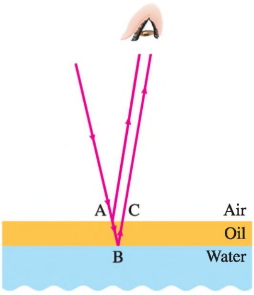
The intensity pattern shows a series of maxima of equal height, and is based on the assumption that each slit (alone) would illuminate the screen uniformly. This is never quite true, if we consider diffraction.

Interference in Thin Films



(a) (b) (c)

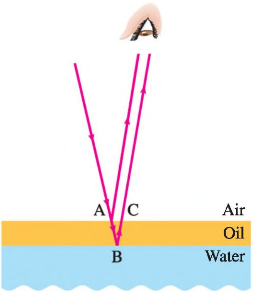
Interference in Thin Films



If path difference ABC is,

- equals $m\lambda_n \rightarrow$ constructive interference

Interference in Thin Films



If path difference ABC is,

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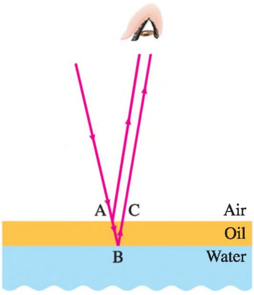
- equals $(2m+1)\lambda_n \rightarrow$ destructive interference

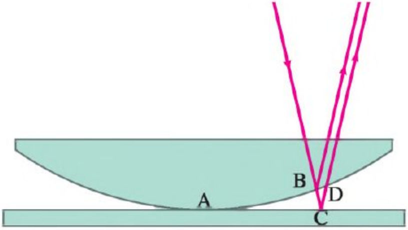
Interference in Thin Films



If path difference ABC is,

- equals $m\lambda_n \rightarrow$ constructive interference
- equals $(2m+1)\lambda_n \rightarrow$ destructive interference
- $\lambda_n = \lambda/n$, n is the index of refraction

Newton's Rings



(a)

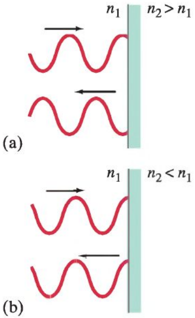
(b)

Newton's Rings

Why is the center dark?

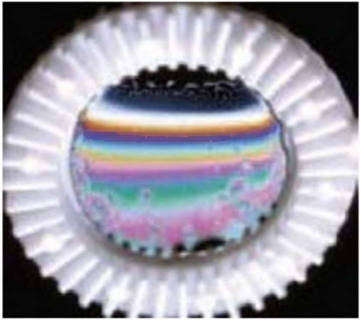
Newton's Rings

Why is the center dark?



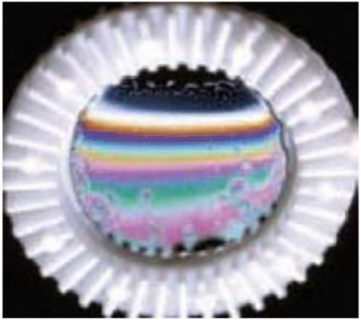
a beam of light reflected by a material with index of refraction greater than that of the material in which it is traveling, changes phase by 180° or $\frac{1}{2}$ cycle;

Colors in a Thin Soap Film



- The thin film stood vertically.

Colors in a Thin Soap Film



- The thin film stood vertically.
- Gravity has pulled much of the soapy water toward the bottom.

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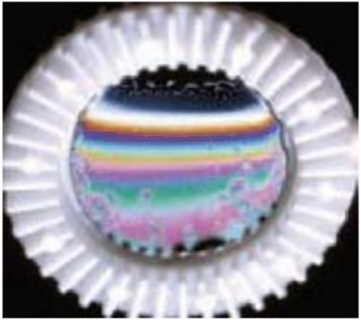

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- The top section is so thin $\rightarrow$ light reflected from the front and back surfaces have almost no path difference.

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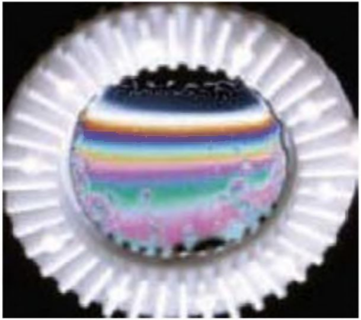
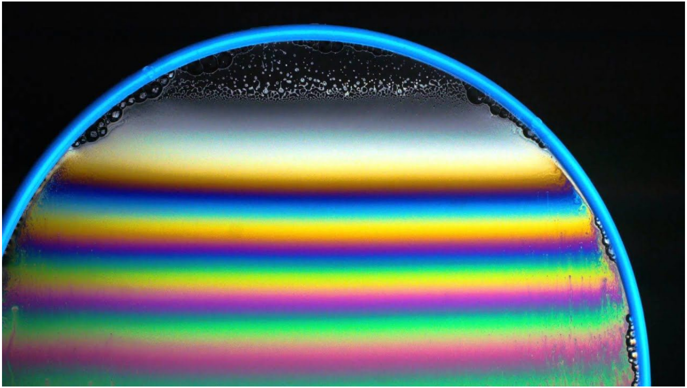


- The thin film stood vertically.
- Gravity has pulled much of the soapy water toward the bottom.
- The top section is so thin $\rightarrow$ light reflected from the front and back surfaces have almost no path difference.
- 180° $\rightarrow$ two reflected waves are out of phase for all wavelengths.

Colors in a Thin Soap Film



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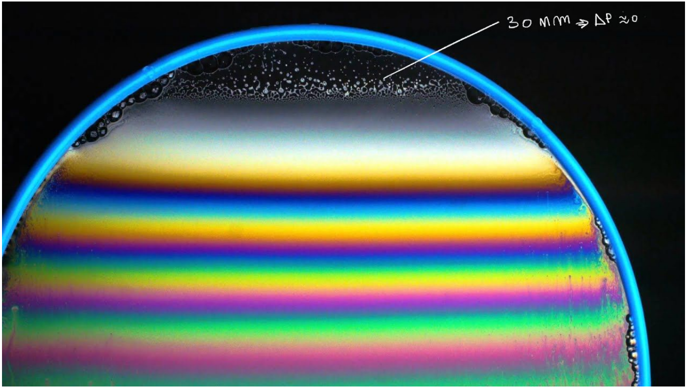

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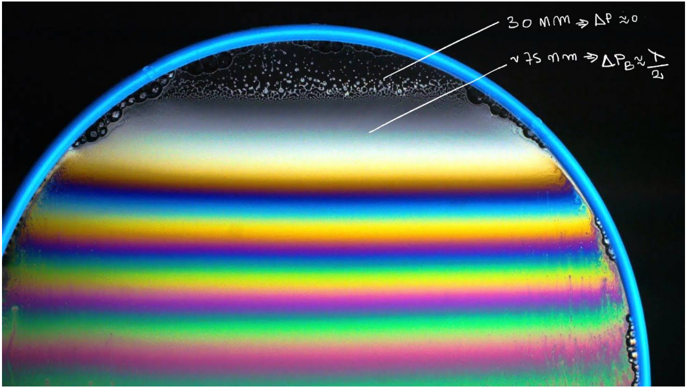

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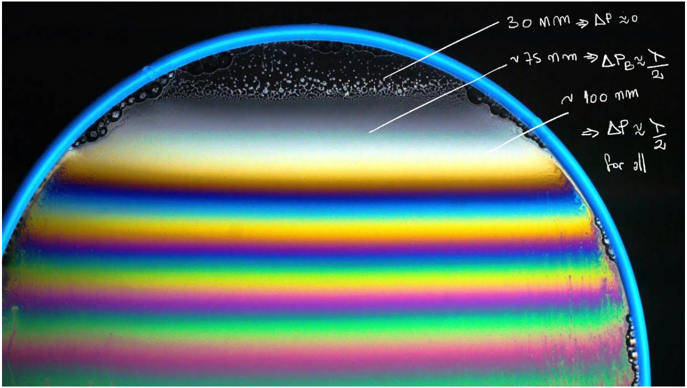

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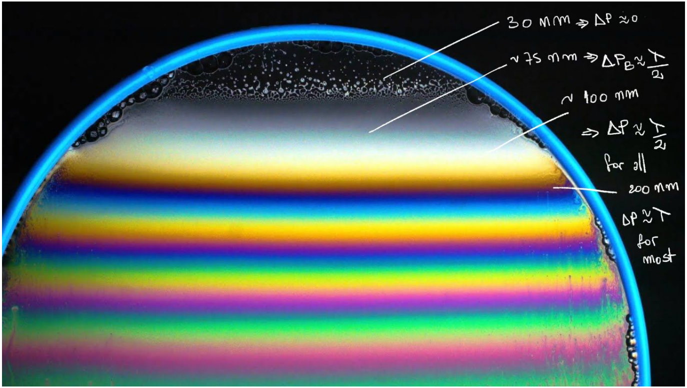

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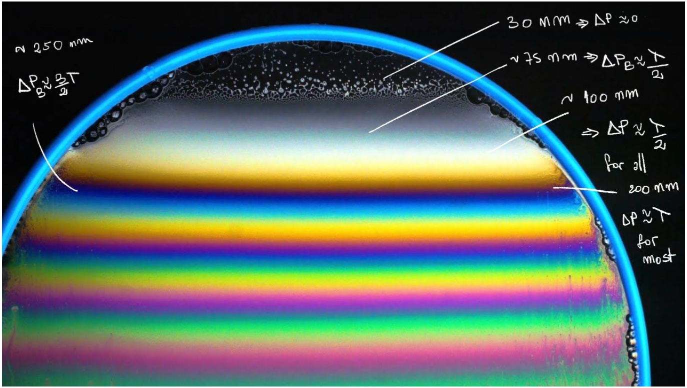
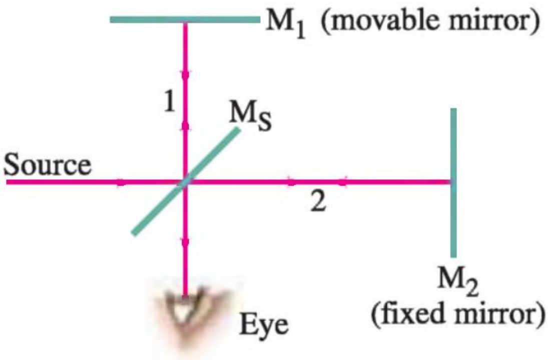


Michelson Interferometer



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- Does Huygens' principle apply to sound waves? To water waves?
- We can hear sounds around corners but we cannot see around corners; yet both sound and light are waves. Explain the difference.
- Two rays of light from the same source destructively interfere if their path lengths differ by how much?

Questions

- Monochromatic red light is incident on a double slit and the interference pattern is viewed on a screen some distance away. Explain how the fringe pattern would change if the red light source is replaced by a blue light source.

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- Monochromatic red light is incident on a double slit and the interference pattern is viewed on a screen some distance away. Explain how the fringe pattern would change if the red light source is replaced by a blue light source.
- Compare a double-slit experiment for sound waves to that for light waves. Discuss the similarities and differences.