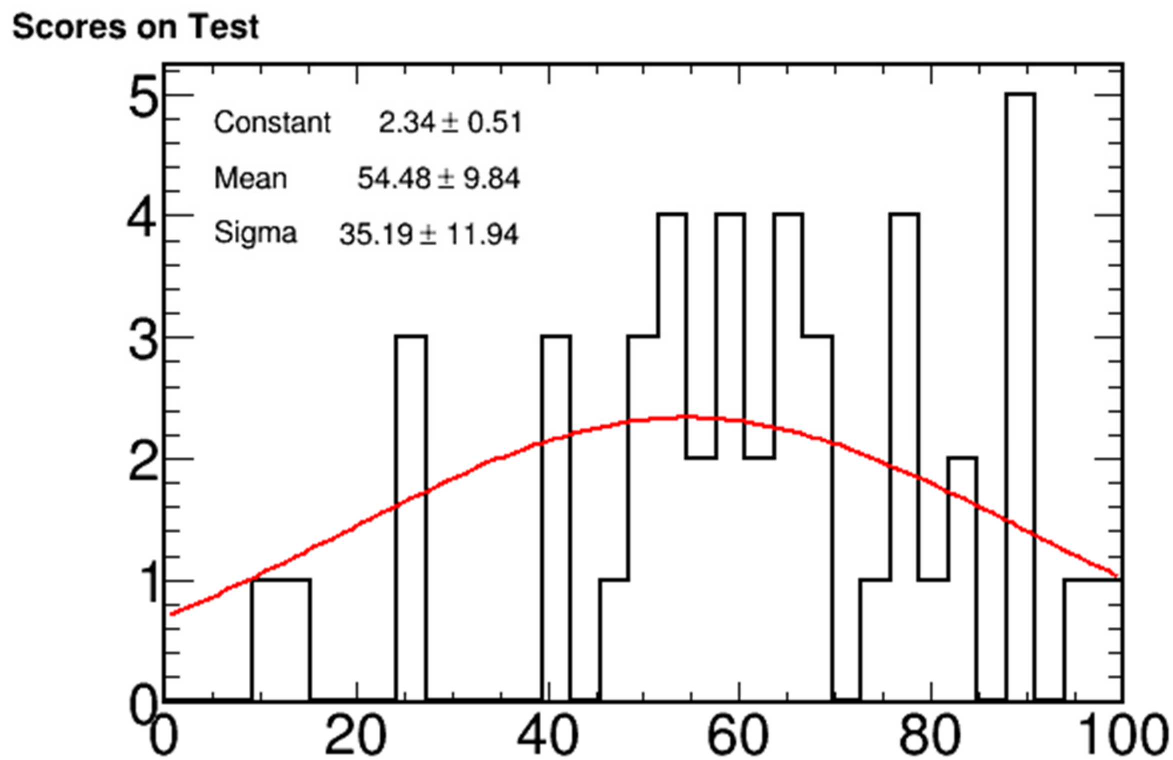
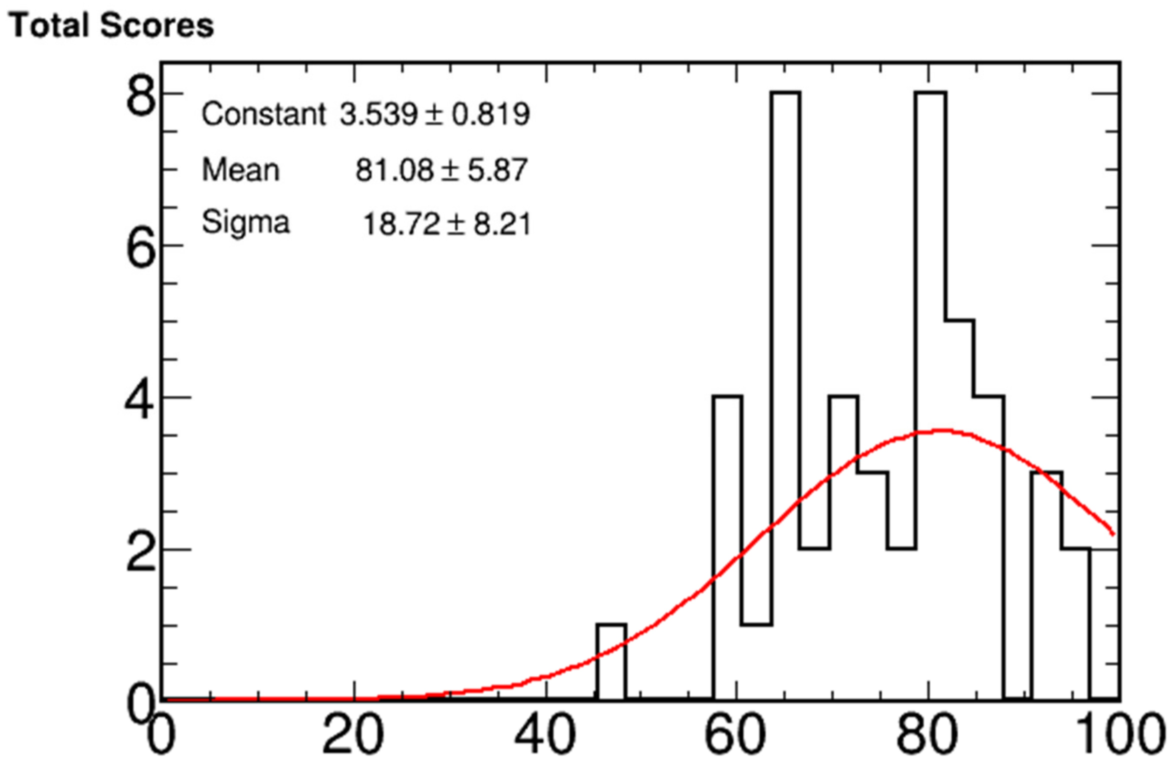

Scores on Test
Constant 2.34 ± 0.51
Mean 54.48 ± 9.84
Sigma 35.19 ± 11.94
0
1
2
3
4
5
0
20
40
60
80
100



Total Scores
Constant 3.539 ± 0.819
Mean 81.08 ± 5.87
Sigma 18.72 ± 8.21
0
2
4
6
8
0
20
40
60
80
100

Energy stored in magnetic field

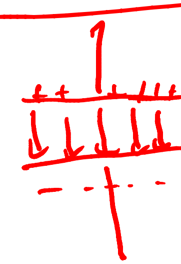
$$u_B = \frac{U_L}{\text{Volume}} = \frac{\frac{1}{2} L I^2}{A \ell}$$

Since $L/\ell = \mu_0 n^2 A$

$$u_B = (\mu_0 n^2 A)\,\frac{\frac{1}{2} I^2}{A} = \frac{1}{2}\mu_0 n^2 I^2$$

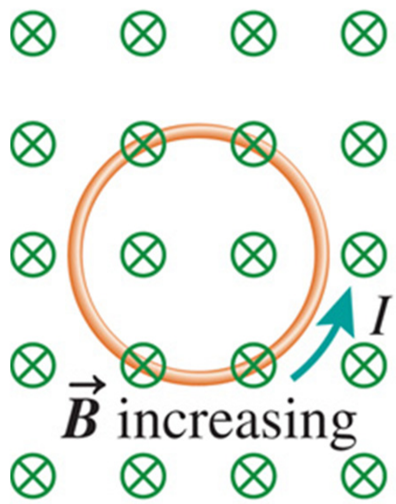
B in solenoid is $\mu_0 n I$

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



$U_C = \frac{1}{2} C V^2$

$u_E = \frac{1}{2}\varepsilon_0 E^2$

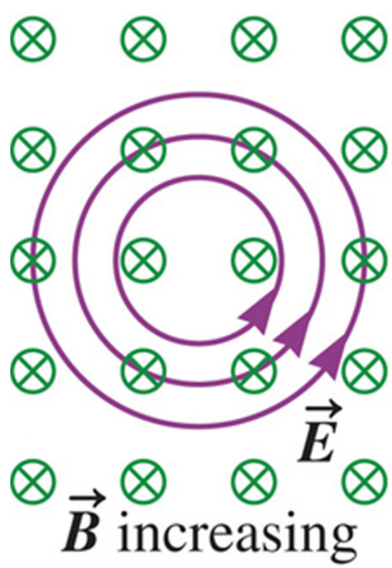


A.

Practical way to look at Faraday's law: Changing magnetic flux induces current in conducting loop, so an emf is induced in conductor.

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

$$\oint \vec{E} \cdot d\vec{l} = -\frac{d}{dt}\int \vec{B} \cdot d\vec{A}$$



B.

General way to look at Faraday's law: Changing magnetic flux induces an electric field whether a conductor is present or not.

Maxwell's Equations

$\oint = \oiint$

Below we summarize the four equations on which electromagnetic theory is based. We use here the complete form of Ampere's law as modified by Maxwell:

Gauss' law for $\vec{E}$: $\oiint \vec{E} \cdot d\vec{A} = \frac{q_{\text{enc}}}{\varepsilon_0}$ $\qquad \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$

Gauss' law for $\vec{B}$: $\oiint \vec{B} \cdot d\vec{A} = 0$ $\qquad \nabla \cdot \mathbf{B} = 0$

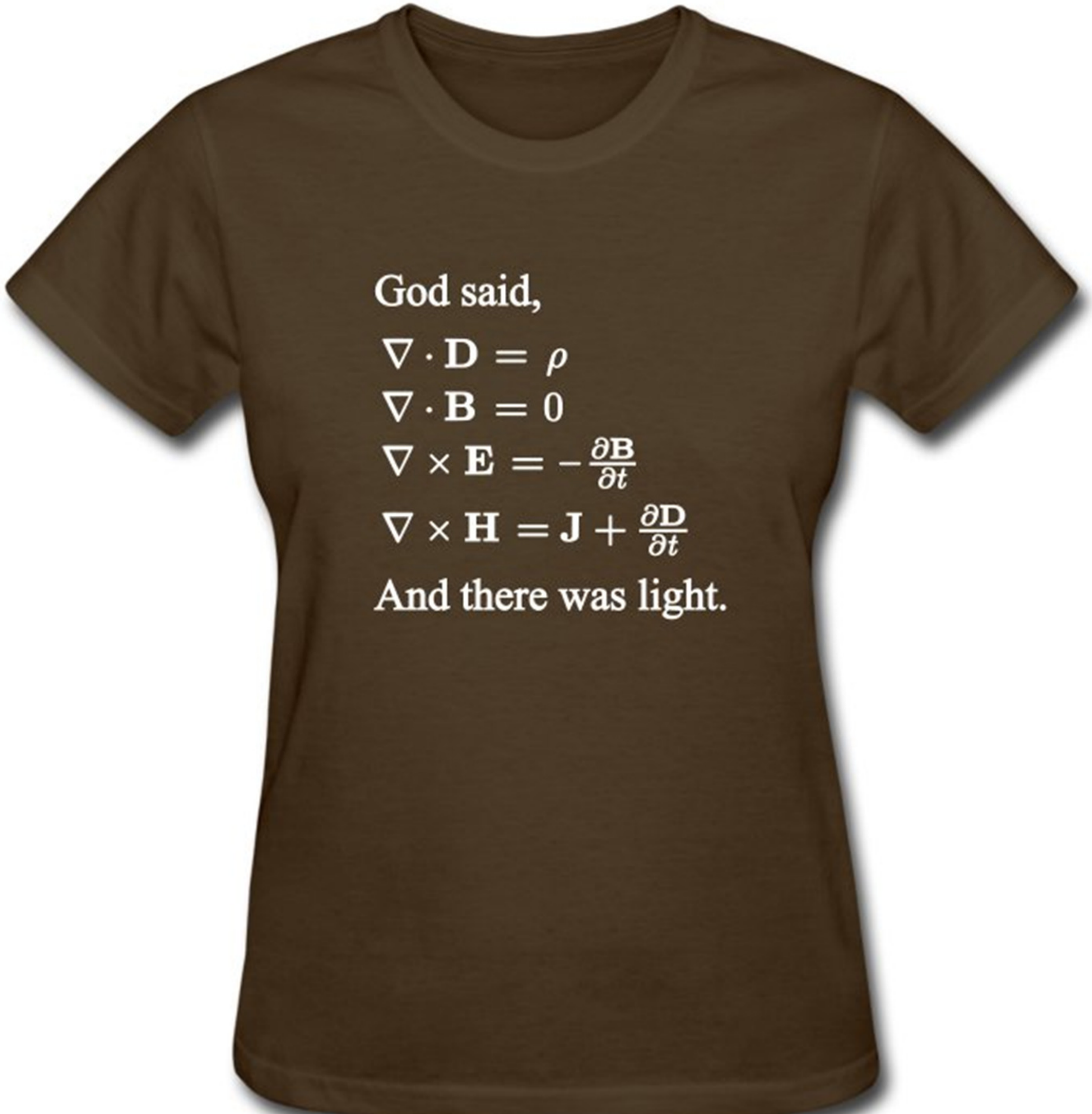
Faraday's law: $\oint \vec{E} \cdot d\vec{S} = -\frac{d\Phi_B}{dt}$ $\qquad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$

Ampere's law: $\oint \vec{B} \cdot d\vec{S} = \mu_0 i_{\text{enc}} + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$ $\qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$

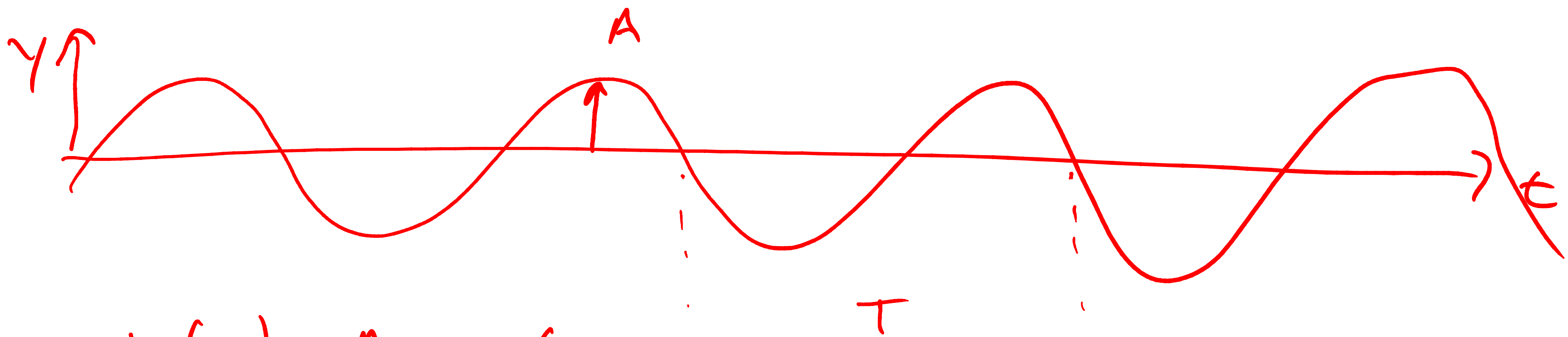
These equations describe a group of diverse phenomena and devices based on them such as the magnetic compass,electric motors, electric generators, radio, television, radar, x-rays, and all optical effects.

All these in just four equations!


And God Said
$$\oint\!\!\!\oint_{\partial V} \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_0}$$
$$\oint\!\!\!\oint_{\partial V} \vec{B} \cdot d\vec{A} = 0$$
$$\oint_{\partial S} \vec{E} \cdot d\vec{l} = -\iint_S \frac{\partial \vec{B}}{\partial t} \cdot d\vec{A}$$
$$\oint_{\partial S} \vec{B} \cdot d\vec{l} = \mu_0 I_S + \mu_0 \epsilon_0 \iint_S \frac{\partial \vec{E}}{\partial t} \cdot d\vec{A}$$
and *then* there was light.


God said,
$\nabla \cdot \mathbf{D} = \rho$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$
And there was light.

Wave review



$$y(t) = A\sin(\omega t - \phi) \qquad \omega = 2\pi f \qquad f = 1/T$$

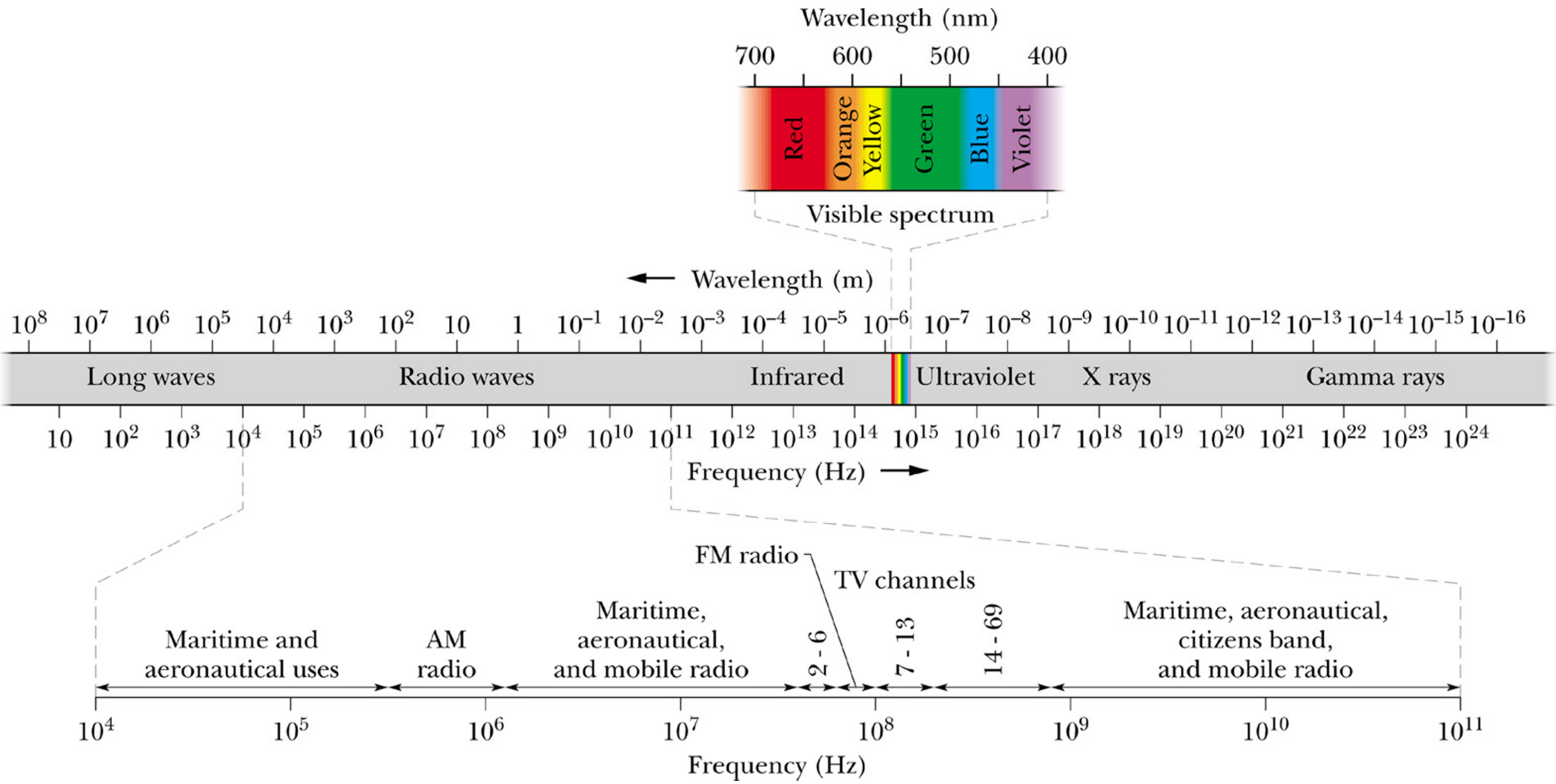
$$y(x,t) = A\sin(kx - \omega t)$$

speed $c = \frac{\lambda}{T} = \frac{\text{meters/cycle}}{\text{sec/cycle}} = \lambda f = \frac{\omega}{k} \quad \frac{\text{rad/sec}}{\text{rad/m}}$

Energy $\propto A^2$

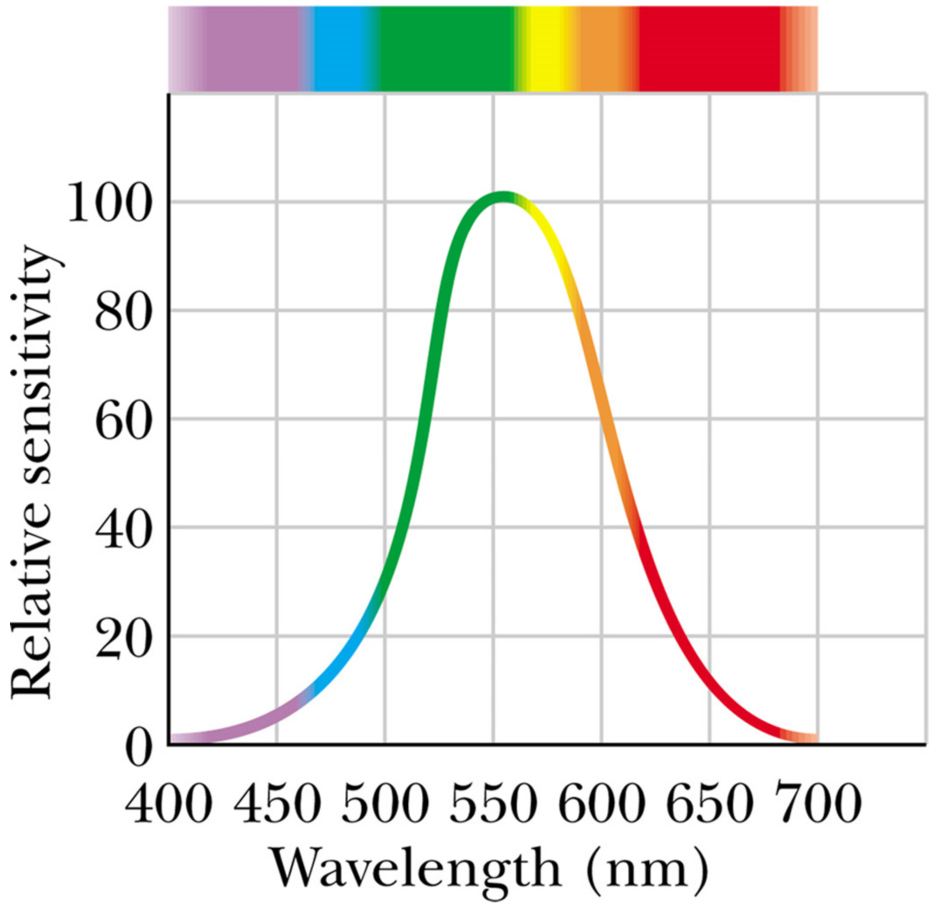
Wave review

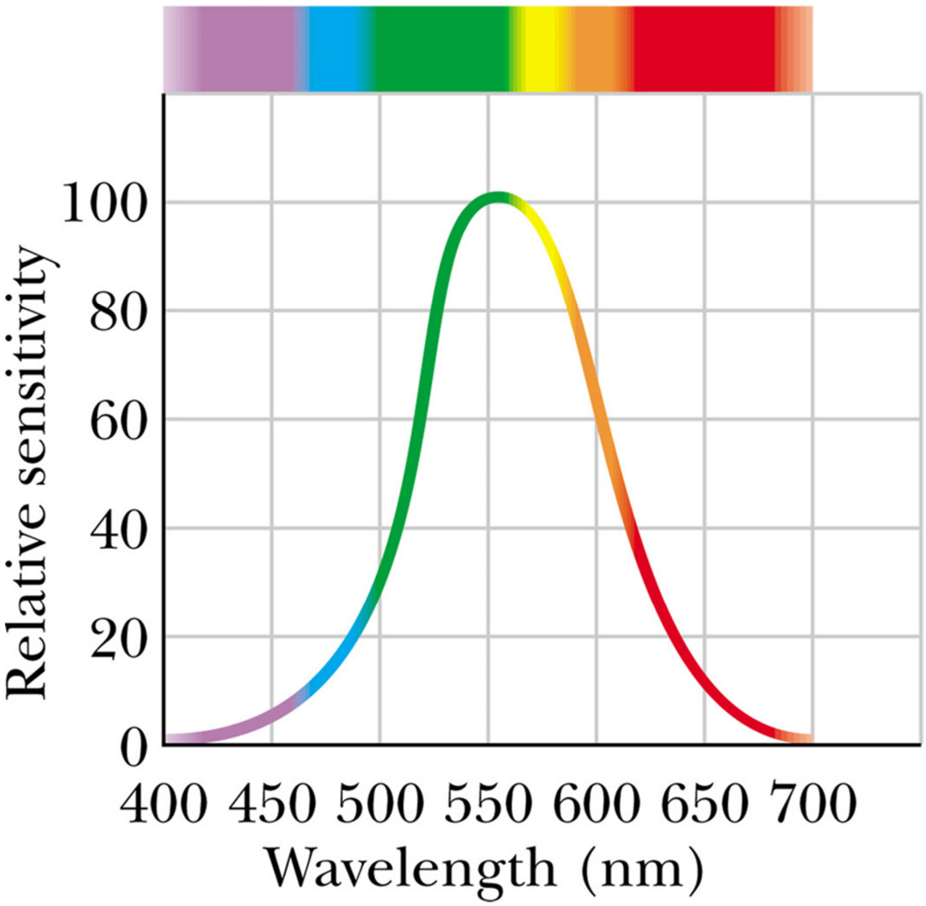
$c = \lambda f$

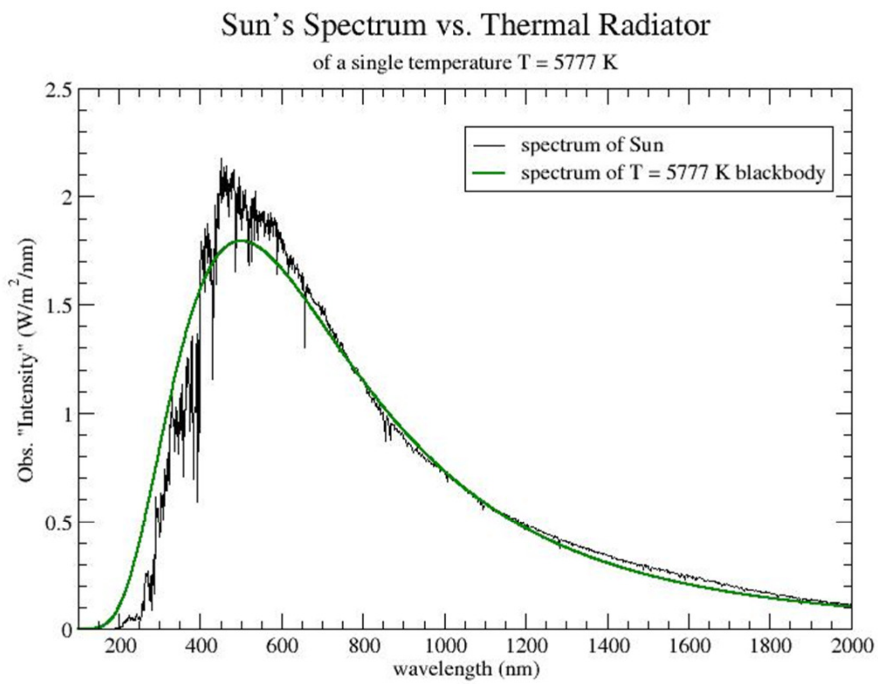


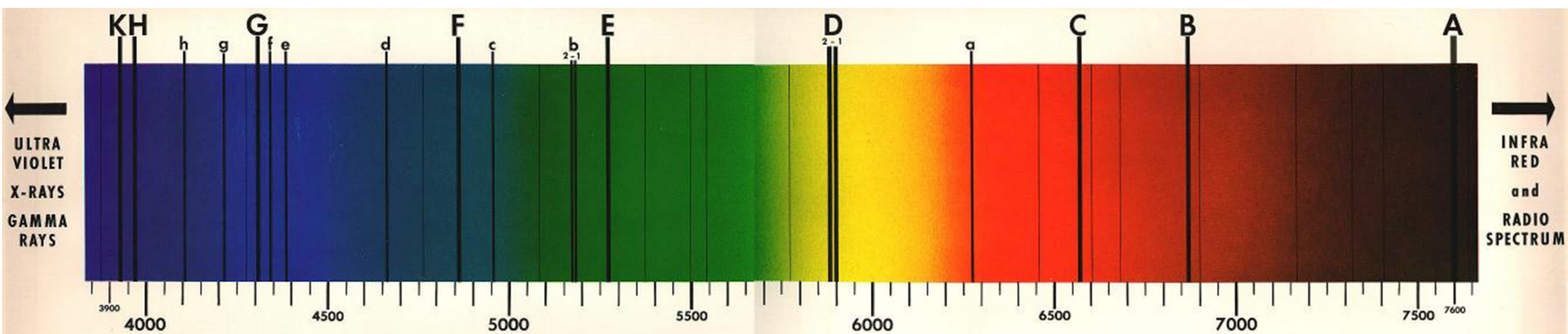
Wavelength (nm)
700
600
500
400
Red
Orange
Yellow
Green
Blue
Violet
Visible spectrum
Wavelength (m)
10^8 10^7 10^6 10^5 10^4 10^3 10^2 10 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12 10^-13 10^-14 10^-15 10^-16
Long waves
Radio waves
Infrared
Ultraviolet
X rays
Gamma rays
10 10^2 10^3 10^4 10^5 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 10^21 10^22 10^23 10^24
Frequency (Hz)
FM radio
TV channels
Maritime and aeronautical uses
AM radio
Maritime, aeronautical, and mobile radio
2 - 6
7 - 13
14 - 69
Maritime, aeronautical, citizens band, and mobile radio
10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11
Frequency (Hz)

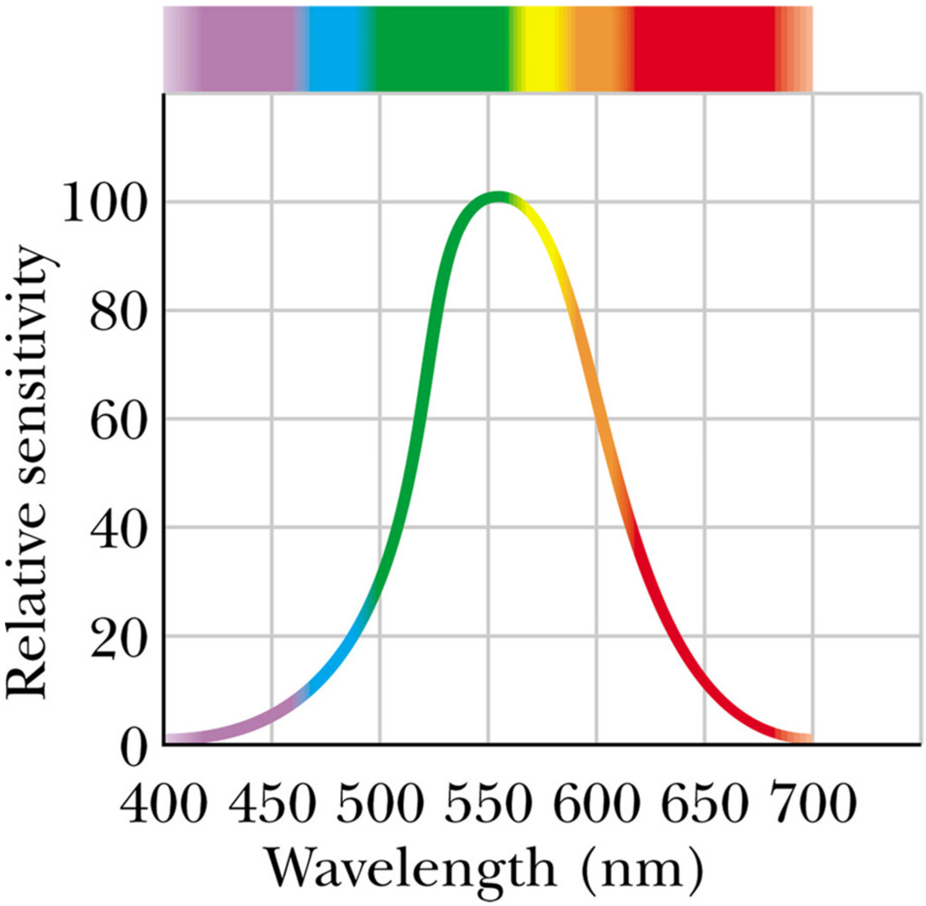
Response of your eye




Relative sensitivity
100
80
60
40
20
0
400 450 500 550 600 650 700
Wavelength (nm)

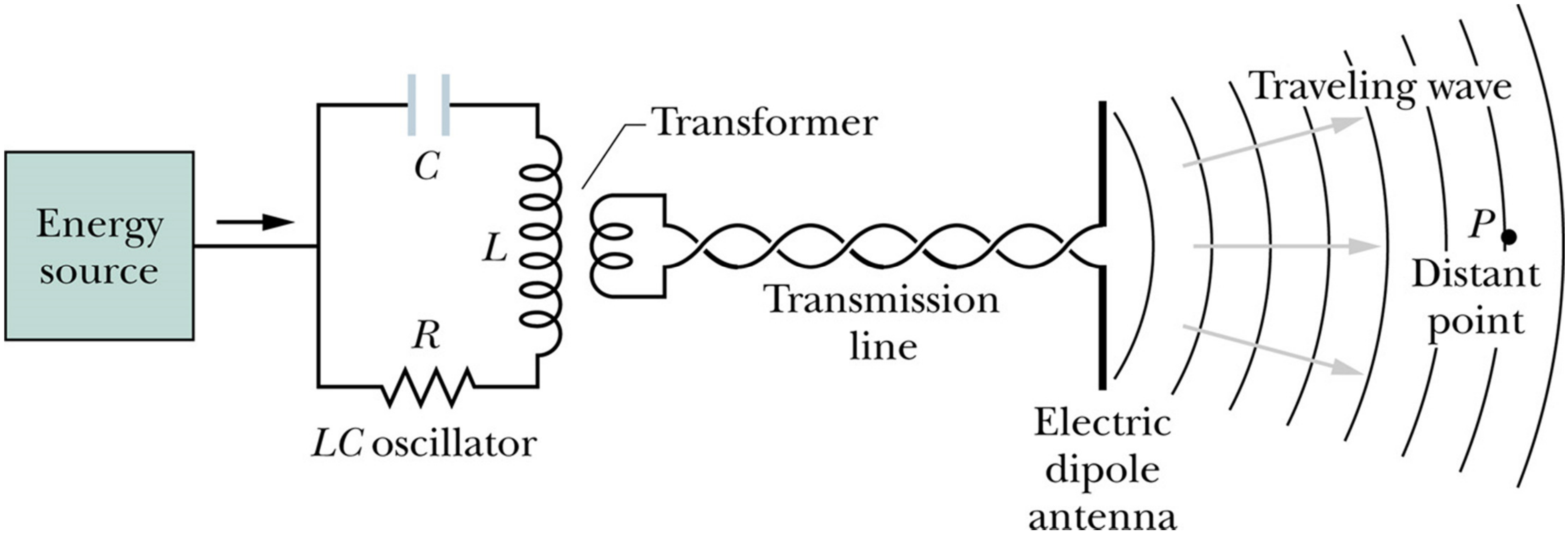

Sun's Spectrum vs. Thermal Radiator
of a single temperature T = 5777 K
spectrum of Sun
spectrum of T = 5777 K blackbody
Obs. "Intensity" (W/m^2/nm)
wavelength (nm)
0
0.5
1
1.5
2
2.5
200 400 600 800 1000 1200 1400 1600 1800 2000


K H h g G f e d F c b E D a C B A
ULTRA VIOLET
X-RAYS
GAMMA RAYS
INFRA RED
and
RADIO SPECTRUM
3900 4000 4500 5000 5500 6000 6500 7000 7500 7600



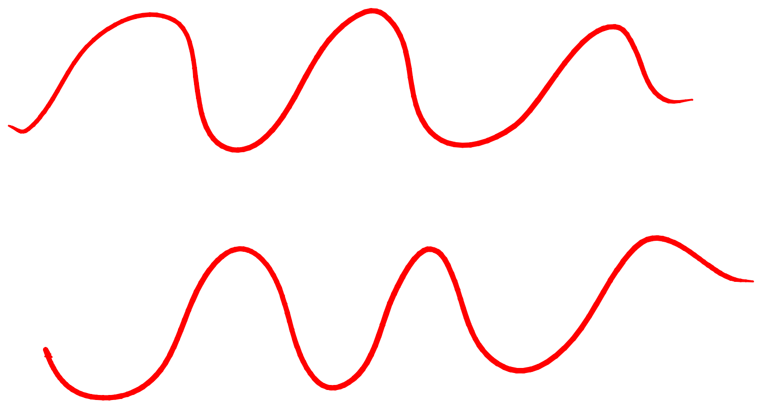
Relative sensitivity
100
80
60
40
20
0
400 450 500 550 600 650 700
Wavelength (nm)

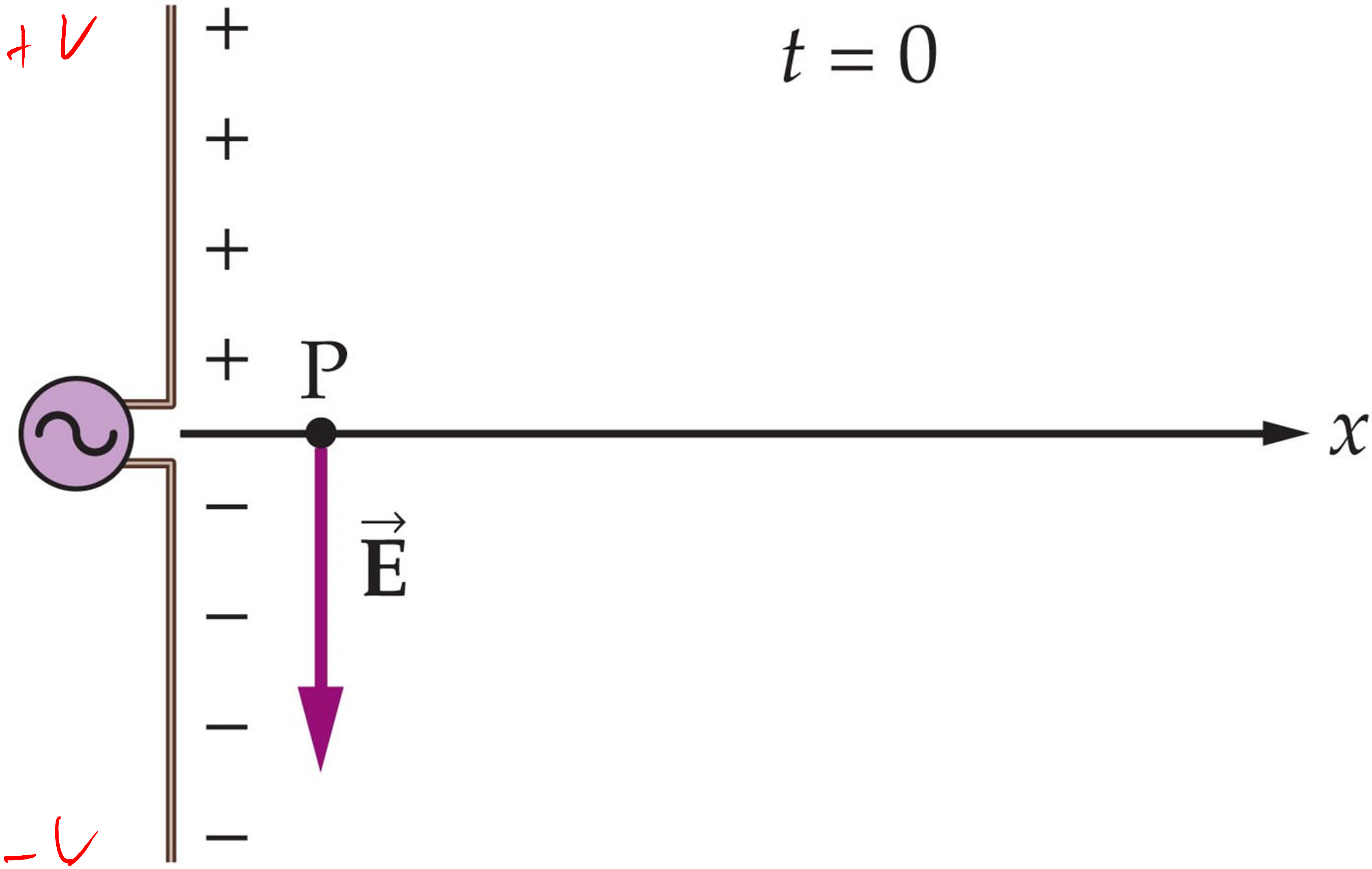
ENGINE
4602
RESORT
F.D.
BEAR CREEK


Energy source
C
L
R
LC oscillator
Transformer
Transmission line
Electric dipole antenna
Traveling wave
P
Distant point

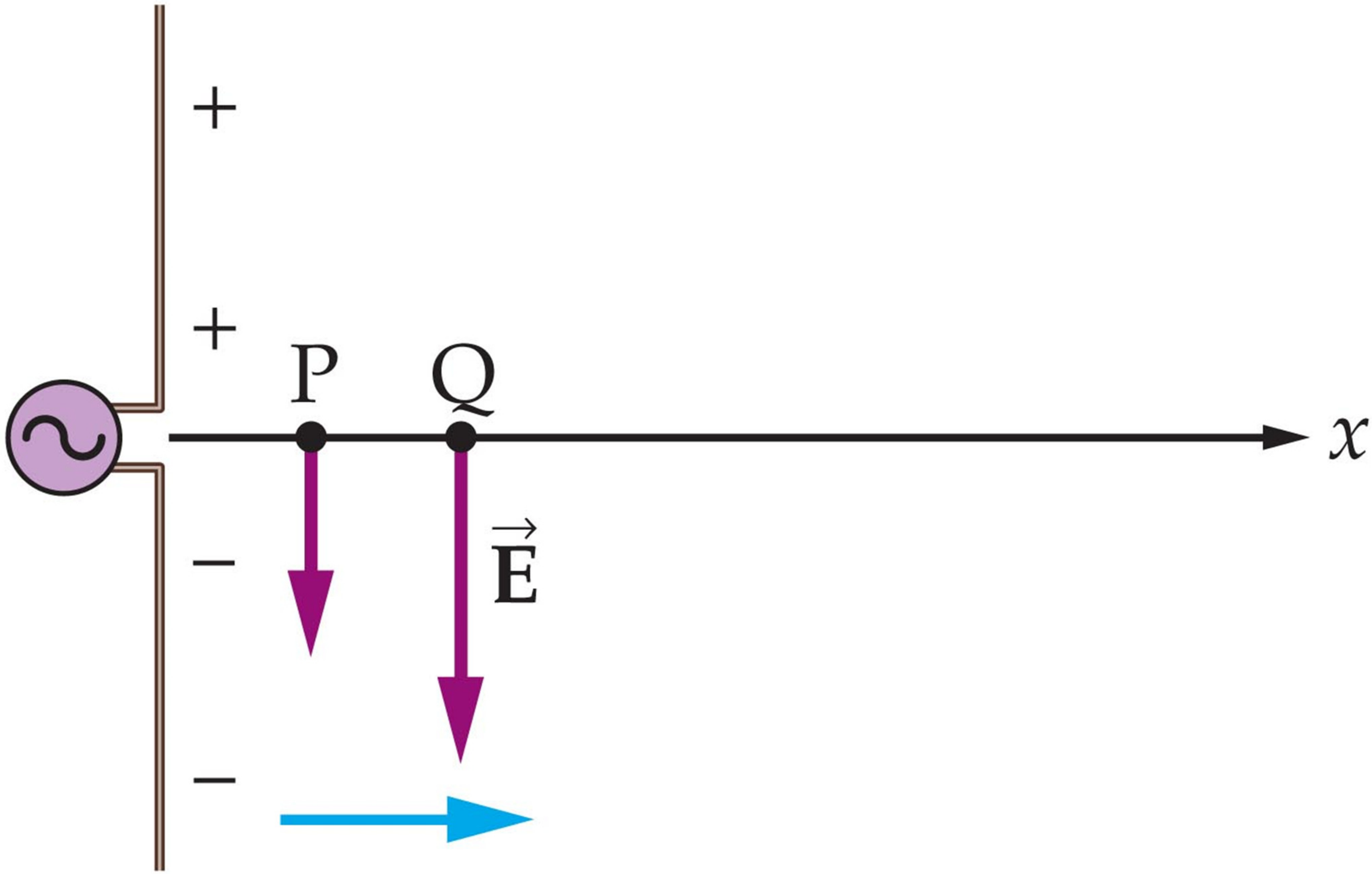
$V(t)$

$I(t)$

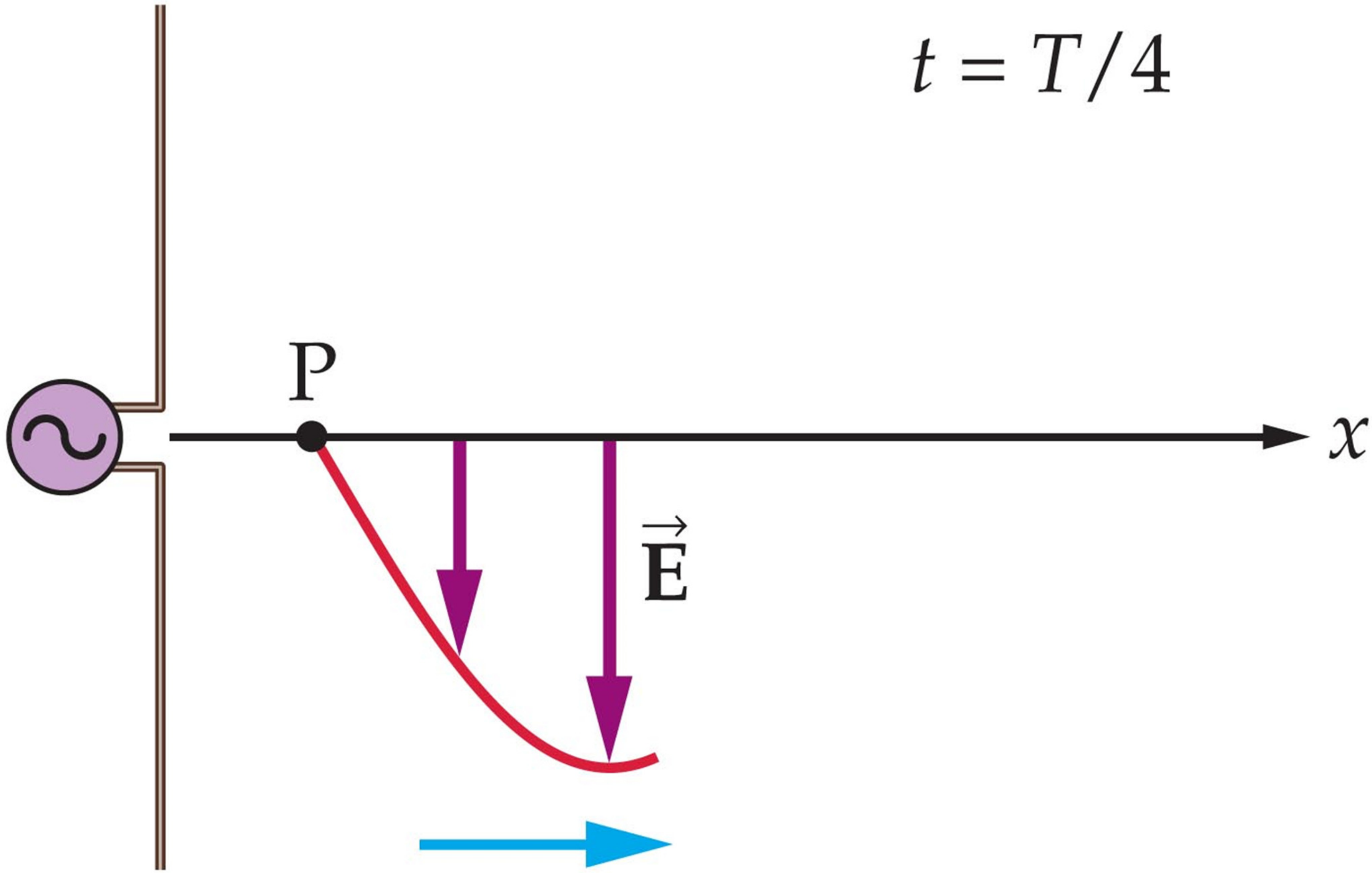




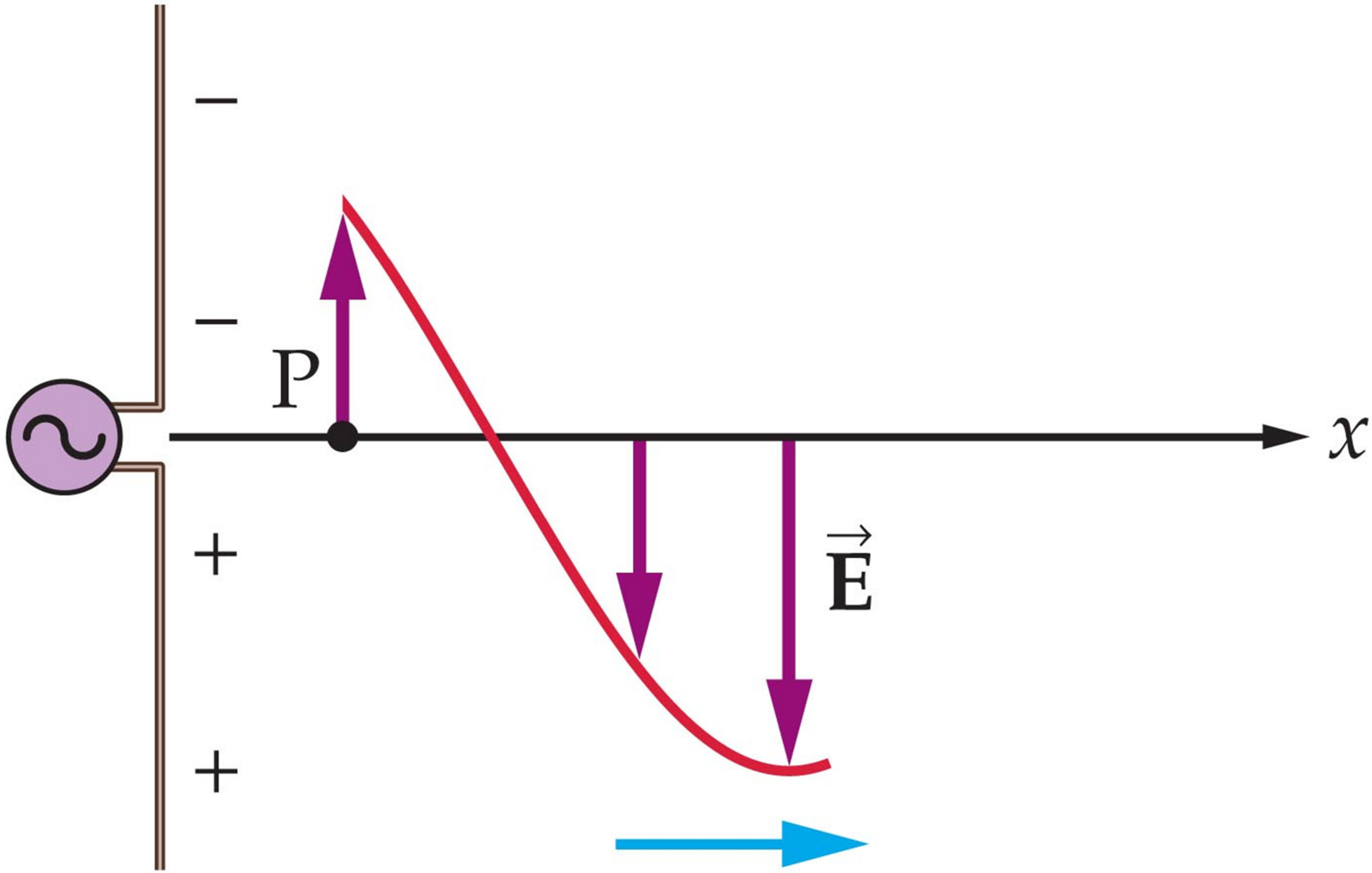
(a)



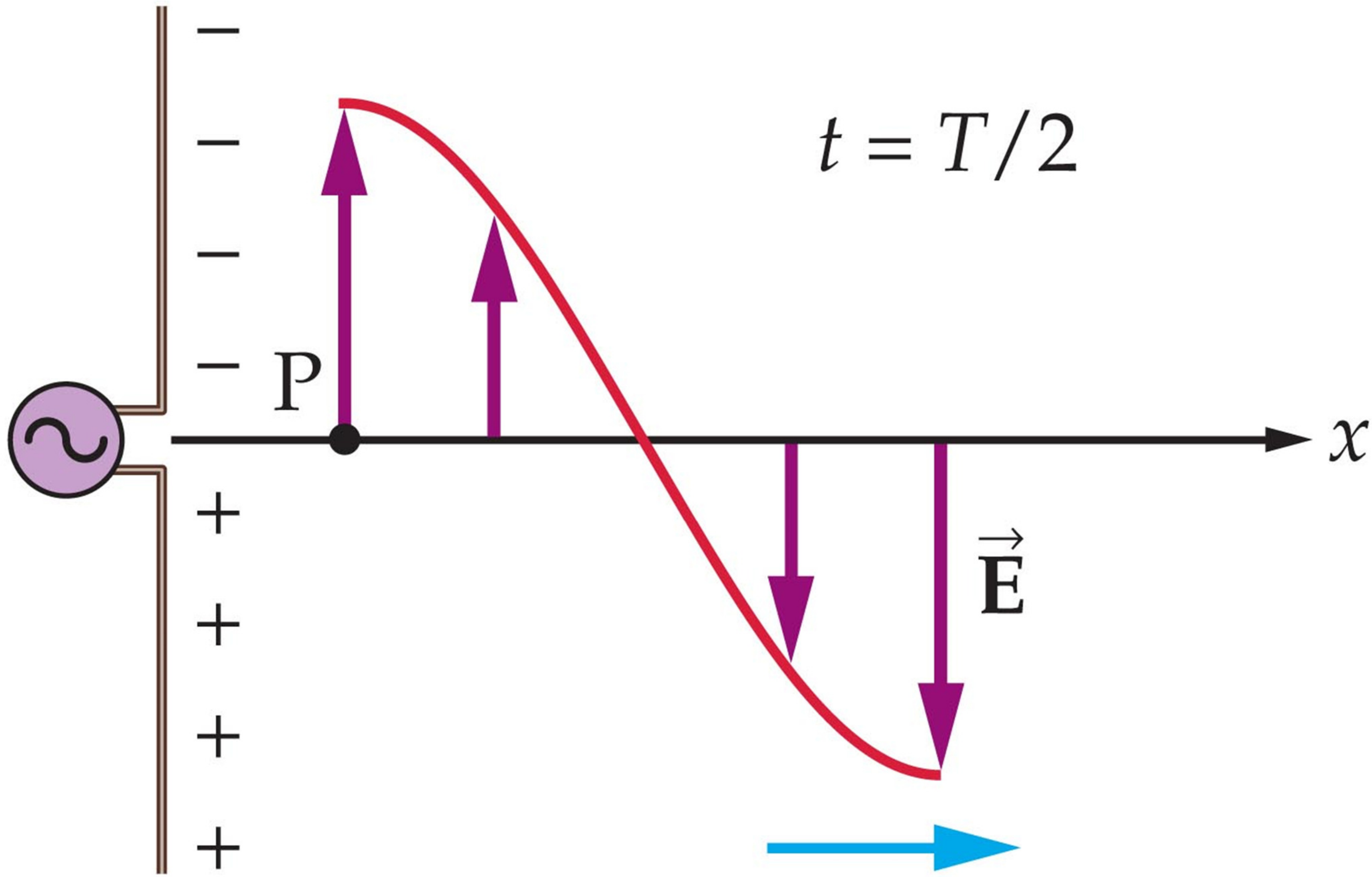
(b)



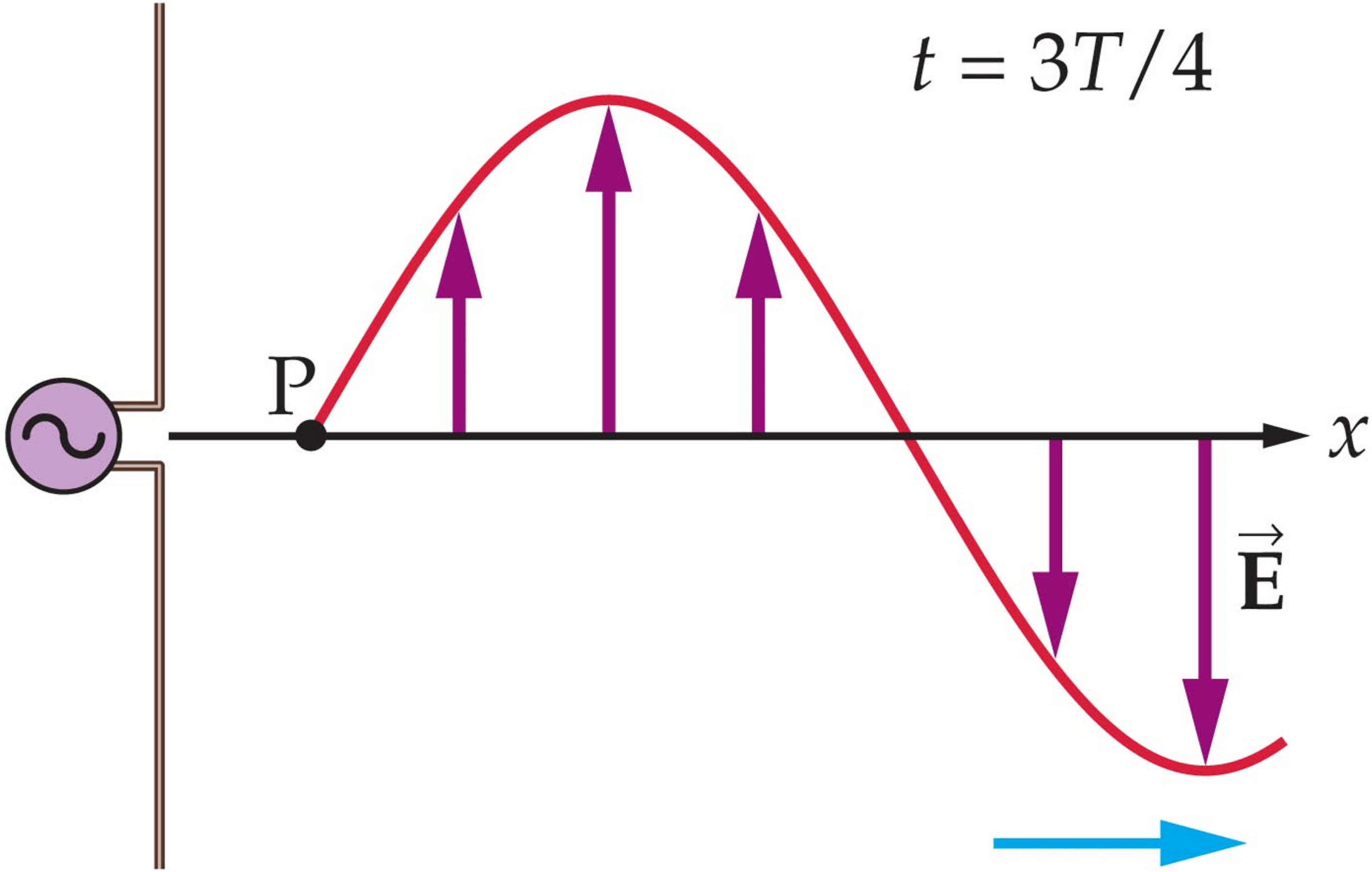
(c)



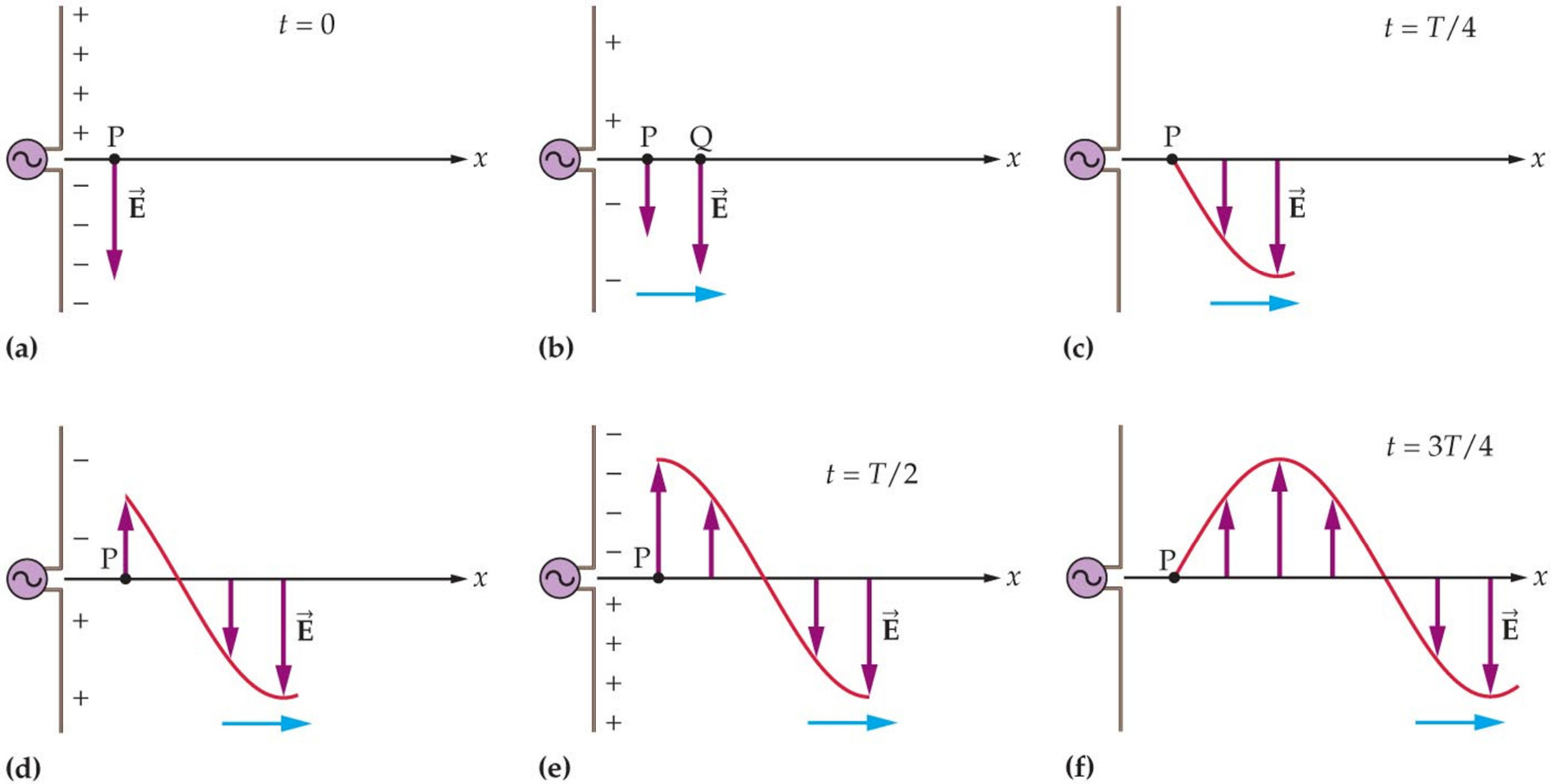
(d)

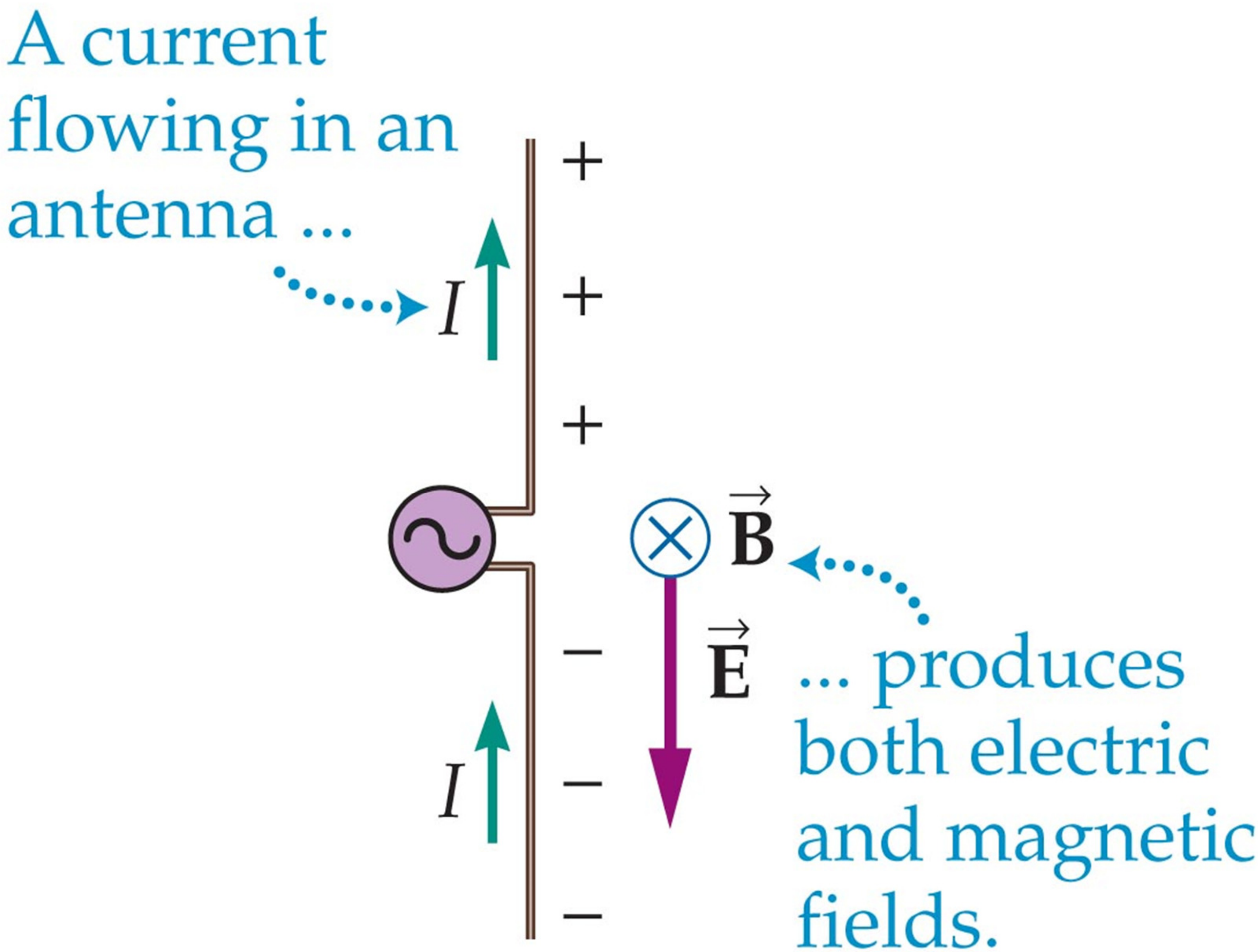


(e)



(f)


t = 0
P
E
x
(a)
P
Q
E
x
(b)
t = T/4
P
E
x
(c)
P
E
x
(d)
t = T/2
P
E
x
(e)
t = 3T/4
P
E
x
(f)

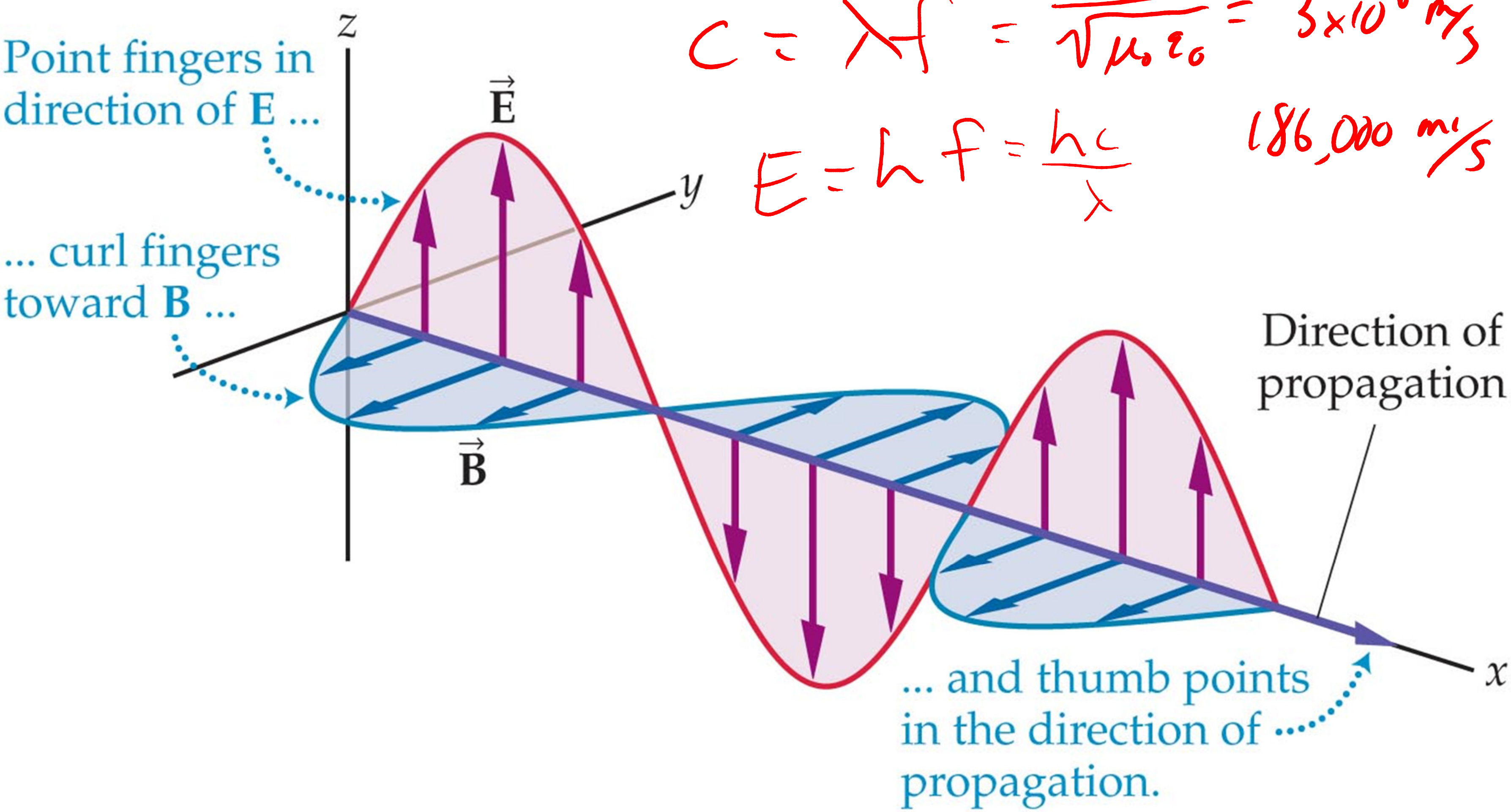

A current flowing in an antenna ...
I
I
+
+
+
−
−
−
$\vec{B}$
$\vec{E}$
... produces both electric and magnetic fields.

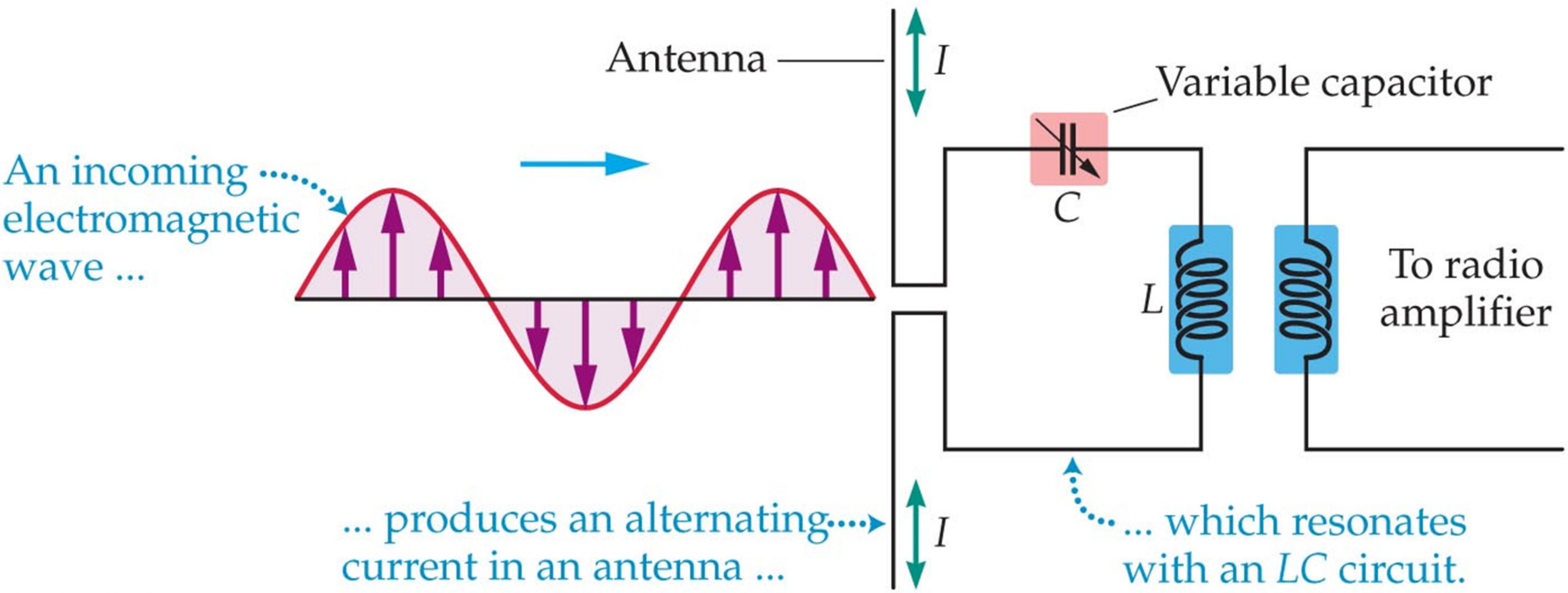
$\vec{E} \times \vec{B}$ gives direction of motion

$$c = \lambda f = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3\times10^8 \text{ m/s}$$

$$E = hf = \frac{hc}{\lambda}$$

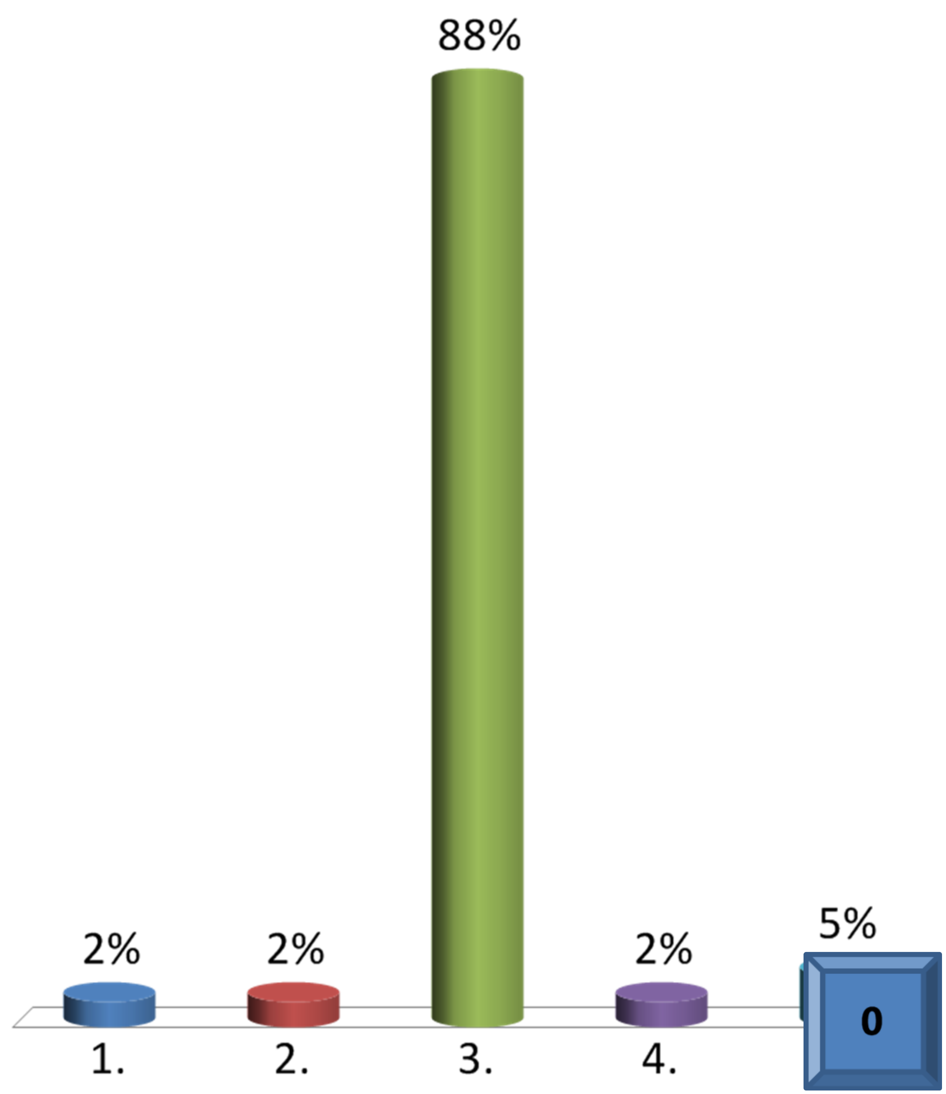
186,000 mi/s




Antenna
I
Variable capacitor
An incoming electromagnetic wave ...
C
L
To radio amplifier
... produces an alternating current in an antenna ...
I
... which resonates with an LC circuit.

For which one of the following properties do visible light and ultraviolet waves have the same value?

1. Wavelength
2. Frequency
3. ✓ Speed
4. Energy
5. Period



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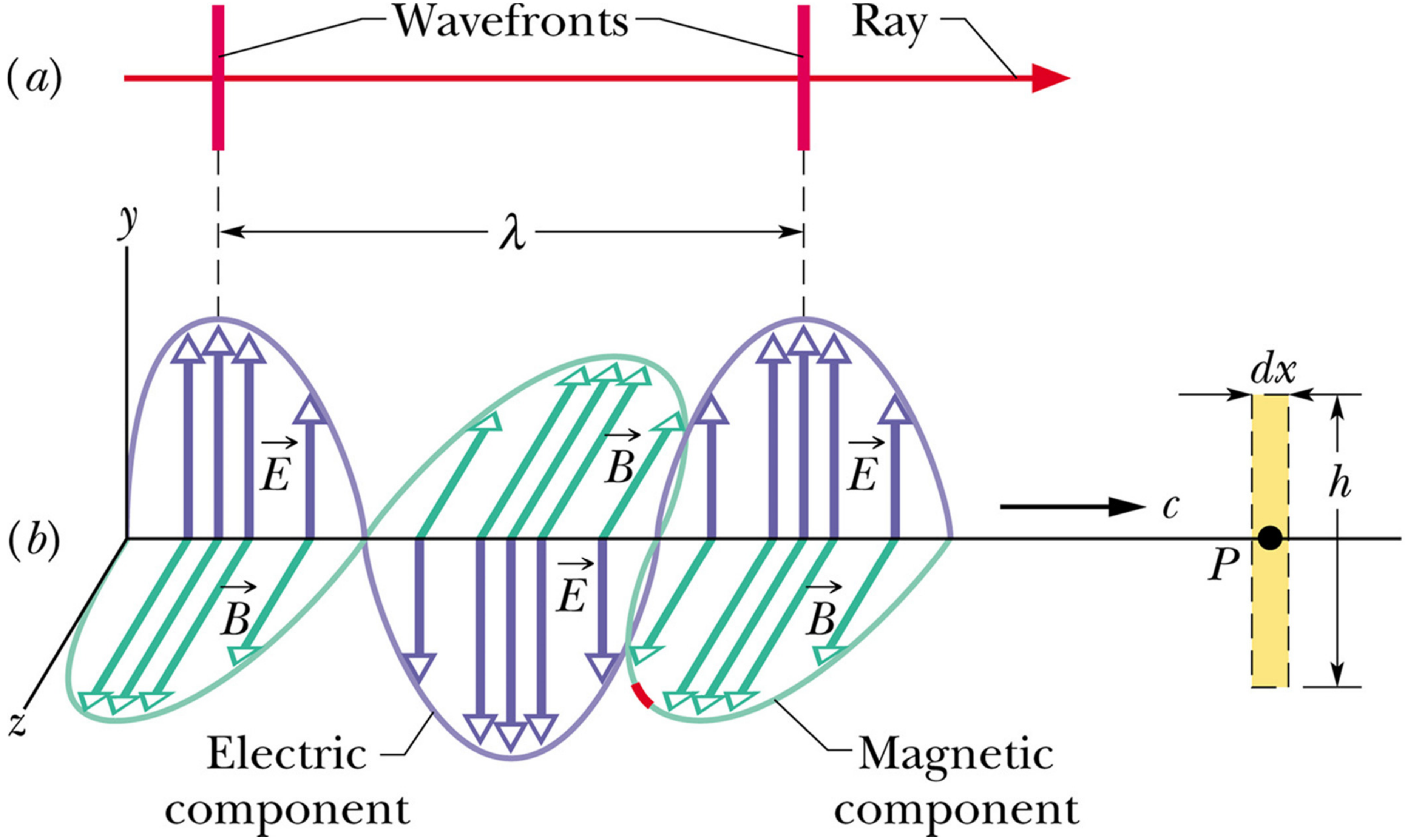
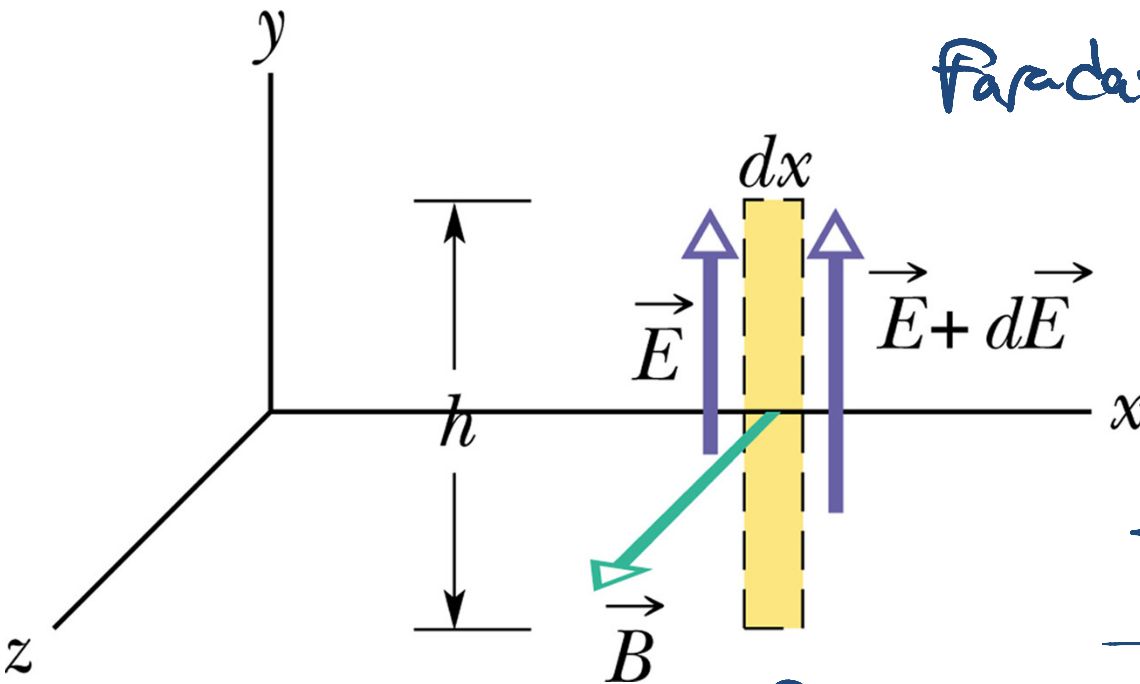


Wavefronts
Ray
(a)
y
λ
E
B
E
B
E
B
c
dx
h
(b)
x
P
z
Electric component
Magnetic component



Faradays Law $\oint E \cdot dl = -\frac{d\Phi_B}{dt}$

$\Phi_B = B\,\text{Area} = B h\, dx$

$\frac{d\Phi_B}{dt} = \frac{dB}{dt} h\, dx$

$\oint E \cdot dl = (E + dE)h + 0 - Eh + 0$

$= (dE)h$

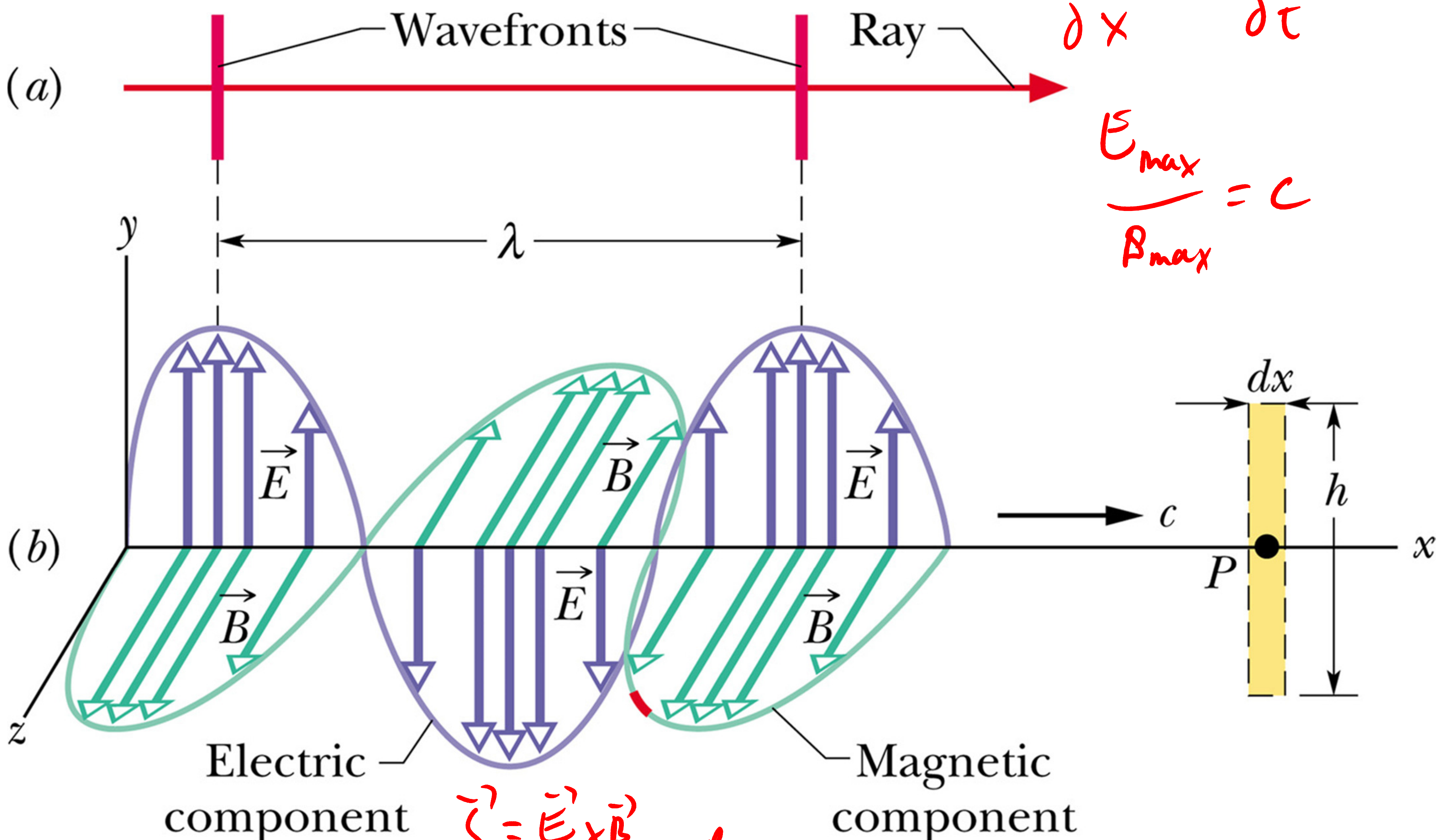
Combine in Faradays Law $(dE)h = -h\, dx\, dB/dt$

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

See page 1096 in your book for the complete workup

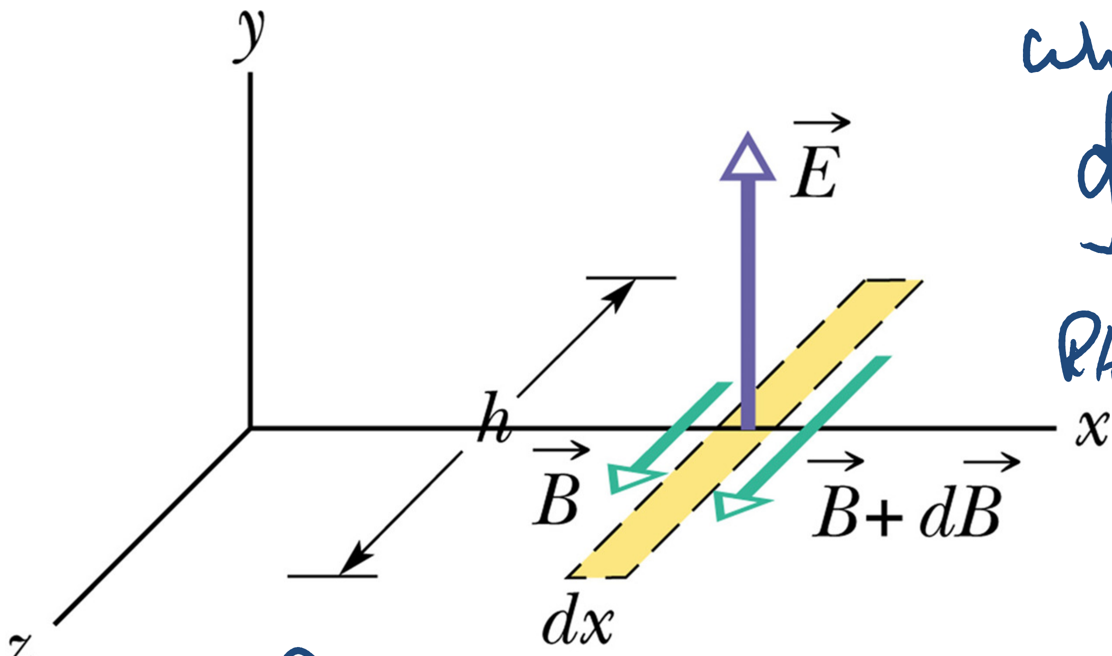
$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

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



$\vec{S} = \vec{E} \times \vec{B}$

Poynting Vector



Why not Ampere's Law?

$$\oint B \cdot dl = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 I_{enclosed}$$ (with $I_{enclosed} \to 0$)

RHS $$\frac{d\Phi_E}{dt} = \frac{d}{dt}(E h dx) = h dx \, dE/dt$$

LHS $$\int B dl = Bh + 0 - (B + dB)h + 0 = -h dB$$

$$-h dB = \mu_0 \varepsilon_0 h dx \, dE/dt$$

$$-dB/dx = \mu_0 \varepsilon_0 dE/dt$$

$$\frac{1}{\varepsilon_0 \mu_0} = \left(\frac{\omega}{k}\right)^2 = c^2$$

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

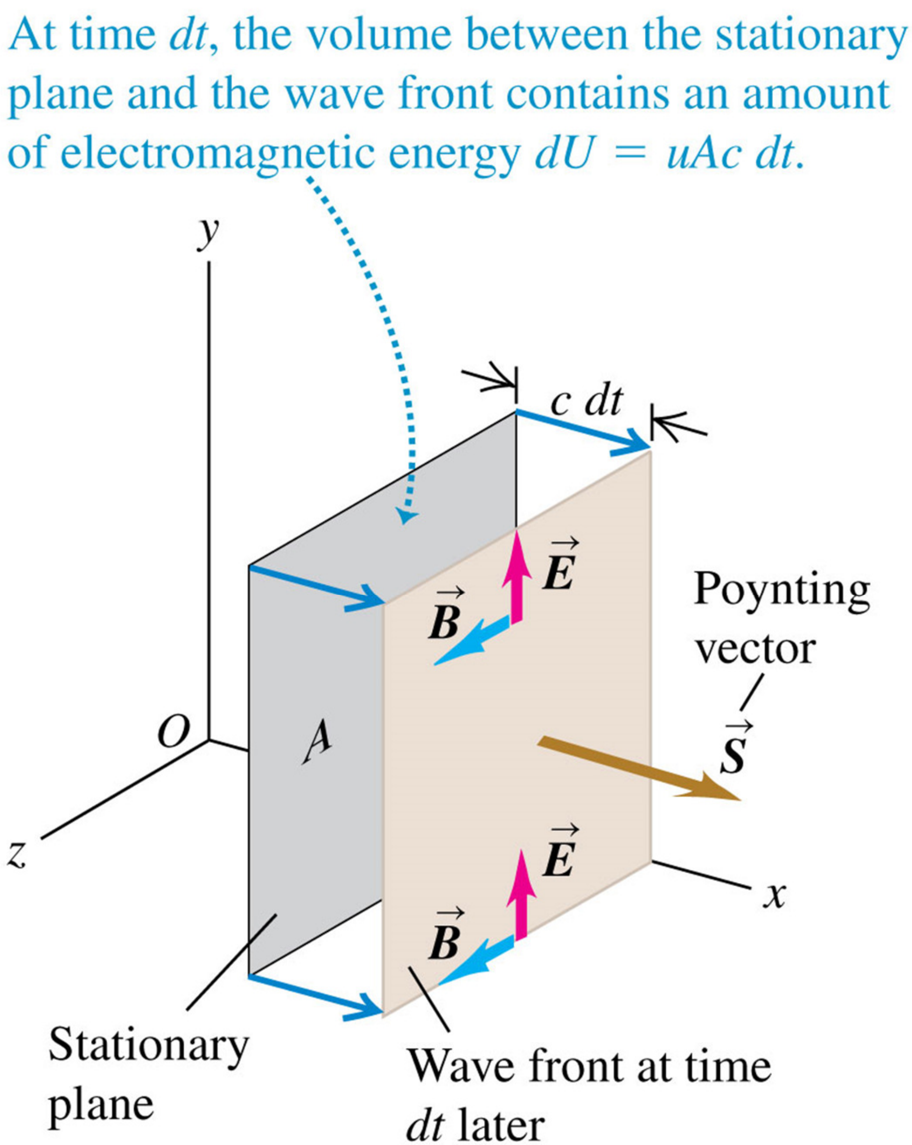
Energy?

$$U_{TOT} = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0}B^2$$

$$u_E \qquad u_B$$

$$B = E/c = \sqrt{\varepsilon_0\mu_0}\,E$$

$$u_{TOT} = \frac{1}{2}\varepsilon_0 E^2 + \frac{1}{2\mu_0}\left(\sqrt{\varepsilon_0\mu_0}\,E\right)^2 = \varepsilon_0 E^2$$



$$dU = u_{TOT}\, dV$$

$$= (\varepsilon_0 E^2)(A\, c \cdot dt)$$

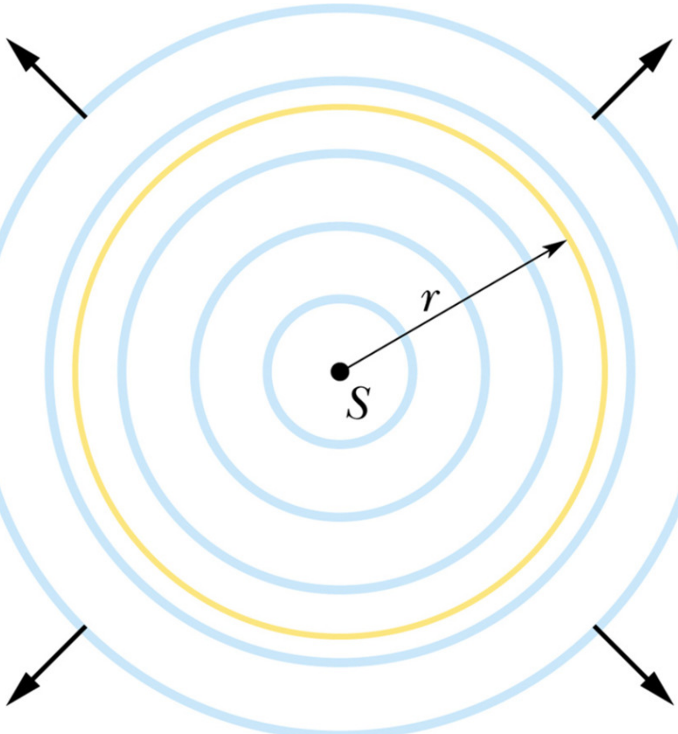
$$S = \frac{dU/dt}{A} = \varepsilon_0 c E^2$$

$$S = \frac{\varepsilon_0 E^2}{\sqrt{\varepsilon_0 \mu_0}} = \sqrt{\frac{\varepsilon_0}{\mu_0}}\, E^2$$

Or, use $B = E/c$

$$S = \frac{EB}{\mu_0} \qquad J/s/m^2 = W/m^2$$

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



S has $\frac{\text{Power}}{\text{Area}}$

$$\frac{P_{source}}{4\pi r^2} = \frac{\text{Power}}{\text{Area}} = I$$

Intensity

Poynting Vector $E \times B = \frac{(E_{avg})^2}{c\mu_0} = \frac{P_{source}}{4\pi r^2}$

Polaris 431 l.y. away $L = 2200\ L_\odot$

Students: work out what is the average electric field produced by light from Polaris in your eye?

Polaris puts out 2200 $L_\odot$ $1\,L_\odot = 3.90\times10^{26}$ W

it is 431 l.y. away. $1\,l_y = 9.46\times10^{15}$ m

$I = \frac{E_{avg}^2}{c\,\mu_0}$ $I = \frac{\text{Power}}{\text{Area}} = \frac{2200\,L_\odot}{4\pi\,(431\,l_y)^2}$

so $E_{avg} = \sqrt{\frac{\text{Power}\,c\,\mu_0}{4\pi r^2}}$

$= 1.24$ mV/m

$E/B = c \Rightarrow B = E/c = 4.1$ pT

Momentum

Shine light for Δt transfers $\Delta p = \frac{\Delta U}{c}$

$$F = \frac{\Delta p}{\Delta t} \qquad F = \frac{d(mv)}{dt} = m\frac{dv}{dt} = ma$$

$$I = \frac{\text{Power}}{\text{Area}} = \frac{\text{energy/time}}{\text{Area}}$$

$$\Delta U = IA\Delta t$$

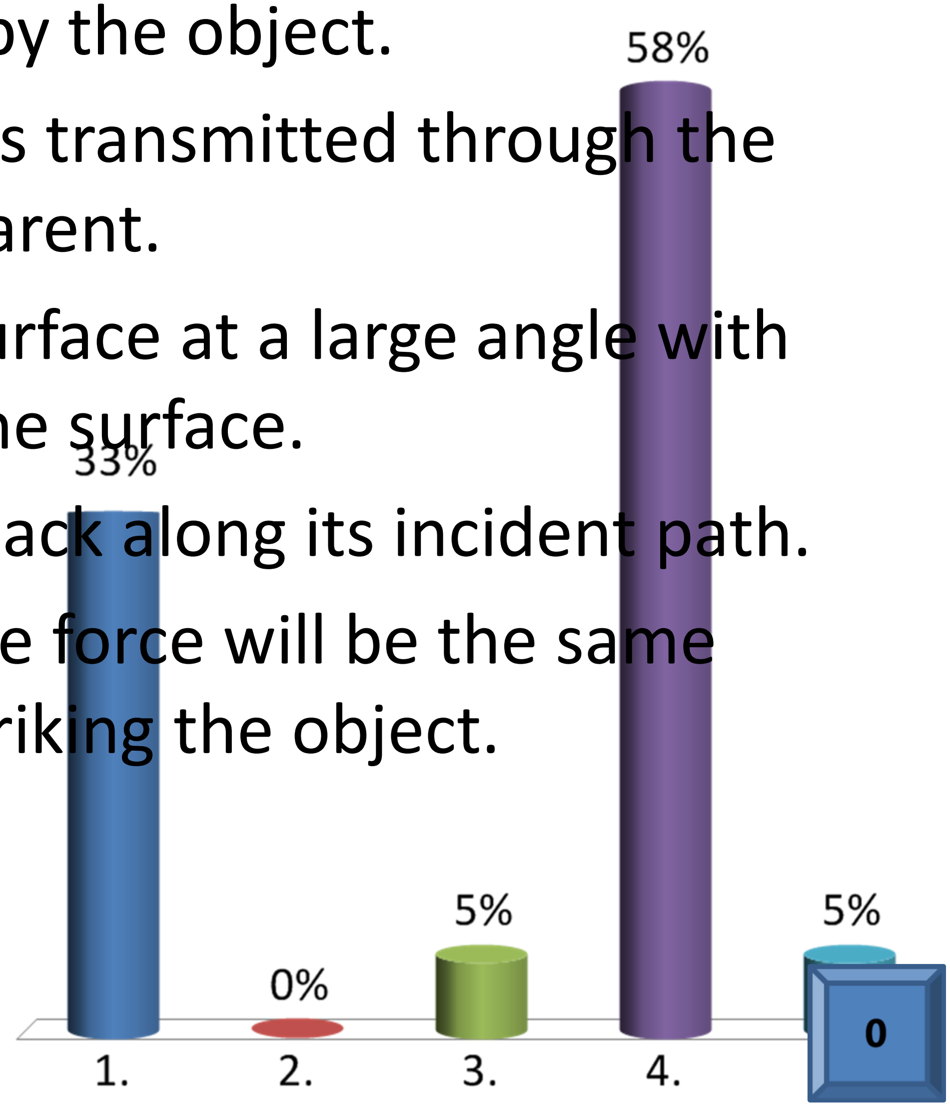
$$\Delta p = \frac{\Delta U}{c} = \frac{IA\Delta t}{c}$$

$$F = \frac{\Delta p}{\Delta t} = \frac{IA}{c}$$

$$F/A = I/c = \text{Pressure}$$

In which of the following cases maximizes the force exerted on an object by electromagnetic radiation?

1. The radiation is absorbed by the object.
2. Nearly all of the radiation is transmitted through the object because it is transparent.
3. The radiation strikes the surface at a large angle with respect to the normal to the surface.
4. The radiation is reflected back along its incident path.
5. In all of the above cases the force will be the same since it is the same light striking the object.



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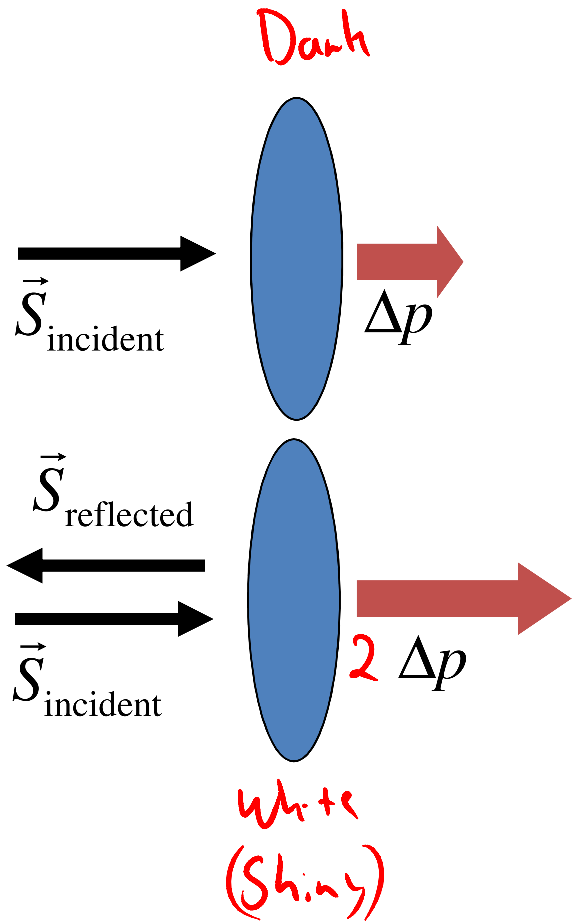
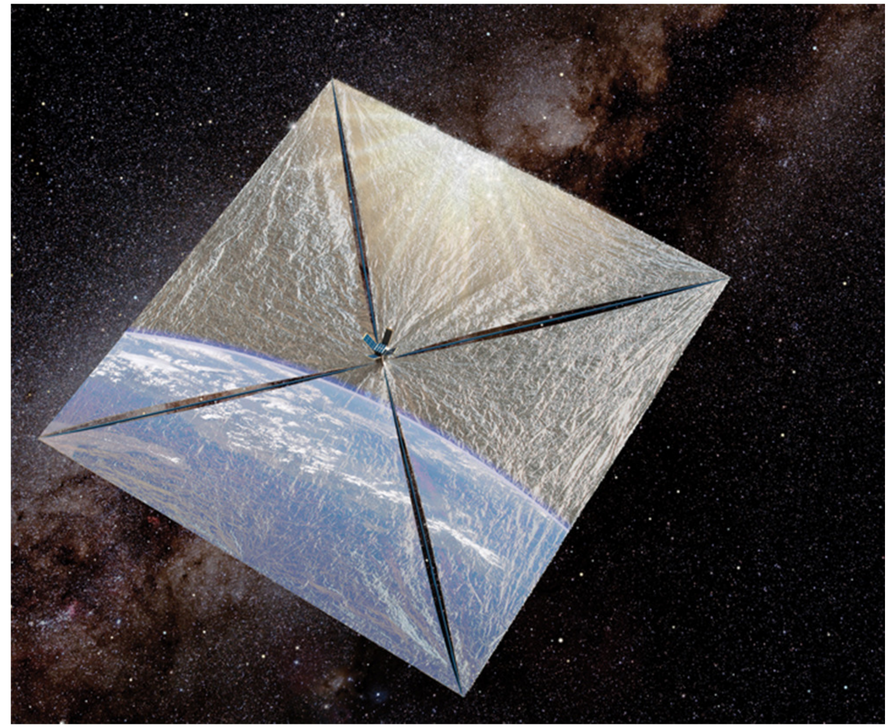
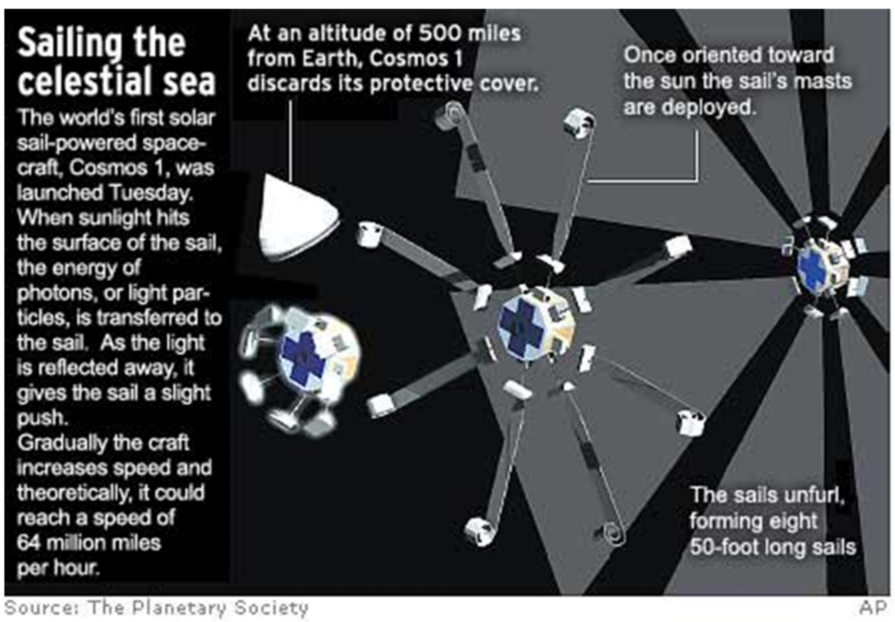


$$\frac{F}{A} = \frac{I}{c}$$

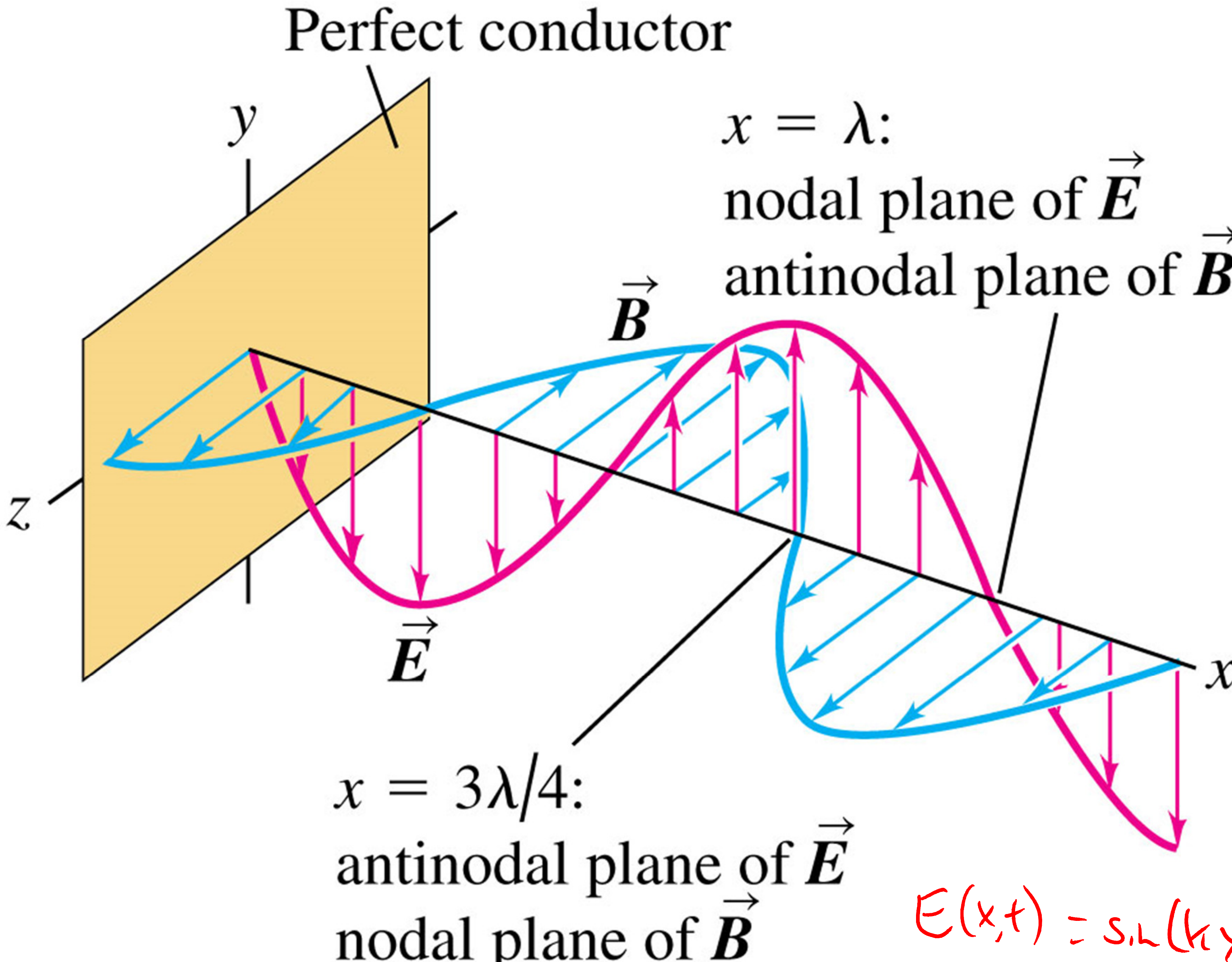
Solar Sailing
(Planetary Society efforts)



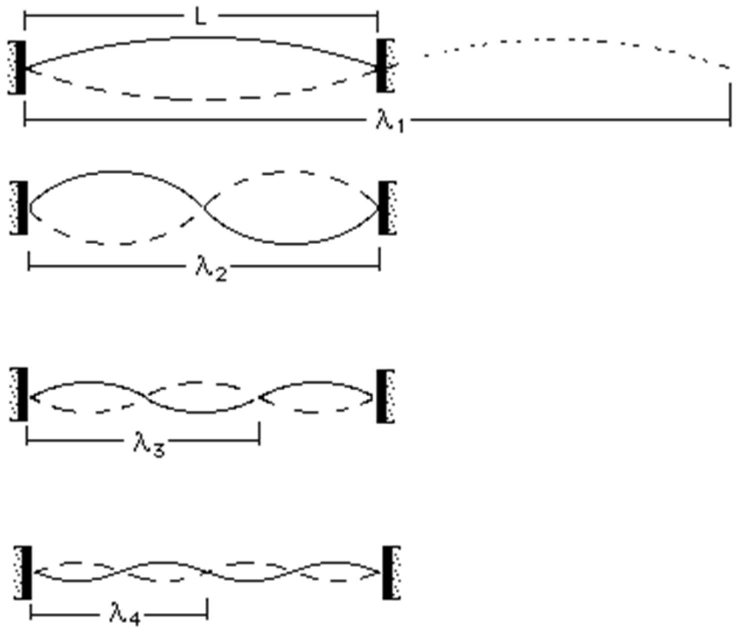
Lightsail-1
(on short list for an
upcoming nanosat launch)



COSMOS-I
(lost in launch failure, 2005)

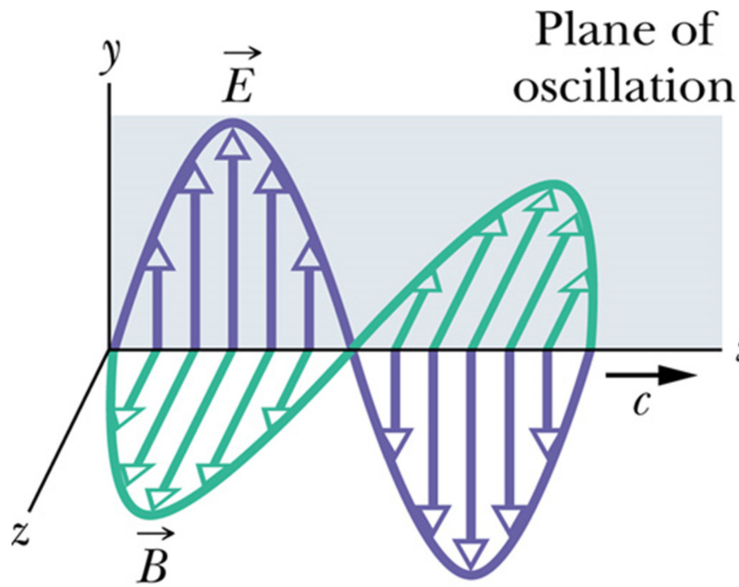


$E(x,t) = \sin(kx - \omega t)$



Cartoon swiped from U. of New South Wales' physics webpage

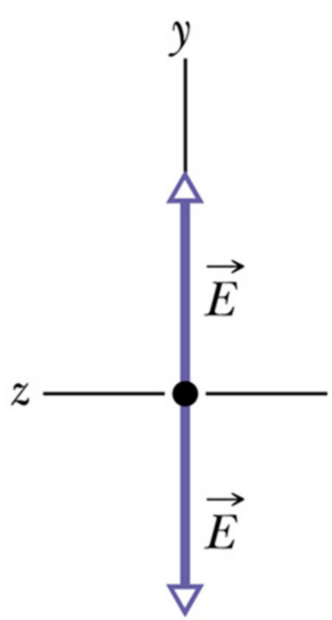

Popcorn
Beverage
Reheat
Frozen Pizza
Cook
Auto Defrost
Time Defrost
Timer
1
2
3
4
5
6
7
8
9
0
Start
Power Level
Clock
Pause Cancel



(a)

"Polarization Axis"

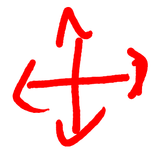
linear

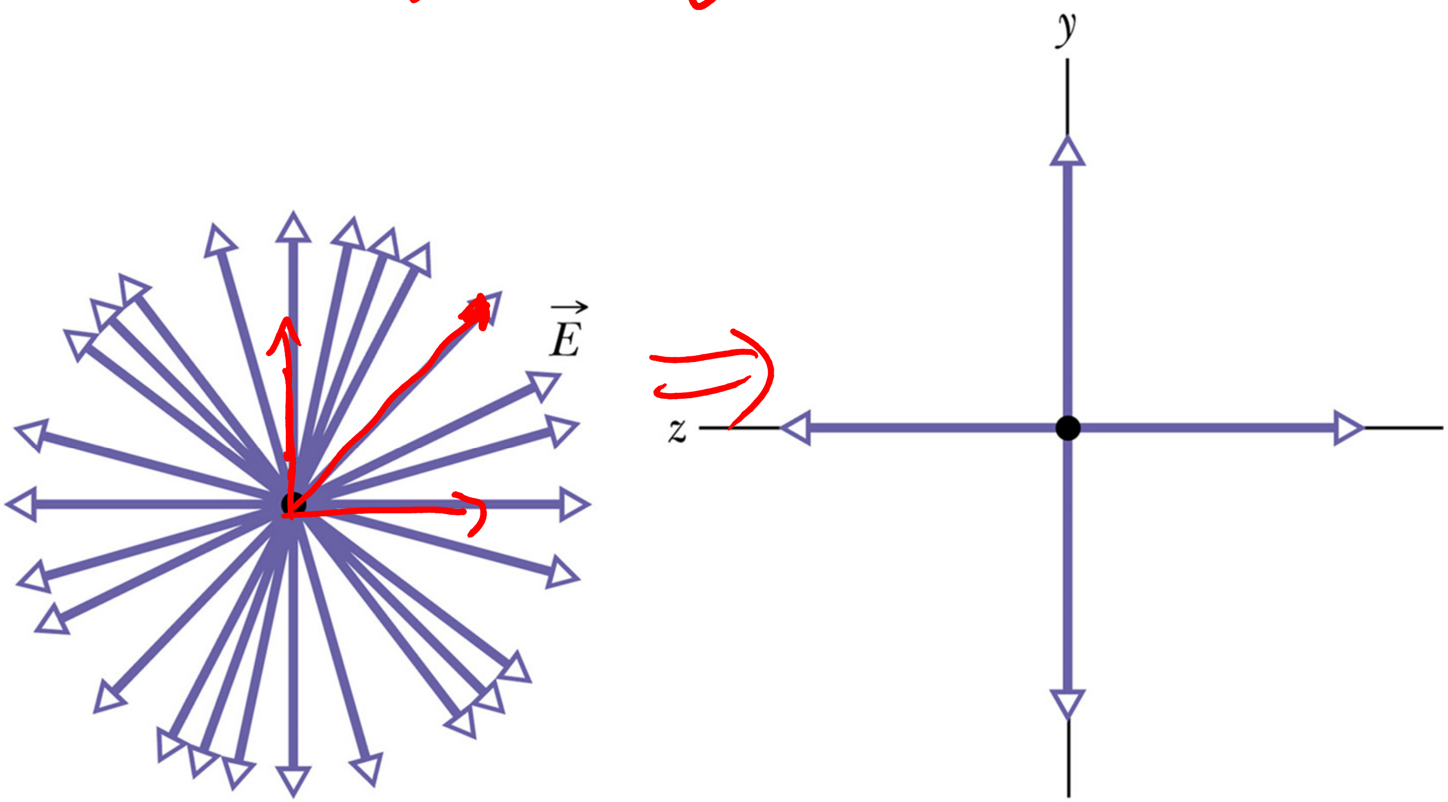


(b)

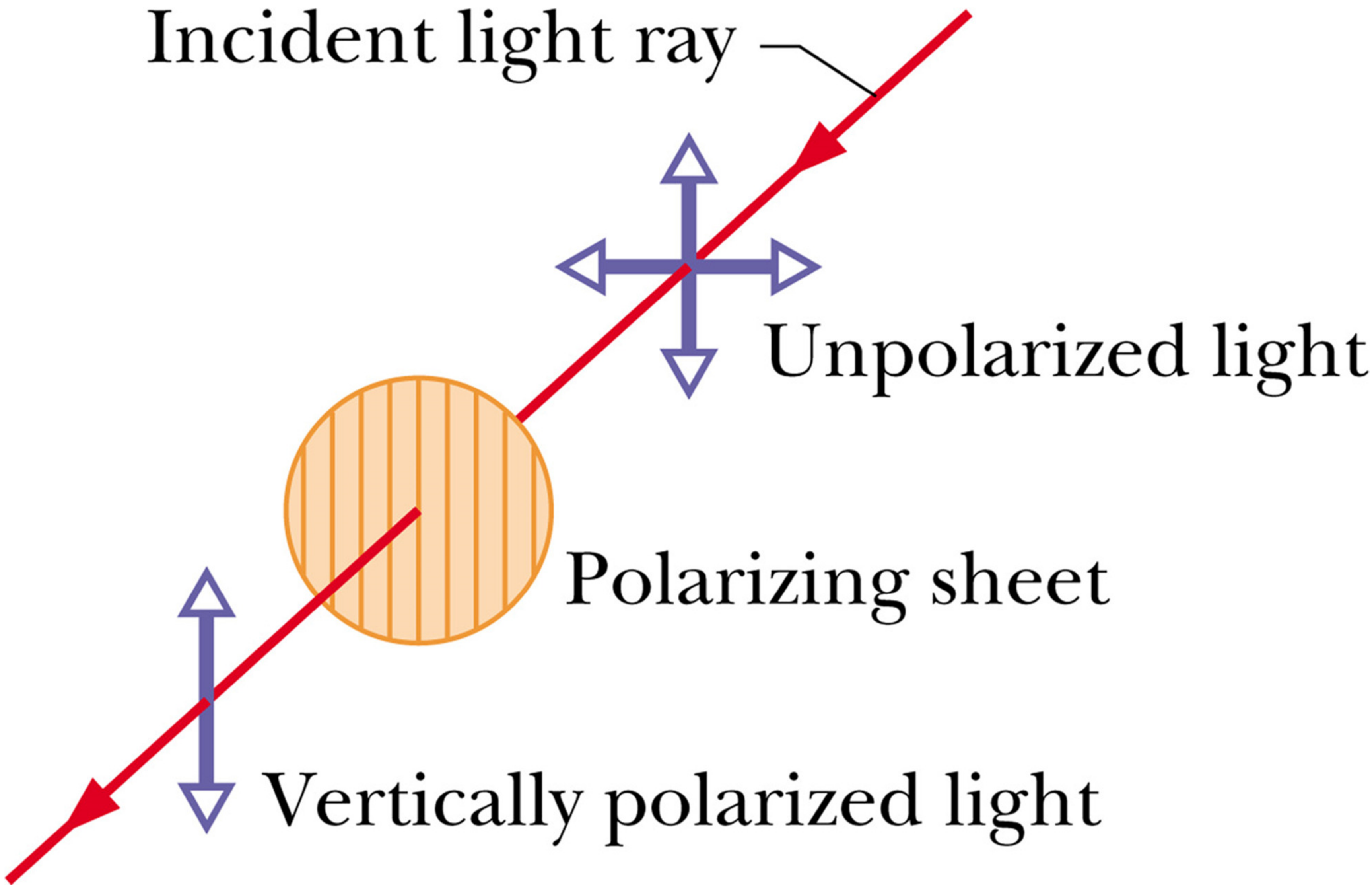
Circular Polarization

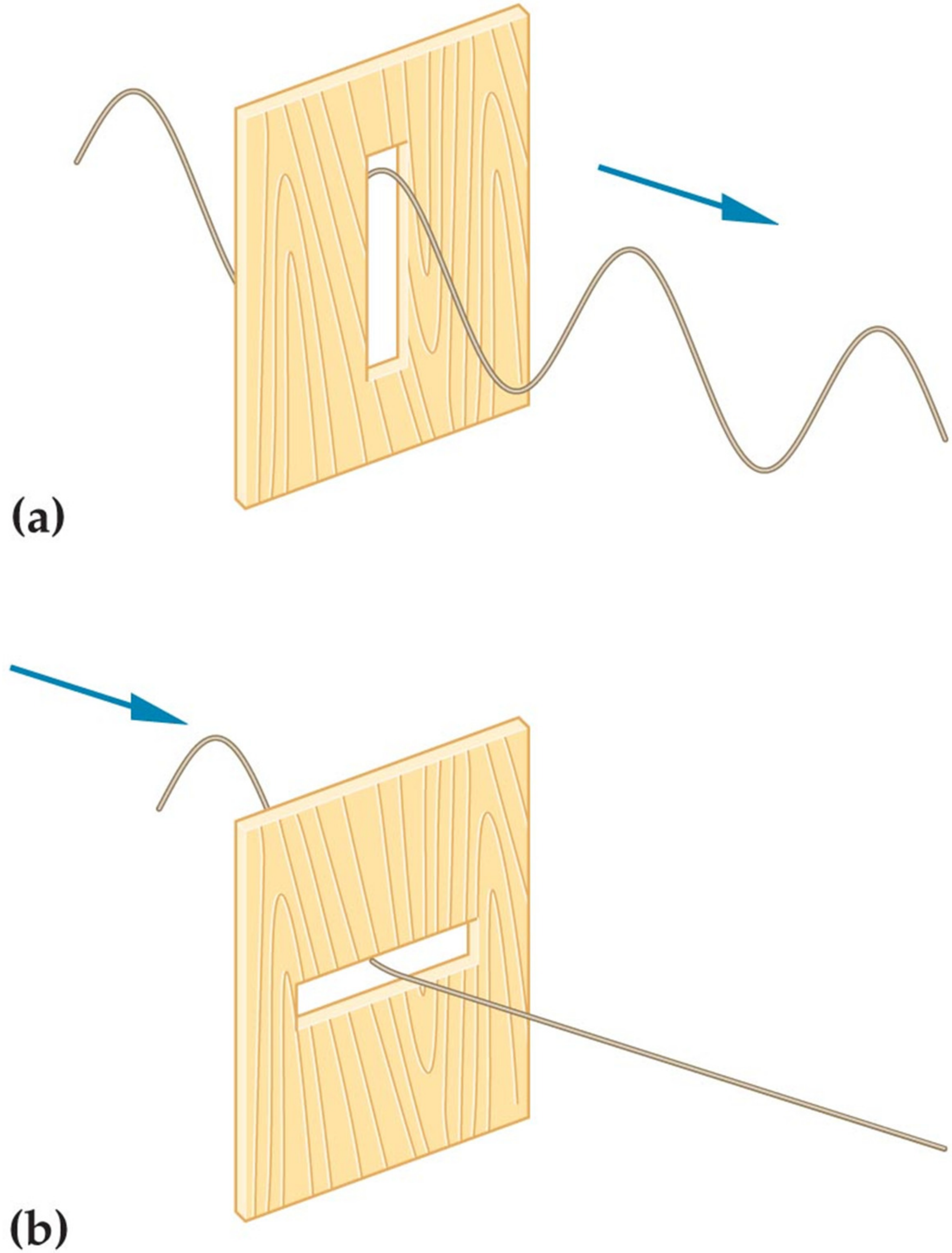
Unpolarized

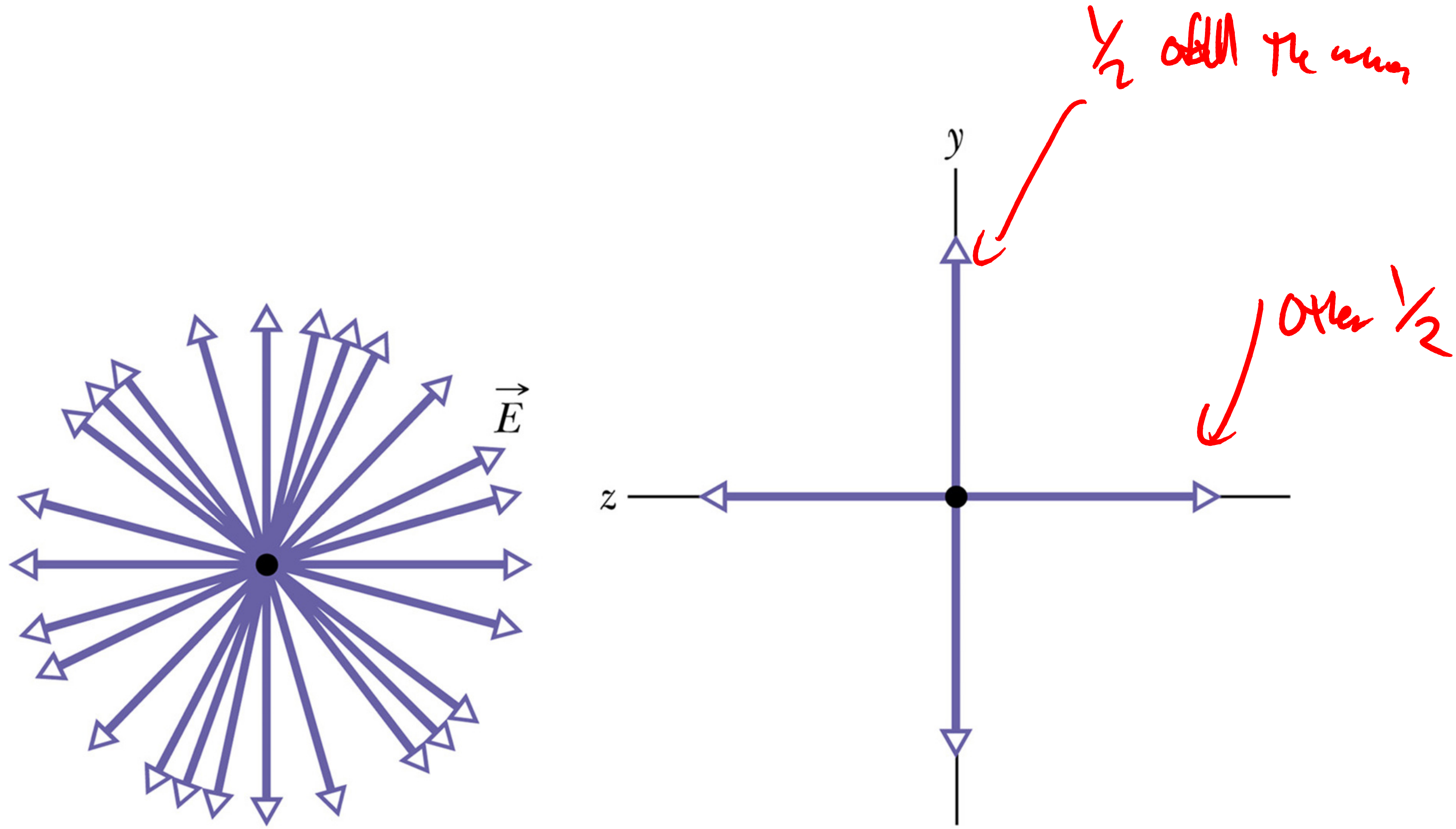




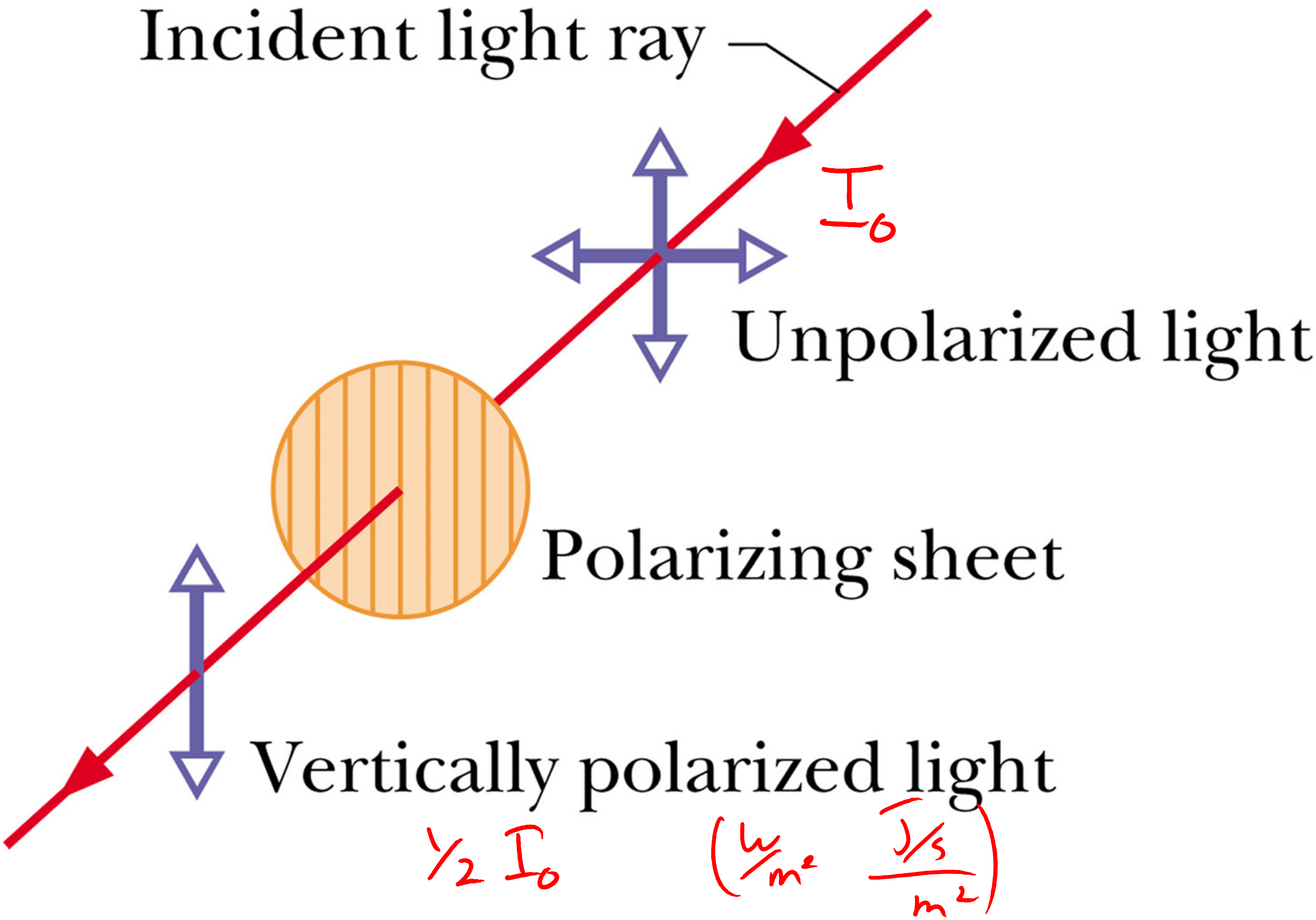
(a) (b)

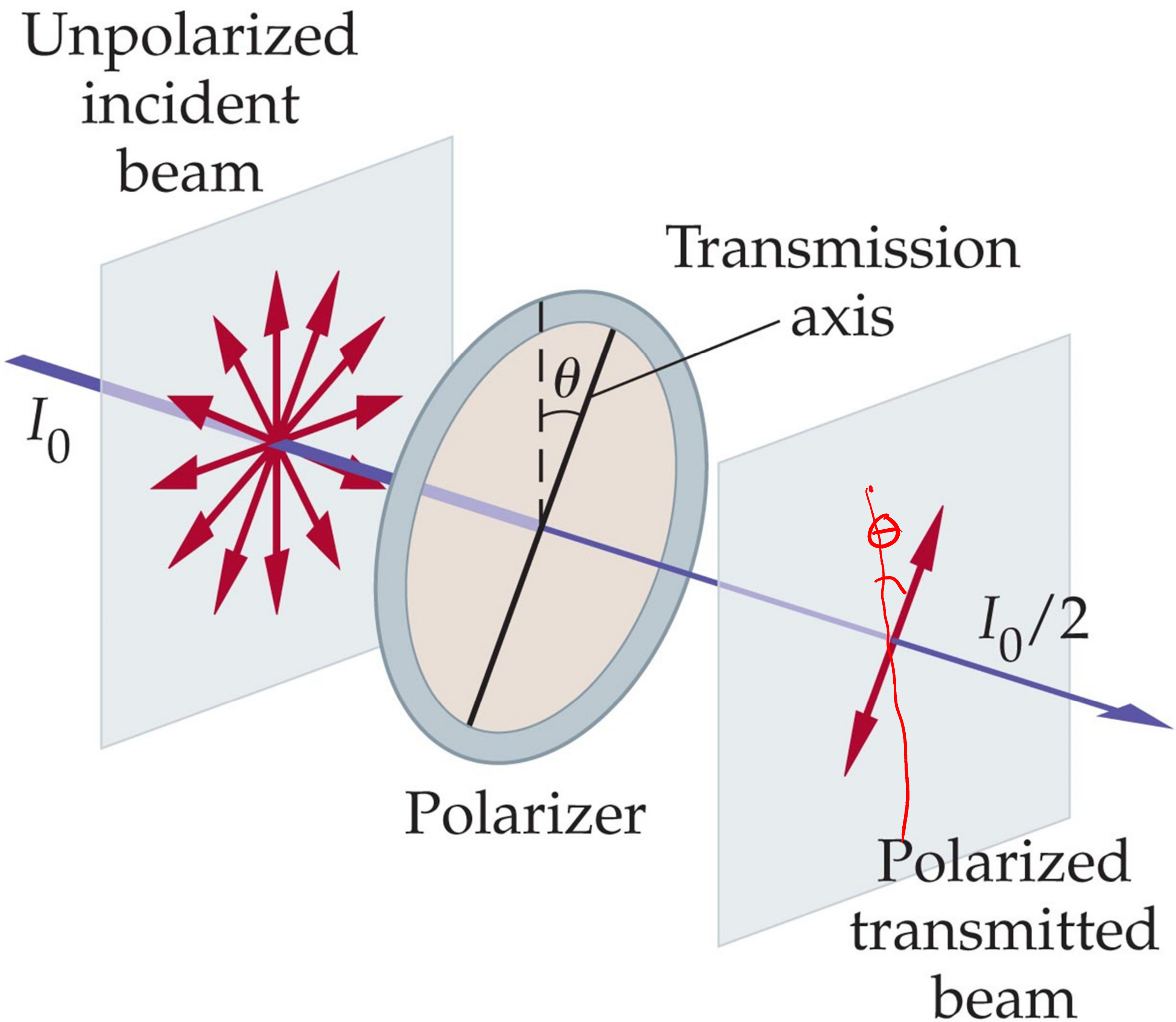

Incident light ray
Unpolarized light
Polarizing sheet
Vertically polarized light


(a)
(b)

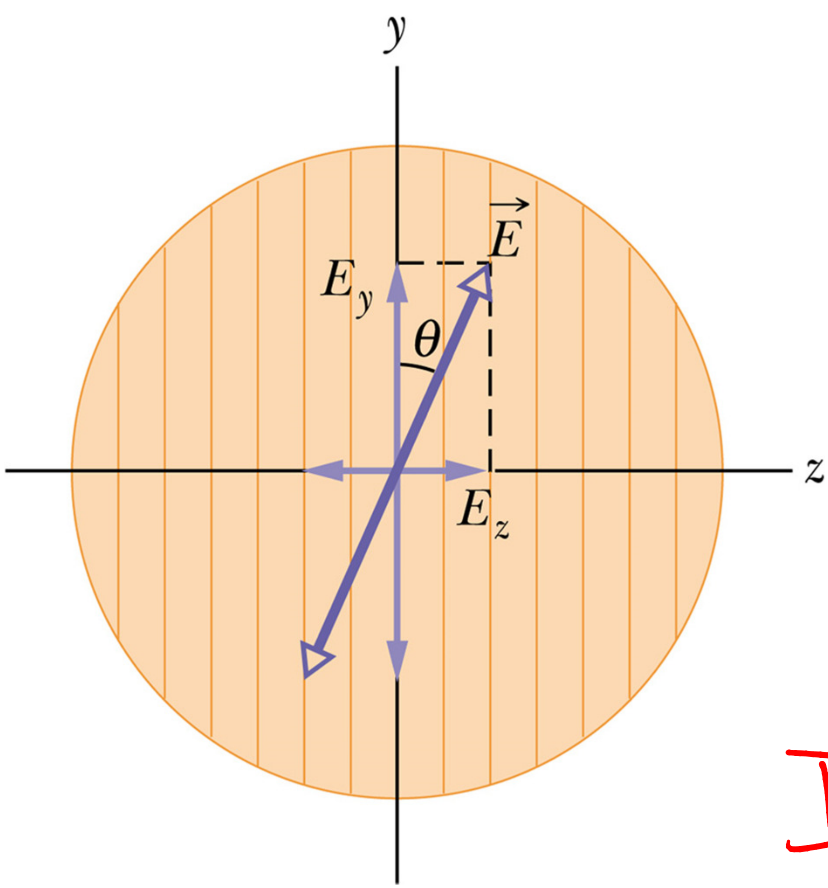


(a) (b)


Incident light ray
I_0
Unpolarized light
Polarizing sheet
Vertically polarized light
$\frac{1}{2} I_0$
$\left(W/m^2 \quad \frac{J/s}{m^2} \right)$



Unpolarized incident beam
I_0
Transmission axis
θ
Polarizer
$I_0/2$
Polarized transmitted beam



$E_y = |E| \cos\theta$

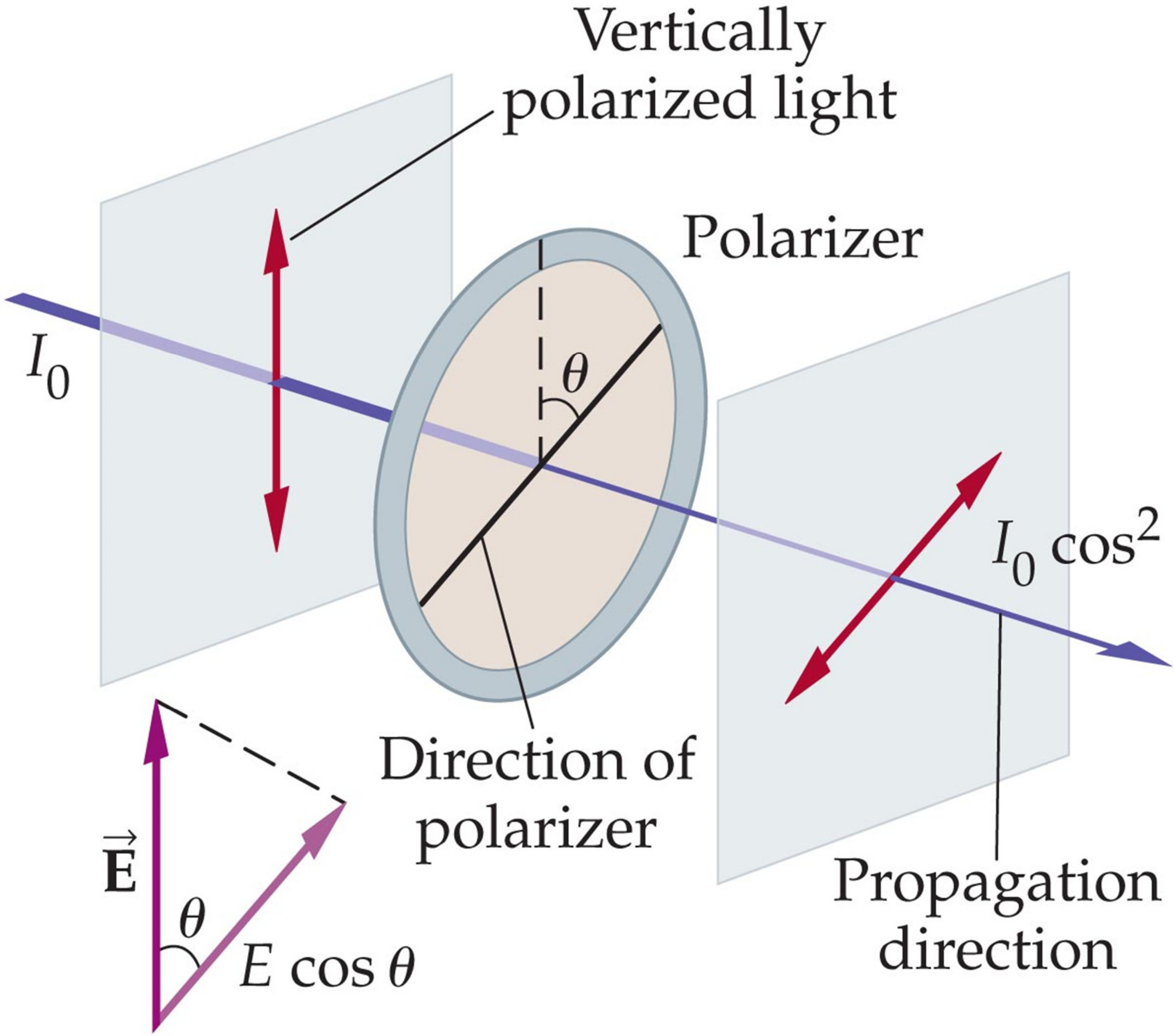
$E_z = |E| \sin\theta$

This E gets through

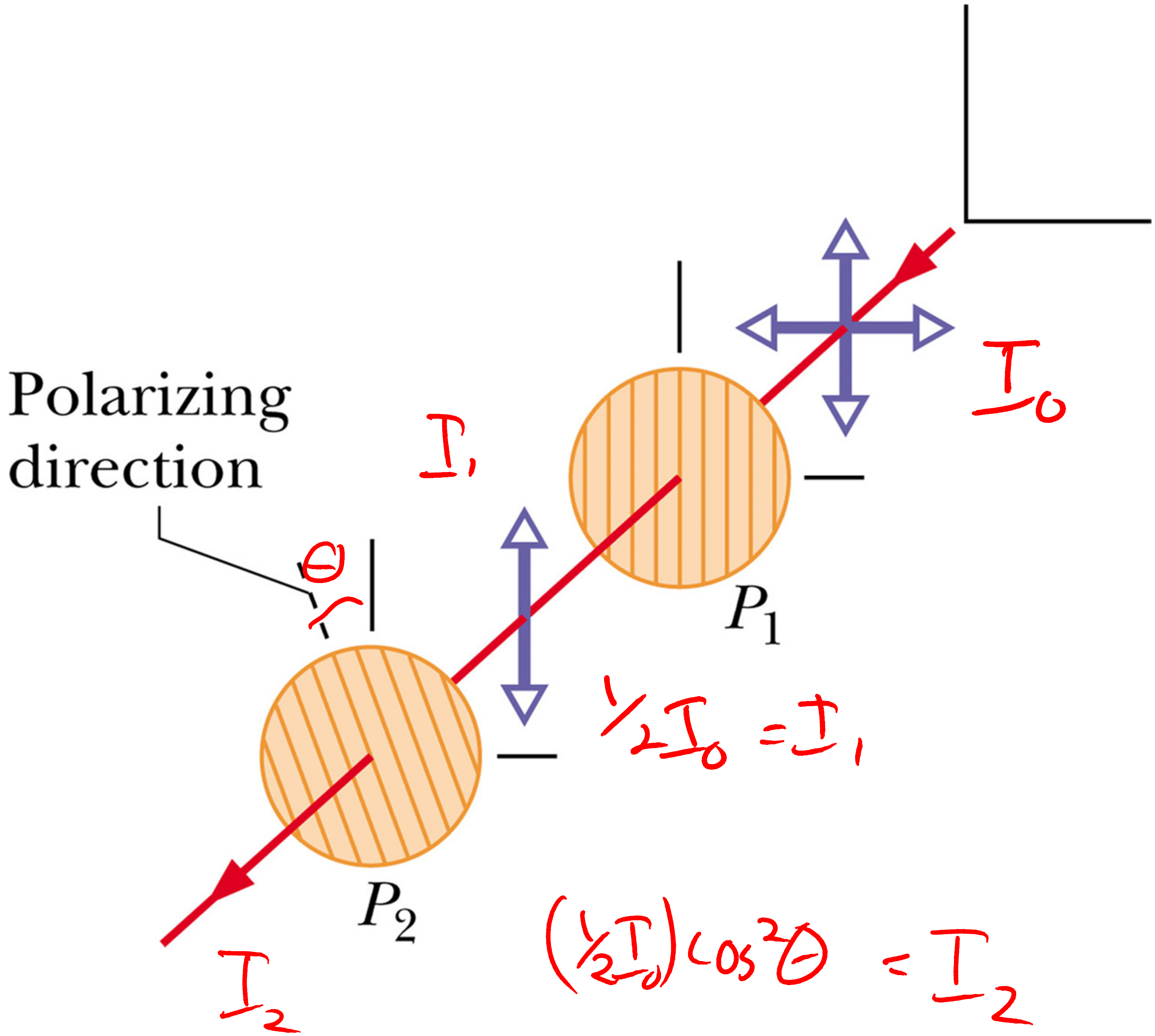
$I \propto \text{Energy} = \frac{E^2_{Avg}}{c\mu_0}$

$I \propto E^2$

$I_{thru} = I_0 \cos^2\theta$

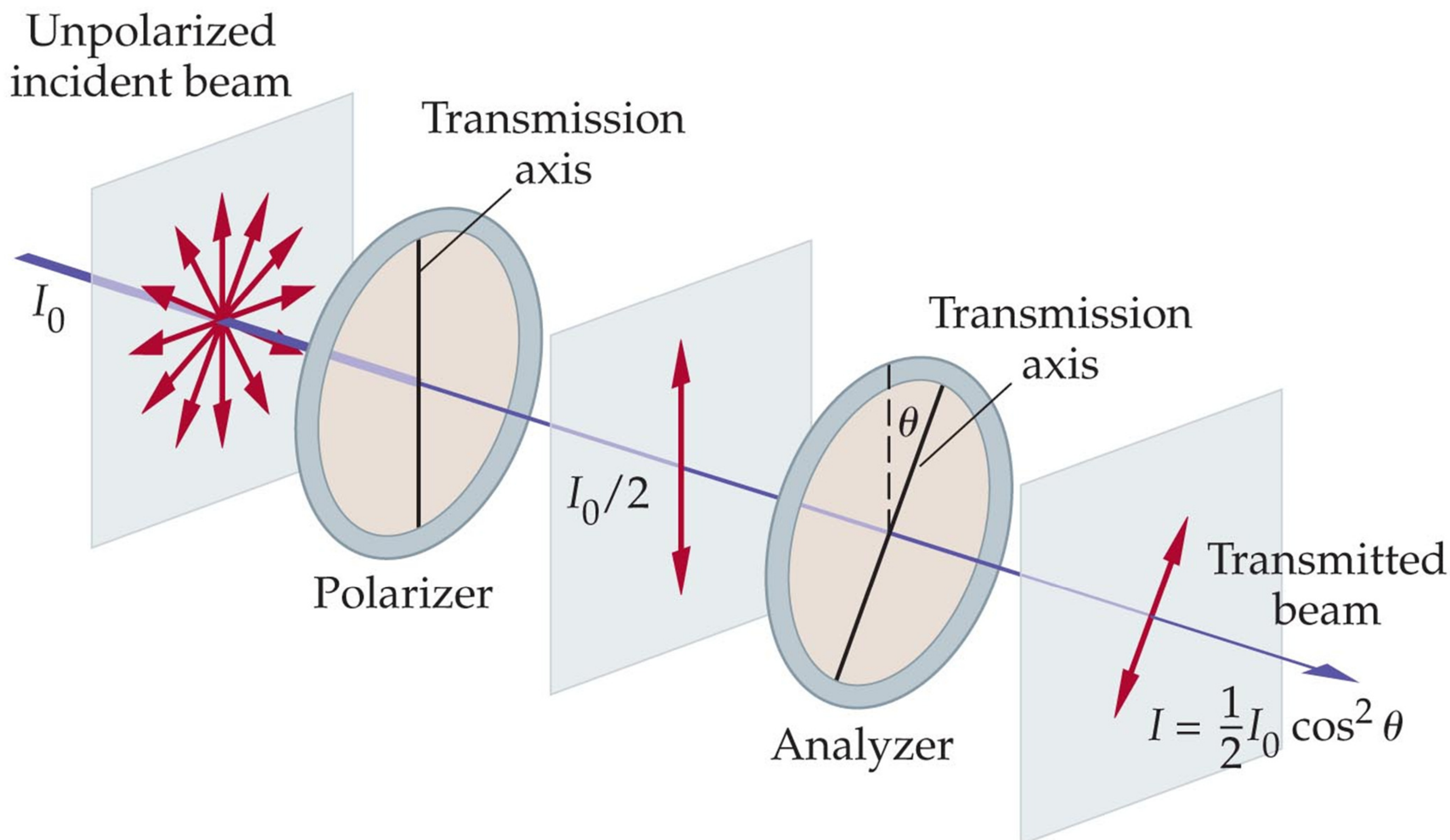


Vertically
polarized light
Polarizer
I_0
θ
$I_0 \cos^2 \theta$
Direction of
polarizer
Propagation
direction
$\vec{\mathbf{E}}$
θ
$E \cos \theta$

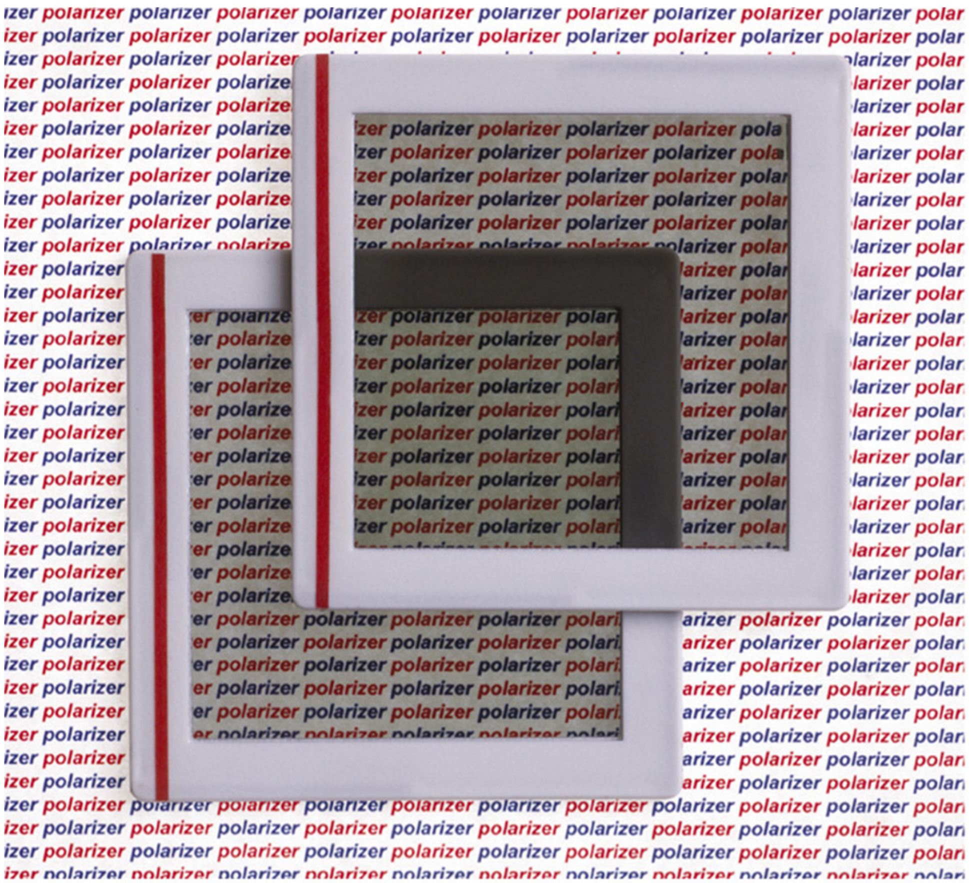


$\frac{1}{2} I_0 = I_1$

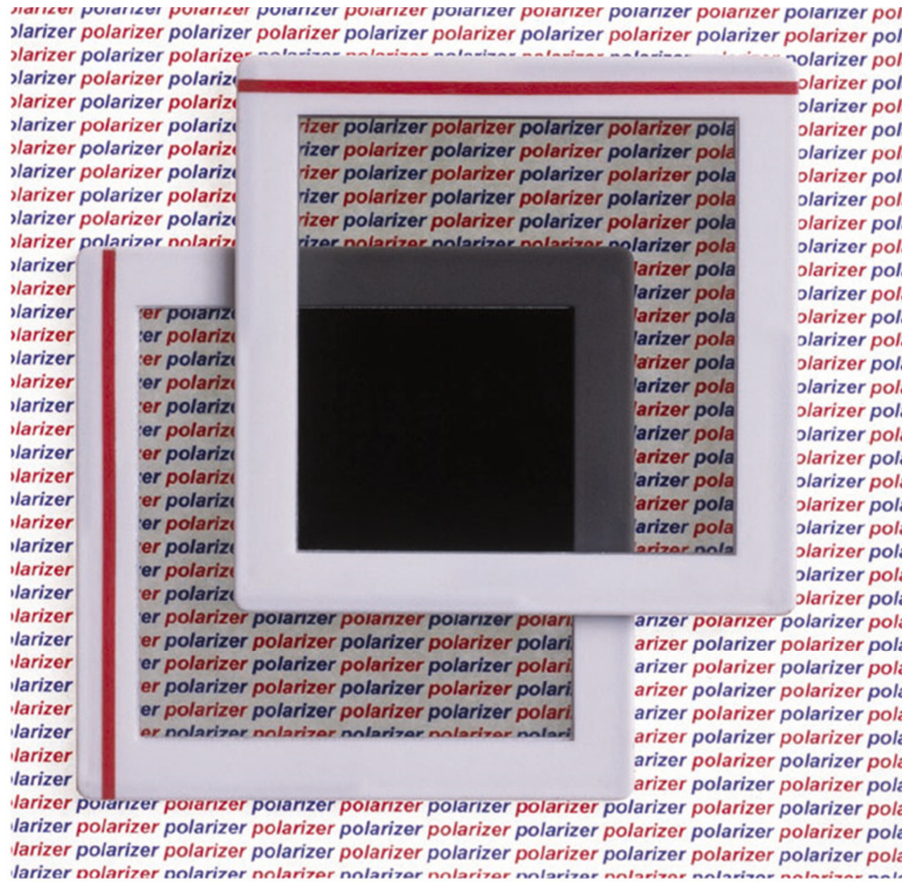
$\left(\frac{1}{2} I_0\right) \cos^2\theta = I_2$



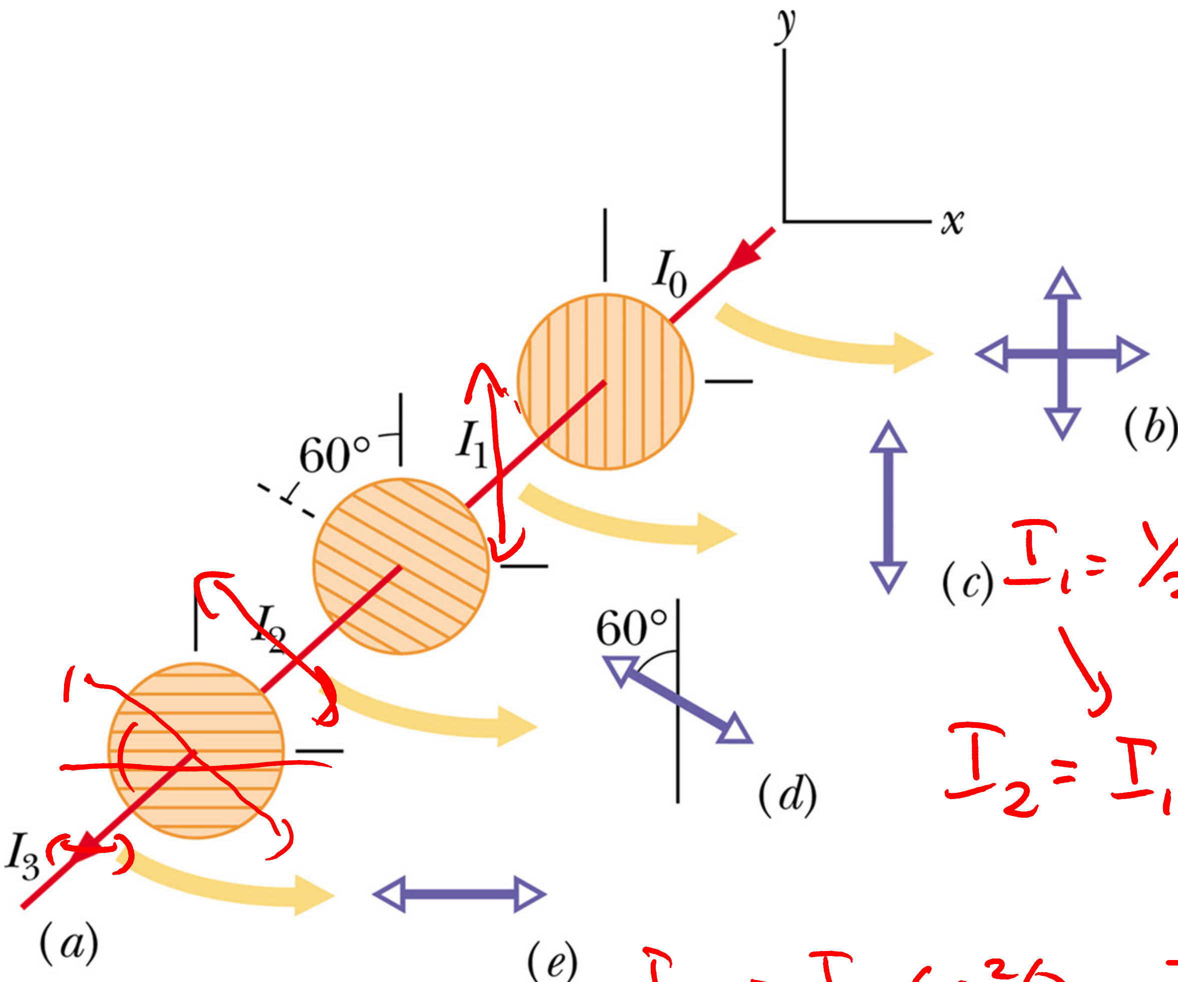
Unpolarized
incident beam
Transmission
axis
I_0
Polarizer
$I_0/2$
Transmission
axis
θ
Analyzer
Transmitted
beam
$I = \frac{1}{2} I_0 \cos^2 \theta$



(*a*)



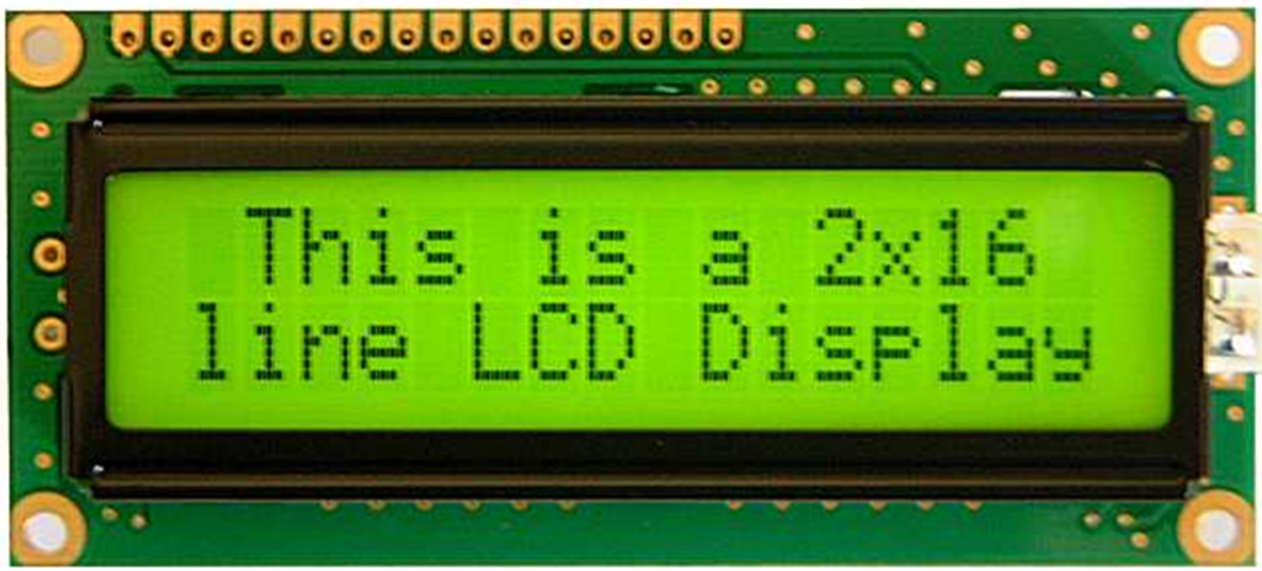
(*b*)

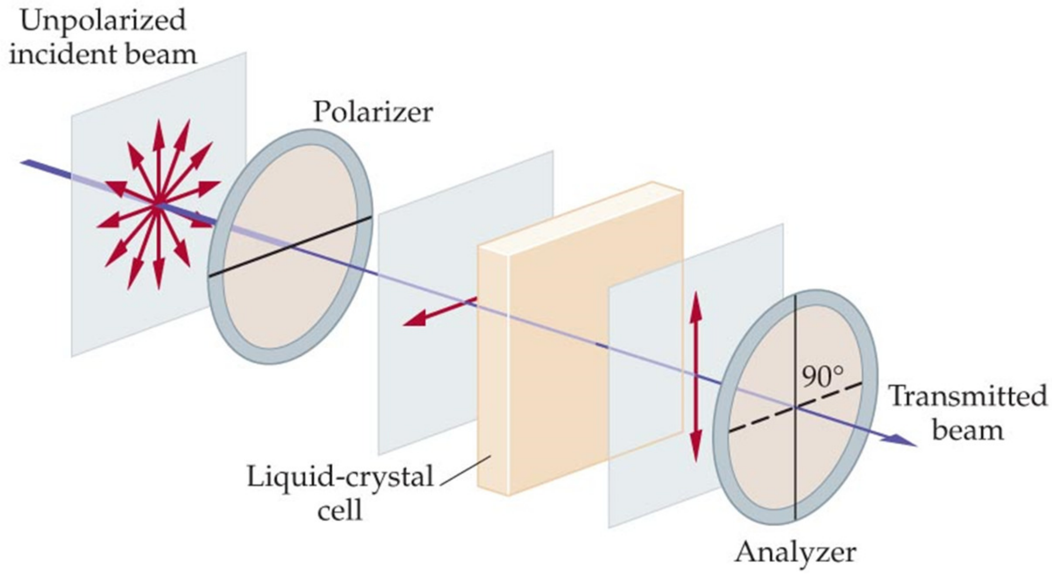


$$I_1 = \tfrac{1}{2} I_0$$

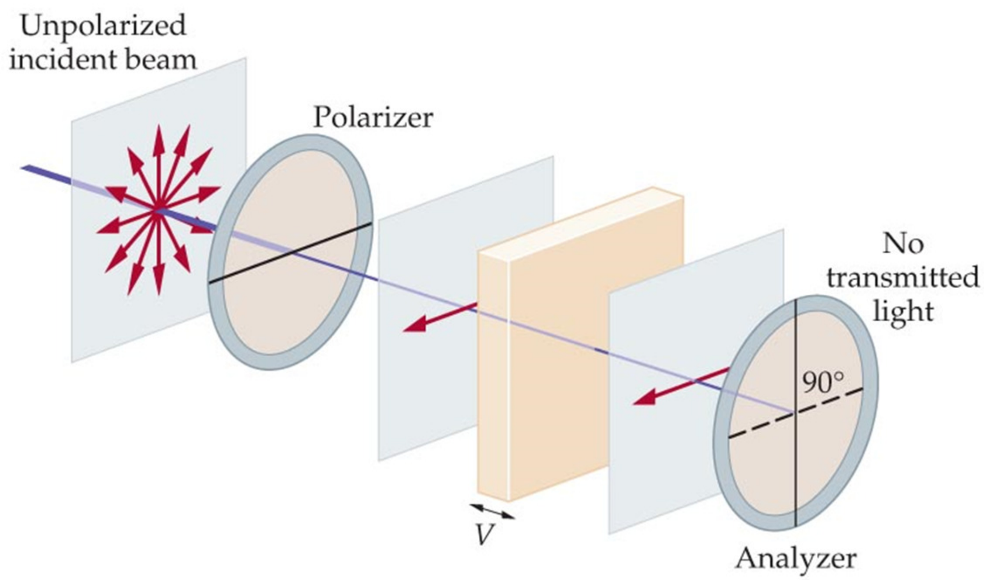
$$I_2 = I_1 \cos^2(60^\circ) = \tfrac{1}{2} I_0 \cos^2 60^\circ$$

$$I_3 = I_2 \cos^2 \theta = I_2 \cos^2(90-60)$$

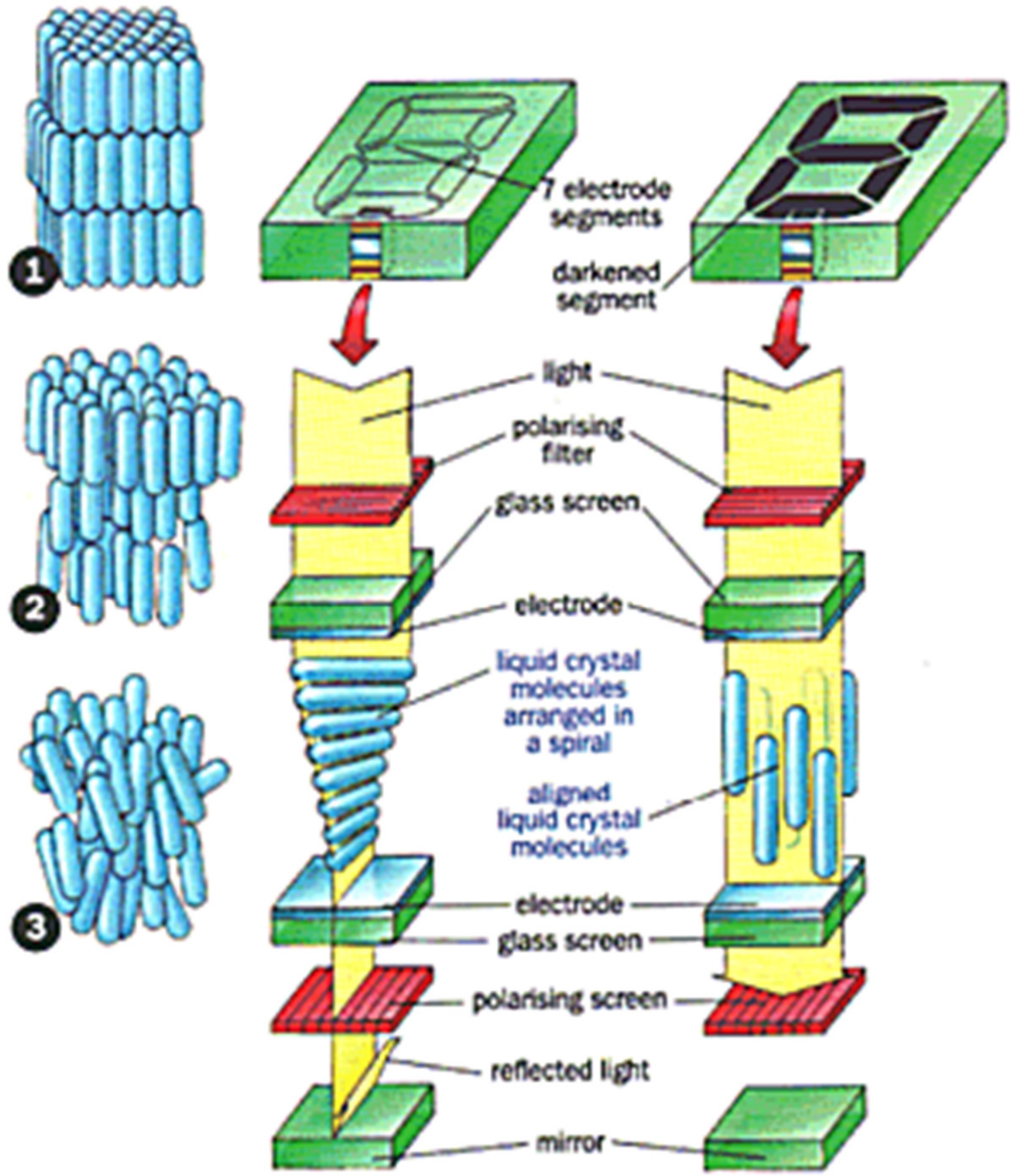

This is a 2x16
line LCD Display

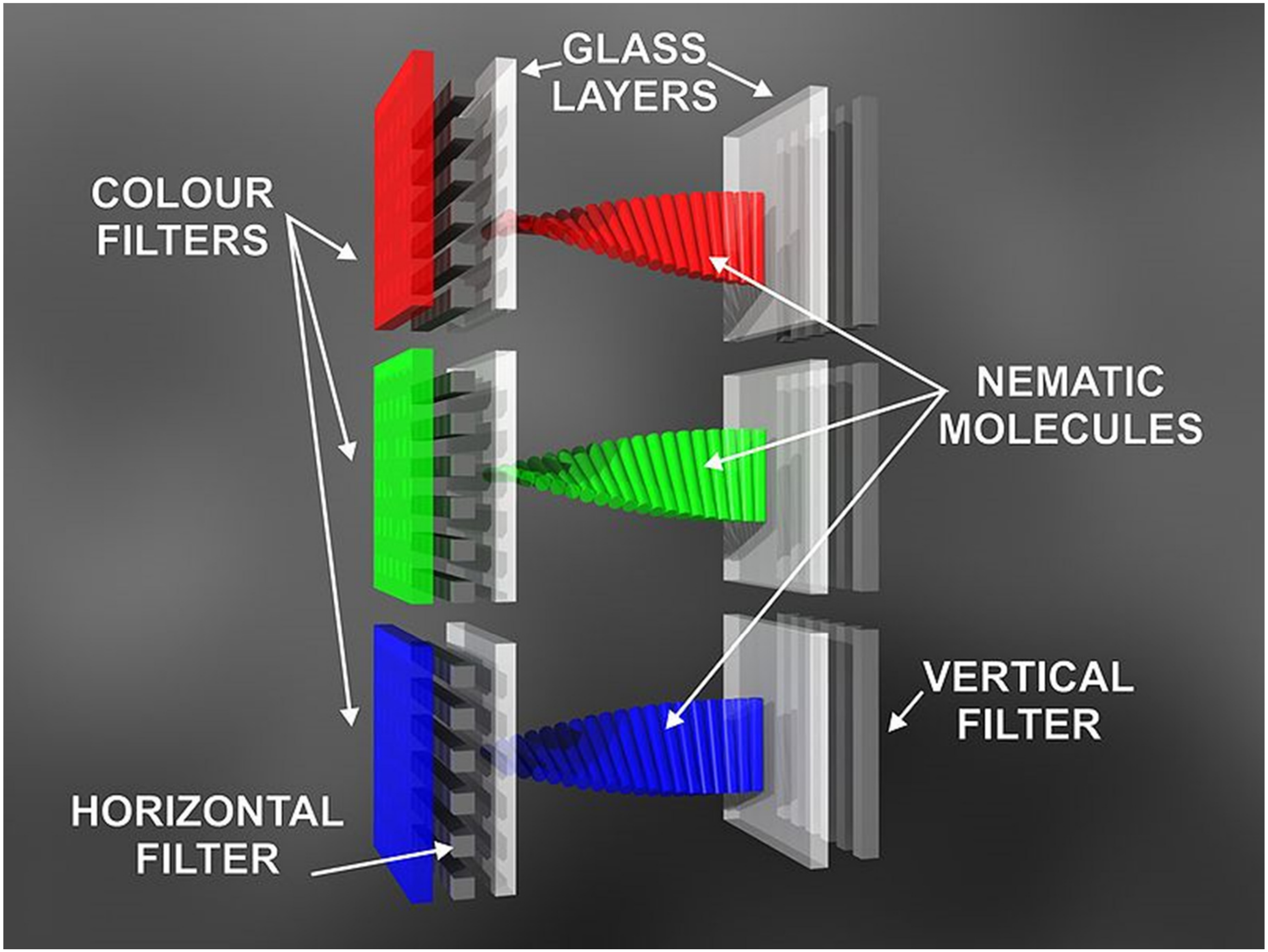


(a) Off (transmitted light gives bright background)



(b) On (dark characters formed where no light is transmitted)


1
2
3
7 electrode segments
darkened segment
light
polarising filter
glass screen
electrode
liquid crystal molecules arranged in a spiral
aligned liquid crystal molecules
electrode
glass screen
polarising screen
reflected light
mirror


GLASS
LAYERS
COLOUR
FILTERS
NEMATIC
MOLECULES
VERTICAL
FILTER
HORIZONTAL
FILTER