

Lecture # 30

EM waves &

Polarization

SPEED OF ELECTROMAGNETIC WAVE

$$\mathcal{E} = \oint \vec{E} \cdot d\vec{\ell} = -\frac{d}{dt} \oint \vec{B} \cdot d\vec{A} \equiv \dot{\Phi}_B; \quad \oint \vec{B} \cdot d\vec{\ell} = \mu_0 \epsilon_0 \frac{d}{dt} \oint \vec{E} \cdot d\vec{A} \equiv \mu_0 \epsilon_0 \dot{\Phi}_E$$

imply EM wave propagate

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3 \times 10^8 \text{ m/s}$$

$$B = \frac{E}{c}, \quad \vec{E} \perp \vec{B} \perp \text{direction of wave propagate of wave}$$

ENERGY DENSITY IN ELECTROMAGNETIC WAVE

$$U_E = \frac{\epsilon E^2}{2}$$

$$U_B = \frac{B^2}{2\mu_0}$$

$$u = \frac{\epsilon_0 E^2}{2} + \frac{1}{2\mu_0} B^2 = \epsilon_0 E^2 \equiv U_{EM}$$

Joules/m³

because

$$U_B = \frac{B^2}{2\mu_0} = \frac{E^2}{2c^2\mu_0} = \frac{\epsilon E^2}{2} = U_E$$

(B = E/c)

$\frac{1}{c^2} = \epsilon_0\mu_0$

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POYNTING VECTORS

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} = \text{joules/m}^2\text{s}$$

$$c^2 = \frac{1}{\epsilon_0 \mu_0}$$

$$|\vec{S}| = \frac{E B}{\mu_0} = \frac{E E}{c \mu_0} = c \frac{E E}{\mu_0 c^2} = c \epsilon_0 \mu_0 \frac{E^2}{\mu_0} = c (\epsilon E^2)$$

$$|\vec{S}| = c U_{EM}$$

energy
density

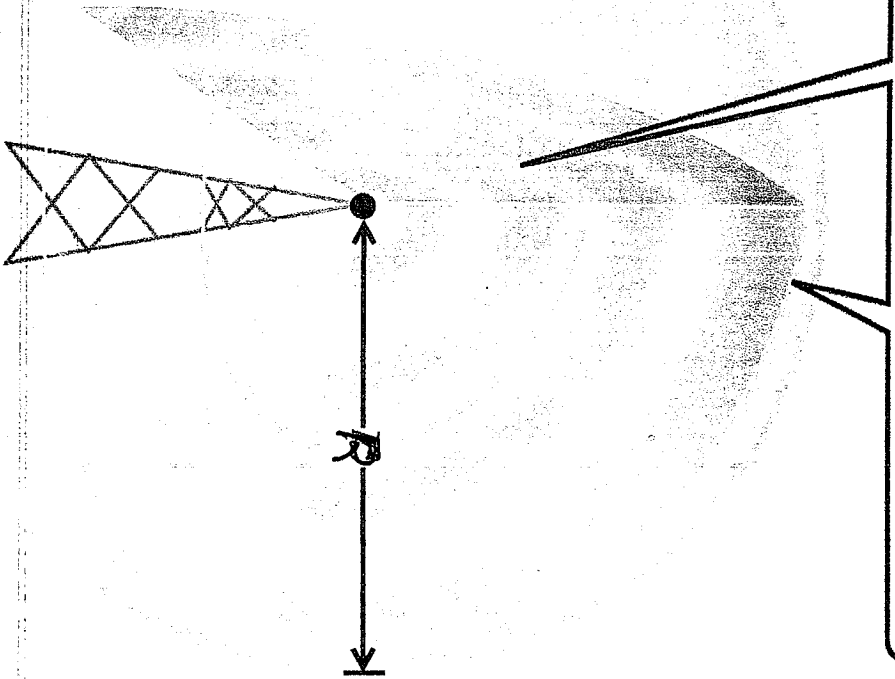
TIME-AVERAGE ENERGY FLUX (INTENSITY) IN PLANE WAVE

$$I_0 \equiv \bar{S} = \frac{1}{2\mu_0 c} E_0^2 = \frac{E_{rms}^2}{\mu_0}$$

Daylight has an energy flux of about 1 kW/m^2
 How much energy would a $5 \times 5 \text{ m}$ solar panel
 produce in one hour?

$$E = 1 \times (5 \times 5) = 25 \text{ kWh}$$

When wave propagates outward in all directions, its energy spreads over spheres of increasing area $A = 4\pi r^2$.



Emerging Energy
~~that~~ independent
of radius

$$\text{Power} = \bar{S} (4\pi R^2)$$

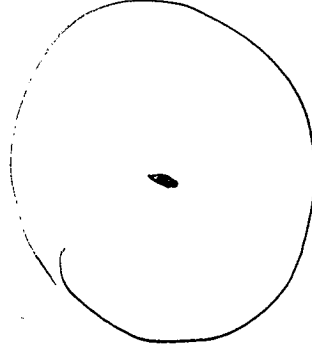
$$\bar{S} = \frac{\text{Power}}{4\pi R^2}$$

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ENERGY FLUX S IN TERMS OF POWER P FOR SPHERICAL WAVE

Intensity

$$I_0 \equiv \bar{S} = \frac{\bar{P}}{4\pi r^2}$$



In which direction

does this E&M wave

propagate?

- a. To the right
- b. To the left

This wave is

- a. Vertically polarized
- b. Horizontally polarized

Propagating E&M waves must be polarized.

- a. True
- b. false

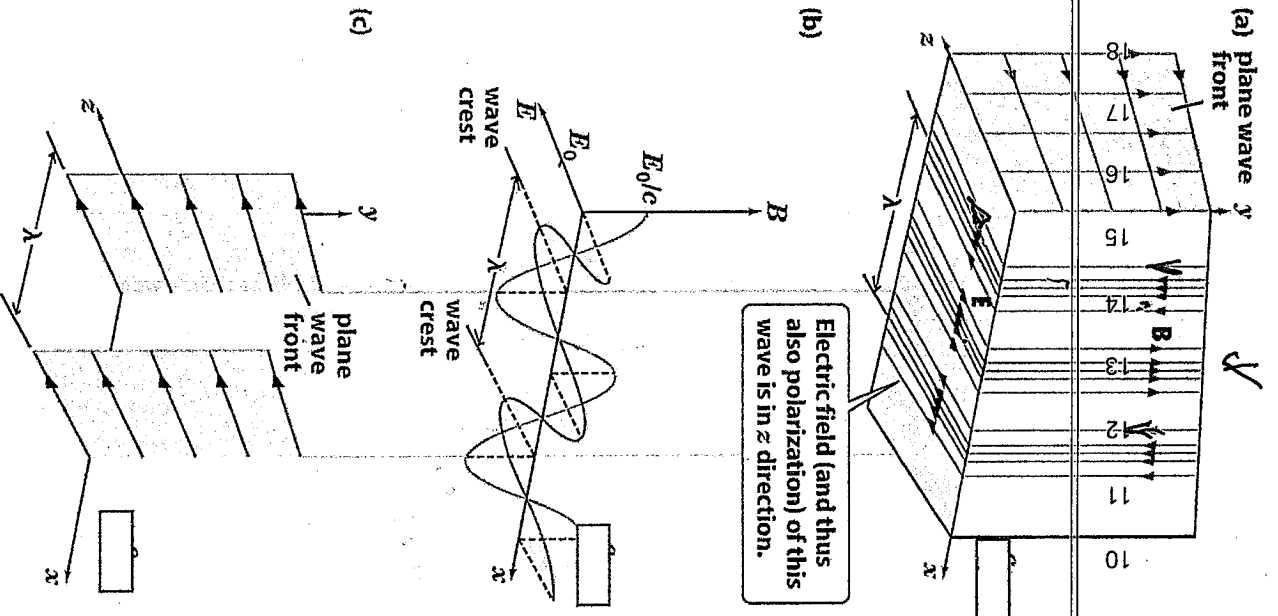


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$$B = -\hat{y} B_0, \quad B = \hat{z} \times \hat{y}$$

$$\vec{E} \times \vec{B} = \hat{z} \times \hat{y} = -\hat{x}$$

$$= \hat{z} \times \hat{y}$$

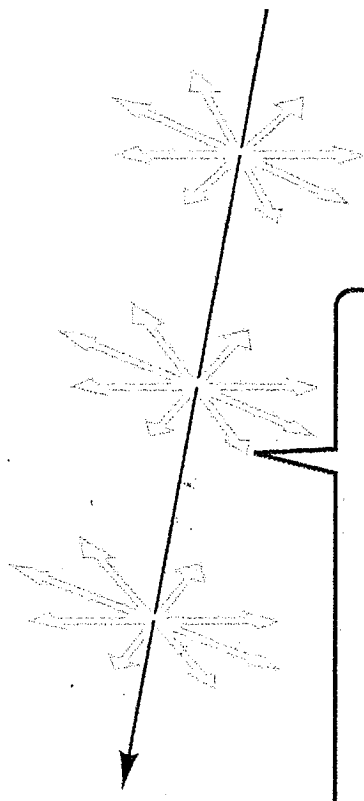
$$B = \hat{y} \times \hat{z} = \hat{x}$$

$$= \hat{z} \times \hat{y}$$

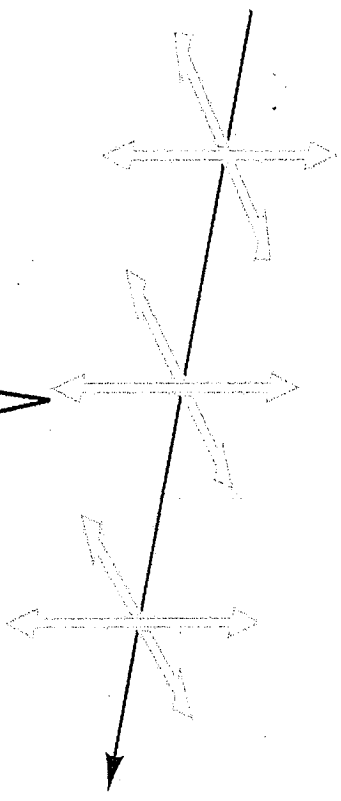
$$E B_0 \hat{x}$$

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Unpolarized light is a mixture of many polarization directions.



(b)



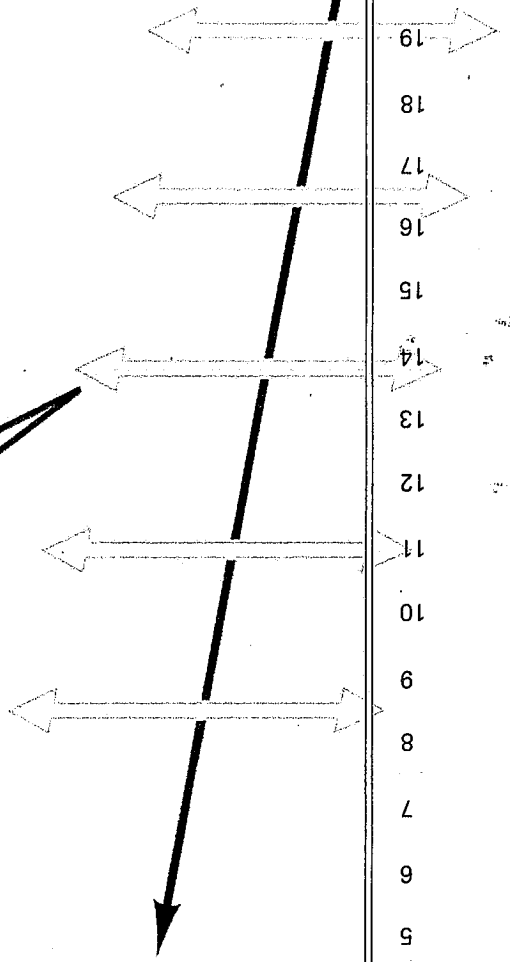
Unpolarized light can be viewed as a mixture of horizontally and vertically polarized waves.

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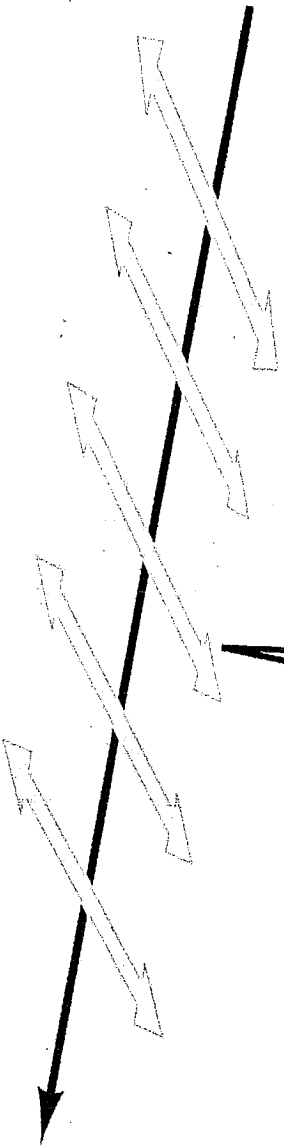
Polarized EM waves

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(a)



(b)



Double-headed arrows indicate direction of polarization (electric field) of wave.

Figure 33-13 Physics for Engineers and Scientists 3/e
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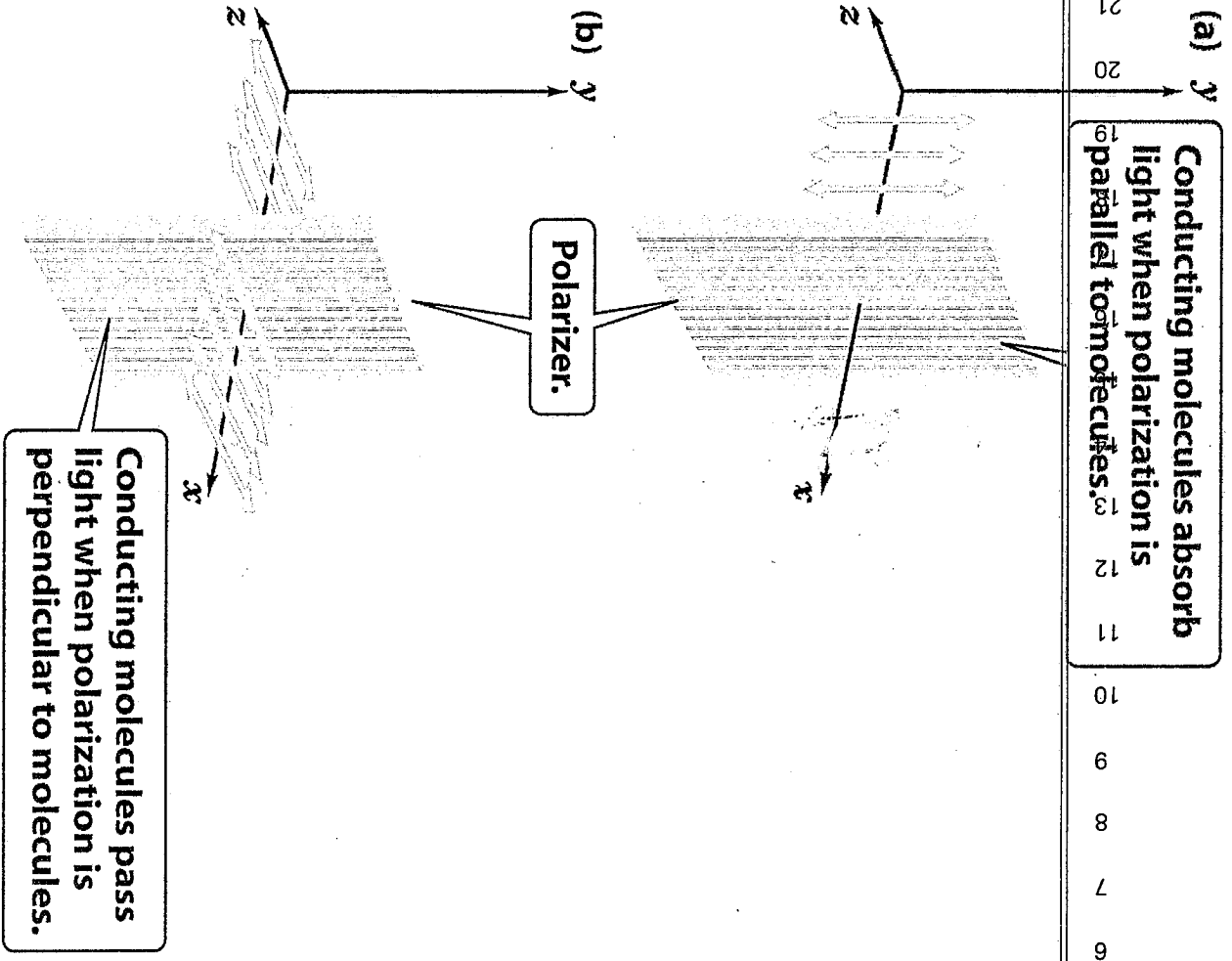


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Fabricating polarized waves

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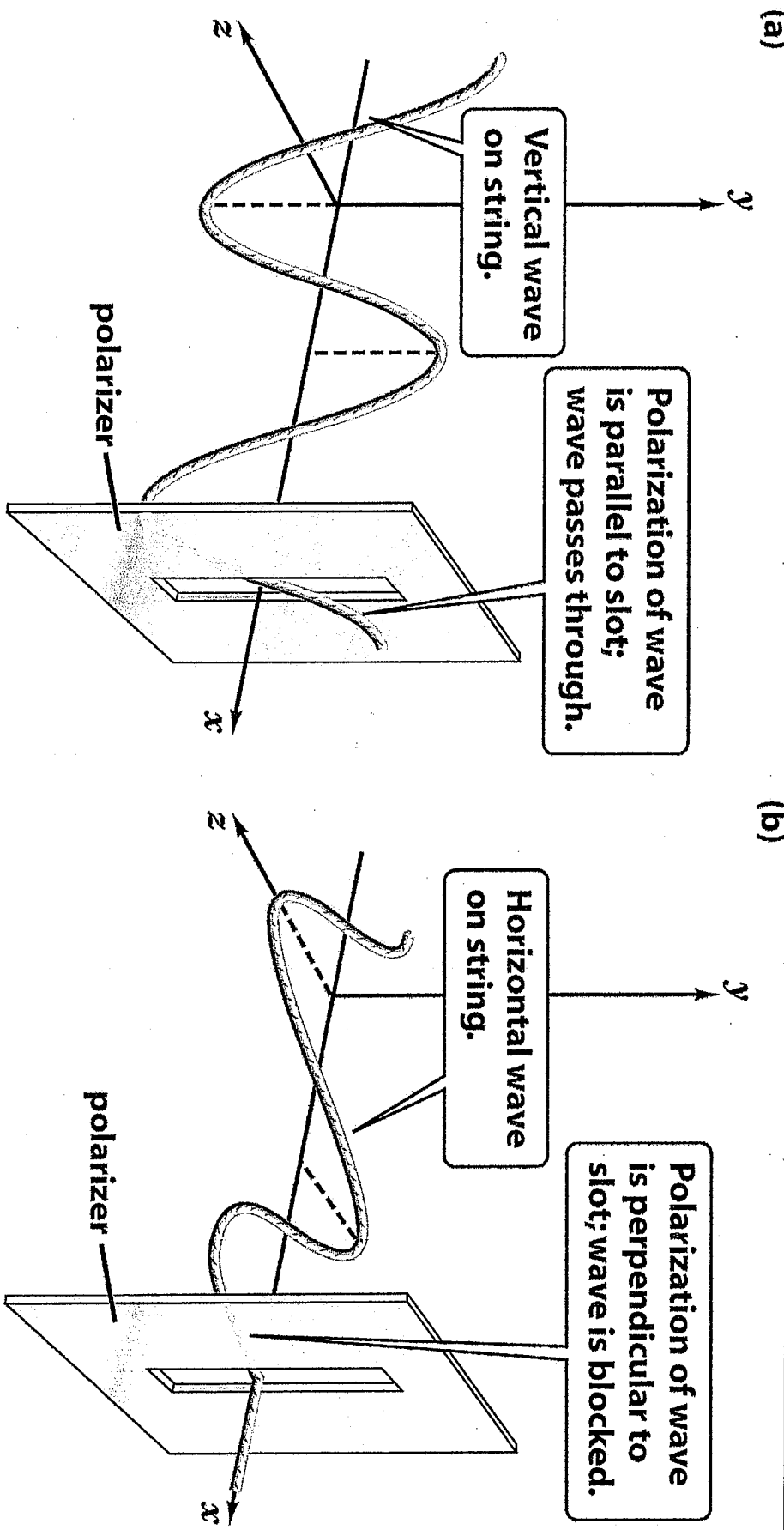


Figure 33-15 Physics for Engineers and Scientists 3/e
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Figure 33-18 Physics for Engineers and Scientists 3/e
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$$E_0' = E_0 \sin \phi$$

$$I_0 \sin^2 \phi$$

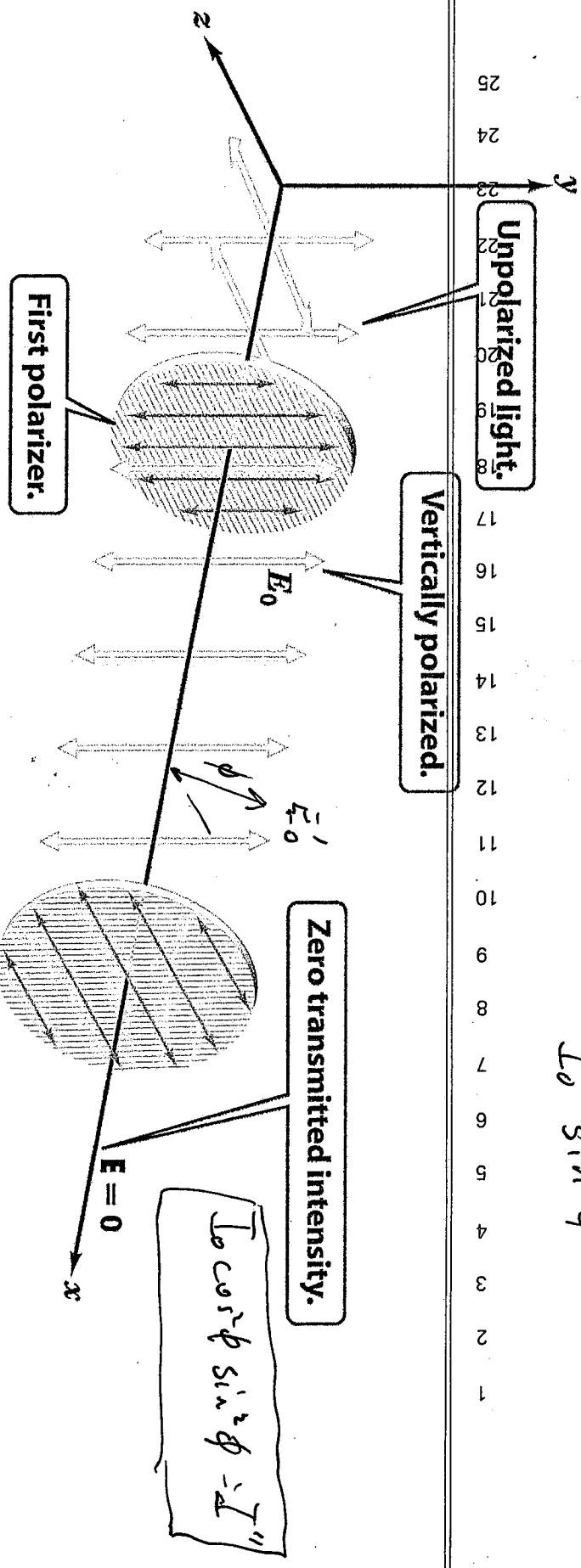


Figure 33-19a Physics for Engineers and Scientists 3/e © 2007 W.W.Norton & Company, Inc.

If we insert a polarizer between first and second polarizer at an intermediate polarization angle, will any wave energy propagate through the second polarizer?

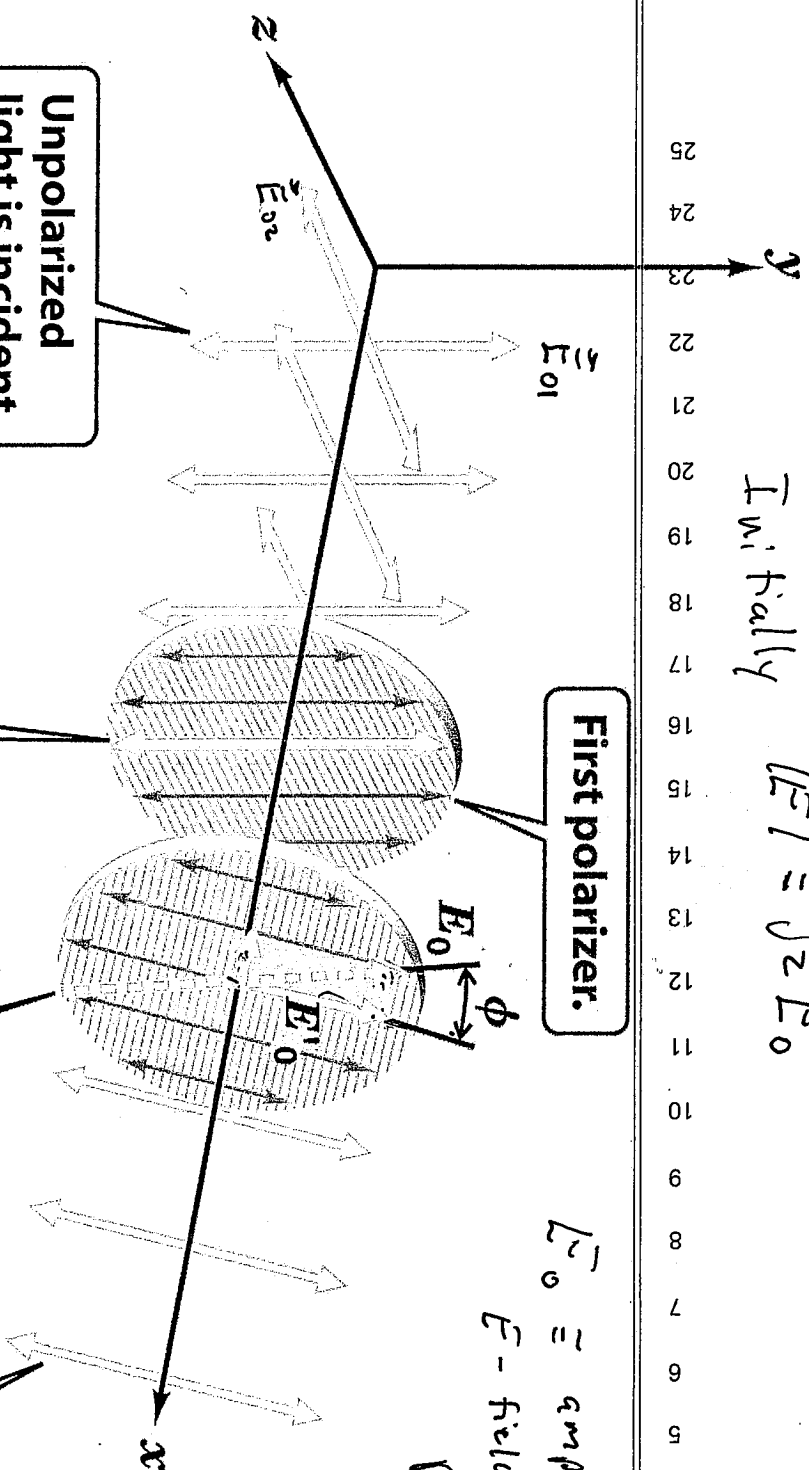
- a. Yes
- b. no

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$|\vec{E}_{01}| \approx |\vec{E}_{02}| \equiv E_0$
I initially
 $|\vec{E}| = \sqrt{2} E_0$

$E_0 \equiv$ amplitude of
 E -field between
 polarizers

$|\vec{E}'_0| = \cos \phi E_0$
 $I' = I_0 \cos^2 \phi$
 $|\vec{E}'_0|^2 = \cos^2 \phi E_0^2$



Unpolarized light is incident.

Polarized light of amplitude E_0 emerges from first polarizer.

Polarized light of amplitude $E'_0 = E_0 \cos \phi$ emerges from second polarizer.

Second polarizer has a preferential direction at angle ϕ with respect to the first.

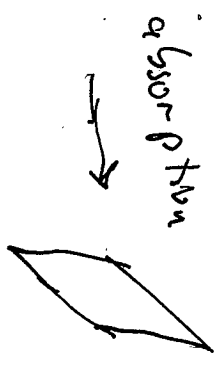
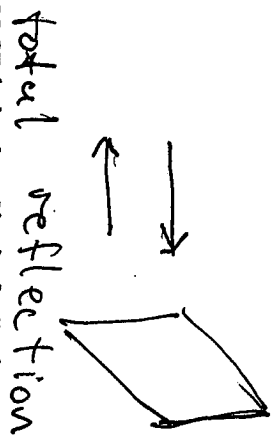
Figure 33-17 Physics for Engineers and Scientists 3/e © 2007 W.W. Norton & Company, Inc.

PRESSURE OF ELECTROMAGNETIC WAVE

Momentum Flux $= (\epsilon_0/\mu_0)^{1/2} \vec{E} \times \vec{B} = \vec{S}/c$

$$[\text{pressure}] = \begin{cases} \frac{S}{c} & \text{(absorption)} \\ \frac{2S}{c} & \text{(reflection)} \end{cases}$$

$S_i - S_t = \text{Pressure}$



Twice as much pressure is generated

Equation 33-27 derivatives Physics for Engineers and Scientists 3/e
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from reflecting light compared to absorbing light for