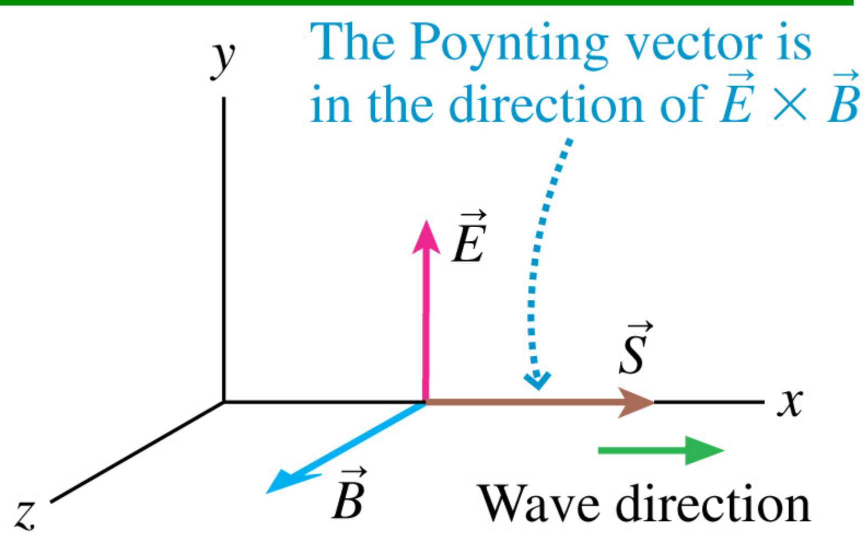
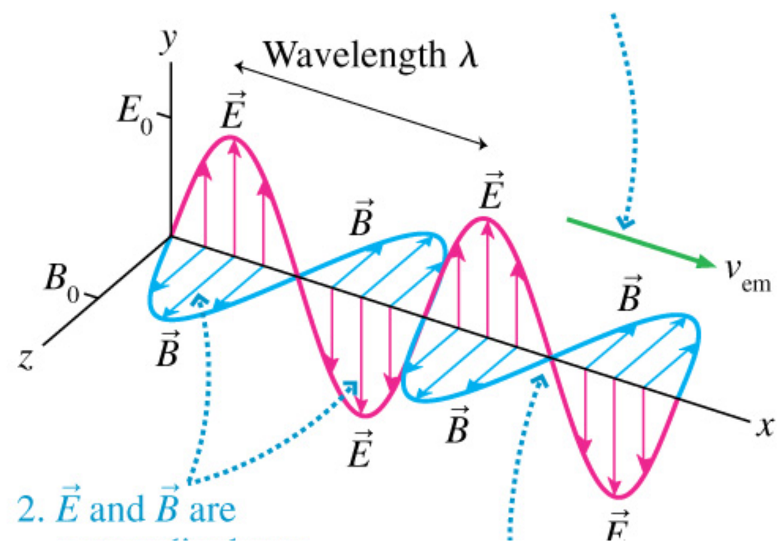
PHY294H

- Professor: Joey Huston
- email:huston@msu.edu
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
    - **Help-room hours: 12:40-2:40 Monday (note change); 3:00-4:00 PM Friday**
    - **hand-in problem for Wed Mar. 23: 34.60**
    - **Note I revised Homework assignment 9 (due 3/23) adding some problems that were due a week later**
- Quizzes by iclicker (sometimes hand-written)
- 2nd exam next Thursday
- **Final exam Thursday May 5 10:00 AM – 12:00 PM 1420 BPS**
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
    - lectures will be posted frequently, mostly every day if I can remember to do so

EM waves

- Properties of an EM wave
  - the electric and magnetic fields are perpendicular to the direction of propagation
  - the electric and magnetic fields are perpendicular to each other such that $\vec{E}$X$\vec{B}$ is in the direction of propagation
  - the electric and magnetic fields are in phase
  - the EM wave travels at c
  - E=cB at any point on the wave
- Define the Poynting vector S
  - the Poynting vector points in the direction that the wave is travelling
  - the magnitude of S measures the rate of energy transfer per unit area of the wave





EM waves

- Poynting vector

$$\vec{S} \equiv \frac{1}{\mu_o} \vec{E} X \vec{B}$$

$$|S| = \frac{EB}{\mu_o} = \frac{E^2}{c\mu_o} = \frac{cB^2}{\mu_o}$$

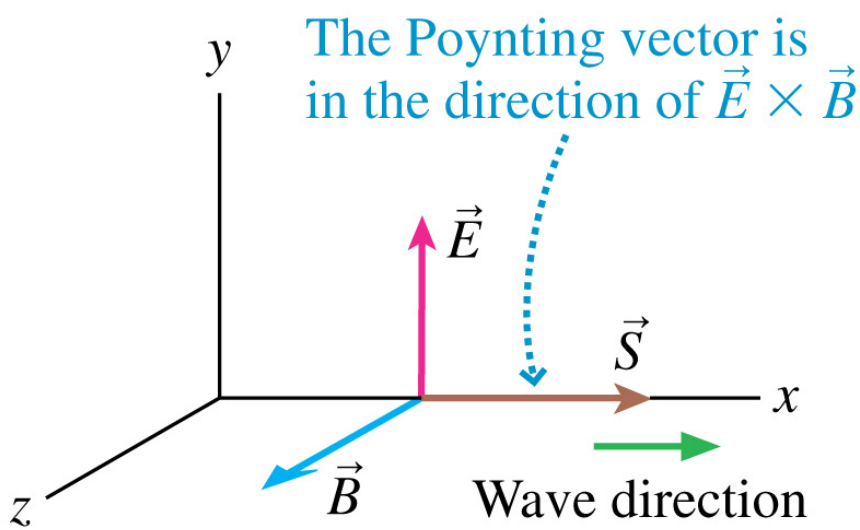
- Define the wave's intensity

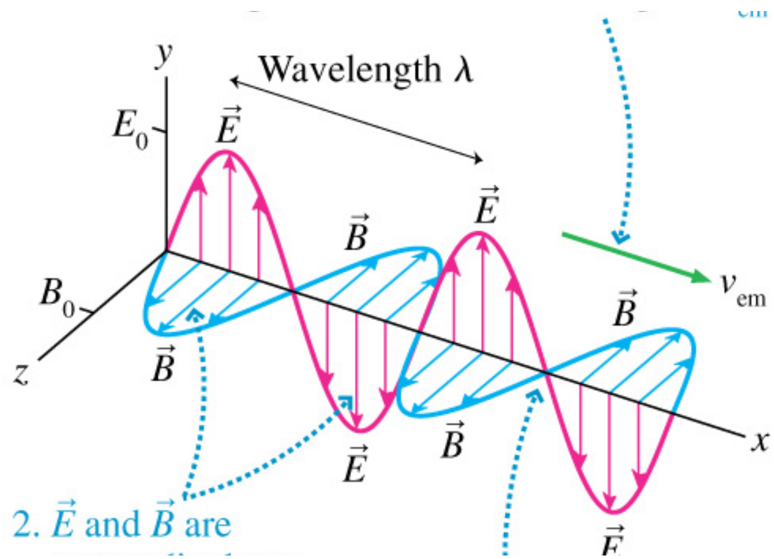
$$I = \frac{P}{A} = S_{avg} = \frac{1}{2c\mu_o} E_o^{\ 2} = \frac{c\varepsilon_o}{2} E_o^{\ 2}$$

- Energy in electric and magnetic fields

$$u_B = \frac{B^2}{2\mu_o}$$

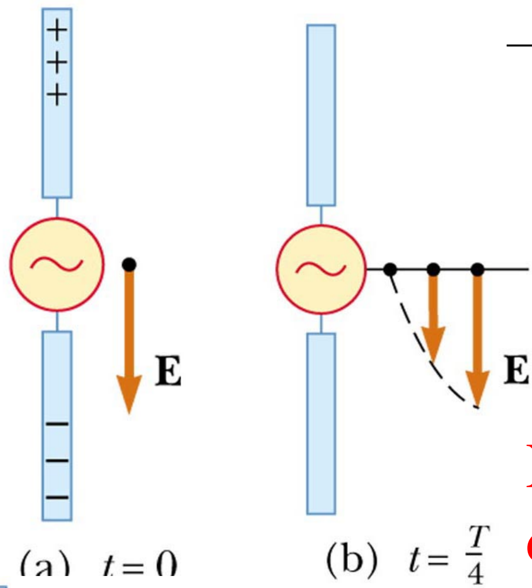
$$u_E = \frac{1}{2}\varepsilon_o E^2 = \frac{1}{2}\varepsilon_o c^2 B^2 = \frac{\varepsilon_o B^2}{2\mu_o \varepsilon_o} = \frac{B^2}{2\mu_o}$$





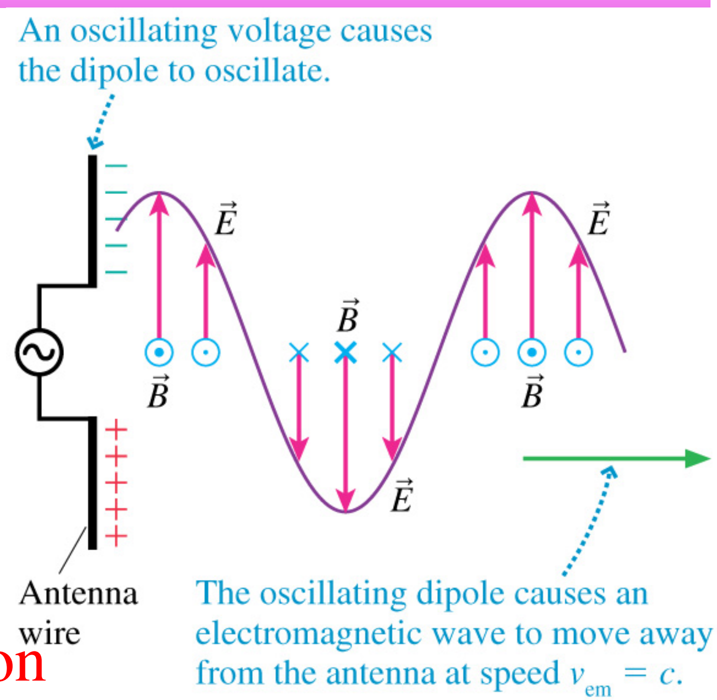
(same energy density in E and B fields)

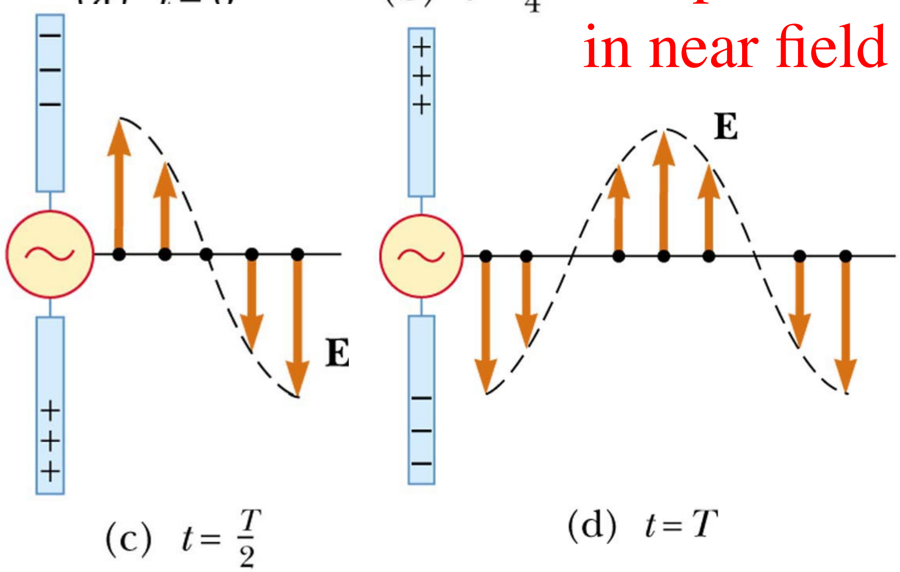
Creating electromagnetic waves



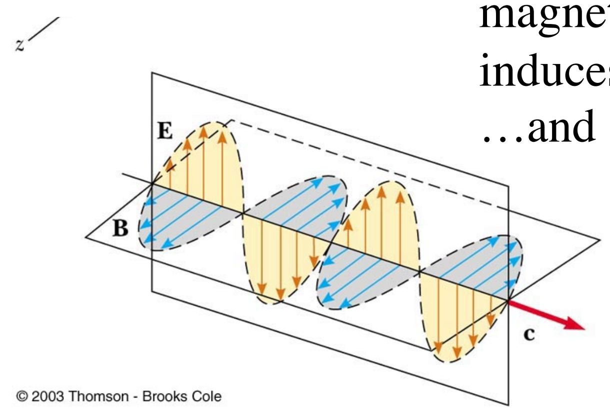
electric field moves out at the speed of light

Note it gets complicated in near field region

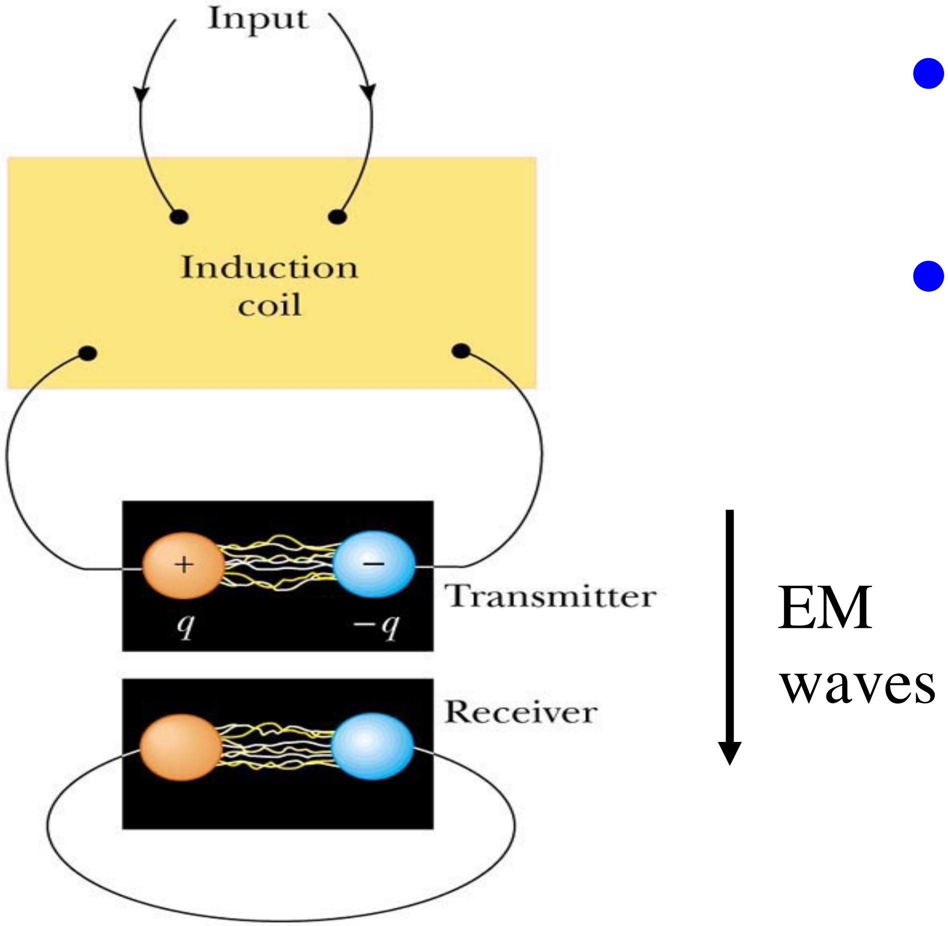




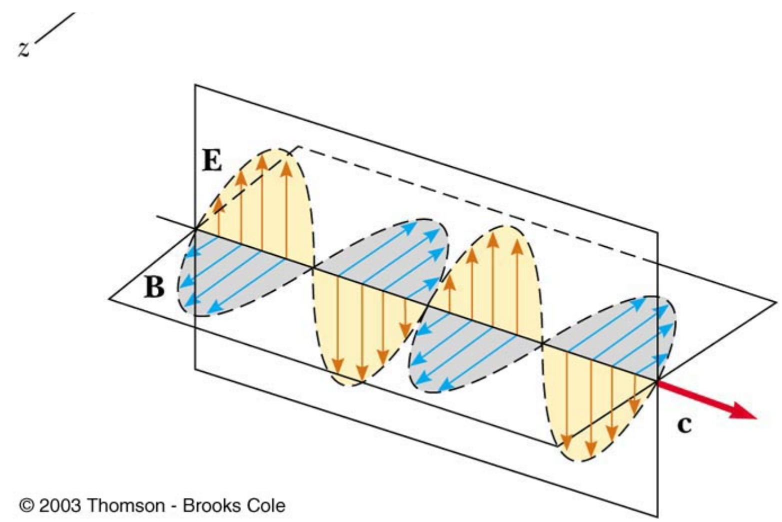
electric field induces a magnetic field, which induces an electric field …and so on



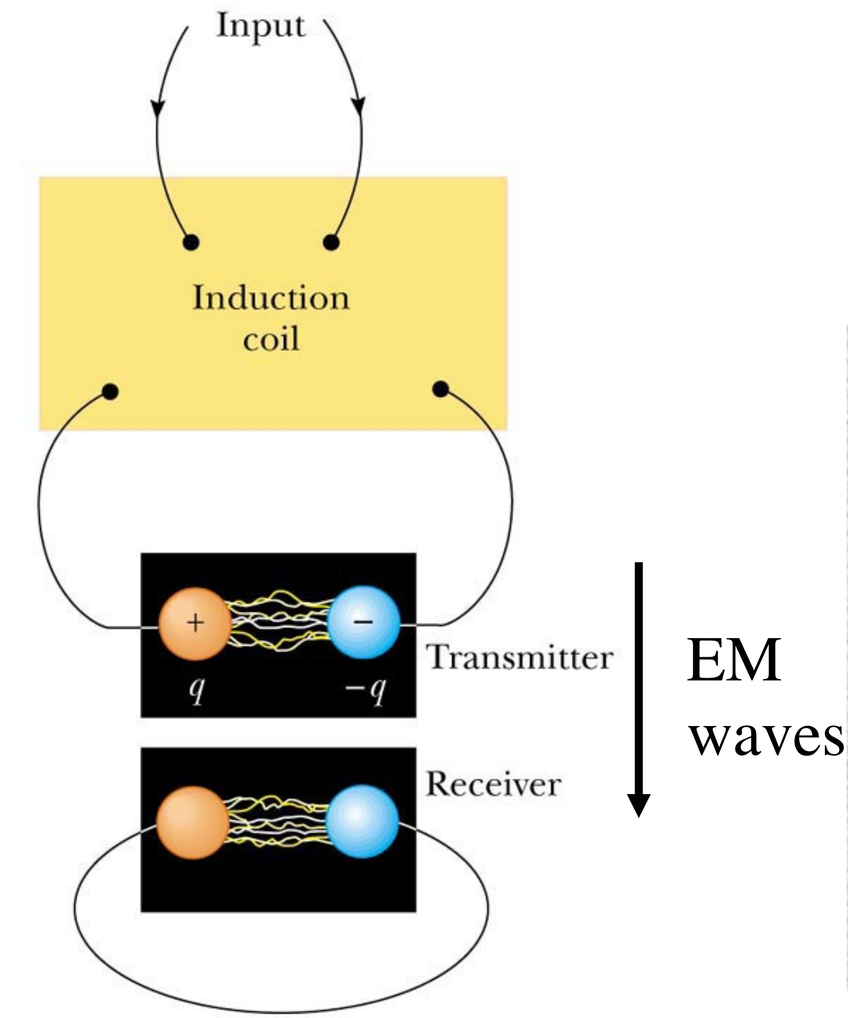
What we know

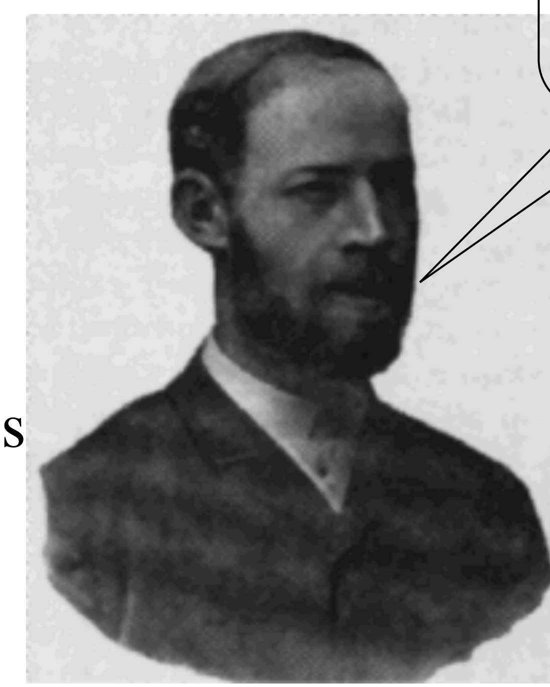


- Stationary electric charges produce electric fields
- Electric charges in uniform motion (currents) produce electric and magnetic fields
- Accelerated electric charges produce electric fields, magnetic fields, and electromagnetic waves



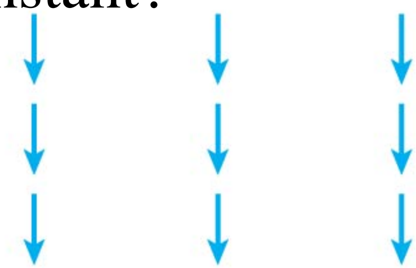
It was left to Heinrich Hertz to verify EM waves



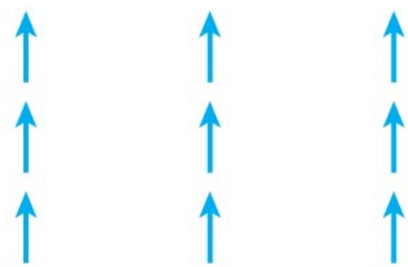


…and for us to replicate his verification

An electromagnetic plane wave is coming toward you, out of the screen. At one instant, the electric field looks as shown. Which is the wave's magnetic field at this instant?

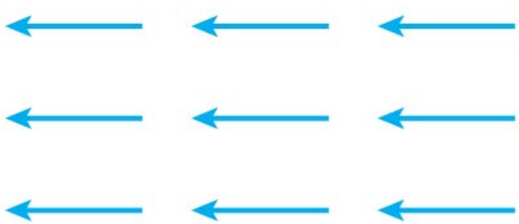


A.



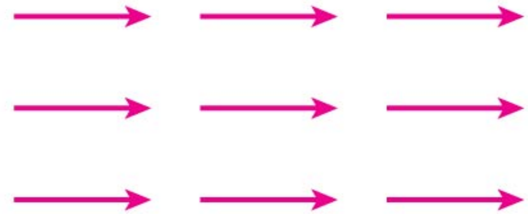
B.

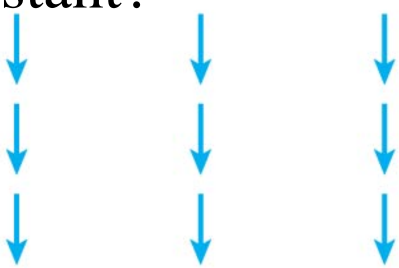
C.



D.

An electromagnetic plane wave is coming toward you, out of the screen. At one instant, the electric field looks as shown. Which is the wave's magnetic field at this instant?

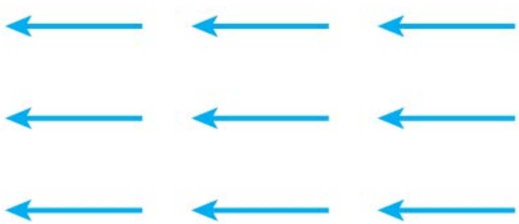




A.

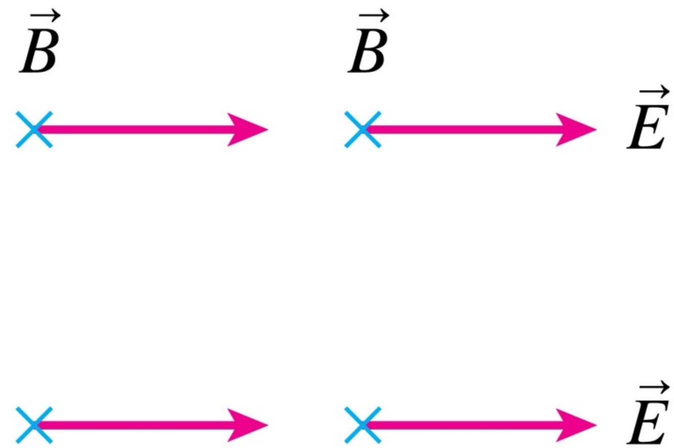
B.

C.



D.

In which direction is this electro-magnetic wave traveling?



A. Up.

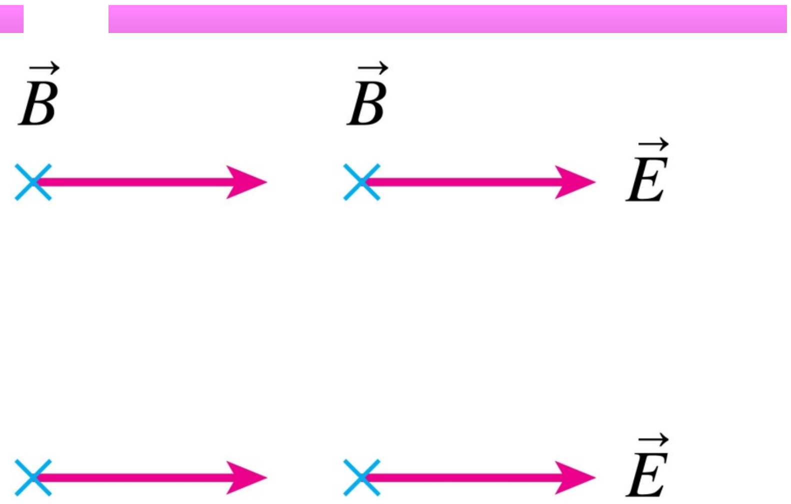
B. Down.

C. Into the screen.

D. Out of the screen.

E. These are not allowable fields for an electromagnetic wave.

In which direction is this electro-magnetic wave traveling?



✔ **A. Up.** $\vec{E} \times \vec{B}$ is in the direction of motion.

B. Down.

C. Into the screen.

D. Out of the screen.

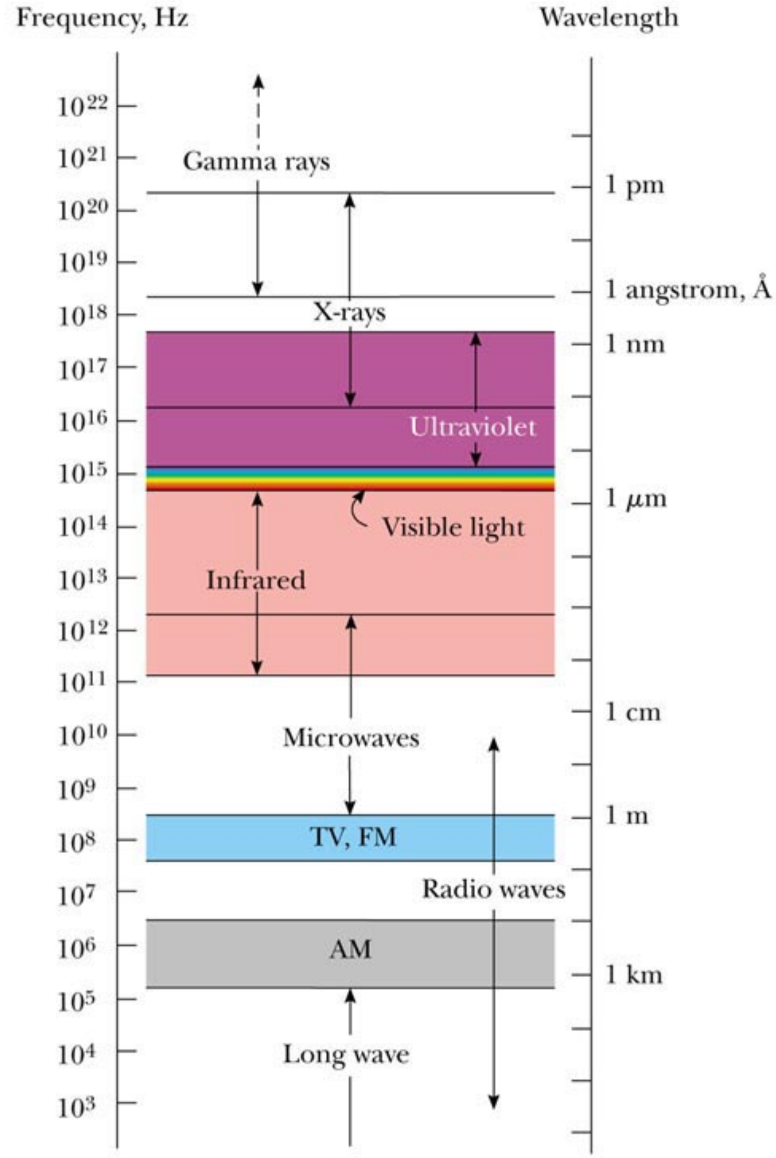
E. These are not allowable fields for an electromagnetic wave.

Example

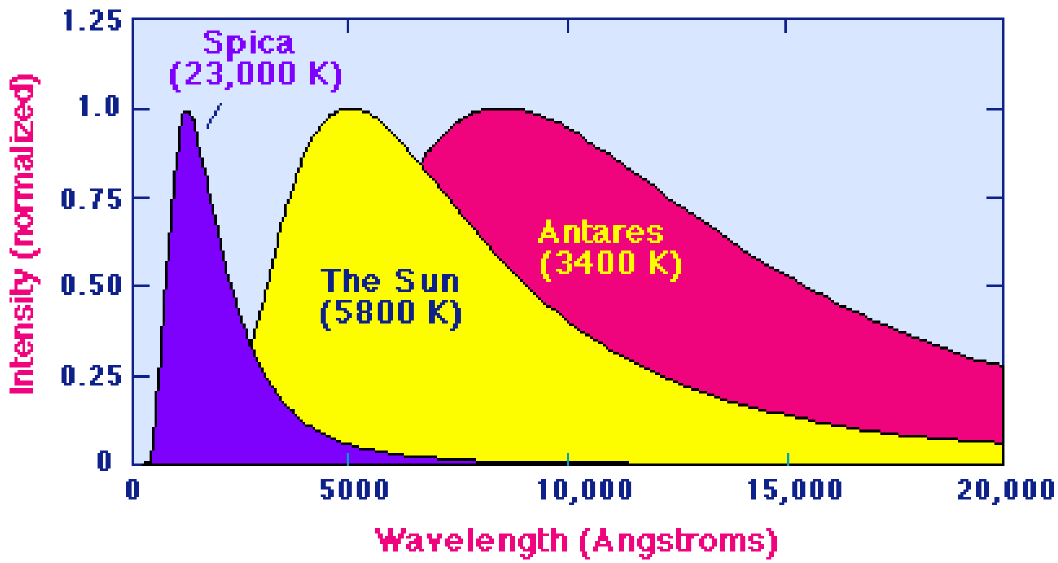
- A radio antenna broadcasts a 1.0 Mhz radio wave with 25 kW of power. Assume that the radiation is emitted uniformly in all directions.
  - what is the wave's intensity 30 km from the antenna?
  - what is the electric field amplitude at this distance?

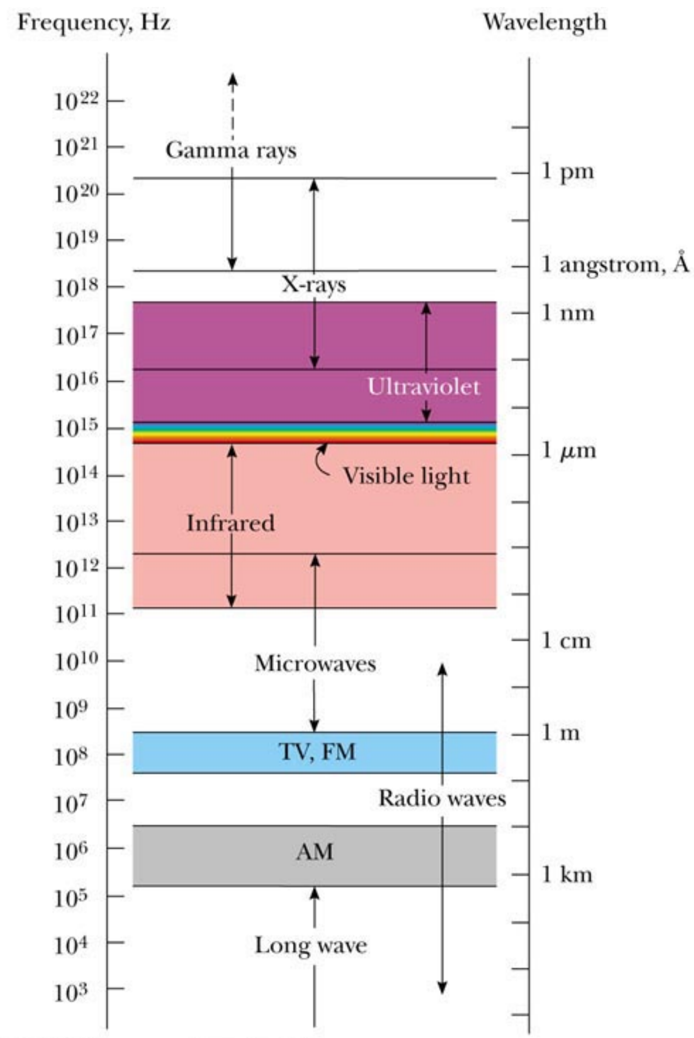
Electromagnetic spectrum

- All electromagnetic waves travel through vacuum with a speed c (3 X 10^8 m/s)
- For all EM waves, $c=\lambda f$ (true for any type of wave)
- $\lambda = c/f$
- The visible portion of the spectrum forms a tiny portion of the total EM spectrum



Electromagnetic spectrum and the sun

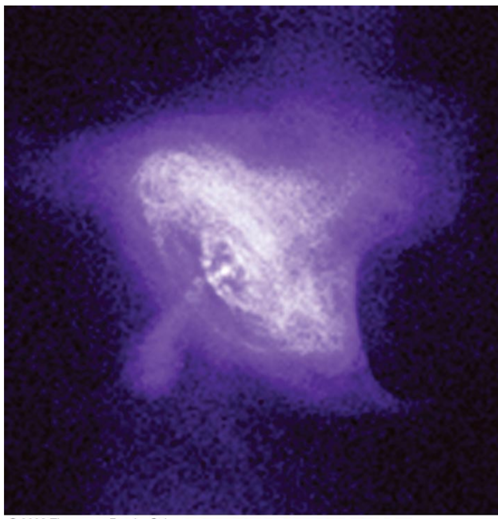




Views of Crab Nebula

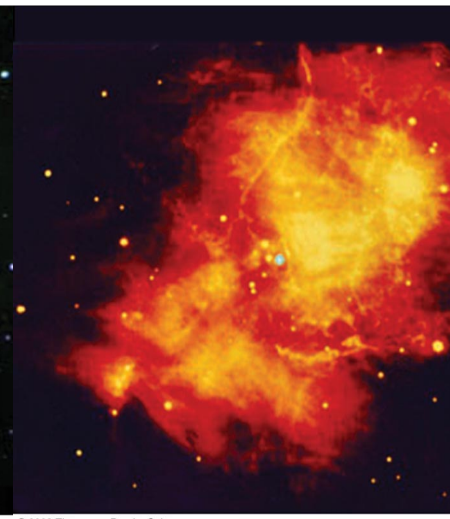
increasing energy ($E = hc/\lambda = hf$)

X-ray

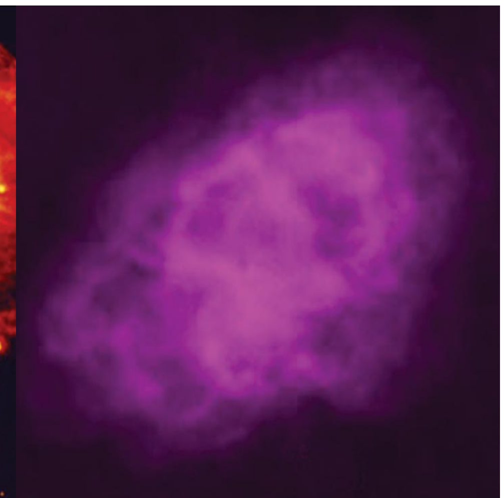


optical

infra-red



radio



increasing wavelength

Electromagnetic waves also carry momentum

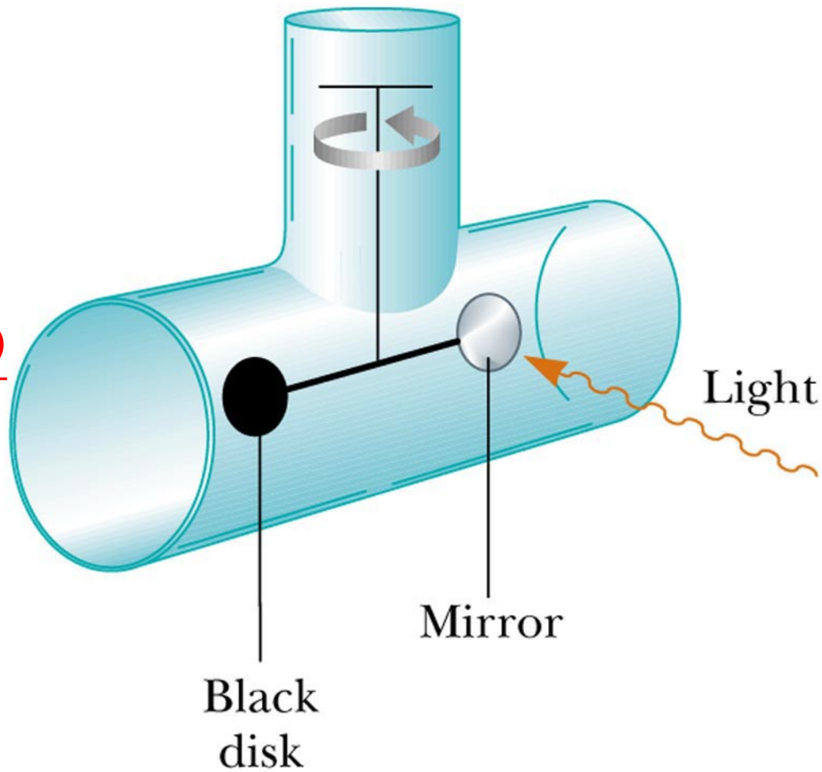
- Suppose an electromagnetic wave delivers an energy U in a time t to some surface
- If the surface absorbs the EM wave, Maxwell showed that the total momentum delivered to surface has a value
  - p=U/c
- If the EM wave reflects off the surface, then the momentum transfer is twice as large

$$F = \frac{\Delta p}{\Delta t} = \frac{(energy absorbed)/\Delta t}{c} = \frac{P(ower)}{c}$$

$$p_{rad} = \frac{F}{A} = \frac{(P/A)}{c} = \frac{I}{c} \longrightarrow \text{Intensity}$$

- Radiation pressure is very small ($5X10^{-6}$ N/m^2) from direct sunlight, but you can easily measure it using an apparatus like the one on the right

more momentum transfer to the mirror then to the black disk so apparatus twists in direction shown



Radiometer

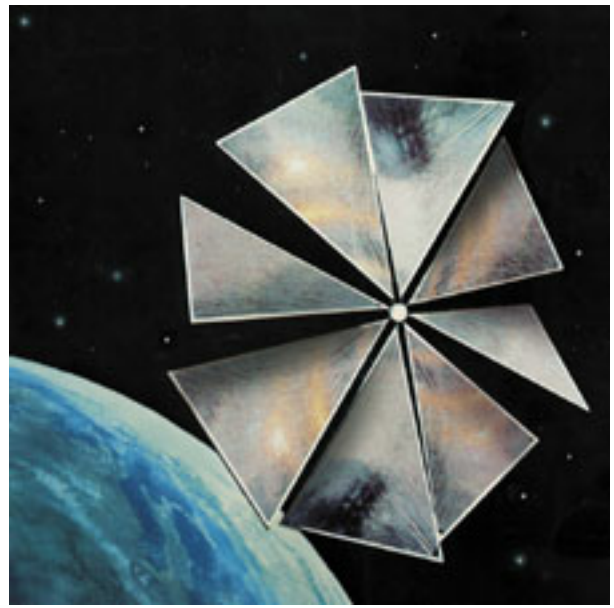
- Expose a radiometer to light and it starts spinning
- One surface of each vane is black and the other is silver
- Crookes thought that this was a demonstration of light pressure
- However, it turns the wrong way; light is absorbed by the black face and is reflected by the silver face.
- There is twice as much momentum transfer from the silver face as from the black face so if it was light pressure, it should spin in the CCW direction
- The spinning is really due to the residual gas molecules in the bulb; the molecules near the black surface are hotter than those near the silver surface and so give a bigger kick to the vanes when they hit

Places where light pressure has an effect

- Tail(s) of a comet
- solar sail

from 'solar wind'

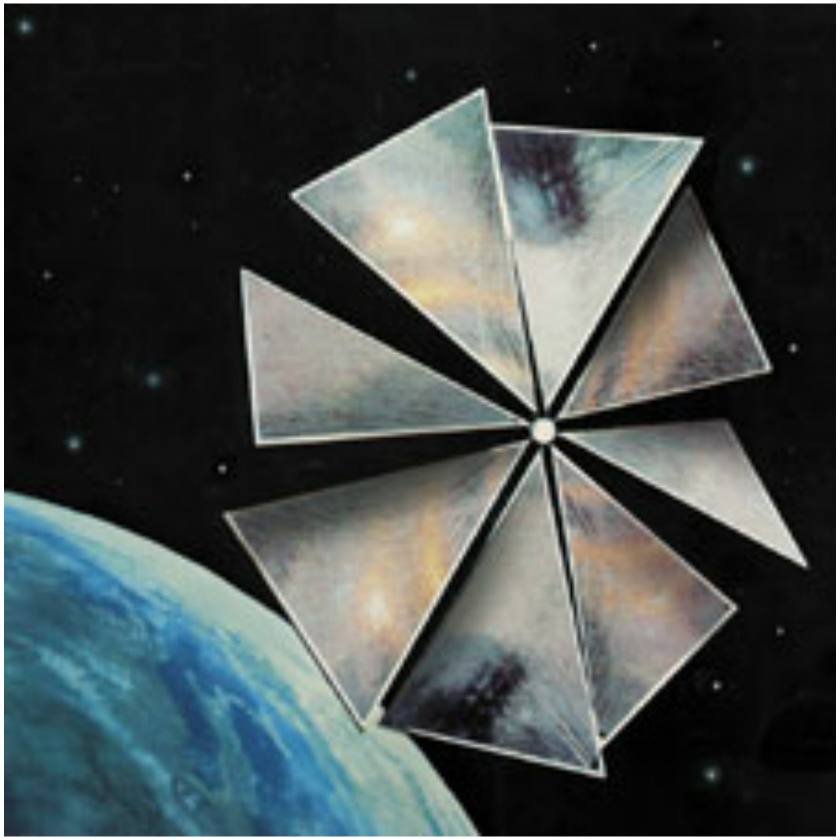
from light pressure



can use light pressure to sail around solar system

Solar sailing

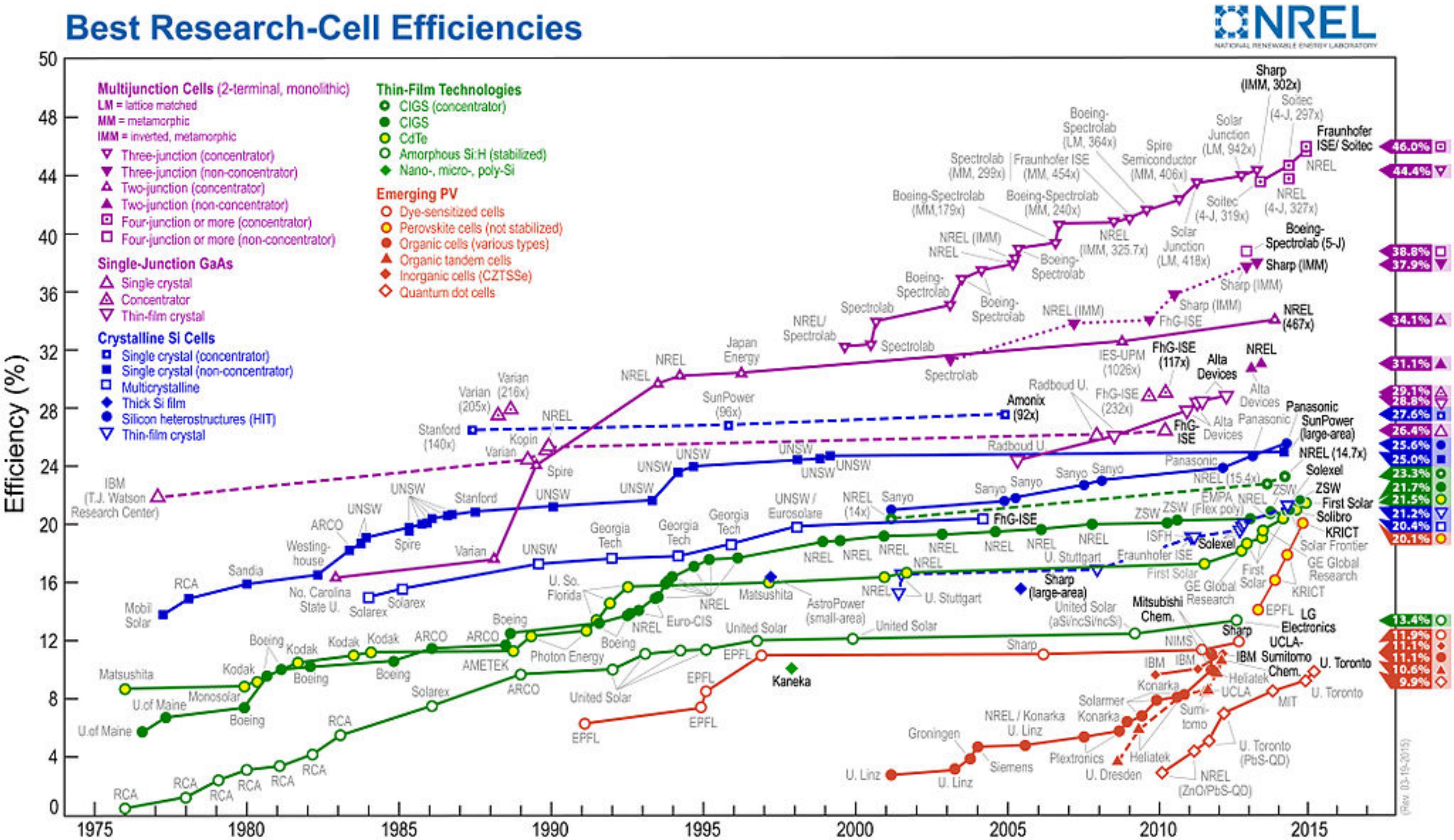
- Test device had an area of 600 m^2
  - X $5X10^{-6}$ N/m^2 $=3X10^{-3}$ N
  - still not very much but enough to show proof of principle
- Need sails about a mile across for example to rondevous with Halley's comet
  - 2.5 X 10^6 m^2
  - 13 N
  - given realistic masses for sail, accelerations of ~1 mm/s^2



Example

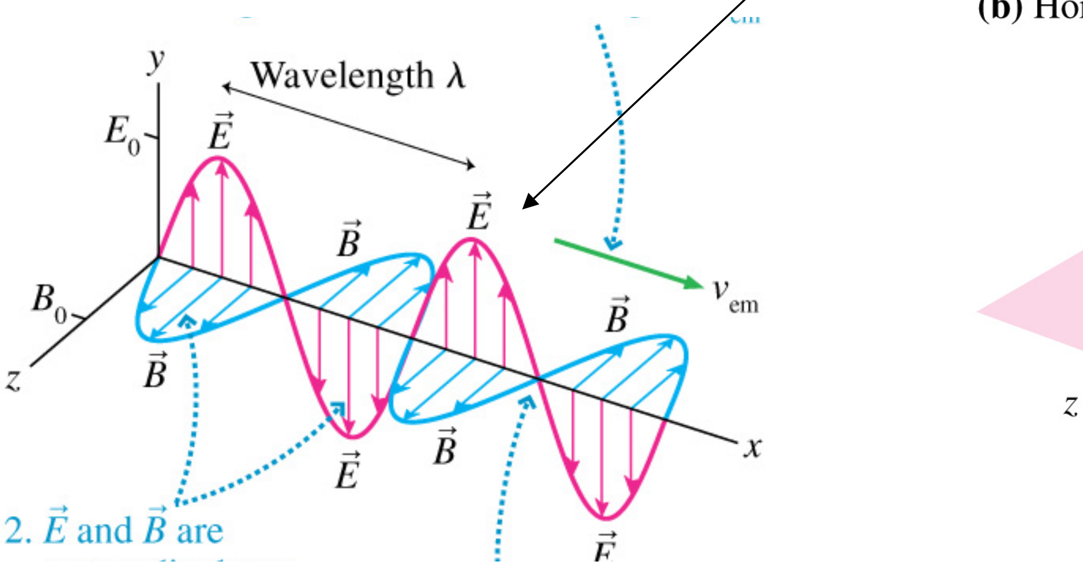
- The intensity of sunlight reaching the Earth is 1360 W/m^2. Assuming all of the sunlight is absorbed by the Earth, what is the radiation pressure force on the Earth. What is the acceleration of the Earth due to this force?

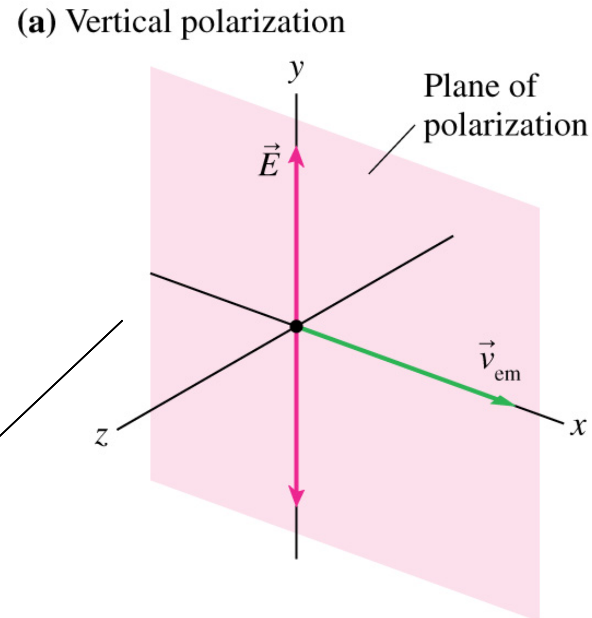
Best Research-Cell Efficiencies

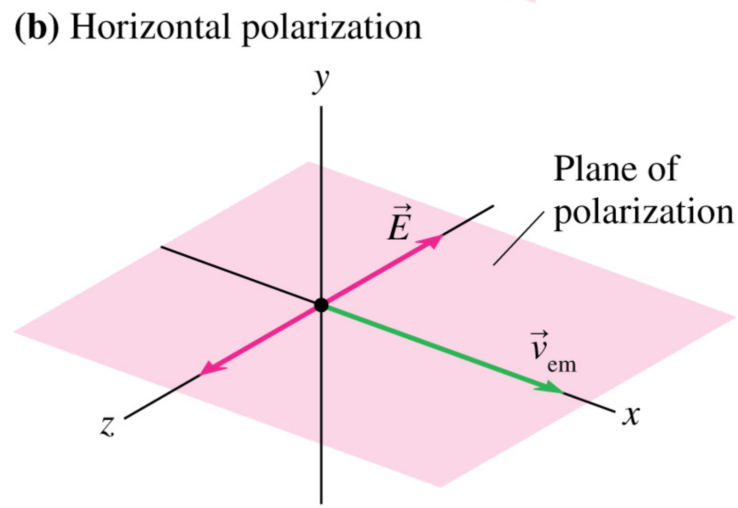


Polarization

- the plane containing the electric field vector and the Poynting vector S is called the plane of polarization of the EM wave







Polarizing filter

- Ordinary electromagnetic waves are unpolarized
  - the electric field vectors for each wave are random
- A polarizing filter lets in only those EM waves with a polarization in a particular direction
  - polymer chains are treated to make them conducting
  - electrons absorb energy from EM waves whose electric fields oscillate in the direction of the chains