Your questions/comments

IMPORTANT ANNOUNCEMENT:
James Scholar HCLA forms due Mar. 13. Proposals due Apr. 7 by email
Review session T Mar. 17, 2015 from 6:30-8:30pm (141 Loomis) -> FA14 EX2

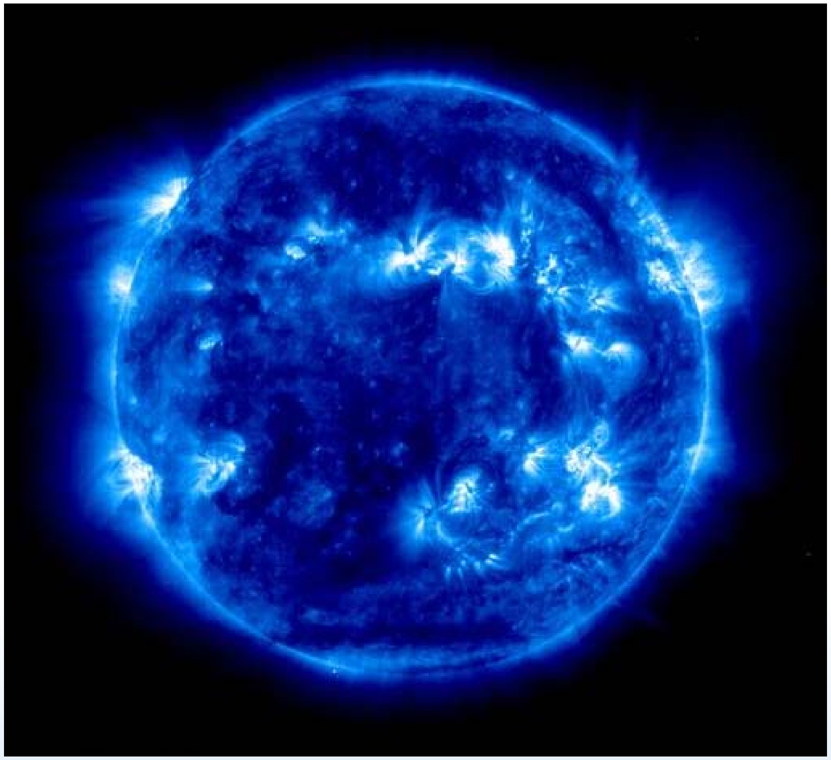
"What in the world did I just learn?!"

"-the picture of the EM wave and the E and B fields: does not make conceptual sense -which way will B be for a propagating EM wave (there are 2 directions where it can be perpendicular to both the E and the v)"

"Is there a simple way or a trick to help visualize things happening in three dimensions?"

"I dislike how we continue to cover new material even though we haven't been tested on the second exam material yet."

"Can we review more content that will be on our upcoming exam, rather than moving so quickly and having to backtrack so much."



Phys 102 – Lecture 15

Electromagnetic waves

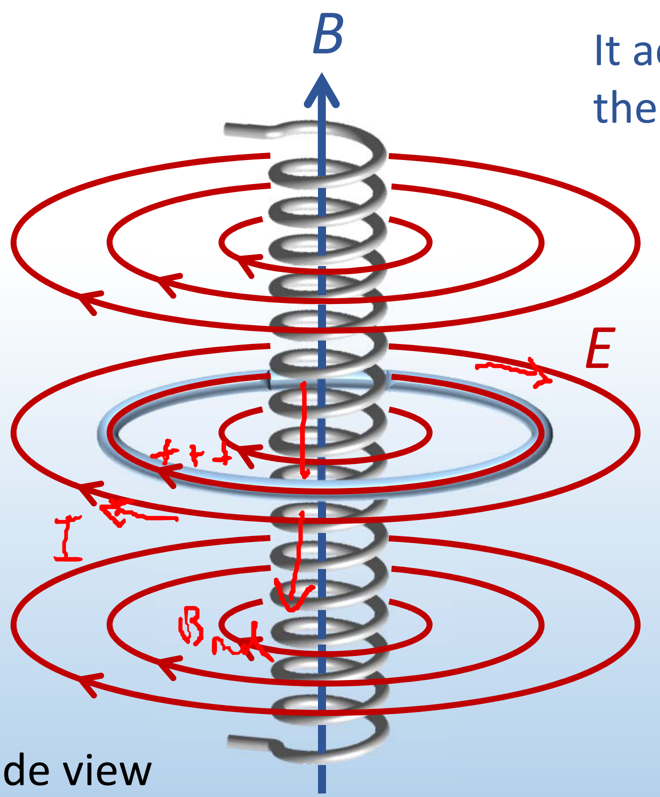
Today we will...

- Introduce/review several key concepts
  - Changing *B* field generates *E* field Faraday's
  - Changing *E* field generates *B* field
  - *E* and *B* field propagate in space at finite speed
- Learn about electromagnetic waves
  - Relationship between *E* and *B* fields in EM waves
  - Properties of waves & spectrum of light
- Learn applications
  - Antennas
  - Doppler effect

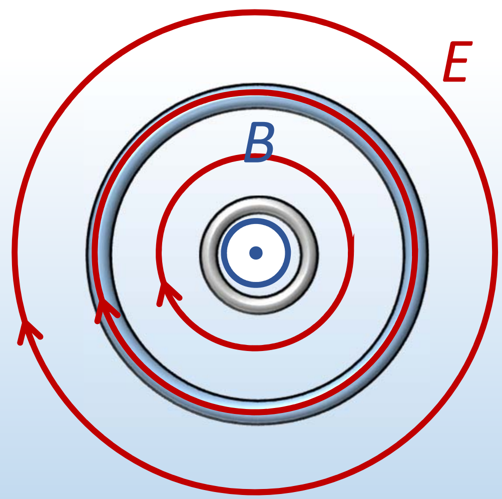
EM induction revisited

By Lenz's law, if *B* field from solenoid increases, a clockwise current flows around loop. What drives current around loop?

It actually does not matter the size of the loop, or even if there is a loop at all!



Side view



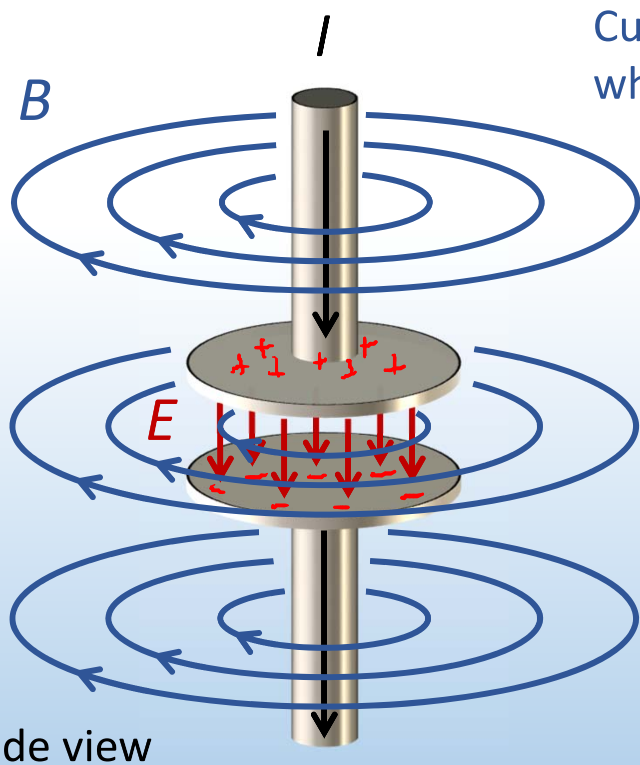
Top view

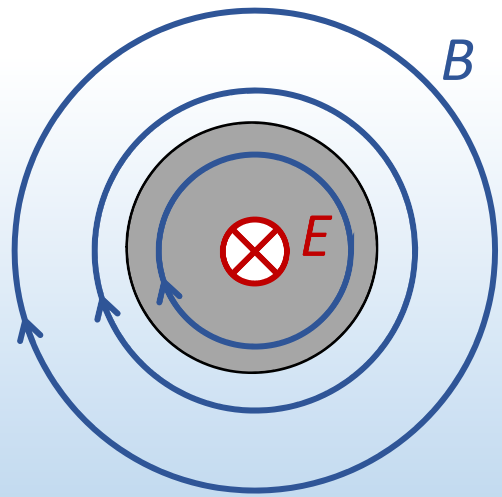
Changing *B* field generates a *E* field

Changing E field creates B field?

Imagine two wires connected to a capacitor. Current drives charge on capacitor plates, increasing *E* field between plates.

Current generates *B* field around wires, but what about between capacitor plates?

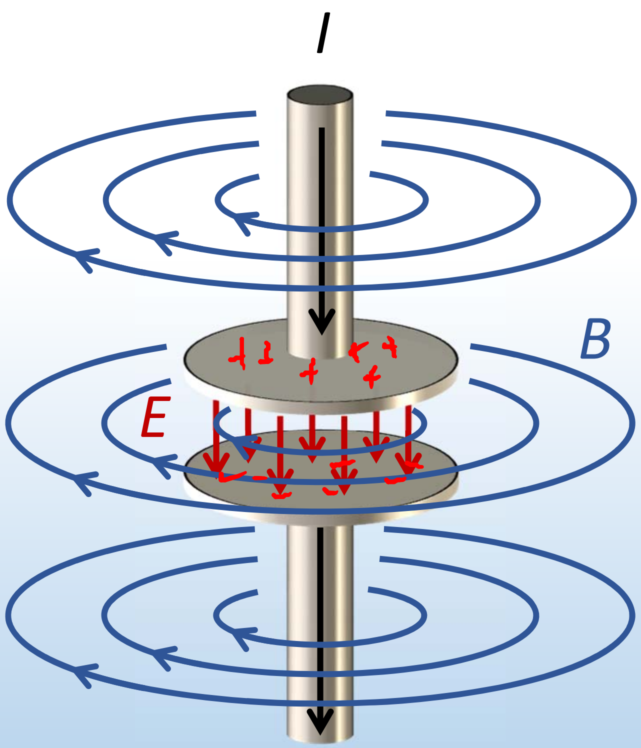




Changing *E* field generates a *B* field

ACT: E fields create B fields

What are the E & B field magnitudes around the wires and capacitor plates after a long time charging?



Side view

Recall Lect. 9

After a while, capacitor is fully charged, so:
$I = 0$ in wires, and $|B| = 0$ around wires
$|E| > 0$ and *constant*, $|B| = 0$ around plates

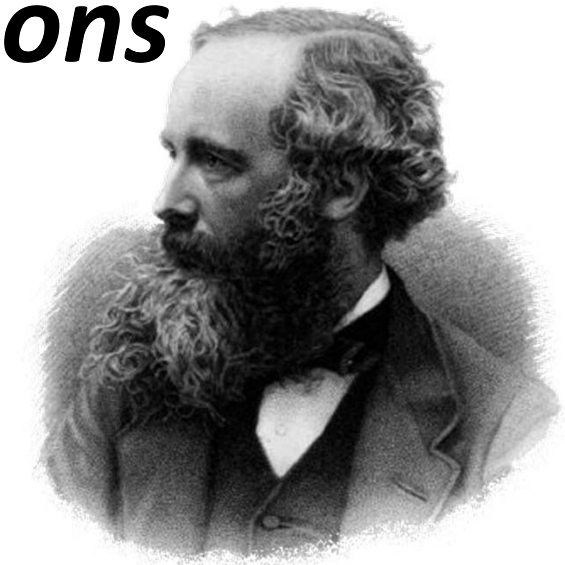
A. $|E| > 0$, $|B| > 0$

B. $|E| = 0$, $|B| = 0$

C. $|E| = 0$, $|B| > 0$

D. $|E| > 0$, $|B| = 0$

Maxwell's equations



James Maxwell
(1831-1879)

4 laws unify electricity & magnetism:

1. *E* field generated by electric charge
   (Gauss' Law – Lecture 3)
2. No magnetic charge
   (Lecture 10)
3. *E* field generated by changing magnetic flux
   (Faraday's Law – Lecture 14)
4. *B* field generated by moving electric charge
   <u>& changing electric flux</u>
   (Ampere-Maxwell Law – Lecture 12 & 15)

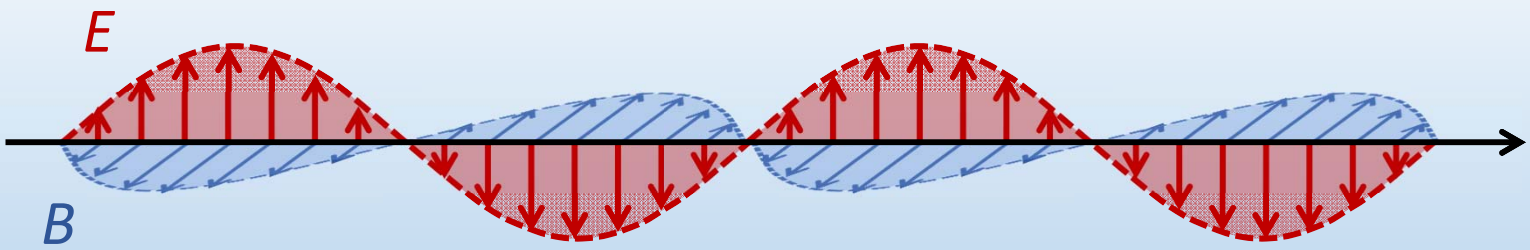
Electromagnetic waves

To recap:

3. Changing *B* field creates *E* field (even in absence of charges)

4. Changing *E* field creates *B* field (even in absence of currents)

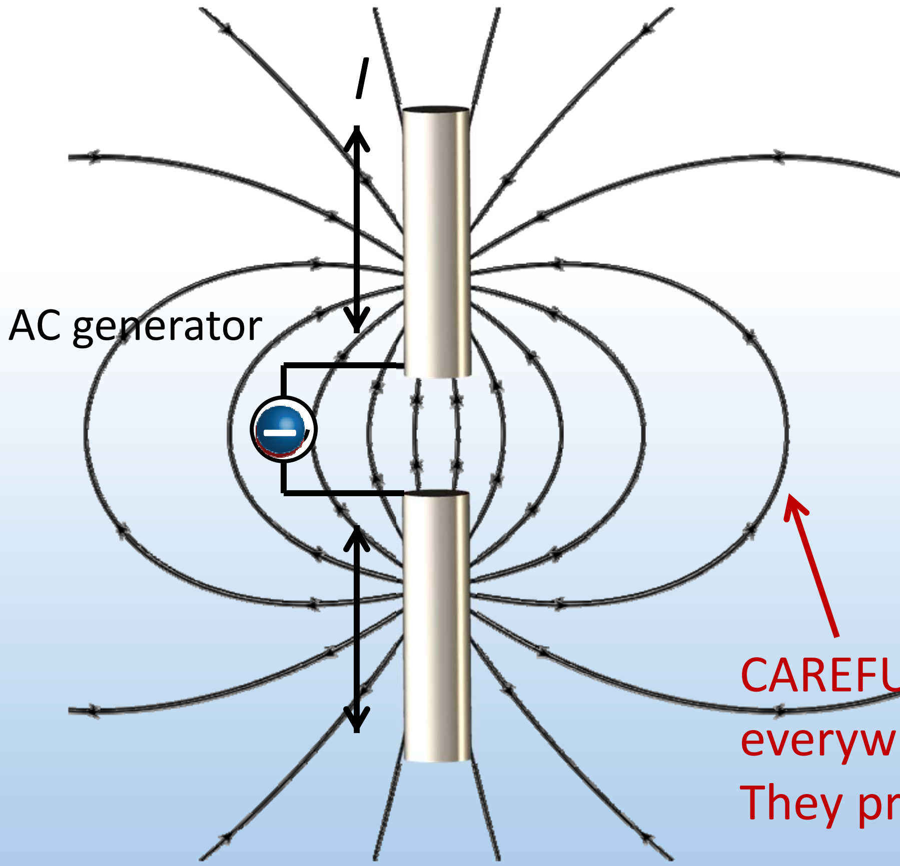
It should be possible to establish a <u>*self-sustaining*</u> *E* and *B* field in empty space. Don't need charges or currents!

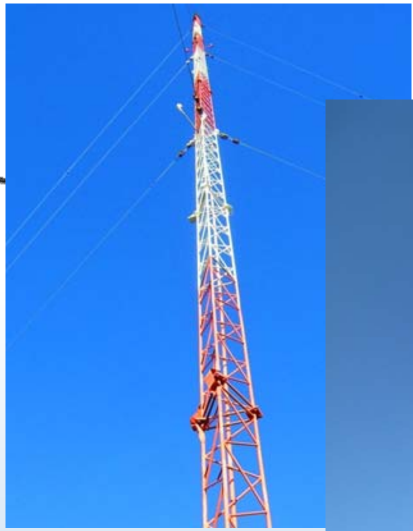


This is achieved by <u>*electromagnetic waves*</u> (light!): oscillating *E* and *B* field propagating in space and time

Antennas

Electric dipole antennas create oscillating *E* fields by oscillating + and – charge   Oscillating *E* field generates oscillating *B* field

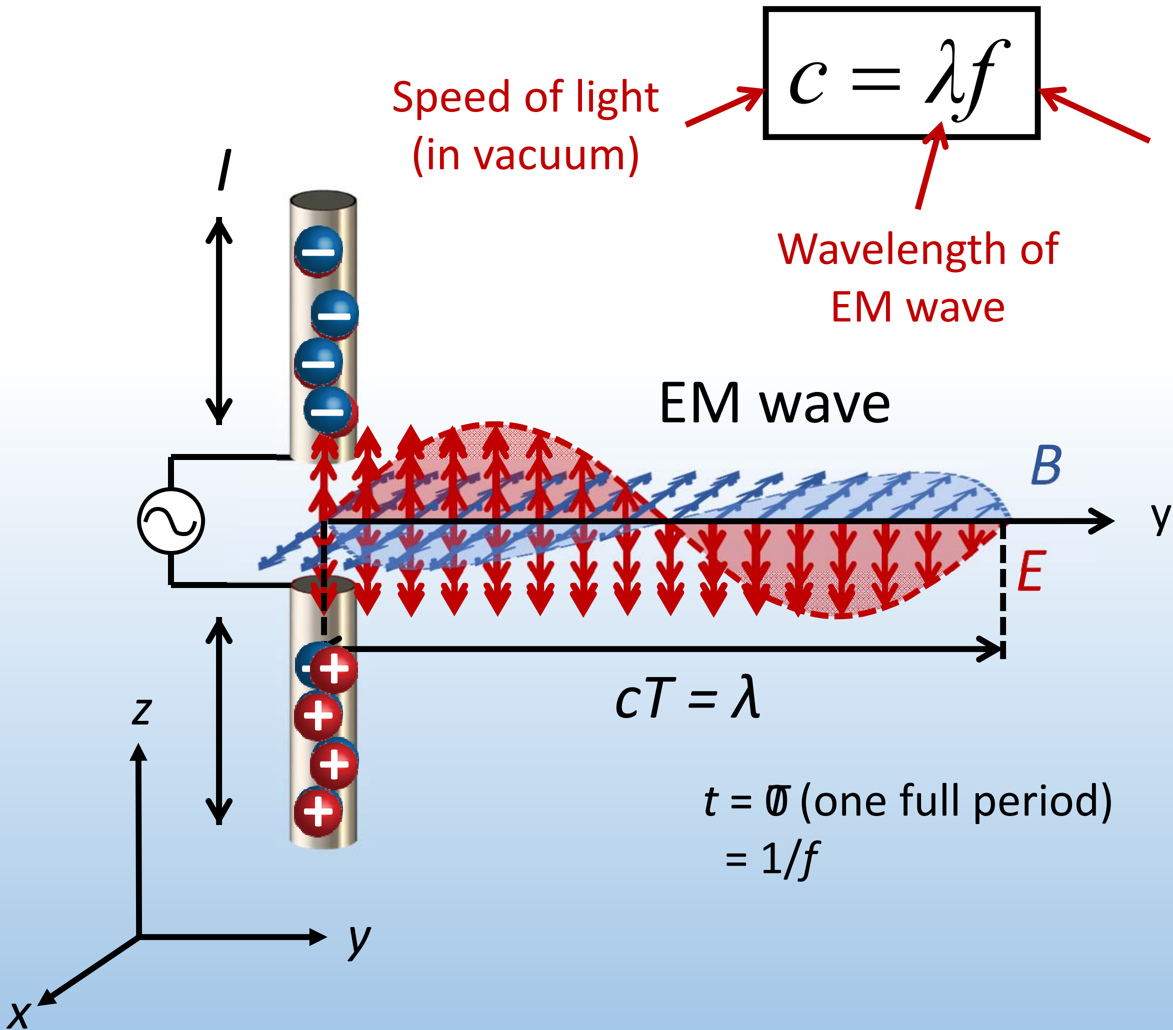


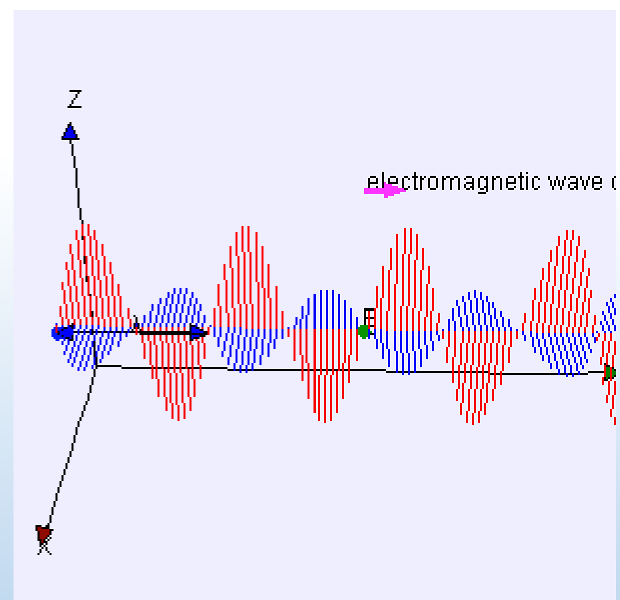


CAREFUL! *E* & *B* fields do NOT appear everywhere in space instantaneously! They propagate at a *finite speed c*

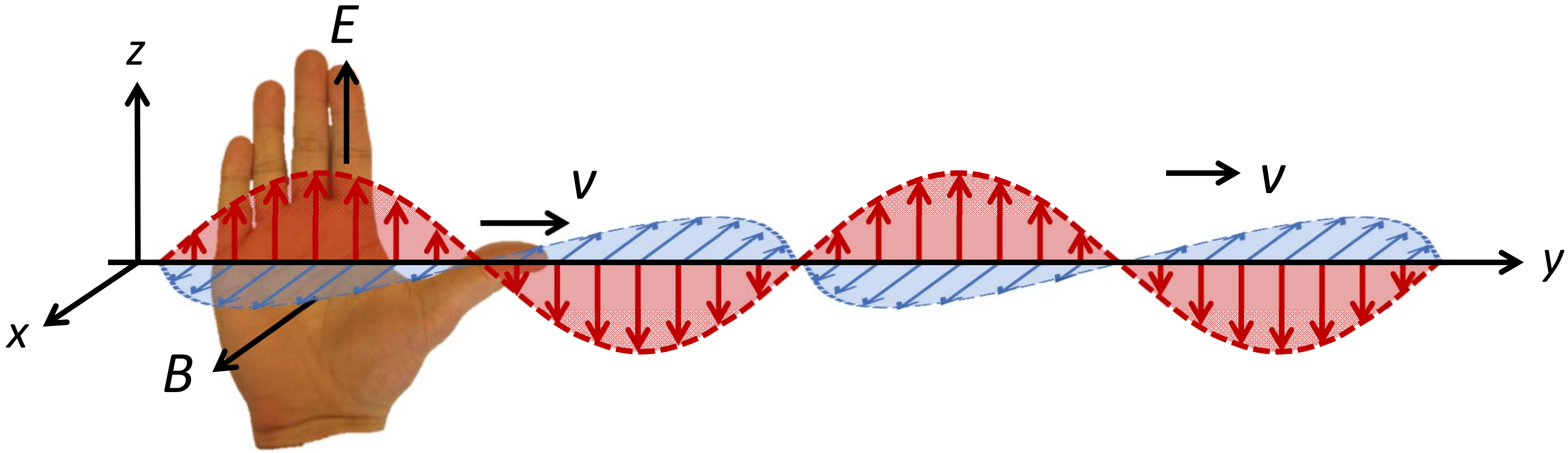
Electromagnetic radiation

Antenna generates oscillating *E* and *B* fields. Look along *y* axis:





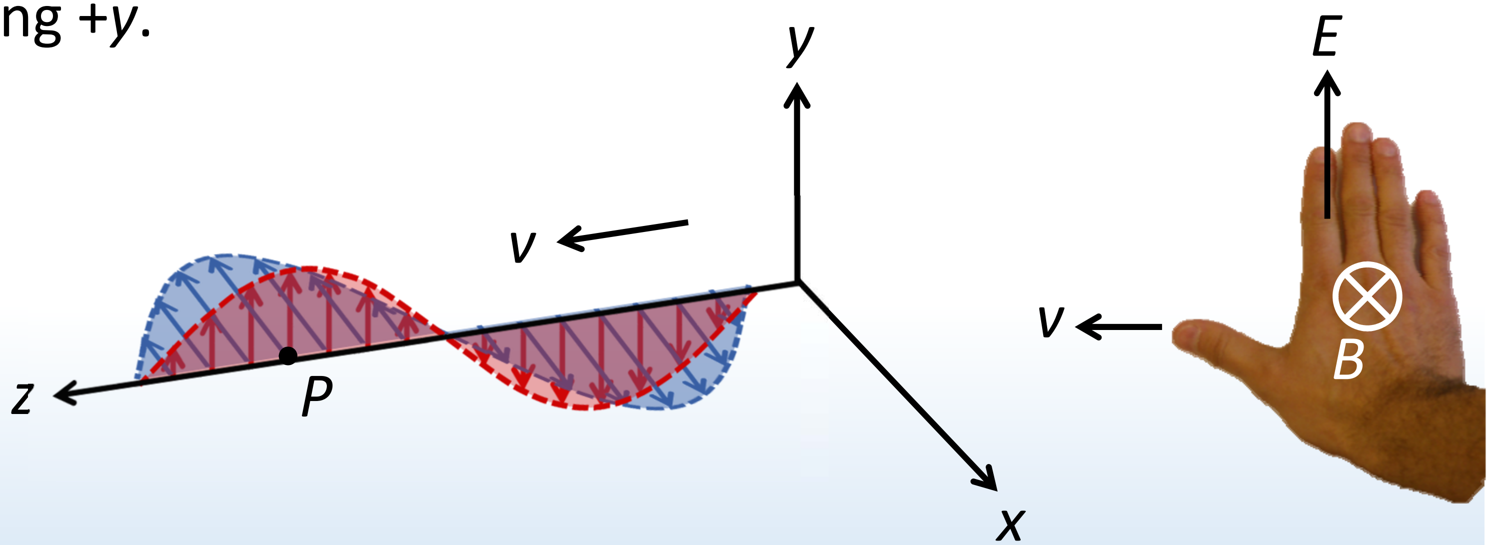
CheckPoint 1.1-1.4: EM waves



- EM wave can propagate in vacuum at speed *v* = *c* — 60%
  No charges or current loops necessary for propagation
- *f* and *λ* of EM wave are related $c = \lambda f$
- *E* and *B* oscillate ***in phase*** and are proportional — 43%
  E & *B* field increase and decrease at same times $E = cB$ — 70%
- *E* and *B* are ⊥ to each other and propagation direction — 76%
  Right hand rule: Thumb along $\vec{v}$
  Fingers along $\vec{E}$
  Out of palm $\vec{B}$

ACT: CheckPoint 2

An EM wave propagates along +*z*. At a point *P*, the *E* field points along +*y*.



In which direction does the *B* field point at *P*?

A. Along +*x* — 39%

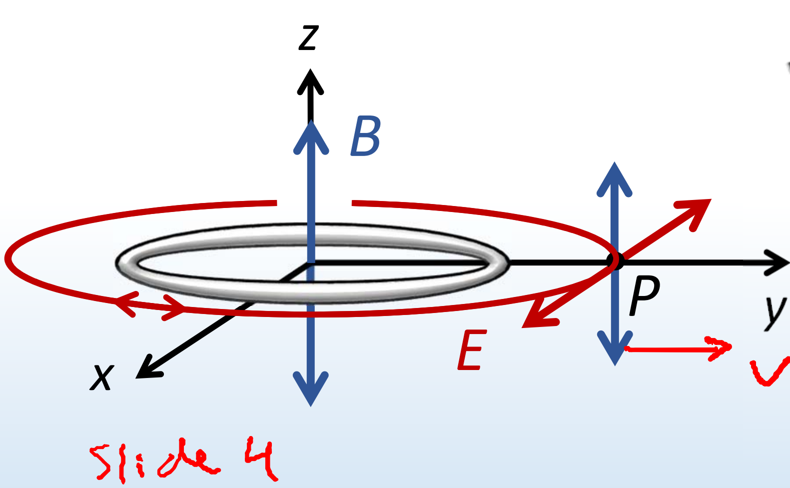
B. Along –*x* — 31%

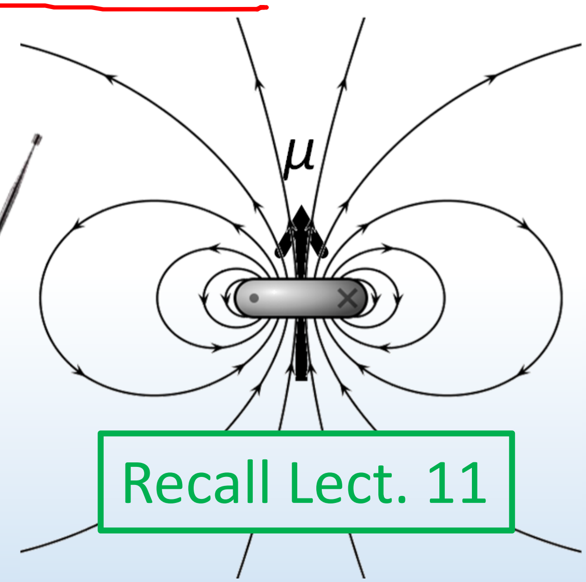
C. Along +*z* — 22%

D. Along –*z* — 8%

ACT: magnetic dipole antenna

Another way to generate an EM wave is to oscillate *current* around a loop. This is called a *magnetic dipole antenna*.





In which direction do the *E* and *B* fields oscillate at point *P*?

A. *B* along *z*, *E* along *x*

B. *B* along *x*, *E* along *y*

C. *B* along *y*, *E* along *z*

Speed of EM wave

Recall fundamental constants of electricity and magnetism:

$$\varepsilon_0 = 8.85\times10^{-12}\,\frac{C^2}{Nm^2}$$

"Permittivity of free space" (electricity)

$$\mu_0 = 4\pi\times10^{-7}\,\frac{Tm}{A}$$

"Permeability of free space" (magnetism)

Now multiply them:

$$\varepsilon_0\mu_0 = 8.85\times10^{-12}\,\frac{C^2}{Nm^2}\cdot 4\pi\times10^{-7}\,\frac{Tm\;Nm}{CAm/s\cdot C/s}$$

$$= 1.11\times10^{-17}\left(\frac{s^2}{m^2}\right)$$

Note:
1T = 1 Ns/Cm from *F* = *qvB* sin(θ)
1A = 1 C/s from *I* = Δ*Q*/Δ*t*

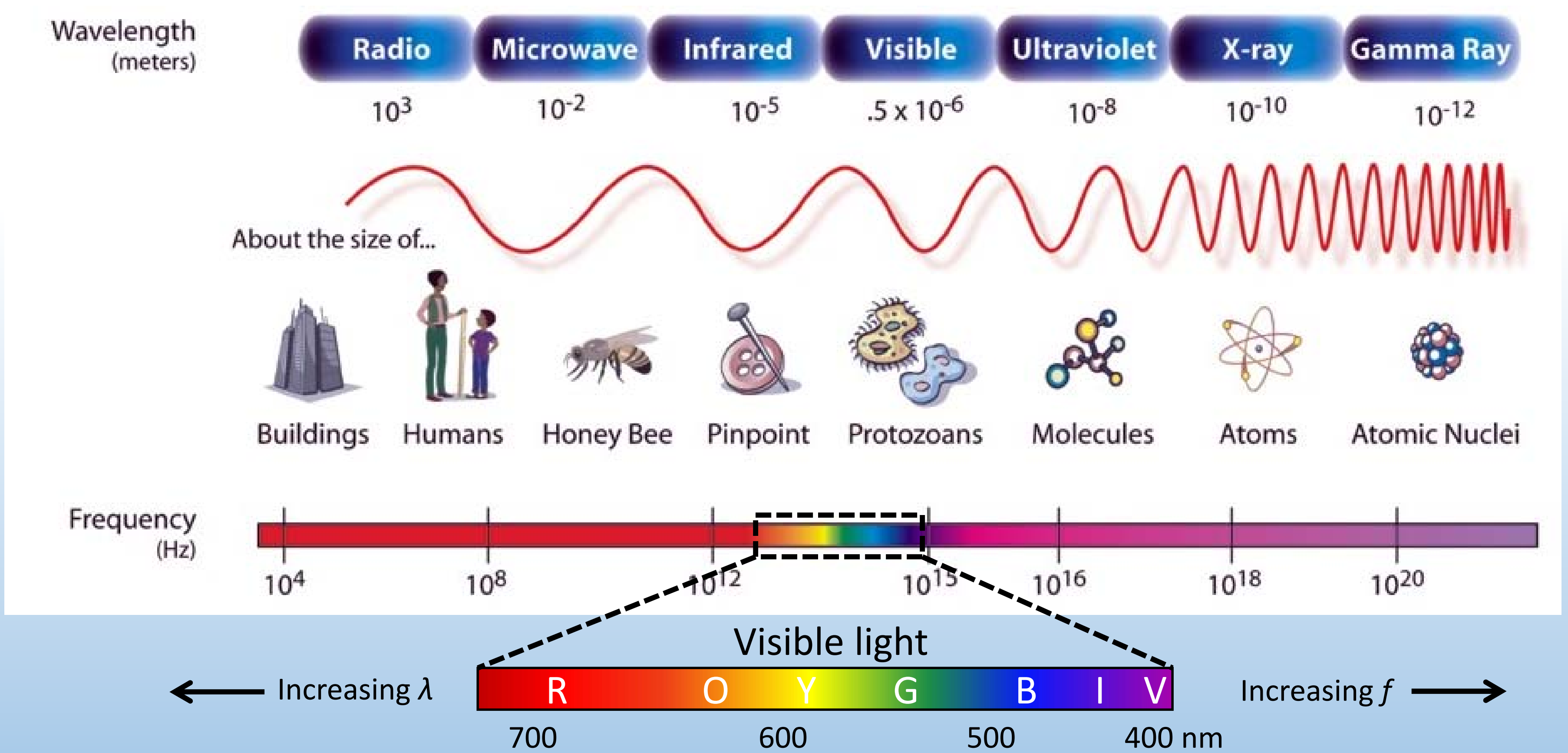
Speed of light in a vacuum →

$$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}} = 3.0\times10^{8}\,\frac{m}{s}$$

Electromagnetic spectrum

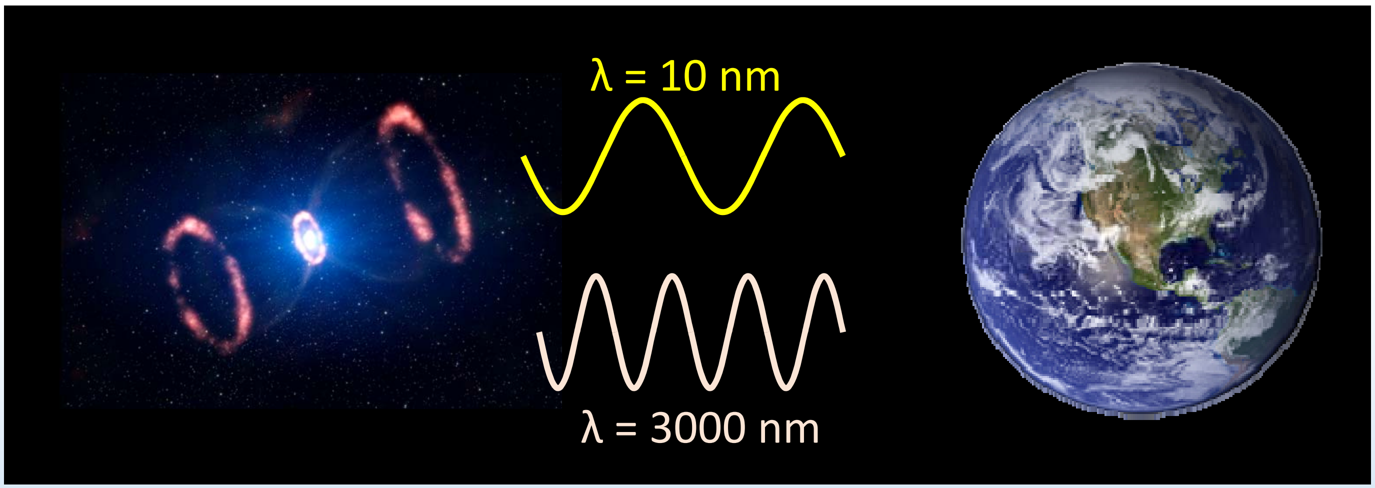
Radio waves, visible light, x-rays, etc. are ***all*** electromagnetic waves

$$c = \lambda f$$



ACT: Supernova

A distant star goes supernova and emits in the X-ray (λ = 10 nm) and infrared (λ = 3000 nm) regions of the EM spectrum.



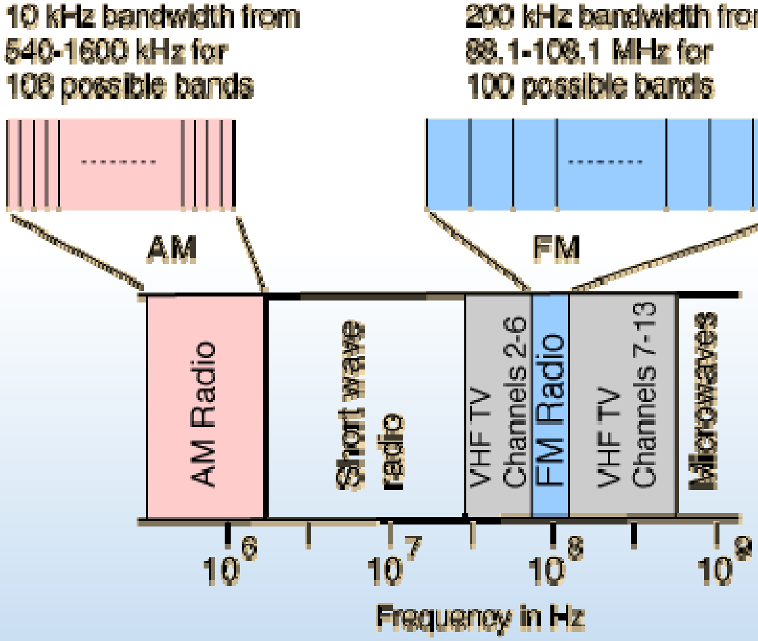
Which light reaches the earth first?

A. X-ray B. Infrared C. Both arrive at the same time

Speed of light *c* is the same for all wavelengths of light

Calculation: EM wavelength

The U of I radio station is WPGU 107.1 FM. At what wavelength does the station broadcast its radio waves?



107.1 FM = 107.1 MHz = 107.1×10^6 cycles/s

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{107.1\times10^6} = 2.8\,\text{m}$$

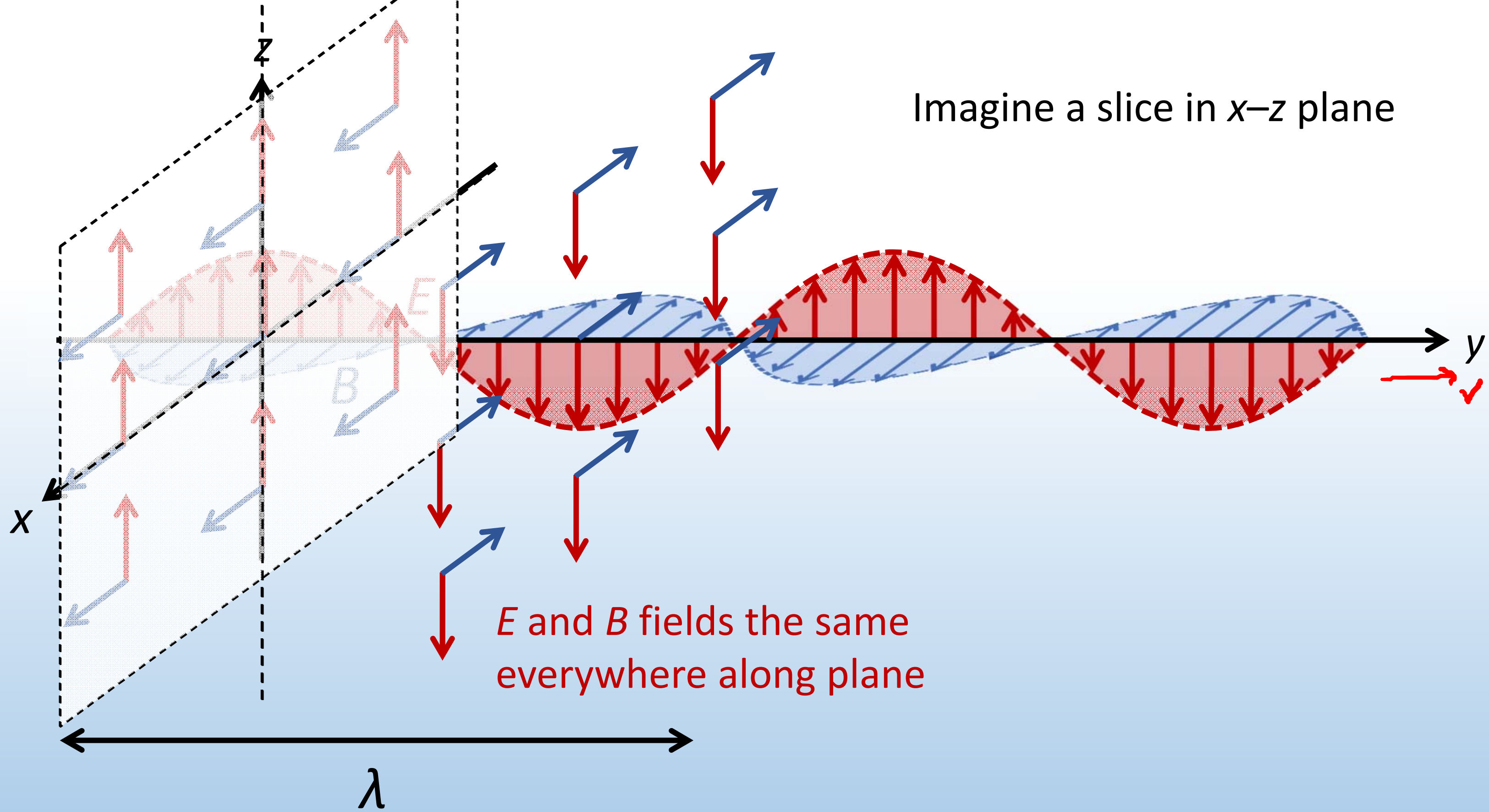
c = speed in vacuum. Air is not a vacuum, but close enough

For comparison, cell phones typically operate at 1.9 GHz

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{1.9\times10^9} = 16\,\text{cm}$$

Representing EM waves

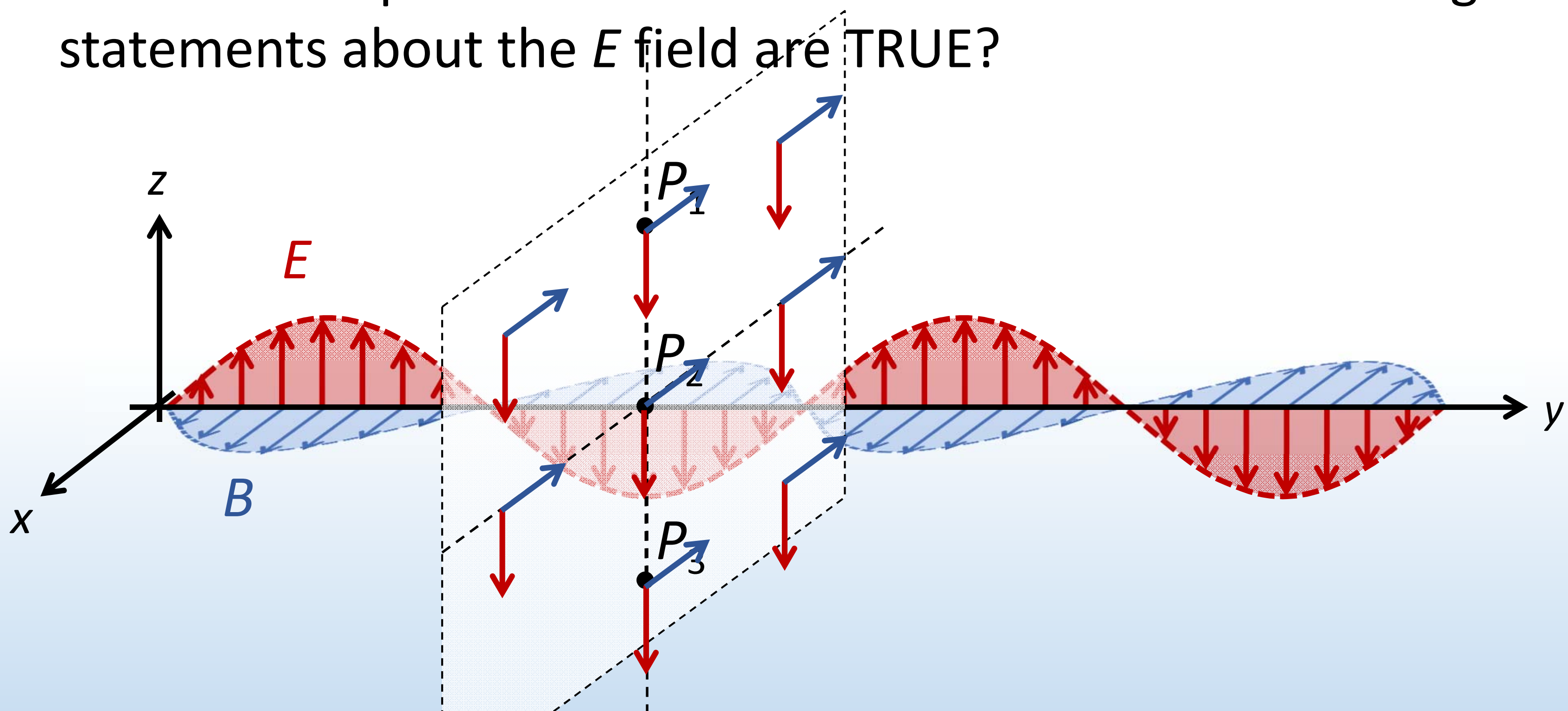
This picture represents EM wave along one line only (*y*-axis)
What about the rest of space?



Wavefront = surfaces at crests of EM wave

ACT: Plane wave

Consider the plane EM wave below. Which of the following statements about the *E* field are TRUE?



A. E is the same at point P_1, P_2, and P_3

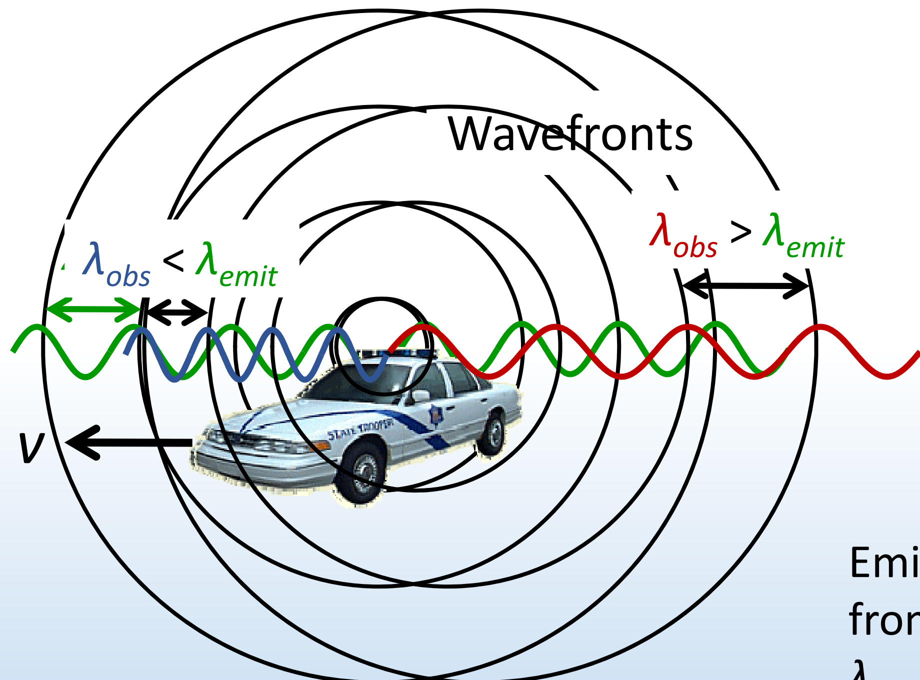
B. $E = 0$ at point P_2

C. $E = 0$ at point P_1 and P_3

Doppler effect

A parked police car emits light of wavelength λ_{emit}

Now the police car moves to the left. The observed wavelength λ_{obs} is different



Emitter moving ***toward*** observer: $v_{rel} > 0$, $\lambda_{obs} < \lambda_{emit}$, $f_{obs} > f_{emit}$

Emitter moving ***away*** from observer: $v_{rel} < 0$, $\lambda_{obs} > \lambda_{emit}$, $f_{obs} < f_{emit}$

$$f_{obs} = f_{emit}\sqrt{\frac{1+v_{rel}/c}{1-v_{rel}/c}} \approx f_{emit}\left(1+v_{rel}/c\right) \quad \text{If } v_{rel} << c$$

Observed frequency

Emitted frequency

Speed *relative* to observer

ACT: Doppler effect

You are driving at 85 mph along Highway 57. A police car is chasing you down at 100 mph.

$v_{Ferrari}$ = 85 mph

v_{police} = 100 mph

In your rearview mirror, the frequency of the light from the police car siren appears:

blue shift — redshift

A. Higher (more blue)

B. Lower (more red)

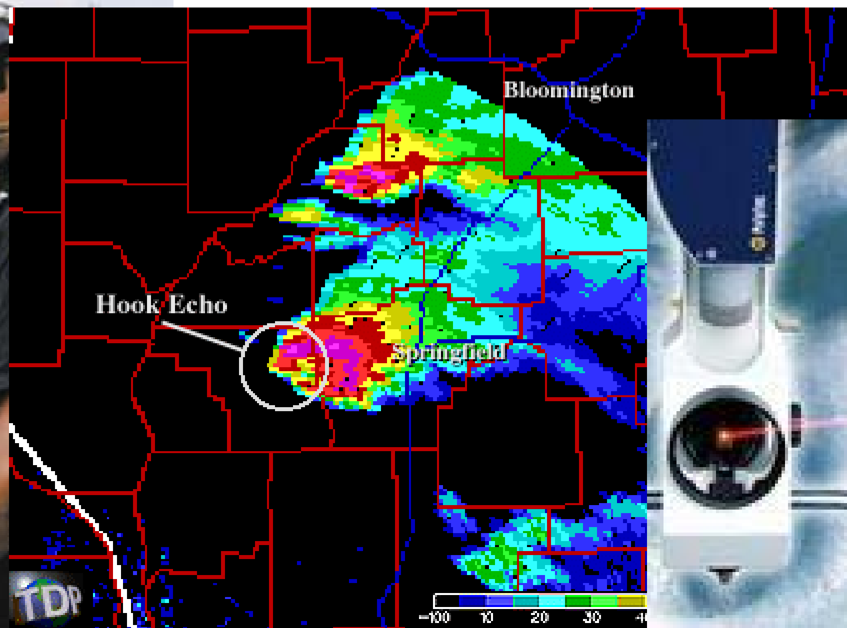
The police car is getting closer, so v_{rel} = 100 – 85 mph > 0

$$f_{obs} \approx f_{emit}\left(1+v_{rel}/c\right) > f_{emit}$$

Doppler velocimetry

Technique uses Doppler shift of EM wave in moving source to determine speed of source

Radar gun



Weather radar

Bio-acousto-mechanics

Summary of today's lecture

- Electromagnetic waves
  - Changing *B* field generates *E* field
  - Changing *E* field generates *B* field
  - *E* and *B* field propagate in space at speed of light *c*
- Properties of electromagnetic waves
  - Wavelength and frequency are related by $c = \lambda f$
  - *E* and *B* fields are always ⊥ each other & propagation direction
  - *E* and *B* fields always oscillate in phase & $E = cB$