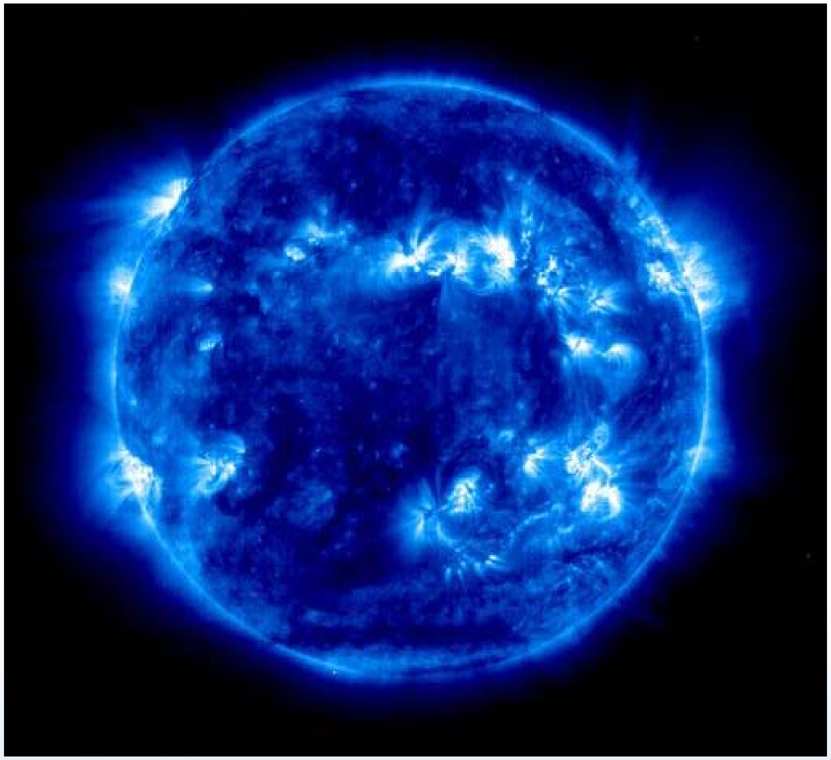


Phys 102 – Lecture 15

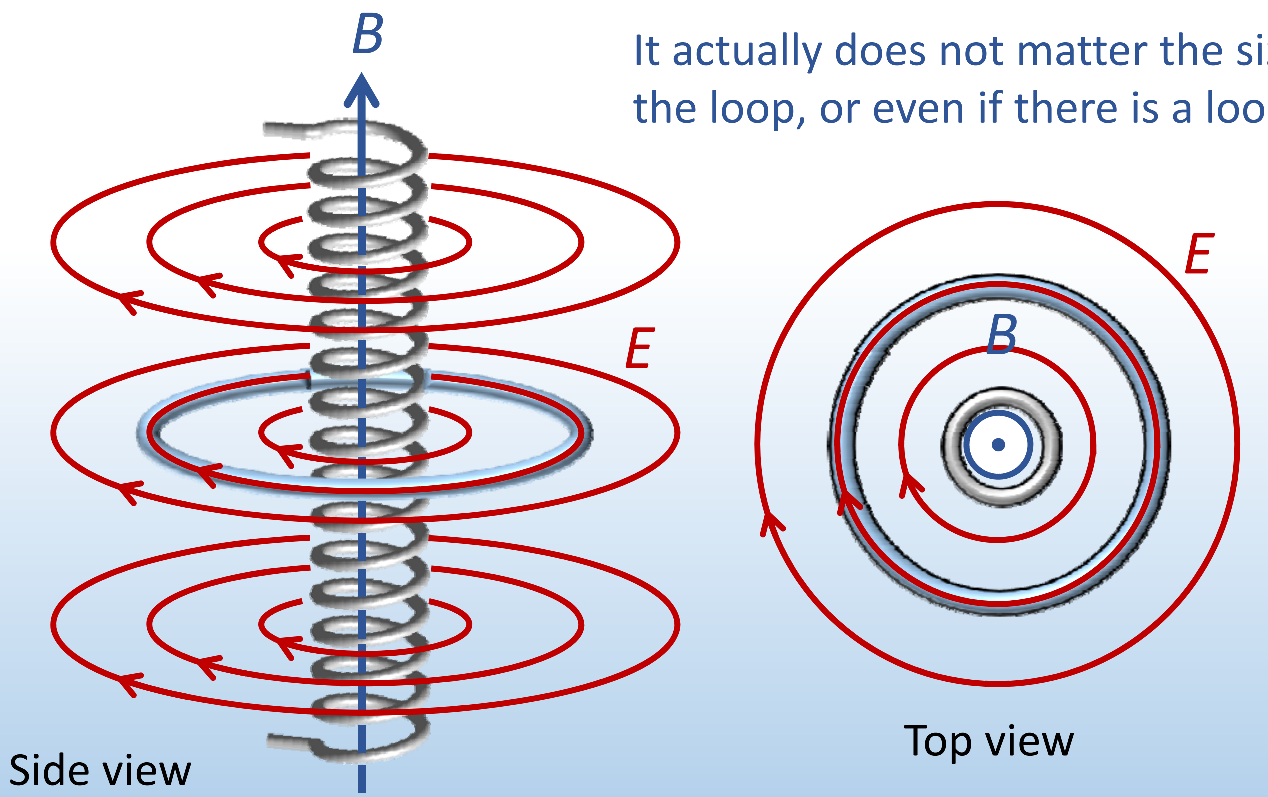
Electromagnetic waves

Today we will...

- Introduce/review several key concepts
  - Changing *B* field generates *E* field
  - 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?



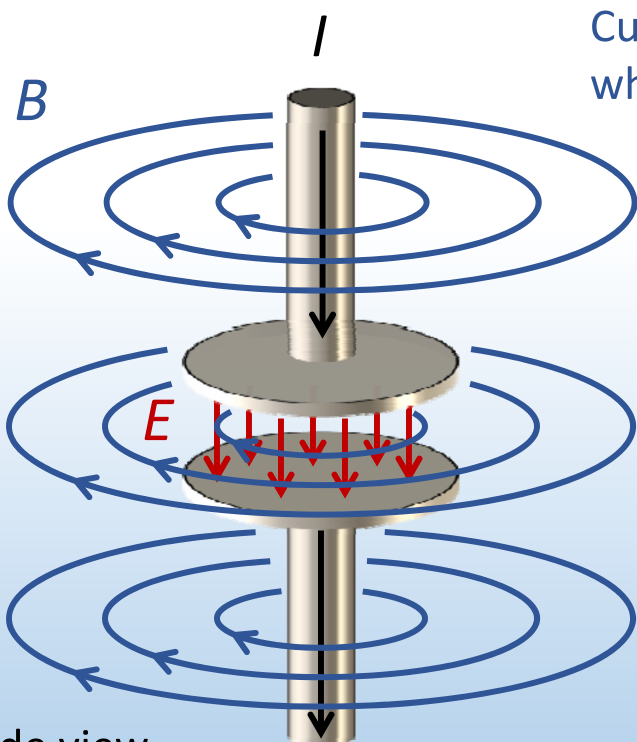
It actually does not matter the size of the loop, or even if there is a loop at all!

Changing *B* field generates a *E* field

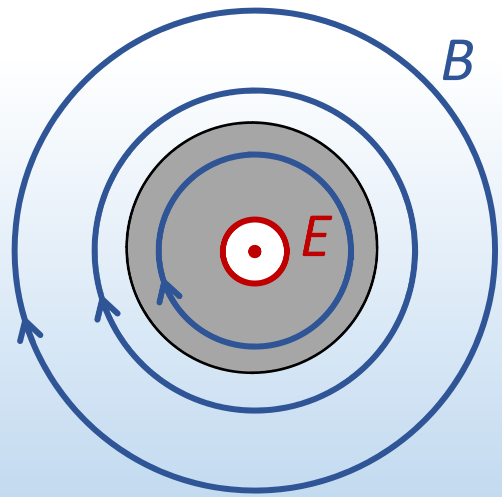
Changing E field creates B field?

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?



Side view

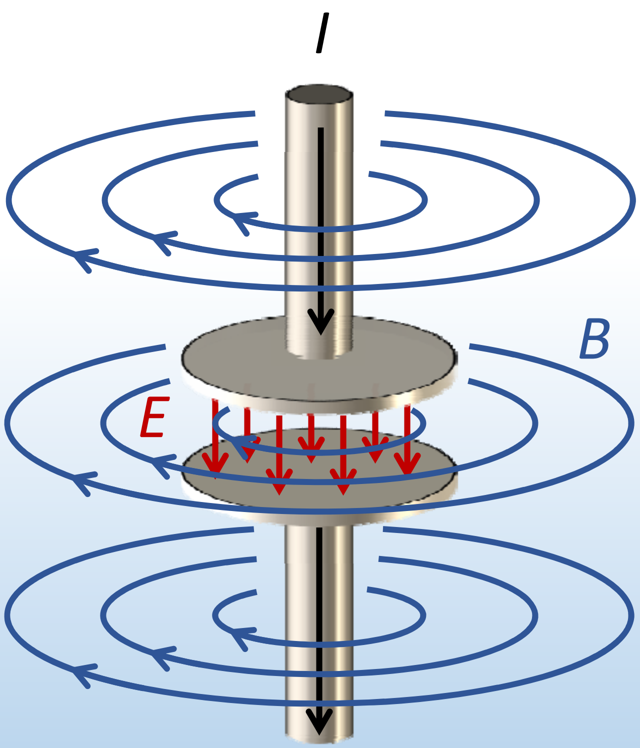


Top view

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

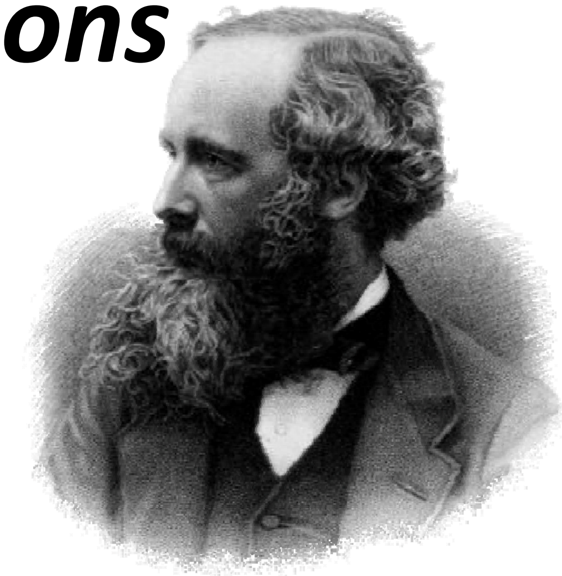
A. $|E| > 0$, $|B| > 0$

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:

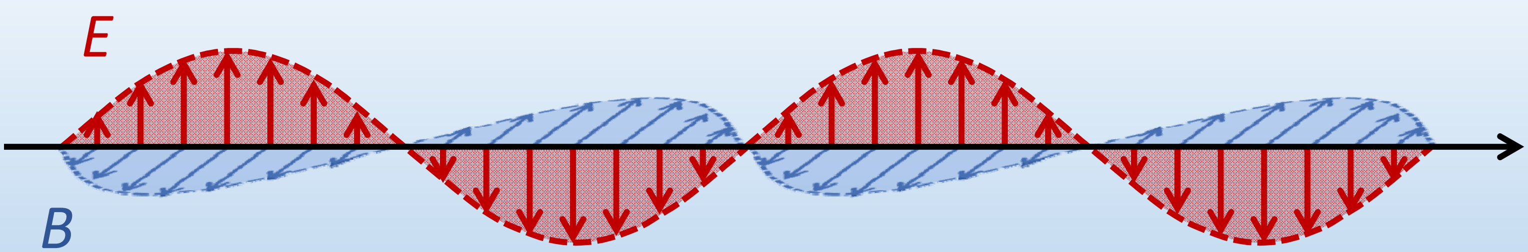
1. *E* field generated by electric charge
   (Gauss' Law – Lecture 3)
2. No magnetic charge
   (Lecture 10)
3. *E* field generated by changing magnetic flux
   (Faraday's Law – Lecture 14)
4. *B* field generated by moving electric charge
   <u>& changing electric flux</u>
   (Ampere-Maxwell Law – Lecture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

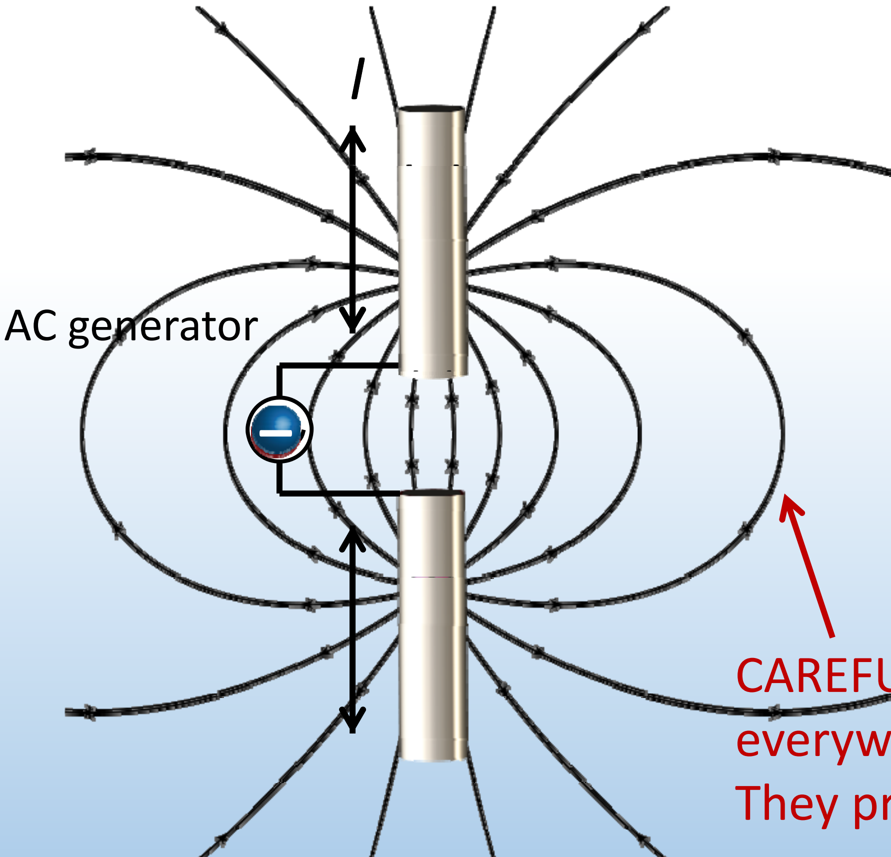
It should be possible to establish a ***self-sustaining*** *E* and *B* field in empty space. Don't need charges or currents!



This is achieved by ***electromagnetic waves*** (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



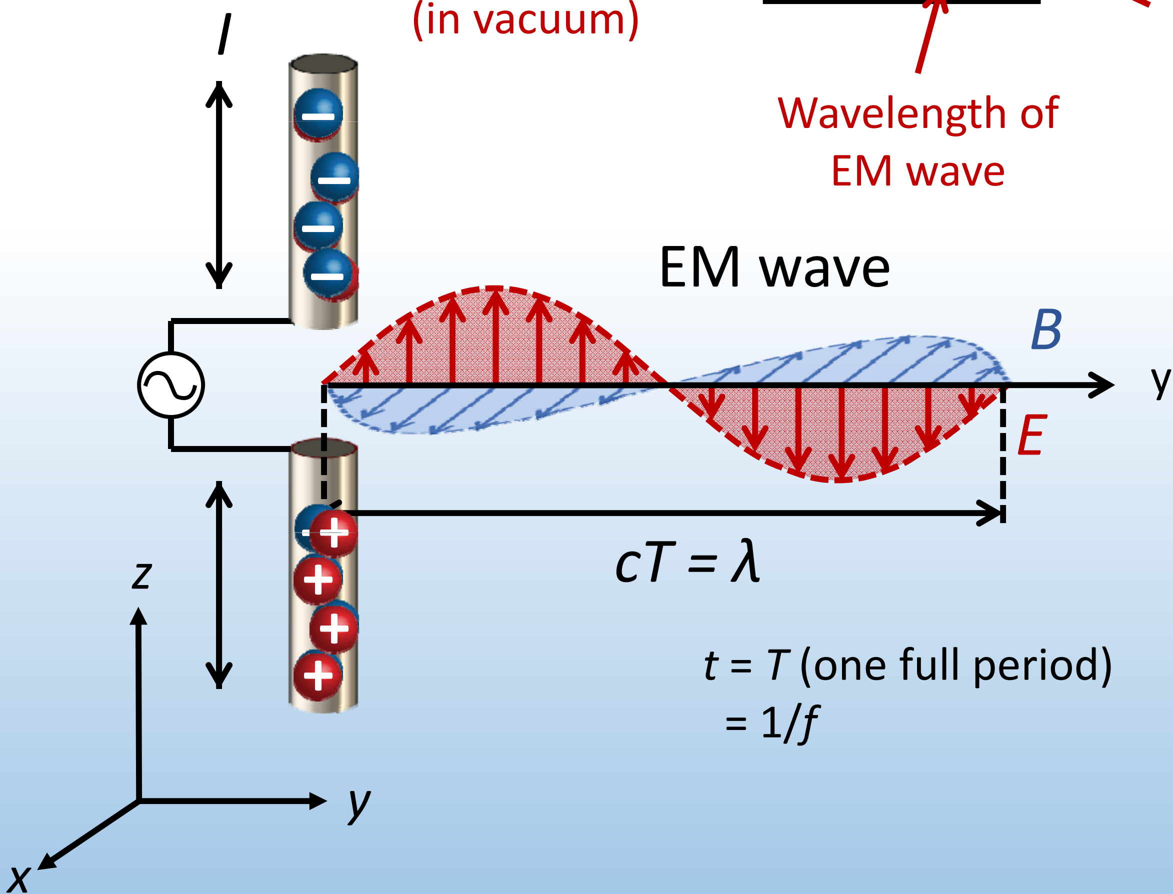
CAREFUL! E & B fields do NOT appear everywhere in space instantaneously! They propagate at a *finite speed c*

Electromagnetic radiation

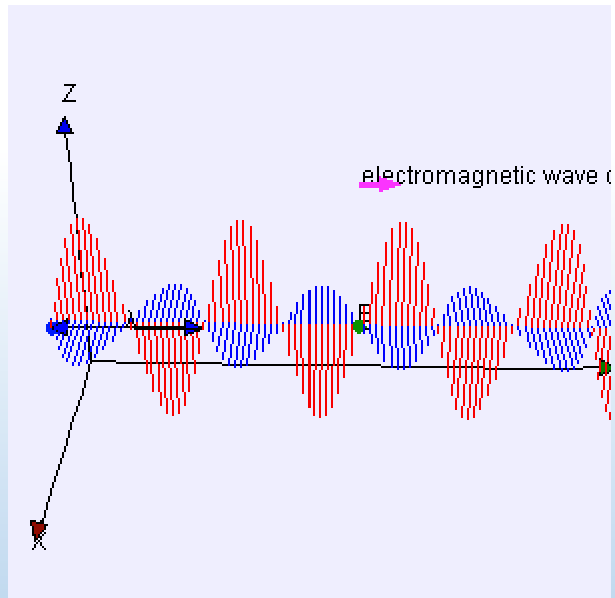
Antenna generates oscillating *E* and *B* fields. Look along *y* axis:

Speed of light (in vacuum) → $c = \lambda f$ ← Frequency of AC generator

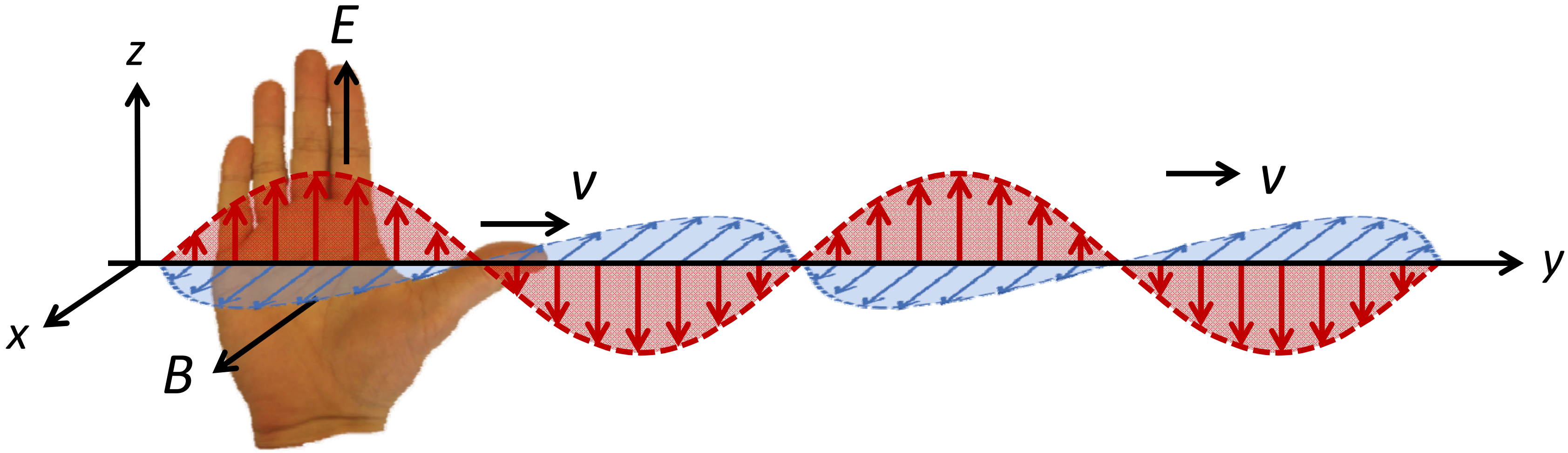
↑ Wavelength of EM wave



$t = T$ (one full period)
$= 1/f$



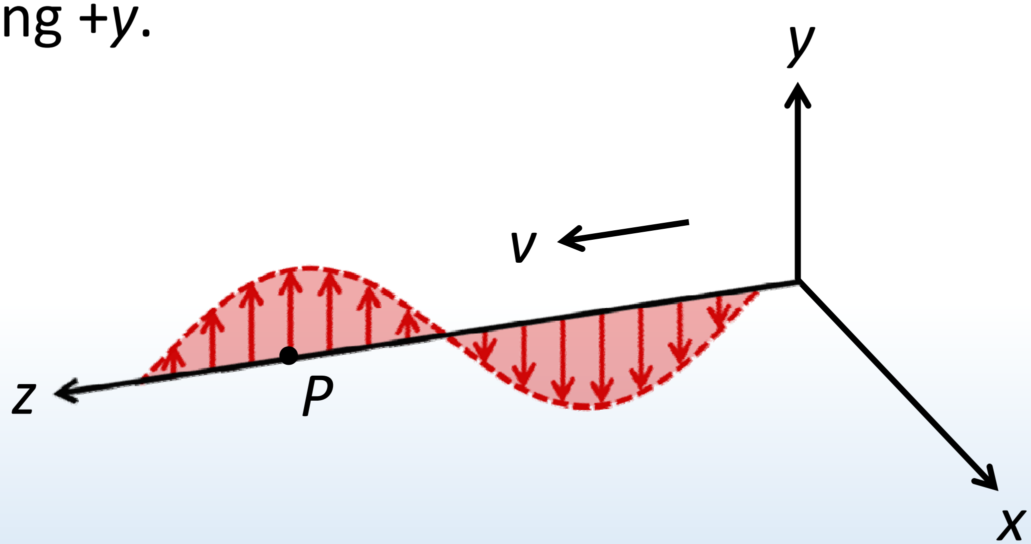
CheckPoint 1.1-1.4: EM waves



- EM wave can propagate in vacuum at speed *v* = *c*
  - 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
  - *E* & *B* field increase and decrease at same times $E = cB$
- *E* and *B* are $\perp$ to each other and propagation direction
  - 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*.

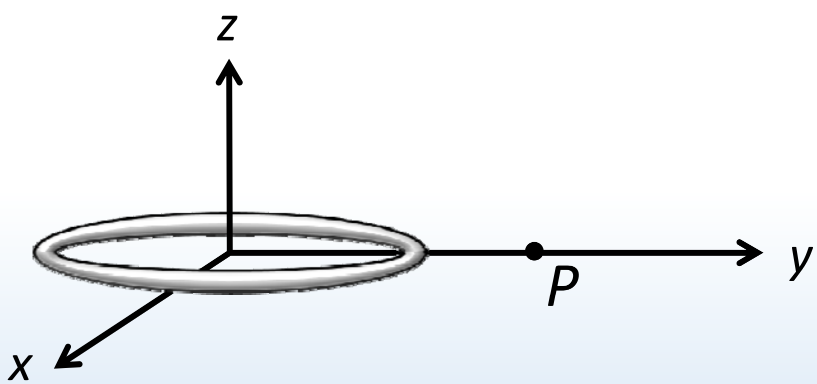


In which direction does the *B* field point at *P*?

A. Along +*x* B. Along –*x* C. Along +*z* D. Along –*z*

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:

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

$$= 1.11\times10^{-17}\,\frac{s^2}{m^2}$$

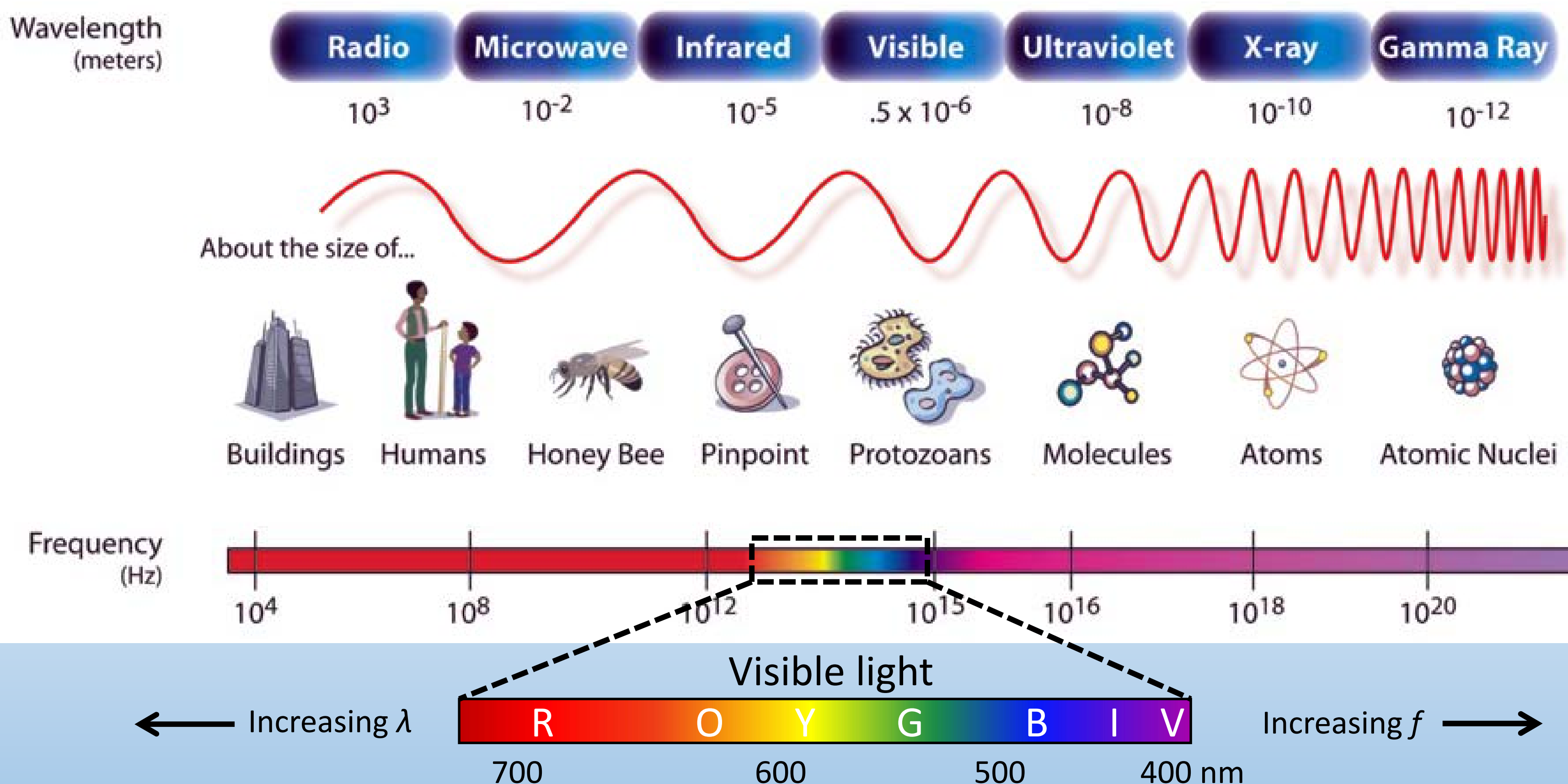
Speed of light in a vacuum →

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

Electromagnetic spectrum

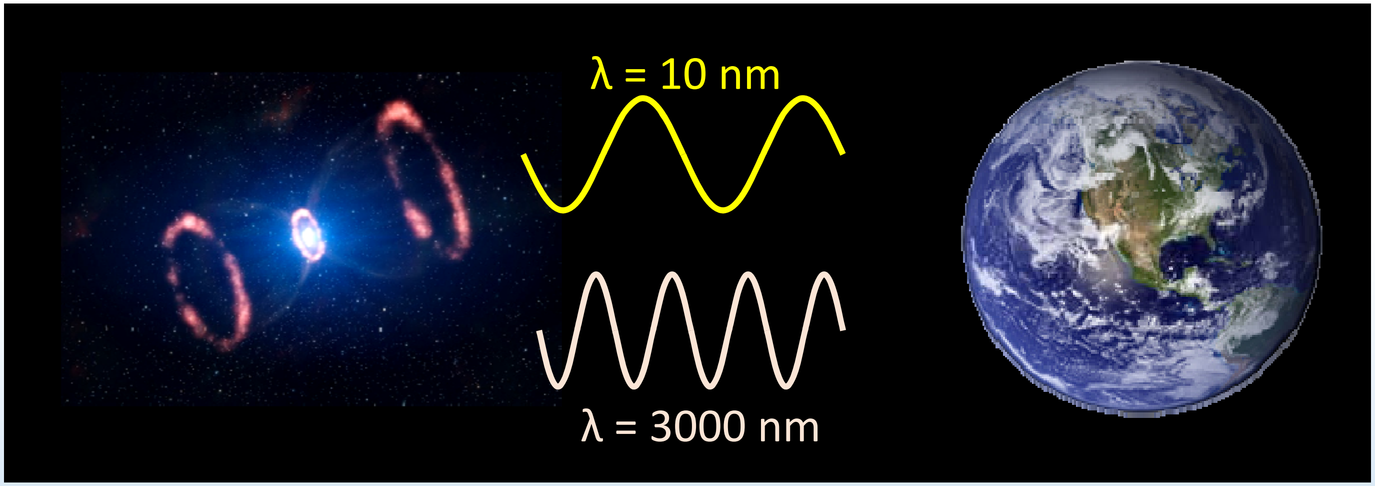
Radio waves, visible light, x-rays, etc. are <u>*all*</u> electromagnetic waves

$$\boxed{c = \lambda f}$$



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?

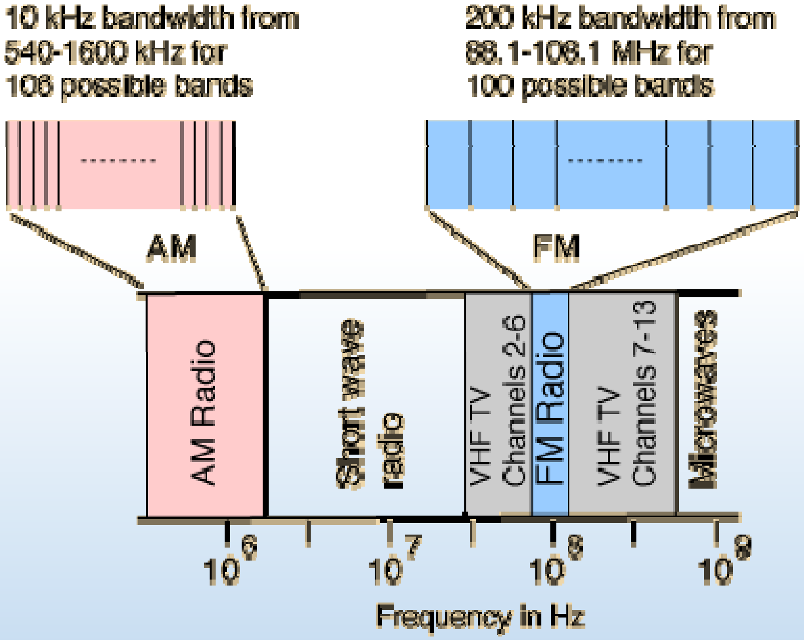
A. X-ray

B. Infrared

C. Both arrive at the same time

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

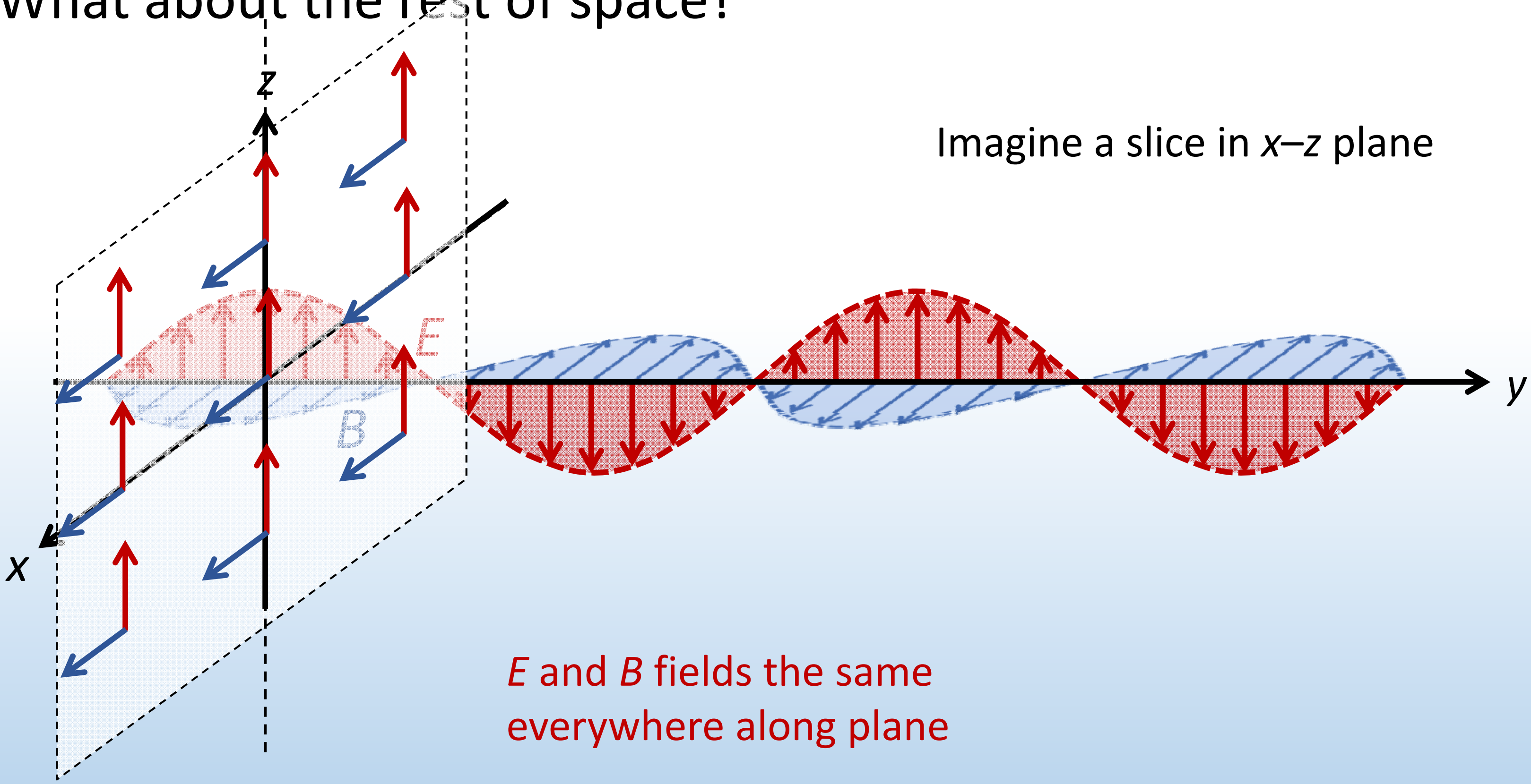
$$\lambda = \frac{c}{f} = \frac{3\times10^{8}}{107.1\times10^{6}} = 2.8\,\mathrm{m}$$

For comparison, cell phones typically operate at 1.9 GHz

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

Representing EM waves

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



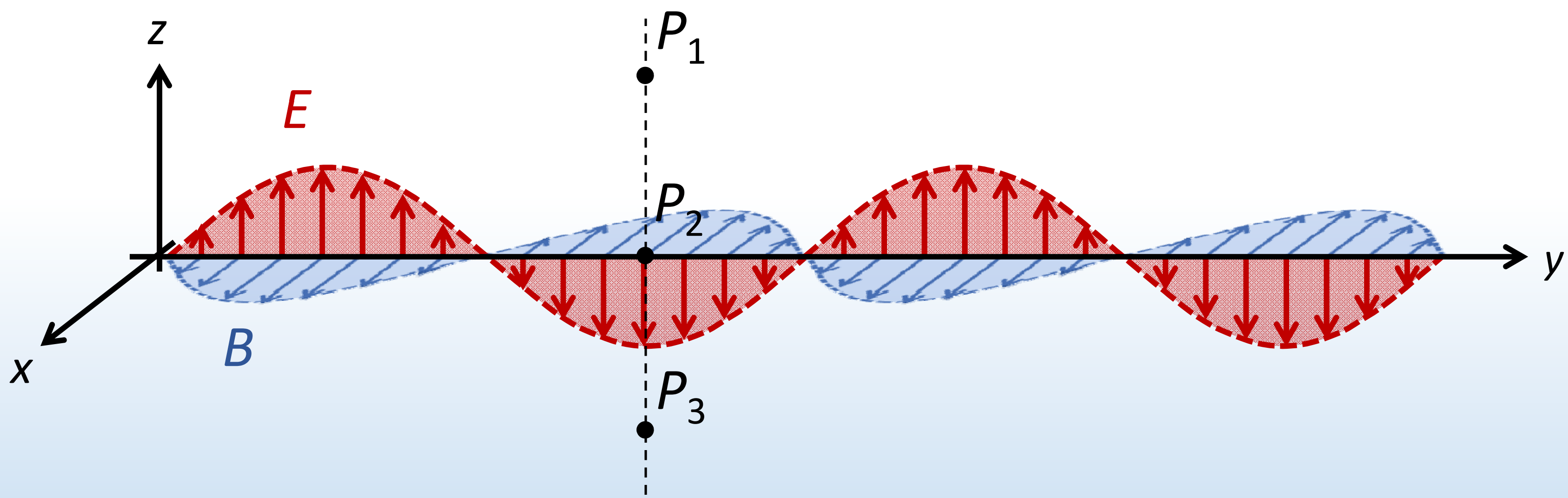
Imagine a slice in *x*–*z* plane

E and *B* fields the same everywhere along plane

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?



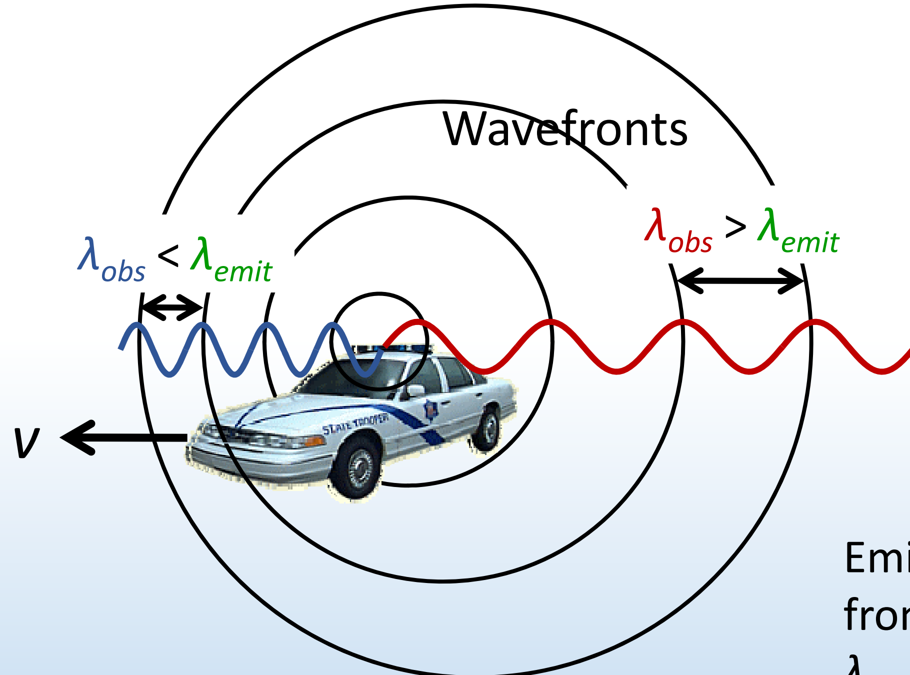
A. E is the same at point P_1, P_2, and P_3

B. $E = 0$ at point P_2

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

Doppler effect

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:

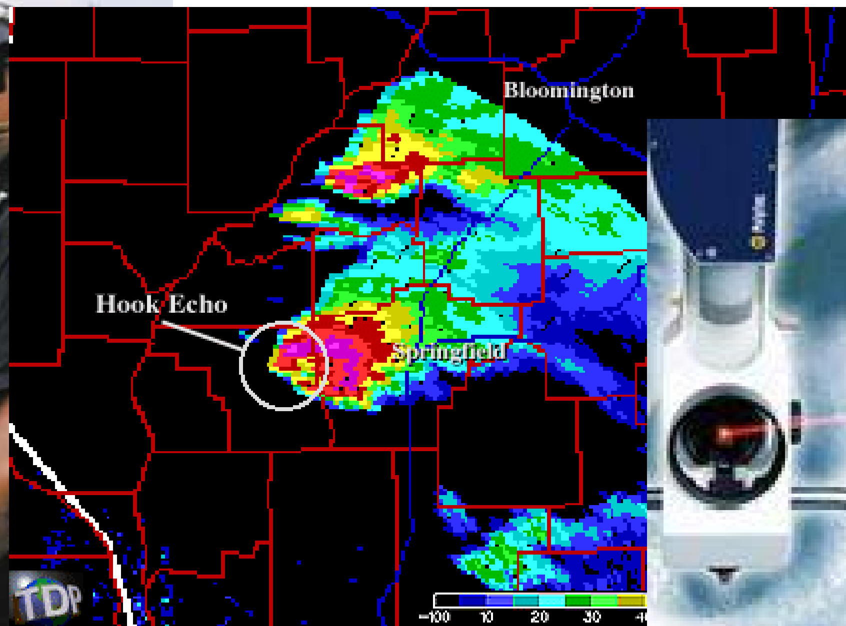
A. Higher (more blue)

B. Lower (more red)

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 $\perp$ each other & propagation direction
  - E and B fields always oscillate in phase & $E = cB$