Purdue University Department of Physics

Physics 21900

General Physics II

Electricity, Magnetism and Optics

Lecture 22 – Chapter 24.2-4

Electromagnetic Waves

Fall 2015 Semester

Prof. Matthew Jones

Maxwell's Equations

- All known fundamental properties of electricity and magnetism are summarized by the equations:

$$\oint_S \hat{n} \cdot \vec{E}\, dA = \frac{Q}{\epsilon_0}$$

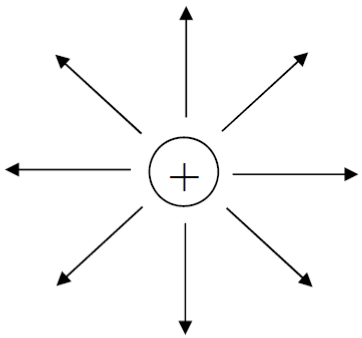
$$\oint_S \hat{n} \cdot \vec{B}\, dA = 0$$

$$\oint_C \vec{E} \cdot d\vec{\ell} = -\frac{d\phi_m}{dt}$$

$$\oint_C \vec{B} \cdot d\vec{\ell} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d\phi_e}{dt}$$

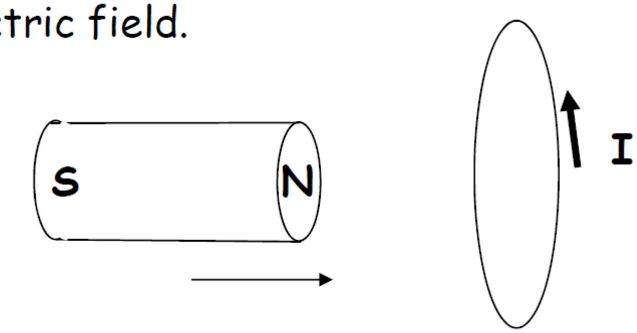
Maxwell's Equations

Stationary electric charges produce a steady electric field.



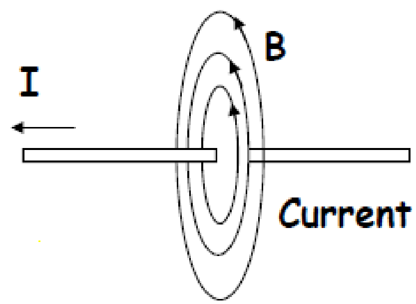
E diverges from point charge

A changing magnetic field produces an electric field.



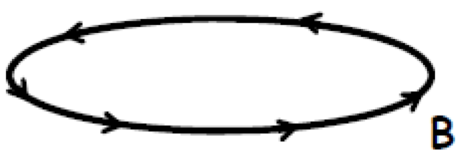
Changing B induces current

A magnetic field is produced by an electric current.



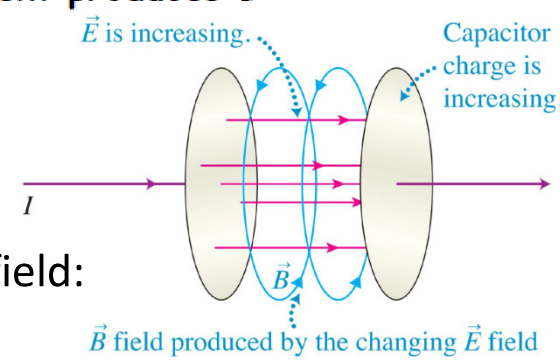
Current produces B

There are no magnetic charges.

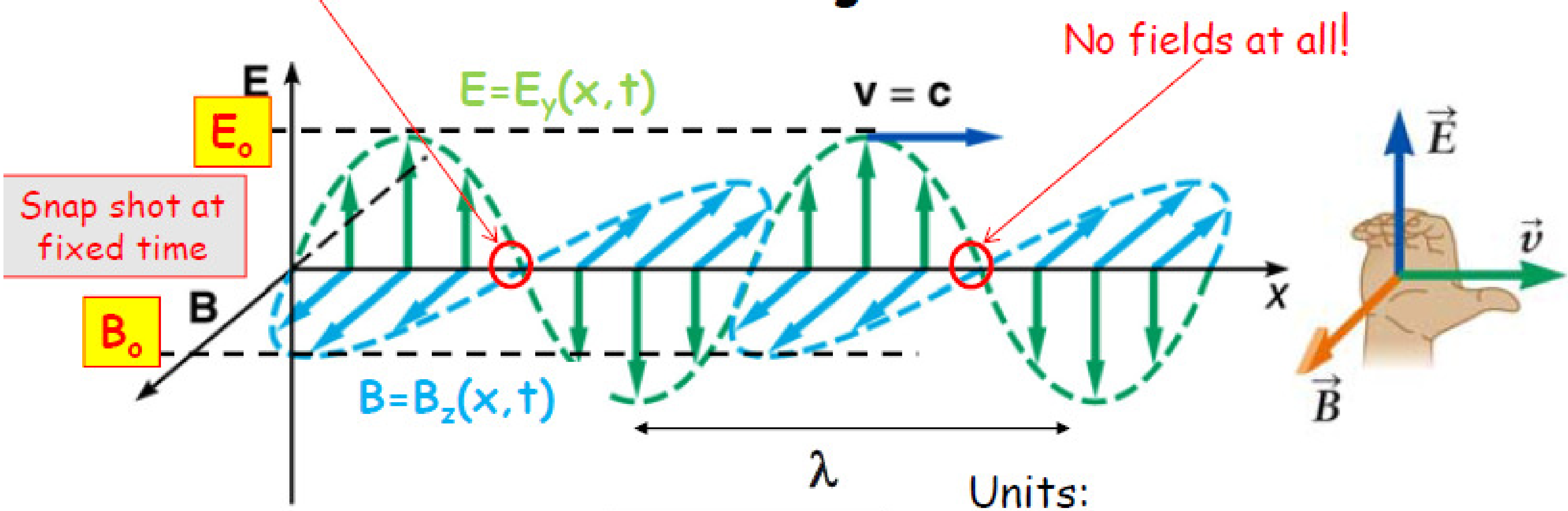


B is continuous in space

Maxwell hypothesized that a changing $\vec{E}$-field induces a $\vec{B}$-field:



Maxwell's Prediction: an Electromagnetic Wave



Relating f and λ: $c = f\,\lambda$

Units:
[c] in m/s; [λ] in m;
[f] in s^{-1} = Hz;
[T] =1/f in s

Relating E and B: $$\frac{E}{B} = c$$ (at any position and at any time)

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}} = \frac{1}{\sqrt{(8.85 \times 10^{-12}\, C^2/N \times m^2)(4\pi \times 10^{-7}\, T \times m/A)}} = 2.998 \times 10^8 \text{ m/s}$$

Equations for E_y and B_z

$$E_y(x,t) = E_{max}\sin\left(2\pi\left(\frac{t}{T} \pm \frac{x}{\lambda}\right)\right)$$

Depends on both time, t, and position, x.

$$B_z(x,t) = B_{max}\sin\left(2\pi\left(\frac{t}{T} \pm \frac{x}{\lambda}\right)\right)$$

+ means the wave travels to the left (-x)

- means the wave travels to the right (+x)

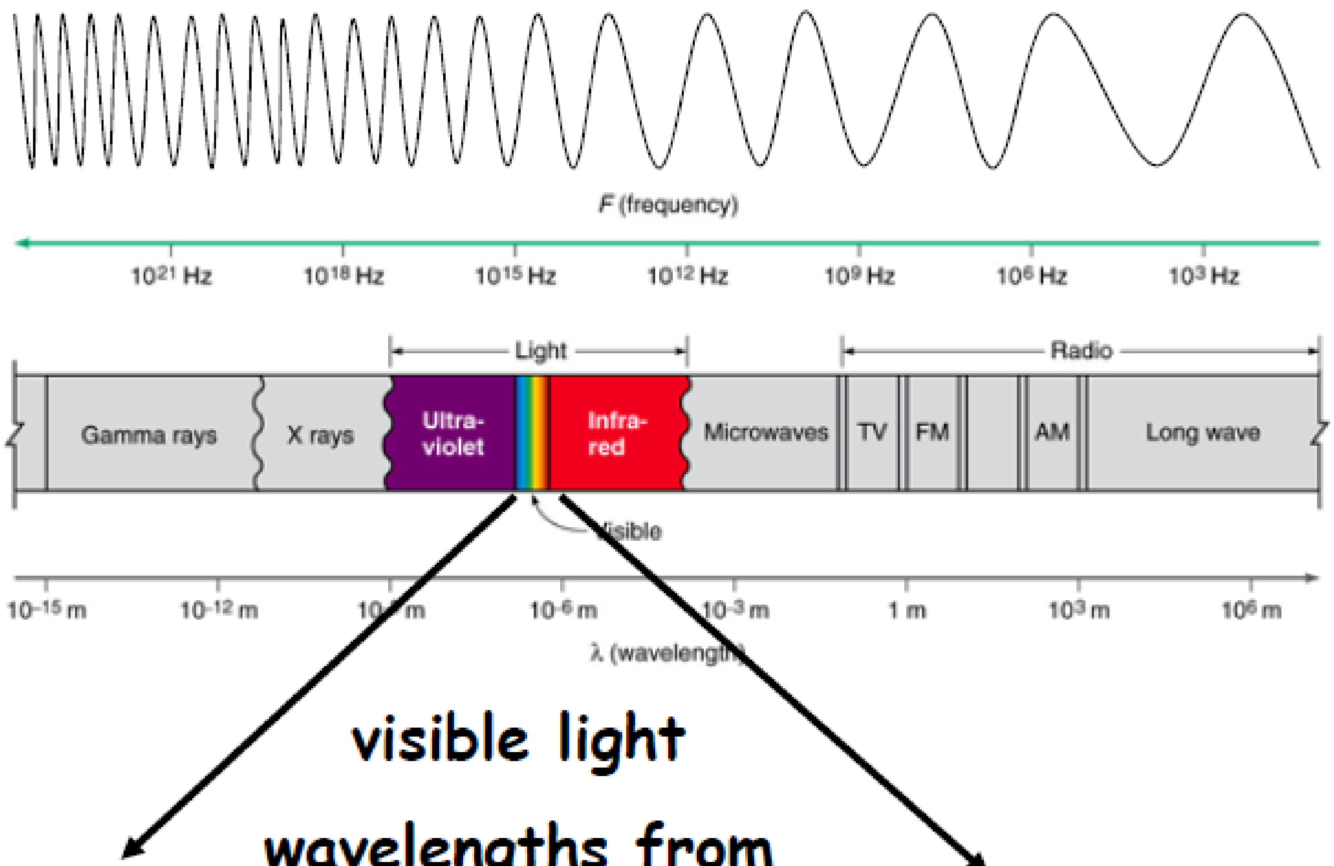
Notation

You must be able to distinguish between three closely-related concepts

Symbol	Meaning	Comment
$E_y(x,t)$; $B_z(x,t)$	Instantaneous values	Depends on exact location and time
E_o ; B_o (or E_{max}, B_{max})	Amplitude, maximum value	Amplitude of the EM wave
E_{rms} ; B_{rms}	Time-averaged values	Average rms of the EM wave

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

Maxwell's Prediction: the Electromagnetic *Spectrum* ($c = f\lambda$)



visible light

wavelengths from
~4×10^{-7} m to ~7.6×10^{-7} m

Examples

1. The radio station WBAA broadcasts at 890 kHz. What is the wavelength of the EM radio waves?

$$c = f\lambda$$

$$\lambda = \frac{c}{f} = \frac{3\times10^{8} m/s}{890\times10^{3} s^{-1}} = 337 \text{ m}$$

2. Cellular frequencies are the sets of frequency ranges within the ultra high frequency band (UHF) that have been allocated for cellular phone use. The ultra high frequency band is also shared with television, Wi-Fi and Bluetooth transmission. Many Global System for Mobile Communications (GSM) phones support three bands (900/1,800/1,900 MHz) (or 850/1,800/1,900 MHz). What is the wavelength of the 1,800 MHz band?

$$c = f\lambda$$

$$\lambda = \frac{c}{f} = \frac{3\times10^{8} m/s}{1800\times10^{6} s^{-1}} = 0.168 \text{ m}$$

Example 3: The frequency of an EM wave is 4.5x10^{14} Hz. The amplitude of the magnetic field is 6.0x10^{-4} Tesla.

- What is the period of the wave?

$$T = \frac{1}{f} = \frac{1}{4.5 \times 10^{14}\ Hz} = 2.2 \times 10^{-15}\ s$$

- What is the wavelength of the wave?

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^{8}\ m/s}{4.5 \times 10^{14}\ Hz} = 6.7 \times 10^{-7}\ m = 670\ nm$$

(A wavelength of 670 nm corresponds to red light)

- What is the amplitude of the oscillating electromagnetic field?

$$E_{max} = cB_{max} = (3.00 \times 10^{8}\ m/s)(6.0 \times 10^{-4}\ T) = 1.8 \times 10^{5}\ N/C$$

- Assuming light travels in the +x direction, write an equation for E_y, B_z

$$E_y(x,t) = (1.8 \times 10^{5}\ N/C) \sin\left[2\pi\left(\frac{t}{2.2 \times 10^{-15}\ s} - \frac{x}{6.7 \times 10^{-7}\ m}\right)\right]$$

$$B_z(x,t) = (6.0 \times 10^{-4}\ T) \sin\left[2\pi\left(\frac{t}{2.2 \times 10^{-15}\ s} - \frac{x}{6.7 \times 10^{-7}\ m}\right)\right]$$

Many Important Properties of an EM Wave

- No electric waves; no magnetic waves; ONLY EM waves
- Direction of E and B fields are perpendicular to each other AND to the direction of travel – TRANSVERSE WAVE
- Magnitude of E and B fields vary at a given point with time
- E and B fields occur simultaneously and have maxima and minima at SAME time and place – they are "IN PHASE"
- EM waves can have a fixed POLARIZATION (plane containing E field)
- EM waves can travel in a vacuum
- Speed of wave depends on properties of medium in which they travel
- EM waves can be absorbed, reflected, change direction
- EM waves carry energy and momentum
- EM waves exhibit INTERFERENCE effects (constructive and destructive)
- EM waves have a frequency and wavelength related by $c=f\lambda$ (ELECTROMAGNETIC SPECTRUM)

Maxwell predicts the velocity c of an EM wave

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}} = \frac{1}{\sqrt{(8.85 \times 10^{-12}\, C^2/N \times m^2)(4\pi \times 10^{-7}\, T \times m/A)}} = 2.998 \times 10^8 \text{ m/s}$$

Date	Investigator	Technique	distance	result
1600's	Galileo	Lanterns/hills	few km (?)	~10x faster than sound
1675	Roemer	Eclipse/Jupiter's moon	600 km	2×10^8 m/s
1728	Bradley	Stellar aberration	Inter-stellar	3.01×10^8 m/s
1849	Fizeau	Rotating toothed wheel	8.6 km	3.13×10^8 m/s
1862	Focault	Spinning mirror	35 km	299,790,000 m/s
1926	Michelson	Rotating 8-sided mirrored "wheel"	35 km	(299,798,000 ± 4000) m/s
today	International Agreement	Defined by length of 1 m	-	2.99792458×10^8 m/s

Discovery of Radio Waves


ELECTRIC WAVES

BEING

RESEARCHES ON THE PROPAGATION OF ELECTRIC ACTION WITH FINITE VELOCITY THROUGH SPACE

BY

DR. HEINRICH HERTZ

PROFESSOR OF PHYSICS IN THE UNIVERSITY OF BONN

AUTHORISED ENGLISH TRANSLATION

BY D. E. JONES, B.Sc.

DIRECTOR OF TECHNICAL EDUCATION TO THE STAFFORDSHIRE COUNTY COUNCIL
LATELY PROFESSOR OF PHYSICS IN THE UNIVERSITY COLLEGE OF WALES, ABERYSTWYTH

WITH A PREFACE BY LORD KELVIN, LL.D., D.C.L.

PRESIDENT OF THE ROYAL SOCIETY, PROFESSOR OF NATURAL PHILOSOPHY IN THE UNIVERSITY OF GLASGOW, AND FELLOW OF ST. PETER'S COLLEGE, CAMBRIDGE

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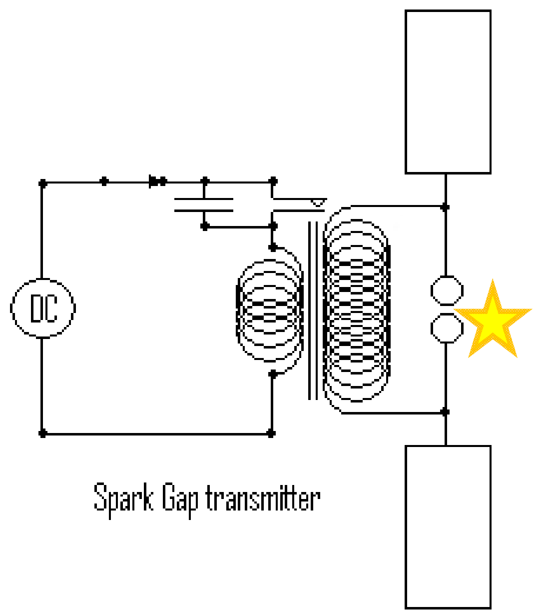
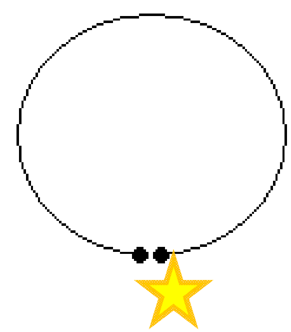
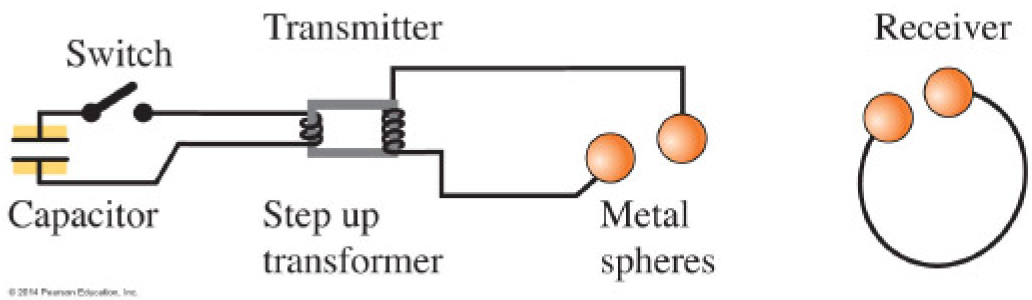
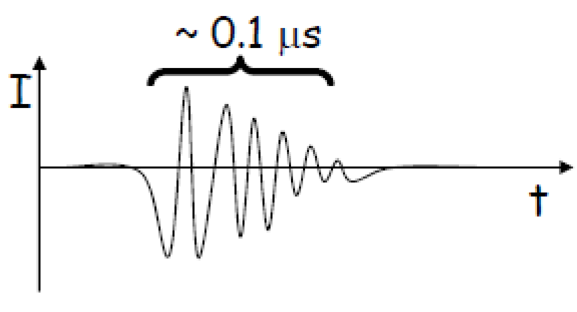




Radio Waves


Switch
Transmitter
Receiver
Capacitor
Step up
transformer
Metal
spheres


~ 0.1 μs
I
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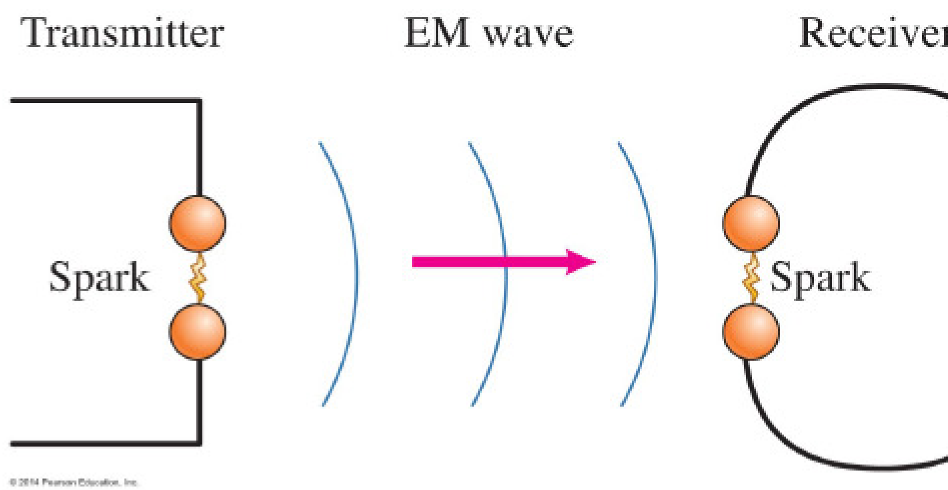
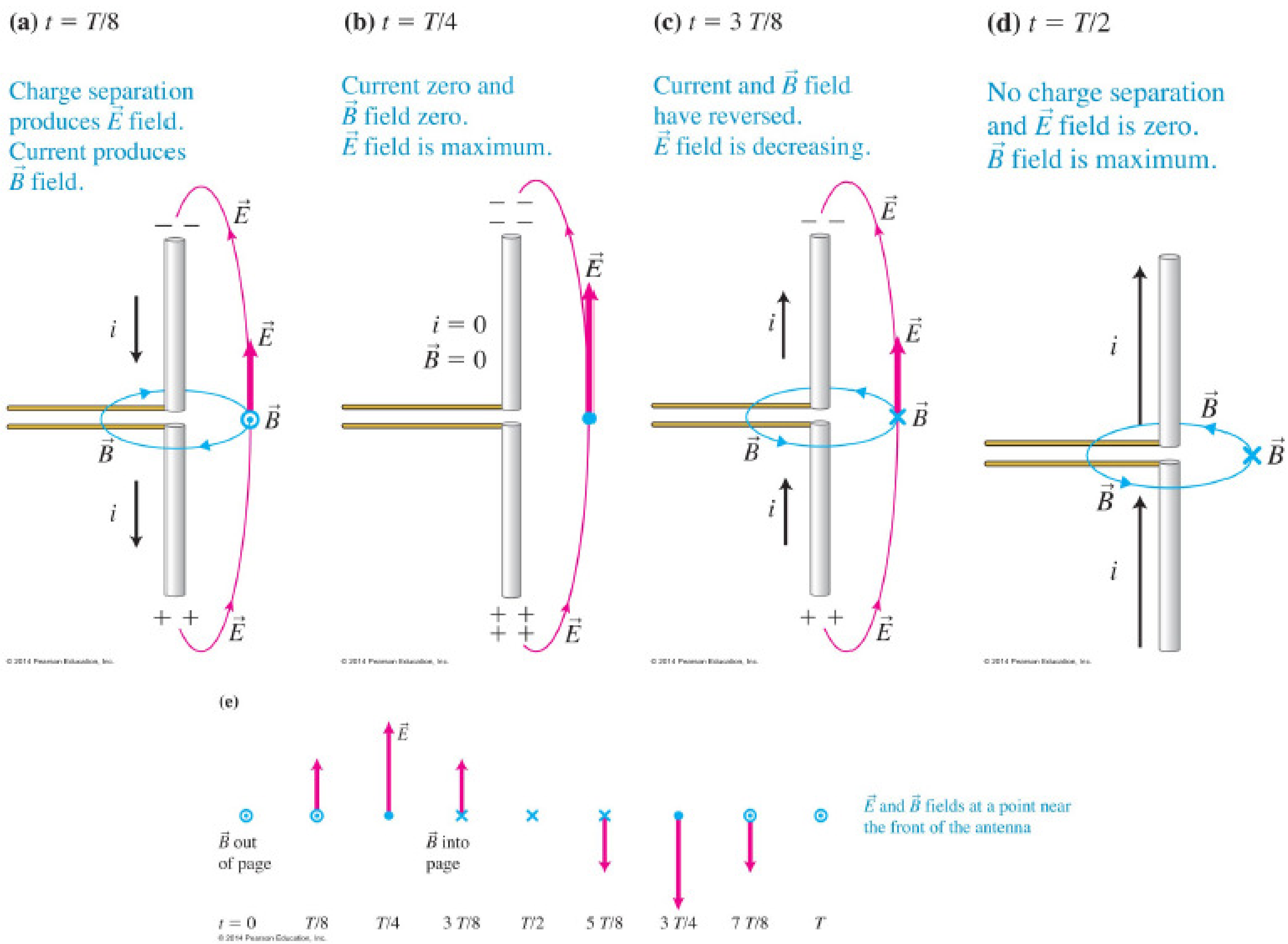

Transmitter
EM wave
Receiver
Spark
Spark

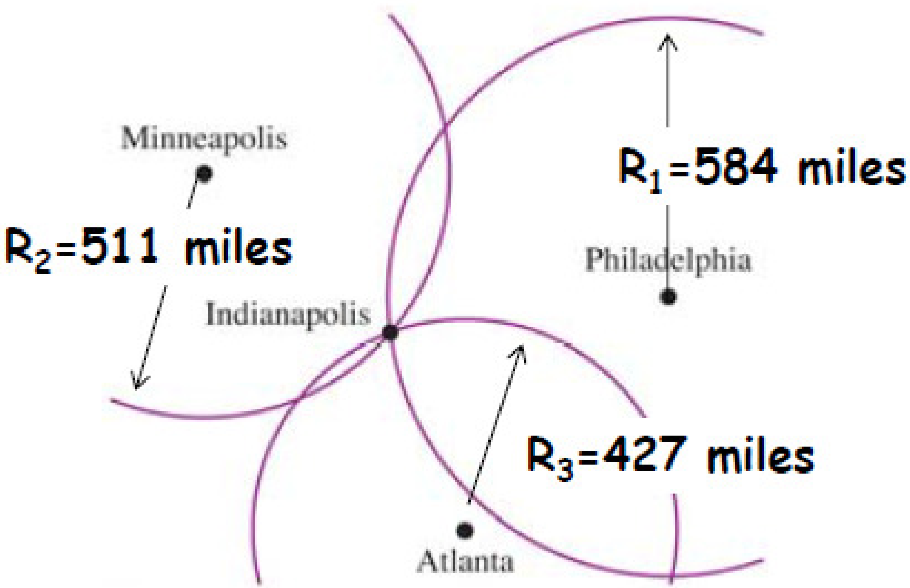
Antennas are used to launch EM waves



Application: Global Positioning Systems

- The GPS receiver detects signals from at least three satellites to determine your position on the ground.
  - Using the known positions of the satellites, the GPS unit is able to calculate your position by a process called trilateration.

Concept of trilateration



Only one place (Indianapolis) is the known distance from the other three cities.

Application: Microwave cooking

The frequency of microwave oven radiation is about **2,450 MHz**, the wavelength of microwave oven radiation is about 12 cm.