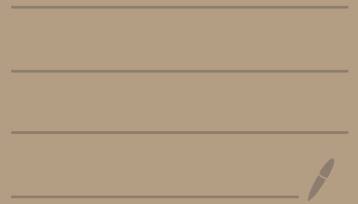


LECTURE 23 NOTES

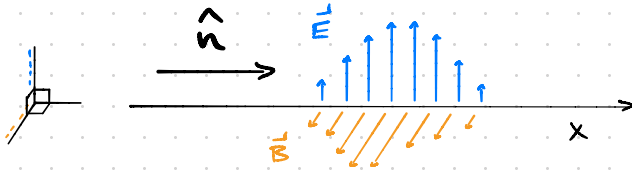
ELECTROMAGNETIC WAVES



SUMMARY:

- A LOT WE CAN SAY ABOUT ELECTROMAGNETIC WAVES, BUT I ONLY WANT YOU TO TAKE AWAY THE FOLLOWING:
- MAXWELL'S HYPOTHESIS: CHANGING \vec{E} FIELDS GENERATE \vec{B} FIELDS.
- THIS, COMBINED W/ FARADAY'S LAW, IMPLIES EXISTENCE OF WAVES OF $\vec{E} + \vec{B}$ FIELDS THAT CAN PROPAGATE IN EMPTY SPACE (VACUUM).
- IN VACUUM, E.M. WAVES TRAVEL W/ A SPEED $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3 \cdot 10^8 \frac{m}{s}$.
- E.M. WAVES ARE CHARACTERIZED BY THEIR FREQUENCY (f) / WAVELENGTH (λ) [$f\lambda = c$], AND VISIBLE LIGHT ARE E.M. WAVES W/ WAVELENGTHS IN THE RANGE OF 400 - 700 nm.
VIOLET RED

SUMMARY CONTINUED :



- E.M. WAVES ARE TRANSVERSE :

$\vec{E} + \vec{B} \perp$ TO PROPAGATION DIRECTION \hat{n} .

- $\vec{E} \perp \vec{B}$

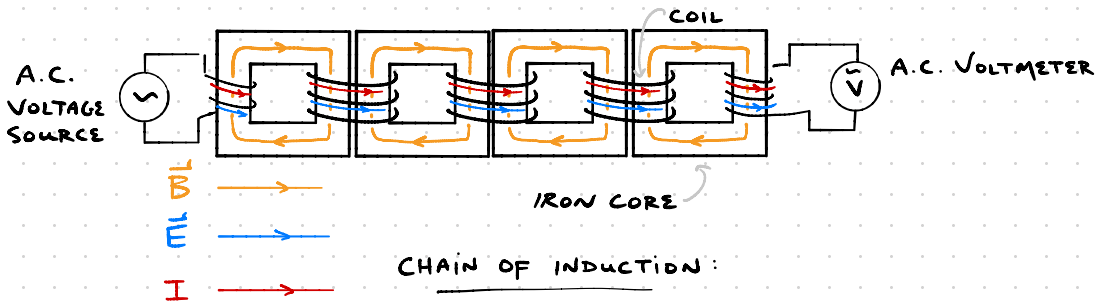
- $B = \frac{E}{c}$ $B = |\vec{B}|$,
 $E = |\vec{E}|$

- E.M. WAVES CARRY ENERGY

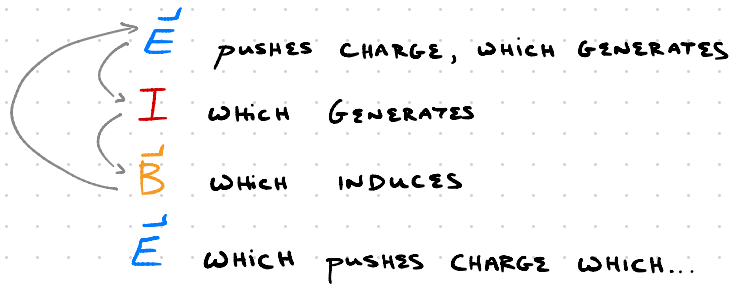
- $I = \frac{1}{2} \times \frac{EB}{\mu_0}$ AMPLITUDES

MAXWELL'S Hypothesis

- SO FAR, WE KNOW THAT, VIA E.M. INDUCTION, WE CAN TRANSMIT A.C. VOLTAGE FROM ONE POINT TO ANOTHER LIKE SO:



CHAIN OF INDUCTION:

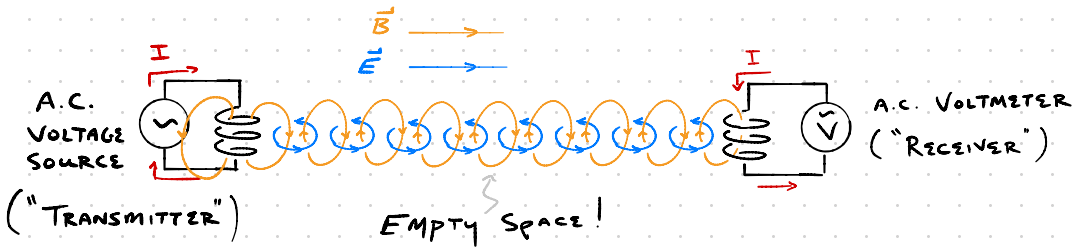


- WE KNOW WE DON'T NEED THE IRON CORES, THAT THEY ONLY HELP TO TRAP/CONCENTRATE THE \vec{B} FIELD LINES.
- AS IT STANDS, THOUGH, IT SEEMS THAT THE COILS ARE INDISPENSIBLE:
 - TO GENERATE \vec{B} FIELD, (IT SEEMS) WE NEED CURRENT (I), AND SO WE NEED THE CHARGE CARRIERS (ELECTRONS) IN THE WIRE.

MAXWELL'S Hypothesis

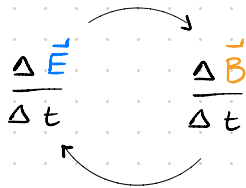
- SCOTTISH PHYSICIST JAMES CLERK MAXWELL (1831-1879)

ELECTRIC CURRENTS ARE NOT NECESSARY FOR
GENERATING MAGNETIC FIELDS - A CHANGING
ELECTRIC FIELD IS SUFFICIENT!



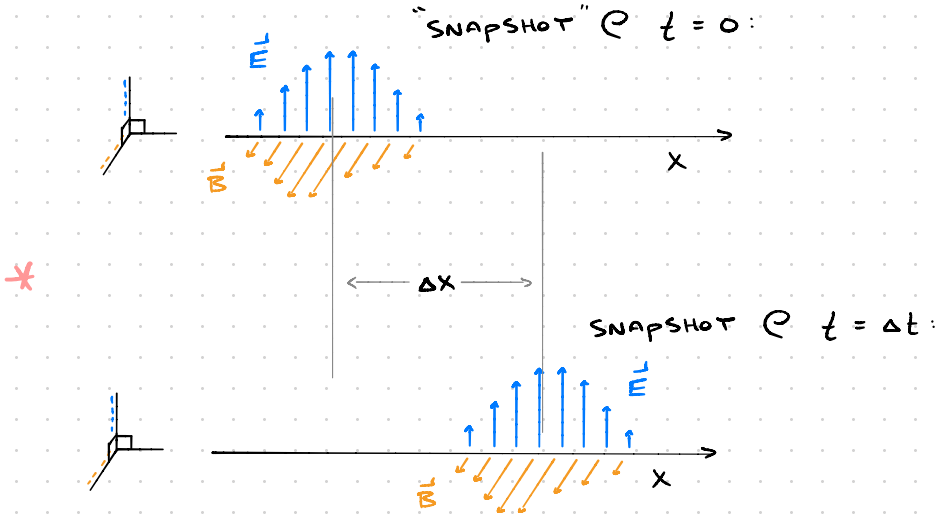
- CAN TRANSMIT SIGNALS ACROSS EMPTY SPACE!
- NOTE THE SYMMETRY:
 - CHANGING B → E [FARADAY'S LAW]
 - CHANGING E → B [MAXWELL'S Hypothesis]

- Symmetry implies A "SELF-SUSTAINING" cycle:



ELECTROMAGNETIC WAVES

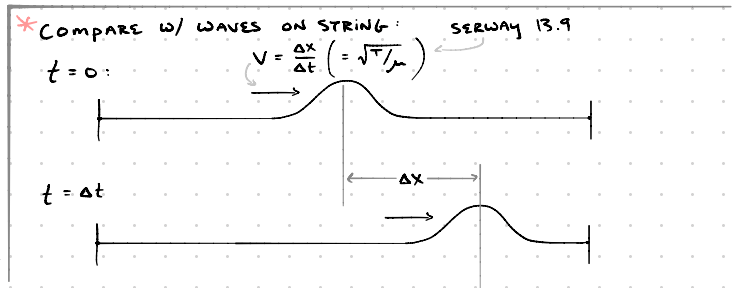
- MAXWELL'S CALCULATIONS REVEALED THAT THIS SELF-SUSTAINING CYCLE COULD GIVE RISE TO WAVES OF $\vec{E} + \vec{B}$ FIELDS IN EMPTY SPACE!



- MAXWELL FOUND THAT WAVES SHOULD

TRAVEL @ A SPEED $\frac{\Delta x}{\Delta t} = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \approx 3 \times 10^8 \frac{m}{s}$ *

FROM MAGNETISM
FROM ELECTRICITY



SPEED OF LIGHT

- MAXWELL FOUND THE VELOCITY $\frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3 \cdot 10^8 \frac{m}{s}$

TO BE CLOSE TO THE KNOWN SPEED OF LIGHT, DENOTED BY THE SYMBOL c .

- THIS STRONGLY SUGGESTED[↑] THAT LIGHT IS AN ELECTROMAGNETIC WAVE! ^{TO HIM}

- SO @ THE SAME TIME MAXWELL BROUGHT TOGETHER ("UNIFIED") THE SUBJECTS OF ELECTRICITY AND MAGNETISM, HE ALSO UNIFIED E & M w/ THE STUDY OF LIGHT (I.E. OPTICS)!

SPEED OF LIGHT

- IN EMPTY SPACE*, THIS SPEED c OF E.M. WAVES IS THE SAME, INDEPENDENT OF:

- THE WAVELENGTH/FREQUENCY*, OR
(SEE LATER)

- THE FRAME OF REFERENCE!

ALICE



$v = 0$

BOB



$v \neq 0$

E.M. WAVE



c



SPECIAL RELATIVITY:

- ALICE AND BOB MEASURE THE SAME SPEED c FOR THE E.M. WAVE!

• HOW CAN THIS BE?!

- THIS FACT HAS STARTLING IMPLICATIONS, INCLUDING:

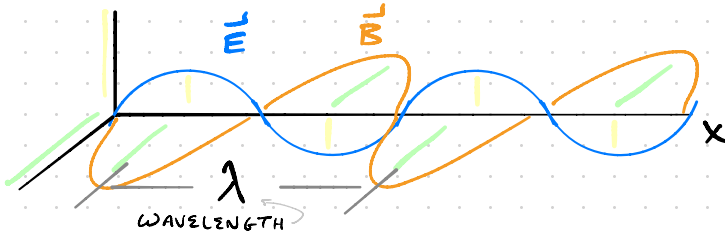
"RELATIVITY OF SIMULTANEITY":

- TWO EVENTS OCCURRING AT THE SAME TIME IN ONE REFERENCE FRAME MAY OCCUR @ DIFFERENT TIMES IN ANOTHER!

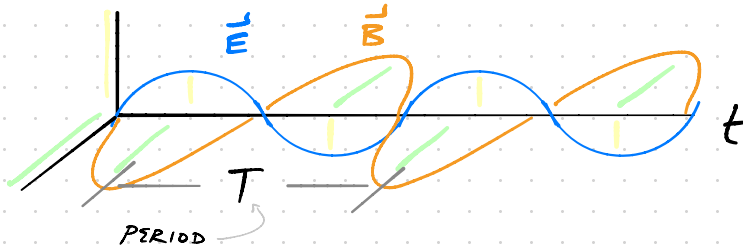
* WHEN E.M. WAVES TRAVEL IN MATTER (E.G. WATER, GLASS, AIR), THEIR SPEED CAN DEPEND ON THEIR WAVELENGTH (OR COLOR, FOR VISIBLE LIGHT). THIS EFFECT IS CALLED DISPERSION.

ELECTROMAGNETIC SPECTRUM:

- A MONOCHROMATIC* E.M. WAVE HAS THE SHAPE OF A SINE-WAVE WHEN LOOKING @ A "SNAPSHOT" IN TIME:



- OR IF WE MONITOR @ A SINGLE POINT IN SPACE:



- THE DISTANCE TRAVELED BY A ^{MONOCHROMATIC} WAVE IN ONE PERIOD T IS ONE WAVELENGTH λ:

$$\lambda = cT$$

$$\rightarrow \boxed{f\lambda = c} \left[f : \text{FREQUENCY} = \frac{1}{T} \right]$$

* MEANS "SINGLE COLOR". VISIBLE LIGHT THAT LOOKS LIKE A SINGLE COLOR OF THE RAINBOW (RED, ORANGE, YELLOW, GREEN, BLUE, PURPLE) FITS THIS DESCRIPTION.

ELECTROMAGNETIC SPECTRUM:

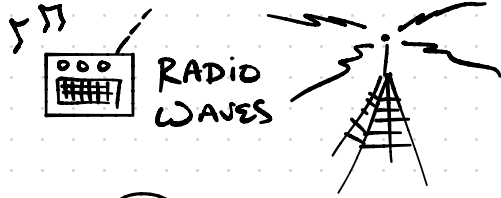
- VISIBLE LIGHT ONLY SMALL PART OF THE FULL SPECTRUM OF E.M. WAVES:

WAVELENGTH
(λ)

FREQUENCY
(f)

1 m - 1 km

100 kHz
- 10 GHz



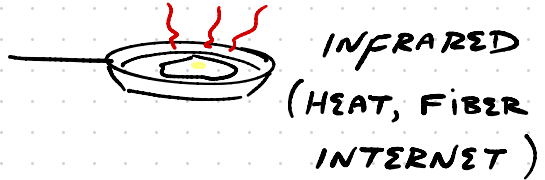
1 mm - 1 m

10 GHz
- 1 THz



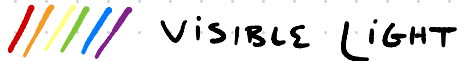
1 μ m - 1 mm

1 THz - 100 THz



400 nm - 700 nm

400 - 750 THz



10 - 100 nm

10^{16} - 10^{17} Hz

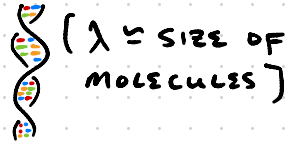
ULTRA-VIOLET



.1 nm - 10 nm

10^{17} - 10^{19} Hz

X-RAYS



< .1 nm

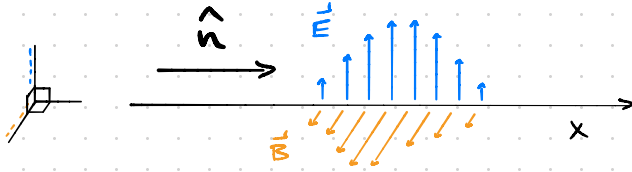
$> 10^{19}$ Hz

GAMMA (γ) RAYS



HIGH-ENERGY PHOTONS
[EMITTED BY NUCLEI]

E. M. WAVES - PROPERTIES

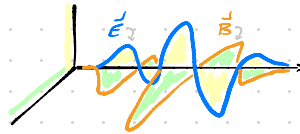


• WAVES ARE TRANSVERSE:

- \vec{E} & \vec{B} FIELDS ARE \perp TO \hat{n} ,
THE DIRECTION OF PROPAGATION.
- \vec{E} & \vec{B} FIELDS ARE ALSO \perp TO ONE ANOTHER.

• AMPLITUDES OF \vec{E} & \vec{B} ARE PROPORTIONAL:

$$B = \frac{E}{c}$$



\vec{B} "TRACKS" \vec{E}
(\neq VICE VERSA)

- * "RIGHT-HAND RULE # 3":
- TO DETERMINE \hat{n} :
 - POINTER FINGER TOWARDS \vec{E} ,
 - MIDDLE FINGER TOWARDS \vec{B} ,
 - THUMB POINTS TOWARDS \hat{n} .



INTENSITY OF E.M. WAVES

- EM WAVES CARRY ENERGY:

- INTENSITY OF ^{MONOCHROMATIC} E.M. WAVE:

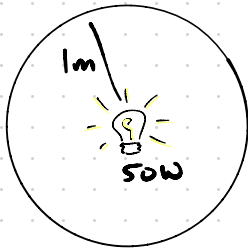
$$I = \frac{1}{2} \times \frac{EB}{\mu_0} \quad \text{Amplitudes}$$

- EXAMPLE:

- RADIO STATION GENERATES RADIO WAVES THAT HAVE ELECTRIC FIELDS OF ABOUT 1V/m A FEW MILES FROM THE STATION.

$$\begin{aligned} I &= \frac{1}{2} \cdot \frac{EB}{\mu_0} = \frac{1}{2} \cdot \frac{E \cdot E/c}{\mu_0} = \frac{1}{2} \frac{E^2}{\mu_0 c} \\ &\approx \frac{1}{2} \frac{[1V/m]^2}{4\pi \cdot 10^{-7} H/m \cdot 3 \cdot 10^8 m/s} \approx \frac{1 \text{ MWATT}}{M^2} \end{aligned}$$

- COMPARE TO INTENSITY OF 50WATT LIGHT-BULB 1m AWAY:



$$I = \frac{P}{A} = \frac{50W}{4\pi(1m)^2} \approx 4 \frac{W}{m^2}$$

$\approx 4000 \times$ MORE INTENSE.