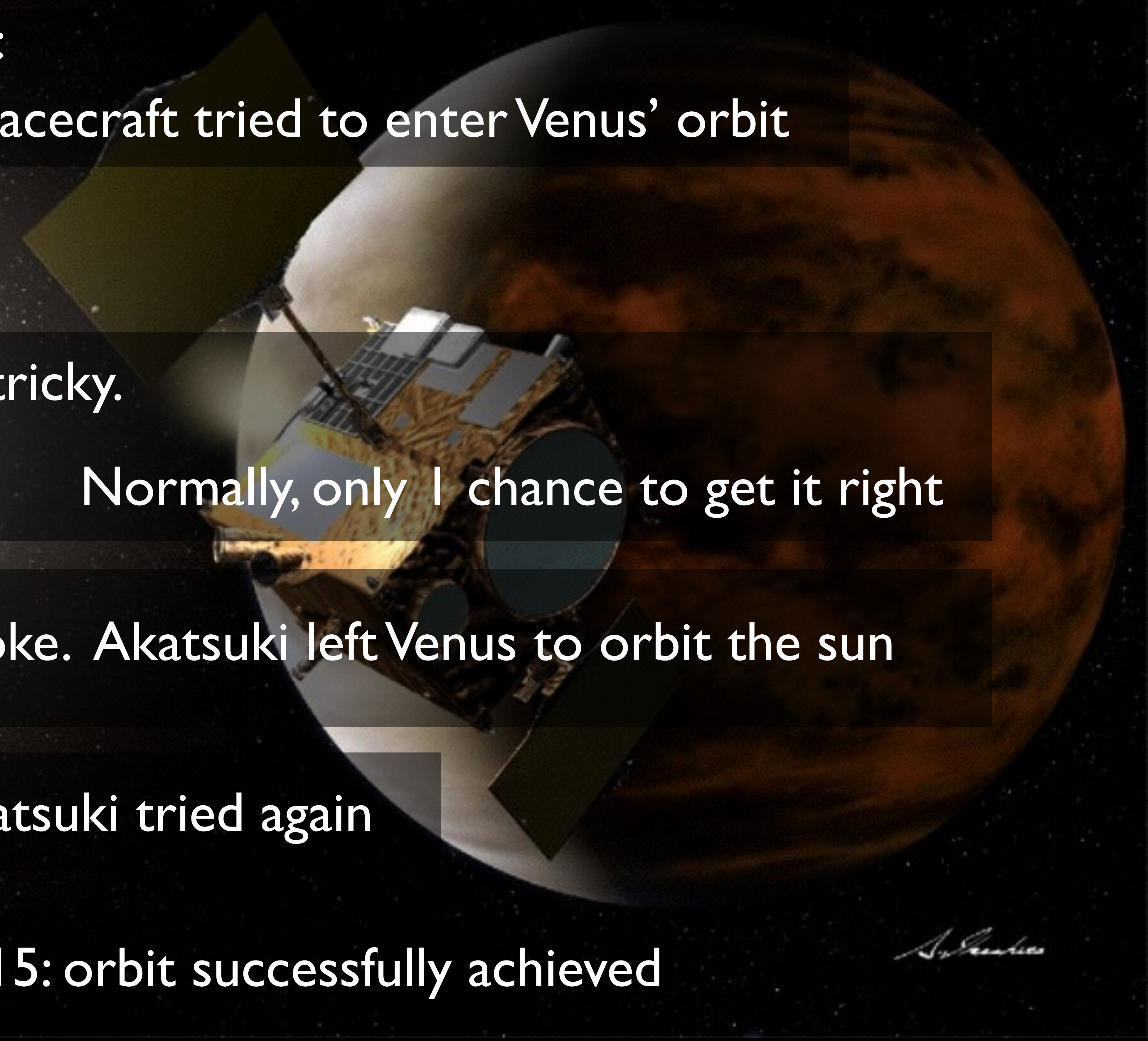
Essential Physics II

英語で物理学の

エッセンス II

Lecture 11:   14-12-15

Science news



December 6, 2010:

JAXA ‘Akatsuki’ spacecraft tried to enter Venus’ orbit

It failed.

Orbit insertion is tricky.

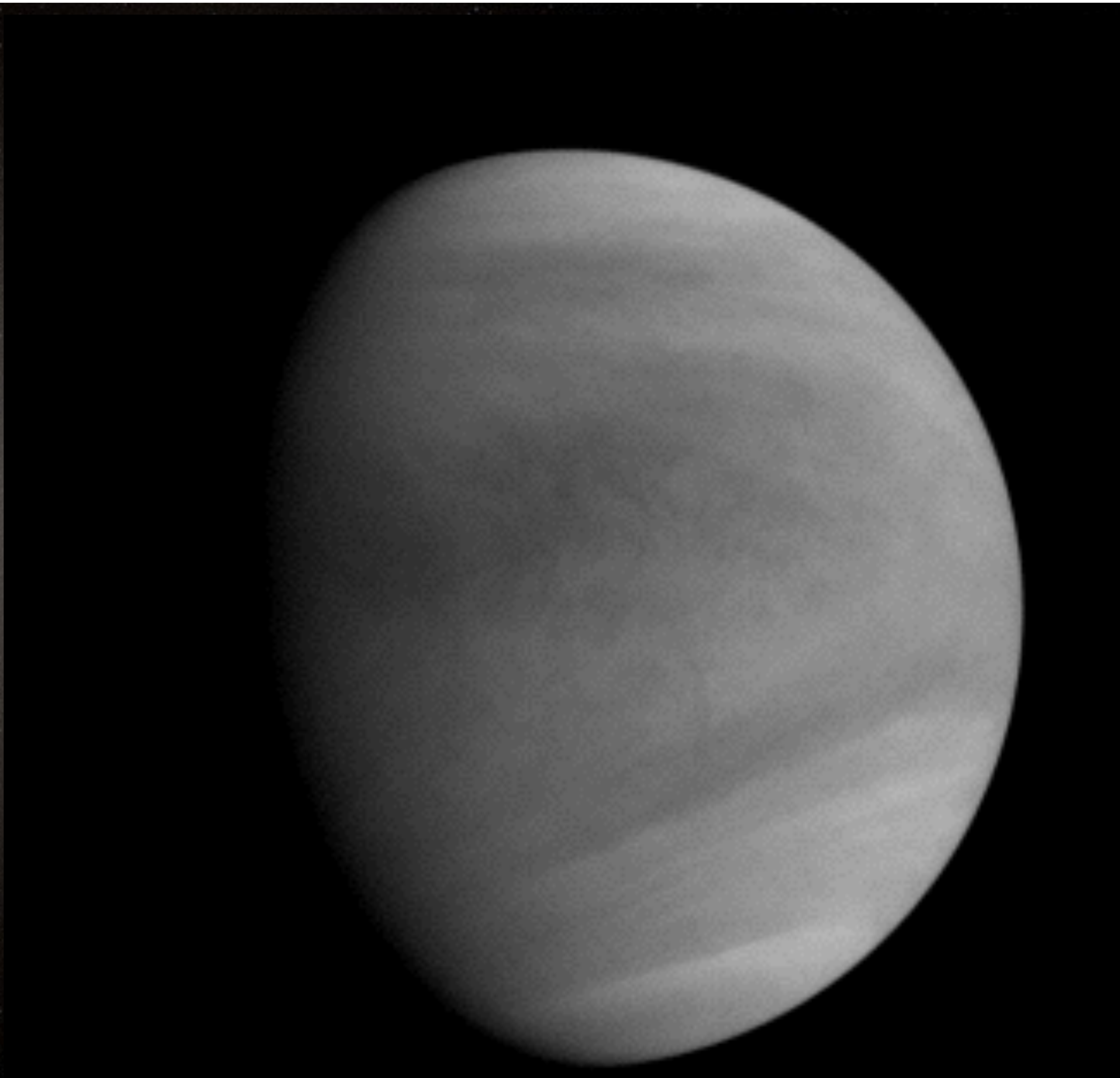
Normally, only 1 chance to get it right

Exhaust nozzle broke. Akatsuki left Venus to orbit the sun

5 years later… Akatsuki tried again

December 9th, 2015: orbit successfully achieved

Science news



Electromagnetism

Maxwell's Equation

Last lecture

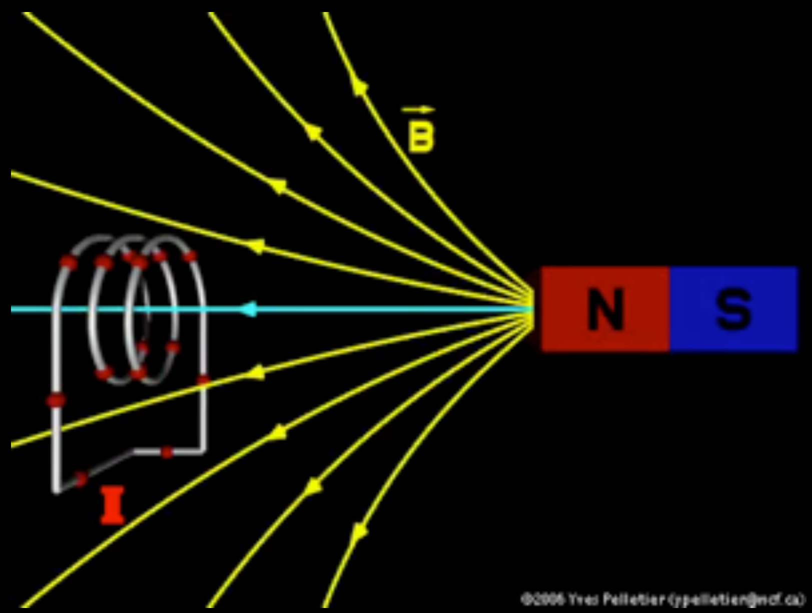
A changing $\bar{B}$ field produces an $\bar{E}$ field:

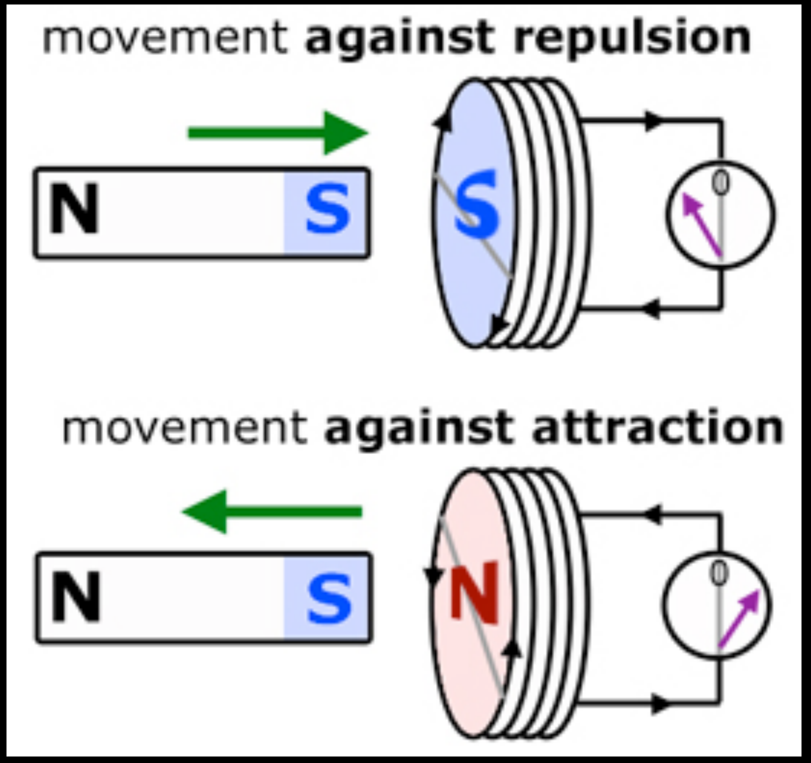
$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Faraday's law

The induced EMF opposes the flux change.

Lenz's law

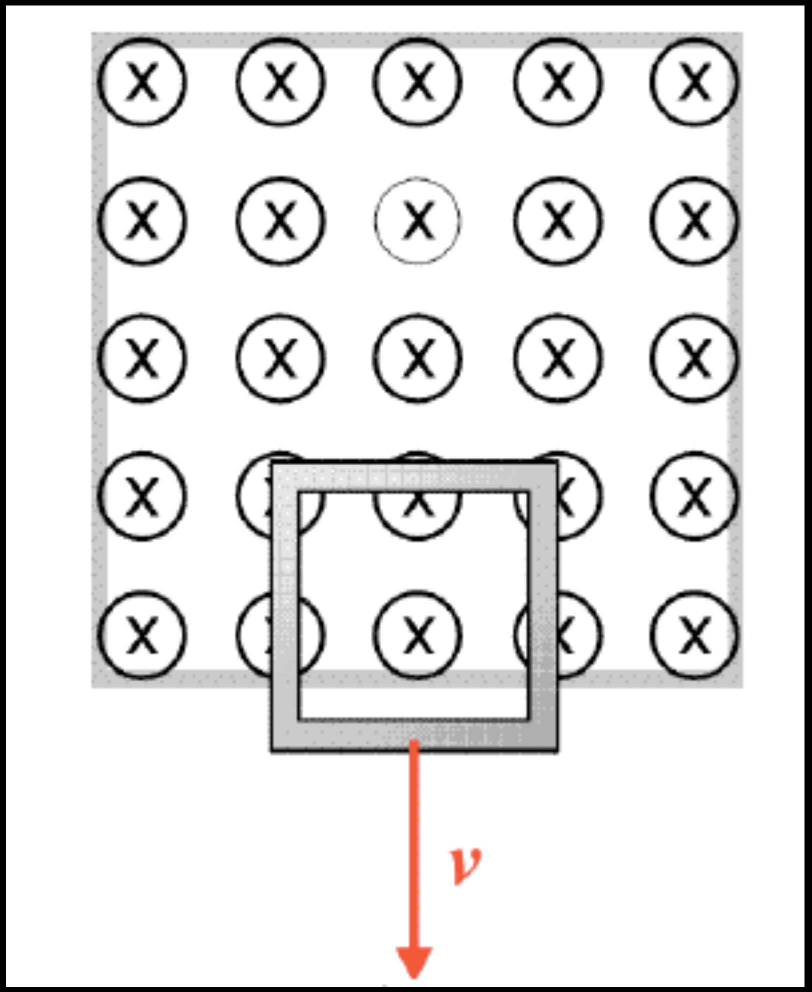




Last lecture

Conducting loop falls through a magnetic field.

What is the direction of the induced current as it leaves the field?



$\bar{B}$ into page

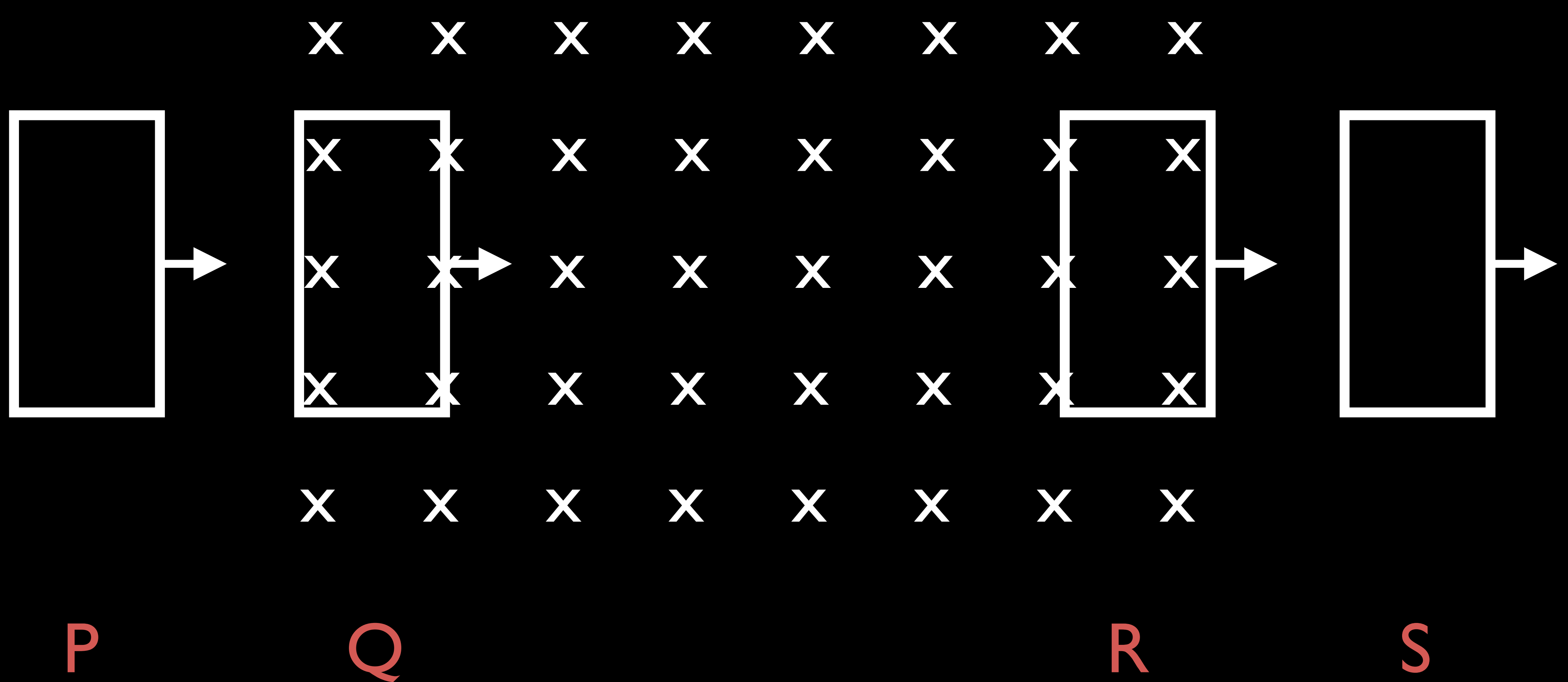
(A) clockwise

(B) anti-clockwise

Current acts to increase B-field

Last lecture

Quiz



Loop moves with constant speed from P to Q to R to S.

What happens to the magnitude of the current, I, in the loop between P and Q?

(A) Increases

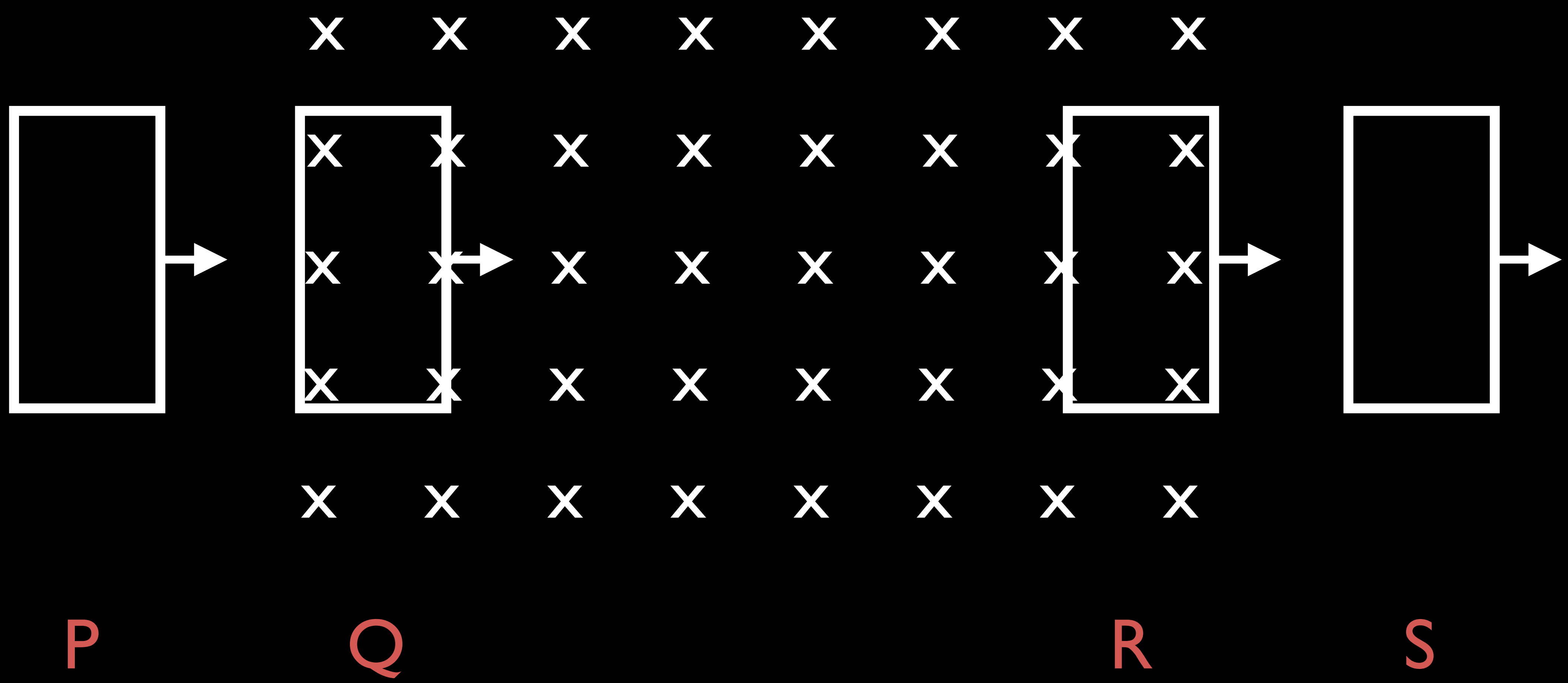
(B) Stays the same

(C) Decreases

(D) Unknown

Last lecture

Quiz



Loop moves with constant speed from P to Q to R to S.

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(A) Increases

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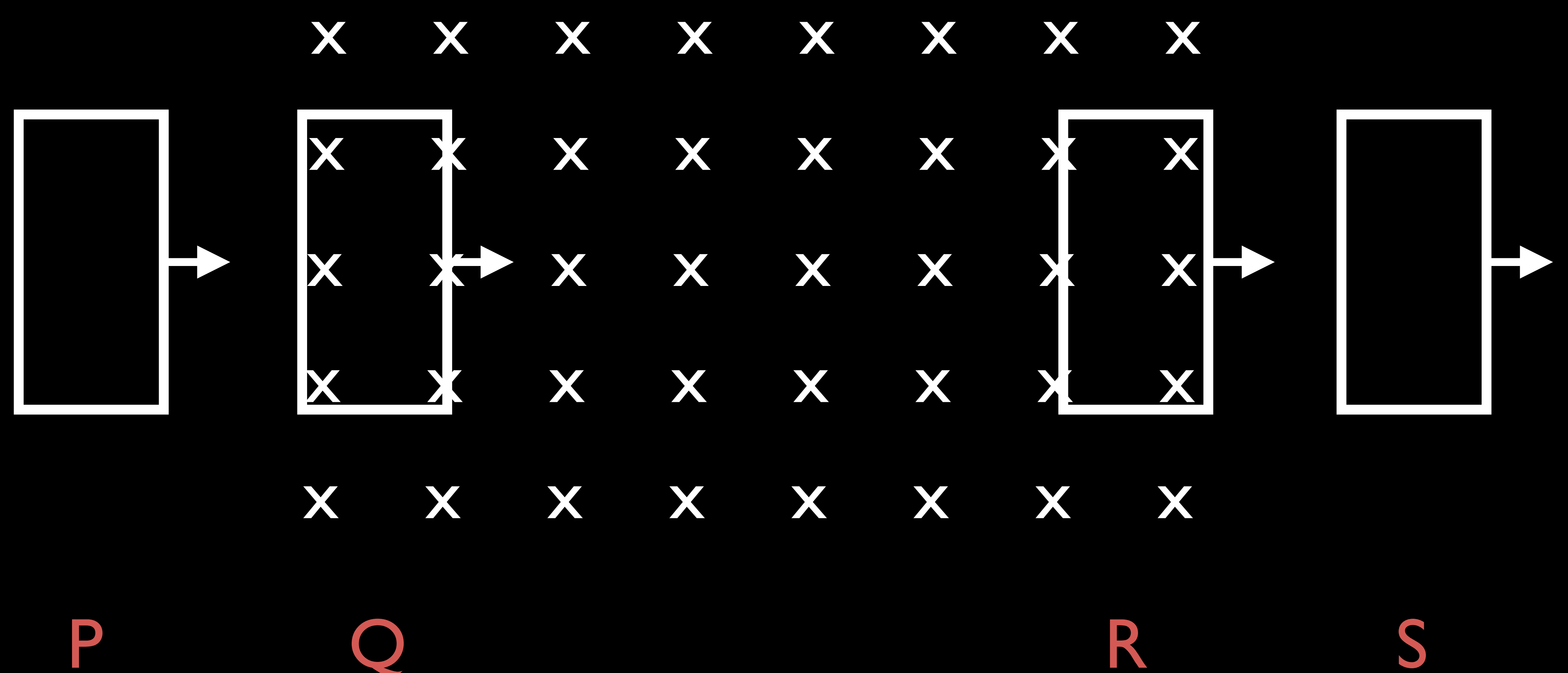
(C) Decreases

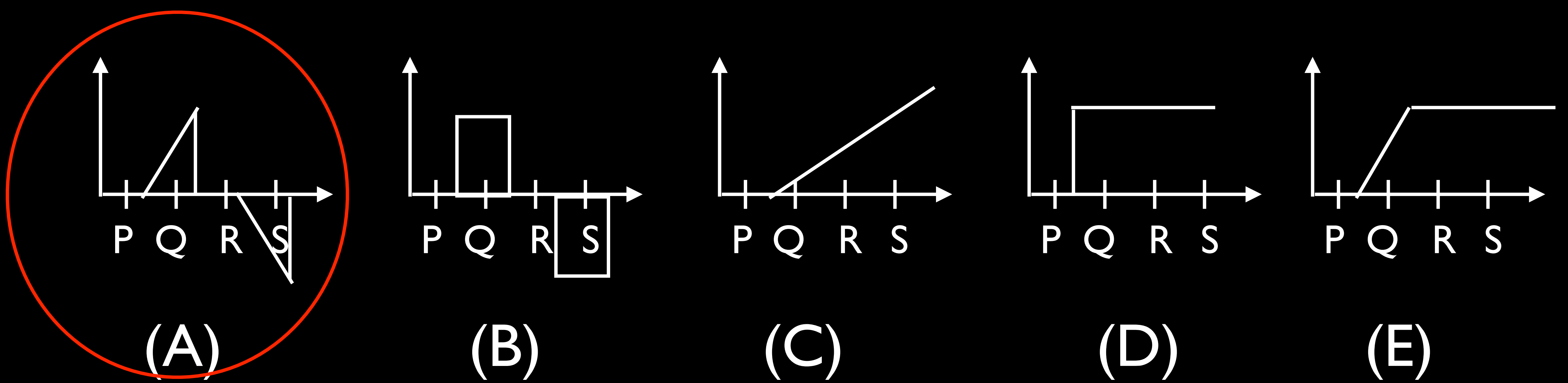
(D) Unknown

Last lecture

Quiz



Loop moves with constant speed from P to Q to R to S.



Last lecture

Quiz

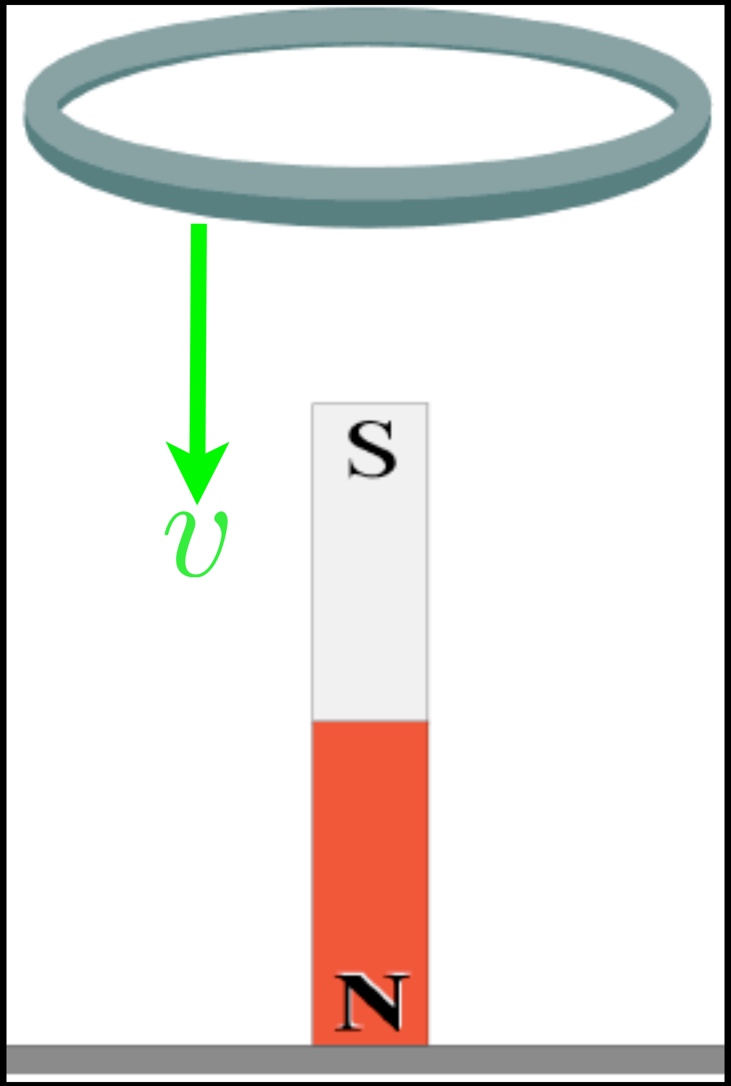
Conducting loop falls onto standing magnet.

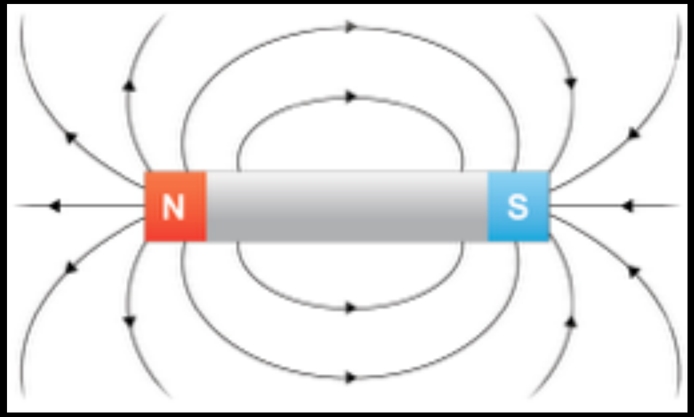
What is the direction of the induced current as the loop approaches (enters) the magnet?

(seen from top of loop)

(A) clockwise

(B) anti-clockwise

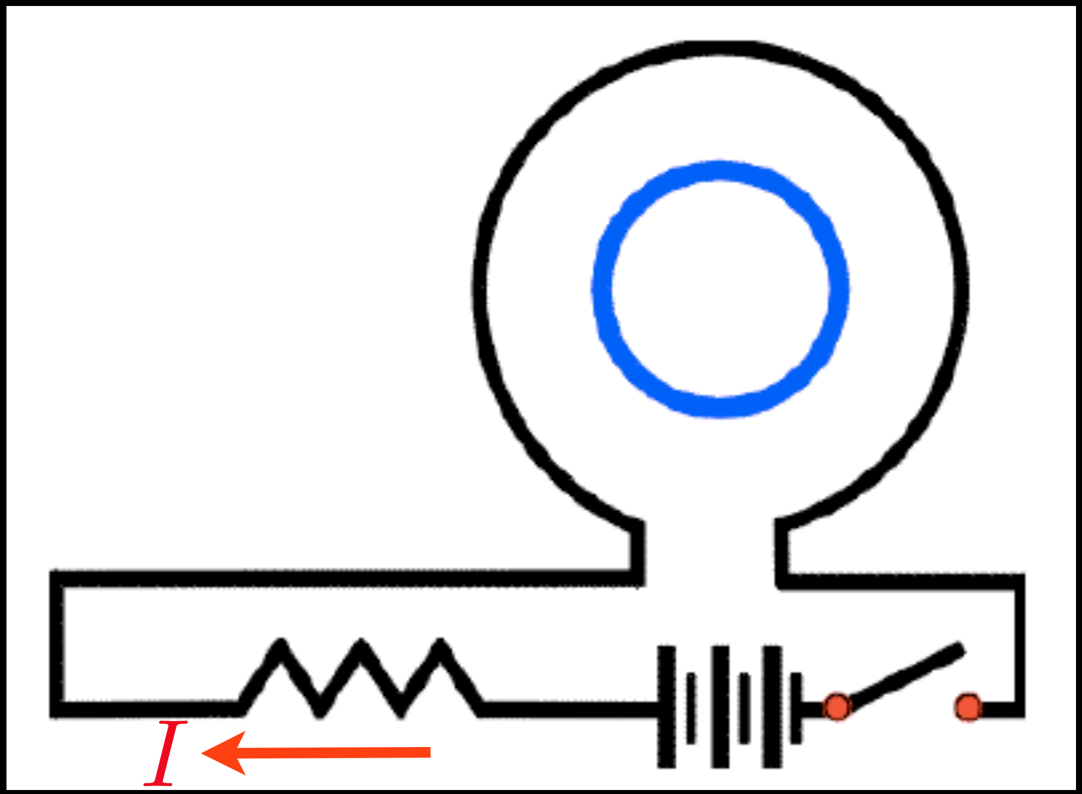




$\bar{B}$ around a bar magnet

Last lecture

Circular wire loop sits in a circuit.



What is the direction of the induced current when the circuit switch is closed?

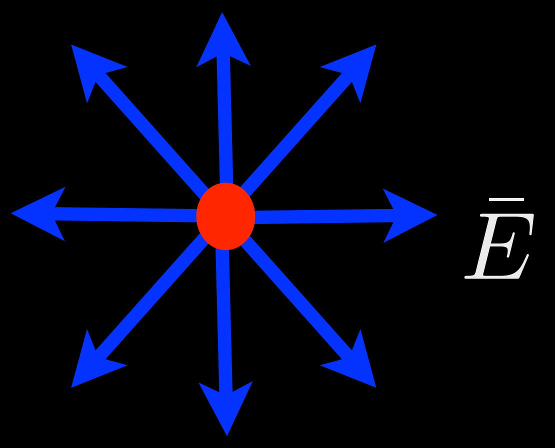
(A) clockwise

(B) anti-clockwise

So far...

We have seen:

Electric fields, $\bar{E}$, are created by charges...



$$\bar{E} = \frac{kq}{r^2}\hat{r}$$

Coulomb's Law

$$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

Gauss's Law for $\bar{E}$

... and charges feel a force in electric fields: $\bar{F}_{12} = q\bar{E}$

The work / charge needed to move a charge in an $\bar{E}$ field:

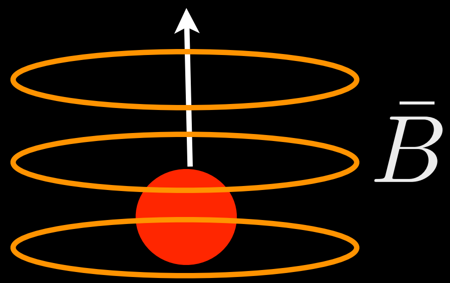
$$V_{\text{AB}} = -\int_A^B \bar{E} \cdot d\bar{r}$$

electric potential difference

So far...

We have seen:

Magnetic fields, $\bar{B}$, are **created by moving charges**.



$$d\bar{B} = \frac{\mu_0}{4\pi}\frac{Id\bar{l} \times \hat{r}}{r^2}$$

Biot-Savart Law

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$

Ampere's Law

$$\oint \bar{B} \cdot d\bar{A} = 0$$

Gauss's Law for $\bar{B}$

... and **moving charges feel a force** in magnetic fields: $\bar{F} = q\bar{v} \times \bar{B}$

So far...

We have seen:

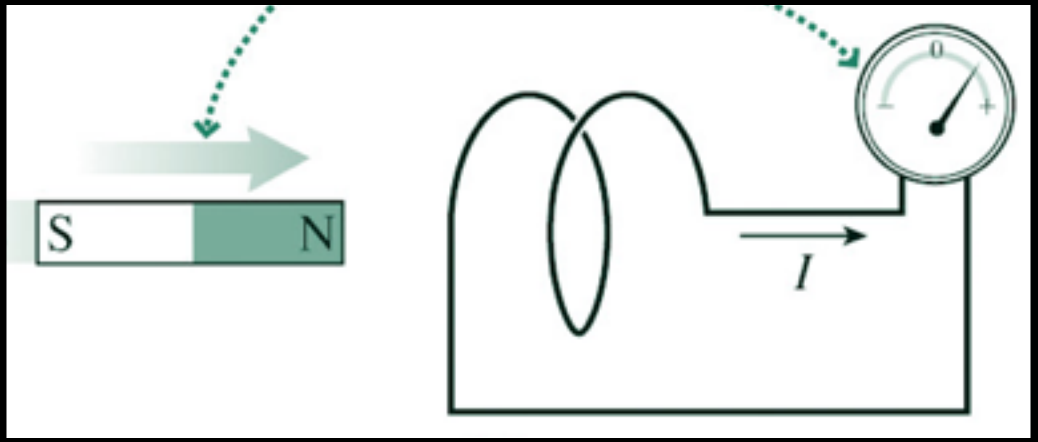
A changing magnetic flux produces an electric field:

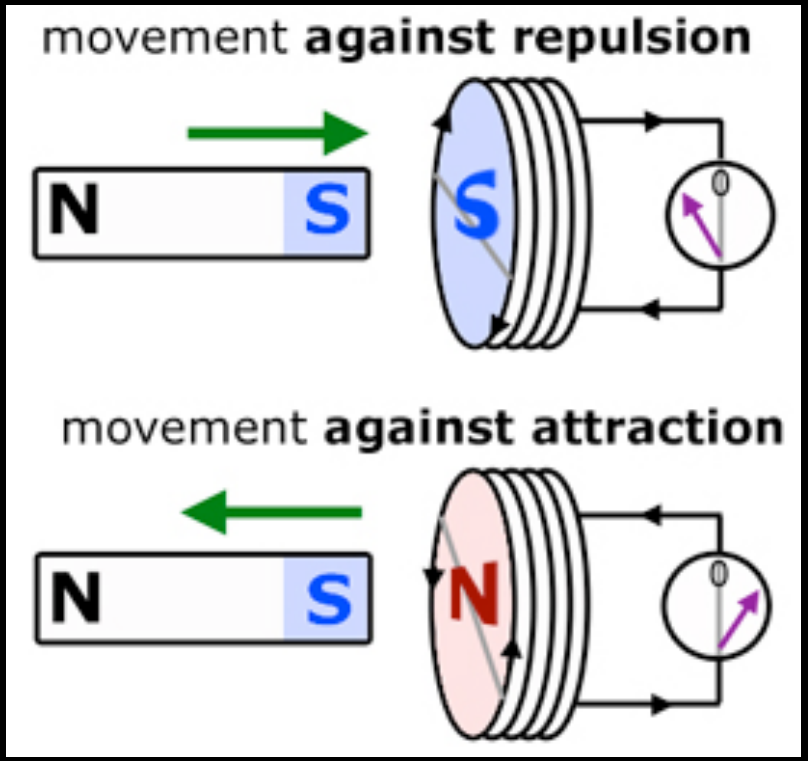
$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Faraday's Law

The induced EMF opposes the flux change.

Lenz's Law





So far...

$$\bar{E} = \frac{kq}{r^2}\hat{r}$$

$$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

$$V_{\text{AB}} = -\int_A^B \bar{E} \cdot d\bar{r}$$

Electric field

$$\oint \bar{B} \cdot d\bar{A} = 0$$

$$d\bar{B} = \frac{\mu_0}{4\pi}\frac{I d\bar{l} \times \hat{r}}{r^2}$$

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$

Magnetic field

$$\bar{F}_{\text{EM}} = q\bar{E} + q\bar{v} \times \bar{B}$$

$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Both

The 4 laws

$$\bar{E} = \frac{kq}{r^2}\hat{r}$$

$$V_{\mathrm{AB}} = -\int_A^B \bar{E} \cdot d\bar{r}$$

Maxwell's equations (... almost)

$$\bar{F}_{\mathrm{EM}} = q\bar{E} + q\bar{v} \times \bar{B}$$

Gauss's Law for $\bar{E}$ $$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\mathrm{enclosed}}}{\epsilon_0}$$

Gauss's Law for $\bar{B}$ $$\oint \bar{B} \cdot d\bar{A} = 0$$

Ampere's Law $$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\mathrm{encircled}}$$

Faraday's Law $$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

The 4 laws

Gauss's Law for $\bar{E}$ $$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

Gauss's Law for $\bar{B}$ $$\oint \bar{B} \cdot d\bar{A} = 0$$

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Faraday's Law $$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

The 4 laws

Gauss's Law for $\bar{E}$ $$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

for

Why name these equations after Maxwell?

w

Because Maxwell made 2 incredible discoveries

Faraday's Law $$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Maxwell 1: Ampere correction

$$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

$$\oint \bar{B} \cdot d\bar{A} = 0$$

Left-side of Gauss's laws

and

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$

$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Left-side of Ampere's law and Faraday's law

are symmetric: $\bar{E} \longleftrightarrow \bar{B}$

Maxwell 1: Ampere correction

$$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

Right-side of Gauss's laws is not symmetric ...

$$\oint \bar{B} \cdot d\bar{A} = 0$$

$\propto m_{\text{enclosed}}$

... *but* because there are no monopoles

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$

If monopoles were found, these laws would be symmetric. $\bar{E} \longleftrightarrow \bar{B}$

$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

OK

Maxwell 1: Ampere correction

$$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

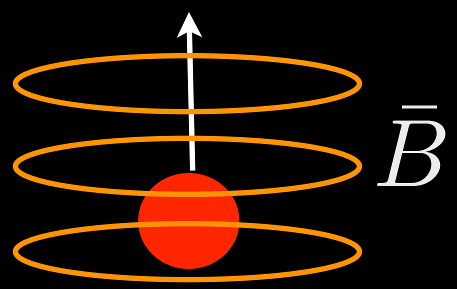
Right-side of Ampere's law and Faraday's law are also not symmetric ...

$$\oint \bar{B} \cdot d\bar{A} = 0$$

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$

Ampere's law:

moving charges are the source of magnetic fields.



$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt} \quad +m_{\text{encircled}}$$

But no moving monopoles!

So we don't expect a matching term in Faraday's law.

OK

Maxwell 1: Ampere correction

$$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

$$\oint \bar{B} \cdot d\bar{A} = 0$$

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}} \quad + ???$$

$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Right-side of Ampere's law and Faraday's law are also not symmetric ...

Faraday's law:

changing magnetic flux is a source of electric fields

.... should a changing electric flux produce a magnetic field?

Is Ampere's law incomplete?

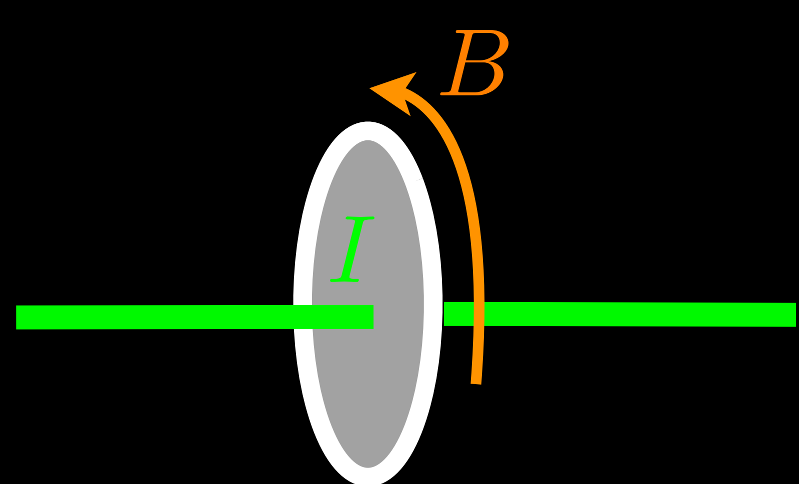
Maxwell 1: Ampere correction

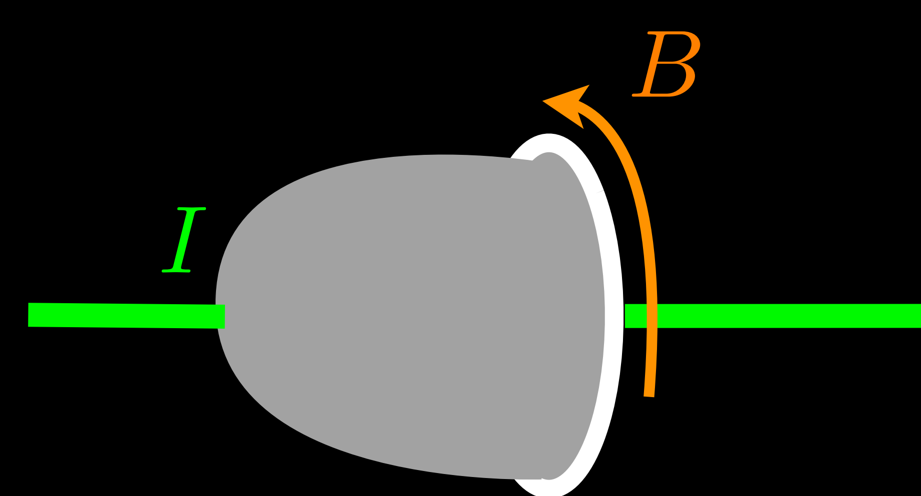
Lecture 9: Ampere's Law for a steady current

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$

Integral of the magnetic field around a closed loop

Current passing through open surface bounded by loop





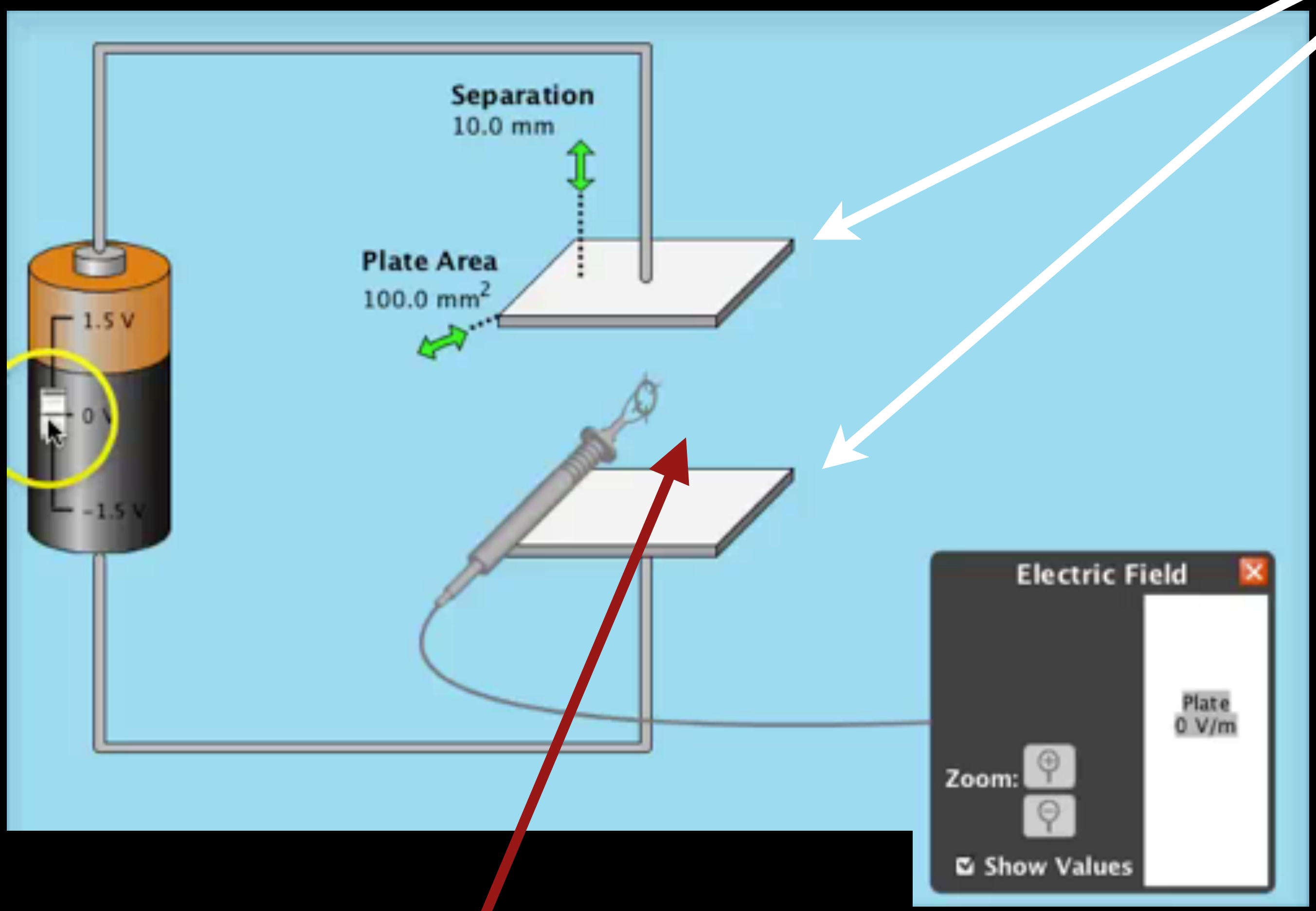
Shape of surface not important

... what if the current is not steady?

Maxwell 1: Ampere correction

Brief aside: capacitors

2 conducting plates



When battery is connected, charge moves top plate to bottom plate.

No charge moves between the plates.

$|\bar{E}|$ changes as plates charge

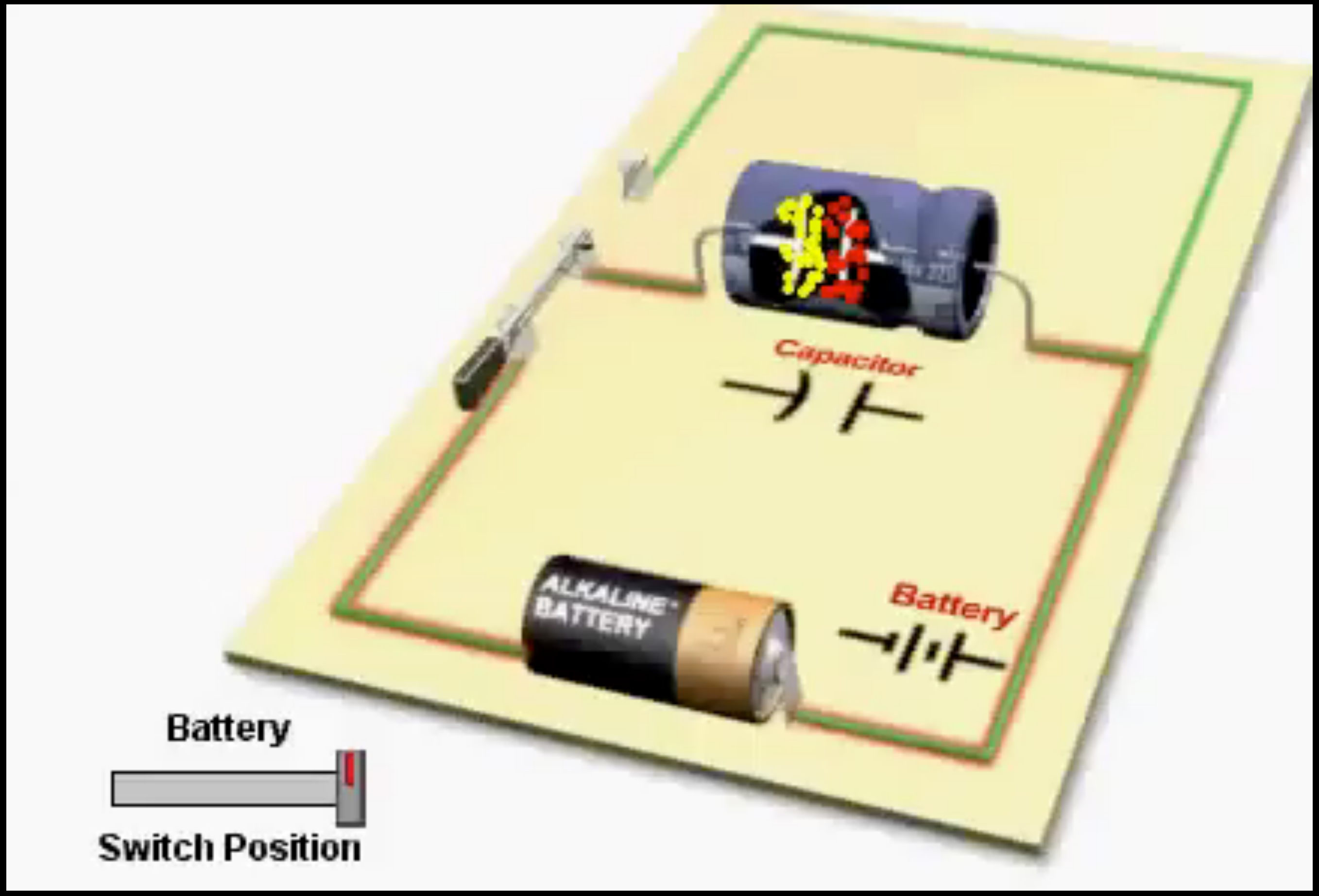
An increasing electric flux is produced as the capacitor charges. $\Phi_E = |\bar{E}||\bar{A}|\cos\theta$

This 'stored charge' can be used later.

Maxwell 1: Ampere correction

Brief aside: capacitors

2 conducting plates



+ capacitor is charged

+ charge is stored

+ charge flows round circuit

When battery is connected, charge moves top plate to bottom plate.

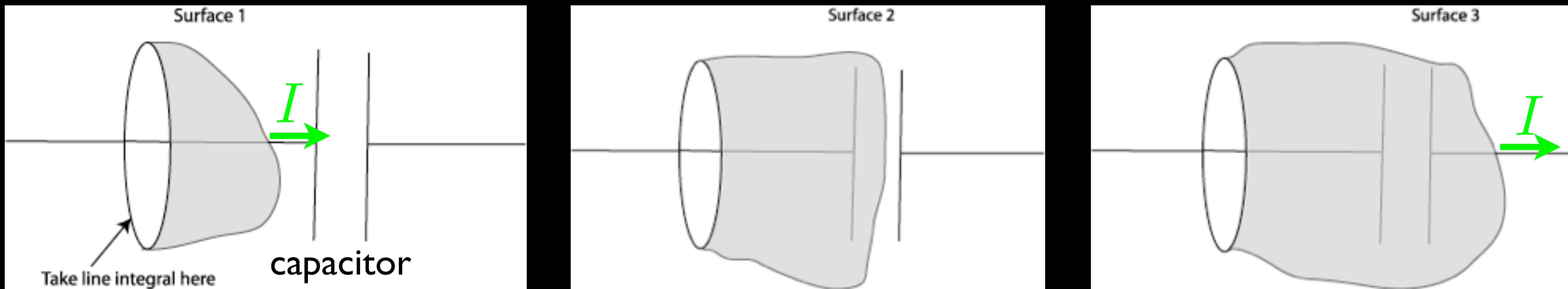
No charge moves between the plates.

An increasing electric flux is produced as the capacitor charges. $\Phi_E = |\bar{E}||\bar{A}|\cos\theta$

This 'stored charge' can be used later.

Maxwell 1: Ampere correction

Consider 3 surfaces:



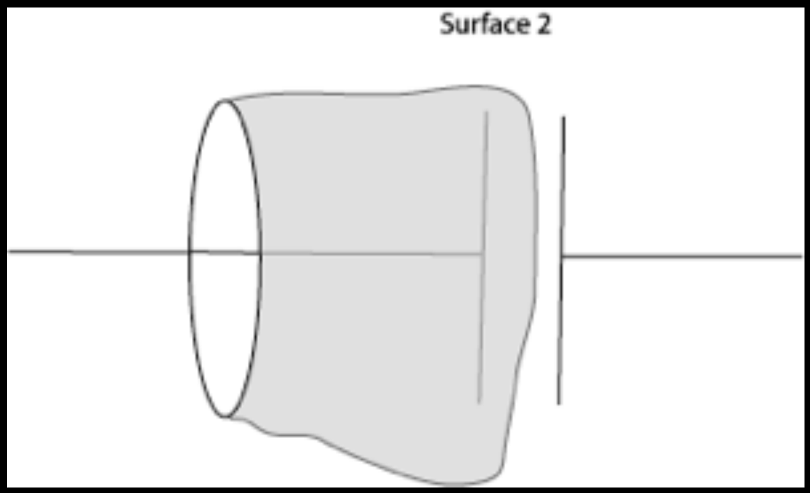
$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$ Ampere's Law

I through surface 1 and 3 is the same: $$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$

But there is no current through surface 2: $$\oint \bar{B} \cdot d\bar{r} = \cancel{\mu_0 I_{\text{encircled}}}$$

$= 0$!!

Maxwell 1: Ampere correction



$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{encircled}}$$

= 0

No current, but there is a changing electric flux, $\frac{d\Phi_E}{dt} \neq 0$

In 1860, Maxwell suggested this could produce a magnetic field:

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

Ampere's Law with Maxwell modification

Maxwell predicted this from symmetry with Faraday's equation:

$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

.... but it has since been proved by experiment.

Maxwell 1: Ampere correction

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

Named displacement current

(but a flux, not a current...)

This law is universal (not just capacitors):

ANY changing electric flux produces a magnetic field.

Likewise,

ANY changing magnetic flux produces an electric field

(Faraday's Law) $$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Maxwell's equations

Law	Mathematical Statement	What It Says
Gauss for $\vec{E}$	$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\epsilon_0}$	How charges produce electric field; field lines begin and end on charges.
Gauss for $\vec{B}$	$\oint \vec{B} \cdot d\vec{A} = 0$	No magnetic charge; magnetic field lines don't begin or end.
Faraday	$\oint \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$	Changing magnetic flux produces electric field.
Ampère	$\oint \vec{B} \cdot d\vec{r} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$	Electric current and changing electric flux produce magnetic field.

Describe ALL electromagnetic phenomena

Maxwell's equations in a vacuum

To understand Maxwell's 2nd huge contribution, let's simplify the equations...

Gauss's Law for $\bar{E}$ $$\oint \bar{E} \cdot d\bar{A} = 0$$

Gauss's Law for $\bar{B}$ $$\oint \bar{B} \cdot d\bar{A} = 0$$

Faraday's Law $$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Ampere's Law $$\oint \bar{B} \cdot d\bar{r} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

Maxwell equations in a vacuum:

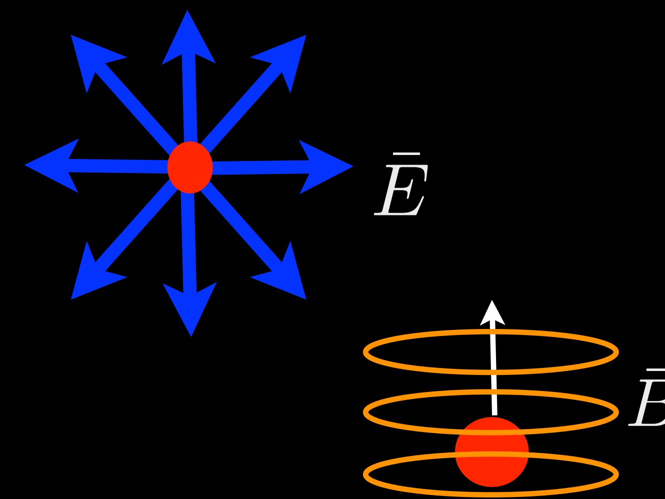
remove matter terms

(charge and current)

Only field source is change in other field.

Maxwell 2: Electromagnetic wave

We have seen electric and magnetic fields from charges, q, current, I and changing flux.



electromagnetic wave?

Maxwell asked:

Could a wave made from alternating electric and magnetic fields exist?

Maxwell 2: Electromagnetic wave

$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Faraday's Law

Changing magnetic field induces an electric field

but then... the electric field changes

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

Ampere's Law

Changing electric field induces a magnetic field

but then... the magnetic field changes

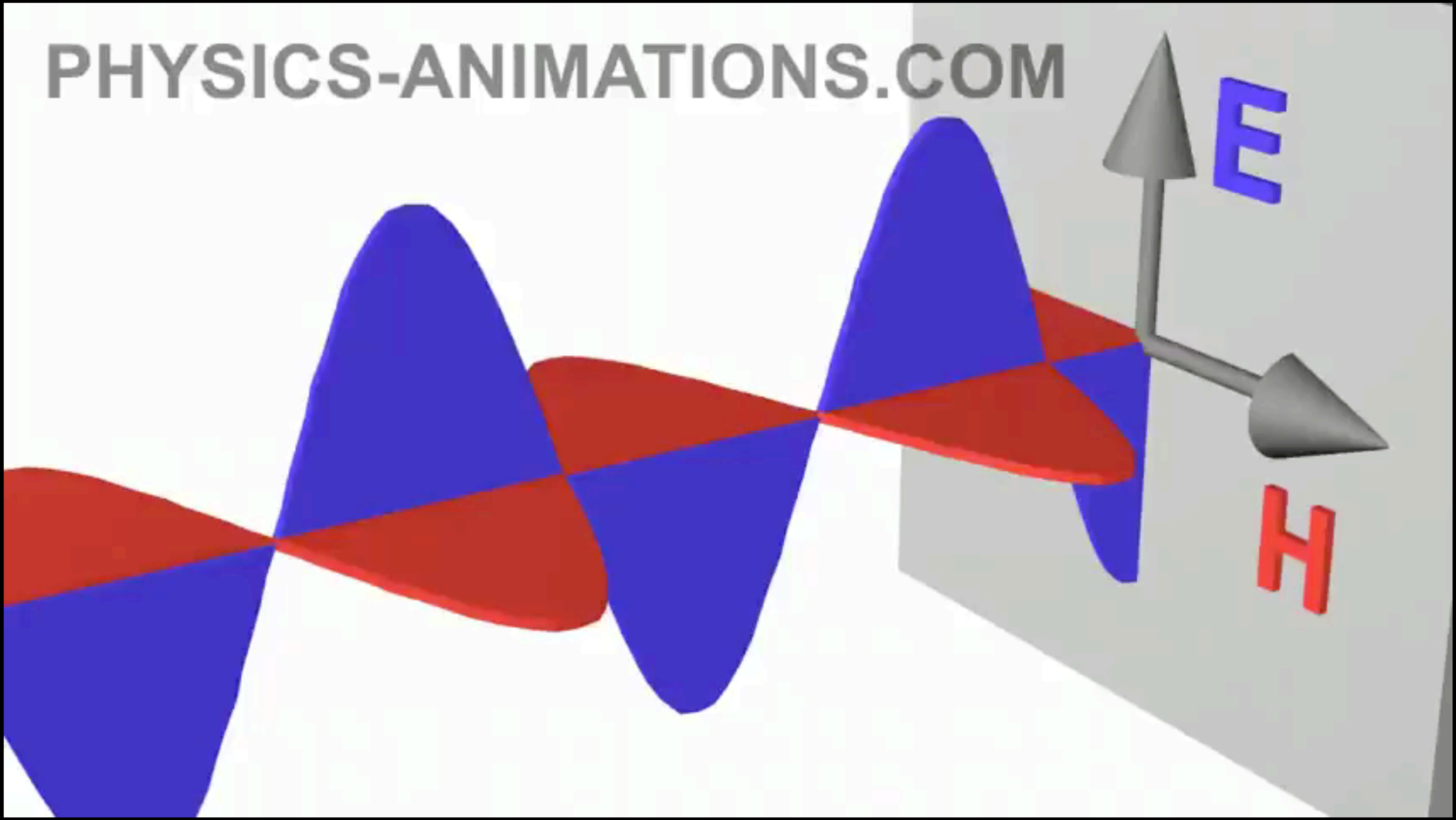
$$\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$

Faraday's Law

Changing magnetic field induces an electric field

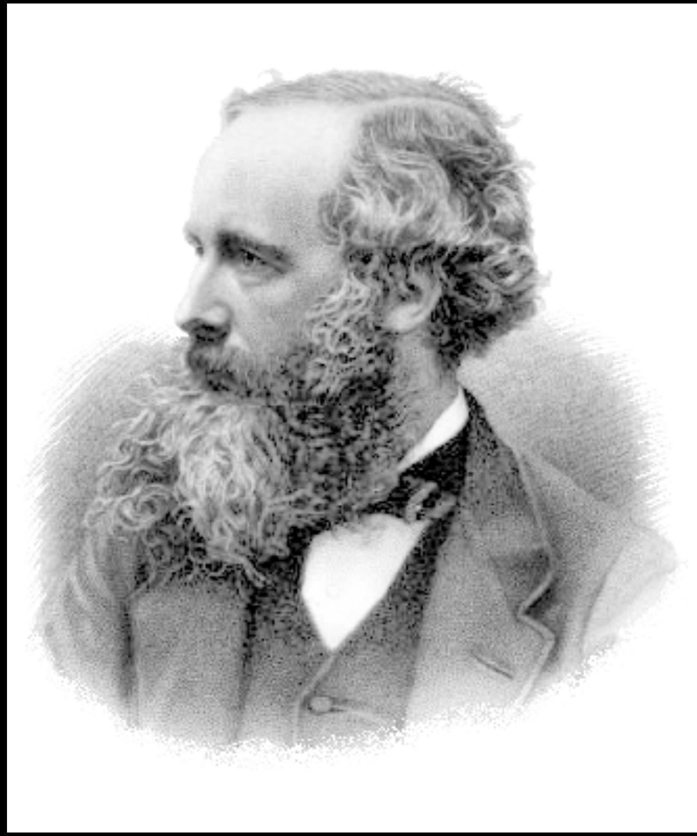
but then... the electric field changes

Maxwell 2: Electromagnetic wave



Electromagnetic wave: each field induces the other

Maxwell 2: Electromagnetic wave



Can we test this?

Plan:

Choose 2 waves (E-field wave and B-field wave)

- shape and orientation

Show they are a solution to Maxwell's Equations

If true, electromagnetic waves can exist

Maxwell 2: Electromagnetic wave

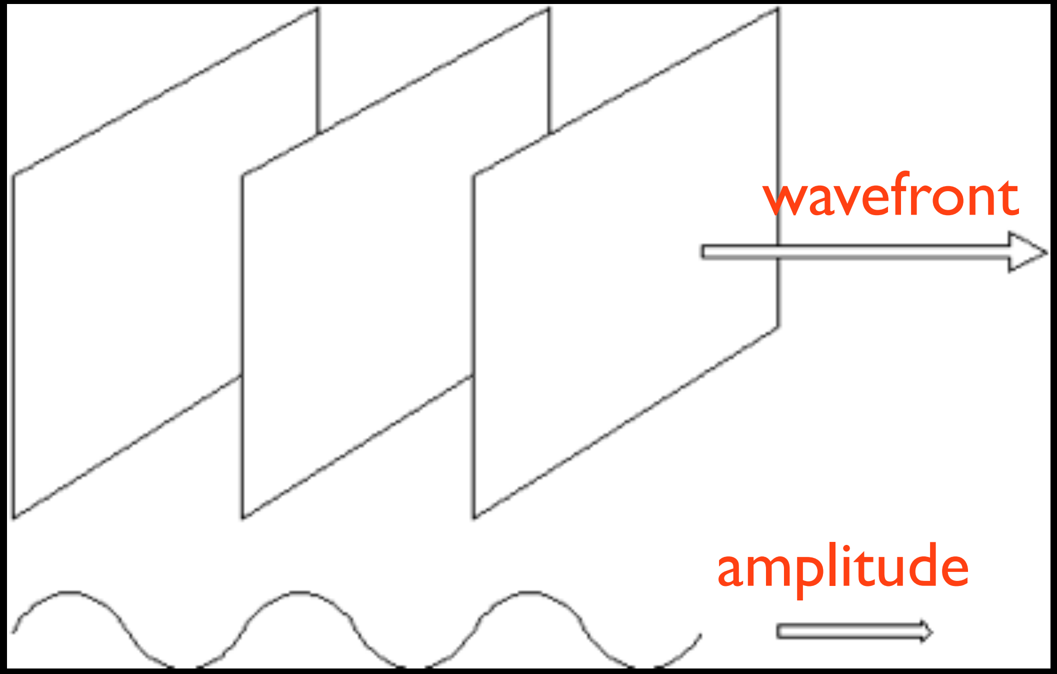
Test waves

Plane wave:

simplest type of electromagnetic wave.

(good approximation for realistic, spherical wave)

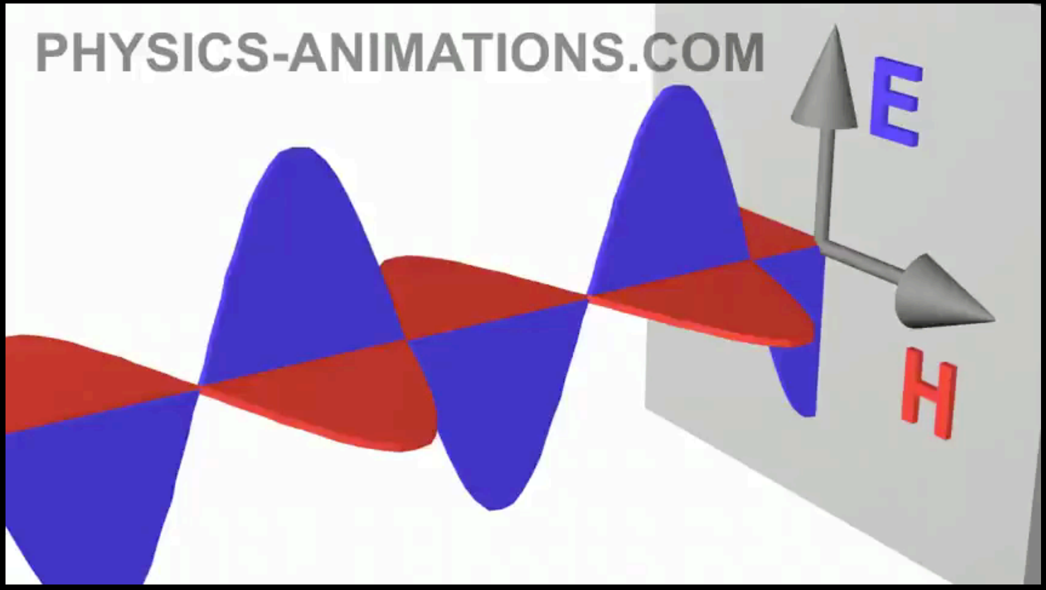
wavefronts are infinite planes



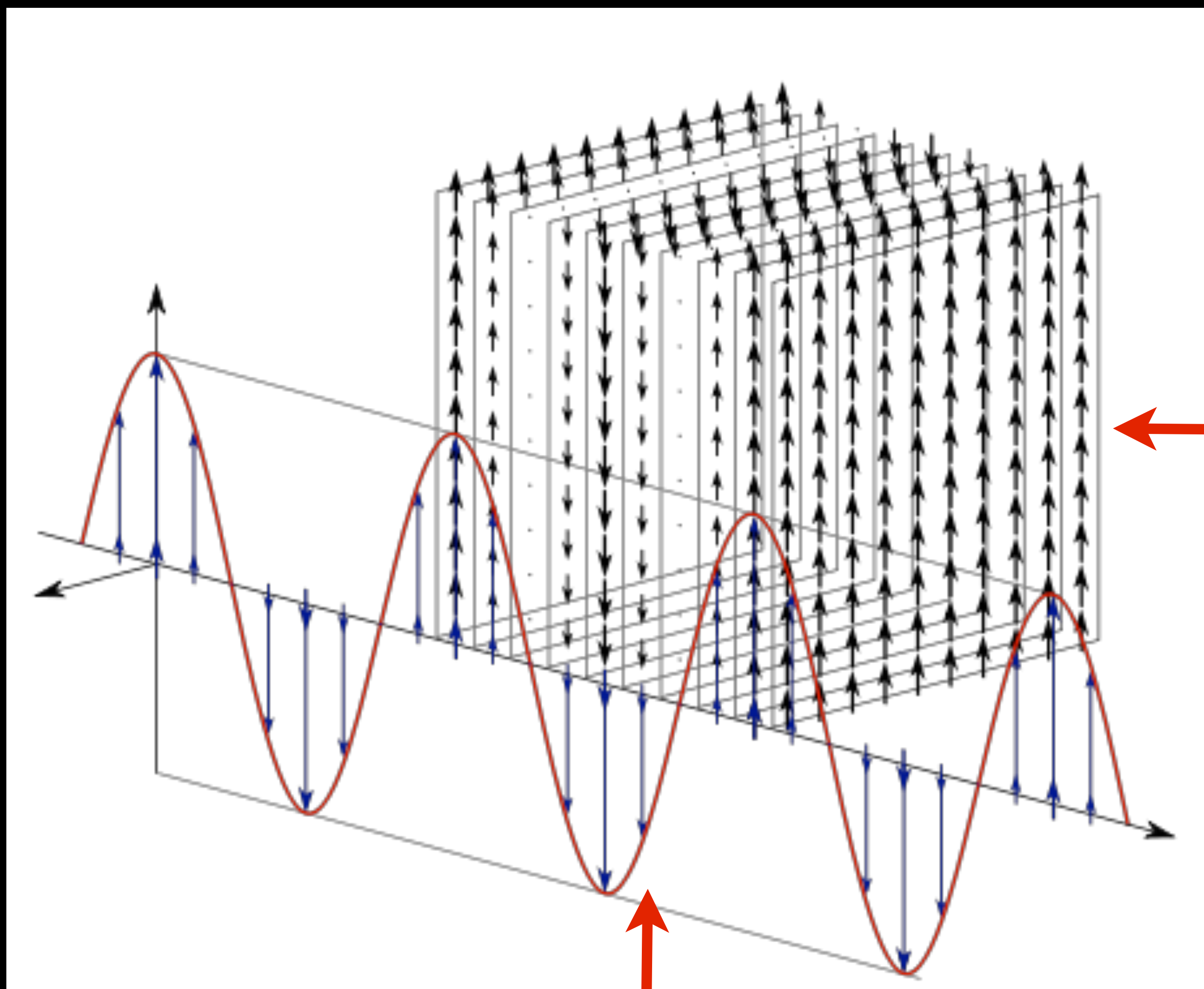
In a vacuum, $\bar{E}$ field and $\bar{B}$ field are perpendicular.

Also perpendicular to direction of propagation.

(transverse wave)



Maxwell 2: Electromagnetic wave



Planewaves:

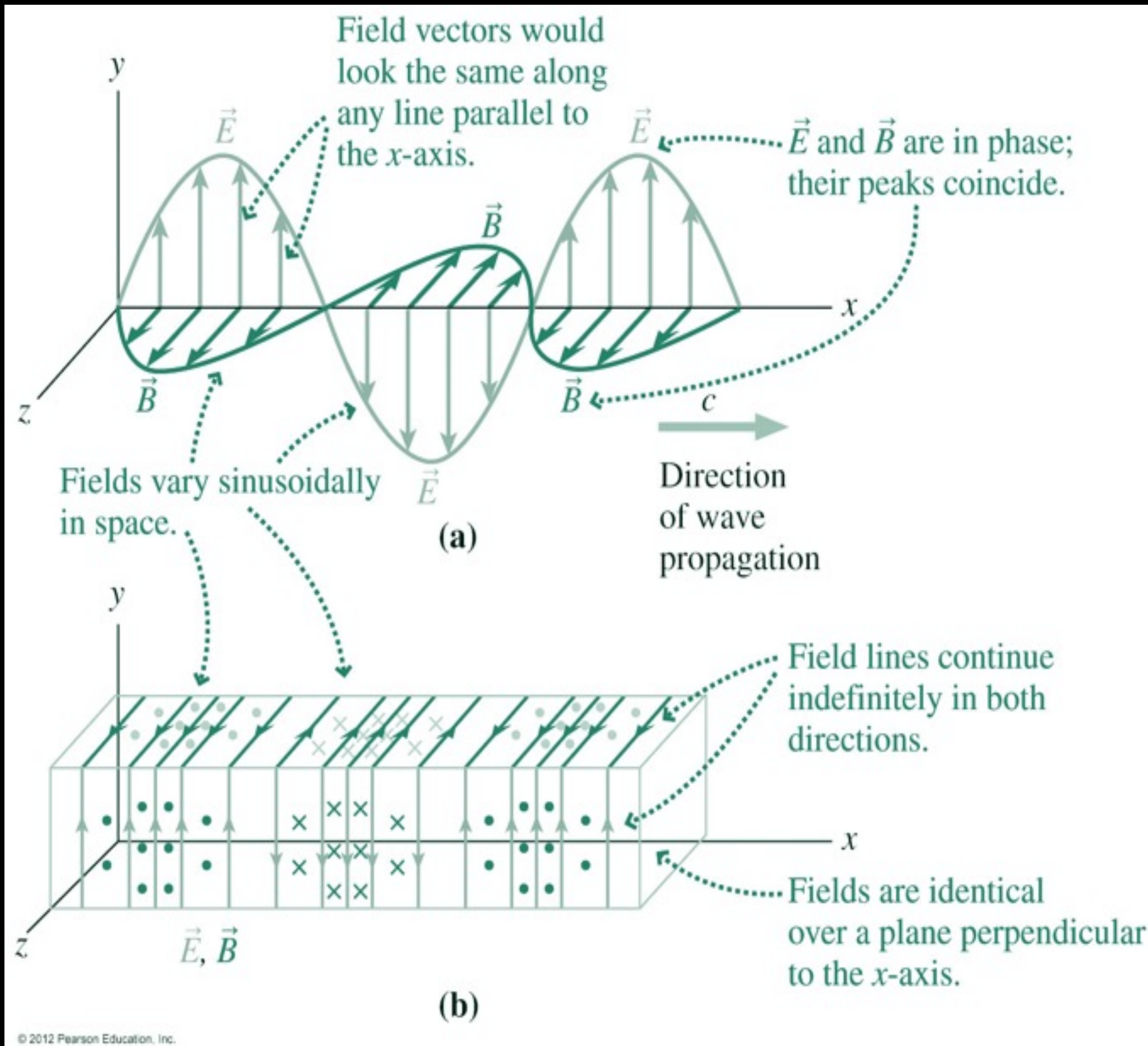
Field lines on infinite sheets

On each sheet, value of field is the same.

Wave vectors

Field properties sinusoidally (sine wave) vary between sheets

Maxwell 2: Electromagnetic wave



Maxwell 2: Electromagnetic wave

Last semester

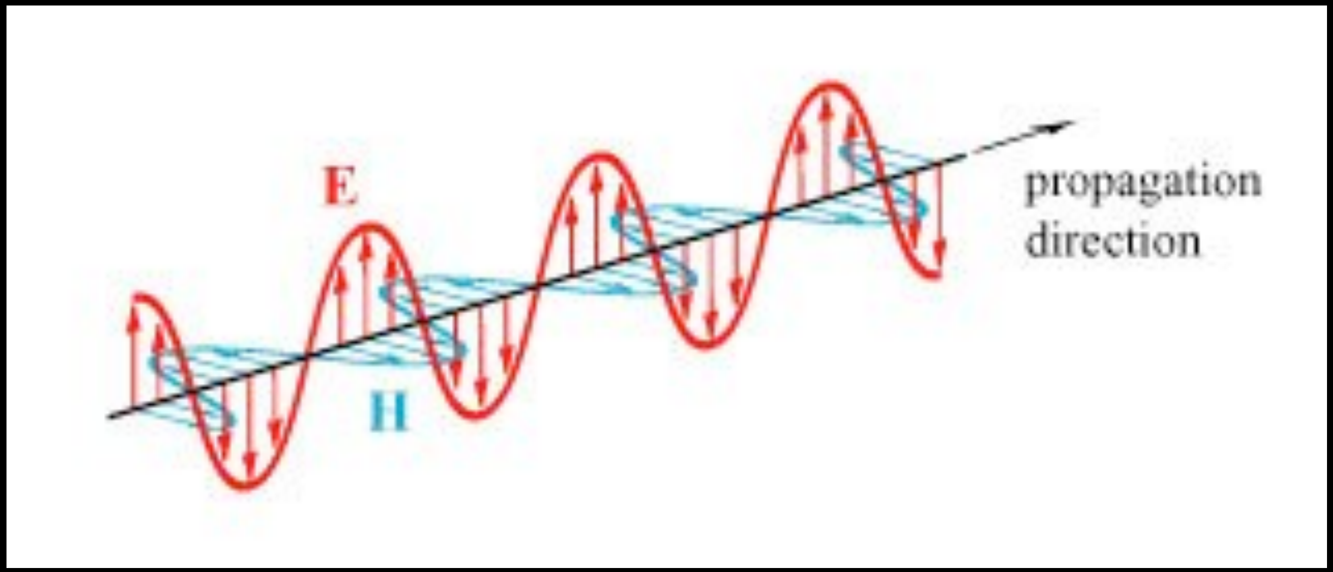
Equation for a wave: $y(x,t) = A\sin(kx - \omega t)$

amplitude (A) wave number (k) angular frequency (ω)

If waves travel in $x-$direction:

$$\bar{E}(x,t) = E_p \sin(kx - \omega t)\hat{j}$$

$$\bar{B}(x,t) = B_p \sin(kx - \omega t)\hat{k}$$



Since we can make any wave by superposing (adding) sine waves, if these waves obey Maxwell's equations, more complex waves will too.

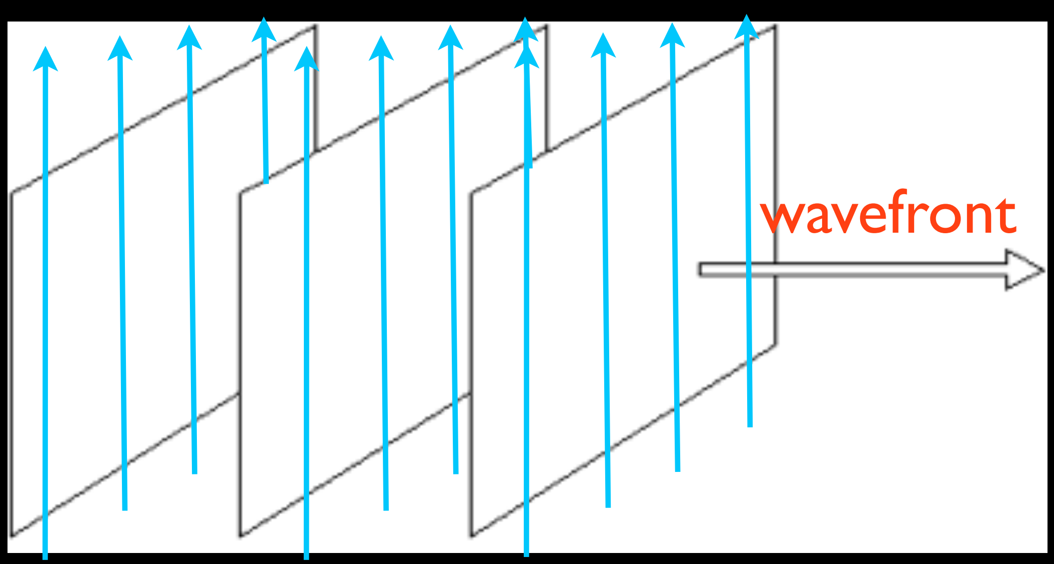
Maxwell 2: Electromagnetic wave

Gauss' Laws

Gauss's Law for $\bar{E}$ $\quad \oint \bar{E} \cdot d\bar{A} = 0$

Gauss's Law for $\bar{B}$ $\quad \oint \bar{B} \cdot d\bar{A} = 0$

Electric and magnetic flux through any closed surface = 0



Plane waves extend forever in 2 directions.

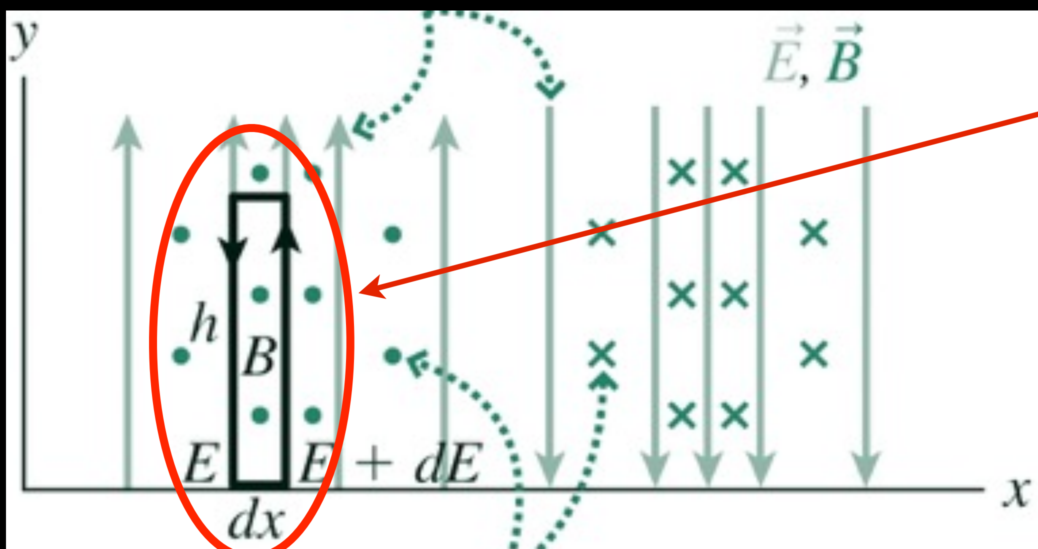
They do not start or end.

So, flux is always zero.

(Net field line number through surface = 0)

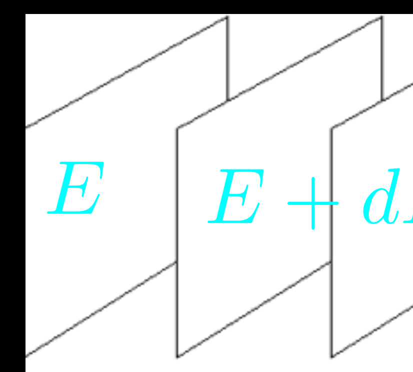
Maxwell 2: Electromagnetic wave

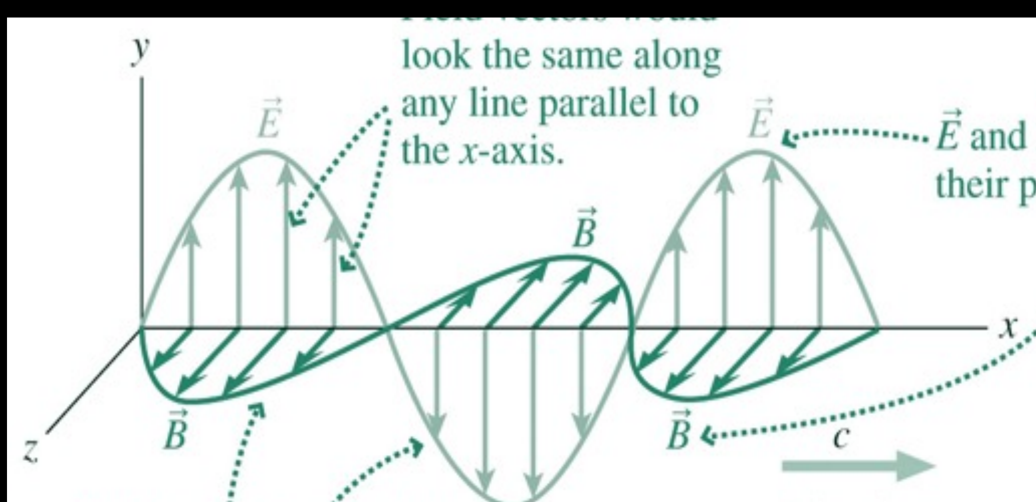
Faraday's law $\oint \bar{E} \cdot d\bar{r} = -\frac{d\Phi_B}{dt}$



Loop parallel to $\bar{E}$ field, perpendicular $\bar{B}$ field.

$h \times dx$





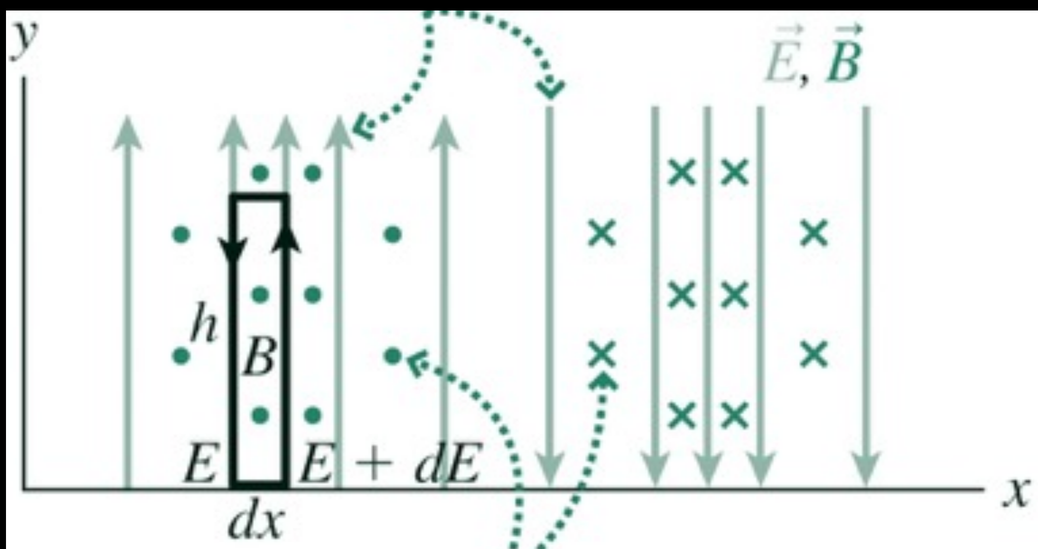
$$\oint \bar{E} \cdot d\bar{r} = -Eh + 0 + (E + dE)h + 0$$

$h \downarrow$ $\quad dx \rightarrow$ $\quad h \uparrow$ $\quad dx \leftarrow$

$$= hdE$$

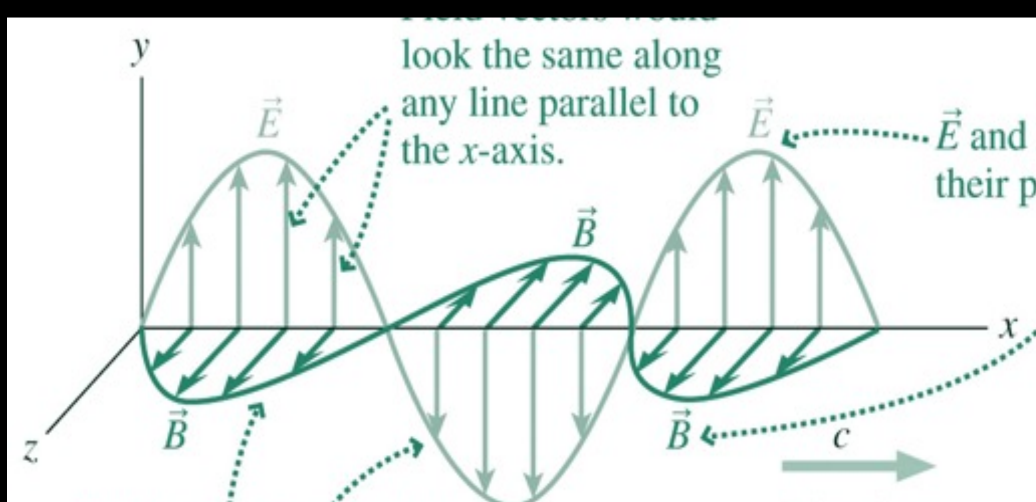
Maxwell 2: Electromagnetic wave

Faraday's law $$\oint \bar{E}\cdot d\bar{r} = -\frac{d\Phi_B}{dt}$$



Magnetic field perpendicular to electric.

$$\Phi_B = BA = Bhdx$$



$$\frac{d\Phi_B}{dt} = hdx\frac{dB}{dt}$$

Faraday's law: $$hdE = -hdx\frac{dB}{dt}$$

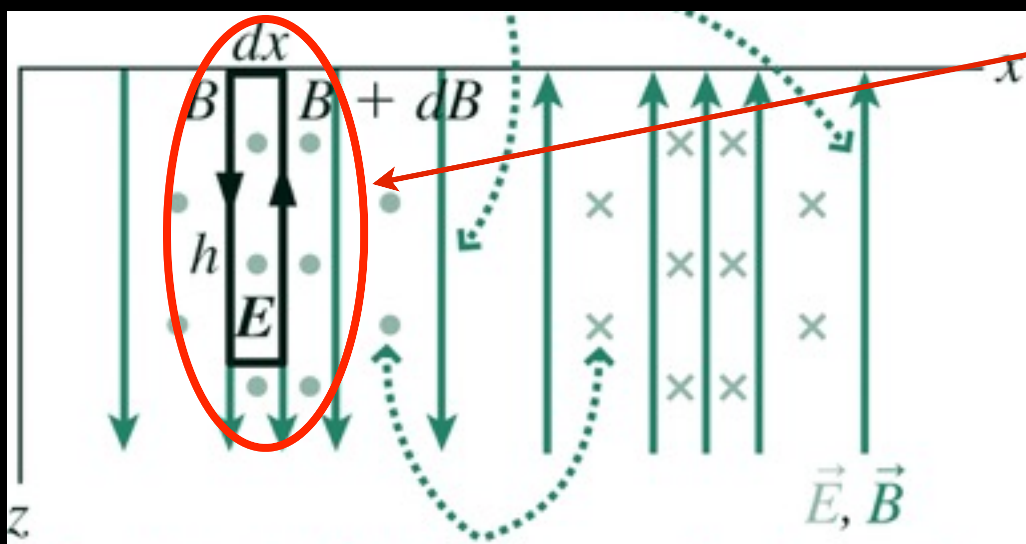
rate of change of E-field with position

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

rate of change of B-field with time

Maxwell 2: Electromagnetic wave

Ampere's law $$\oint \bar{B} \cdot d\bar{r} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$



Loop parallel to $\bar{B}$ field, perpendicular $\bar{E}$ field.

$$\oint \bar{B} \cdot d\bar{r} = Bh + 0 - (B + dB)h + 0$$

$h \downarrow \quad dx \rightarrow \quad h \uparrow \quad dx \leftarrow$

$$= -hdB$$

$$\frac{d\Phi_E}{dt} = hdx \left(\frac{dE}{dt} \right)$$

rate of change of B-field with position

$$\frac{\partial B}{\partial x} = -\epsilon_0 \mu_0 \frac{\partial E}{\partial t}$$

rate of change of E-field with time

Maxwell 2: Electromagnetic wave

$$\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$$

$$\frac{\partial B}{\partial x} = -\epsilon_0 \mu_0 \frac{\partial E}{\partial t}$$

Change in one field induces the other field

If our wave equations work,

$$\bar{E}(x,t) = E_p \sin(kx - \omega t)\hat{j}$$

$$\bar{B}(x,t) = B_p \sin(kx - \omega t)\hat{k}$$

try them

then an electromagnetic wave IS a solution to Maxwell's equations and our configuration is possible.

Maxwell 2: Electromagnetic wave

1st equation: $\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}$

$$\frac{\partial E}{\partial x} = \frac{\partial}{\partial x}\left[E_p \sin(kx - \omega t)\right] = kE_p \cos(kx - wt)$$

and

$$\frac{\partial B}{\partial t} = \frac{\partial}{\partial t}\left[B_p \sin(kx - \omega t)\right] = -\omega B_p \cos(kx - wt)$$

Therefore: $kE_p \cos(kx - \omega t) = -\left[-\omega B_p \cos(kx - \omega t)\right]$

True if $kE_p = \omega B_p$

Maxwell 2: Electromagnetic wave

2nd equation: $$\frac{\partial B}{\partial x} = -\epsilon_0 \mu_0 \frac{\partial E}{\partial t}$$

$$\frac{\partial B}{\partial x} = k B_p \cos(kx - \omega t)$$

and

$$\frac{\partial E}{\partial t} = -\omega E_p \cos(kx - \omega t)$$

Therefore: $$k B_p \cos(kx - \omega t) = -\epsilon_0 \mu_0 \left[-\omega E_p \cos(kx - \omega t)\right]$$

True if $$k B_p = \epsilon_0 \mu_0 \omega E_p$$

Maxwell 2: Electromagnetic wave

The waves:

$$\bar{E}(x,t) = E_p \sin(kx - \omega t)\hat{j}$$

$$\bar{B}(x,t) = B_p \sin(kx - \omega t)\hat{k}$$

where

$$kE_p = \omega B_p$$

$$kB_p = \epsilon_0 \mu_0 \omega E_p$$

are solutions to Maxwell's equations!

This shows electromagnetic waves are possible....

... but what are their properties?

Electromagnetic wave properties

Wave speed

Last semester: wave speed $= \frac{\omega}{k}$

From $kE_p = \omega B_p \longrightarrow E_p = \frac{\omega B_P}{k}$

Put in $kB_p = \epsilon_0 \mu_0 \omega E_p = \frac{\epsilon_0 \mu_0 \omega^2 B_P}{k}$

Therefore wave speed $= \frac{\omega}{k} = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$ EM wave speed in a vacuum

$$\frac{1}{\sqrt{\epsilon_0 \mu_0}} = \frac{1}{\sqrt{8.85 \times 10^{-12} \mathrm{C}^2/\mathrm{Nm}^2)(4\pi \times 10^{-7} \mathrm{N}/\mathrm{A}^2)}} = 3.00 \times 10^8 \mathrm{m/s}$$

Electromagnetic wave properties

$$\frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.00 \times 10^8 \mathrm{m/s}$$

speed of light

WAIT!!

... and light is a wave....

Therefore: light is an electromagnetic wave!

$$\frac{\omega}{k} = c$$ EM wave speed in a vacuum

since $\omega = 2\pi f$ and $k = 2\pi/\lambda$: $f\lambda = c$

Electromagnetic wave properties

Wave amplitude

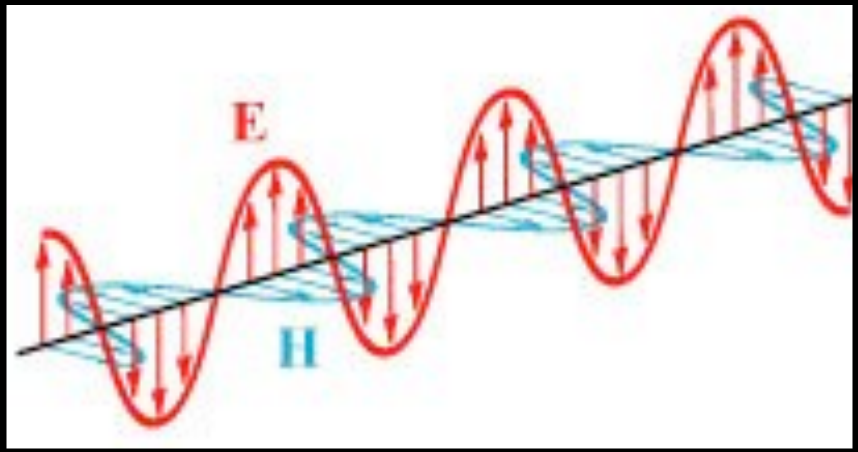
From $\frac{\omega}{k} = c$ and $kE_p = \omega B_p$ $\longrightarrow$ $E = \frac{\omega}{k}B = cB$

Phase and orientation

$\bar{E}$ and $\bar{B}$ in phase in *time*

$\bar{E}$ and $\bar{B}$ perpendicular *in space*

and to propagation direction.

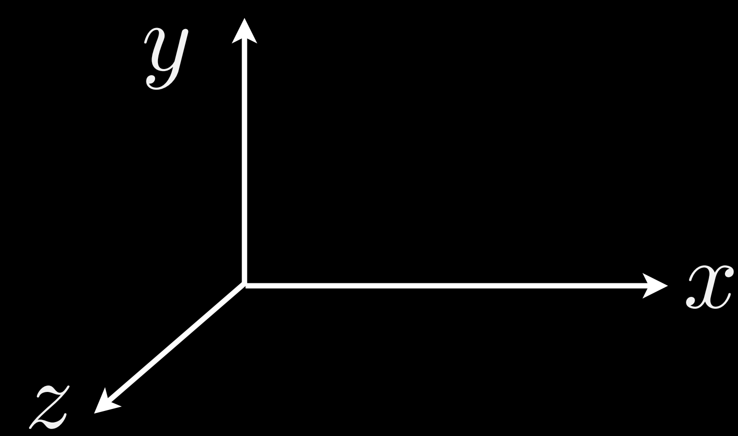


Propagation direction: $\bar{E} \times \bar{B}$

EM wave properties

Quiz

At a point, the electric field of an electromagnetic wave points in the +y direction, while the magnetic field points in the -z direction.



Is the propagation direction:

(A) +x

(B) -x

(C) either +x or -x, cannot tell which

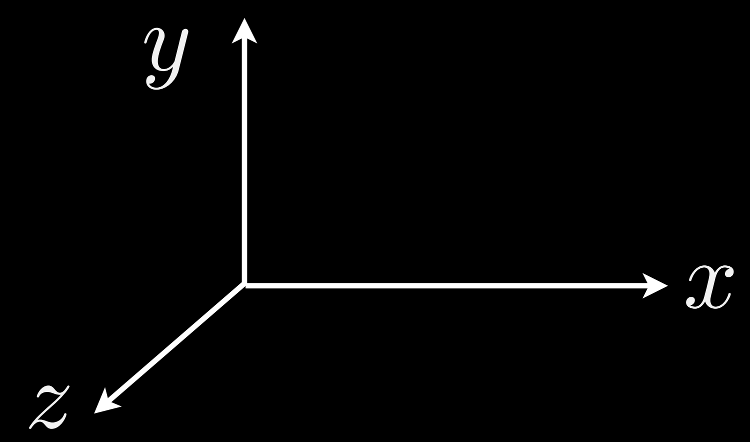
(D) -y

(E) +z

(F) not along coordinate axes

EM wave properties

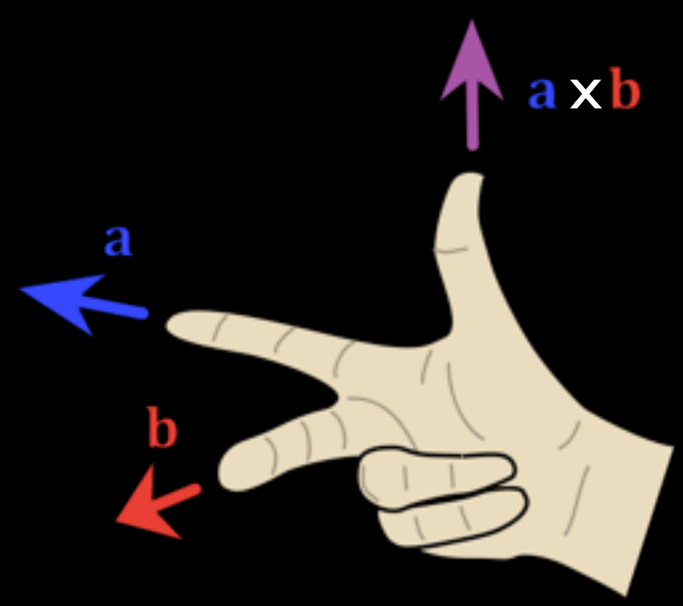
At a point, the electric field of an electromagnetic wave points in the +y direction, while the magnetic field points in the -z direction.



Is the propagation direction:

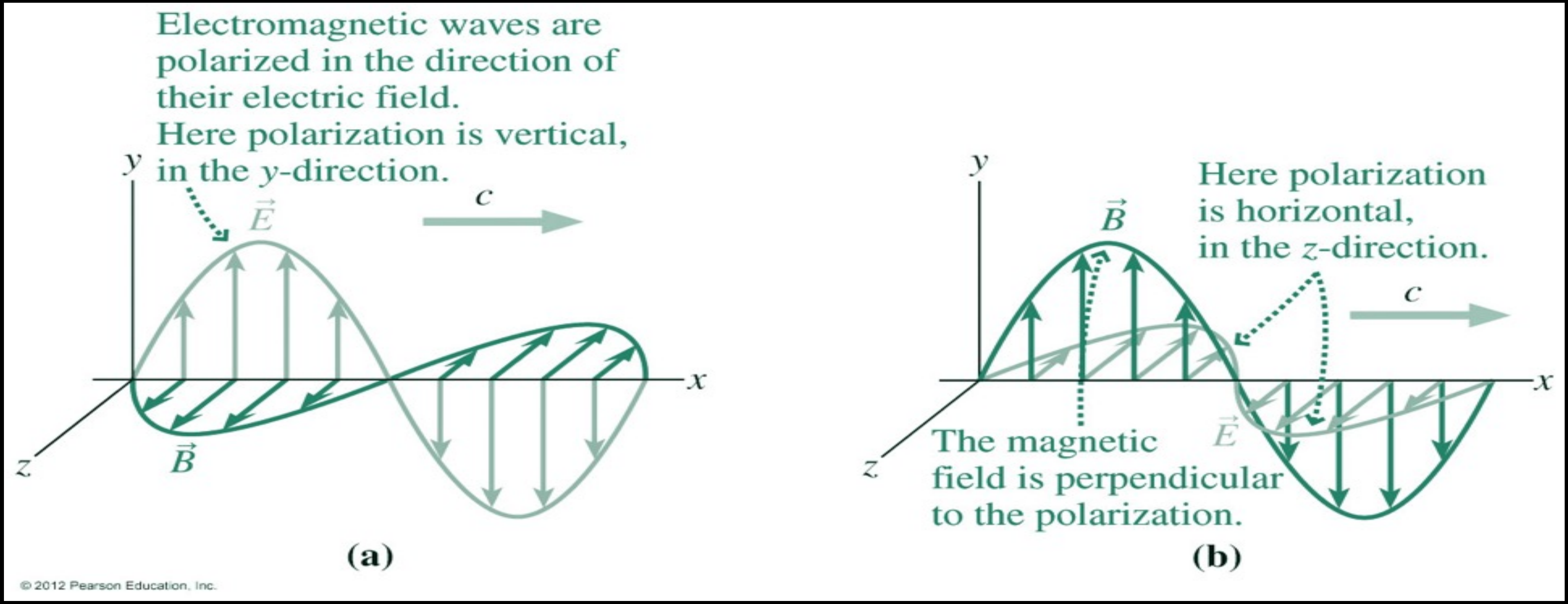
(B) -x

Propagation direction: $\bar{E} \times \bar{B}$



Polarisation

Polarisation specifies the direction of the $\bar{E}$ field.



$\bar{E}$ and $\bar{B}$ are always perpendicular,

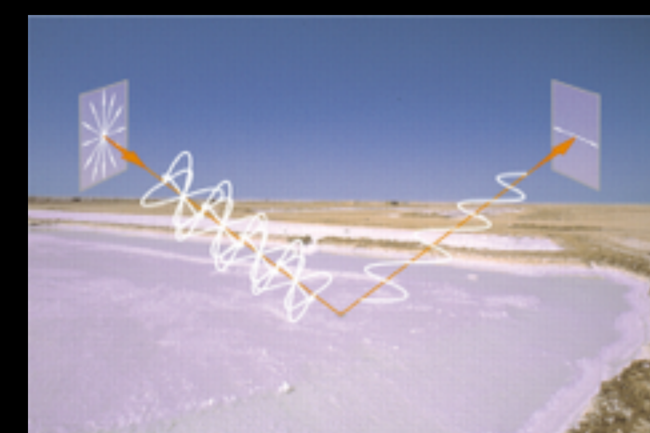
but there is still a choice in their orientation.

Polarisation

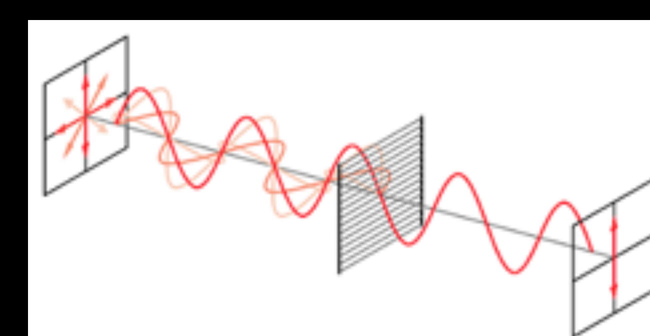
EM waves from antennaes (e.g for TV / radio) are polarised.

EM waves from the sun or a light bulb are unpolarised; mix of orientations

Unpolarised light can become polarised by reflecting .....



... or passing through....



substances whose structure has a preferred direction.

These are polarising materials.

Polarisation

A polarising material has a transmission axis.

Only the component of the E-field aligned with the transmission axis ($E\cos\theta$) can pass through.

Polarisation

Law of Malus:

$$S = S_0 \cos^2 \theta$$

output intensity

input intensity

angle between field and transmission axis

Electromagnetic waves are blocked completely if the transmission axis is perpendicular to the waves polarisation.

2 pieces of polarising material with transmission axes at right angles block all light.

Polarisation

Quiz

Unpolarised light shines on a pair of polarisers with perpendicular transmission axes.

A 3rd polariser is placed between them with a transmission axis at 45 degrees to the others.

What happens to the light?

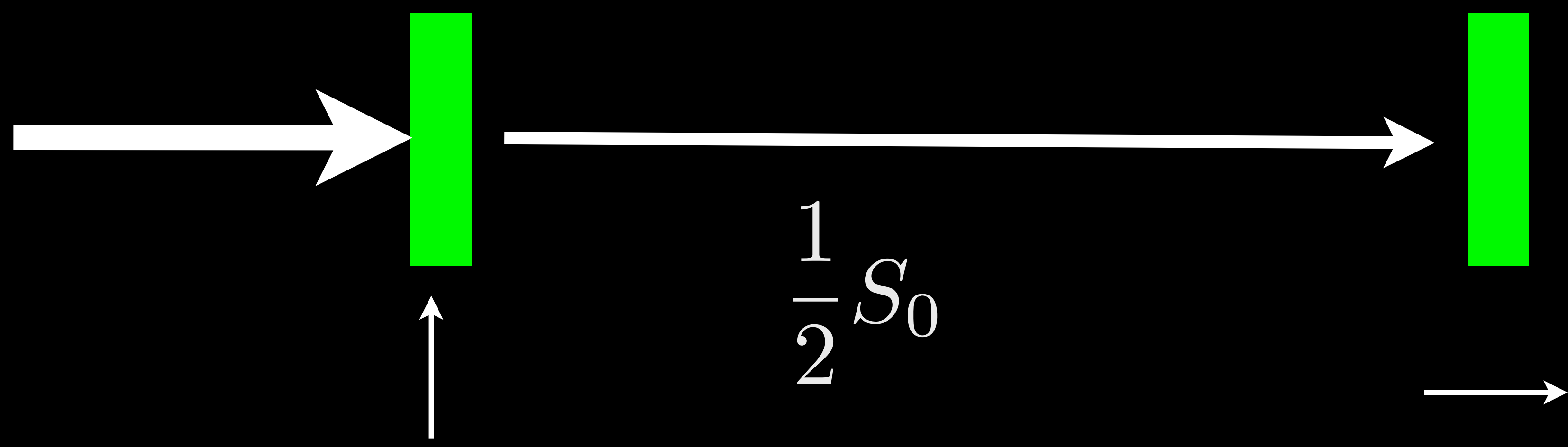
(A) nothing will change

(B) transmitted light with decrease

(C) transmitted light with increase

(D) transmitted light will be zero

Polarisation



Unpolarised light: Mix of directions $\cos^2\theta$ between $0 \rightarrow 1$

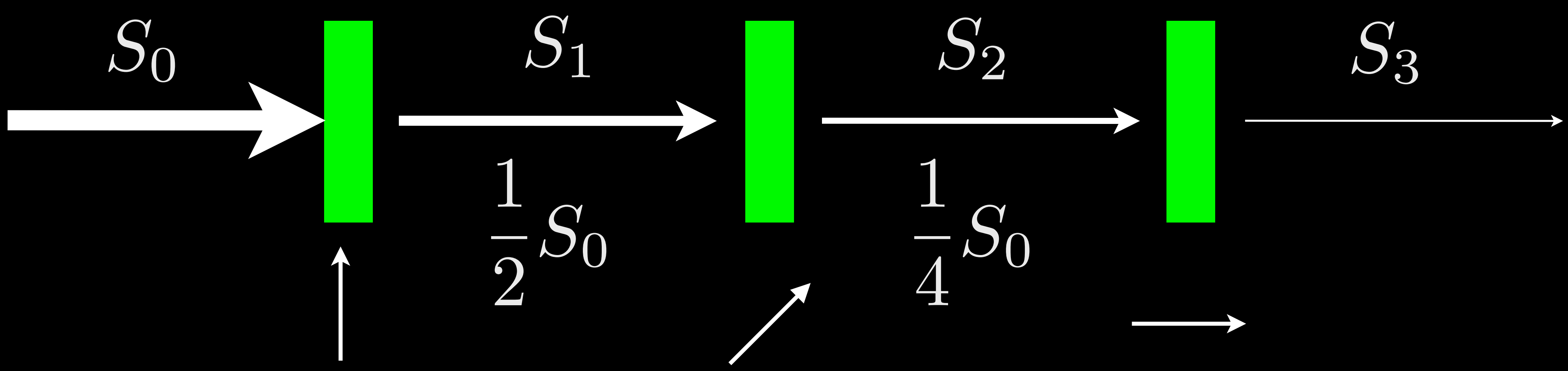
average $<\cos^2\theta>=\frac{1}{2}$

After 1st filter: $S=\frac{1}{2}S_0$ polarisation $\uparrow$

After 2nd filter: $\cos^2\theta=\cos^2 90=0.0$

$S=0$

Polarisation



After 1st filter: $S_1 = \frac{1}{2}S_0$ polarisation $\uparrow$

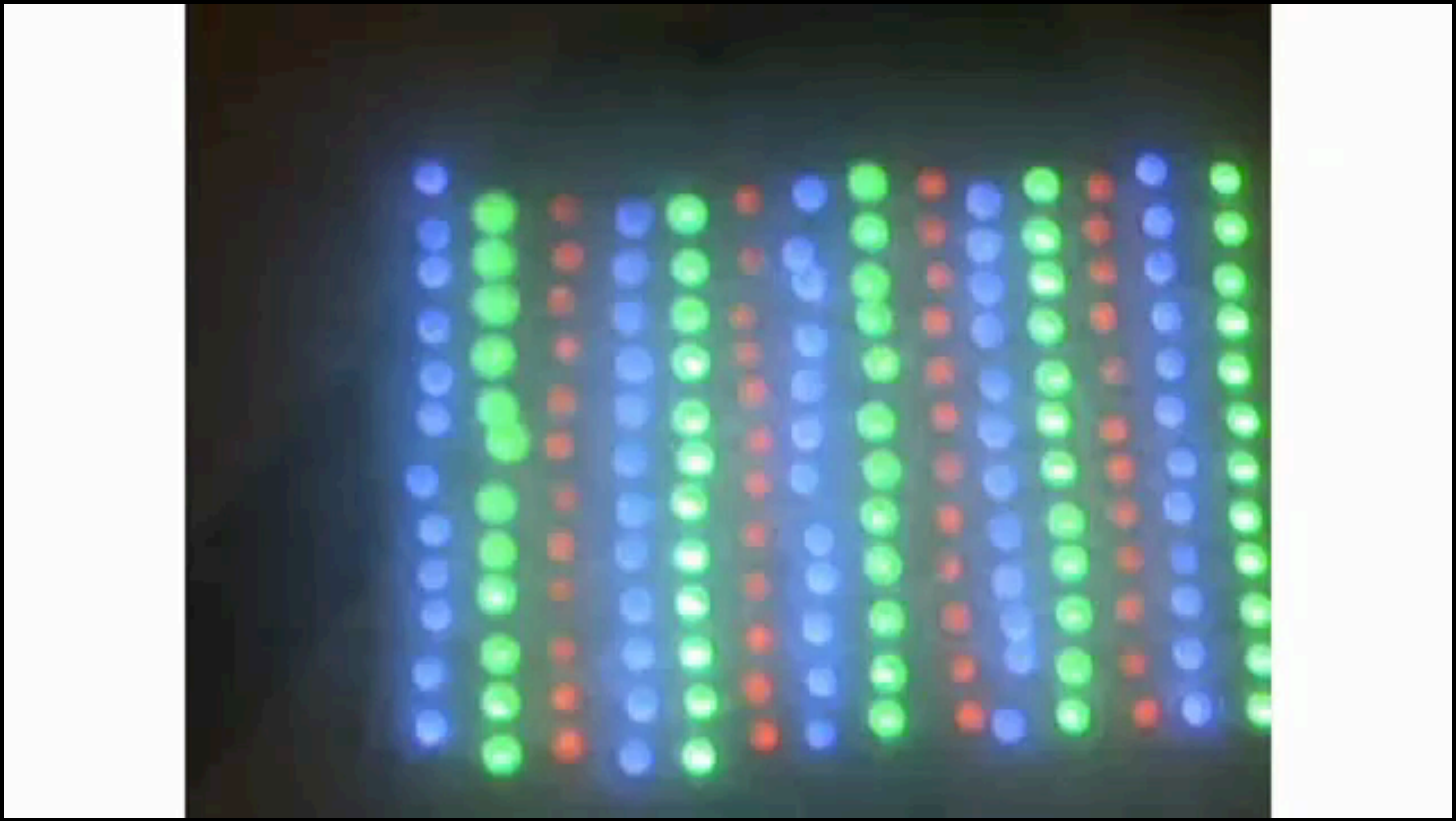
After 2nd filter: $\cos^2\theta = \cos^2 45 = \left(\frac{1}{\sqrt{2}}\right)^2$

$$S_2 = \frac{1}{2}\frac{1}{2}S_0$$

After 3rd filter: $\cos^2\theta = \cos^2 45 = \left(\frac{1}{\sqrt{2}}\right)^2$

$$S_3 = \frac{1}{2}\frac{1}{2}\frac{1}{2}S_0 = \frac{1}{8}S_0$$

Polarisation



Polarisation

Polarised light is incident on a sheet of polarising material.

20% of the light passes through.

What is the angle between the electric field and transmission axis?

(A) 12°

(B) 90°

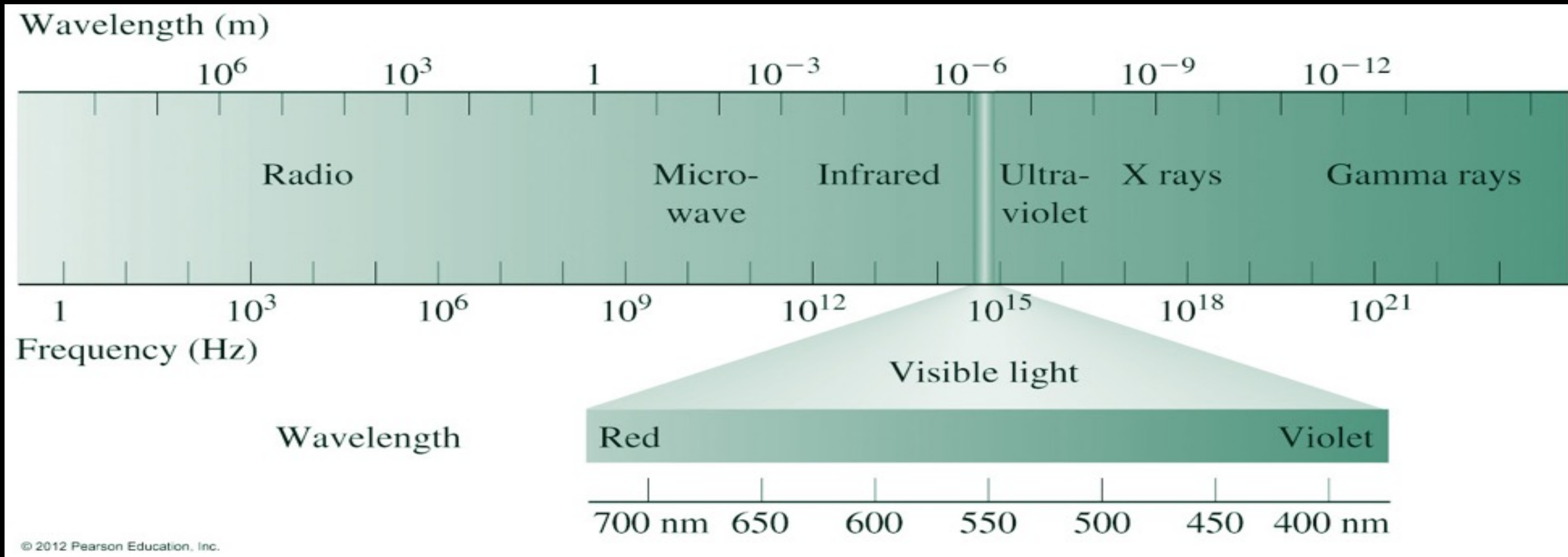
(C) 45°

(D) 63°

$$\frac{S}{S_0} = \cos^2\theta = 0.2$$

$$\theta = \cos^{-1}(\sqrt{0.2})$$

Electromagnetic spectrum



EM waves have a large range of frequencies and wavelengths.

Visible light is only a small part of the spectrum!

Electromagnetic spectrum

Quiz

A 60 Hz power line emits electromagnetic radiation. What is the wavelength?

(A) $1.2 \times 10^7 \text{m}$

(B) $5 \times 10^6 \text{m}$

(C) $1.2 \times 10^9 \text{m}$

(D) $5 \times 10^5 \text{m}$

$$\lambda = \frac{c}{f} = \frac{3.0 \times 10^8 \text{m/s}}{60 \text{Hz}}$$

$$c = 3.0 \times 10^8 \text{m/s}$$

Electromagnetic waves

Quiz

Which of the following does NOT result in emissions of an EM wave?

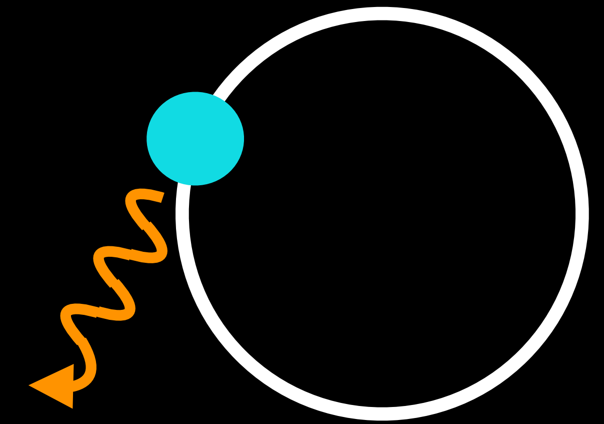
(A) A charged particle moving in a circle at constant speed

(B) A charged particle moving in a straight line at constant speed

(C) A stationary solid sphere with its total charge, Q, changing in time

Electromagnetic waves

Why does a charged particle moving in a circle at constant speed create EM radiation?



(A) The charge's speed is not constant and this causes a changing field

(B) The charge is accelerating. Accelerating charges cause a changing field

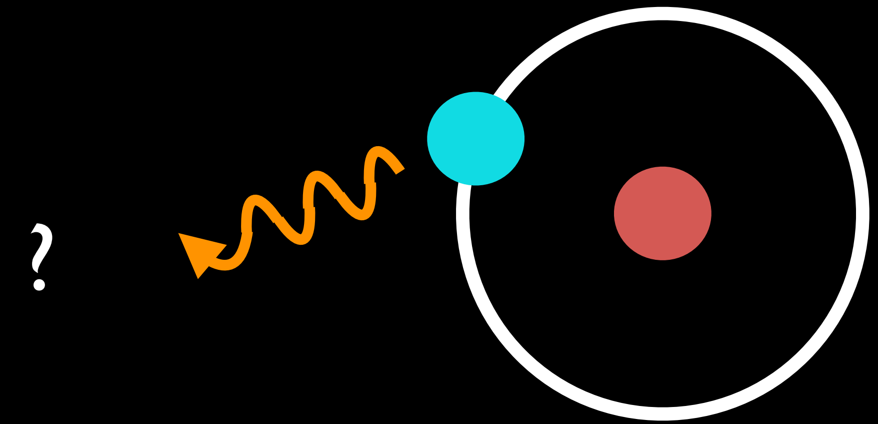
(C) There must be a magnet in the circle centre and this creates an EM wave.

(D) Christmas magic. 

Electromagnetic waves

Quiz

So…..



Does an atom (and electron moving around a proton) create an electromagnetic wave?

(A) Yes

Next lecture…..

(B) No