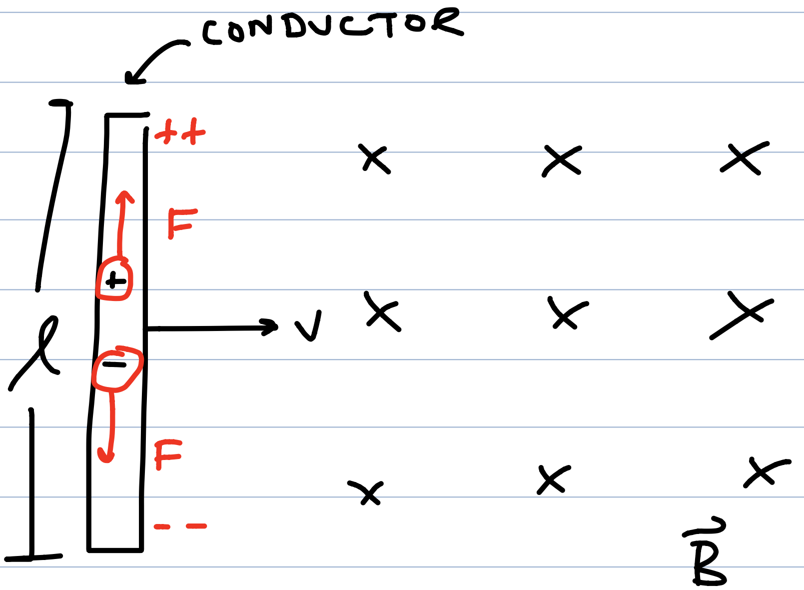
ELECTROMAGNETIC INDUCTION

INDUCED EMF



- THE MAGNETIC FORCE ON MOVING CHARGES ACTS IN A WAY THAT SEPARATES CHARGES - INCREASING THEIR POTENTIAL ENERGY.

- CONSIDER THE WORK DONE ON THE CHARGES:

$$V = \frac{E_p}{q}$$

$$E_p = qV$$

$$W = Fd$$
$$= qvB\ell$$

$$W = \Delta E_p$$
$$= q\Delta V$$

$$\cancel{q}\Delta V = \cancel{q}vB\ell$$

$$\Delta V = vB\ell$$

$$\boxed{\varepsilon = B\ell v}$$

ε : INDUCED ELECTRIC POTENTIAL, V

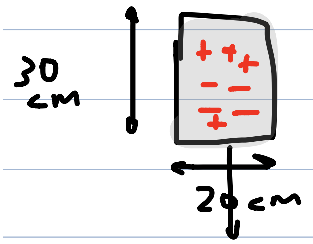
B : MAGNETIC FIELD STRENGTH, T

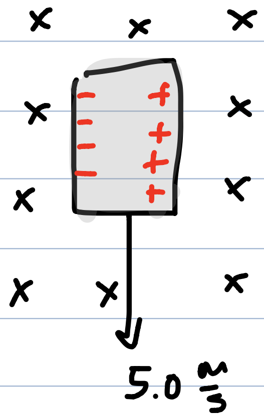
ℓ : WIDTH OF CHARGE SEPARATION, m ($\perp$ TO $\vec{v}$ AND $\vec{B}$)

v : VELOCITY, $\frac{m}{s}$

EXAMPLE

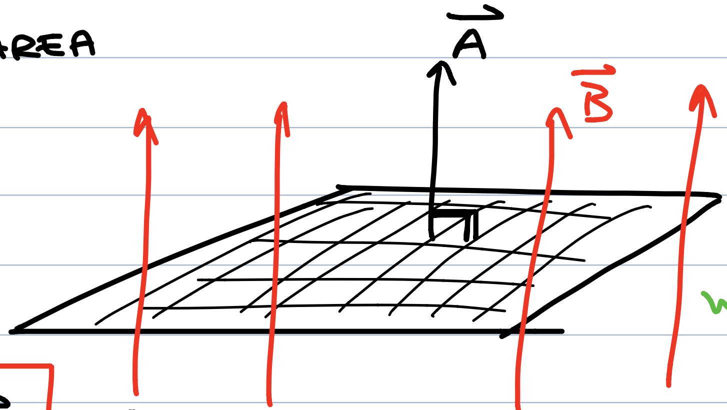
A 20 cm × 30 cm ALUMINUM PLATE IS DROPPED THROUGH A MAGNETIC FIELD OF 0.002 T. WHAT IS THE INDUCED VOLTAGE WHEN THE SPEED REACHES 5.0 $\frac{m}{s}$? WHICH SIDE IS POSITIVE?





MAGNETIC FLUX

- **MAGNETIX FLUX** IS THE SCALAR PRODUCT BETWEEN THE MAGNETIC FIELD AND THE AREA VECTOR.
- **AREA VECTOR**: MAGNITUDE IS EQUAL TO THE AREA; DIRECTION IS PERPENDICULAR TO THE AREA



PHI

$$\boxed{\Phi = \vec{B} \cdot \vec{A}}$$

WEBERS

Φ : MAGNETIC FLUX, Wb

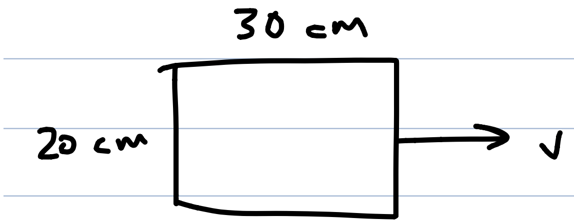
$\vec{B}$: MAGNETIC FIELD STRENGTH, T

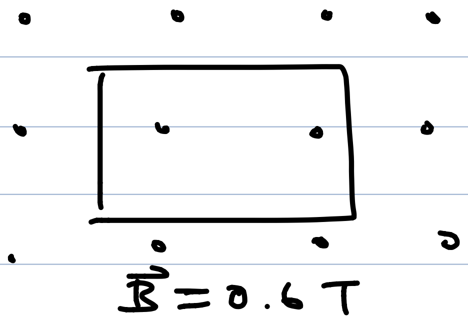
$\vec{A}$: AREA OF LOOP, m^2

- IF $\vec{B}$ IS PARALLEL TO THE SURFACE (I.E. THE MAGNETIC FIELD DOES NOT GO THROUGH THE AREA), THERE IS NO FLUX

EXAMPLE

CALCULATE THE CHANGE IN MAGNETIC FLUX THAT OCCURS IN THE LOOP.





$$\Delta \Phi = \Phi_f - \cancelto{0}{\Phi_i}$$

$$= B A$$

$$= (0.6)(0.2 \times 0.3) = \boxed{0.036 \text{ Wb}}$$

FARADAY'S LAW

- WHEN THERE IS A CHANGE TO THE MAGNETIC ENVIRONMENT OF A COIL OF WIRE, AN EMF IS INDUCED WHICH IS PROPORTIONAL TO THE NUMBER OF COILS AND THE RATE OF CHANGE OF FLUX.

$$\varepsilon = N \frac{\Delta \Phi}{\Delta t}$$

LENZ'S LAW

- THE INDUCED CURRENT ACTS IN A DIRECTION THAT ATTEMPTS TO OPPOSE NEUTRALIZE ANY EXTERNAL CHANGE IN FLUX.

$$\boxed{\varepsilon = -N\frac{\Delta\Phi}{\Delta t}}$$

ε : INDUCED ELECTRIC POTENTIAL, V

N: NUMBER OF COILS

Φ : MAGNETIC FLUX, Wb

t : TIME, s

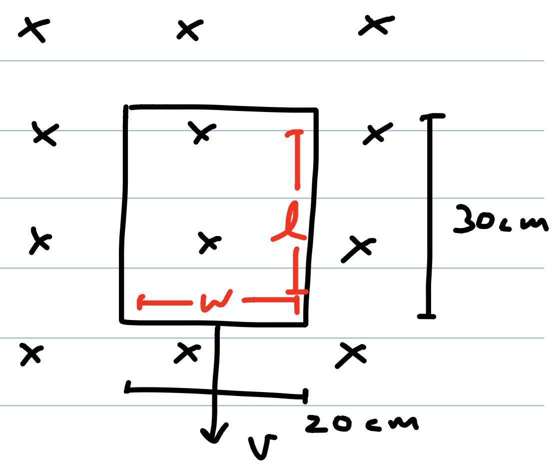
EXAMPLE

A 20 cm × 30 cm RECTANGULAR LOOP MOVES OUT OF A 5.0×10^{-2} T MAGNETIC FIELD. CALCULATE THE EMF INDUCED AT THE FOLLOWING SPEEDS.

a) $1.0 \frac{m}{s}$

b) $4.0 \frac{m}{s}$

WHAT IS THE DIRECTION OF THE CURRENT?



$$\mathcal{E} = \overset{1}{\cancel{N}} \frac{\Delta \Phi}{\Delta t}$$

$$= \frac{B \Delta A}{\Delta t}$$

$$= B\, w \left(\overset{v}{\frac{\Delta \ell}{\Delta t}} \right)$$

$$= B w v$$

$$= (0.050)(0.2)(1.0)$$

$$= \boxed{0.01 \text{ V}}$$

b) $\boxed{\mathcal{E} = 0.04 \text{ V}}$

1. MAGNETIC FLUX IS DECREASING AS IT LEAVES B-FIELD

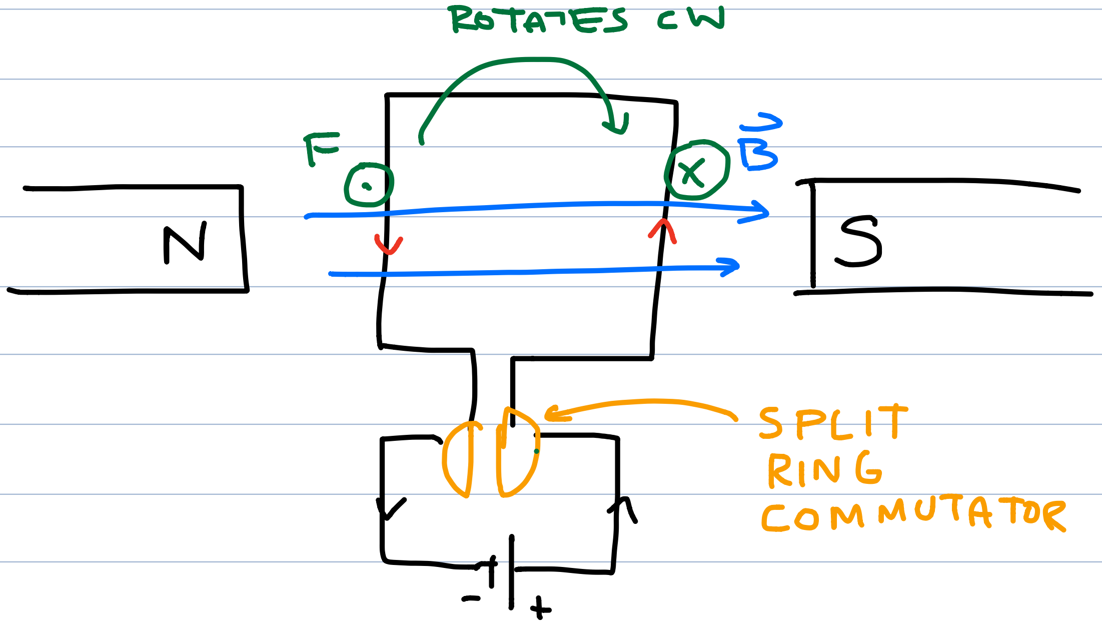
2. CURRENT WILL FLOW IN A DIRECTION THAT INCREASES MAGNETIC FLUX

3. THE EXTERNAL B-FIELD IS INTO THE PAGE SO WE WANT THE B-FIELD GENERTED BY THE LOOP TO BE INTO THE PAGE

→ CLOCKWISE

ELECTRIC MOTORS AND GENERATORS

- A **MOTOR** USES CURRENT IN A MAGNETIC FIELD TO PRODUCE MOTION
- A **GENERATOR** USES MOTION IN A MAGNETIC FIELD TO INDUCE AN EMF



- A **SPLIT RING COMMUTATOR** REVERSES THE CURRENT IN THE LOOP WHEN THE LOOP HAS ROTATED 180° (SO THE TORQUE IS ALWAYS IN THE SAME DIRECTION)

COUNTER EMF AKA BACK EMF

- WHENEVER A COIL TURNS IN A B-FIELD, AN EMF IS INDUCED IN THE COIL THAT OPPOSES THE CURRENT IN THE COIL (ACCORDING TO FARADAY'S LAW AND LENZ'S LAW).
- A MOTOR ACTS AS A GENERATOR WHENEVER IT TURNS.

$$\boxed{\underbrace{\mathcal{E} - V_{\text{COUNTER}}}_{\text{effective EMF}} = Ir}$$

$\mathcal{E}$: APPLIED VOLTAGE, V

V_{COUNTER} : INDUCED COUNTER EMF, V

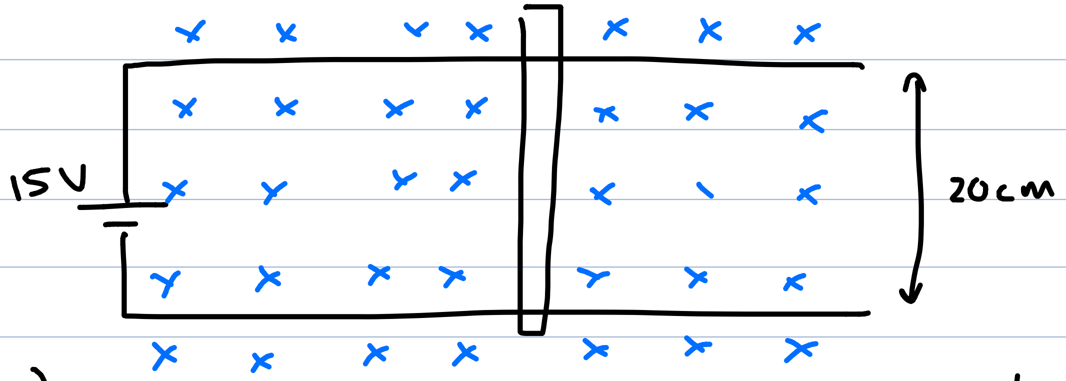
I : CURRENT, A

r : RESISTANCE, Ω

- WHEN THE MOTOR DOES NOT MOVE, $V_{\text{COUNTER}} = 0$ AND $\mathcal{E} = Ir$. BECAUSE r IS SMALL, I IS BIG - DANGEROUSLY BIG.

EXAMPLE: RAIL GUN

A 25cm LONG METAL ROD OF MASS 1.0 kg IS LAID ACROSS TWO LEVEL CONDUCTING RAILS IN A UNIFORM MAGNETIC FIELD $B = 0.5\,T$. WHEN A VOLTAGE OF $\mathcal{E} = 15V$ IS CONNECTED, THE ROD IS INITIALLY AT REST. THE ROD HAS A RESISTANCE OF $0.75\,\Omega$



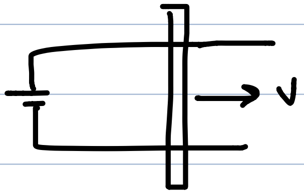
a) WHAT IS THE INITIAL ACCELERATION OF THE ROD?

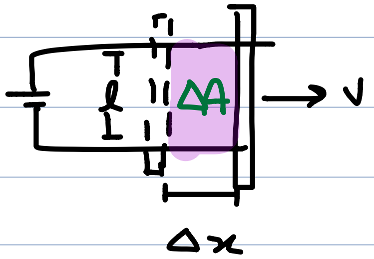
$$F_B = \ell I B$$
$$= (0.2)(20)(0.5)$$
$$= 2\,N$$

$$I = \frac{V}{R}$$
$$= \frac{15}{0.75}$$
$$= 20A$$

$$F_{NET} = ma$$
$$F_B = ma$$
$$a = \frac{F_B}{m}$$
$$= \frac{2}{1.0} = \boxed{2\ \frac{m}{s^2}}$$ RIGHT

b) WHAT IS THE COUNTER EMF WHEN THE ROD REACHES A SPEED OF $50 \frac{m}{s}$?





$$\mathcal{E} = -\frac{\Delta \Phi}{\Delta t} \qquad (N=1)$$

$$= -\frac{B \Delta A}{\Delta t}$$

$$= -\frac{B \ell \overset{v}{\left(\Delta x\right.}}{\left.\Delta t\right)}$$

$$= -B \ell v$$

$$= -(0.5)(0.2)(50)$$

$$= \boxed{5 \text{ V}}$$

c) WHAT IS THE MAXIMUM SPEED OF THE ROD?

THE ROD STOPS ACCELERATING WHEN $F_B = 0$

$$F_B = \ell I B$$

$F_B = 0$ WHEN $I = 0$

$I = 0$ WHEN $V_{APPLIED} \overset{\approx 15V}{=} V_{COUNTER}$

FROM b)

$$\varepsilon = -Bl v$$

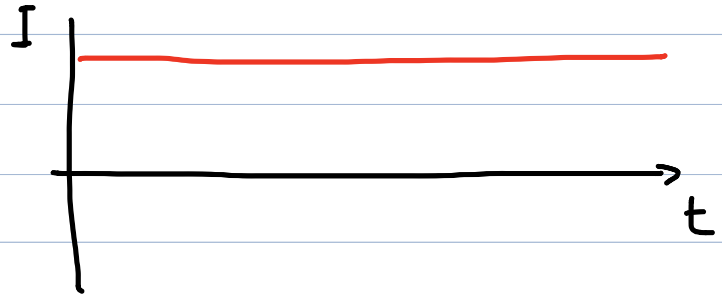
$$v = -\frac{\varepsilon}{Bl}$$

$$= \frac{15}{(0.5)(0.2)}$$

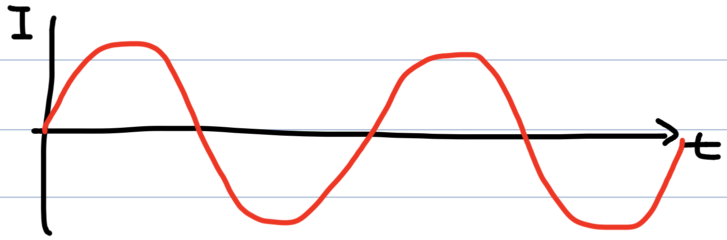
$$= \boxed{150 \frac{m}{s}}$$

ALTERNATING CURRENT (AC) VS DIRECT CURRENT (DC)

- DIRECT CURRENT: VOLTAGE AND CURRENT ARE STEADY AND ACT IN ONE DIRECTION

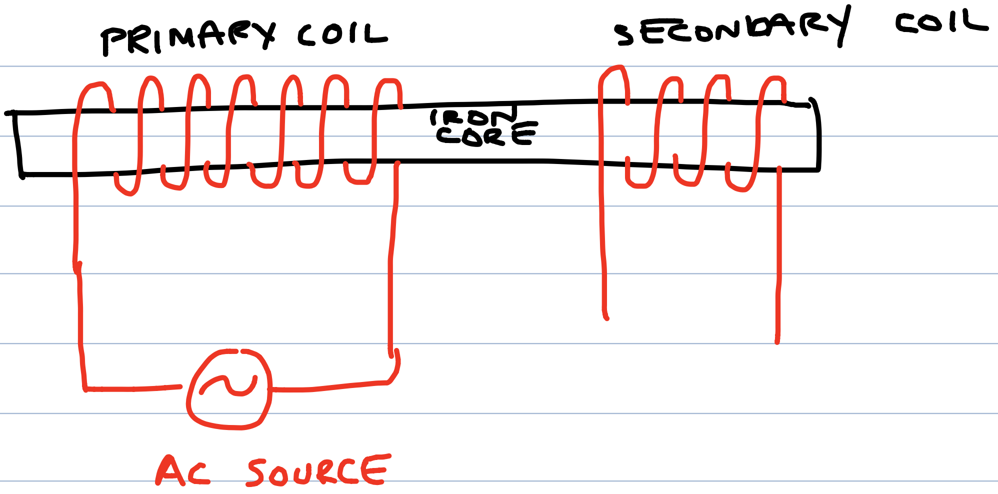


- ALTERNATING CURRENT: VOLTAGE AND CURRENT PERIODICALLY REVERSE DIRECTION



TRANSFORMERS

- TRANSFORMERS ARE DEVICES THAT CHANGE VOLTAGE AND CURRENT USING THE PRINCIPLE OF ELECTROMAGNETIC INDUCTION.



① AN ALTERNATING CURRENT IN THE PRIMARY COIL PRODUCES AN ALTERNATING B-FIELD

② THE ALTERNATING B-FIELD IS ALMOST TOTALLY CONTAINED IN THE IRON CORE WHICH IS CONNECTED TO THE SECONDARY COIL

③ AN ALTERNATING B-FIELD MEANS THERE IS A CHANGE IN FLUX. THIS RESULTS IN AN INDUCED VOLTAGE IN THE SECONDARY COIL. THE RATE OF CHANGE IN FLUX IS ESSENTIALLY THE SAME FOR BOTH COILS (A and ΔB ARE

THE SAME)

CONSIDER THE EMF IN EACH COIL:

① $V_p = -N_p \frac{\Delta\Phi}{\Delta t}$ ② $V_s = -N_s \frac{\Delta\Phi}{\Delta t}$

DIVIDE ① BY ②

$$\boxed{\frac{V_p}{V_s} = \frac{N_p}{N_s}}$$

- STEP-UP TRANSFORMER: $N_s > N_p$ so $V_s > V_p$
- STEP-DOWN TRANSFORMER: $N_s < N_p$ so $V_s < V_p$

- CONSIDER THE CONSERVATION OF ENERGY:

$$E_p = E_s$$

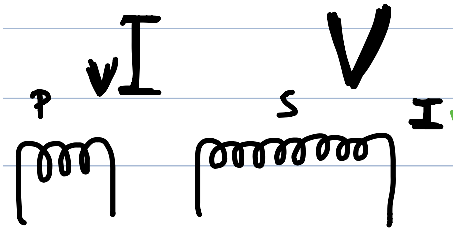
$$\frac{E_p}{t} = \frac{E_s}{t}$$

$$P_p = P_s$$

$$I_p V_p = I_s V_s$$

$$\boxed{\frac{V_p}{V_s} = \frac{I_s}{I_p}}$$

- A DECREASE IN VOLTAGE RESULTS IN AN INCREASE IN CURRENT.



VOLTAGE INCREASES

current decreases

- STEP-UP TRANSFORMERS ARE USED WHEN DISTRIBUTING POWER OVER LARGE DISTANCES TO DECREASE POWER LOSS. $\uparrow V$ $\downarrow I$

  Power loss $P = I^2R$

- STEP-DOWN TRANSFORMER ARE USED WHEN THE VOLTAGE REACHES ITS DESTINATION.