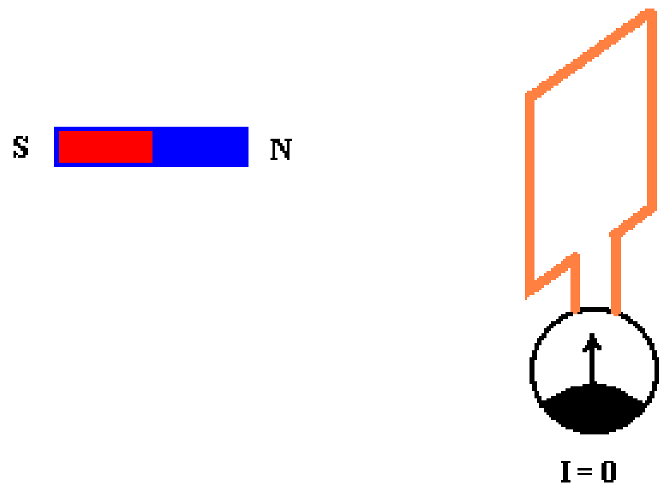
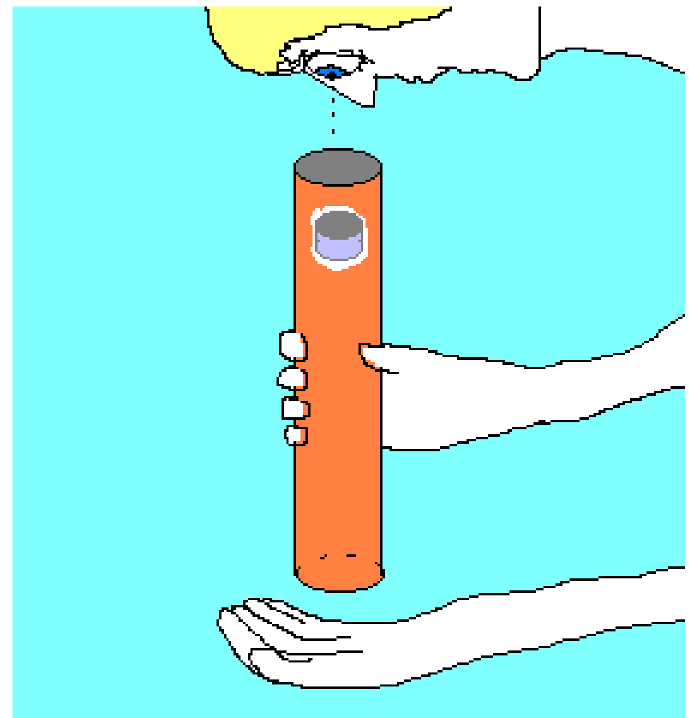
Electromagnetic Induction





PHY232 – Spring 2007

Jon Pumplin

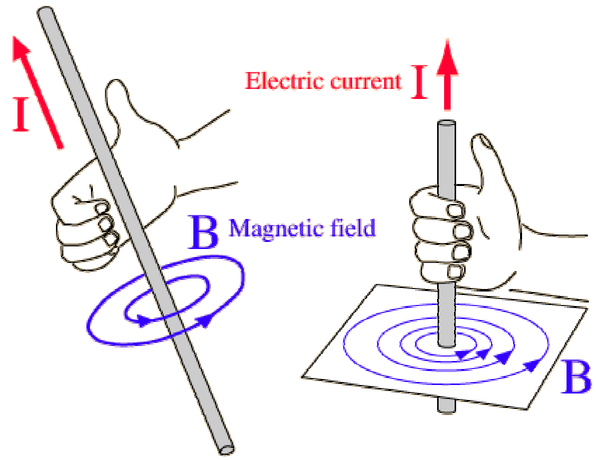
http://www.pa.msu.edu/~pumplin/PHY232

(Ppt courtesy of Remco Zegers)

MICHIGAN STATE UNIVERSITY

previously:

- Electric currents generate magnetic fields. If a current is flowing in a straight wire, you can determine the direction of the field with the **(curly) right-hand rule:**

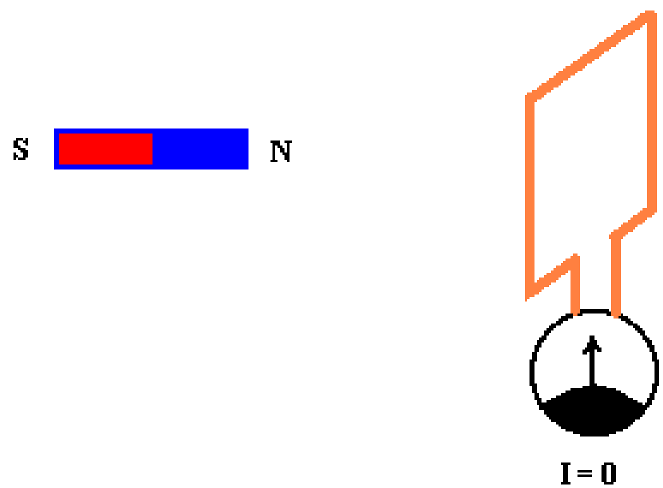


- and calculate the field strength with the equation: $B=\mu_0 I/(2\pi d)$
- For a loop (which is a solenoid with one turn): $B=\mu_0 IN/(2R)$ **(at the center of the loop)**
- For a long solenoid is long: $B=\mu_0 I\ N/L$ (anywhere way inside)

Electromagnetic Induction:

- The reverse is true also: a changing magnetic field can generate an electric field.
- This effect is called induction: In the presence of a changing magnetic field, an electromotive force (= "emf" = "voltage") is produced.

demo: coil and galvanometer



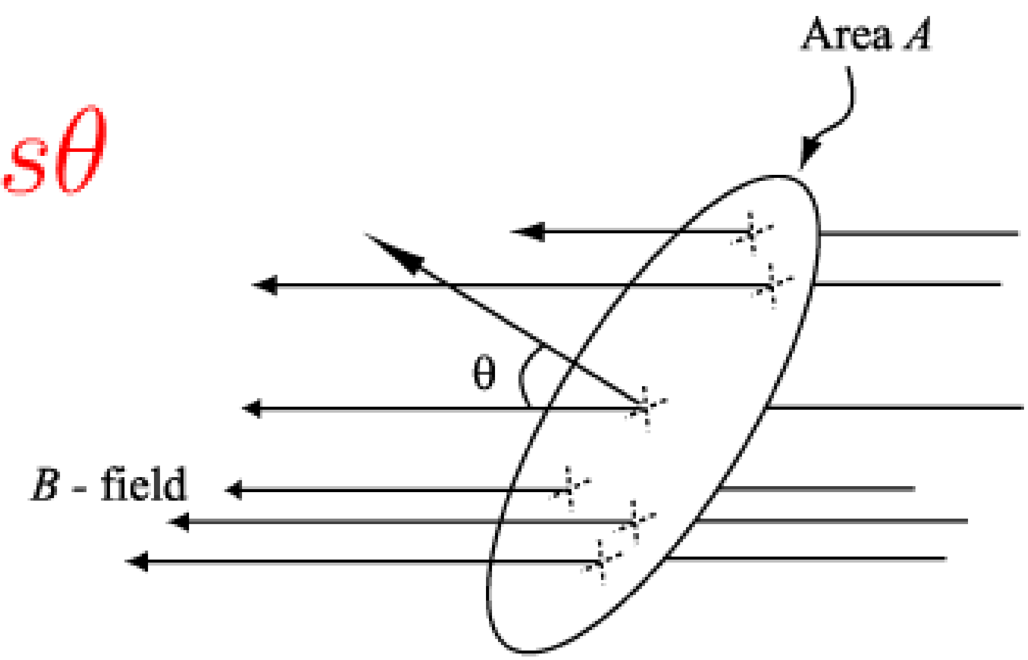
Moving the magnet closer to the loop, or farther away, produces a current.

If the magnet and loop are held stationary, there is no current.

Necessary definition: magnetic flux

- A magnetic field with strength B passes through a loop with area A
- The angle between the B-field lines and the normal to the loop is θ
- Then the magnetic flux Φ_B is defined as:

$$\Phi_B = BA\cos\theta$$



Units: Tm^2 or Weber

lon-capa uses Wb

example: magnetic flux

- A rectangular-shaped loop is put perpendicular to a magnetic field with a strength of 1.2 T. The sides of the loop are 2 cm and 3 cm respectively. What is the magnetic flux?
- $\Phi_B = BAcos\theta$ B=1.2 T, A=0.02x0.03=$6x10^{-4}$ m^2, θ=0.
- Φ_B=1.2 x $6x10^{-4}$ x 1 = $7.2x10^{-4}$ Tm
- Is it possible to put this loop such that the magnetic flux becomes 0?
  - a) yes
  - b) no

Faraday's law:

- By changing the magnetic flux $\Delta\Phi_B$ in a time-period Δt a potential difference V (electromagnetic force ε) is produced

$$\varepsilon = V = -\frac{\Delta\Phi_B}{\Delta t}$$

Warning: the minus sign is never used in calculations. It is an indicator for Lenz's law which we will see in a bit.

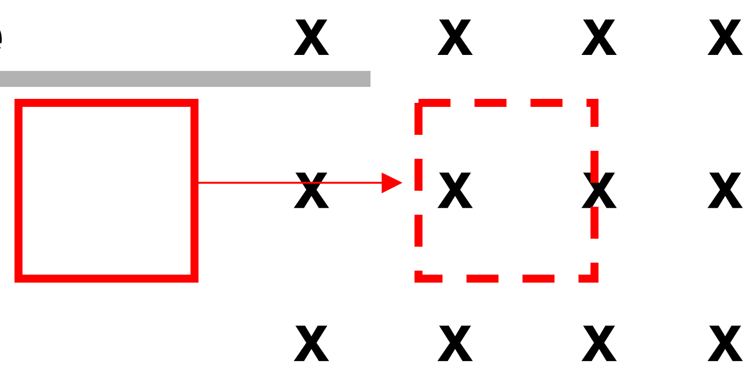
changing the magnetic flux

- Ø changing the magnetic flux can be done in 3 ways:
  - Ø change the magnetic field
  - Ø change the area
  - Ø changing the angle

$$V = -\frac{\Delta\Phi_B}{\Delta t} = -\frac{\Delta(BAcos\theta)}{\Delta t}$$

$$V = -\frac{\Delta\Phi_B}{\Delta t} = -\frac{\Delta(BAcos\theta)}{\Delta t}$$

example



- a rectangular loop ($A=1m^2$) is moved into a B-field ($B=1$ T) perpendicular to the loop, in a time period of 1 s. How large is the induced voltage?

The field is changing: $V=A\Delta B/\Delta t=1x1/1=1$ V

- While in the field (not moving) the area is reduced to $0.25m^2$ in 2 s. What is the induced voltage?

The area is changing by $0.75m^2$: $V=B\Delta A/\Delta t=1x0.75/2=0.375$ V

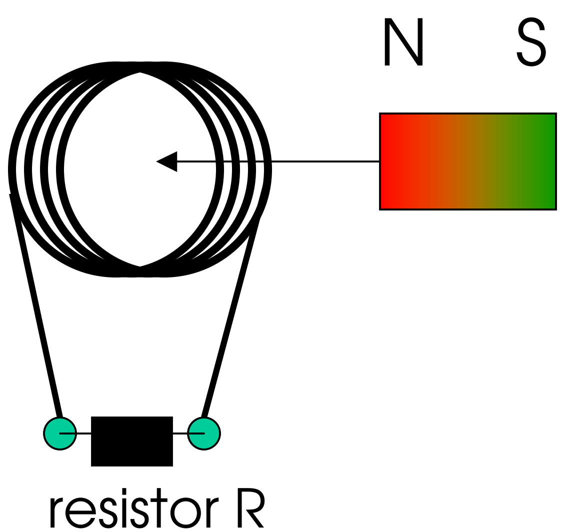
- This new coil in the same field is rotated by 45° in 2 s. What is the induced voltage?

The angle is changing ($cos0^0=1$ to $cos45^0=1/2\sqrt{2}$) :
$V=BA\ \Delta(cos\theta)/\Delta t=1x0.25x0.29/2=0.037$ V

Faraday's law for multiple loops

- If, instead of a single loop, there are multiple loops (N), the the induced voltage is multiplied by that number:

$$V = -N\frac{\Delta\Phi_B}{\Delta t}$$

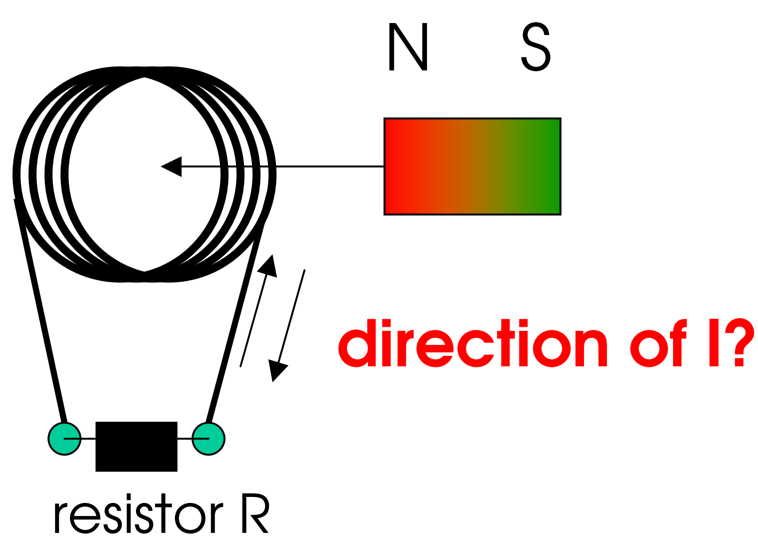


demo: loops.

If an induced voltage is put over a resistor with value R or the loops have a resistance, a current **I=V/R** will flow

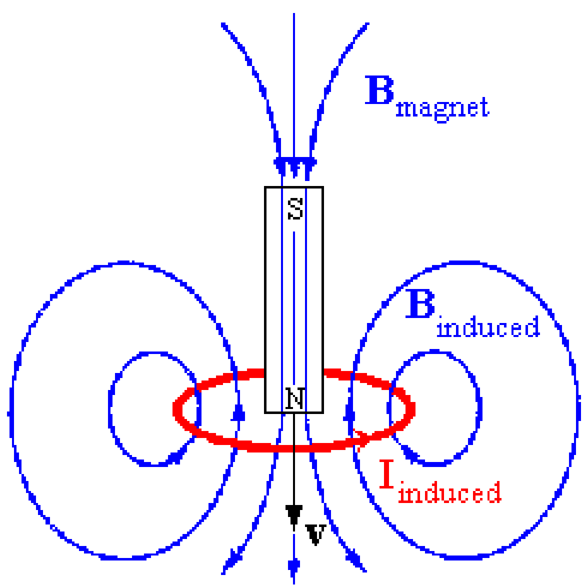
first magnitude, now the direction…

- So far we haven't worried about the direction of the current (or rather, which are the high and low voltage sides) going through a loop when the flux changes…



Lenz's Law

- The direction of the voltage would always make a current to oppose the change in magnetic flux.



When a magnet approaches the loop, with north pointing towards the loop, a current is induced.

As a result, a B-field is made by the loop ($B_{center}=\mu_0 I/(2R)$), so that the field opposes the incoming field made by the magnet.

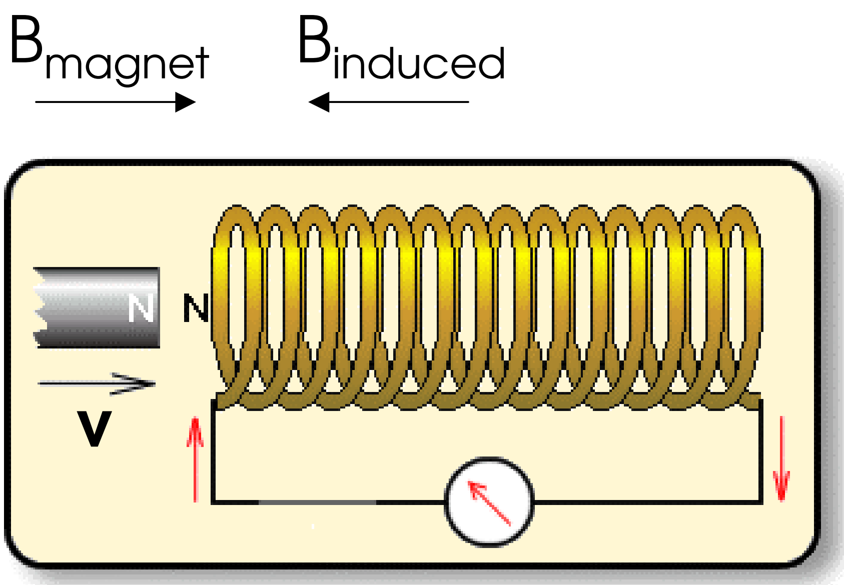
Use right-hand rule: to make a field that is pointing up, the current must go counter clockwise

demo: magic loops

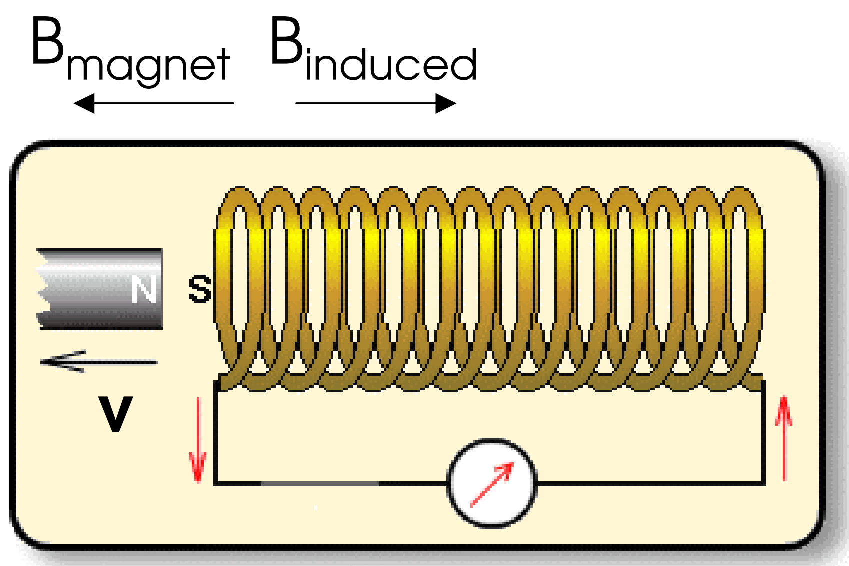
The loop is trying to push the magnet away

Lenz's law II

- In the reverse situation where the magnet is pulled away from the loop, the coil will make a B-field that attracts the magnet (clockwise). It opposes the removal of the B-field.



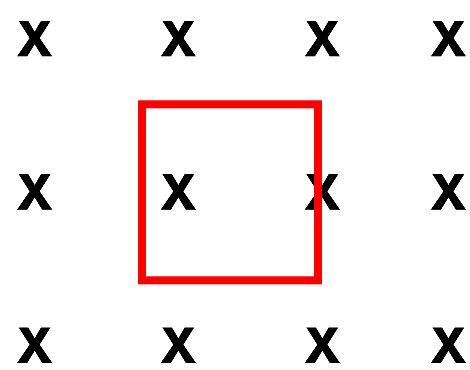
magnet approaching the coil



magnet moving away from the coil

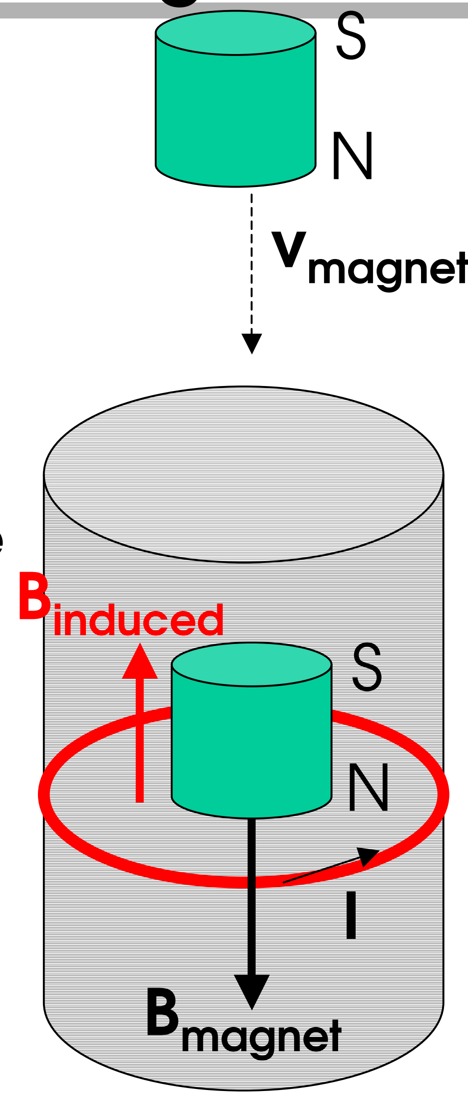
Be careful

- The induced magnetic field is not always pointing opposite to the field produced by the external magnet.

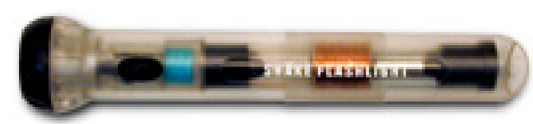


If the loop is stationary in a field, whose strength is reducing, it wants to counteract that reduction by producing a field pointing into the page as well:
current clockwise

demo magnet through cooled pipe

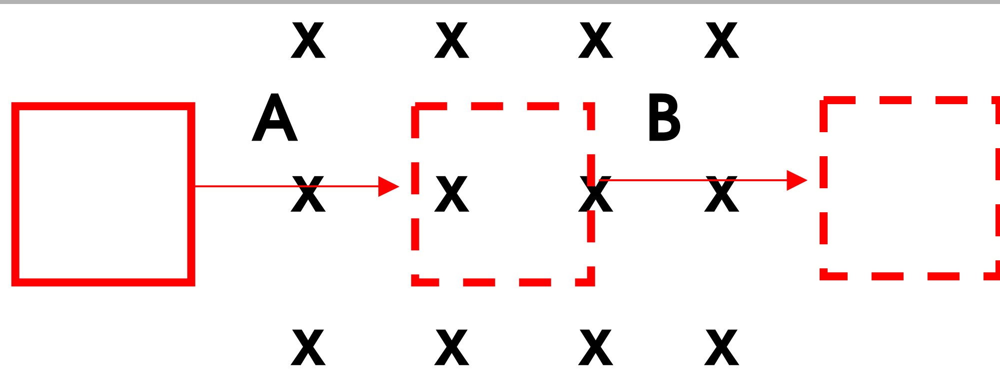


- when the magnet passes through the tube, a current is induced such that the B-field produced by the current loop opposes the B-field of the magnet
- opposing fields: repulsive force
- this force opposes the gravitational force and slow down the magnet
- cooling: resistance lower current higher, B-field higher, opposing force stronger



can be used to generate electric energy (and store it e.g. in a capacitor): demo: torch light

question



A rectangular loop moves in, and then out, of a constant magnet field pointing perpendicular (into the screen) to the loop.

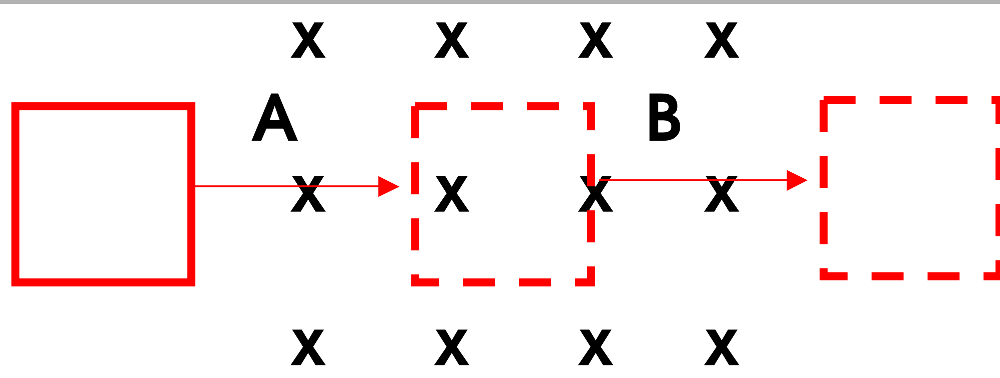
Upon entering the field (A), a …. current will go through the loop.

a) clockwise b) counter clockwise

When entering the field, the loop feels a magnetic force to the …

a) left b) right

question



A rectangular loop moves in, and then out, of a constant magnet field pointing perpendicular (into the screen) to the loop.

Upon entering the field (A), a …. current will go through the loop.

a) clockwise b) counter clockwise

The loop will try to make a B-field that oppose the one present, so out of the screen. Use second right-hand rule: counterclockwise.

When entering the field, the loop feels a magnetic force to the …

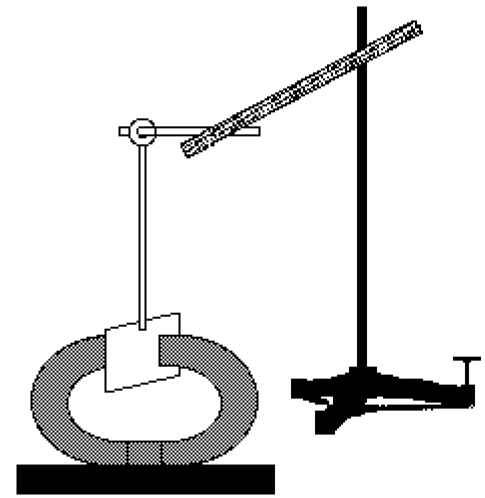
a) left b) right

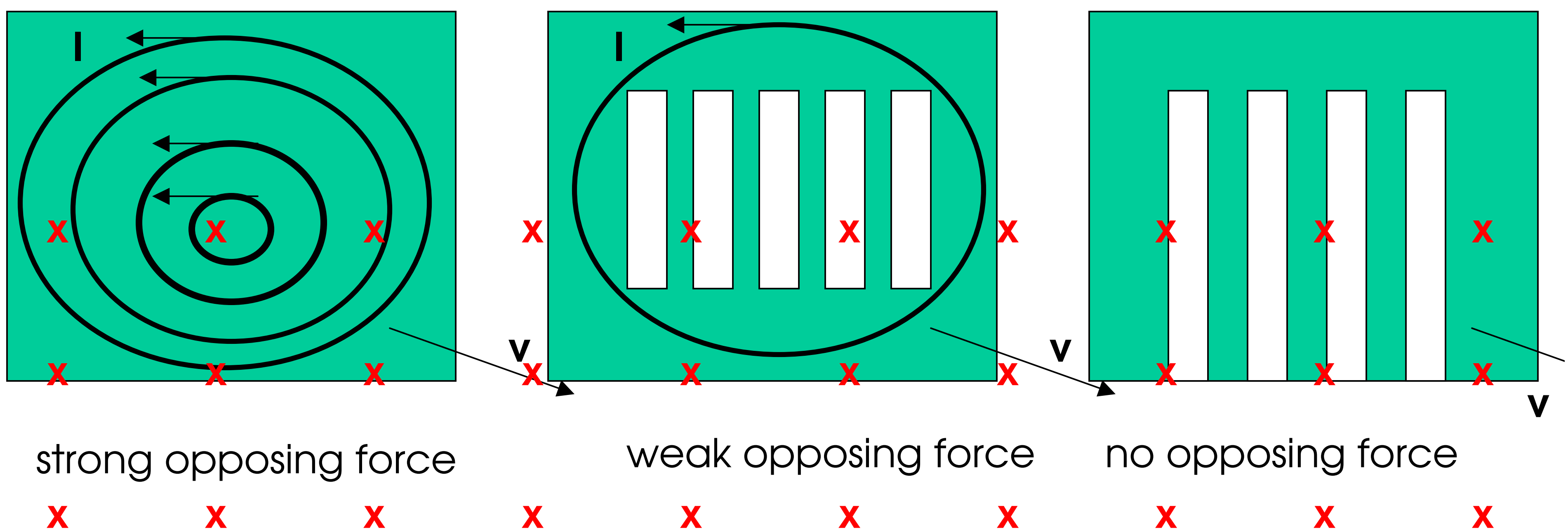
Method 1: Use first right hand rule with current and B-field that is present: left

Method 2: The force should oppose whatever is happening, in this case, it should oppose the motion of the loop, so point to the left to slow it down.

Eddy current+demo

- Magnetic damping occurs when a flat strip of conducting material pivots in/out of a magnetic field
- current loops run to counteract the B-field
- At the bottom of the plate, a force is directed the opposes the direction of motion

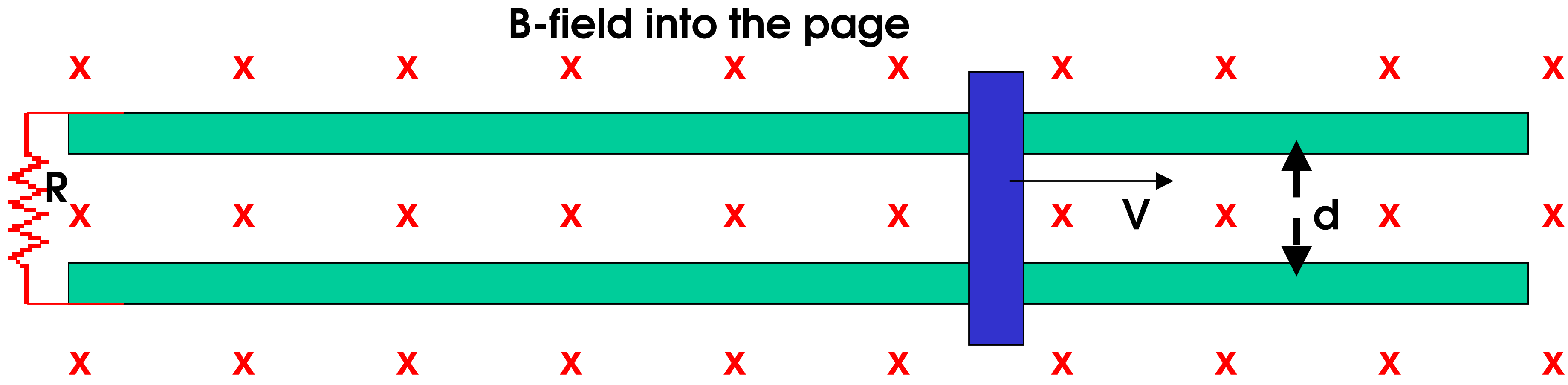




applications of eddy currents

- brakes: apply magnets to a brake disk. The induced current will produce a force counteracting the motion
- metal detectors: The induced current in metals produces a field that is detected.

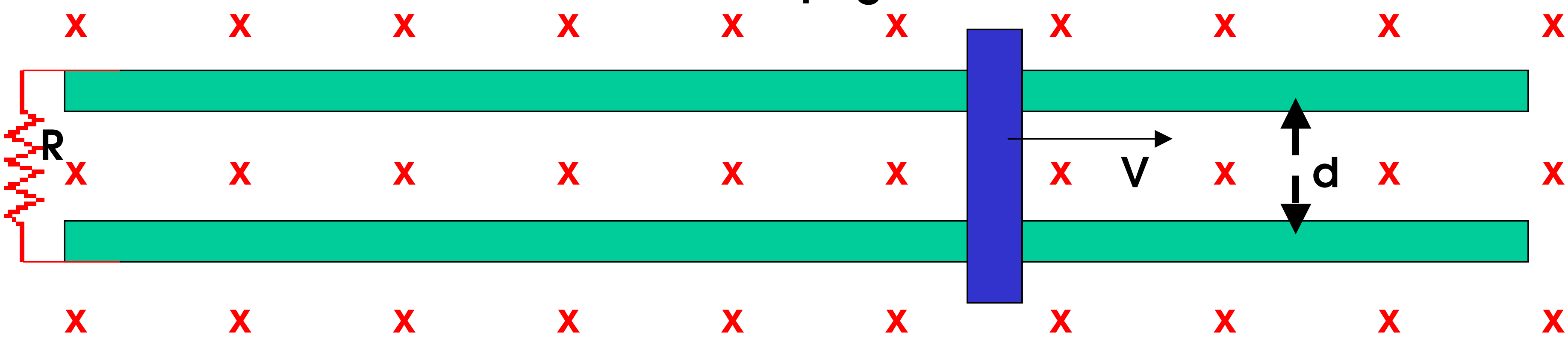
A moving bar



- Two metal rods (green) placed parallel at a distance d are connected via a resistor R. A blue metal bar is placed over the rods, as shown in the figure and is then pulled to the right with a velocity v.
- a) what is the induced voltage?
- b) in what direction does the current flow? And how large is it?
- c) what is the induced force (magnitude and direction) on the bar? What can we say about the force that is used to pull the blue bar?

answer

B-field into the page



Ø a) induced voltage? $V = -\frac{\Delta\Phi_B}{\Delta t} = -\frac{\Delta(BAcos\theta)}{\Delta t}$

B: constant, $\cos\theta=1$ $\Delta A/\Delta t = v \times d$

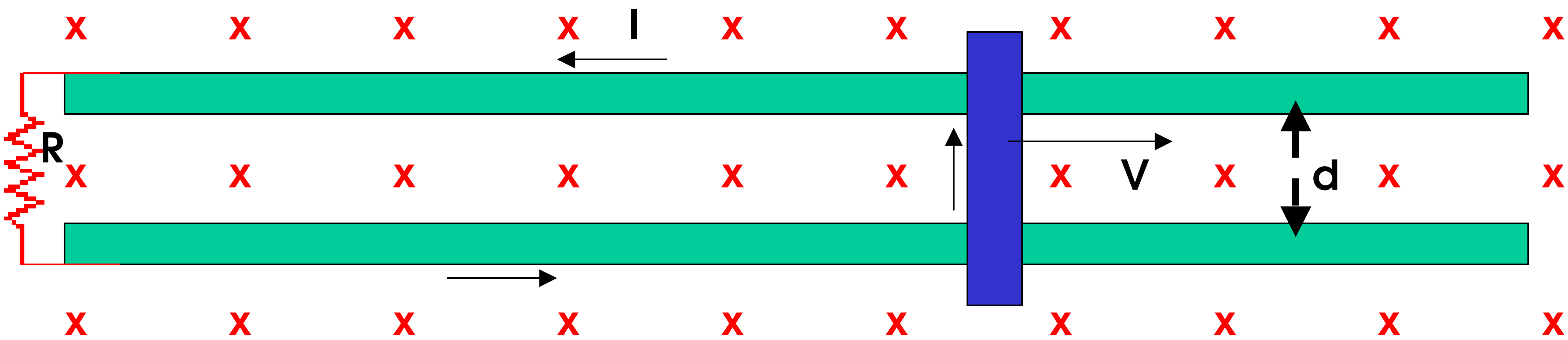
so $\Delta\Phi_B/\Delta t = Bvd$ = induced voltage

- B) Direction and magnitude of current?

The induced field must come out of the page (i.e. oppose existing field). Use 2nd right hand rule: counter-clockwise

$I=V/R=Bvd/R$

answer II



- Induced force?:

Direction?

Method I: The force must oppose the movement of the bar, so to the left.

Method II: Use first right hand rule for the bar: force points left.

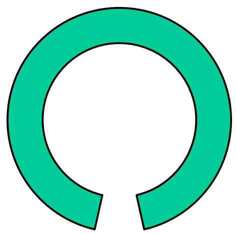
Magnitude?:

$F_{induced}$ =BIL (see chapter 19) = B x I x d

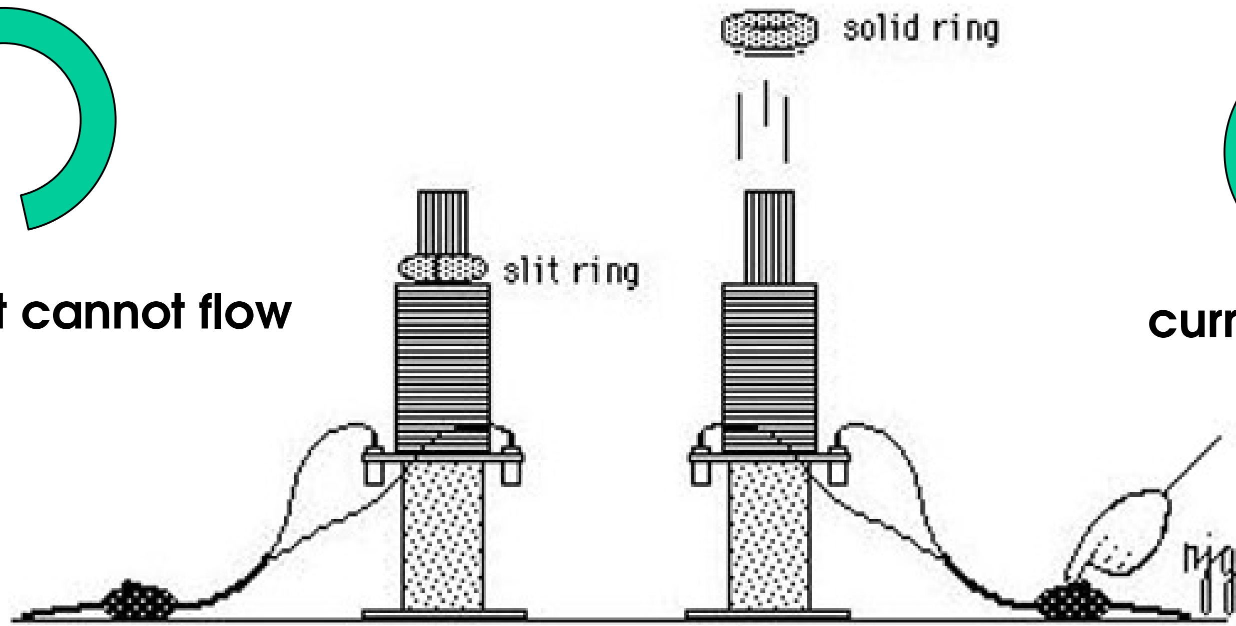
This force must be just as strong as the one pulling the rod, since the velocity is constant.

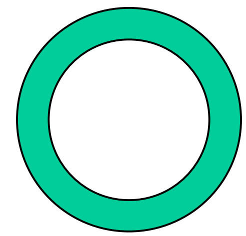
Doing work

- Since induction can cause a force on an object to counter a change in the field, this force can be used to do work.
- Example jumping rings: demo



current cannot flow





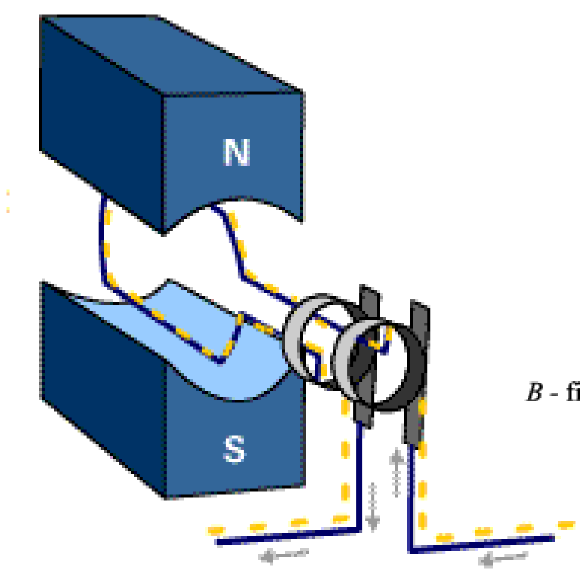
current can flow

The induced current in the ring produces a B-field opposite from the one produced by the coil: the opposing poles repel and the ring shoots in the air

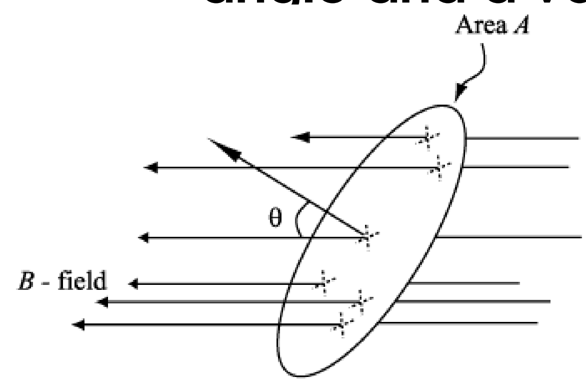
application: magnetic propulsion, for example a train.

generating current.

- The reverse is also true: we can do work and generate currents



By rotating a loop in a field (by hand, wind water, steam…) the flux is constantly changing (because of the changing angle and a voltage is produced.



$\theta=\omega t$ with

ω: angular velocity

$\omega=2\pi f = 2\pi/T$

f: rotational frequency

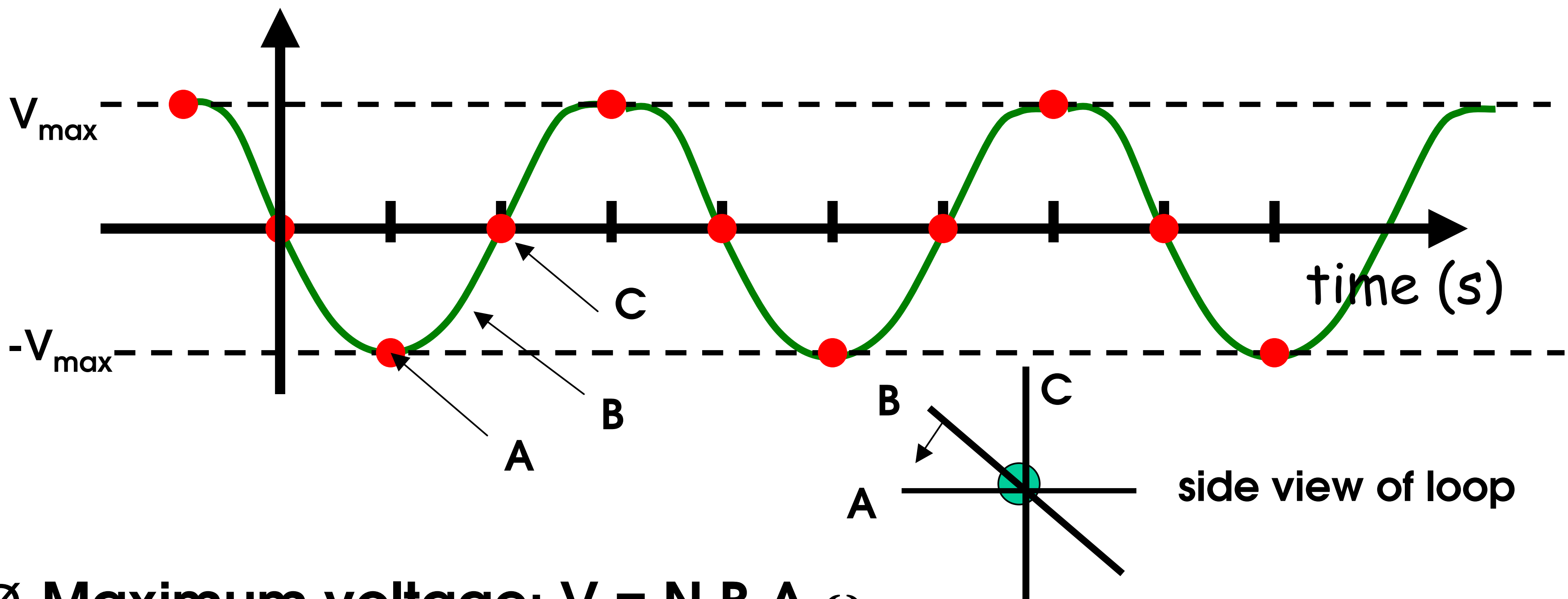
T: period of oscillation

$$V = -NBA\frac{\Delta(cos\theta)}{\Delta t} = -NBA\frac{\Delta(cos\omega t)}{\Delta t} = NBA\omega\sin(\omega t)$$

demo: hand generator

Time varying voltage

$$V = -NBA\frac{\Delta(cos\theta)}{\Delta t} = -NBA\frac{\Delta(cos\omega t)}{\Delta t} = NBA\omega\sin(\omega t)$$



- Maximum voltage: $V = N B A \omega$
- This happens when the change in flux is largest, which is when the loop is just parallel to the field

Question

- A current is generated by a hand-generator. If the person turning the generator increased the speed of turning:

A) the electrical energy produced by the system remains the same

B) the electrical energy produced by the generator increases

C) the electrical energy produced by the generator decreased

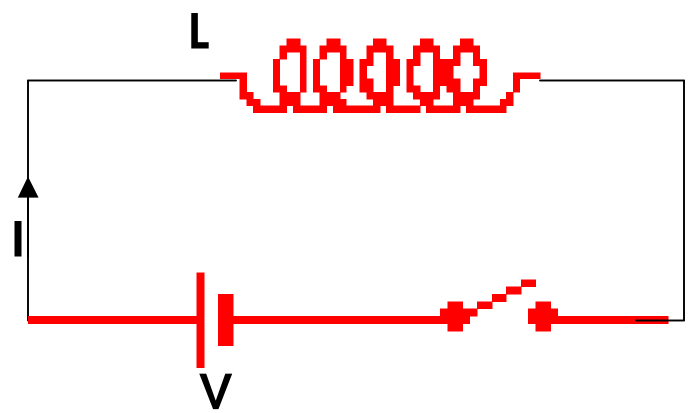
question

- A current is generated by a hand-generator. If the person turning the generator increased the speed of turning:

- a) the electrical energy produced by the system remains the same
- b) the electrical energy produced by the generator increases
- c) the electrical energy produced by the generator decreased

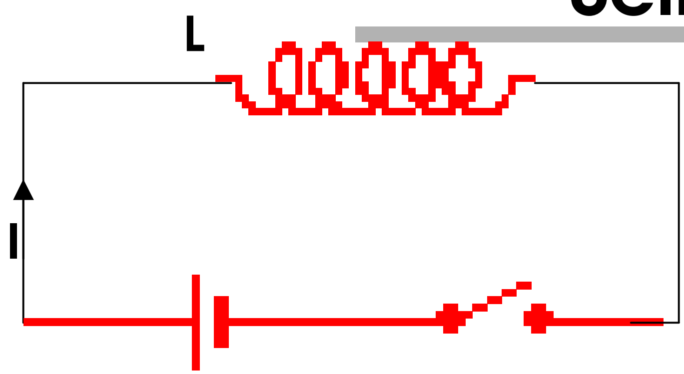
The change of flux per time unit increases and thus the output voltage. Or one can simply use conservation of energy: More energy put into the system, more must come out

Self inductance



- Before the switch is closed: I=0, and the magnetic field inside the coil is zero as well. Hence, there is no magnetic flux present in the coil
- After the switch is closed, I is not zero, so a magnetic field is created in the coil, and thus a flux.
- Therefore, the flux changed from 0 to some value, and a voltage is induced in the coil that opposed the increase of current

Self inductance II



- The self-induced current is proportional to the change in flux
- The flux Φ_B is proportional to B. e.g. $B_{center} = \mu_0 I N/\text{length}$ for a solenoid
- B is proportional to the current through the coil.

- So, the self induced emf (voltage) is proportional to change in current

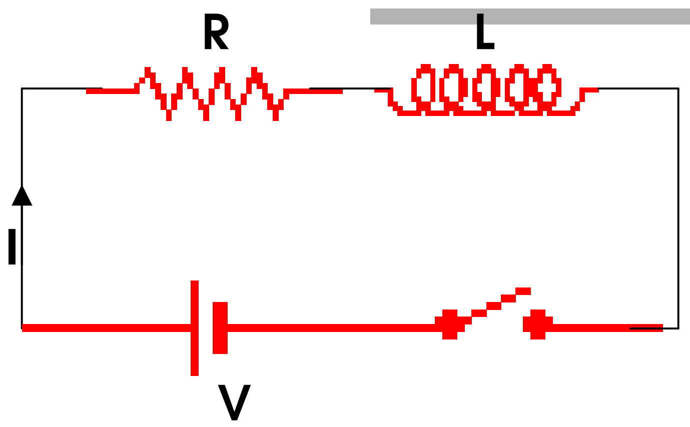
$$\varepsilon = V_{self-induced} = -L\frac{\Delta I}{\Delta t}$$

L inductance : proportionality constant
Units: V/(A/s)=Vs/A
usually called Henrys (H)

Induction of a Solenoid

- flux of a coil: $\Phi = BA = \mu_0 n I A$
- Change of flux with time: $\frac{\Delta\Phi}{\Delta t} = BA = -\mu_0 n A \frac{\Delta I}{\Delta t}$
- induced voltage: $V = -N\frac{\Delta\Phi}{\Delta t} = -\mu_0 n N A \frac{\Delta I}{\Delta t}$

An RL circuit



A solenoid and a resistor are placed in series. At t=0 the switch is closed. One can now set up Kirchhoff's 2nd law for this system:

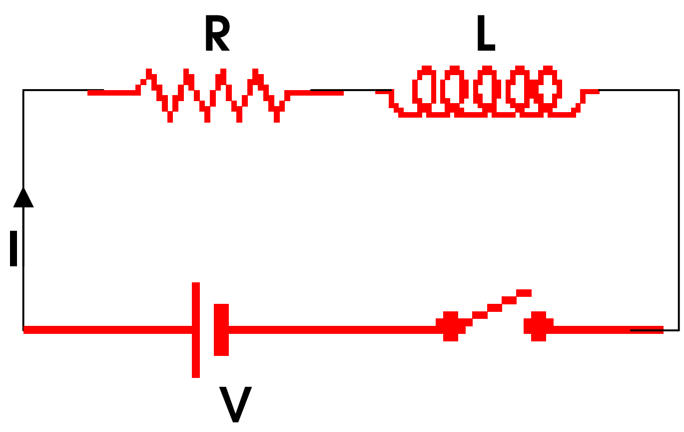
$$V - IR - L\frac{\Delta I}{\Delta t} = 0$$

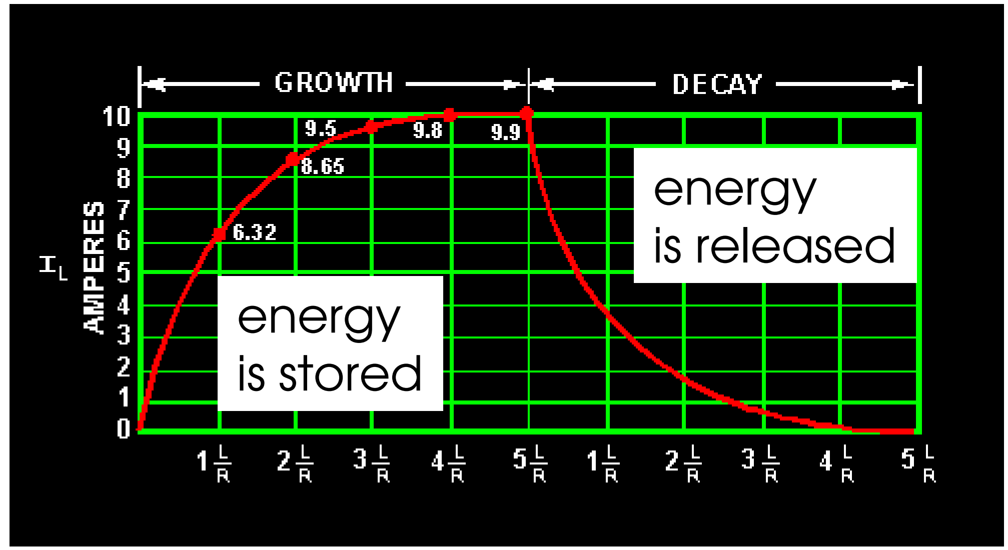
If you solve this for I, you will get:

$$I = \frac{V}{R}(1 - e^{-t/\frac{L}{R}})$$

The energy stored in the inductor : $W = \frac{1}{2} L I^2$

RL Circuit II





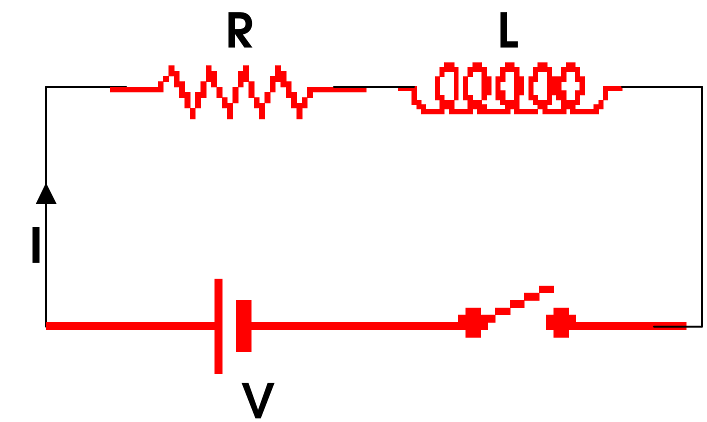
- When the switch is closed the current only rises slowly because the inductance tries to oppose the flow.

$$I = \frac{V}{R}(1 - e^{-t/\frac{L}{R}})$$

- Finally, it reaches its maximum value (I=V/R)
- When the switch is opened, the current only slowly drops, because the inductance opposes the reduction
- $\tau = L/R$ is the time constant (s)

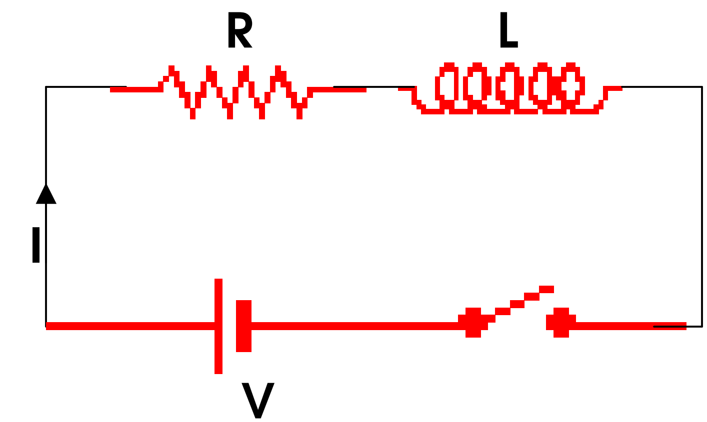
$$I = \frac{V}{R}e^{-t/\frac{L}{R}}$$

question



- What is the voltage over an inductor in an RL circuit long after the switched has been closed?
- a) 0   b) V/R   c) L/R   d) infinity

question

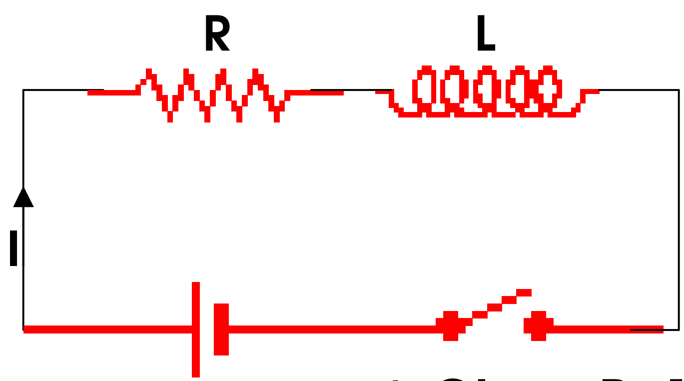


- What is the voltage over an inductor in an RL circuit long after the switched has been closed?
- a) 0 b) V/R c) L/R d) infinity

Answer: Zero! The current is not changing anymore, so the change per unit time is zero and hence the voltage.

$$\varepsilon = V_{self-induced} = -L\frac{\Delta I}{\Delta t}$$

example



- Given R=10 Ohm and L=$2x10^{-2}$ H and V=20 V.
- a) what is the time constant?
- b) what is the maximum current through the system
- c) how long does it take to get to 75% of that current if the switch is closed at t=0

a) $\tau = L/R$ Use given L and R: time constant is $2x10^{-3}$

b) maximum current (after waiting for some time): I=V/R=2 A

c) $I = \frac{V}{R}(1 - e^{-t/\frac{L}{R}})$ $0.75*2=2x(1-e^{-t/(L/R)})$

$0.25=e^{-t/(L/R)}$ so -1.39=-t/(L/R) and t=1.39 x $2x10^{-3}$=$2.78x10^{-3}$

lon-capa

For question 9, note that the voltage over the inductor is constant and the situation thus a little different from the situation of the previous page. You have done this before for a capacitor as well…