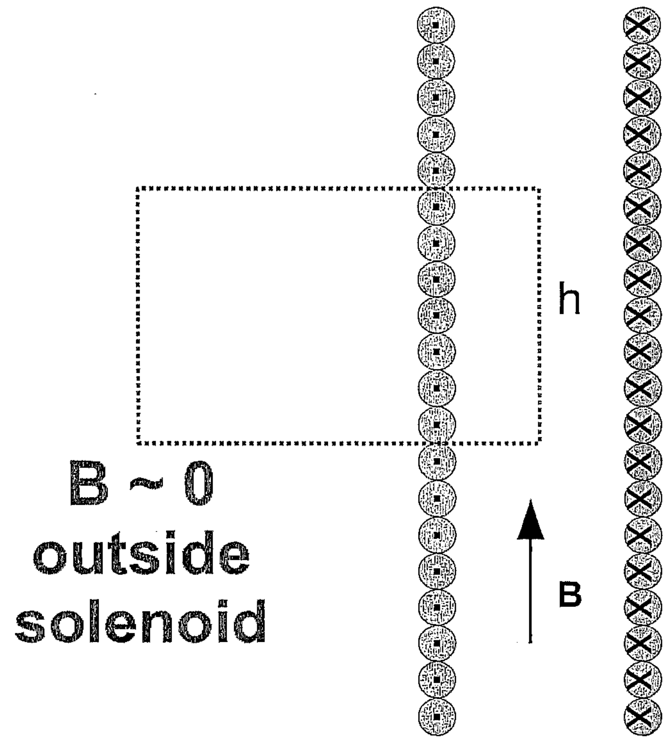
Magnetic field of Solenoid

- A solenoid is a long coil of wire.
  - This geometry gives a uniform field
  - Just like flat plate capacitor gives uniform E field
- The field is entirely contained inside the coil, outside it is very weak
  - N_{TPM} = number turns per meter
  - **I** = current in the wire
  - B = the magnetic field inside the solenoid is aligned exactly along the axis h



Inside the solenoid:

$$B = \mu_0 N_{TPM} I$$

The solenoid, like the capacitor, has a uniform field inside

Solenoid vis-a-vis Capacitor

- Magnetic field inside a Solenoid is uniform
- The field outside the solenoid is ~ zero
- The inductance depends only on geometric factors

$$Inductance = \mu_0 N_{TPM}^2 \, l \, A$$

- The solenoid can store energy in its magnetic field
- The stored energy can be drained slowly to create a timing element (L/R)

- Electric field inside a Capacitor is uniform
- The field outside the capacitor is ~ zero
- The capacitance depends only on geometric factors

$$Capacitance = \frac{A}{4\pi k d}$$

- The capacitor can store energy in its electric field
- The stored energy can be drained slowly to create a timing element (RC)

Voltagedue to ΔB through Wire Loop

-Faraday's Law-

- Voltage in loop due to changing B-flux is proportional to *rate of change* of flux through the loop of wire

$$'EMF' = Voltage = -\frac{\Delta \overbrace{BA}^{\text{B-flux}}}{\Delta t}$$

- Each of the N turns of the loop contributes to the voltage like adding another battery in series

$$'EMF' = Voltage = -N\frac{\Delta \Phi}{\Delta t}$$

B-flux has the units T-m^2 = Webers (Wb)

Emf Direction

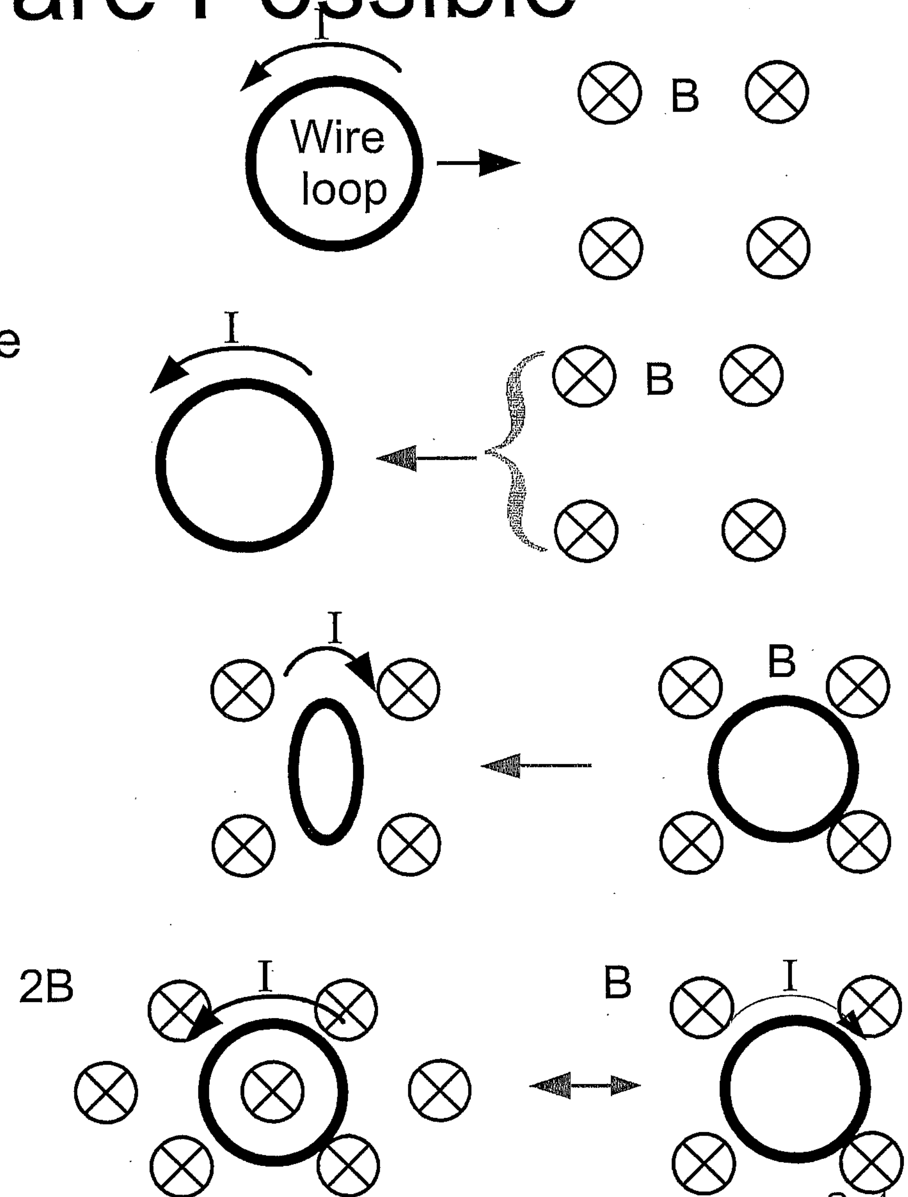
-Lenz's Law-

- (–) sign → 'Lenz's Law'

The sign of the EMF is such as to produce a current whose own B-field **opposes** *the externally imposed change that has occurred*

Various Scenarios between Loop and Magnetic Field are Possible

- When a wire moves at right angles to a magnetic field, this generates a current in the wire
  - There is voltage caused by the motion!
- OR keep wire stationary and move a magnet across the wire
- OR wire immersed in B-field can change orientation
- OR wire can change shape
- OR applied B-field can increase or decrease in strength

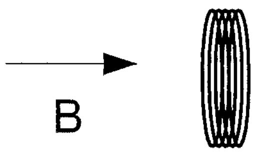


S 4

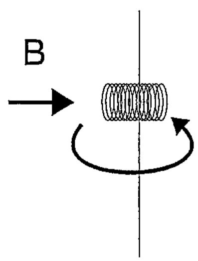
Almos any change at all can cause a ltage EMF to be induced in t coil

Faraday's Law Problems – different types

1. A 20-turn coil has an area 10 cm^2. If the magnetic field increases from 0 to 0.5 Tesla through the coil in 1/60 s, what is the EMF generated in the coil?

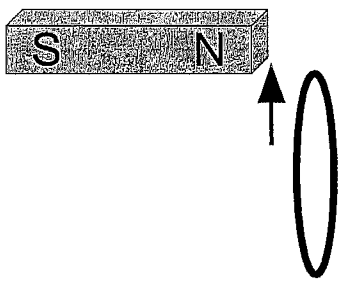


2. Inside a solenoid having 10,000 turns and 10 cm^2 cross-sectional area, a B-field of 0.05 T is aligned along the axis. The field is held constant in size and fixed in direction. In 0.3 second the solenoid flips around so its long axis points in the exact opposite direction. What is the size of the EMF generated in the solenoid?

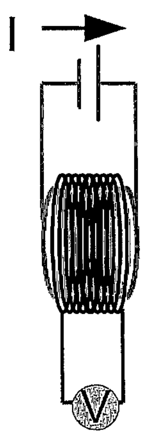


More different types of Faraday Problems

1. A wire bent into a large, circular loop slides across the face of a magnet. At the beginning of the motion, the magnetic field in the loop is zero, and at the end of the motion the loop circles the entire pole face of the magnet. The loop area is 300 cm^2 . The area of the pole faces is 200 cm^2. The B-field of the magnet is 1.2 T. If the loop takes 0.5 s to complete this motion, what is the average EMF induced in the loop?

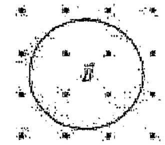


2. Two solenoids are wound around the same tube that has a cross-sectional area of 6 cm^2. Solenoid 1 has 10,000 turns per meter and carries a current of 10 A. Solenoid 2 has 2,000 turns of wire and has a meter reading the voltage between the two ends of the wire. If the current in solenoid 1 decreases from 10 A to zero in 0.2 s, what is the reading on the voltmeter?



Lenz's law

12. Does the loop of wire have a clockwise current, a counterclockwise current, or no current under the following circumstances? Explain.

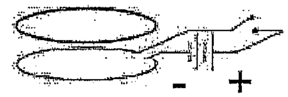


a. The magnetic field points out of the page and its strength is increasing.

b. The magnetic field points out of the page and its strength is constant.

c. The magnetic field points out of the page and its strength is decreasing.

13. Two loops of wire are stacked vertically, one above the other. Does the upper loop have a clockwise current, a counterclockwise current, or no current at the following times? Explain.



a. Before the switch is closed.

b. Immediately after the switch is closed.

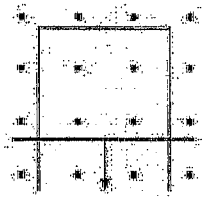
c. Long after the switch is closed.

d. Immediately after the switch is reopened.

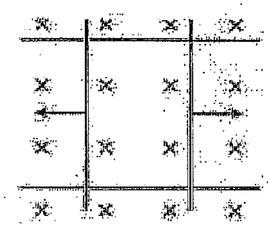
33.2 Motional EMF

1. The figures below show one or more metal wires sliding on fixed metal rails in a magnetic field. For each, determine if the induced current flows clockwise, flows counterclockwise, or is zero.

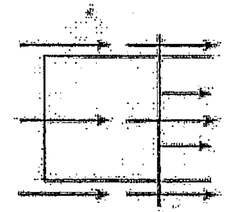
a.



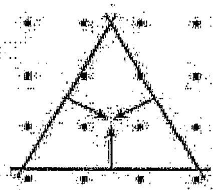
b.



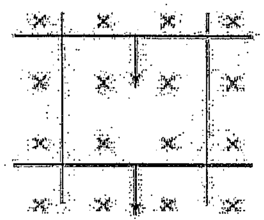
c.



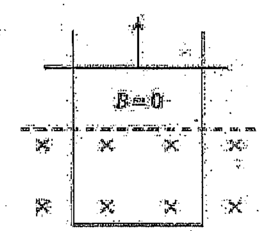
d.



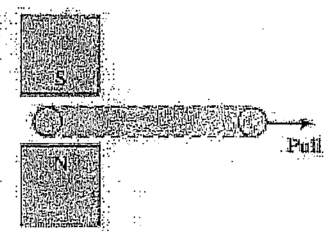
e.



f.



2. A loop of copper wire is being pulled from between two magnetic poles.



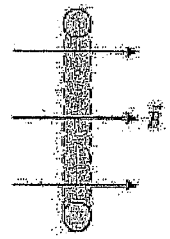
a. Show on the figure the current induced in the loop. Explain your reasoning.

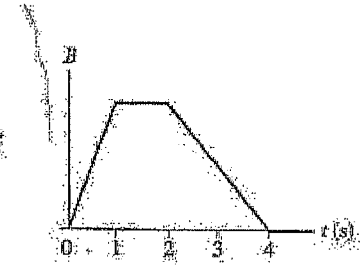
b. Does either side of the loop experience a magnetic force? If so, draw a vector arrow or arrows on the figure to show any forces.

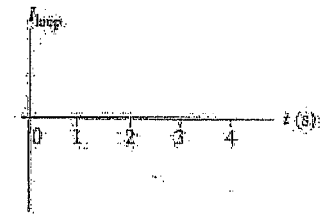
c. Label the magnetic poles of the induced current in the loop. Do this on the figure.

d. Are the magnetic poles you labeled in part c attracted to or repelled by the permanent magnet?

14. A loop of wire is perpendicular to a magnetic field. The magnetic field strength as a function of time is given by the top graph. Draw a graph of the current in the loop as a function of time. Let a positive current represent a current that comes out of the top of the loop and enters the bottom of the loop. There are no numbers for the vertical axis, but your graph should have the correct shape and proportions.

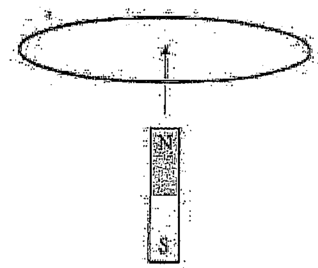






15. A loop of wire is horizontal. A bar magnet is pushed toward the loop from below, along the axis of the loop.

a. What is the current direction in the loop? Explain.

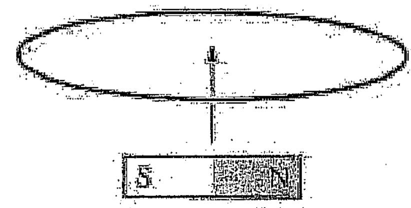


b. Is there a magnetic force on the loop? If so, in which direction? Explain.

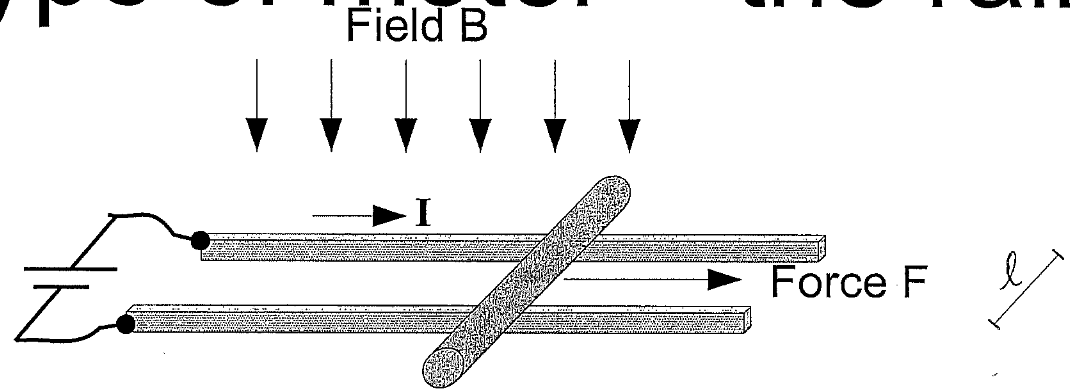
Hint: A current loop is a magnetic dipole.

c. Is there a force on the magnet? If so, in which direction?

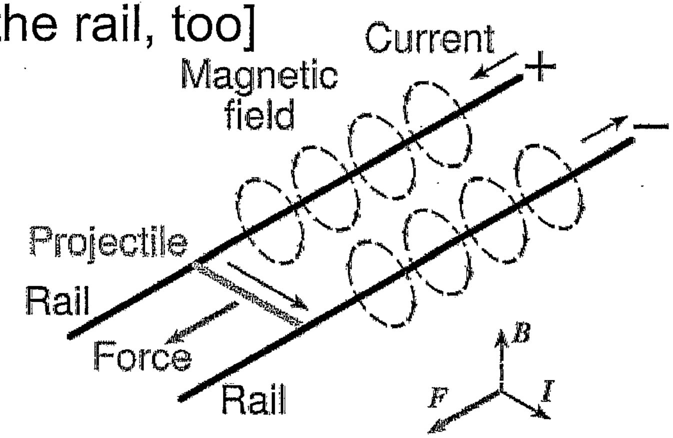
16. A bar magnet is pushed toward a loop of wire, as shown. Is there a current in the loop? If so, in which direction? If not, why not?



A simple type of motor – the rail gun



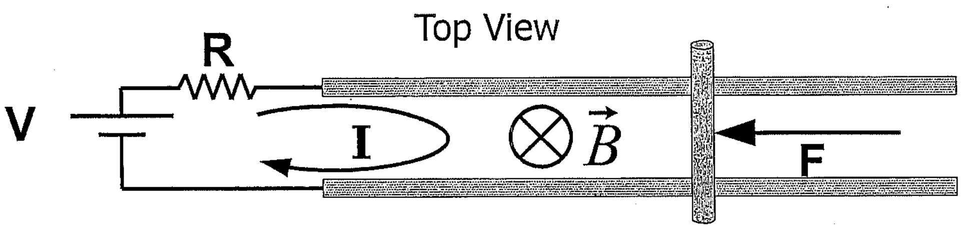
- The force on the cylinder is $BI\ell$
- The military has worked on the railgun as a way to launch payloads into space
  - [Actually, the current in the rails is also a source of the magnetic field, as shown below:
  - This field propels the rail, too]



By moving the rail in the direction of the force, the battery adds energy to the rail

Current depends on whether the rail gun performs work or not

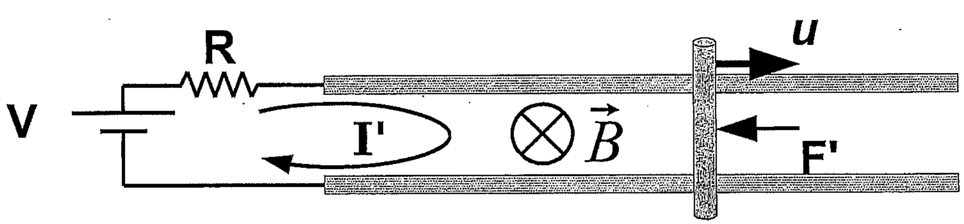
- Apply force F so the rail cannot move:



$$V = IR \qquad F = IlB$$

  - No work is done by rail
  - Battery puts power into resistor only $\quad P = I^2 R$

- Reduce force F to F'. Let blue rail move at speed *u* :

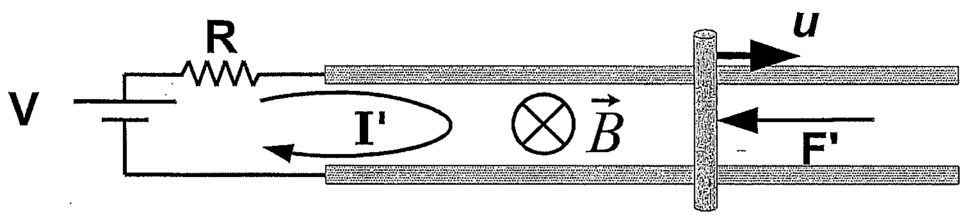


$$P_{rail} = F' \cdot u \qquad F' = I' lB$$

  - Battery puts power into <u>resistor</u> *and* <u>rail</u> $\quad P = I'^2 R + F' u$
  - Less current flows: I' < I (Why?)

The cu ent going to a motor depends n how much work the motor i doing

Rail moving causes 'Back EMF'



Calculate power going into the rail

$$P_{rail} = F' \cdot u$$

$$= F' \frac{\Delta x}{\Delta t}$$

$$= I' l B \frac{\Delta x}{\Delta t}$$

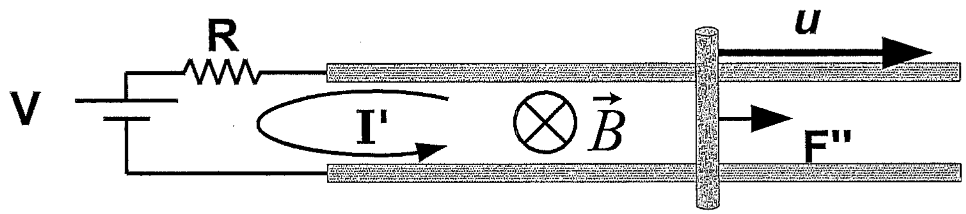
$$= I' B \underbrace{\frac{\Delta A}{\Delta t}}$$

$$= I' \cdot Emf_B$$

- As the rail moves, it sweeps through area occupied by the B field
  - This generates a voltage, Emf_B, called the *back Emf*
  - $\text{Emf}_B = B\Delta A/\Delta t$
  - This result is an example of Faraday's Law
- All types of motors produce an Emf_B

Faraday's Law: A changing B-flux through a loop generates an EMF

Now Reverse F to make power Negative



Calculate power going into the rail

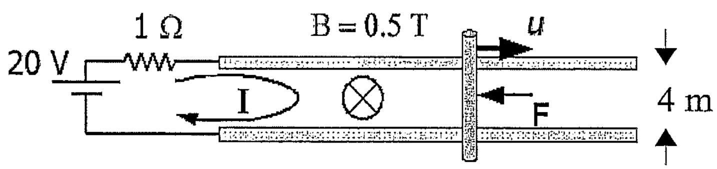
$$P_{rail} = F''\cdot u$$

$$P_{rail} < 0$$

- F'' is now moving the rail, so is doing work
- $EMF_B > V$, so current flows back into the battery
  - Power output from the battery is negative, ie, power is flowing into the battery
  - This charges the battery
- Now the 'motor' has become a generator

All types of electric motors ·e generators, and vice-versa

Rail Gun Motor/Generator



Problem: The rail gun is powered by a 20 Volt battery. There is 1 ohm resistance in the circuit. The rail is 4 m wide and moves at various speeds, u, because we are externally applying whatever force is necessary to keep it moving at that speed.

a. Use Faraday's law to determine the back EMF.
b. That combines with the battery to give a net voltage in the circuit.
c. Find the external force F needed to balance the magnetic force, so that the rail moves at constant velocity.
d. Figure out the electrical power and the mechanical power.

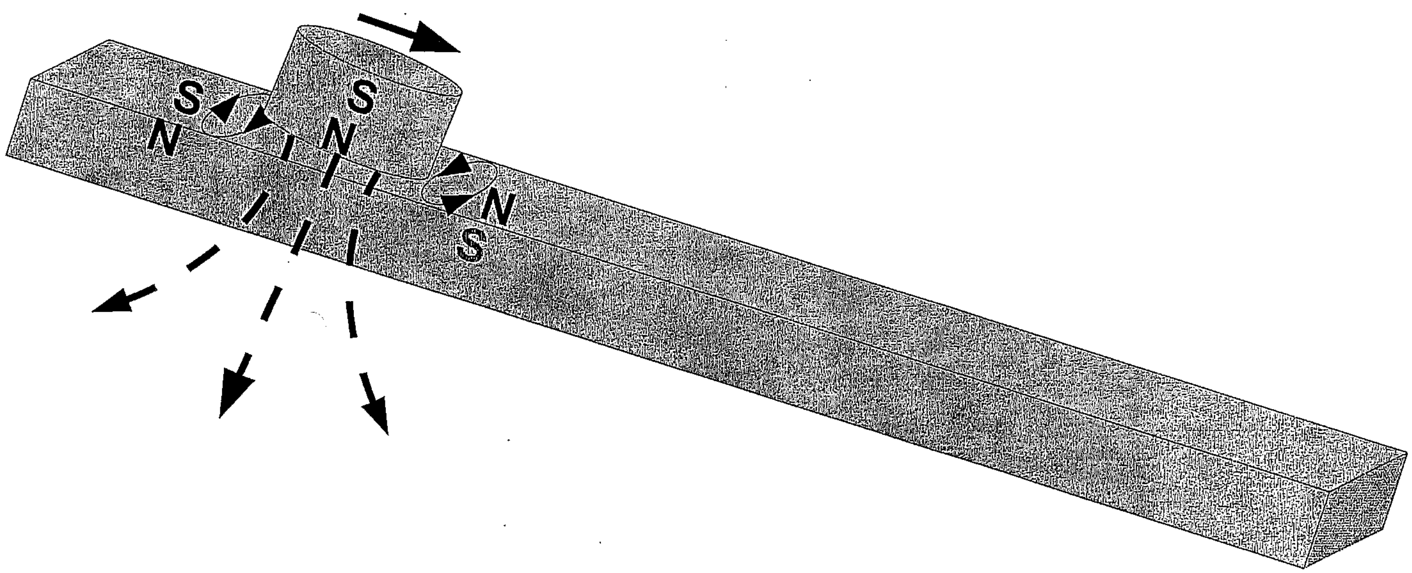
(m/s) u rail vel.	(V) Vback Back EMF	(V) Vnet Net Voltage	(A) I Current	(W) Pbatt Batt. Power	(N) Force on rail, F	(W) Prail Mech Power
0						
2						
5						
8						
10						
12						

Faraday's Law and the force on a current in a B field are two aspects of of one idea: the current causes a force; OR the force makes a current.

Every Motor IS A Generator

Faraday's Law - Magnetic Damping

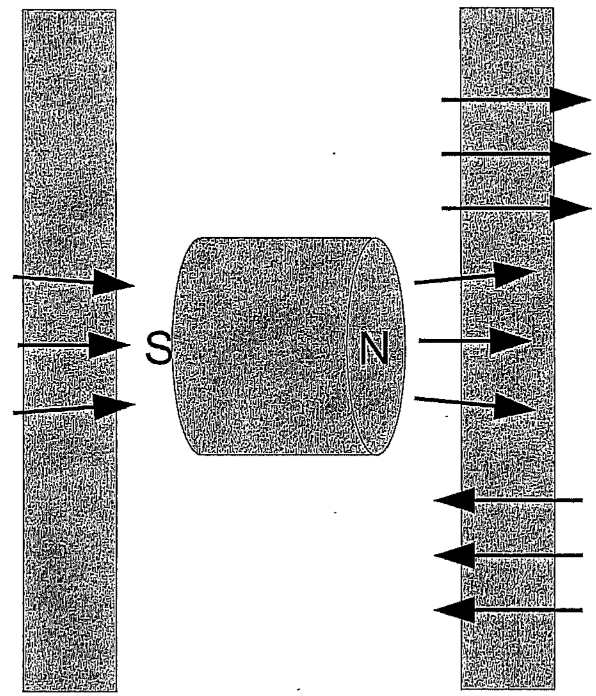
- A good conductor will hinder the motion of a strong magnet



- **Eddy currents** produce electromagnets in the conductor

Induced currents oppose motion but do not attract the magnet

Magnetic Damping in Pipe



•Magnetic Field **Rejection**: if the pipe is a superconductor, the magnet will just stand still and float

- This is called superconducting magnetic levitation
  - Any change in the magnetic field is completely rejected by the superconductor – except at defects