# Announcements

EXAM 2 is Wednesday, Nov. 7

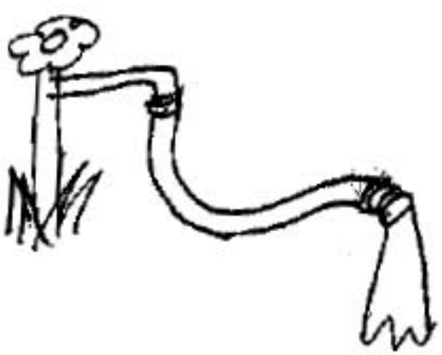
@ 8:00pm-9:30pm in ELLIOT HALL of MUSIC.

Practice Exam is on Blackboard Learn.

# Hall Effect gives sign of charge carriers

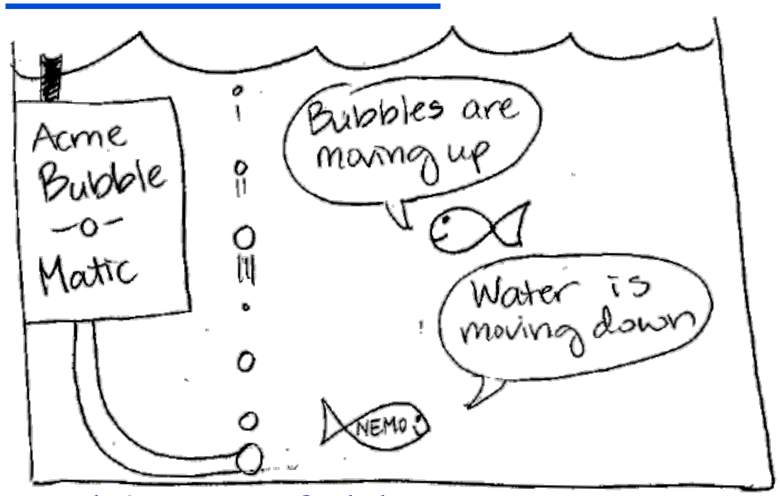
In some metals and semiconductors,
current is ***not*** carried by electrons,
but is carried by ***"holes"*** = bubbles in the electron sea.

Water from a hose



"Holes" not useful here

Bubbles in water

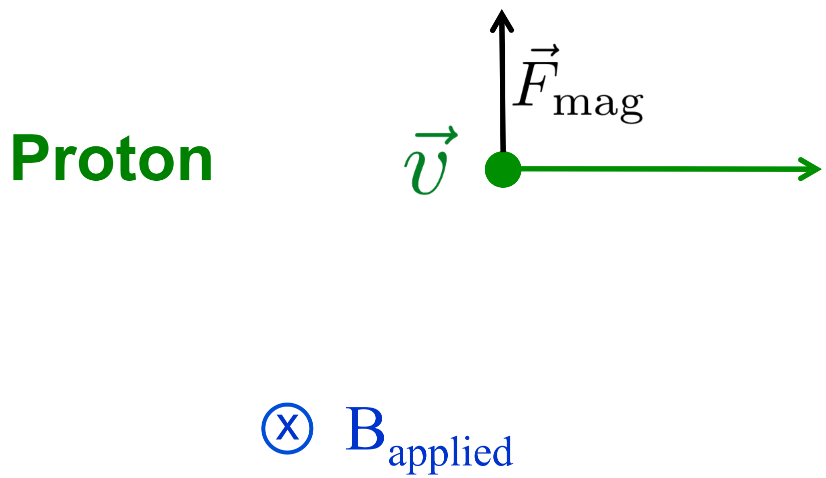



"Holes" useful here

# iClicker

$$\vec{F}_{\text{mag}} = q\vec{v} \times \vec{B}$$

**MAGNETIC FORCE**
**point charge**




In which direction does **$F_{mag}$** point for the **proton**?

A) Up

B) Down

C) Into the Board

D) Out of the Board

# iClicker

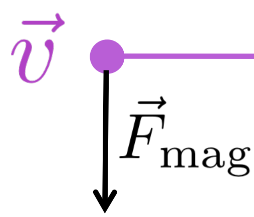
$$\vec{F}_{\text{mag}} = q\vec{v} \times \vec{B}$$

**MAGNETIC FORCE**
**point charge**

**Proton**


$\otimes$ $B_{\text{applied}}$

**Electron**




A) Up

B) Down

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In which direction does $\mathbf{F}_{\text{mag}}$ point for the **electron**?

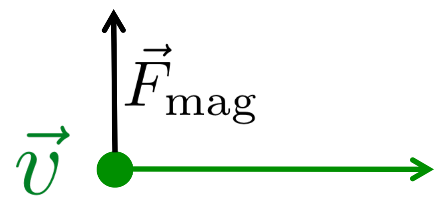
# Hall Effect

$$\vec{F}_{\text{mag}} = q\vec{v} \times \vec{B}$$

**MAGNETIC FORCE**
**point charge**

A **hole** in the electron sea behaves like a **proton**.

**Proton or "Hole"**



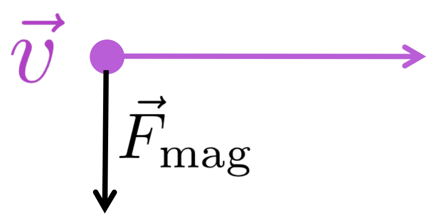

## Inside a Material:

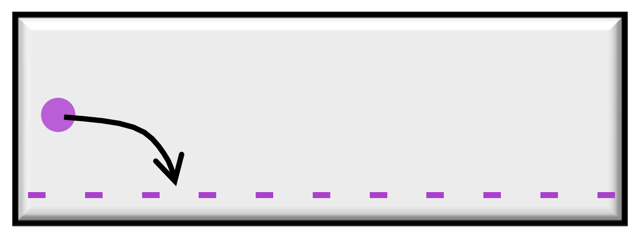

Moving **holes** get pushed to the top

ⓧ $B_{\text{applied}}$

ⓧ $B_{\text{applied}}$

**Electron**




Moving **electrons** get pushed to the bottom

# Hall Effect

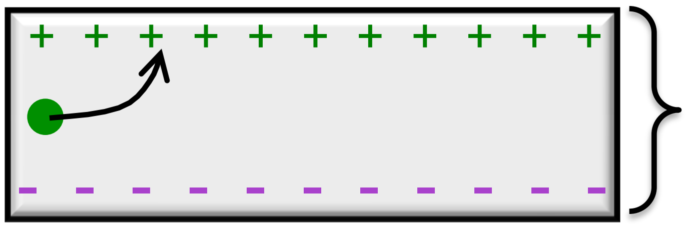
$$\vec{F}_{\text{mag}} = q\vec{v} \times \vec{B}$$

**MAGNETIC FORCE**
**point charge**

A **hole** in the electron sea behaves like a **proton**.

## Inside a Material:

Moving **holes** get pushed to the top



$\Delta V$ = Hall Voltage

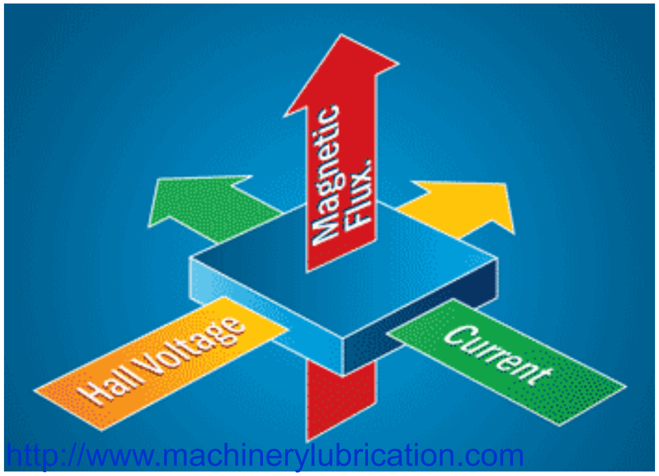
$\otimes$ $\mathrm{B}_{\text{applied}}$

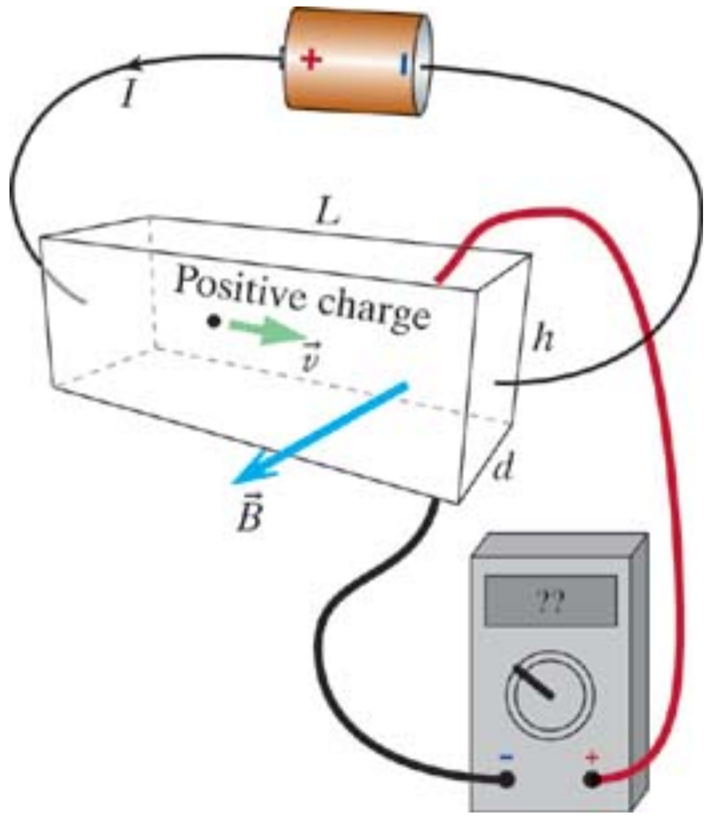
How long does this go on?
→ Until the Hall Voltage is strong enough to balance the magnetic force $\vec{F}_{\text{mag}}$

Moving **electrons** get pushed to the bottom

$\Delta V$ = Hall Voltage

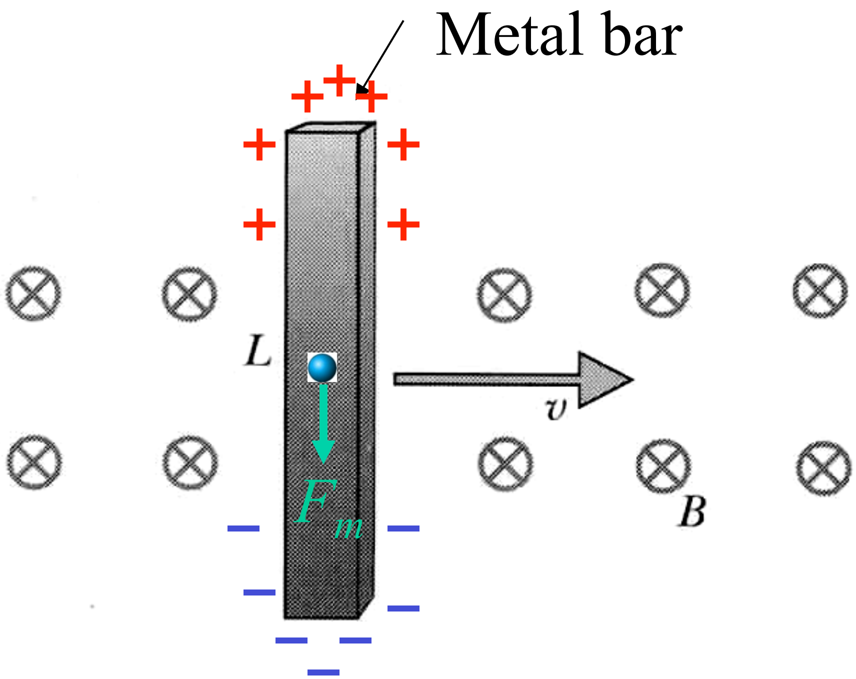
# Measuring the Hall Effect




1. Apply B-Field
2. Apply Current I
3. Measure "Hall Voltage"

# Currents Due to Magnetic Forces




$$\boxed{\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}}$$

$$\vec{F}_m = (-e)\vec{v} \times \vec{B}$$

$$\downarrow$$

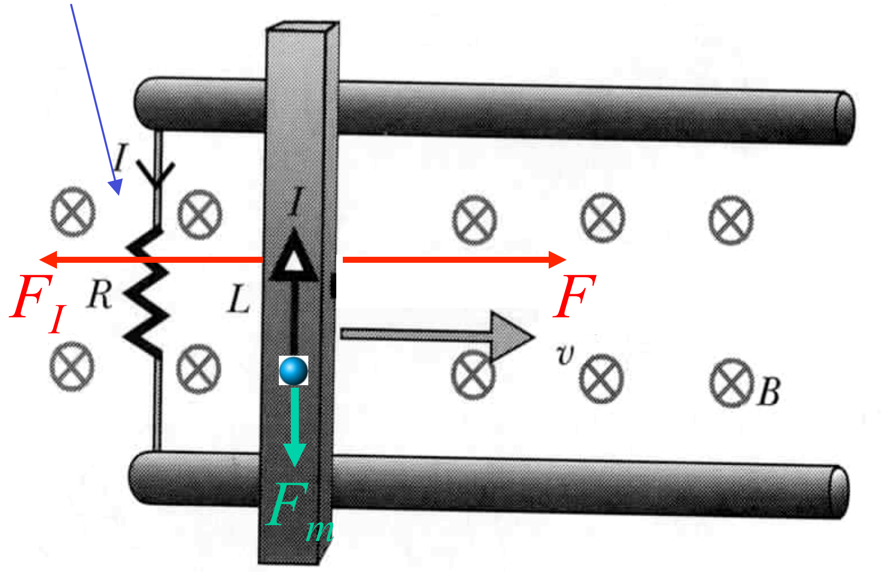
polarization

How much force do we need to apply to keep the bar moving at constant speed?


Does this polarized bar remind you anything we’ve already studied?

# Moving Bar and Energy Conservation

P=IΔV=I(emf)




$$emf = vBL$$

x

Are we getting something for nothing?

Bar – current *I*:

$$\vec{F}_I = I\Delta\vec{l} \times \vec{B} = -\vec{F}$$

$$F_I = ILB$$

Work: $W = F\Delta x = ILB\Delta x$

Power: $P = \dfrac{W}{\Delta t} = ILB\dfrac{\Delta x}{\Delta t}$

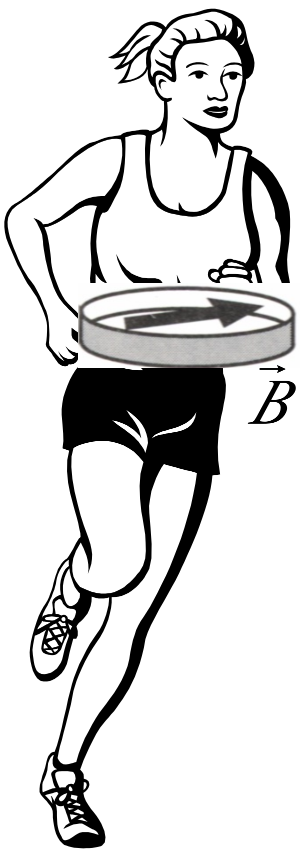
$$P = ILB$$

$$P = I(emf)$$

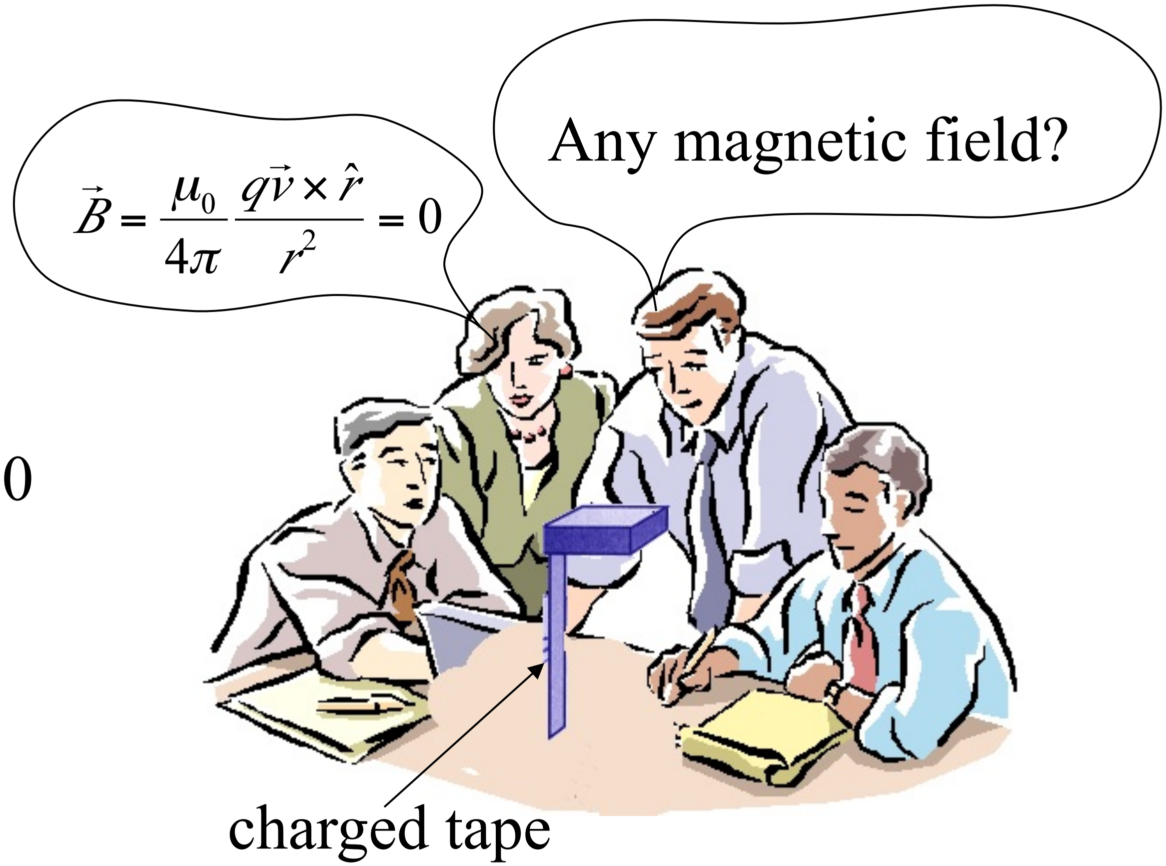
Main principle of electric generators:

Mechanical power is converted to electric power

# Reference Frame

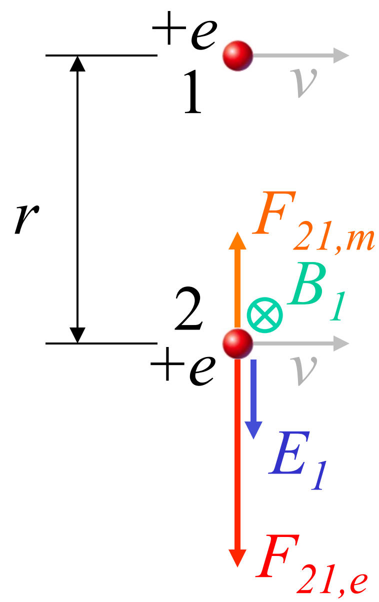


$$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} \neq 0$$



# Magnetic Forces in Moving Reference Frames

Two protons




Electric force:

$$\vec{F}_{21,e} = q_2 \vec{E}_1 = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{r^2} \hat{r}$$

Magnetic field:

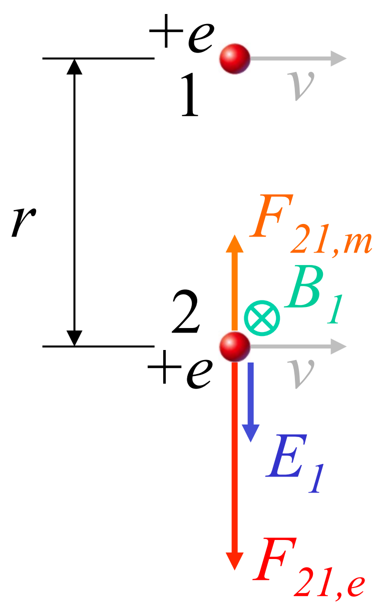
$$\vec{B}_1 = \frac{\mu_0}{4\pi} \frac{q_1 \vec{v}_1 \times \hat{r}}{r^2}$$

Magnetic force:

$$\vec{F}_{21,m} = q_2 \vec{v}_2 \times \vec{B}_1$$

$$F_{21,m} = q_2 v B_1 = \frac{\mu_0}{4\pi} \frac{e^2 v^2}{r^2}$$

# Magnetic Forces in Moving Reference Frames




Electric force: $$F_{21,e} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2}$$

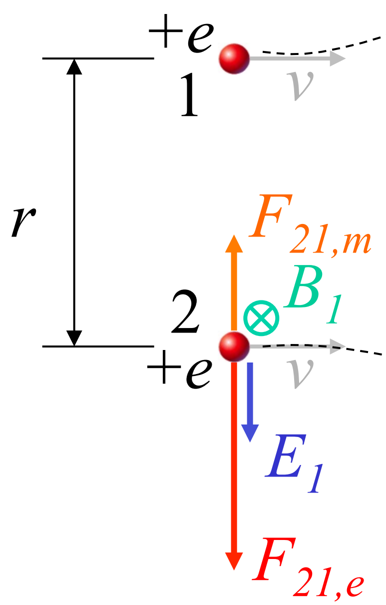
Magnetic force: $$F_{21,m} = \frac{\mu_0}{4\pi}\frac{e^2 v^2}{r^2}$$

Ratio: $$\frac{F_{21,m}}{F_{21,e}} = \left(\frac{\mu_0}{4\pi}\frac{e^2 v^2}{r^2}\right) \Big/ \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2}\right)$$

$$\frac{F_{21,m}}{F_{21,e}} = \left(\mu_0\varepsilon_0\right)v^2$$

$$\frac{F_{21,m}}{F_{21,e}} = \frac{v^2}{c^2}$$

# Magnetic Forces in Moving Reference Frames




$$\frac{F_{21,m}}{F_{21,e}} = \frac{v^2}{c^2}$$

For $v \ll c$ the magnetic force is much smaller than electric force

How can we detect the magnetic force on a current carrying wire?

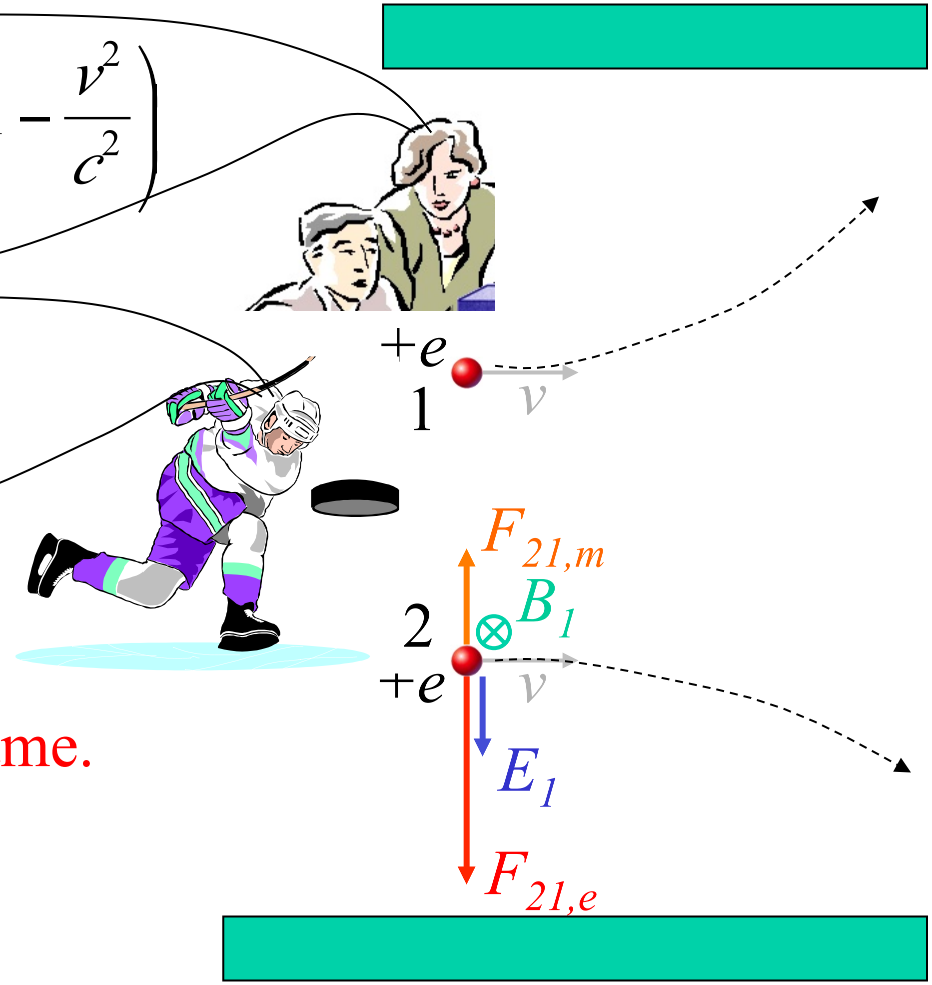
Full Lorentz force: $$F = F_{21,e} - F_{21,m} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2}\left(1 - \frac{v^2}{c^2}\right)$$

downward

# Magnetic Forces in Moving Reference Frames

20 $ns$ $$F = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2}\left(1 - \frac{v^2}{c^2}\right)$$

15 $ns$ $$F = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2}$$




Who will see protons hit floor and ceiling first?

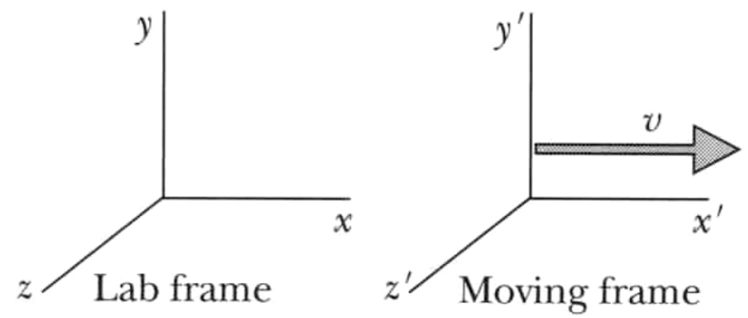
Time must run slower in moving frame.

Einstein 1905:
"On the electrodynamics of moving bodies"

# Relativistic Field Transformations

Our detailed derivations are not correct for relativistic speeds, but the ratio $F_m/F_e$ is the same for any speed:

$$\frac{F_m}{F_e} = \frac{v^2}{c^2}$$




According to the theory of relativity:

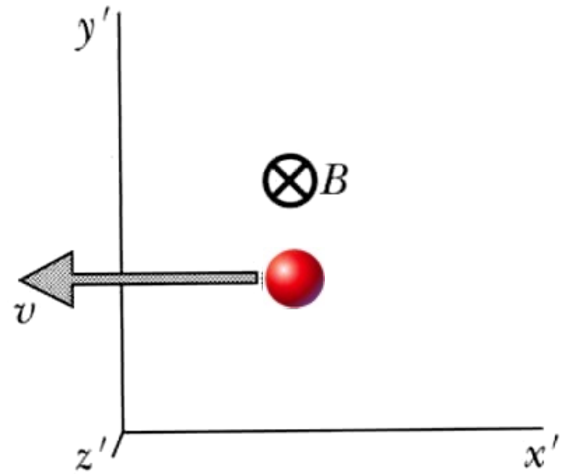
$$E'_x = E_x \qquad E'_y = \frac{\left(E_y - vB_z\right)}{\sqrt{1 - v^2/c^2}} \qquad E'_z = \frac{\left(E_z + vB_y\right)}{\sqrt{1 - v^2/c^2}}$$

$$B'_x = B_x \qquad B'_y = \frac{\left(B_y + \dfrac{v}{c^2}E_z\right)}{\sqrt{1 - v^2/c^2}} \qquad B'_z = \frac{\left(B_z - \dfrac{v}{c^2}E_y\right)}{\sqrt{1 - v^2/c^2}}$$

# Magnetic Field of a Moving Particle

Still: $$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2} \qquad B = 0$$

Moving: $$B_z' = \frac{\left(B_z - \frac{v}{c^2}E_y\right)}{\sqrt{1 - v^2/c^2}} = \frac{-\frac{v}{c^2}E_y}{\sqrt{1 - v^2/c^2}}$$




Slow case: $v \ll c \rightarrow B_z' = -\frac{v}{c^2}\frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$

$$\frac{1}{\mu_0\varepsilon_0} = c^2$$

$$B_z' = -\frac{\mu_0}{4\pi}\frac{qv}{r^2}$$

Field transformation is consistent with Biot-Savart law

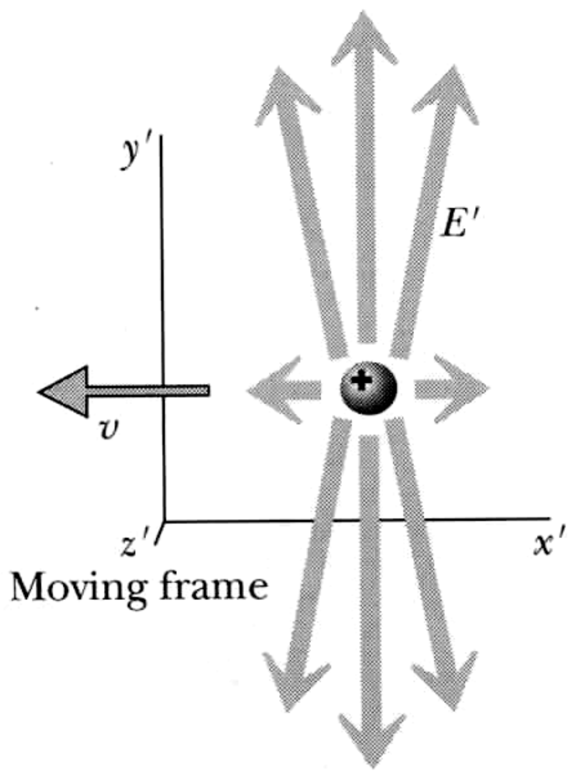
Electric and magnetic fields are interrelated

Magnetic fields are relativistic consequence of electric fields

# Electric Field of a Rapidly Moving Particle

$$E'_x = E_x \qquad E'_y = \frac{\left(E_y - vB_z\right)}{\sqrt{1 - v^2/c^2}} \qquad E'_z = \frac{\left(E_z + vB_y\right)}{\sqrt{1 - v^2/c^2}}$$

$$E'_y = \frac{E_y}{\sqrt{1 - v^2/c^2}} \qquad E'_z = \frac{E_z}{\sqrt{1 - v^2/c^2}}$$

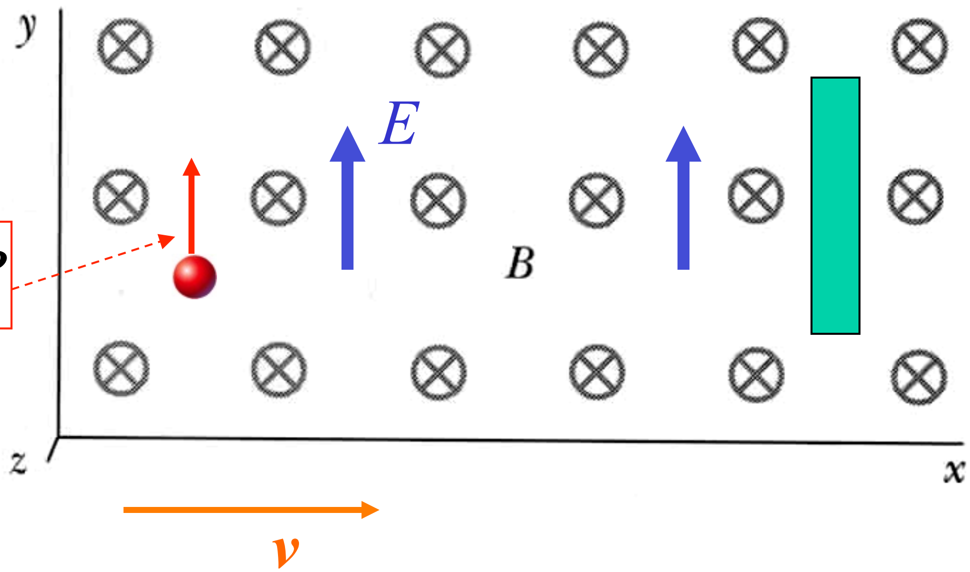


# Moving Through a Uniform Magnetic Field

$$\vec{B}_{lab} = \langle 0,0,-B \rangle$$

$$\boxed{\vec{F}_m = q\vec{v}\times\vec{B}}$$

$$\boxed{\vec{F}_e = q\vec{E}}$$




$$E'_x = E_x \qquad E'_y = \frac{(E_y - vB_z)}{\sqrt{1-v^2/c^2}} \qquad E'_z = \frac{(E_z + vB_y)}{\sqrt{1-v^2/c^2}}$$

$$\downarrow$$

$$E'_y = \frac{-vB_z}{\sqrt{1-v^2/c^2}} \approx vB \text{ if } v \ll c$$

# The Principle of Relativity

E and B look different for different observers in different reference frames, but all observers can correctly predict what will happen in their own frames, using the same relativistically correct physical laws.

E and B are "unified" – two sides of the same coin.