# Fall 2004 Physics 3
# Tu-Th Section

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Lecture 15: 18 Nov. 2004

Web page:
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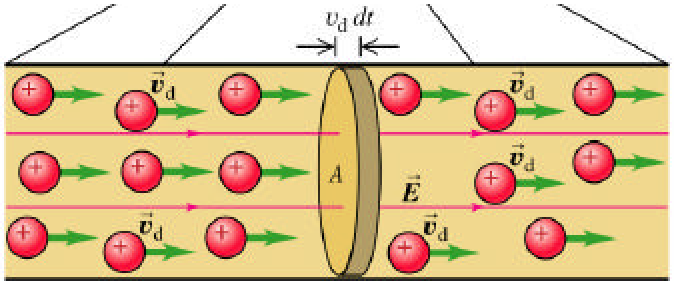
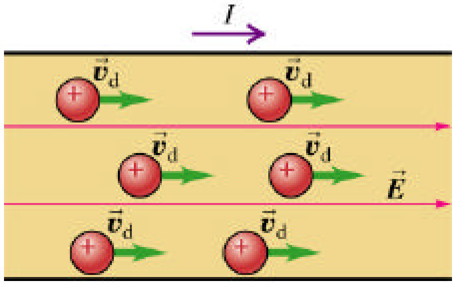
# Last Time: Electrical Current

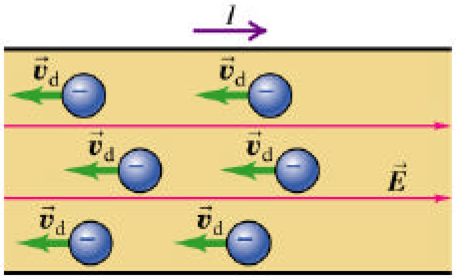
- Electrical Current = measure of the flow of charge




$$I = \frac{dQ}{dt}$$

- Defined in terms of flow of <u>positive</u> charge
  - ➢ even if in most case moving charges are electrons

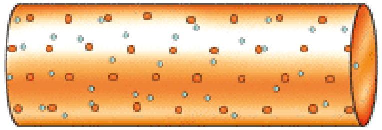


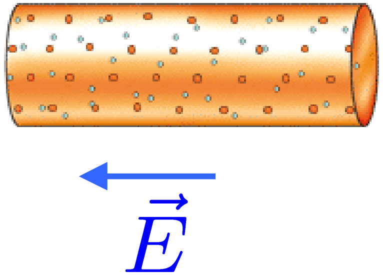

- Measured in Coulomb/sec = Ampere (A)

# Last Time: Drift Velocity

- In a conductor the free electrons are moving very fast in random directions ($v \sim 10^6$ m/sec)
- They collide with the atoms of the lattice and are scattered in random directions

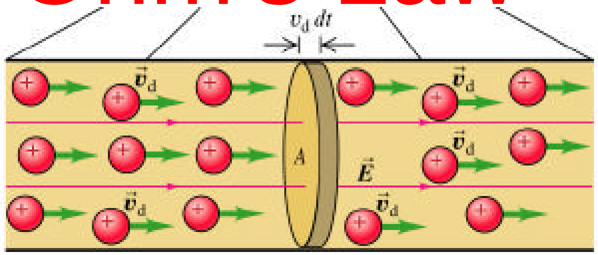


- If an electric field is present, there is a slow net drift of electrons in the direction opposite the electric field

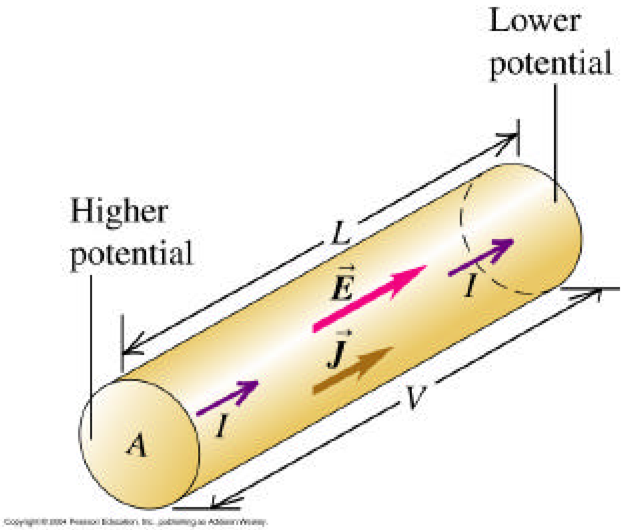



- $v_{DRIFT}$ ~ mm/sec

# Last Time: Current & Current Density Ohm's Law

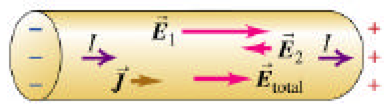



- $I = n\,q\,v_d\,A$
  - n = number of free charge carriers/unit volume
- Current density $J = I/A$
- Ohm's Law: $E = \rho\,J$
  - $\rho$ = resistivity
  - $\sigma = 1/\rho$ = conductivity
  - Good conductor: low $\rho$ / high $\sigma$
- Ohm's Law: $I = \frac{V}{R}$
  - R = resistance
  - Measured in Volt/Ampere = Ohm ($\Omega$)

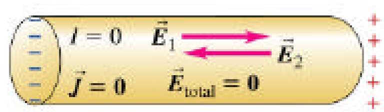


- Consider a piece of wire with E-field....

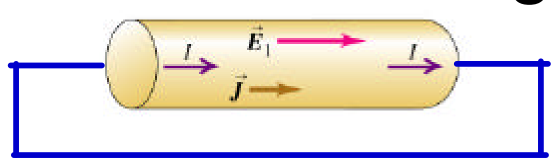

- ...current flows, charge builds-up at ends...



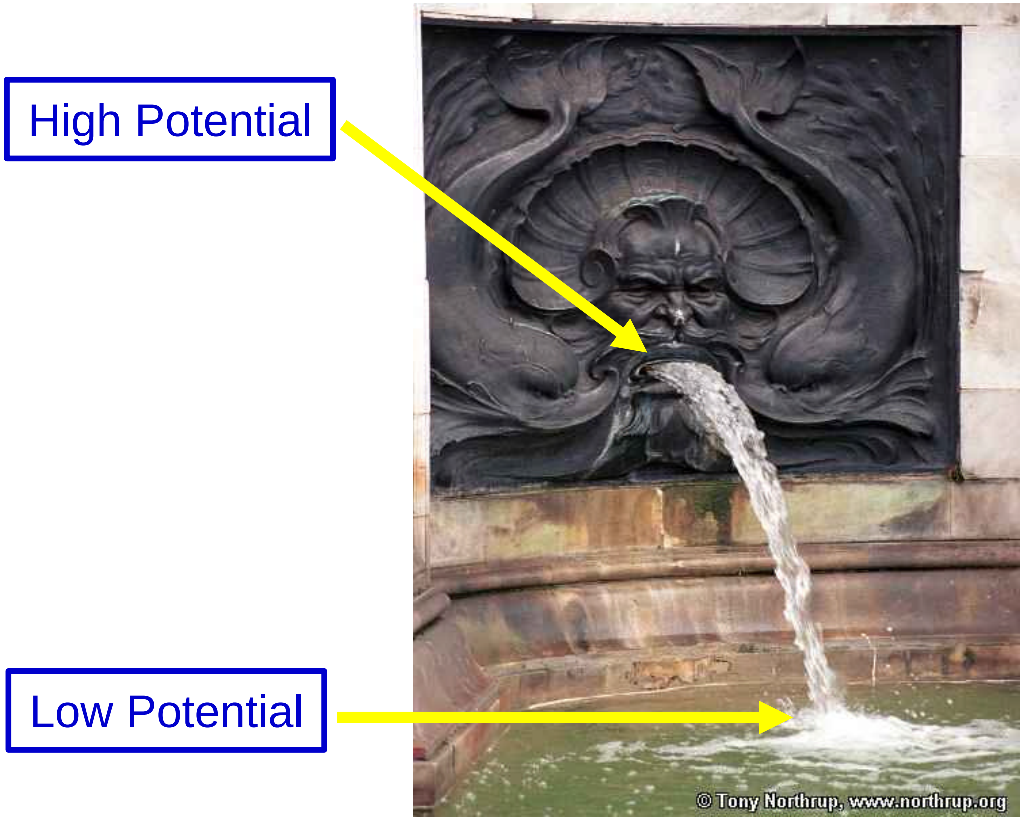
- ...until the electric field from the build up of charge cancels the original electric field....




- ...and the current stops!
- To keep the current going, I need to somehow move the charges around a loop



# Analogy: Water Fountain




- Water moves from high potential energy to low potential energy
- Just like +ve charge moves from high electric potential to low electric potential
- To keep the water circulating, the water needs to be brought back to the top
- This process costs energy (work needs to be done)
- In a fountain the work is done by a pump

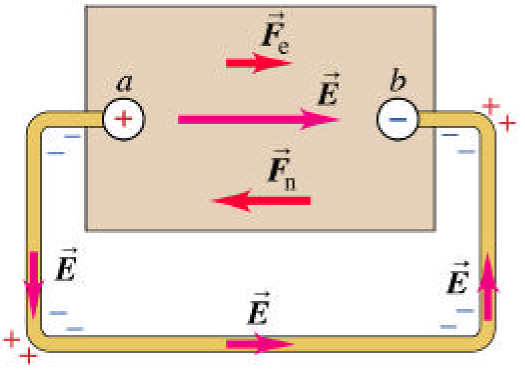
# Electromotive Force

- In a electric circuit the "something" that makes charge move from low potential to high potential is called electromotive force (emf)
- It is not a mechanical force, the term is a bit confusing
- The device that provides the emf is called the "source of emf"
  - e.g. a battery
  - moral equivalent of the pump in a fountain

# Source of emf

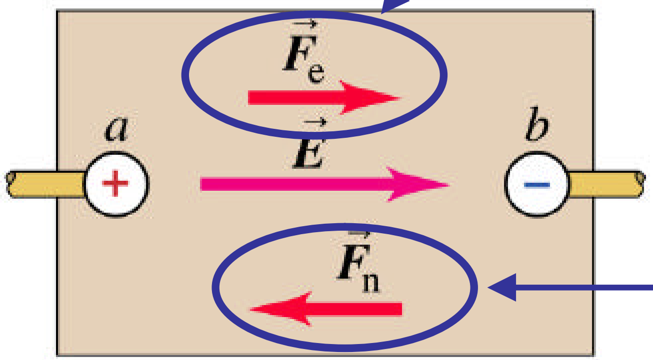
- An <u>ideal</u> source of emf is a device that maintains a constant potential difference across its <u>terminals</u>
- $V_{ab}$ constant


- When connected to an external circuit, the positive charges move in the circuit from the + to the – terminal. When they reach the – terminal the emf is able to move them back, internally, to the + terminal



# Ideal source of emf (continued)

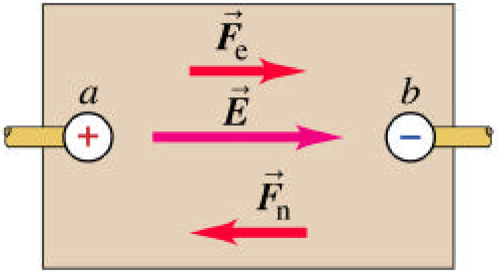
electric force that prevents +ve charge from moving from b→a This is due to internal E-field




force supplied by the emf to move +ve charge from b→a. This force must overcome the elctric force

- The emf ($\varepsilon$) is defined as the energy expended by the source to move unit charge from b→a
- $\varepsilon = V_{ab}$

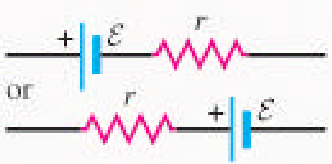
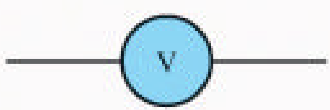
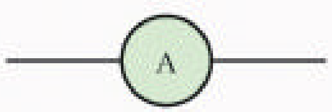
# Real source of emf



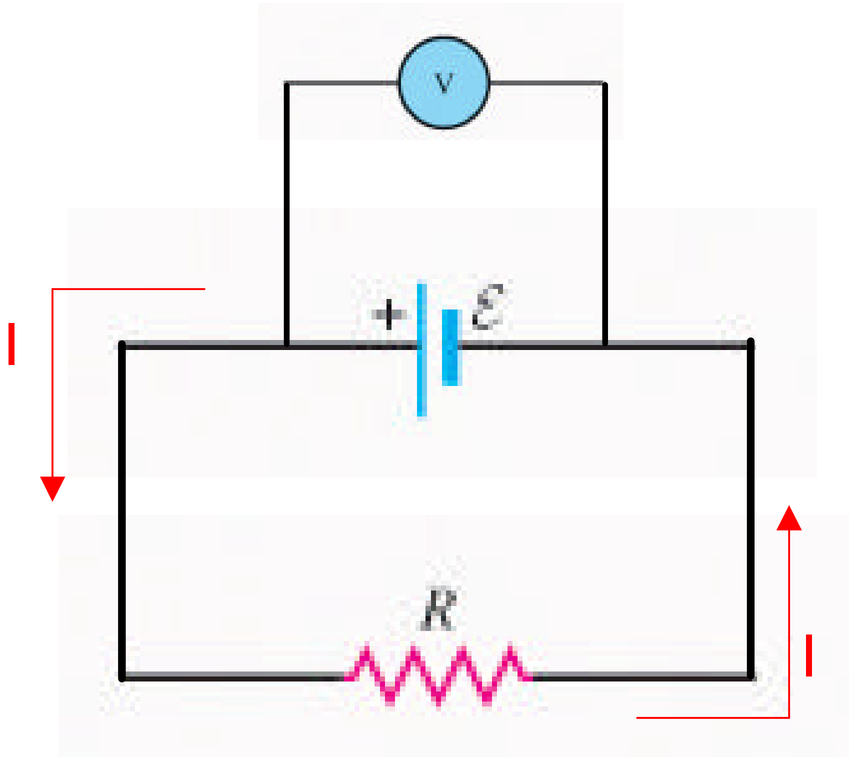

- In reality the source of emf needs to overcome
  - ➢ Potential difference $V_{ab}$ (ideal and real source)
  - ➢ Some small resistance to current flow within the battery (real sources)
    - Internal resistance r
- If current I moves through the source, there will be an associated drop of potentaial V=Ir
- $V_{ab} = \varepsilon - Ir$

# Circuit diagram symbols

**Table 25.4 Symbols for Circuit Diagrams**

| | |
|---|---|
|  | Conductor with negligible resistance |
|  | Resistor |
|  | Source of emf (longer vertical line always represent the positive terminal, usually the terminal with higher potential) |
|  | Source of emf with internal resistance *r* (*r* can be placed on either side) |
|  | Voltmeter (measures potential difference between its terminals) |
|  | Ammeter (measures current through it) |

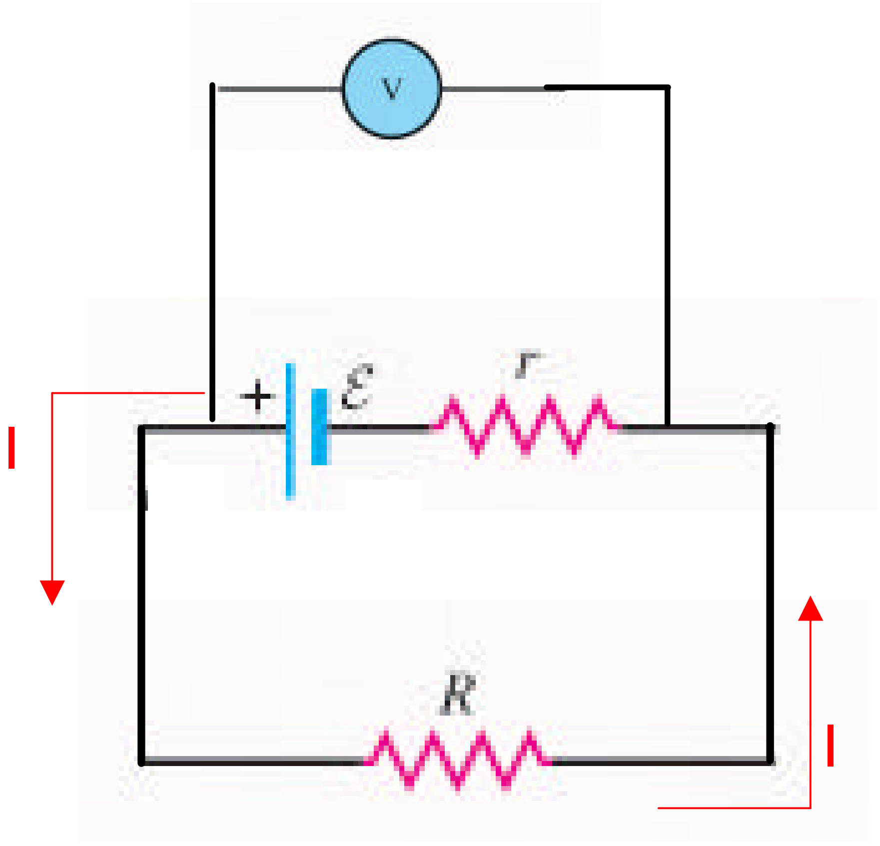
# Ideal source of emf connected to resistor




$$V = \mathcal{E}$$

$$I = \frac{\mathcal{E}}{R}$$

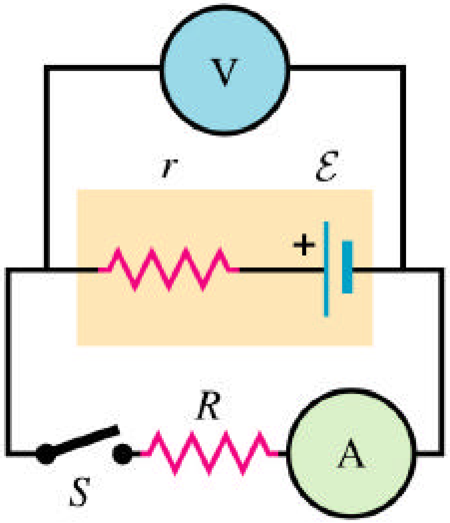
# Real source of emf connected to resistor




$$V = \mathcal{E} - Ir$$

$$I = \frac{\mathcal{E}}{R+r}$$

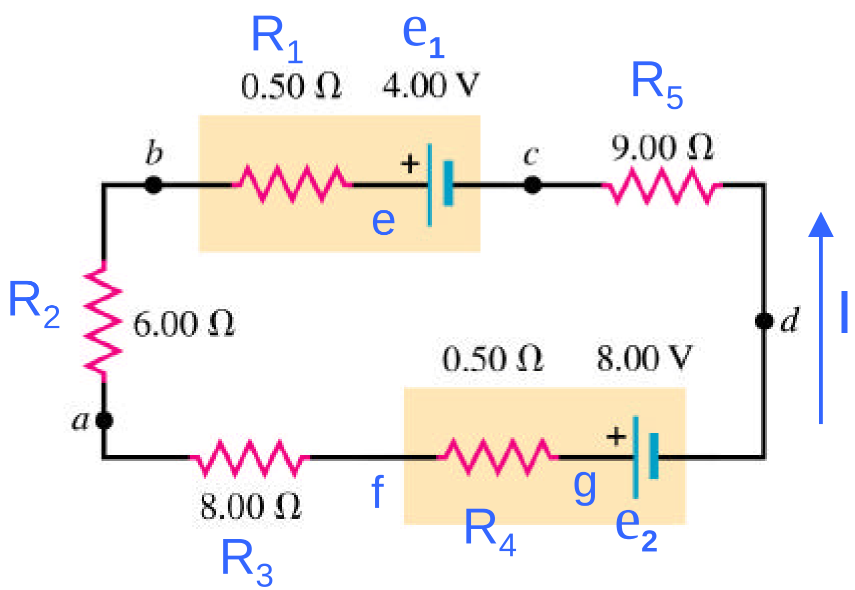
# Example: Problem 25.35




- Switch open: $V_{open}$=3.08 V
- Switch closed: $V_{closed}$=2.97 V, I=1.65 A
- Find emf, r, R

- Switch open:
  - no current flows
  - $\mathcal{E} = V_{open} = 3.08$ V
- Switch closed:
  - $V_{closed} = \mathcal{E} - Ir \rightarrow r = (\mathcal{E} - V_{closed})/I = (3.08 - 2.97)/1.65 = 0.067\ \Omega$
  - $\mathcal{E} = I(R+r) \rightarrow R = \mathcal{E}/I - r = (3.08/1.65 - 0.067)\ \Omega = 1.8\ \Omega$
  - OR: Voltage across R is $V_{closed} \rightarrow R = V_{closed}/I = 2.97/1.65 = 1.8\ \Omega$

# Example: Problem 25.64

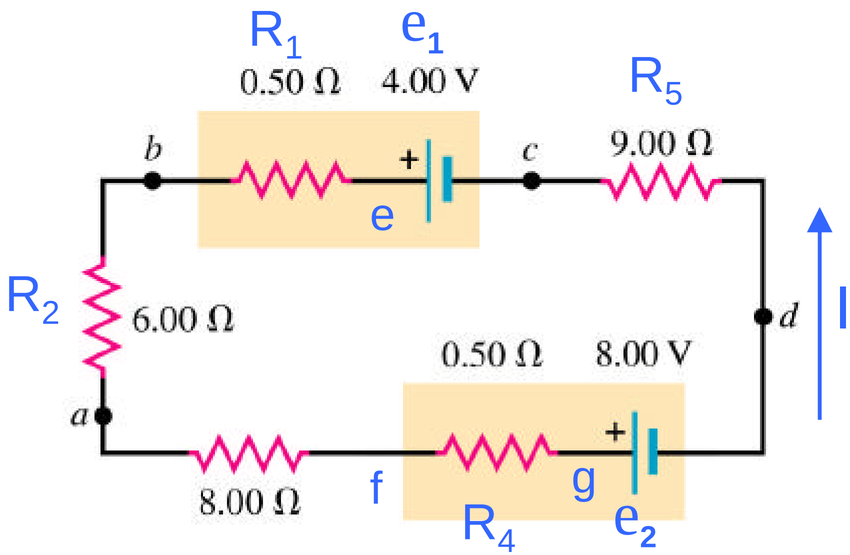



What is $V_{ad} = V_a – V_d$?

1. Label resistances, emfs, and intermediate points
2. Define direction of current (arbitrary)
3. Go around the circuit
   - $V_e – V_b = I\ R_1$
   - $V_b – V_a = I\ R_2$
   - $V_a – V_f = I\ R_3$
   - $V_f – V_g = I\ R_4$
   - $V_g – V_d = \varepsilon_2$

$V_d – V_c = I\ R_5$

$V_c – V_e = -\varepsilon_1$



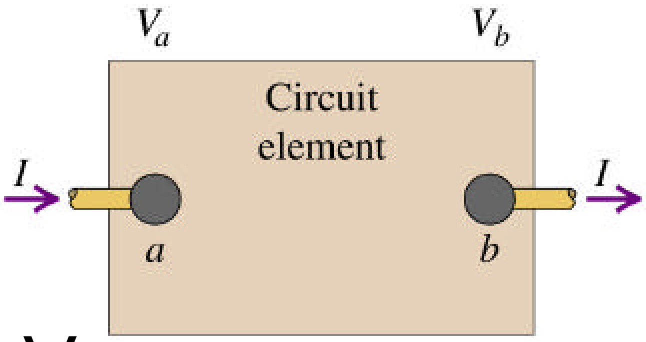

$V_e – V_b = I R_1$
$V_b – V_a = I R_2$
$V_a – V_f = I R_3$
$V_f – V_g = I R_4$
$V_g – V_d = \varepsilon_2$
$V_d – V_c = I R_5$
$V_c – V_e = -\varepsilon_1$

Clearly, I want to know the current I.
Sum up the 7 equations.
The left hand side is zero. This is no accident! I went around the loop and calculated potential drops. The total drop around the loop is zero.

$0 = IR_1 + IR_2 + IR_3 + \varepsilon_2 + IR_5 - \varepsilon_1$
$0 = IR_{tot} + \varepsilon_2 - \varepsilon_1$
(where $R_{tot}$ is the sum of all resistances, $R_{tot} = 32\ \Omega$)
$I = (\varepsilon_1 - \varepsilon_2)/R_{tot} = (4\text{-}8)/32\ A = -1/8\ A$

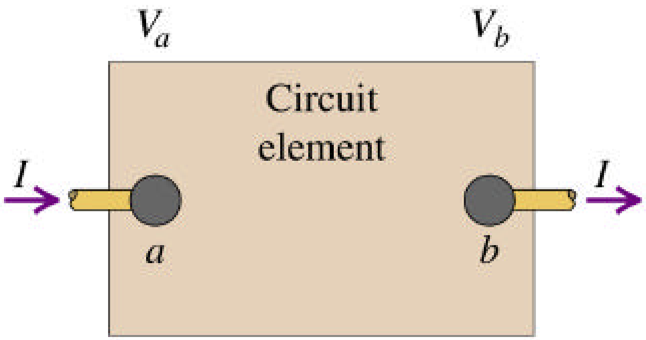
$V_{ad} = V_a – V_d = (V_a – V_f) + (V_f – V_g) + (V_g – V_d) = I R_3 + I R_4 + \varepsilon_2$
$V_{ad} = (-1/8)8\ V + (-1/8)(1/2)\ V + 8\ V = -1\ V – 1/16\ V + 8\ V = 6.94\ V$

# Energy




- Consider circuit element
- Charge q moves a→b
- Change in potential energy $qV_{ab}$
  - $\Delta U = U_{final} - U_{initial} = -qV_{ab}$
- Suppose $q>0$, $V_{ab}>0$
  - This would be what happens, e.g., for resistor
    - The charge "falls" to a lower potential energy
  - $\Delta U < 0$
- What happened to the energy?
  - In the mechanical analogue of a falling mass, the loss of potential energy is compensated by an increase in kinetic energy

- In the electric case we know that the charges are not really accelerated
  - ➢ Because they collide with the atoms of the material and get scattered
  - ➢ All we get is a very slow drift
  - ➢ Also, we know that the current (= flow of charge) into the element is equal to the current out of the element
    - This could not happen if there was a net acceleration
- The energy is transferred from the charges to the atoms of the material in the collisions
- The atoms vibrate more violently → the material heats up.
  - ➢ Principle of toaster oven, electric space heater, lightbulb

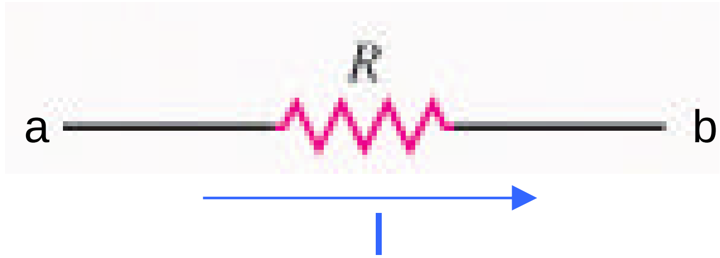



- Could also have $V_b > V_a$
  - e.g., in a source of emf
- Then the change of potential energy is positive
  - the element delivers electrical energy to the system
- The amount of energy delivered to the system or delivered by the system is always $q|V_{ab}|$
  - where q is the amount of charge that is moved from one terminal to the other

# Power

- Reminder: Power is the rare of energy delivered or absorbed per unit time
- P = dE/dt
  - Units: Joule/second = Watt (W)
- But $E = qV_{ab}$
- $P = V_{ab}\, dq/dt = V_{ab}I$

# Power dissipated as heat in a resistance



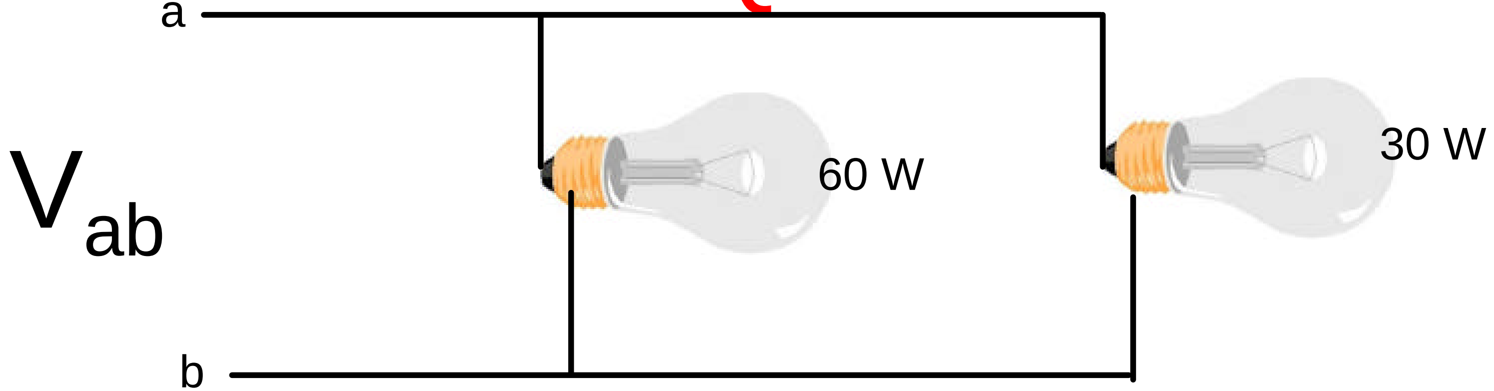

$V_{ab} > 0$

- $P = I V_{ab}$
- But Ohm's law: $I = V_{ab}/R$

$$P = V_{ab} I = I^2 R = \frac{V_{ab}^{\ 2}}{R}$$

- Resistors have a "power rating" = the maximum power that can be transferred to them before they get damaged (catch on fire!)

# Quiz




1. The 30 W bulb carries the greater current and has the higher resistance
2. The 30 W bulb carries the greater current and the 60 W bulb has the higher resistance
3. The 30 W bulb has the higher resistance, but the the 60 W bulb carries the greater current
4. The 60 W bulb carries the greater current and has the higher resistance

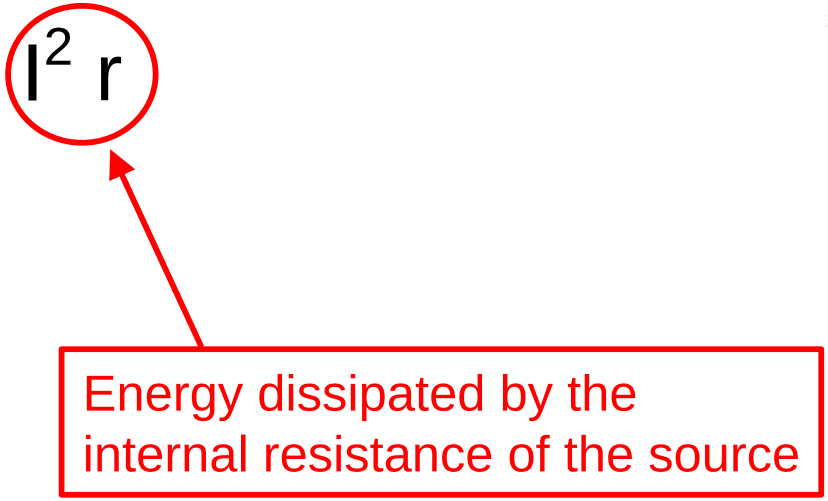
# Answer

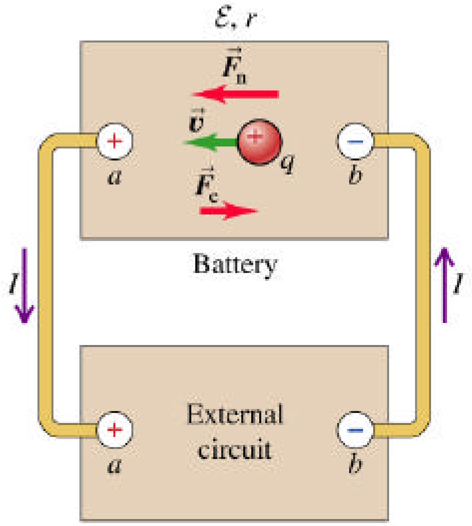
3: The 30 W bulb has the higher resistance, but the the 60 W bulb carries the greater current

- The potential difference is the same across the two bulbs. The power delivered is $P = V_{ab} I$. Then the 60 W bulb with its higher power rating must carry the highest current. But high current flows where the resistance is smallest, so the 60 W bulb must have the smaller resistance

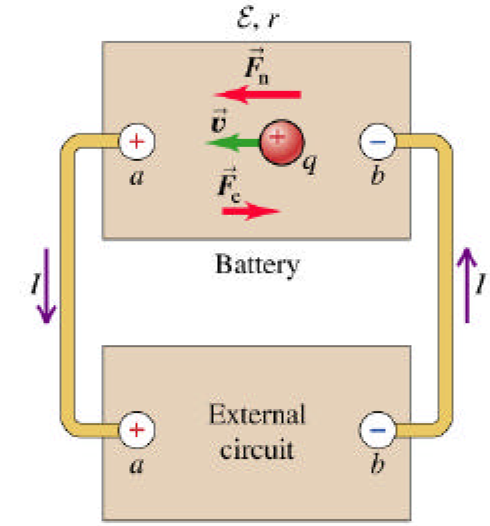
# Power output of a source

- $P = V_{ab} I$
- $V_{ab} = \varepsilon - Ir$
- $P = \varepsilon I - I^2 r$

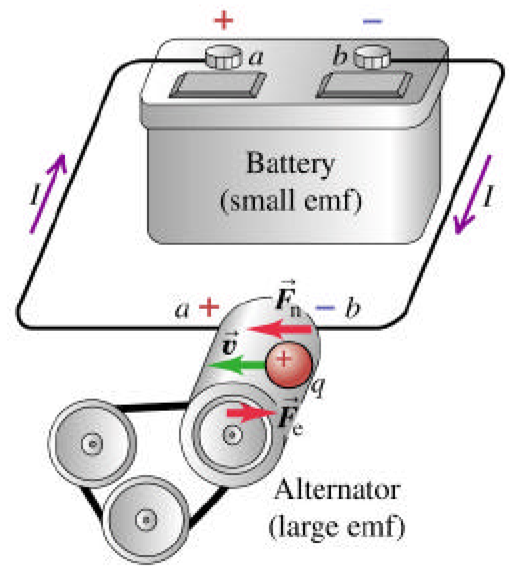


# Power input to a source




- Suppose that the external circuit is itself a source of emf
- For example, the alternator of a car recharging its battery
- Or the charger of your cell phone or notebook or ipod


$V_{ab} = V_a - V_b = (V_a - V_c) + (V_c - V_b)$

$V_{ab} = Ir + \varepsilon$

Then: $P = V_{ab}\, I = \varepsilon + I^2 r$

input power (P)

power dissipated by internal resistance ($I^2 r$)

# Problem

- A copper cable needs to carry a current of 300 A with a power loss of < 2 W/m. What is the required radius of the copper cable?

$P = I^2 R$

Want $P < P_0 = 2$ W (per meter)

→ R (per meter) $< P_0/I^2$.

Last time, R of cylindrical wire, length L, radius r

$R = \rho L/(\pi r^2)$

→ $\rho/(\pi r^2) < P_0/I^2$

$$r > I\sqrt{\frac{\rho}{\pi P_0}} = 200\sqrt{\frac{1.7\cdot 10^{-8}}{\pi 2}} = 1.6 \text{ cm}$$