

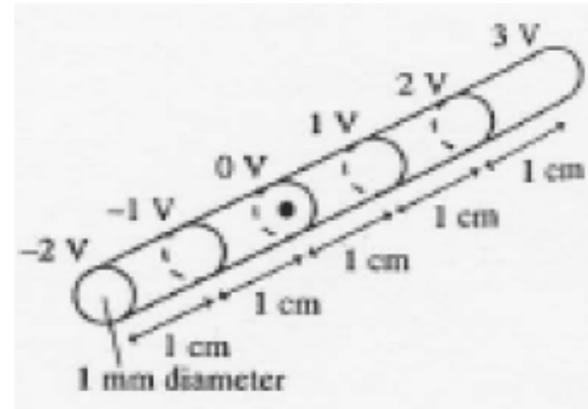
# PHY294H

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- Professor: Joey Huston
- email: [huston@msu.edu](mailto:huston@msu.edu)
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - ◆ **Added problem 28.68 for 3<sup>rd</sup> MP assignment due Wed Feb. 3 as a hand-in problem**
  - ◆ **Problem 29.78 (already assigned) will be the hand-in problem for 4<sup>th</sup> MP assignment (due Wed Feb. 10)**
  - ◆ **Help-room hours: 12:40-2:40 Tues; 3:00-4:00 PM Friday**
- Quizzes by iclicker (sometimes hand-written)
- Course website: [www.pa.msu.edu/~huston/phy294h/index.html](http://www.pa.msu.edu/~huston/phy294h/index.html)
  - ◆ lectures will be posted frequently, mostly every day if I can remember to do so

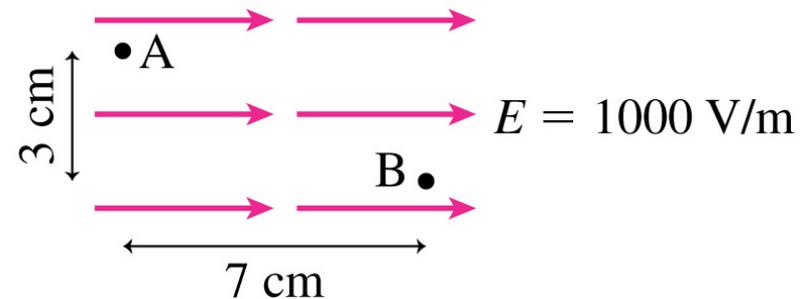
# Field and potential

- What is the electric field at the dot?



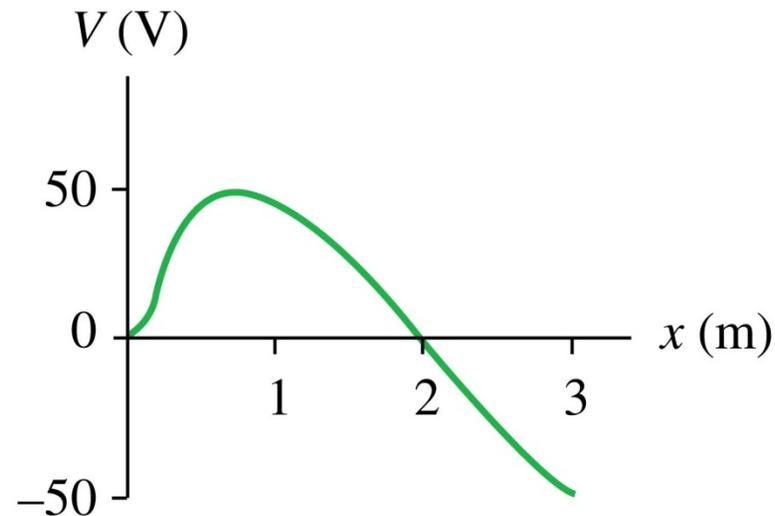
$$E = -\frac{\Delta V}{\Delta s} = -\frac{1V}{.01m} = 100 \frac{V}{m} \text{ in direction of decreasing potential}$$

- Which point has the larger potential? What is the potential difference between A and B?



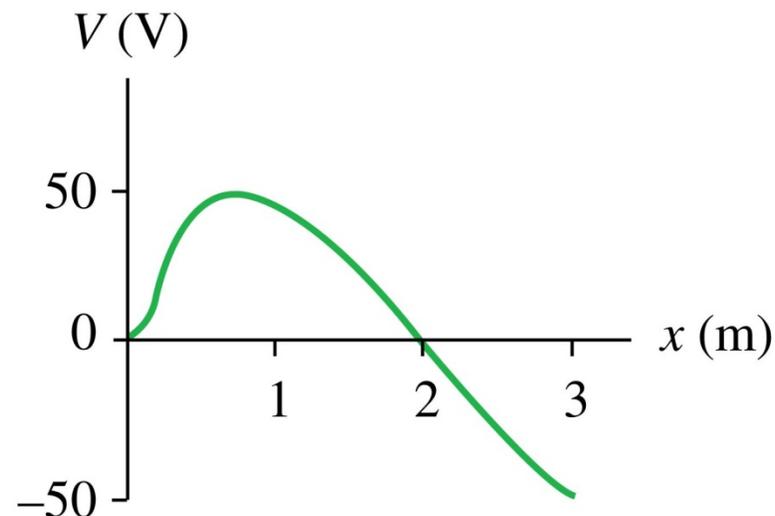
An electron is released from rest at  $x = 2$  m in the potential shown. What does the electron do right after being released?

- A. Stay at  $x = 2$  m.
- B. Move to the right ( $+x$ ) at steady speed.
- C. Move to the right with increasing speed.
- D. Move to the left ( $-x$ ) at steady speed.
- E. Move to the left with increasing speed.



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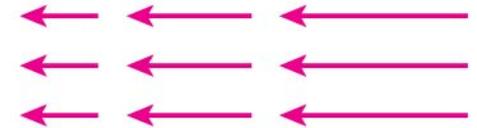
- A. Stay at  $x = 2$  m.
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- C. Move to the right with increasing speed.
- D. Move to the left ( $-x$ ) at steady speed.
- ✓ E. Move to the left with increasing speed.



Slope of  $V$  negative  
 $\Rightarrow E_x$  is positive  
(field to the right).  
Electron is negative  
 $\Rightarrow$  force to the left.  
Force to the left  $\Rightarrow$   
acceleration to the  
left.

---

Which set of equipotential surfaces matches this electric field?



A.



B.



C.



D.



E.



F.

Which set of equipotential surfaces matches this electric field?



Stronger field  
⇒ closer equipotentials



A.



B.



C.



D.



E.

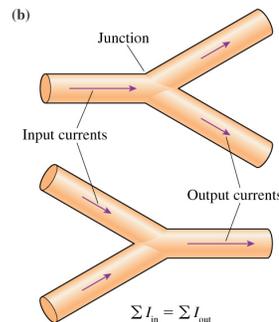


F.

# Kirchoff' s loop rule

- Kirchoff' s junction rule is straightforward

$$\Sigma I_{in} = \Sigma I_{out}$$

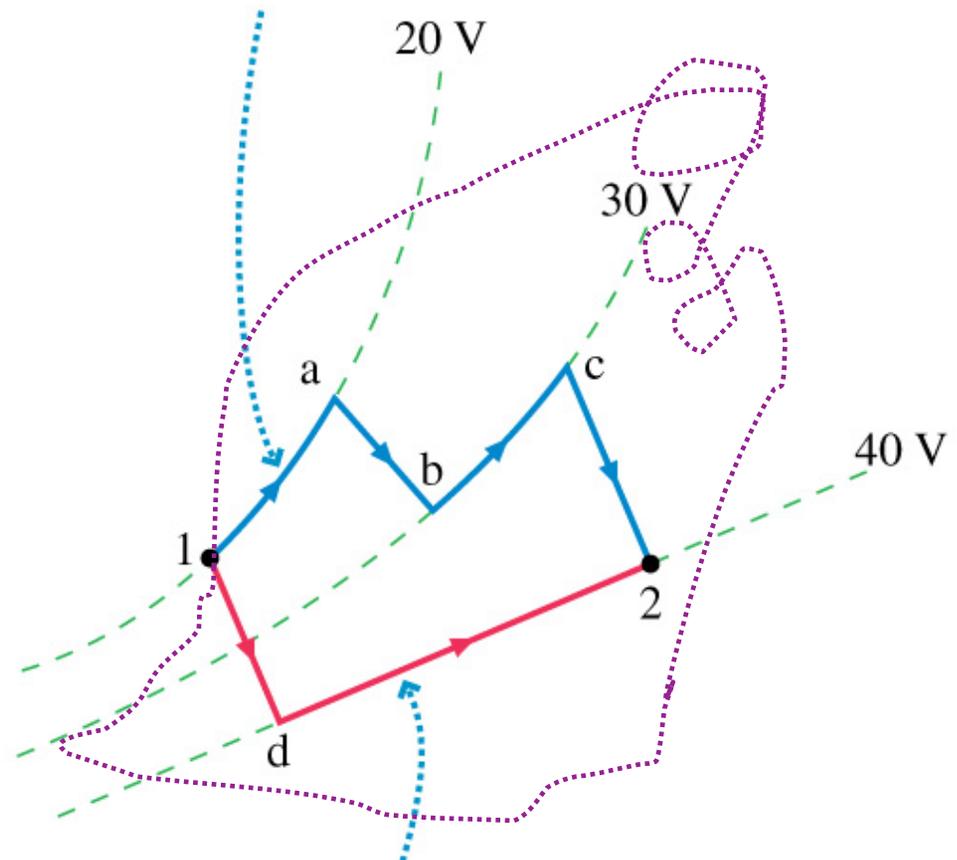


- Kirchoff' s loop rule states that the sum of all potential differences around a closed loop equals zero

$$\Delta V_{loop} = \sum_i (\Delta V)_i = 0$$

- ◆ it' s just a statement of the conservation of energy;  
 $\Delta U = q\Delta V = 0$

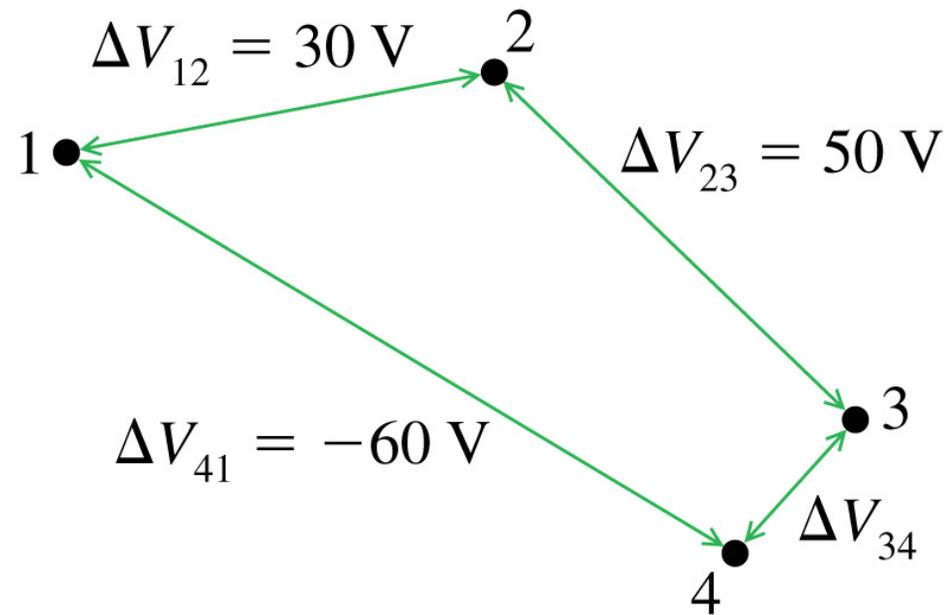
The potential difference along path 1-a-b-c-2 is  $\Delta V = 0 \text{ V} + 10 \text{ V} + 0 \text{ V} + 10 \text{ V} = 20 \text{ V}$ .



The potential difference along path 1-d-2 is  $\Delta V = 20 \text{ V} + 0 \text{ V} = 20 \text{ V}$ .

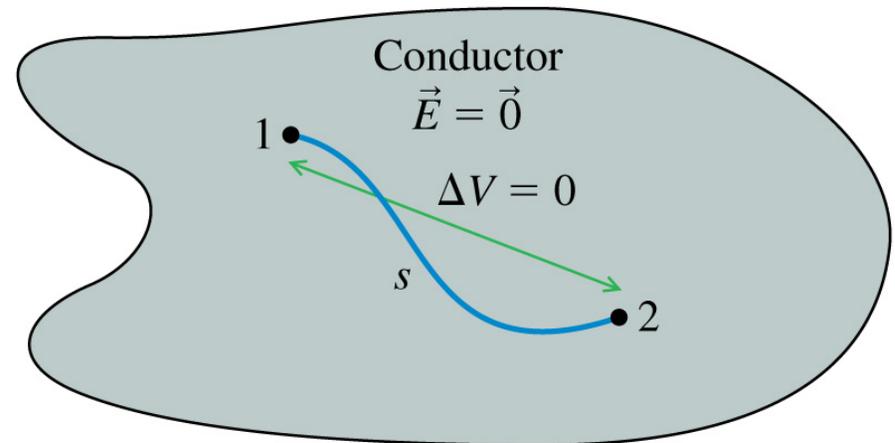
# Example

- What is  $\Delta V_{34}$ ?



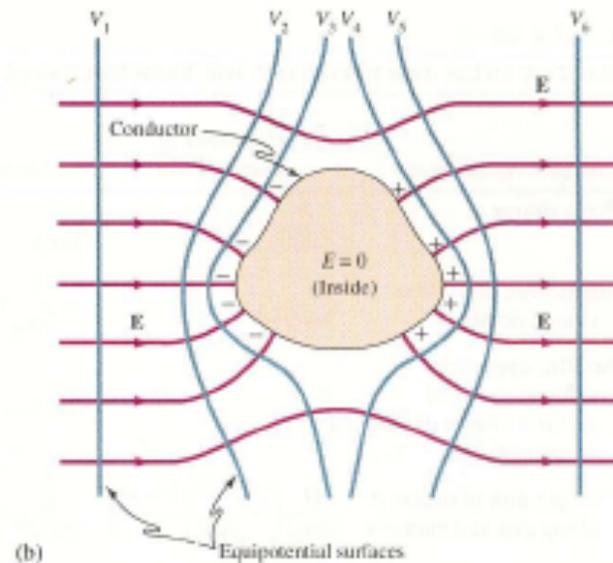
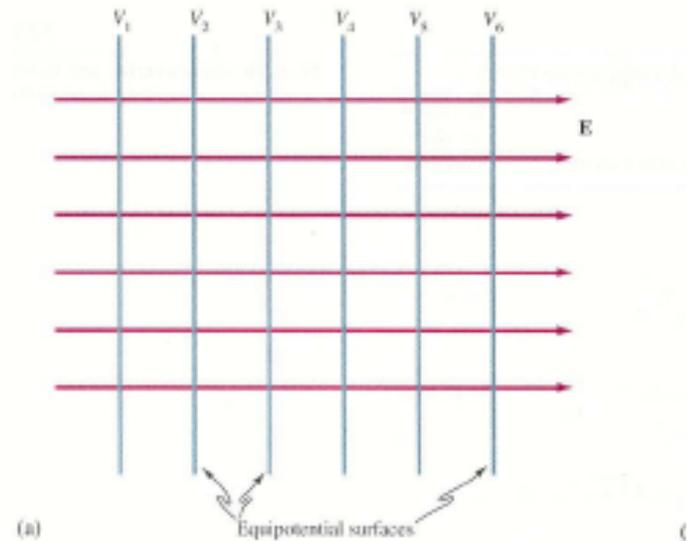
# Electric fields and conductors

- We've stated before that any excess charge on a conductor resides on the surface
- We also state that the electric field inside any conductor (in equilibrium) is zero
  - ◆ if not, there would be a movement of electrons to make it so
- As a result, the interior of a conductor is all the same potential
  - ◆ if not, then the electric field would be non-zero



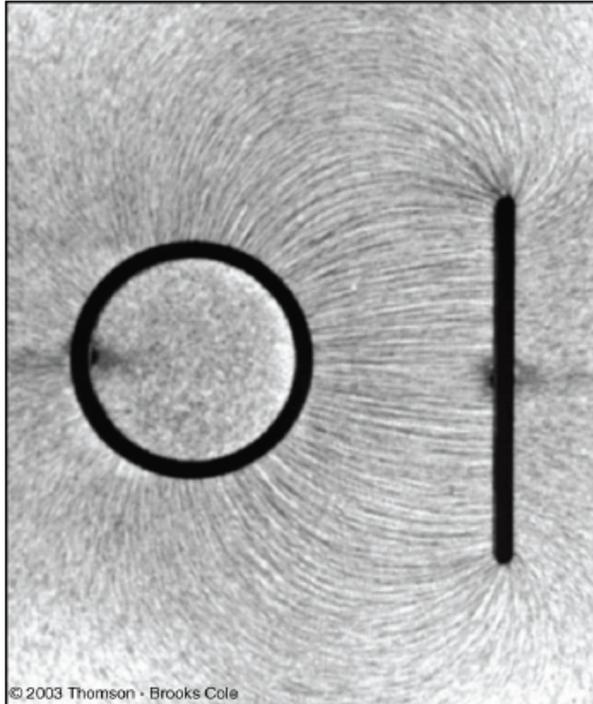
# Electric fields and conductors

- What happens to the electric field (and the equipotential surfaces) in the presence of a conductor
  - ◆ conductor is all at one potential
  - ◆ electric field is always perpendicular to the surface of the conductor
  - ◆ electric field is always perpendicular to equipotential surfaces
  - ◆ this means the equipotential surfaces near the conductor surface must match the shape of the conductor



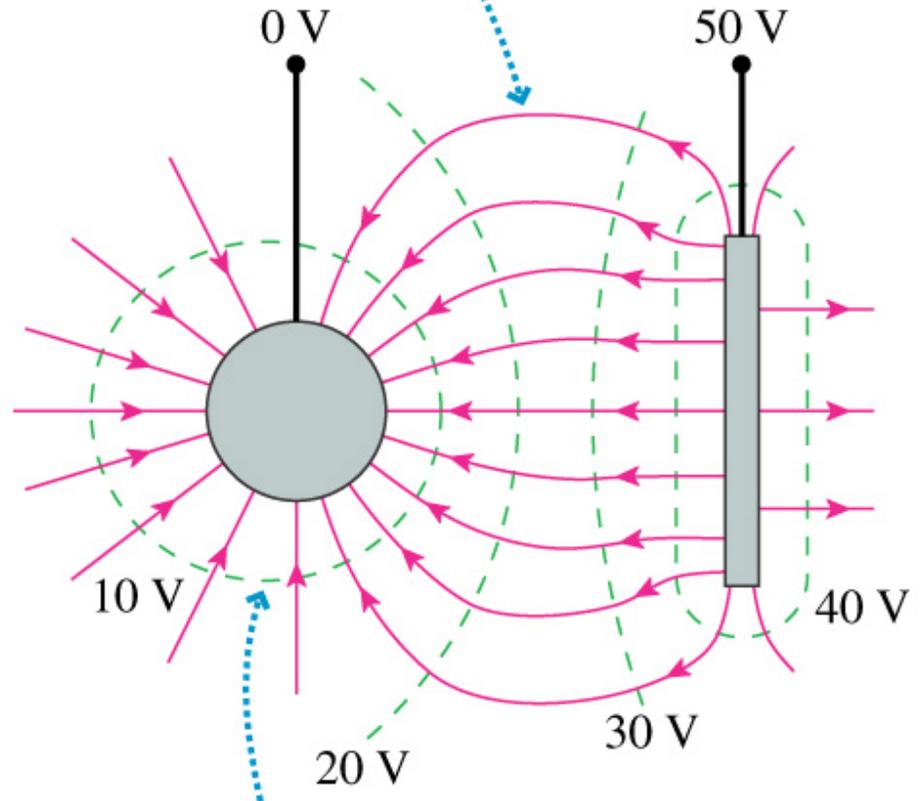
# Equipotential surfaces

- ◆ this means the equipotential surfaces near the conductor surface must match the shape of the conductor



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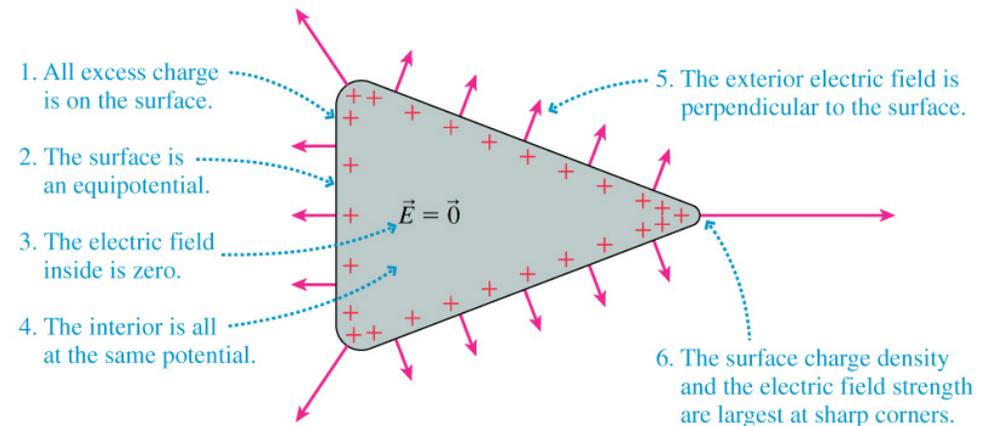
- (a) The field lines are perpendicular to the equipotential surfaces.



The equipotential surfaces gradually change from the shape of one electrode to the shape of the other.

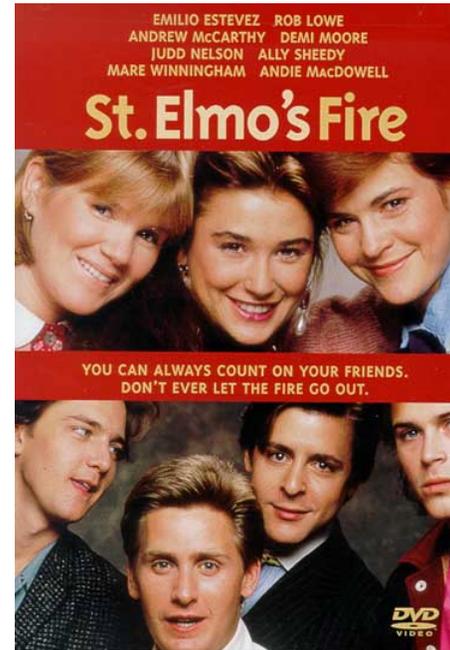
# Sharp ends

- The surface charge density is greater on a conductor in regions of severe curvature (sharp edges)
- The electric field is proportional to the surface charge density
- Thus the electric field is larger near sharp ends of a conductor
  - ◆ the electric field is inversely proportional to the radius of curvature



# Corona discharge

- When an electric field is strong enough to overcome the attraction between ions and electrons, corona discharge occurs
  - ◆ the electrons are ripped loose from the molecules which are said to be ionized
- In air, this occurs for electric fields of the order of  $3 \times 10^6$  V/m or more
  - ◆ ionization of air molecules can cause a glow
  - ◆ sailors called this St. Elmo's fire
    - ▲ top of mast of ship
  - ◆ we call it dielectric breakdown



not St. Elmo's  
fire



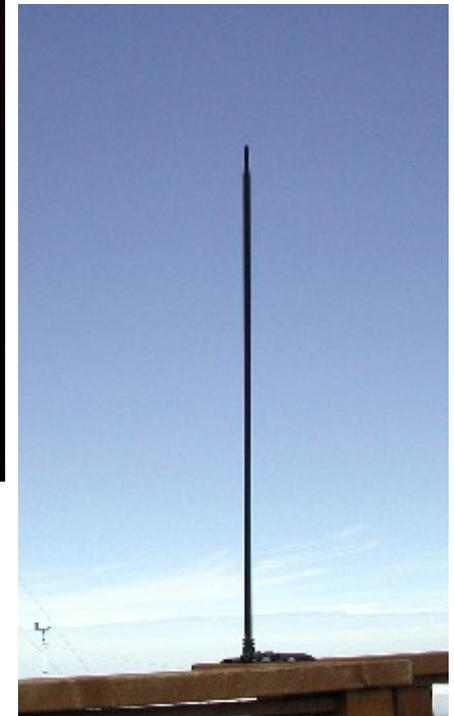
St. Elmo's  
fire

# St. Elmo's fire

- The positively charged ionized molecules are accelerated by the large electric fields and move away from the region of breakdown
- Thus after dielectric breakdown, the air in effect becomes a conductor that carries away the excess charge
- This lowers the electric potential around the original conductor
- In thunderstorms, there are large potential differences between the ground and clouds because of a buildup of charges in the clouds
- Lightning rods cause a local dielectric breakdown and lower the potential difference between the rods and the clouds
- They can prevent lightning by lowering the potential difference



...plus provide a safe path to ground if lightning does strike



# Fun fact: who was St. Elmo

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No



# Fun fact: who was St. Elmo

No



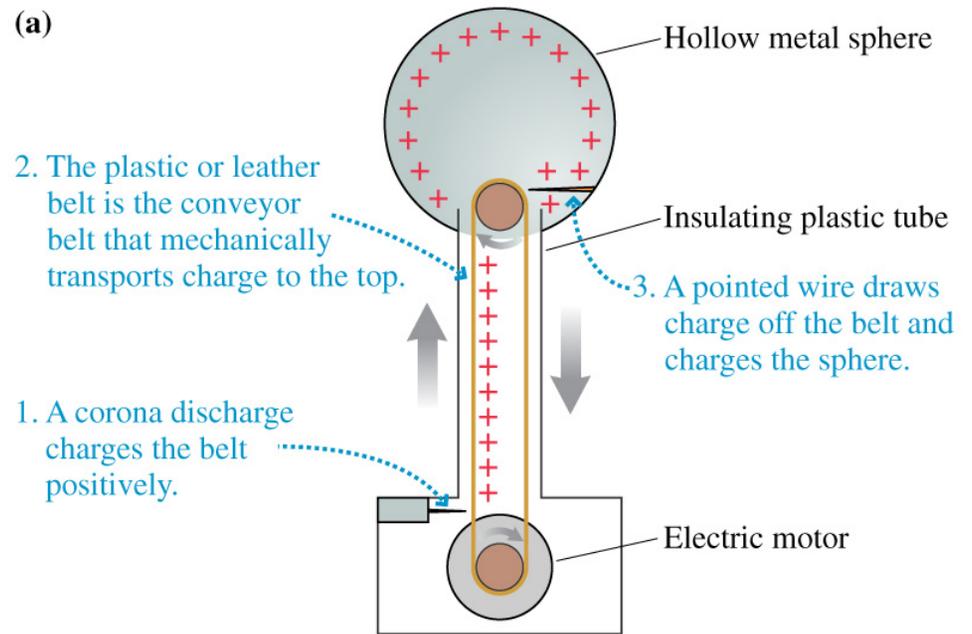
Yes

patron saint  
of sailors (and  
abdominal  
pain)



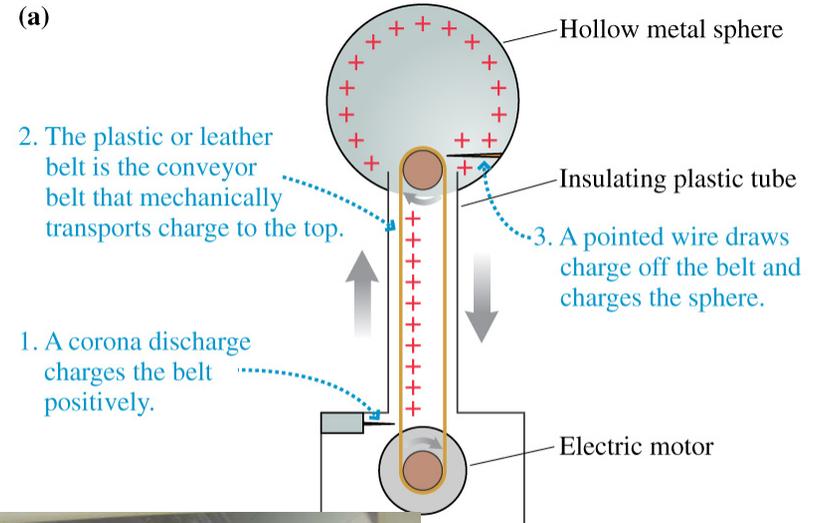
# Breakdown

- For a spherical conductor, the potential and electric field are related by
  - ◆  $V=RE$
  - ◆ where  $R$  is the radius of curvature
- The maximum potential that can be put on a surface in air is  $R(3 \times 10^6 \text{ V/m})$ 
  - ◆  $10^7 \text{ V}$  for  $R= 3 \text{ m}$
  - ◆  $300 \text{ V}$  for  $R=0.1 \text{ mm}$



# Van de Graaf

- Let's return to the van de Graaf and how it works
- Invented by Robert Van de Graaf in 1931 as a way of accelerating charged particles
  - ◆ an insulated belt continuously brings charge to the inside of a hollow conductor where brushes extract charge from the belt
  - ◆ the brushes are connected to the hollow conductor
  - ◆ so the charge proceeds to the outside surface of the conductor
  - ◆ the electric potential on the outside surface is
    - ▲  $V=q/4\pi\epsilon_0 R$
    - ▲ can develop up to 25 million volt potentials



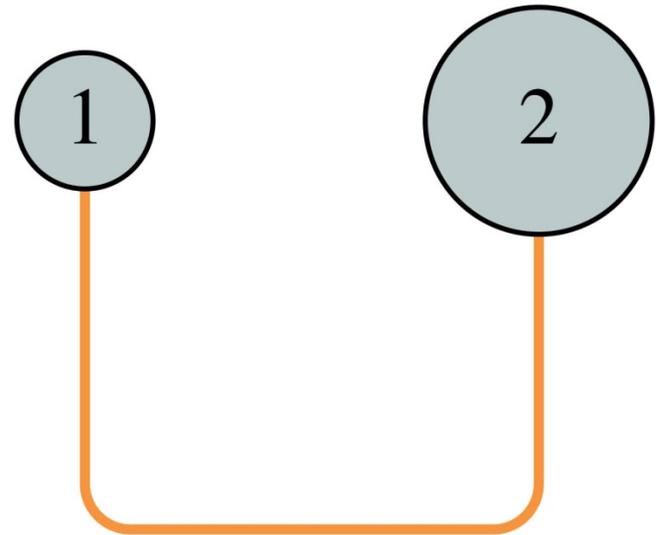
The Fermilab and CERN accelerators start with a Van de Graaf

Notice anything  
about the van de Graf

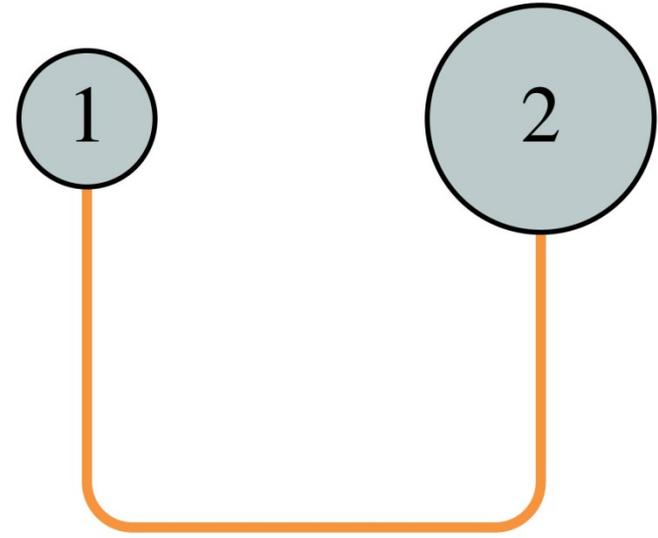


Metal spheres 1 and 2 are connected by a metal wire. What quantities do spheres 1 and 2 have in common?

- A. Same potential.
- B. Same electric field.
- C. Same charge.
- D. Both A and B.
- E. Both A and C.



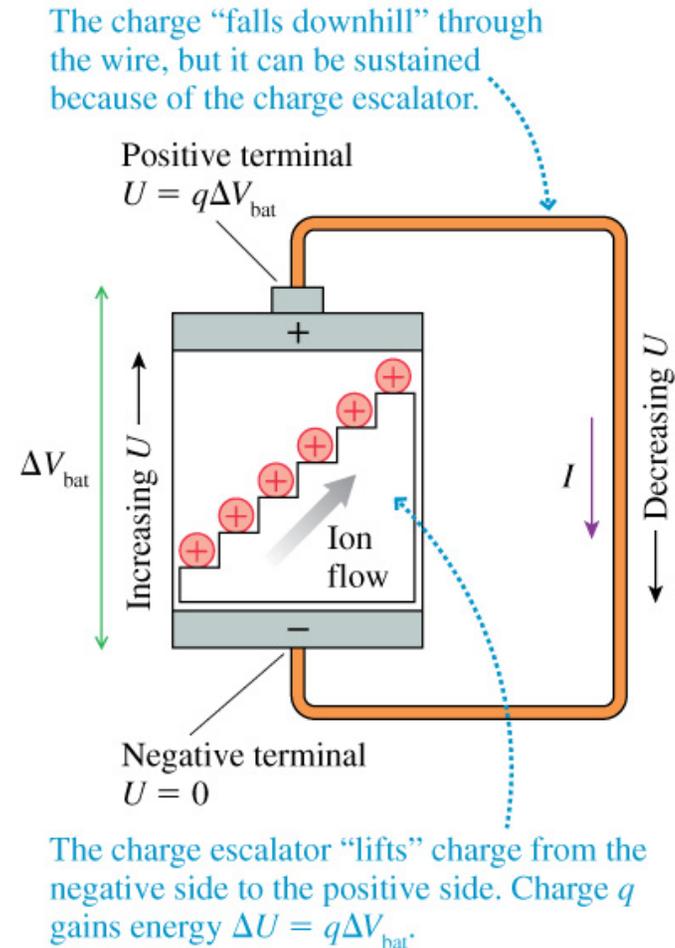
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- ✓ A. **Same potential.**
- B. Same electric field.
- C. Same charge.
- D. Both A and B.
- E. Both A and C.

# Batteries

- A battery is another way of creating a potential difference by movement of charges
- In the escalator model, positive charges are lifted from the negative terminal of the battery to the positive terminal
  - ◆ chemical reactions inside the battery provide the energy necessary to do this work
  - ◆ by separating the charge, the escalator establishes a potential difference between the two terminals
- In an ideal battery,  $\Delta U = W_{\text{chem}}$ , the charge gains a potential energy equal the work performed by the chemical reactions



$$\Delta V_{\text{battery}} = \frac{W_{\text{chem}}}{q} = \text{emf}(\varepsilon)$$

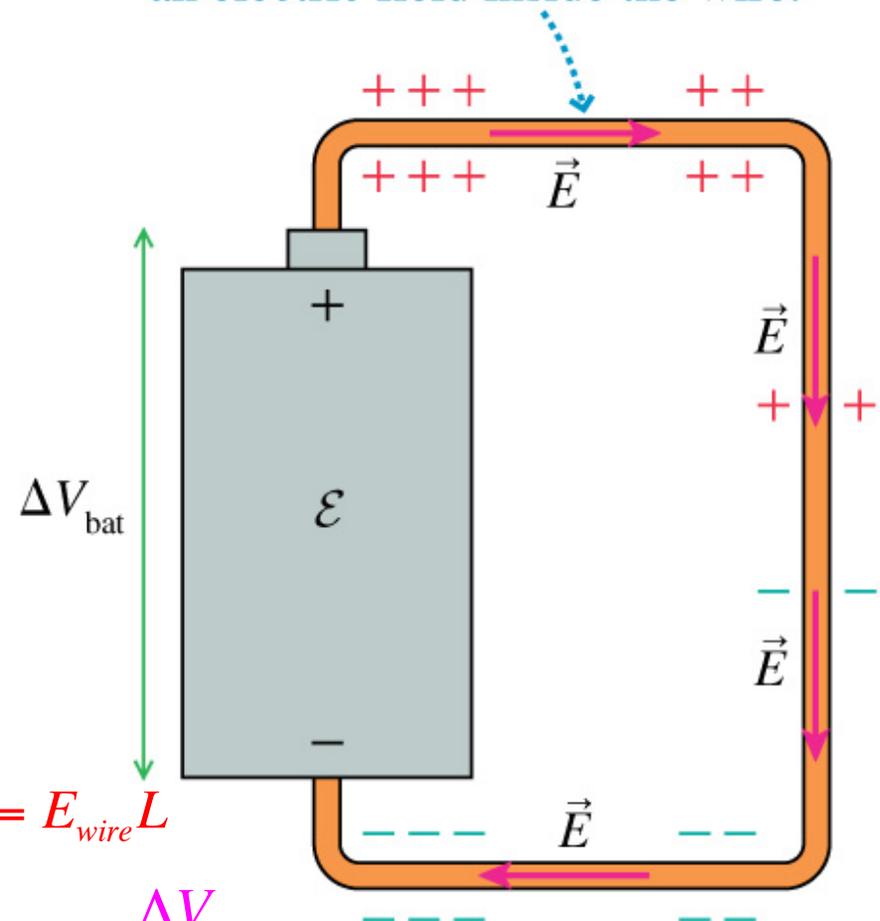
# Electric field and current

- So the battery establishes a potential difference between the positive and negative terminals
- Which is also the potential difference between the two ends of the wire
- If there's a potential difference, then there's an electric field
- And if there's an electric field then there will be a current flow

$$\Delta V_{\text{wire}} = -\int_0^L E_s ds = -\int_0^L (-E_{\text{wire}}) ds = E_{\text{wire}} \int_0^L ds = E_{\text{wire}} L$$

$$E_{\text{wire}} = \frac{\Delta V_{\text{wire}}}{L}$$

(a) The potential difference between the ends of the wire establishes an electric field inside the wire.

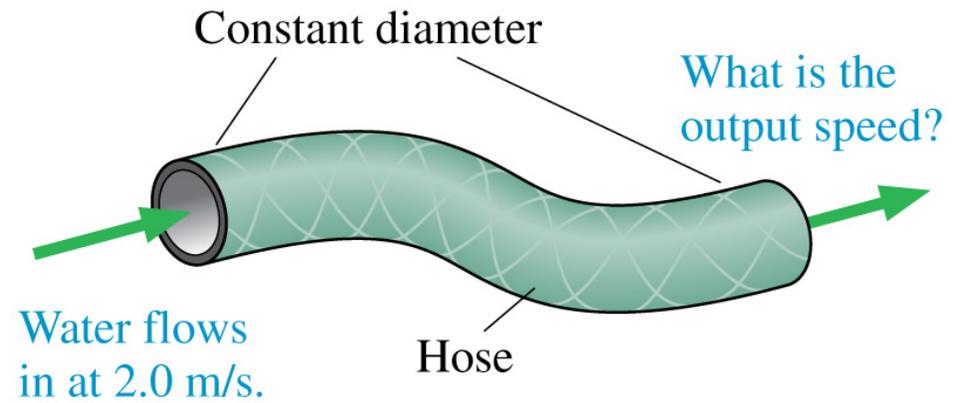


# Analogy

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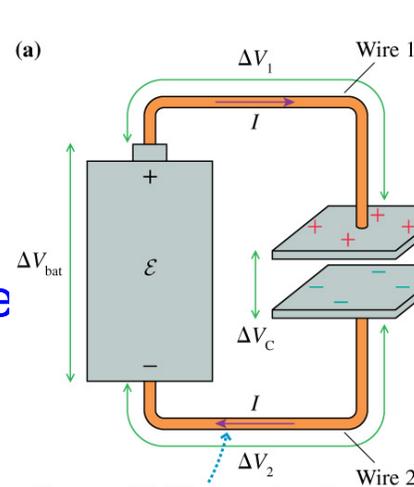
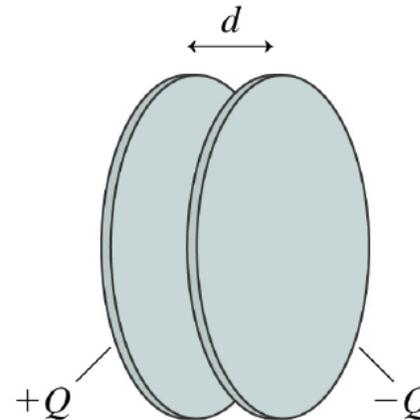
$$I = \frac{A}{\rho L} \Delta V_{wire} = \frac{\Delta V_{wire}}{R}$$

$$R = \frac{\rho L}{A}$$

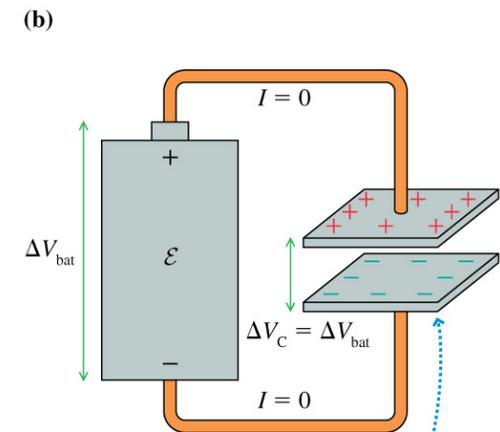


# Capacitors

- We've already introduced capacitors as a convenient way of producing a uniform electric field
- One way of producing the field is to connect a battery to the two surfaces of the capacitor
- The charges are separated due to the work performed by the battery and the potential difference of the battery appears across the capacitor creating an electric field inside the capacitor



The potential differences along the wires create a current that moves charge from one capacitor plate to the other.



When  $\Delta V_{\text{C}} = \Delta V_{\text{bat}}$ , the current stops and the capacitor is fully charged.

# Capacitance

- We know the electric field inside the capacitor

$$E = \frac{\sigma}{\epsilon_0} = \frac{Q}{\epsilon_0 A}$$

- And we also know the relation between the electric field and voltage

$$\Delta V_c = Ed; E = \frac{\Delta V_c}{d}$$

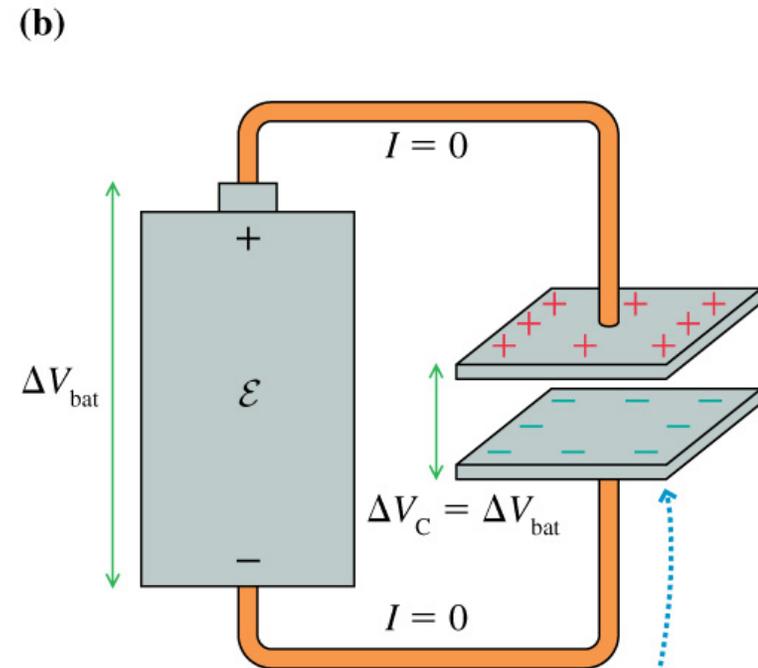
- So

$$\frac{\Delta V_c}{d} = \frac{Q}{\epsilon_0 A}$$

- Define

$$C = \frac{Q}{\Delta V_c} = \frac{\epsilon_0 A}{d} \quad \text{unit} = \text{C/V} = \text{F (Farad, after Michael Faraday)}$$

...as the ability of a capacitor to store charge given a certain voltage



When  $\Delta V_c = \Delta V_{\text{bat}}$ , the current stops and the capacitor is fully charged.