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# PHYS2326
# Lecture #08

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# Goals for this lecture (Ch. 23)

- Review/conclude:
  - Gauss's Law
  - Conductors in electrostatic equilibrium

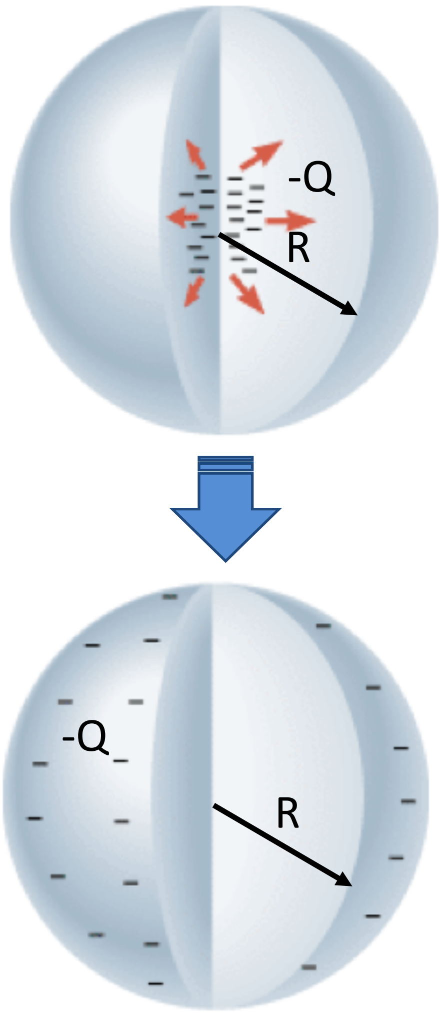
- Understand electric potential energy

- Define and understand electric potential

Sections 23.1 and 23.2

**Exercise:** What is the electric field inside and outside the spherical conductor?

$$\Phi_E = \oint \vec{E} \cdot d\vec{A} = \frac{Q_{enclosed}}{\epsilon_0}$$



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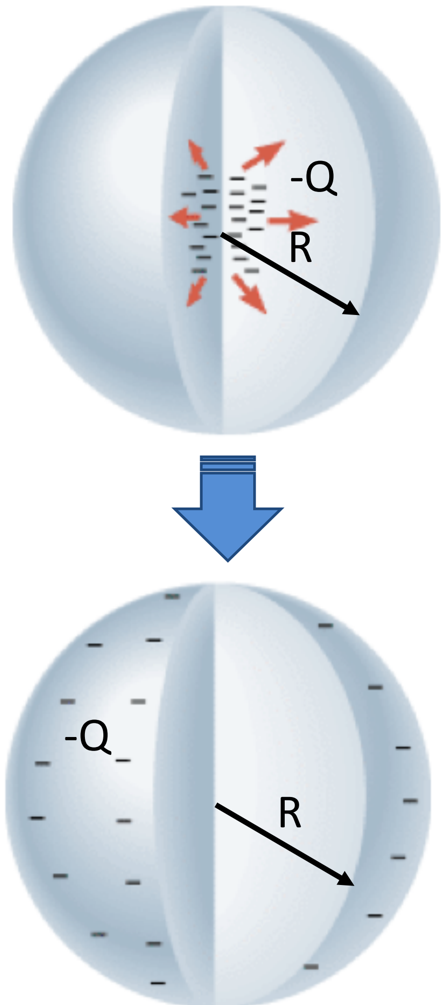


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$$E(r < R) = 0$$

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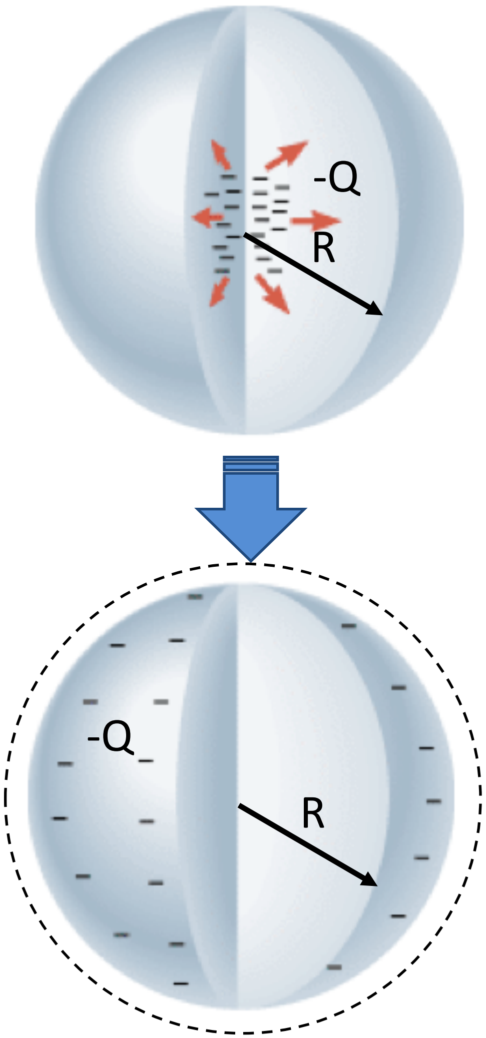
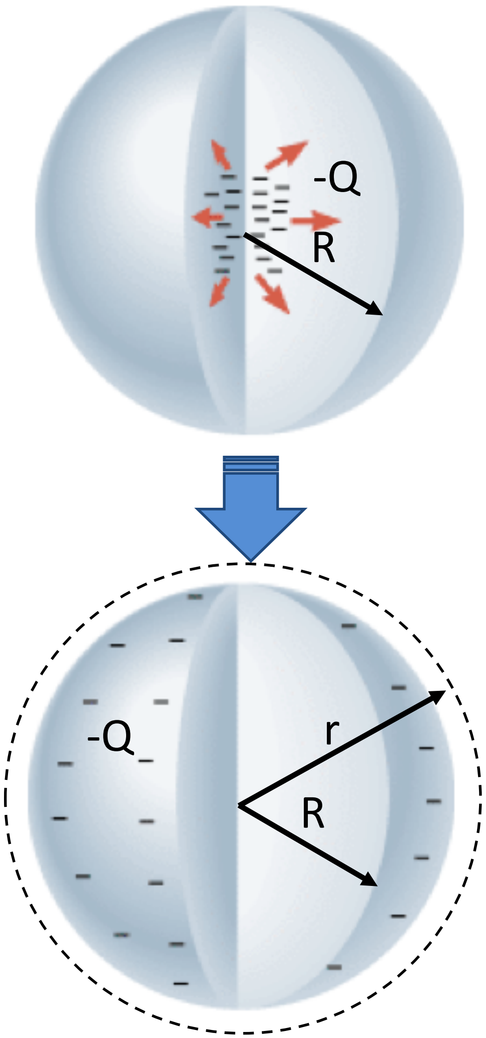



$$\Phi_E = \oint \vec{E} \cdot d\vec{A} = \frac{Q_{enclosed}}{\epsilon_0}$$

$$E(r < R) = 0$$

$$E(r > R) = ?$$

**Exercise:** What is the electric field inside and outside the spherical conductor?




$$\Phi_E = \oint \vec{E} \cdot d\vec{A} = \frac{Q_{enclosed}}{\epsilon_0}$$

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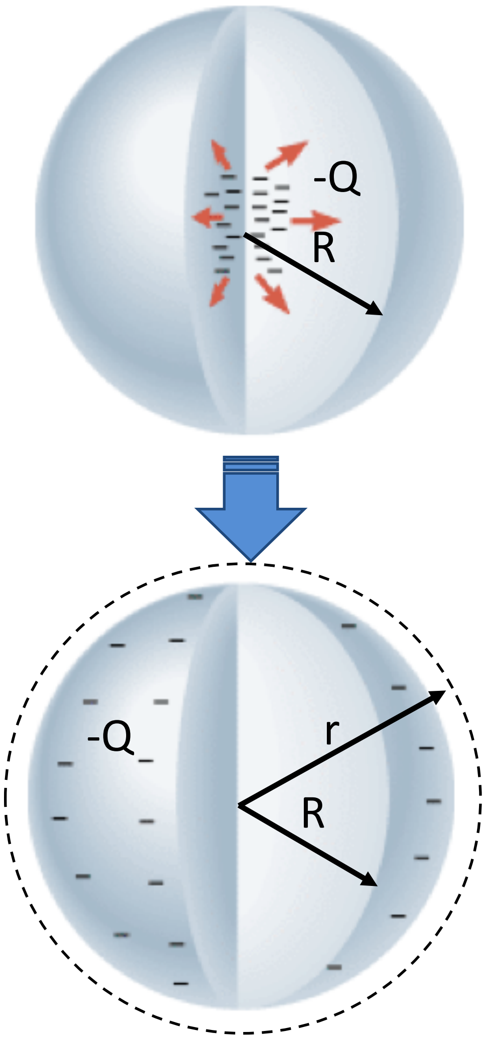
$$E(r)A = \frac{-Q}{\epsilon_0}$$

**Exercise:** What is the electric field inside and outside the spherical conductor?

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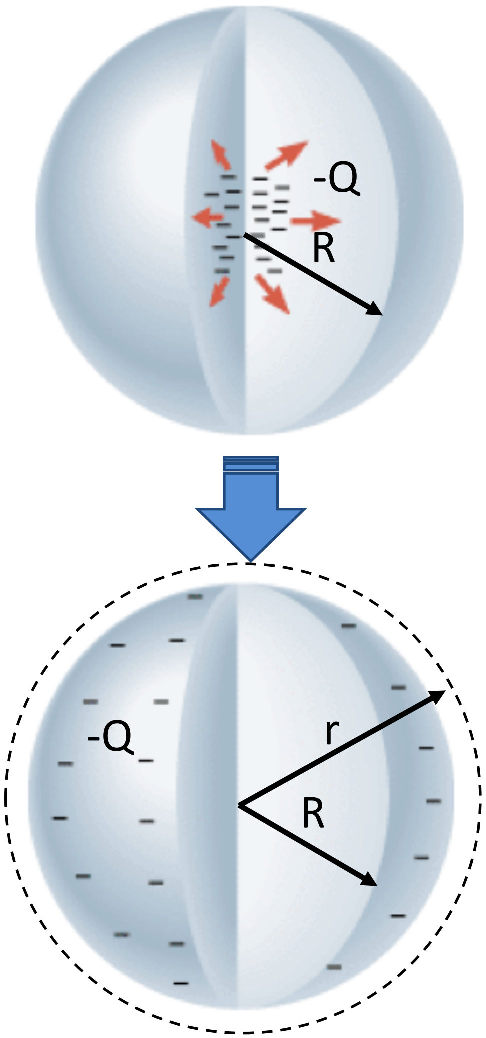
$$E(r)4\pi r^2 = \frac{-Q}{\epsilon_0}$$

**Exercise:** What is the electric field inside and outside the spherical conductor?

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$$E(r > R) = ?$$

$$E(r)A = \frac{-Q}{\epsilon_0}$$

$$E(r)4\pi r^2 = \frac{-Q}{\epsilon_0}$$

$$\boxed{E(r) = \frac{-Q}{4\pi\epsilon_0 r^2}} \quad for\, r > R$$

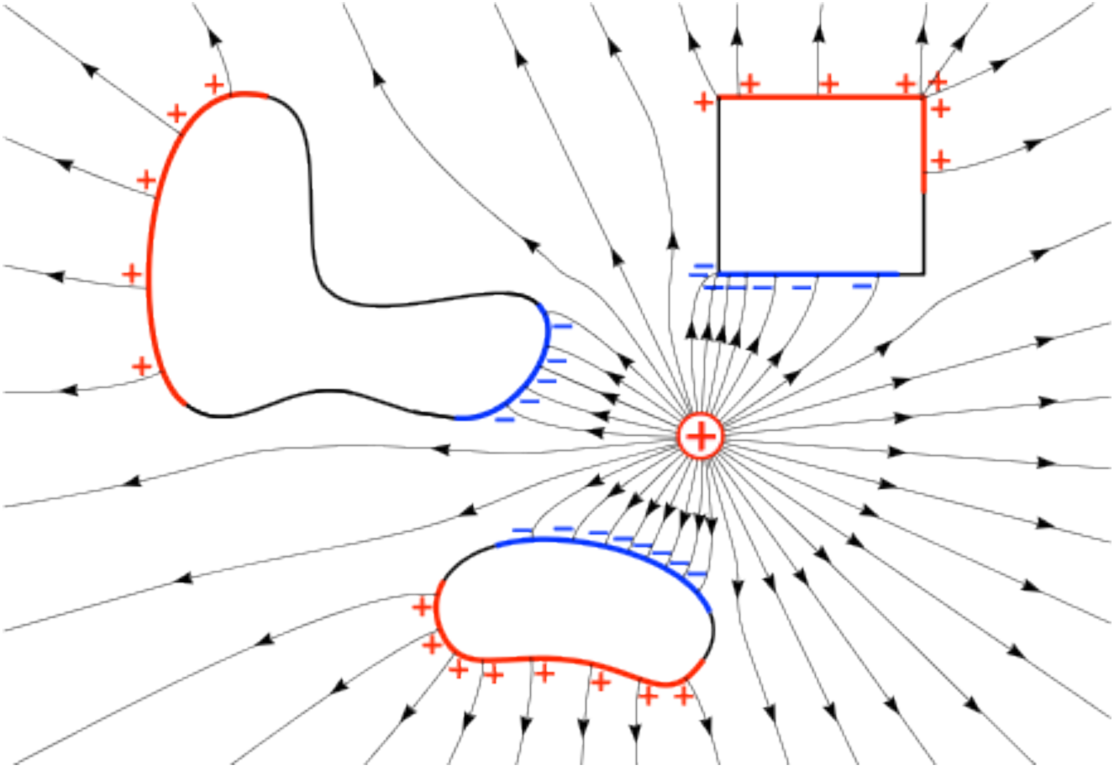
# Conductors in Electrostatic Equilibrium

# Properties

1. **E** is zero anywhere inside the conductor, solid or hollow
2. Net charge, if any, reside on the surface of a conductor
3. **E** just outside the conductor is perpendicular to its surface and has magnitude $|E| = \sigma/\varepsilon_0$
4. On irregularly shaped conductors, $\sigma$ is greatest where the radius of curvature is smallest

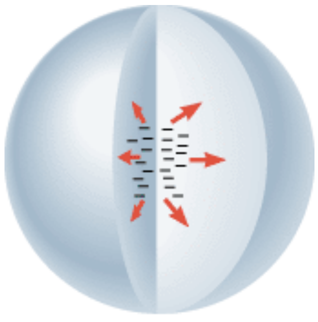
# Property #1

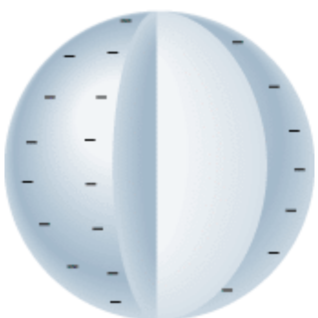
- **E** is zero anywhere inside the conductor, solid or hollow

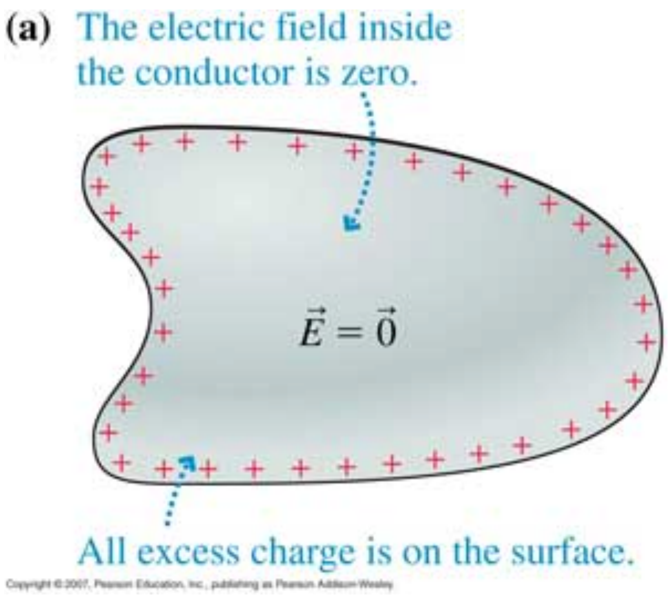


# Property #2

- Net charge, if any, will reside on the surface of a conductor

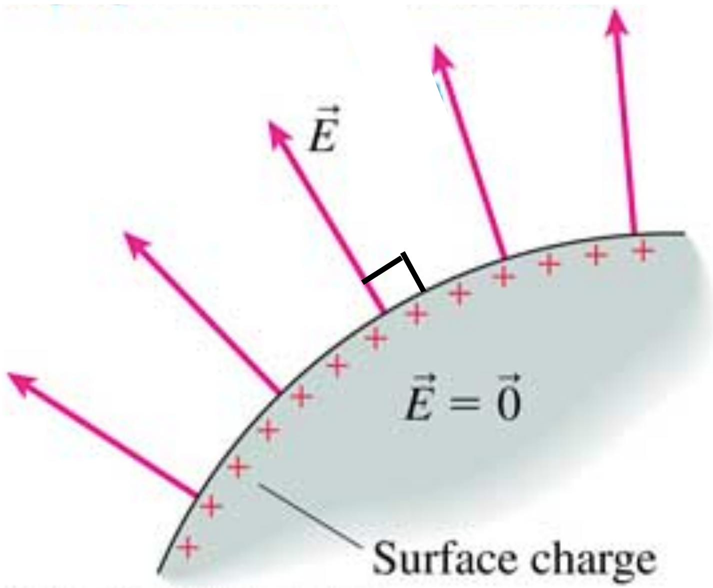


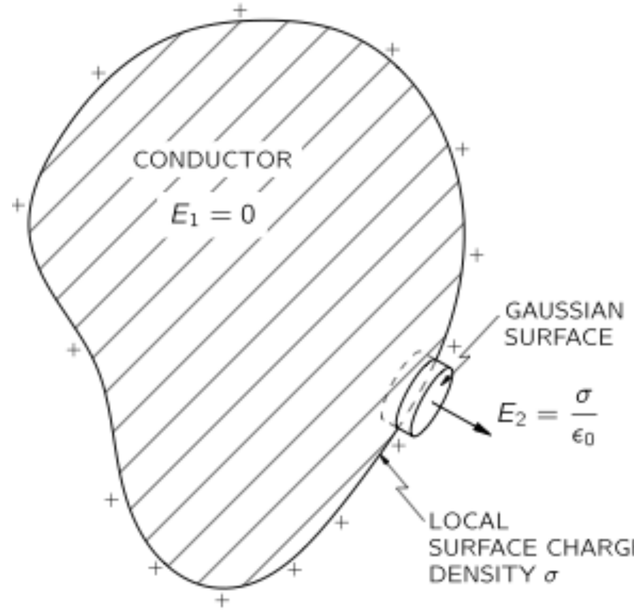



# Property #3

- **E** just outside the conductor is perpendicular to its surface and has magnitude $|E| = \sigma/\varepsilon_0$

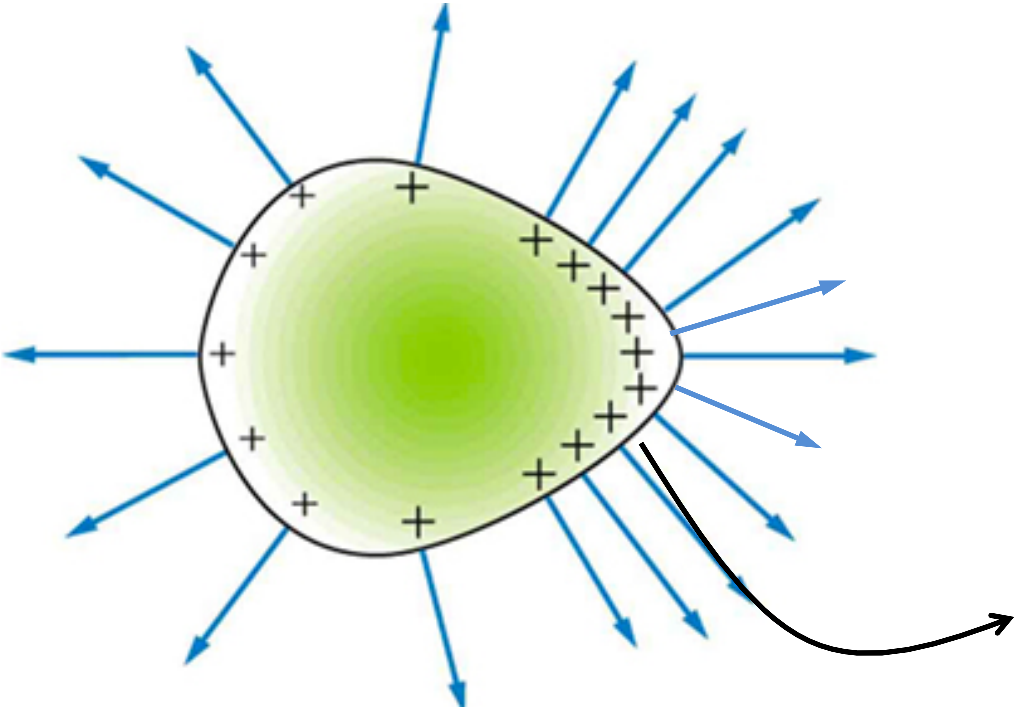






# Property #4

- On irregularly shaped conductors, $\sigma$ is greatest where the radius of curvature is smallest



Higher charge density
Stronger electric field

# Electric Potential Energy

# Back to PHYS2325

Work-Energy Theorem

$$\boxed{U_{final} + K_{final} = U_{initial} + K_{initial} + W_{other}}$$

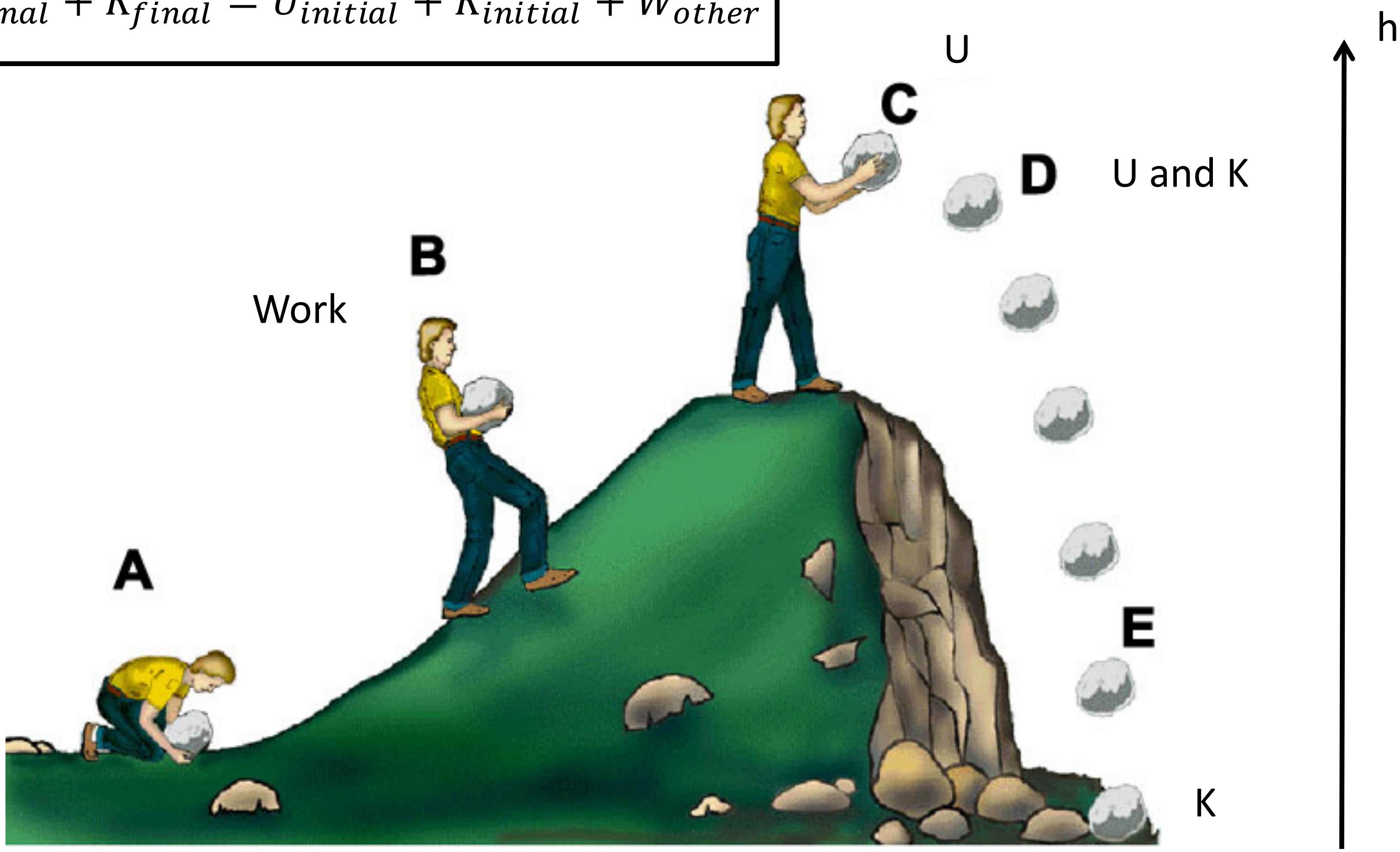
$Potential\ Energy$:   $U = mgh$

$Kinetic\ Energy$:   $K = \frac{1}{2}mv^2$

$W_{other} = \int \vec{F}_{other} \cdot d\vec{s}$ : $Work\ done\ by\ forces\ other\ than\ gravity$

# Back to PHYS2325

$$\boxed{U_{final} + K_{final} = U_{initial} + K_{initial} + W_{other}}$$



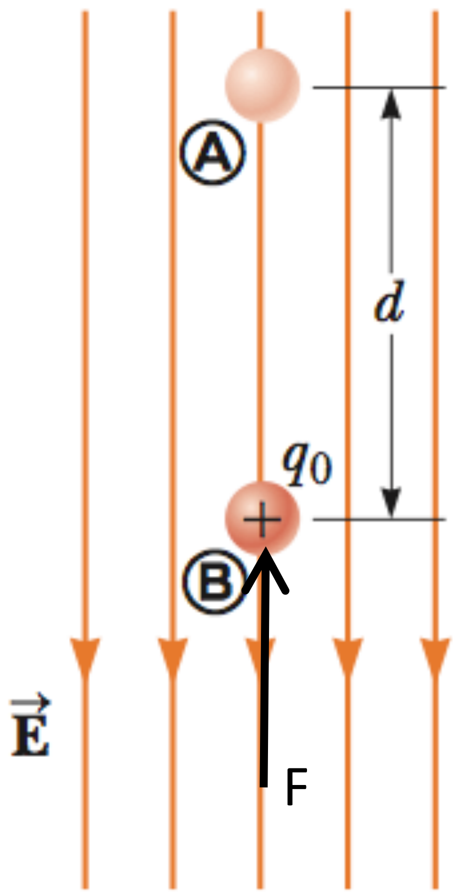
# Electric Potential Energy

# Electric Potential Energy

- Like in the gravitational field case, the electric field has potential energy U
- Also, like in the gravitational case, we are interested in changes (or differences) in electric potential energy ($\Delta U$)

# Potential Energy in Uniform E

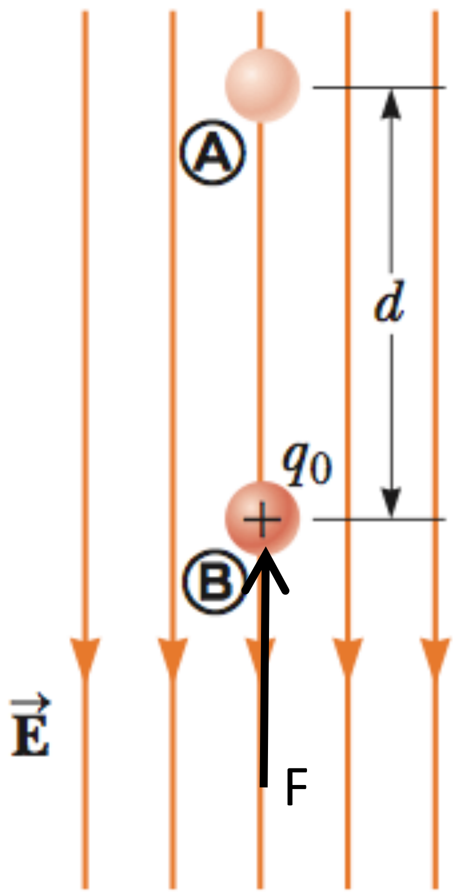
# Potential Energy in Uniform E




Lets consider the simple case:

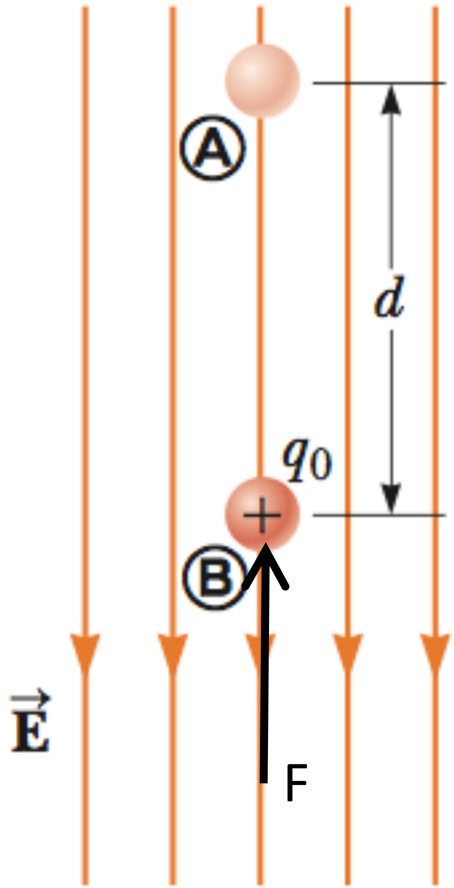
- Uniform E field
- +Q moves along E from <u>B</u> to <u>A</u>

# Potential Energy in Uniform E




$$U_f + K_f = U_i + K_i + W_{other}$$

# Potential Energy in Uniform E

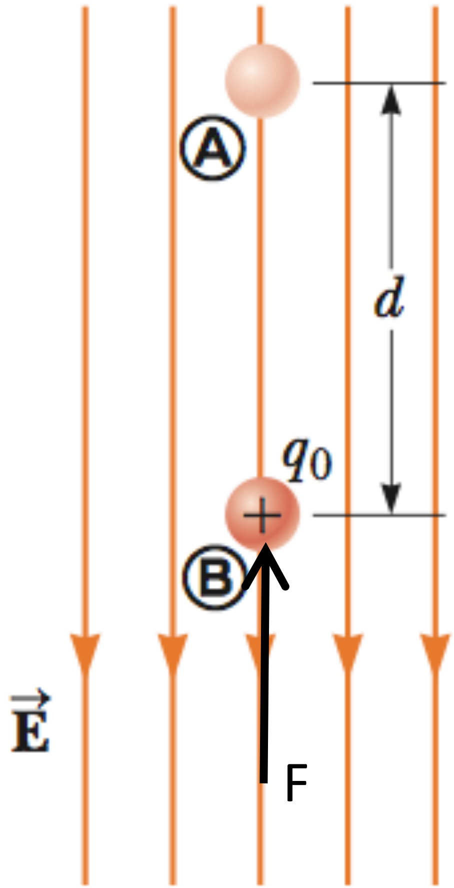



$$U_f + K_f = U_i + K_i + W_{other}$$

From B to A:

$$U_f + 0 = U_i + 0 + W_{other}$$

# Potential Energy in Uniform E



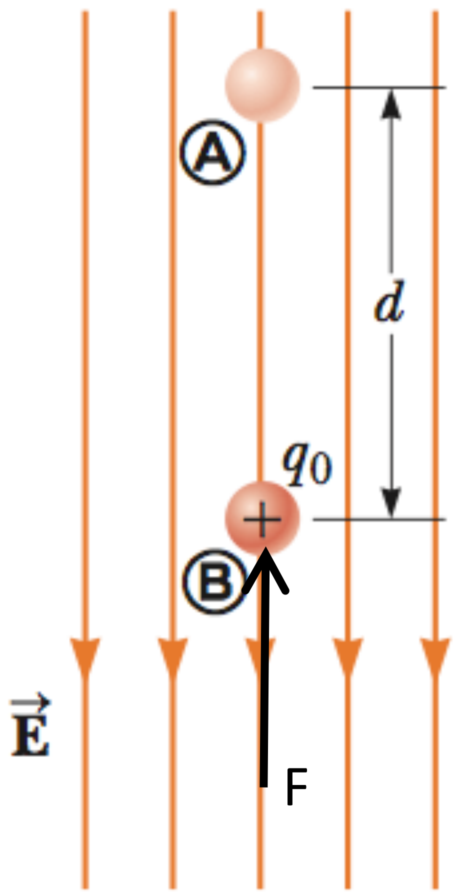

$$U_f + K_f = U_i + K_i + W_{other}$$

From B to A:

$$U_f + 0 = U_i + 0 + W_{other}$$

$$\Delta U = U_f - U_i = W_{other}$$

# Potential Energy in Uniform E

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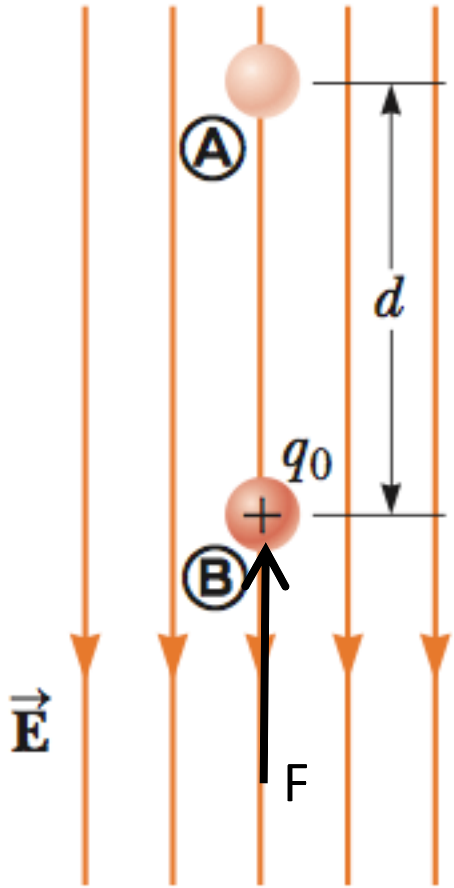
$$\Delta U = \int_B^A \vec{F} \cdot d\vec{s}$$

# Potential Energy in Uniform E




$$U_f + K_f = U_i + K_i + W_{other}$$

From B to A:

$$U_f + 0 = U_i + 0 + W_{other}$$

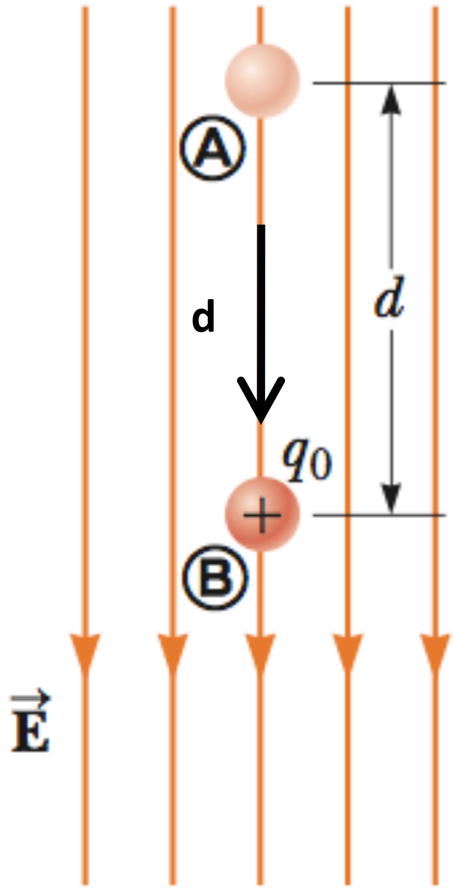
$$\Delta U = U_f - U_i = W_{other}$$

$$\Delta U = \int_B^A \vec{F} \cdot d\vec{s}$$

$$\Delta U = Fd$$

Uniform E, constant F

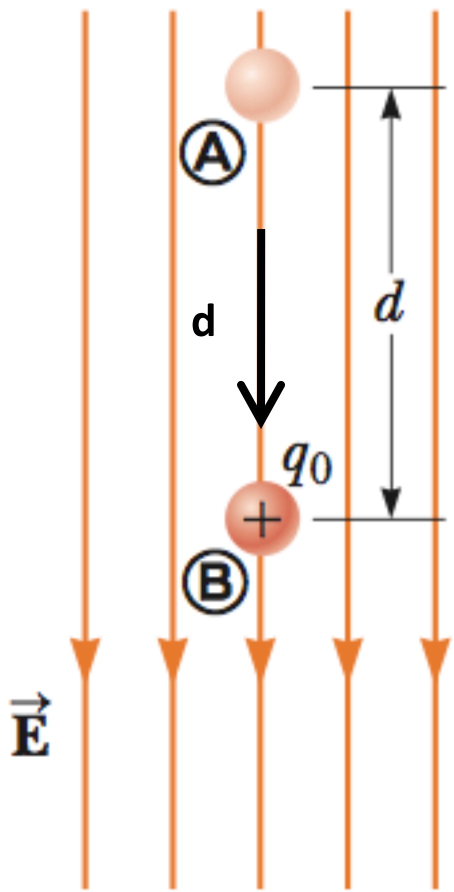
# Potential Energy in Uniform E




Now, from A to B

$\Delta U = ?$

# Potential Energy in Uniform E

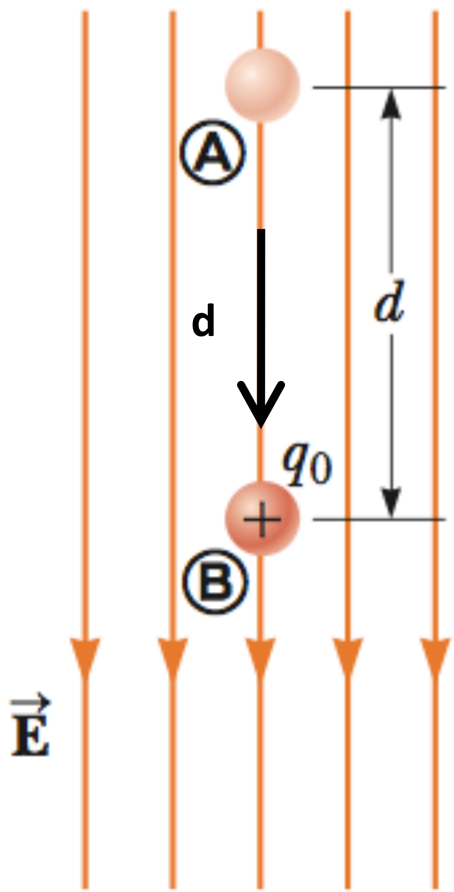



Now, from A to B

$\Delta U = ?$

$\Delta U = -W_E$

# Potential Energy in Uniform E




Now, from A to B

$\Delta U = ?$

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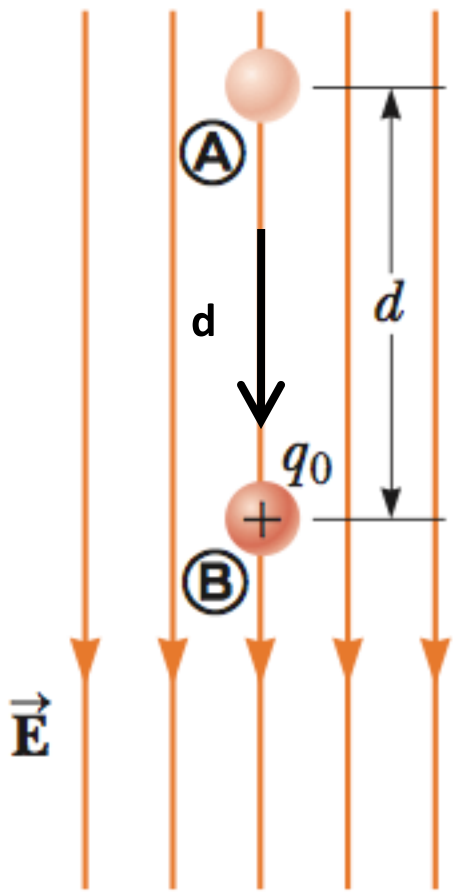
$$\Delta U = -\int_A^B \vec{F}_E \cdot d\vec{s}$$

# Potential Energy in Uniform E

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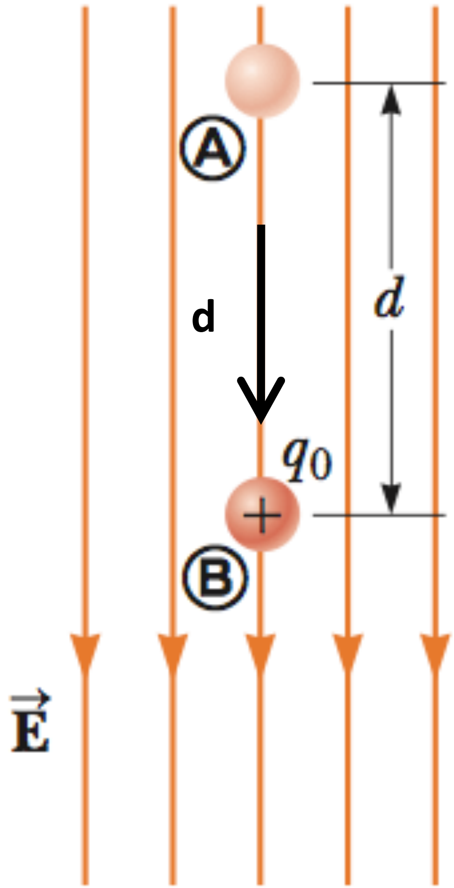



Now, from A to B

$$\Delta U = ?$$

$$\Delta U = -W_E$$

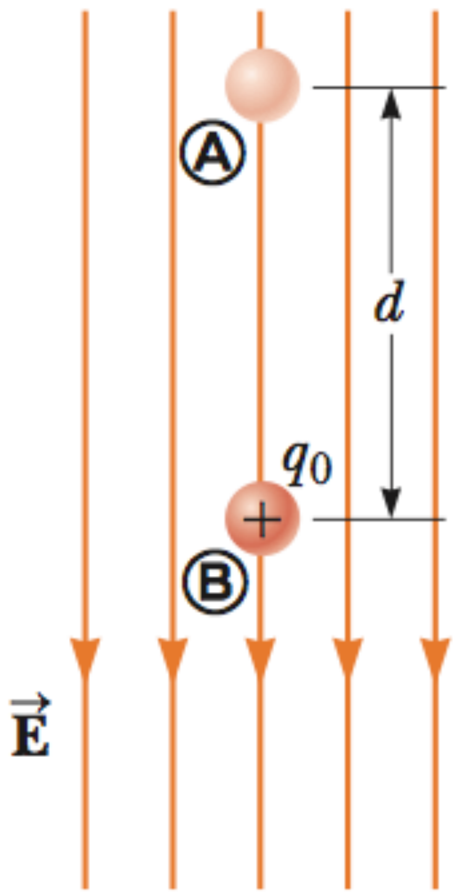
$$\Delta U = -\int_A^B \vec{F}_E \cdot d\vec{s}$$

$$\Delta U = -\vec{F}_E \cdot \vec{d}$$

$$\Delta U = -q\vec{E} \cdot \vec{d}$$

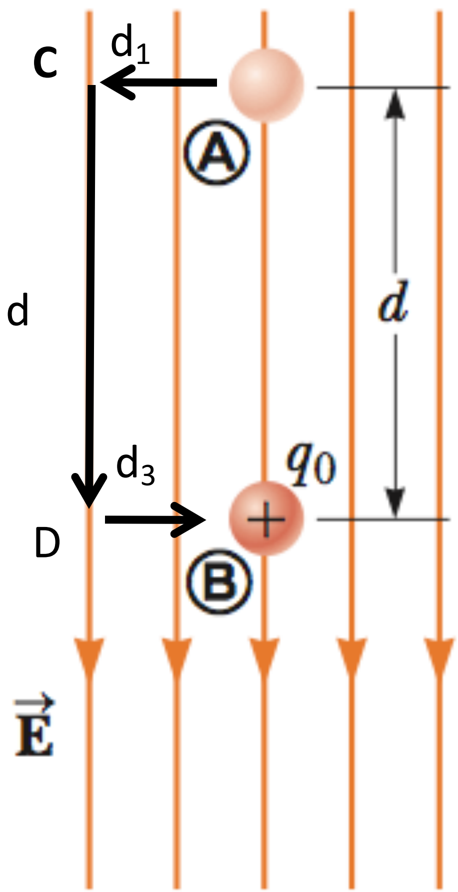
Uniform E, constant F

# Potential Energy in Uniform E




- What if we changed the path to get from A to B?

# Potential Energy in Uniform E

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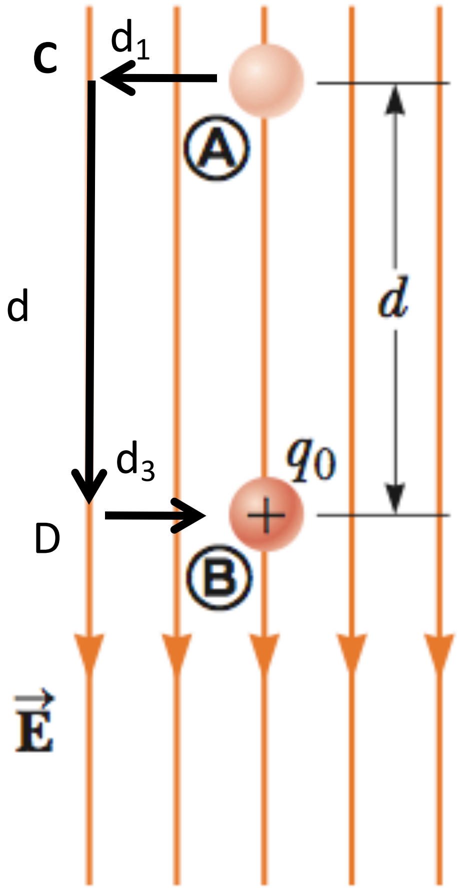
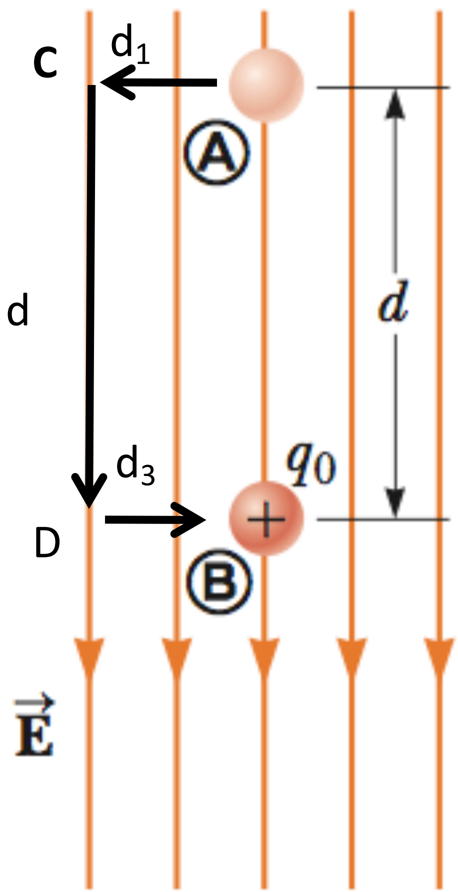



$$\Delta U = -W_E$$

$$\Delta U = -\int_A^B \vec{F} \cdot d\vec{l}$$

# Potential Energy in Uniform E

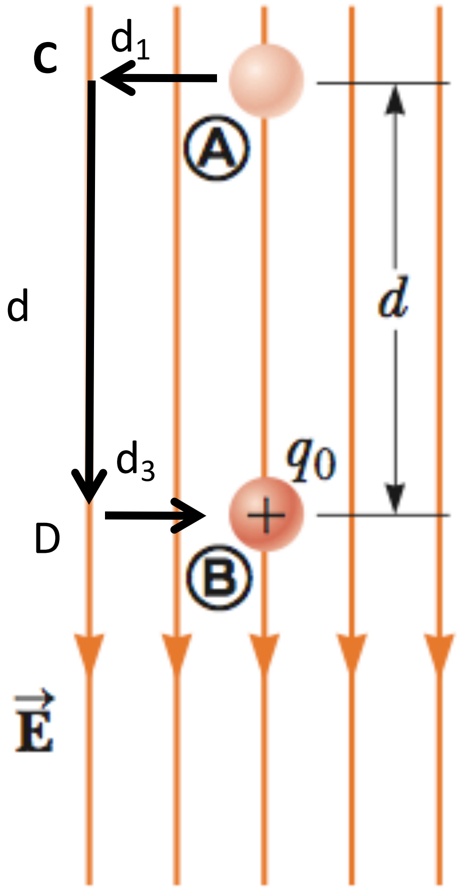



$$\Delta U = -W_E$$

$$\Delta U = -\int_A^B \vec{F} \cdot d\vec{l}$$

$$\Delta U = -(\vec{F}_E \cdot \vec{d}_1 + \vec{F}_E \cdot \vec{d}_2 + \vec{F}_E \cdot \vec{d}_3)$$

# Potential Energy in Uniform E




$$\Delta U = -W_E$$

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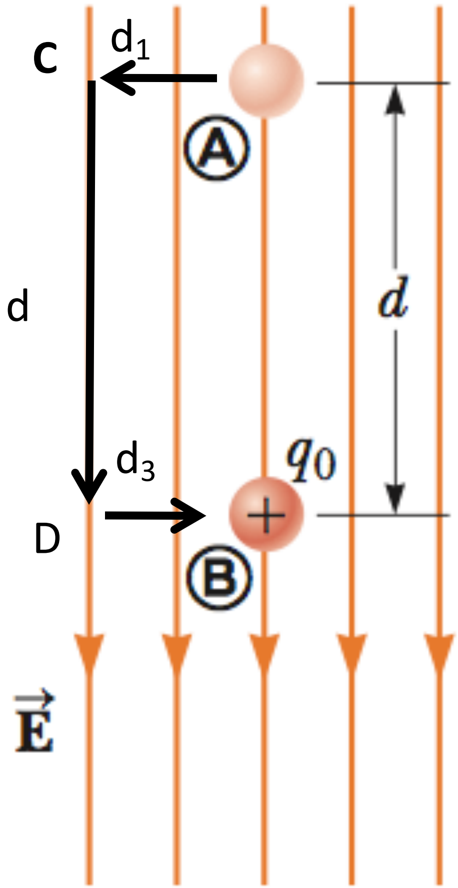
$$\Delta U = -(\vec{F}_E \cdot \vec{d}_1 + \vec{F}_E \cdot \vec{d}_2 + \vec{F}_E \cdot \vec{d}_3)$$

$$\Delta U = -(0 + \vec{F}_E \cdot \vec{d} + 0)$$

$$\Delta U = -\left(q\vec{E}\right) \cdot \vec{d}$$

# Potential Energy in Uniform E

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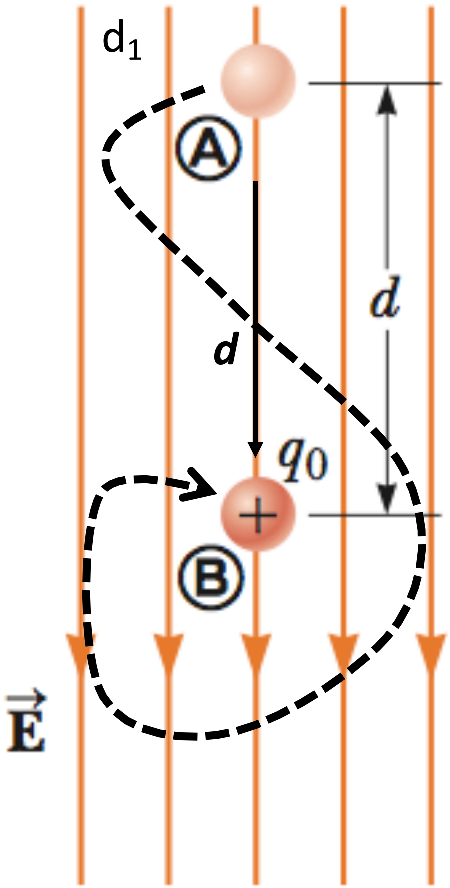
$$\Delta U = -(0 + \vec{F}_E \cdot \vec{d} + 0)$$

$$\Delta U = -\left(q\vec{E}\right) \cdot \vec{d}$$

$$\boxed{\Delta U = -q\vec{E} \cdot \vec{d}}$$

Same result of taking shortest path between A and B

# Potential Energy in Uniform E

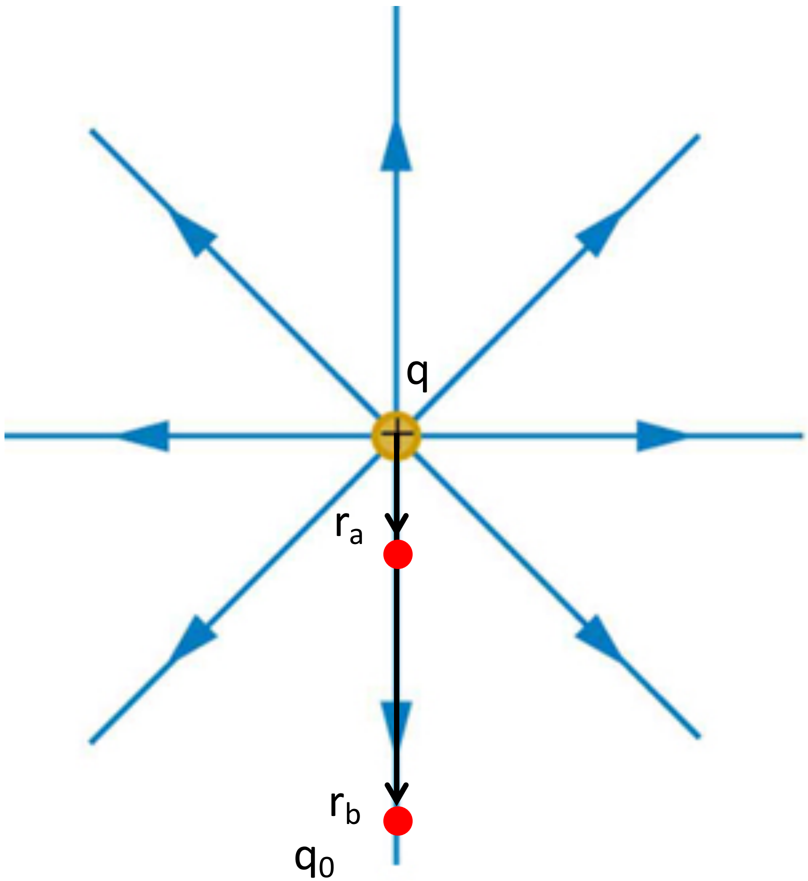



$$\Delta U = -q\vec{E} \cdot \vec{d}$$

Result is independent of path taken

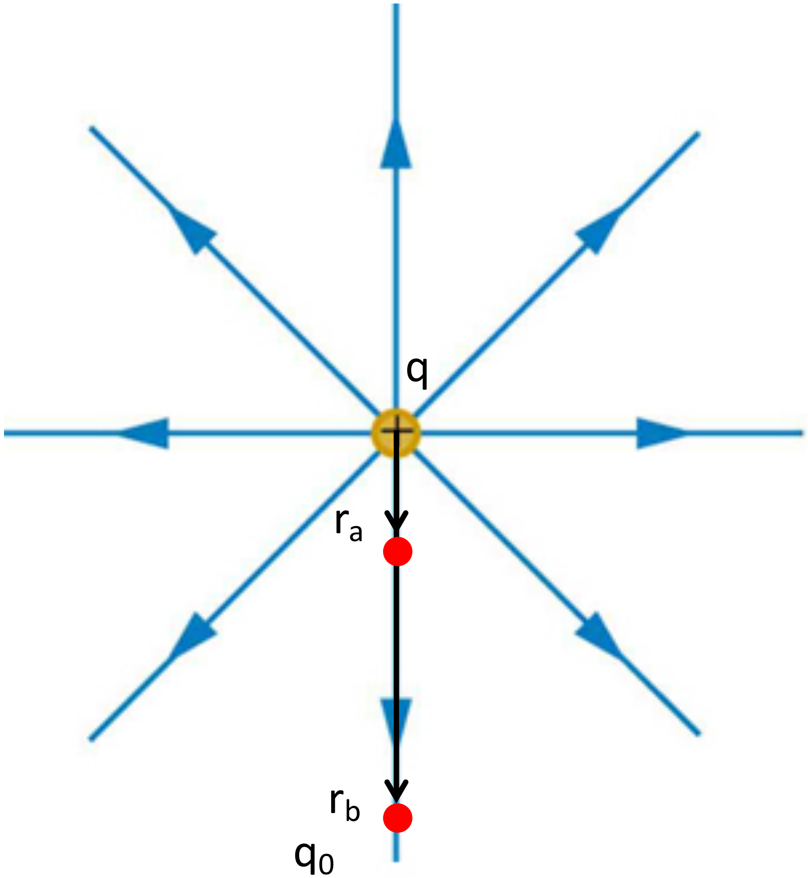
# Potential Energy in Non-Uniform E

# Electric Potential Energy 1: Single Point Charge




Change in U due to work done in $q_0$ by E-field produced by q?

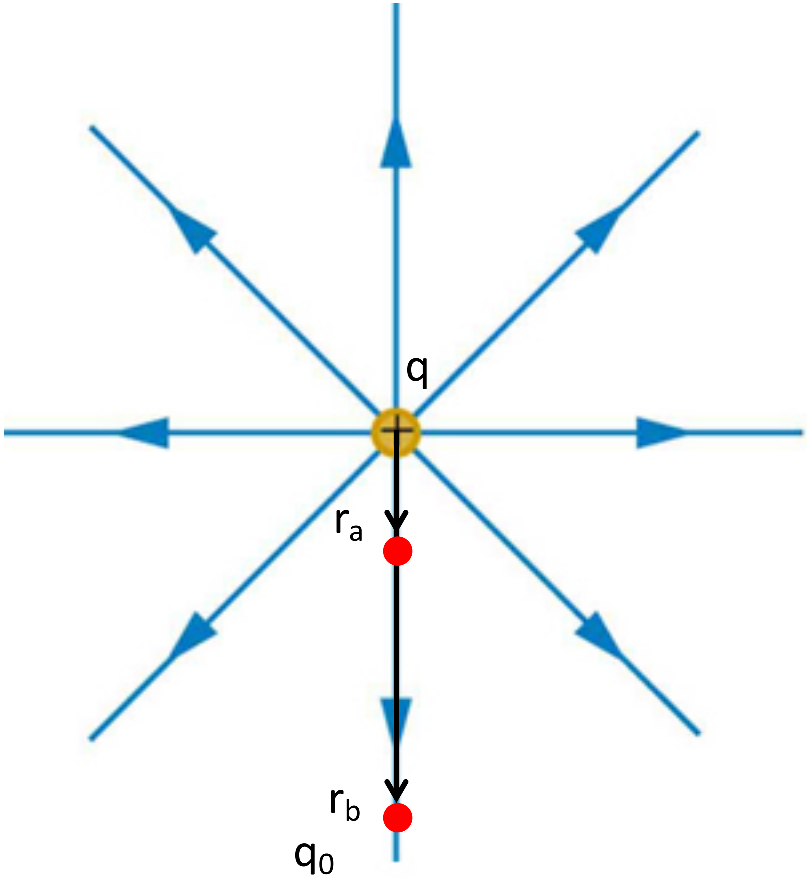
# Electric Potential Energy 1: Single Point Charge




$$\Delta U = U_b - U_a = -\mathrm{W_E}$$

Change in U due to work done in $q_0$ by E-field produced by q?

# Electric Potential Energy 1: Single Point Charge

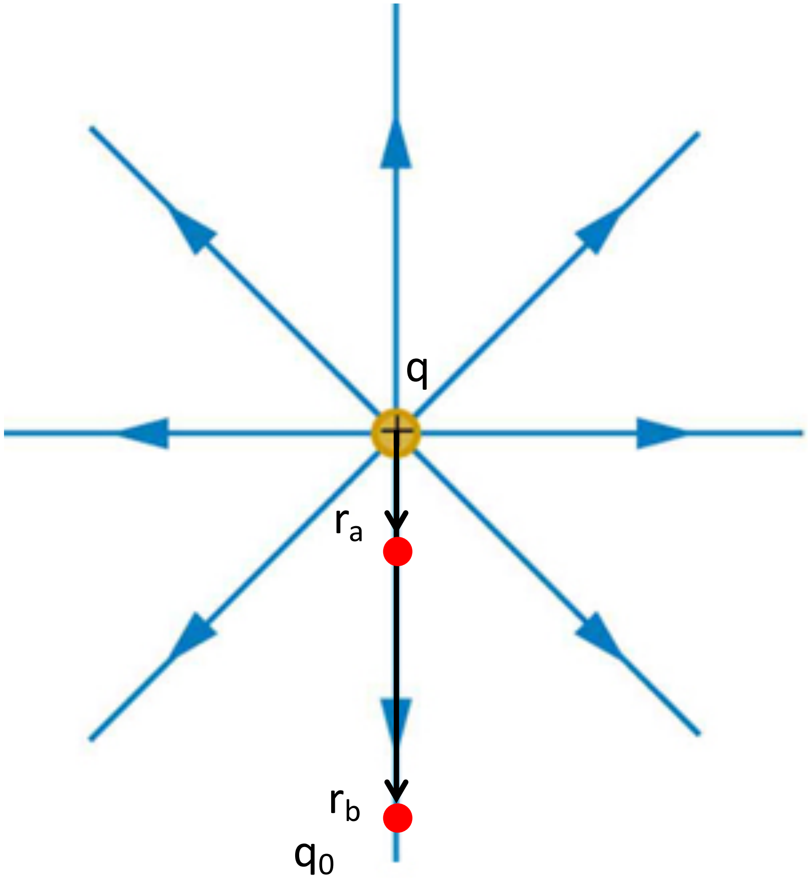



$$\Delta U = U_b - U_a = -\mathrm{W_E}$$

$$\Delta U = -\int_{r_a}^{r_b} \vec{F}_E \cdot d\vec{r}$$

Change in U due to work done in $q_0$ by E-field produced by q?

# Electric Potential Energy 1: Single Point Charge

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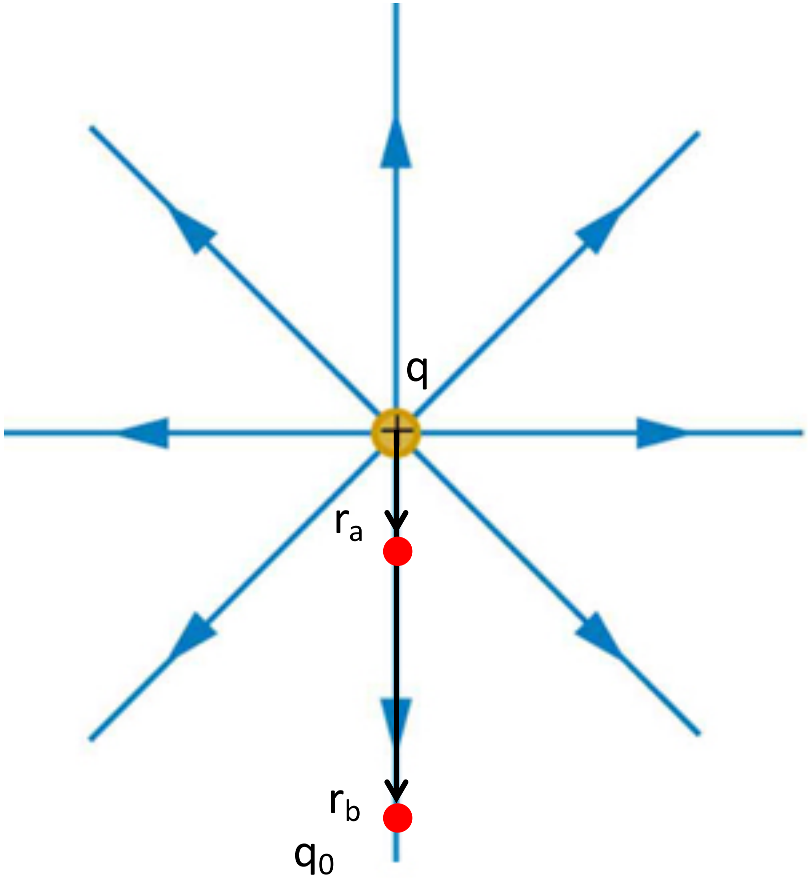


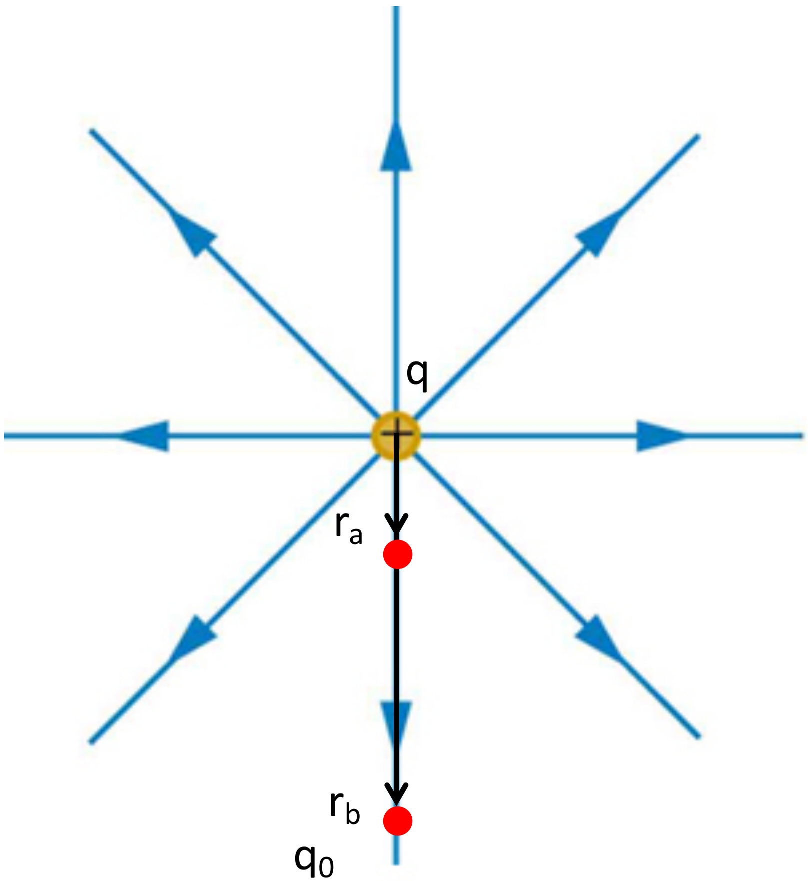

$$\Delta U = U_b - U_a = -\mathrm{W_E}$$

$$\Delta U = -\int_{r_a}^{r_b} \vec{F}_E \cdot d\vec{r}$$

$$\Delta U = -\int_{r_a}^{r_b} (q_0\vec{E}) \cdot d\vec{r} = -q_0 \int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

Change in U due to work done in $q_0$ by E-field produced by q?

# Electric Potential Energy 1: Single Point Charge

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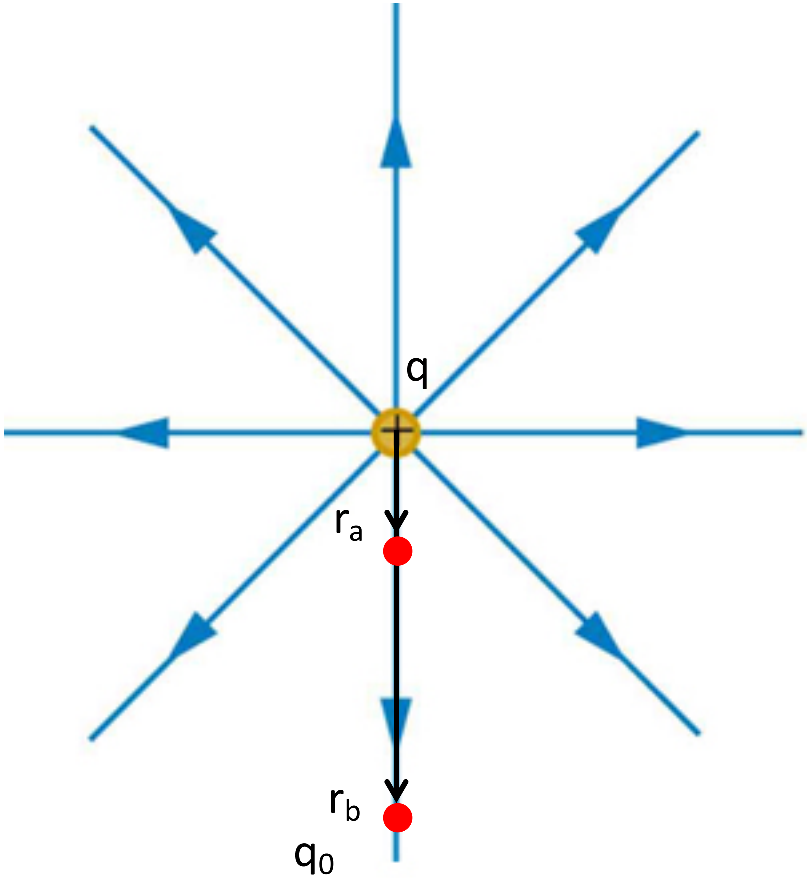
$$\Delta U = -q_0 \int_{r_a}^{r_b} \left(\frac{q}{4\pi\epsilon_0 r^2}\hat{r}\right) \cdot d\vec{r}$$

Change in U due to work done in $q_0$ by E-field produced by q?

# Electric Potential Energy 1: Single Point Charge

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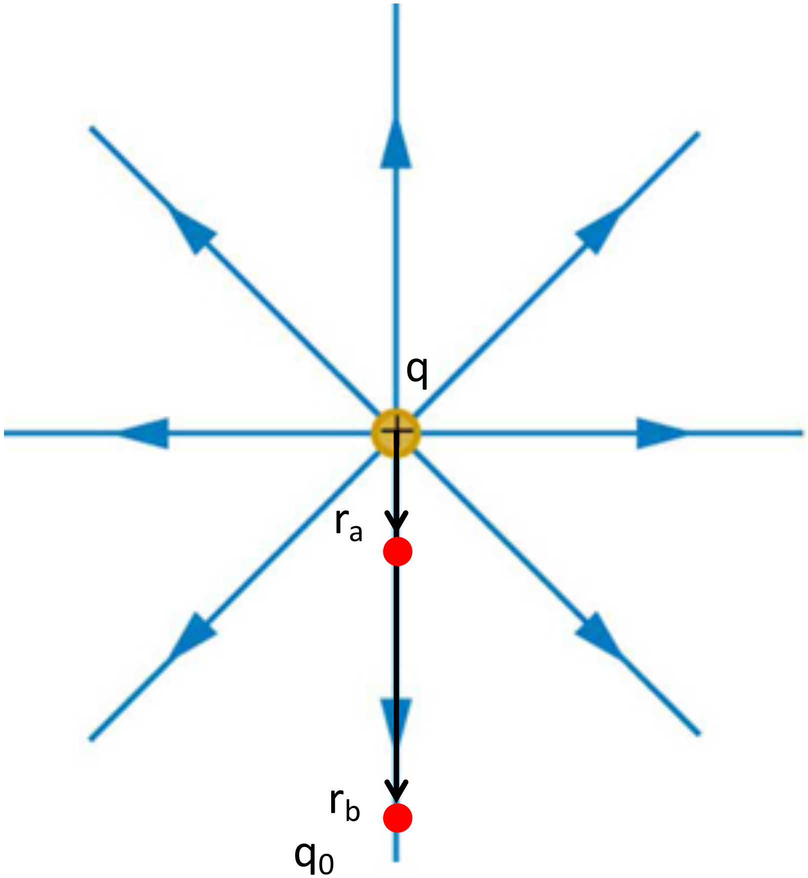
$$\Delta U = -q_0 \left(\frac{q}{4\pi\epsilon_0}\right) \int_{r_a}^{r_b} \frac{1}{r^2} dr$$

Change in U due to work done in $q_0$ by E-field produced by q?

# Electric Potential Energy 1: Single Point Charge

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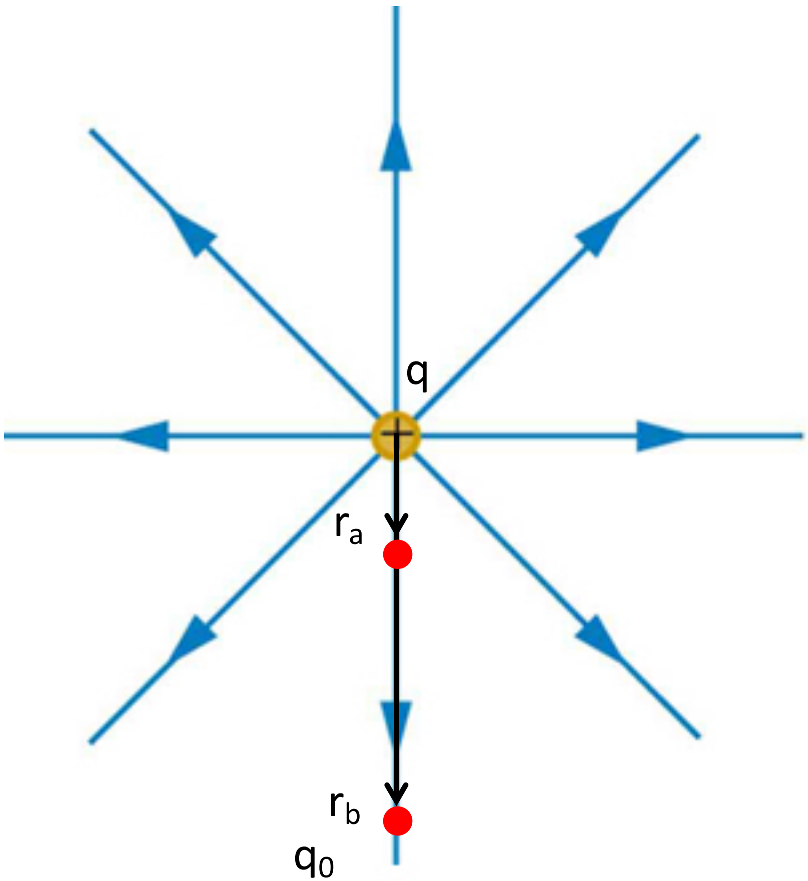
$$\Delta U = -q_0 \int_{r_a}^{r_b} \left(\frac{q}{4\pi\epsilon_0 r^2}\hat{r}\right) \cdot d\vec{r}$$

$$\Delta U = -q_0 \left(\frac{q}{4\pi\epsilon_0}\right) \int_{r_a}^{r_b} \frac{1}{r^2}\, dr = -q_0 \left(\frac{q}{4\pi\epsilon_0}\right) \left[-\frac{1}{r}\right]_{r_a}^{r_b}$$

Change in U due to work done in $q_0$ by E-field produced by q?

# Electric Potential Energy 1: Single Point Charge

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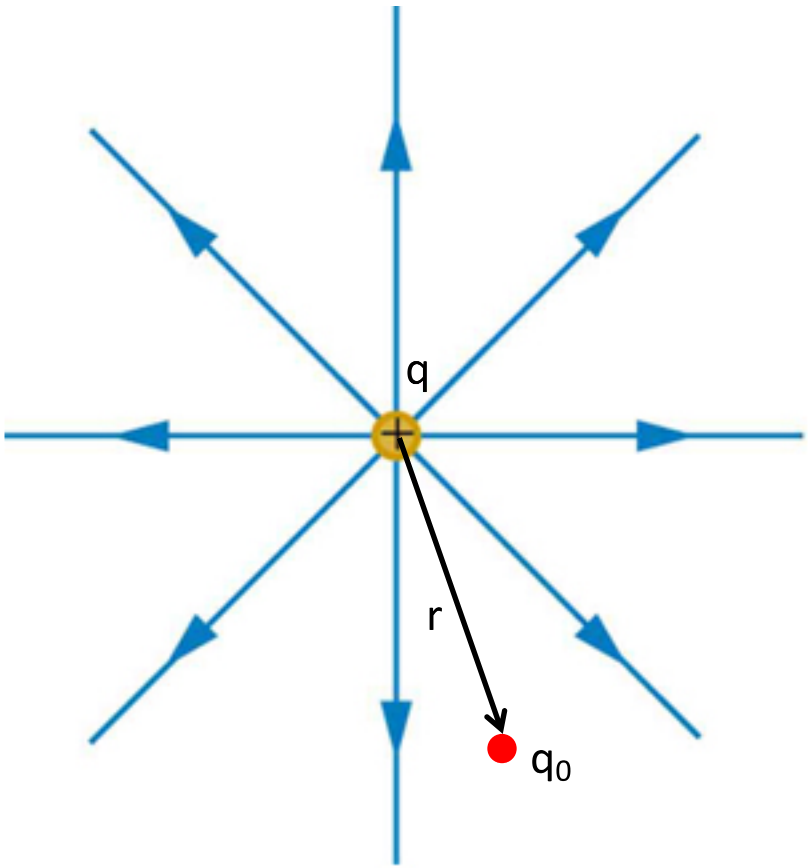
$$\Delta U = \left(\frac{q q_0}{4\pi\epsilon_0}\right) \left[\frac{1}{r_b} - \frac{1}{r_a}\right]$$

Change in U due to work done in $q_0$ by E-field produced by q?

# Electric Potential Energy: Reference




$$\Delta U = U(r_b) - U(r_a) = \left(\frac{q q_0}{4\pi\epsilon_0}\right)\left[\frac{1}{r_b} - \frac{1}{r_a}\right]$$

What is the value of U at a given point? U(r)=?

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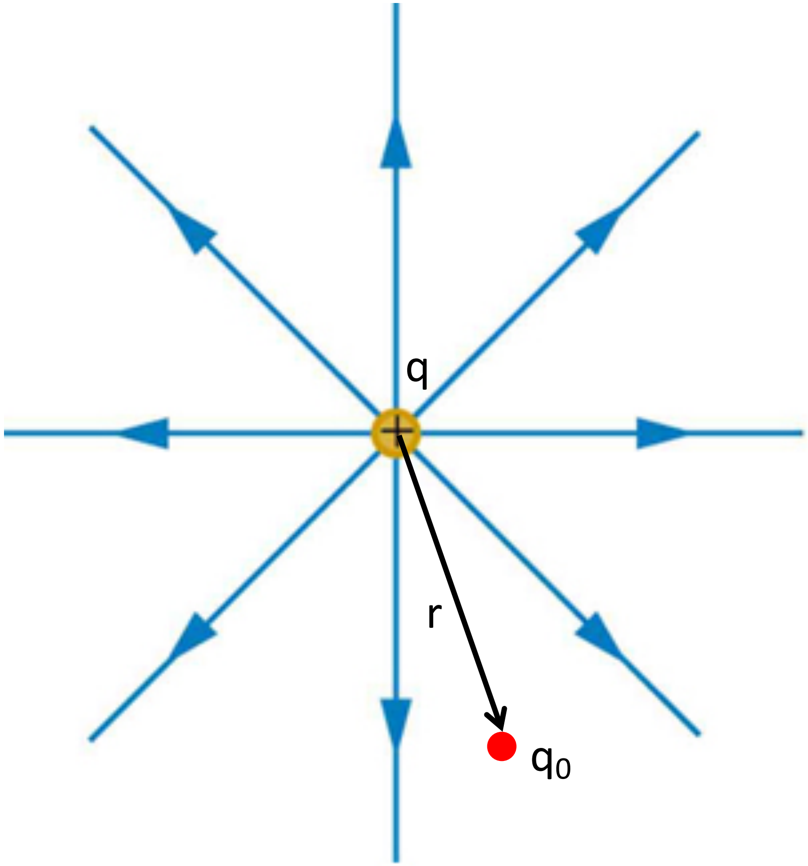


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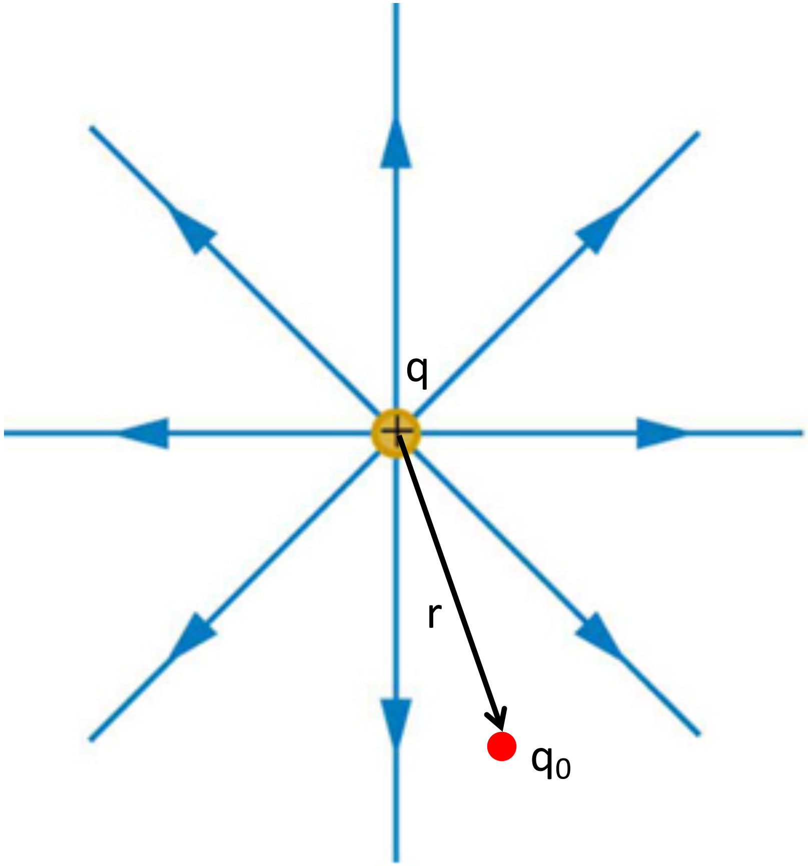


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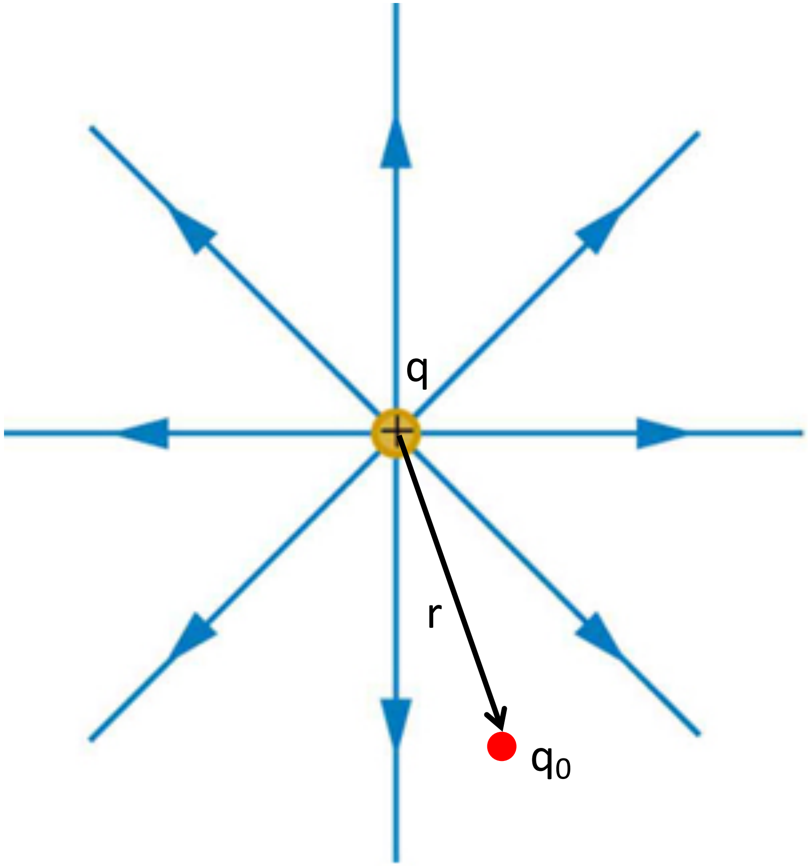


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What is the value of U at a given point? U(r)=?

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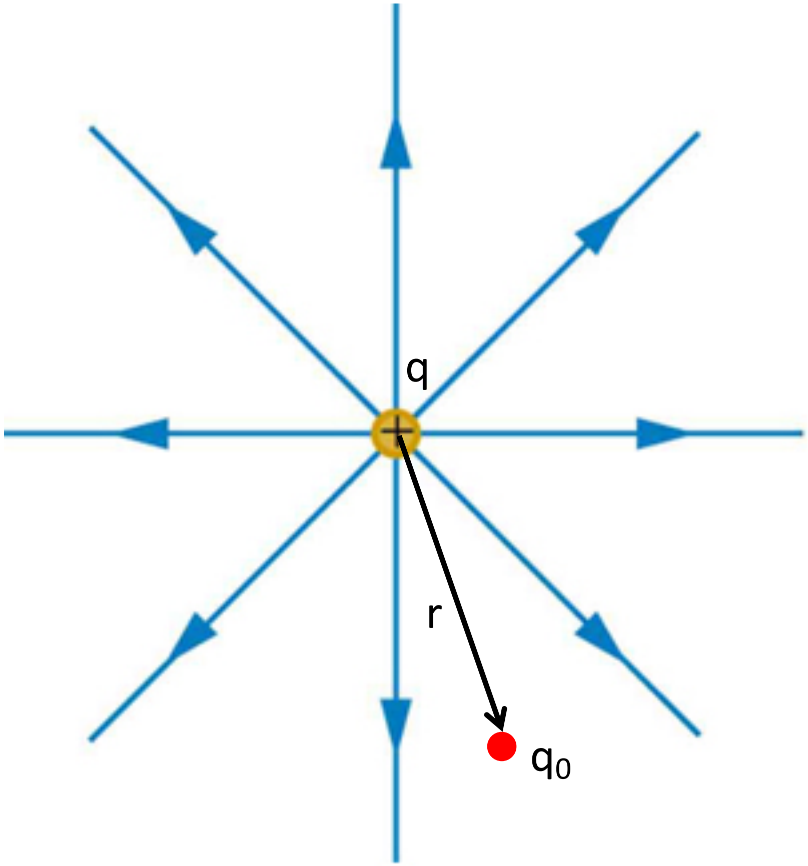


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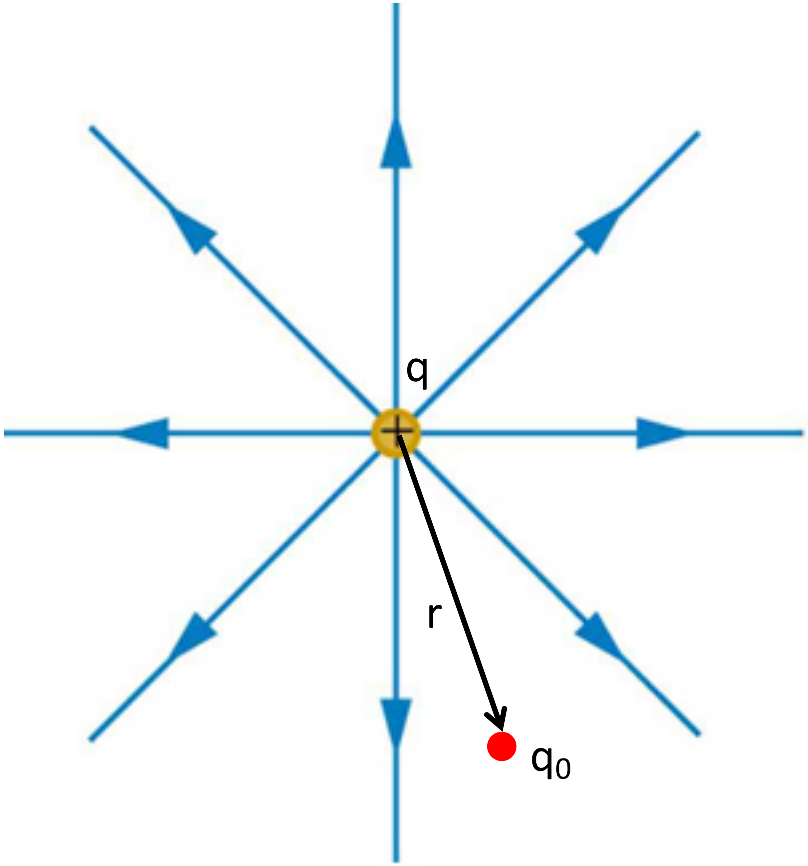


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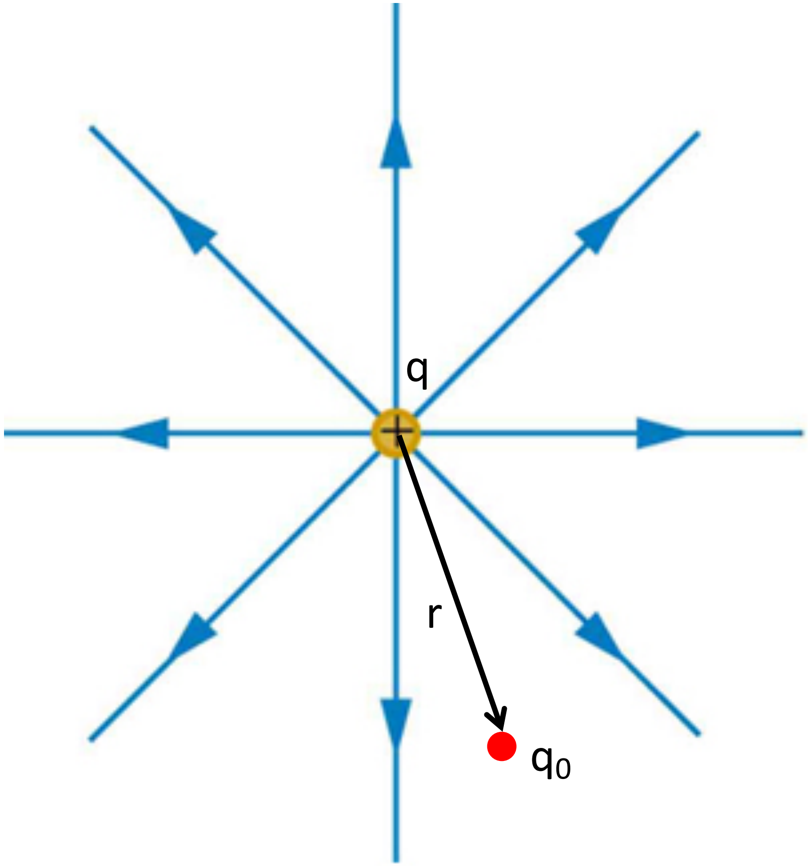


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$$\boxed{U = \frac{q q_0}{4\pi\epsilon_0 r}}$$

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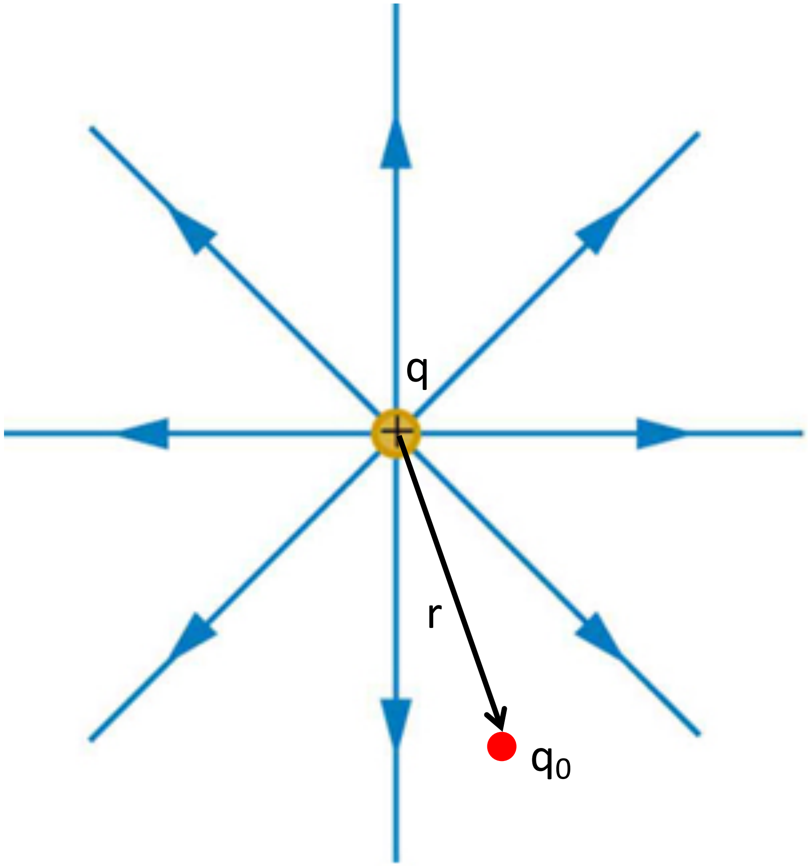


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$$U = \frac{qq_0}{4\pi\epsilon_0 r}$$

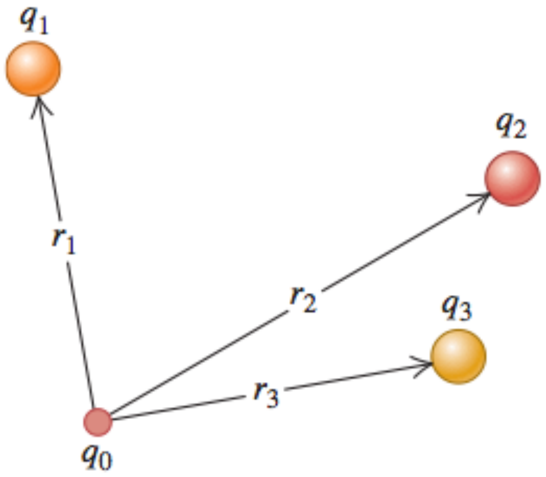
U at a given point "r" is given with respect to U(∞) = 0

What is the value of U at a given point? U(r)=?

# Electric Potential Energy 2: Multiple Point Charges

Electric potential energy of $q_0$ due to field caused by point charge $q_1$

$$U = \frac{q_0 q_1}{4\pi\epsilon_0 r}$$



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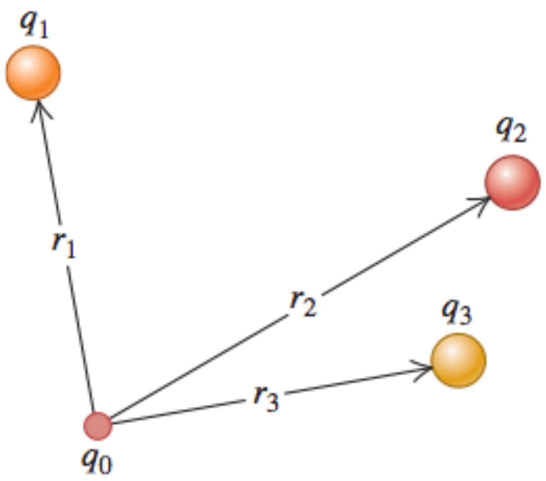


Electric potential energy of $q_0$ due to field caused by multiple point charges

$$U = \frac{q_0}{4\pi\epsilon_0}\left(\frac{q_1}{r_1} + \frac{q_2}{r_2} + \frac{q_3}{r_3} + \cdots\right) = \frac{q_0}{4\pi\epsilon_0}\sum_{i=1}^{N}\frac{q_i}{r_i}$$

# Electric Potential

# Electric Potential

- We found the potential energy of a "test" charge "$q_0$" within an electric field "E"

$$\Delta U = -q_0 \int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

# Electric Potential

- We found the potential energy of a "test" charge "$q_0$" within an electric field "E"

$$\Delta U = -q_0 \int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

- However, it is more useful to have a quantity that does not depend on $q_0$. We start with:

$$\frac{\Delta U}{q_0} = -\frac{W}{q_0} = -\int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

# Electric Potential

$$\frac{\Delta U}{q_0} = -\int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

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$$\frac{\Delta U}{q_0} = -\int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

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Defining the electric potential as $V = \frac{U}{q_0}$ we can write:

# Electric Potential

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Defining the electric potential as $V = \frac{U}{q_0}$ we can write:

$$V_b - V_a = \Delta \mathrm{V} = -\int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

# Electric Potential

$$\frac{\Delta U}{q_0} = -\int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

$$\frac{U_b}{q_0} - \frac{U_a}{q_0} = -\int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

Defining the electric potential as $V = \frac{U}{q_0}$ we can write:

$$V_b - V_a = \Delta \mathrm{V} = -\int_{r_a}^{r_b} \vec{E} \cdot d\vec{r}$$

Electric potential (V): It is the amount of electric potential energy per unit charge, at a given point within an electric field.

$$Units: \frac{Joules}{C} = \frac{Nm}{C} \equiv Volts$$

# Electric Potential 1: Single Point Charge

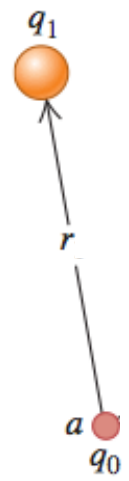
$$V = \frac{U}{q_0}$$

U for $q_0$ within E field of $q_1$:

$$U = \frac{q_1 q_0}{4\pi\epsilon_0 r}$$

Therefore:

$$V = \frac{q_1}{4\pi\epsilon_0 r}$$



# Electric Potential 2: Multiple Point Charges

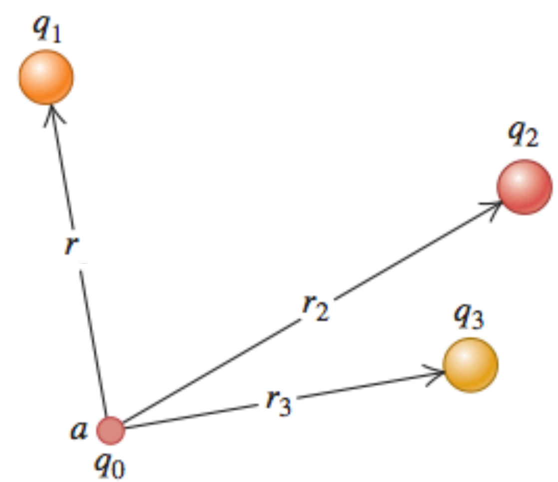
$$V = \frac{U}{q_0}$$

U for $q_0$ within E field created by multiple charges:

$$U = \frac{q_0}{4\pi\epsilon_0}\sum_{i=1}^{N}\frac{q_i}{r_i}$$

Therefore:

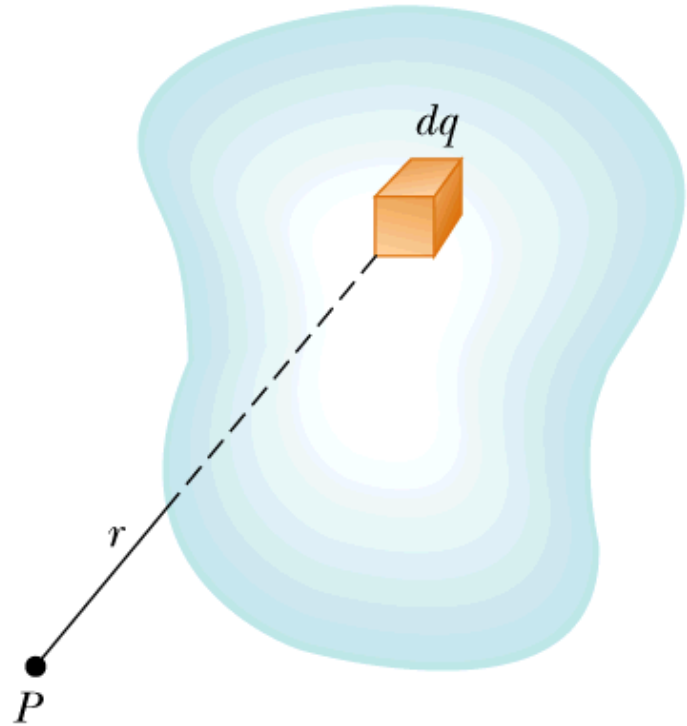
$$\boxed{V = \frac{1}{4\pi\epsilon_0}\sum_{i=1}^{N}\frac{q_i}{r_i}}$$



# Electric Potential 3: Continuous Distribution of Charges

$$V = \frac{1}{4\pi\epsilon_0}\sum_{i=1}^{N}\frac{q_i}{r_i}$$

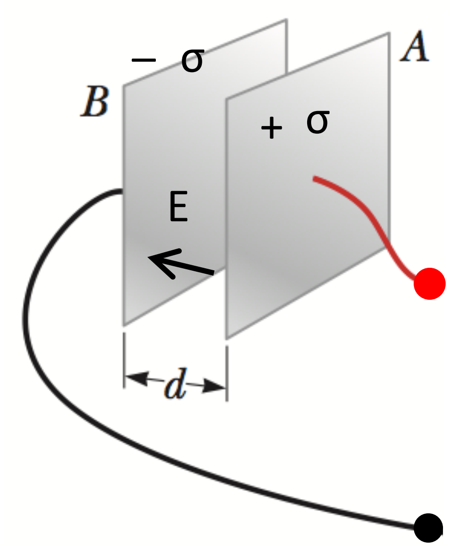
$$V = \frac{1}{4\pi\epsilon_0}\int\frac{dq}{r}$$



# Potential Difference

- What is the electric potential difference between the plates?

$$\Delta V = -\int_a^b \vec{E} \cdot d\vec{s}$$




**ΔV = ?**

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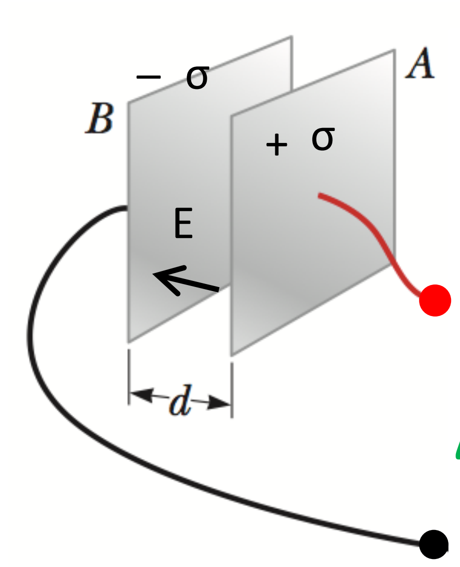


$$\Delta V = -\int_a^b \vec{E} \cdot d\vec{s}$$

$$\Delta V = -\int_a^b \left(\frac{\sigma}{\epsilon_0}\right) ds = -\frac{\sigma}{\epsilon_0}\int_a^b ds$$

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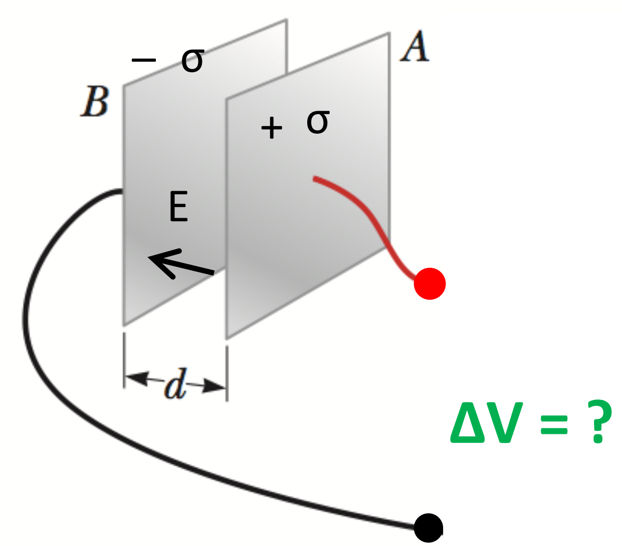


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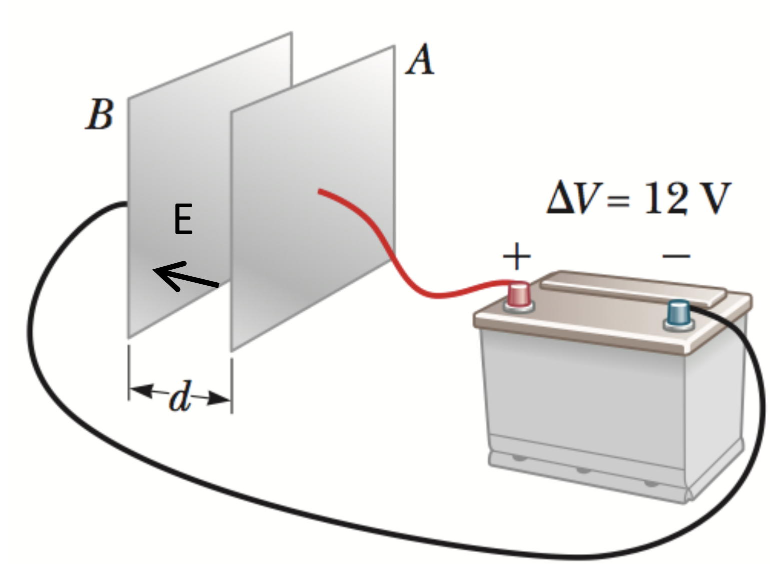
$$\Delta V = -\frac{\sigma}{\epsilon_0} d$$

# Potential Difference

- Now, what is the electric field (in terms of ΔV and d) between the plates?

$$\Delta V = -\int_a^b \vec{E} \cdot d\vec{s}$$

**E = ?**



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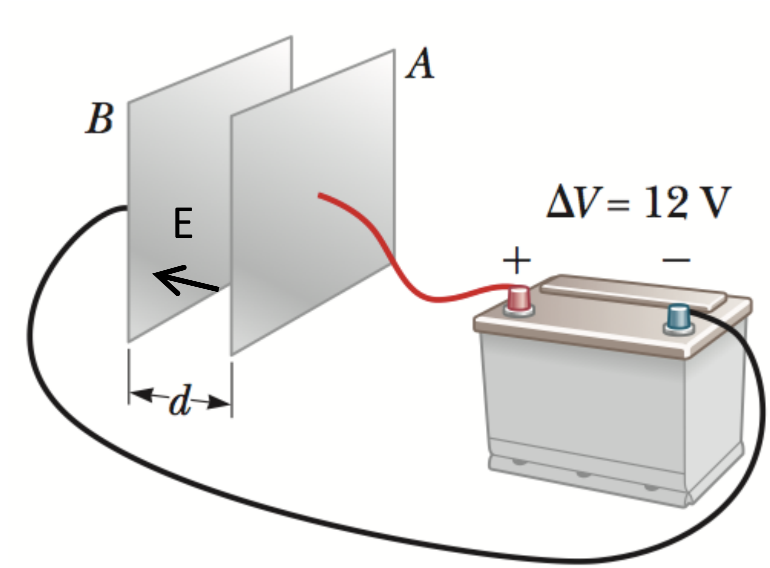


$$\Delta V = -\int_a^b \vec{E} \cdot d\vec{s}$$

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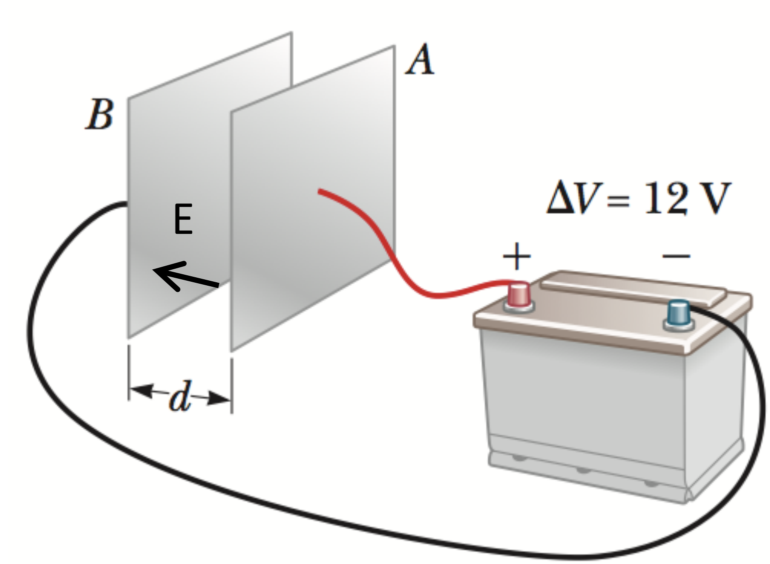


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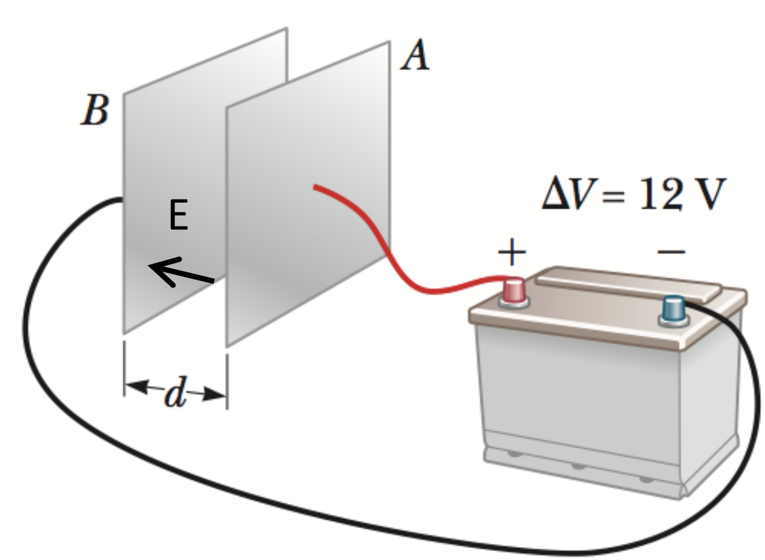


$$\Delta V = -\int_a^b \vec{E} \cdot d\vec{s}$$

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$$\mathrm{E} = -\frac{\Delta V}{d}$$