PHYS 1442 – Section 001
Lecture #3

Wednesday, June 10, 2009

Dr. Jaehoon Yu

- Chapter 16
  - Electric Field Lines
- Chapter 17
  - Electric Potential Energy
  - Electric Potential
  - Electric Potential and Electric Field
  - Equi-potential Lines
  - The Electron Volt, a Unit of Energy

Today's homework is homework #2, due 9pm, next Thursday!!

Announcements

- Your five extra credit points for e-mail subscription extended till midnight tonight! Please take a full advantage of the opportunity.
  - Seven of you have subscribed so far. Thank you!!!
- All of you have registered in the homework system.
  - Fantastic job!!
  - Remember, the due is 9pm tomorrow.
- Reading assignments: CH17 – 6 and 17 – 10
- Summer clinic hours extended to cover
  - Mon – Fri: 11am – 6pm
  - Saturdays: 11am – 4pm

Reminder: Special Project – Angels & Demons

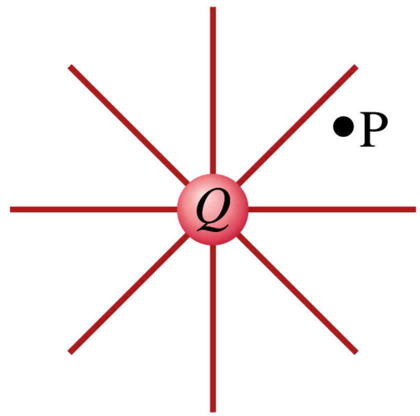
- Compute the total possible energy released from an annihilation of x-grams of anti-matter and the same quantity of matter, where x is the last two digits of your SS#. (20 points)
  - Use the famous Einstein's formula for mass-energy equivalence
- Compute the power output of this annihilation when the energy is released in x ns, where x is again the last two digits of your SS#. (10 points)
- Compute how many cups of gasoline (8MJ) this energy corresponds to. (5 points)
- Compute how many months of electricity usage it corresponds to (3.6GJ). (5 points)
- Due by the beginning of the class Monday, June 15.

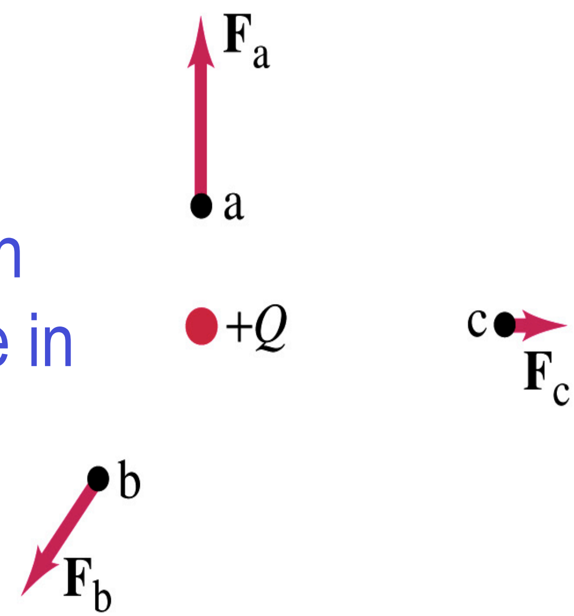
Reminder: Special Project – Magnitude of Forces

- What is the magnitude of the Coulomb force one proton exerts to another 1m away? (10 points)
- What is the magnitude of the gravitational force one proton exerts to another 1m away? (10 points)
- Which one of the two forces is larger and by how many times? (10 points)
- Due at the beginning of the class Monday, June 22.

The Electric Field

- Both gravitational and electric forces act over a distance without touching objects → What kind of forces are these?
  - Field forces
- Michael Faraday developed an idea of field.
  - Faraday argued that the electric field extends outward from every charge and permeates through all of space.
- Field by a charge or a group of charges can be inspected by placing a small test charge in the vicinity and measuring the force on it.





The Electric Field

- The electric field at any point in space is defined as the force exerted on a tiny positive test charge divide by the magnitude of the test charge
  - Electric force per unit charge

$$\vec{E} = \frac{\vec{F}}{q} \Rightarrow \vec{F} = q\vec{E}$$

- What kind of quantity is the electric field?
  - Vector quantity. Why?
- What is the unit of the electric field?
  - N/C
- What is the magnitude of the electric field at a distance r from a single point charge Q?

$$\left|\vec{E}\right| = \frac{\left|\vec{F}\right|}{q} = \frac{kQq/r^2}{q} = \frac{kQ}{r^2} = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$$

Direction of the Electric Field

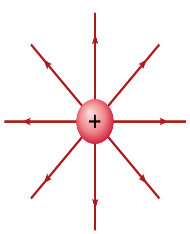
- If there are more than one charge, the individual field due to each charge is added vectorially to obtain the total field at any point.

$$\vec{E}_{Tot} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \vec{E}_4 + ...$$

- This superposition principle of electric field has been verified by experiments.
- For a given electric field **E** at a given point in space, we can calculate the force **F** on any charge q, **F**=q**E**.
  - What happens to the direction of the force and the field depending on the sign of the charge q?
  - The two are in the same directions if $q>0$
  - The two are in opposite directions if $q<0$

Field Lines

- The electric field is a vector quantity. Thus, its magnitude can be expressed in the length of the vector and the arrowhead pointing to the direction.
- Since the field permeates through the entire space, drawing vector arrows is not an ideal way of expressing the field.
- Electric field lines are drawn to indicate the direction of the force due to the given field on a **positive** test charge.
  - Number of lines crossing unit area perpendicular to E is proportional to the magnitude of the electric field.
  - The closer the lines are together, the stronger the electric field in that region.
  - Start on positive charges and end on negative charges.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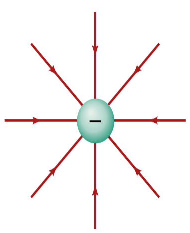
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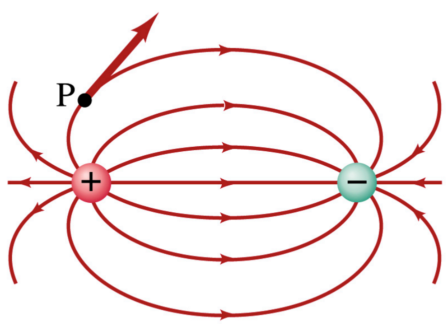
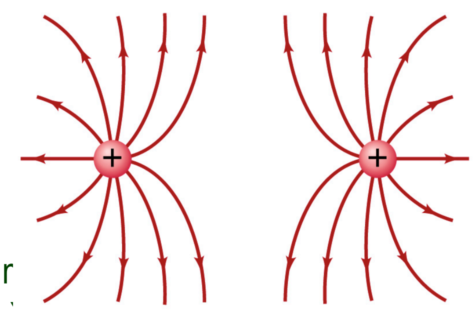
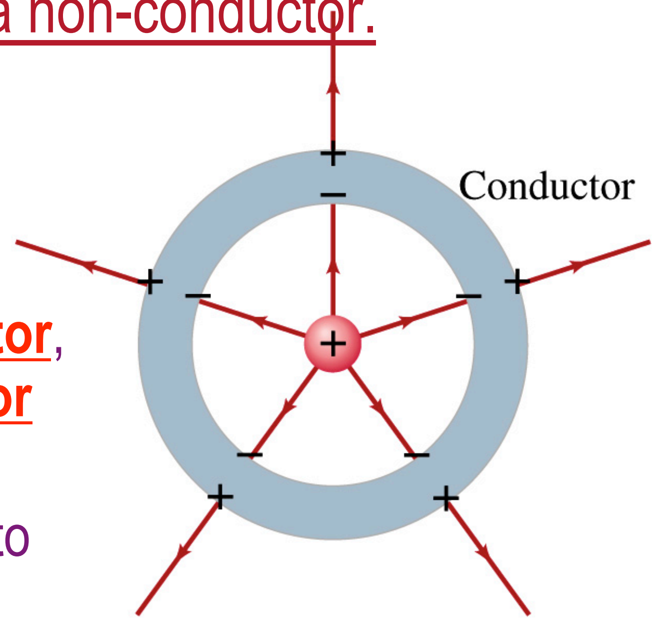




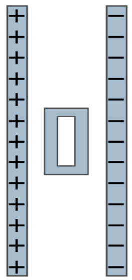
Earth's G-field lines

Electric Fields and Conductors

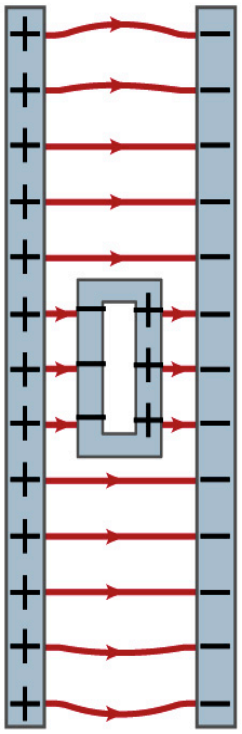
- The electric field inside a conductor is ZERO in the static situation. (If the charge is at rest.) Why?
  - If there were an electric field within the conductor, there would be a force on free electrons inside of it.
  - The electrons will move until they reached positions where the electric field becomes zero.
  - Electric field, however, can exist inside a non-conductor.
- Consequences of the above
  - Any net charge on a conductor distributes itself **on the surface**.
  - Although **no field exists inside a conductor**, the **fields can exist outside the conductor** due to induced charges on either surface
  - The electric field is always **perpendicular** to the surface outside of the conductor.



Example 16-10

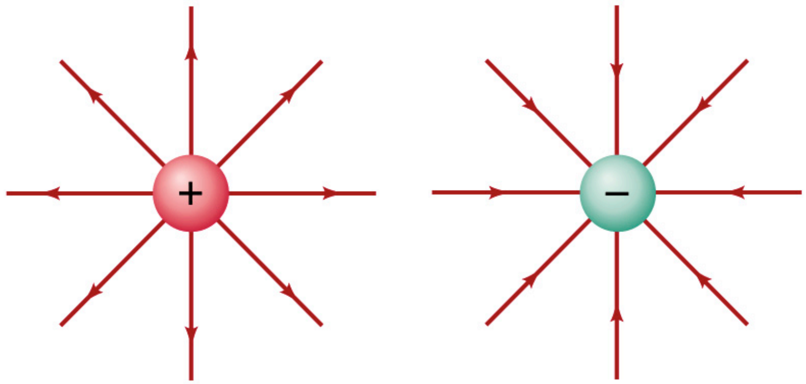


- **Shielding, and safety in a storm.** A hollow metal box is placed between two parallel charged plates. What is the field like in the box?
- If the metal box were solid
  - The free electrons in the box would redistribute themselves along the surface so that the field lines would not penetrate into the metal.
- The free electrons do the same in hollow metal boxes just as well as it did in a solid metal box.
- Thus a conducting box is an effective device for shielding. ➔ Faraday cage
- So what do you think will happen if you were inside a car when the car was struck by a lightening?



Motion of a Charged Particle in an Electric Field

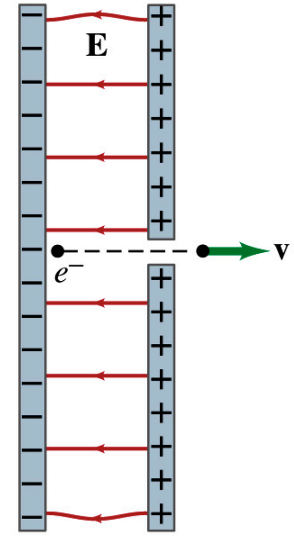
- If an object with an electric charge +q is at a point in space where electric field is **E**, the force exerting on the object is $\vec{F} = q\vec{E}$
- What do you think will happen to the charge?
  - Let's think about the cases like these on the right.
  - The object will move along the field line…Which way?
  - The charge gets accelerated.



(a) (b)

Example

- **Electron accelerated by electric field**. An electron (mass m = 9.1×10^{-31}kg) is accelerated in the uniform field E (E=2.0×10^{4}N/C) between two parallel charged plates. The separation of the plates is 1.5cm. The electron is accelerated from rest near the negative plate and passes through a tiny hole in the positive plate. (a) With what speed does it leave the hole? (b) Show that the gravitational force can be ignored. Assume the hole is so small that it does not affect the uniform field between the plates.



The magnitude of the force on the electron is F=qE and is directed to the right. The equation to solve this problem is

$$F = qE = ma$$

The magnitude of the electron's acceleration is $a = \dfrac{F}{m} = \dfrac{qE}{m}$

Between the plates the field **E** is uniform, thus the electron undergoes a uniform acceleration

$$a = \frac{eE}{m_e} = \frac{\left(1.6\times10^{-19}C\right)\left(2.0\times10^{4}N/C\right)}{\left(9.1\times10^{-31}kg\right)} = 3.5\times10^{15}\,m/s^2$$

Example cont'd

Since the travel distance is 1.5x10^{-2}m, using one of the kinetic eq. of motions,

$$v^2 = v_0^2 + 2ax \quad \therefore v = \sqrt{2ax} = \sqrt{2 \cdot 3.5\times10^{15} \cdot 1.5\times10^{-2}} = 1.0\times10^{7}\ m/s$$

Since there is no electric field outside the conductor, the electron continues moving with this speed after passing through the hole.

- (b) Show that the gravitational force can be ignored. Assume the hole is so small that it does not affect the uniform field between the plates.

The magnitude of the electric force on the electron is

$$F_e = qE = eE = \left(1.6\times10^{-19}\,C\right)\left(2.0\times10^{4}\,N/C\right) = 3.2\times10^{-15}\,N$$

The magnitude of the gravitational force on the electron is

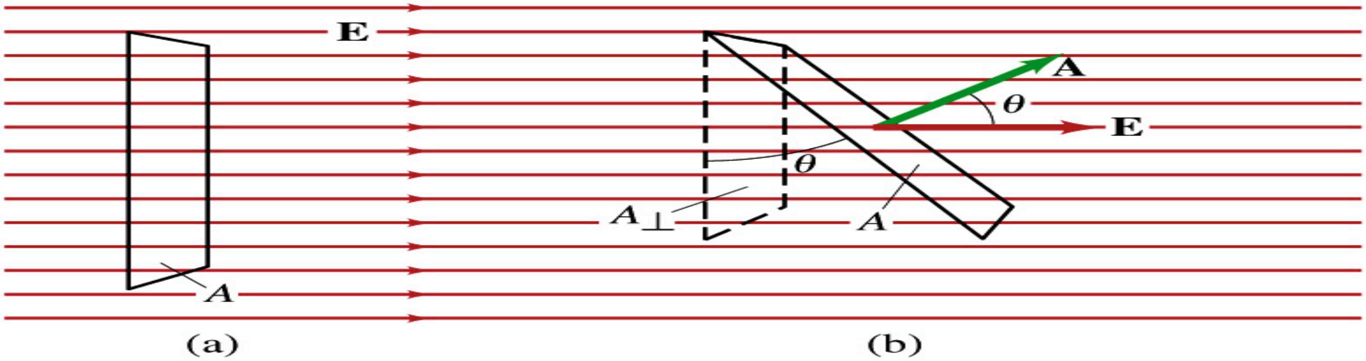
$$F_G = mg = 9.8\,m/s^2 \times \left(9.1\times10^{-31}\,kg\right) = 8.9\times10^{-30}\,N$$

Thus the gravitational force on the electron is negligible compared to the electromagnetic force.

Gauss' Law

- Gauss' law states the relationship between electric charge and electric field.
  - More general and elegant form of Coulomb's law.
- The electric field by the distribution of charges can be obtained using Coulomb's law by summing (or integrating) over the charge distributions.
- Gauss' law, however, gives an additional insight into the nature of electrostatic field and a more general relationship between the charge and the field

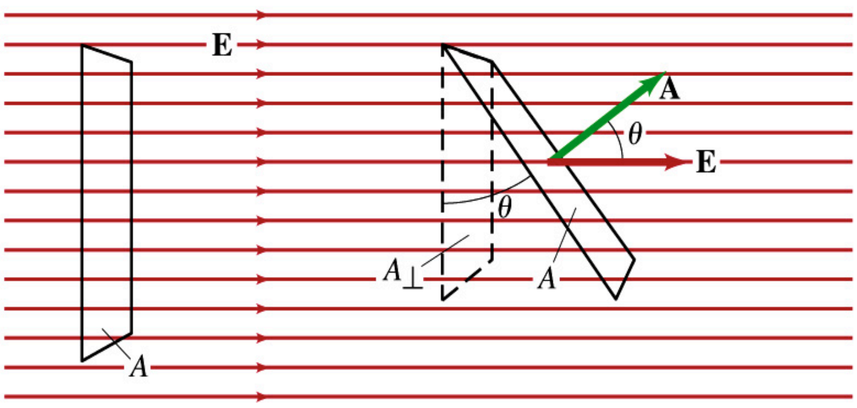
Electric Flux



- Let's imagine a surface of area A through which a uniform electric field E passes
- The electric flux is defined as
  - ϕ_E=EA, if the field is perpendicular to the surface
  - ϕ_E=EAcosθ, if the field makes an angle θ to the surface
- So the electric flux is defined as $\Phi_E = \vec{E} \cdot \vec{A}.$
- How would you define the electric flux in words?
  - Total number of field lines passing through the unit area perpendicular to the field. $N_E \propto EA_\perp = \Phi_E$

Example of Flux

- **Electric flux**. (a) Calculate the electric flux through the rectangle in the figure (a). The rectangle is 10cm by 20cm and the electric field is uniform with magnitude 200N/C. (b) What is the flux in figure if the angle is 30 degrees?



(a) (b)

The electric flux is

$$\Phi_E = \vec{E}\cdot\vec{A} = EA\cos\theta$$

So when (a) θ=0, we obtain

$$\Phi_E = EA\cos\theta = EA = (200N/C)\cdot(0.1\times 0.2m^2) = 4.0\,\mathrm{N}\cdot\mathrm{m}^2/C$$

And when (b) θ=30 degrees, we obtain

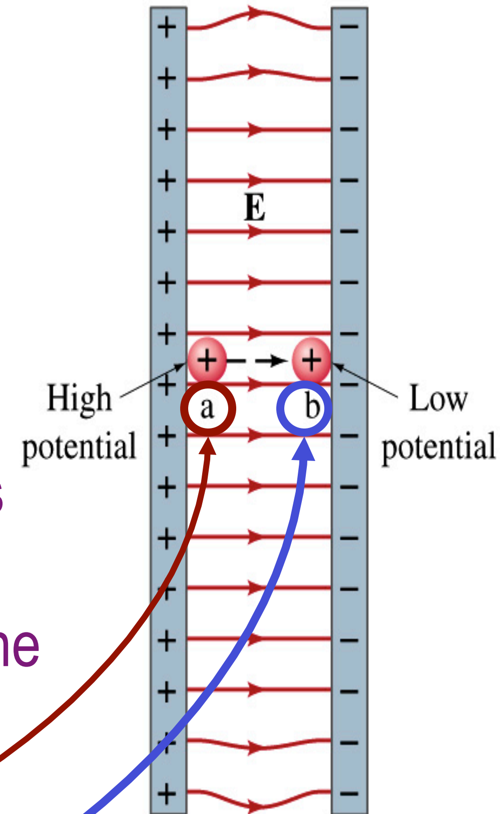
$$\Phi_E = EA\cos 30^\circ = (200N/C)\cdot(0.1\times 0.2m^2)\cos 30^\circ = 3.5\,\mathrm{N}\cdot\mathrm{m}^2/C$$

Electric Potential Energy

- Concept of energy is very useful solving mechanical problems
- Conservation of energy makes solving complex problems easier.
- When can the potential energy be defined?
  - Only for a conservative force.
  - The work done by a conservative force is independent of the path. What does it only depend on??
    - The difference between the initial and final positions
  - Can you give me an example of a conservative force?
    - Gravitational force, Spring force
- Is the electrostatic force between two charges a conservative force?
  - Yes. Why?
  - The dependence of the force to the distance is identical to that of the gravitational force.
    - The only thing matters is the direct linear distance between the object not the path.

Electric Potential Energy

- What does this mean in terms of energies?
  - The electric force is a conservative force.
  - Thus, the mechanical energy (K+U) is conserved under this force.
  - A charged object has only the electric potential energy at the positive plate.
  - The electric potential energy decreases and turns into kinetic energy of the charge object as the electric force works on the charged objects and the charged object gains speed.



- Point of greatest potential energy for
  - Positively charged object
  - Negatively charged object

	a	b
PE=	U	0
KE=	0	K
ME=	U	K

U+K

Electric Potential

- How is the electric field defined?
  - Electric force per unit charge: F/q
- We can define electric potential (potential) as
  - The electric potential energy per unit charge
  - This is like the voltage of a battery…
- Electric potential is written with the symbol V
  - If a positive test charge q has potential energy U_a at a point *a*, the electric potential of the charge at that point is

$$V_a = \frac{U_a}{q}$$

Electric Potential

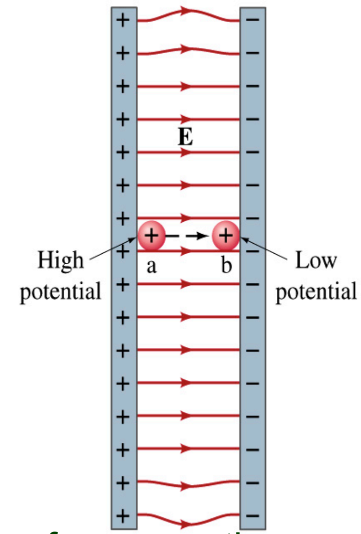
- Since only the difference in potential energy is meaningful, only the potential difference between two points is measurable
- What happens when the electric force does "positive work"?
  - The charge gains kinetic energy
  - Electric potential energy of the charge decreases
- Thus the difference in potential energy is the same as the negative of the work, W_{ba}, done on the charge by the electric field to move the charge from point a to b.
- The potential difference V_{ba} is

$$V_{ba} = V_b - V_a = \frac{U_b - U_a}{q} = \frac{-W_{ba}}{q}$$

  - Electric potential is independent of the test charge!!

A Few Things about Electric Potential

- What does the electric potential depend on?
  - Other charges that creates the field
  - What about the test charge?
    - No, the electric potential is independent of the test charge
    - Test charge gains potential energy by existing in the potential created by other charges
- Which plate is at a higher potential?
  - Positive plate. Why?
    - Since positive charge has the greatest potential energy on it.
  - What happens to the positive charge if it is let go?
    - It moves from higher potential to lower potential
  - How about a negative charge?
    - Its potential energy is higher on the negative plate. Thus, it moves from negative plate to positive. Potential difference is the same.
- The unit of the electric potential is Volt (V).
- From the definition, 1V = 1J/C.

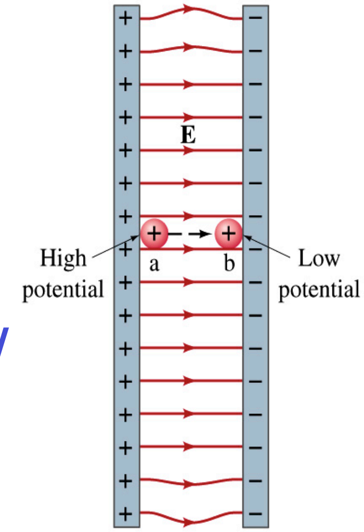


Zero point of electric potential can be chosen arbitrarily.

Often the ground, a conductor connected to Earth, is zero.

Example 17 – 1

A negative charge: Suppose a negative charge, such as an electron, is placed at point *b* in the figure. If the electron is free to move, will its electric potential energy increase or decrease? How will the electric potential change?



- An electron placed at point *b* will move toward the positive plate since it was released at its highest potential energy point.
- It will gain kinetic energy as it moves toward left, decreasing its potential energy.
- The electron, however, moves from the point *b* at a lower potential to point *a* at a higher potential. $\Delta V = V_a - V_b > 0$.
- This is because the potential is generated by the charges on the plates not by the electron.

Electric Potential and Potential Energy

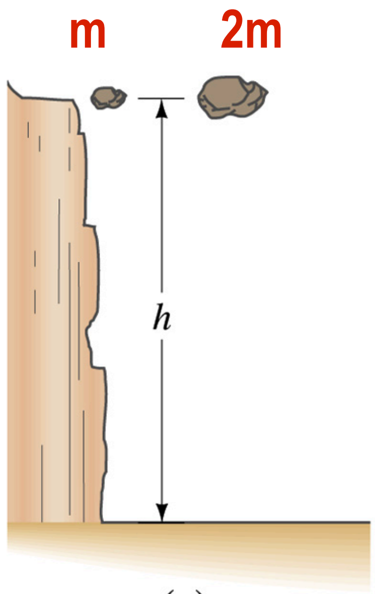
- What is the definition of the electric potential?
  - The potential energy difference per unit charge
- OK, then, how would you express the potential energy that a charge q would obtain when it is moved between point *a* and *b* with the potential difference V_{ba}?

$$U_b - U_a = q\left(V_b - V_a\right) = qV_{ba}$$

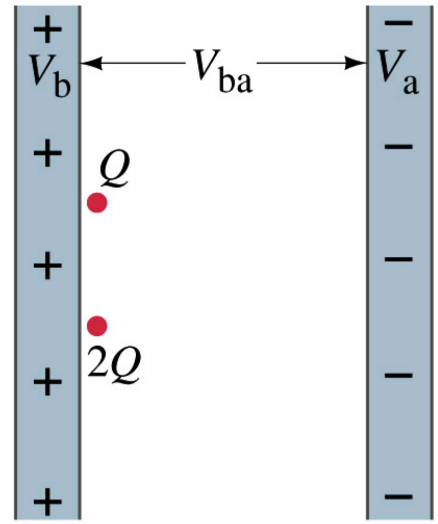
  - In other words, if an object with charge q moves through a potential difference V_{ba}, its potential energy changes by qV_{ba}.
- So based on this, how differently would you describe the electric potential in words?
  - A measure of how much energy an electric charge can acquire in a given situation
  - A measure of how much work a given charge can do.

Comparisons of Potential Energies

- Let's compare gravitational and electric potential energies



(a)



(b)

- What are the potential energies of the rocks?
  - mgh and 2mgh
- Which rock has a bigger potential energy?
  - The rock with a larger mass
- Why?
  - It's got a bigger mass.

- What are the potential energies of the charges?
  - QV_{ba} and $2QV_{ba}$
- Which object has a bigger potential energy?
  - The object with a larger charge.
- Why?
  - It's got a bigger charge.

The potential is the same but the heavier rock or larger charge can do a greater work.

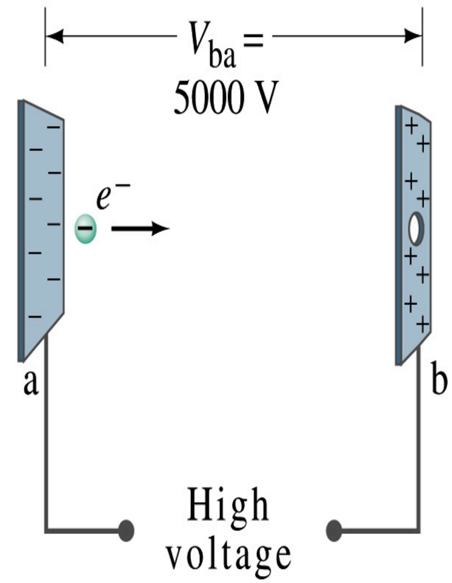
Electric Potential and Potential Energy

- The electric potential difference gives potential energy or possibility to do work depending on the charge of the object.
- So what is happening in batteries or generators?
  - They maintain a potential difference.
  - The actual amount of energy used or transformed depends on how much charge flows.
  - How much is the potential difference maintained by a car's battery?
    - 12Volts
  - If for a given period, 5C charge flows through the headlight lamp, what is the total energy transformed?
    - E_{tot}=5C*12V=60 Umm… What is the unit? **Joules**
  - If it is left on twice as long? E_{tot}=10C*12V=120J.

Some Typical Voltages

Sources	Approximate Voltage
Thundercloud to ground	10^8 V
High-Voltage Power Lines	10^6 V
Power supply for TV tube	10^4 V
Automobile ignition	10^4 V
Household outlet	10^2 V
Automobile battery	12 V
Flashlight battery	1.5 V
Resting potential across nerve membrane	10^{-1} V
Potential changes on skin (EKG and EEG)	10^{-4} V

Example 17 – 2



Electrons in TV tube: Suppose an electron in the picture tube of a television set is accelerated from rest through a potential difference V_{ba}=+5000V. (a) What is the change in potential energy of the electron? (b) What is the speed of the electron ($m=9.1\times10^{-31}$kg) as a result of this acceleration? (c) Repeat for a proton ($m=1.67\times10^{-27}$kg) that accelerates through a potential difference of V_{ba}=-5000V.

- (a) What is the charge of an electron?
  - $e = -1.6\times10^{-19}C$
- So what is the change of its potential energy?

$$\Delta U = qV_{ba} = eV_{ba} = \left(-1.6\times10^{-19}C\right)\left(+5000V\right) = -8.0\times10^{-16}J$$

Example 17 – 2

- (b) Speed of the electron?
  - The entire potential energy of the electron turns to its kinetic energy. Thus the equation is

$$\Delta K = \frac{1}{2}m_e v_e^2 - 0 = W = -\Delta U = -eV_{ba} =$$
$$= -\left(-1.6\times10^{-19}C\right)5000V = 8.0\times10^{-16}J$$

$$v_e = \sqrt{\frac{2\times eV_{ba}}{m_e}} = \sqrt{\frac{2\times8.0\times10^{-16}}{9.1\times10^{-31}}} = 4.2\times10^{7}m/s$$

- (C) Speed of a proton?

$$\Delta K = \frac{1}{2}m_p v_p^2 - 0 = W = -\Delta U = -\{(-e)(-V_{ba})\} = -eV_{ba} = 8.0\times10^{-16}J$$

$$v_p = \sqrt{\frac{2\times eV_{ba}}{m_p}} = \sqrt{\frac{2\times8.0\times10^{-16}}{1.67\times10^{-27}}} = 9.8\times10^{5}m/s$$