NAD 2023 Standard EM1 (Electric fields)

CREDITS

- This Slideshow was developed to accompany the textbook
  - *OpenStax High School Physics*
    - *Available for free at https://openstax.org/details/books/physics*
    - *By Paul Peter Urone and Roger Hinrichs*
    - *2020 edition*
- Some examples and diagrams are taken from the *OpenStax College Physics, Physics,* and *Cutnell & Johnson Physics* 6th ed.

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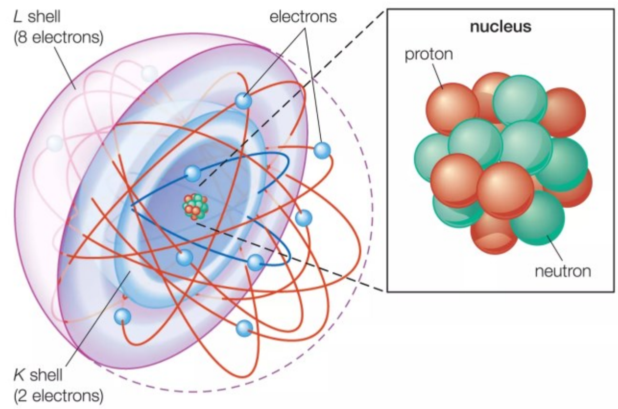
OpenStax High School Physics 18.1
OpenStax College Physics 2e 18.1-18.2

7-01 Electric Charge

- An atom
  - Nucleus
    - Protons – positive charge
    - Neutrons – no charge, but same mass as proton
  - Electron cloud
    - Electron – negative charge, little mass
    - $q_e = -1.60 \times 10^{-19}\ C$
      - Unit of charge: Coulomb (C)
      - q_e is the smallest charge discovered
      - Electricity is quantized → comes in discreet numbers
      - $|q_e|$ is the elementary charge
        - $e = 1.60 \times 10^{-19}\ C$
  - In nature atoms have no net charge
    - # protons = # electrons



LAB 7-01

- Determine what types of materials can create and hold static electricity.

7-01 Electric Charge

- How many electrons does it take to make a charge of $-4 \times 10^{-6}\ C$? What is their mass ($m_e = 9.11 \times 10^{-31}\ kg$)?

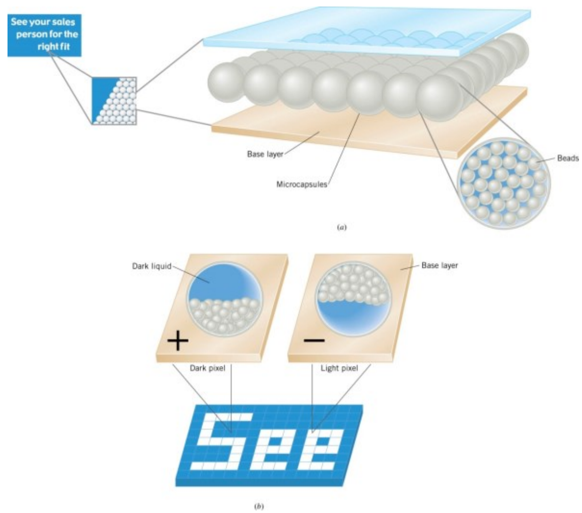
- N = 2.5×10^{13} electrons (a lot)
- m = 2.28×10^{-17} kg (very small)

$$N = \frac{q}{e} \rightarrow N = \frac{4 \times 10^{-6}\ C}{1.6 \times 10^{-19}\ C} = 2.5 \times 10^{13}$$
$$m = 2.5 \times 10^{13}\ (9.11 \times 10^{-31}\ kg) = 2.28 \times 10^{-17}\ kg$$

7-01 Electric Charge

- Law of Conservation of Charge
  - During any process, the net electrical charge of a closed system remains constant
- Like charges repel
- Unlike charges attract
  - The attraction and repulsion are forces and can be used with Newton's Laws and other dynamics problems

- When you rub a balloon on your hair, the balloon steals electrons from the hair. The balloon gets a negative charge and the hair gets a positive charge.
- When the balloon takes electrons from the hair, each hair is positively charged. It stands on end because the like positive charges repel
- The balloon with the extra electrons sticks to other objects because it has a charge and the other objects don't. The unlike charges attract



- Electric Ink

This is different than LCD (in LCD the material is naturally transparent, the charge makes it become opaque)

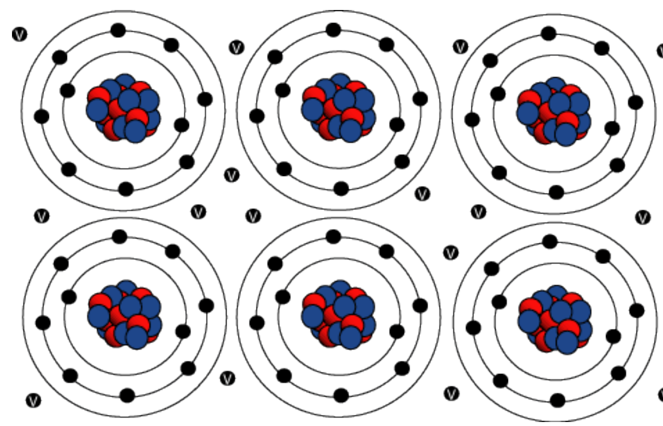
- Made of two layers (base and transparent top)
- Microcapsules diameter of hair contain white charged beads and dark liquid.
- The base layer is electrically charged (some pixels (picture element) are dark because the beads are attracted to the base layer and some are white because the beads are repelled by the base layer)

7-01 Electric Charge

- Electricity can flow through objects

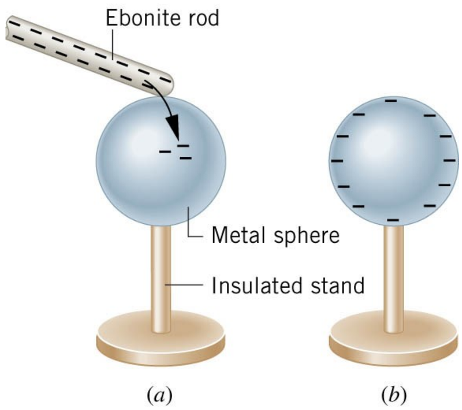
- Conductors let electrons flow easily
  - Most heat conductors are also electrical conductors
  - Metals

- Insulators are very poor conductors
  - Rubber
  - Plastic
  - Wood



•Metals make good conductors because of metallic bonds (chemistry) where the electrons are not strongly attached to the individual nuclei. This happens partly because the outer most layer of electrons is so far away from the nucleus, there isn't much attraction.
•Insulators are made of atoms that hold tightly to their electrons i.e. their electron shells are full or almost full.
•Hence electrical wires are coated in plastic

7-01 Electric Charge

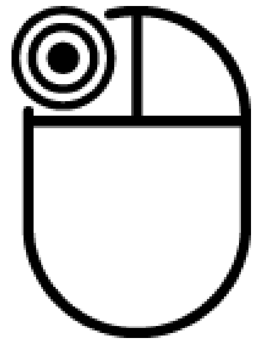


- Charging by contact
- Negative charged rod gives some electrons to sphere
- Sphere becomes negatively charged until charges are equal

7-01 Electric Charge

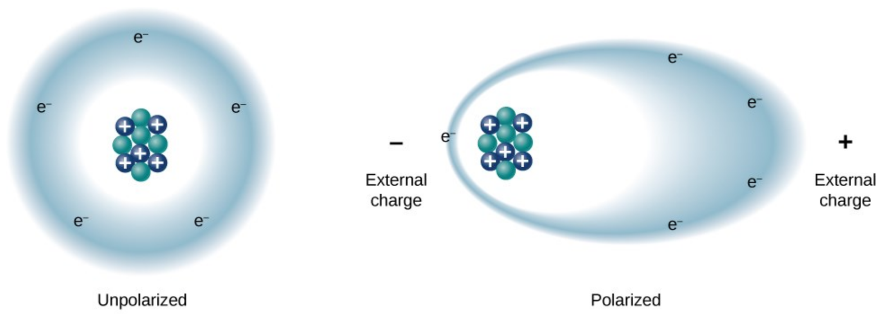
- Static Electricity Charging
  - When two insulators are rubbed together
    - One steals the electrons from the other
    - It becomes negatively charged
    - The other becomes positively charged

- Balloons and Static Electricity simulation. (http://www.openstaxcollege.org/l/28balloons)



7-01 Electric Charge

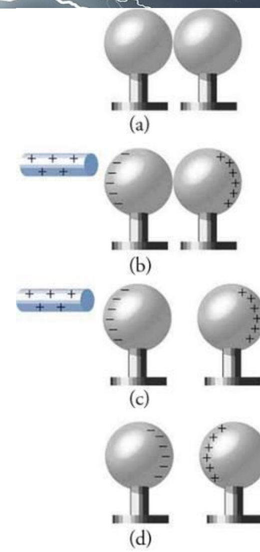
- Polarization
  - Insulators
    - Electrons are not free to move away from the atoms or molecule
    - When a charge is brought near, the electrons move to one side of the atom/molecule so that more electrons are on that side
    - One side is negative, and the other side is more positive



7-01 Electric Charge

Charge by Induction

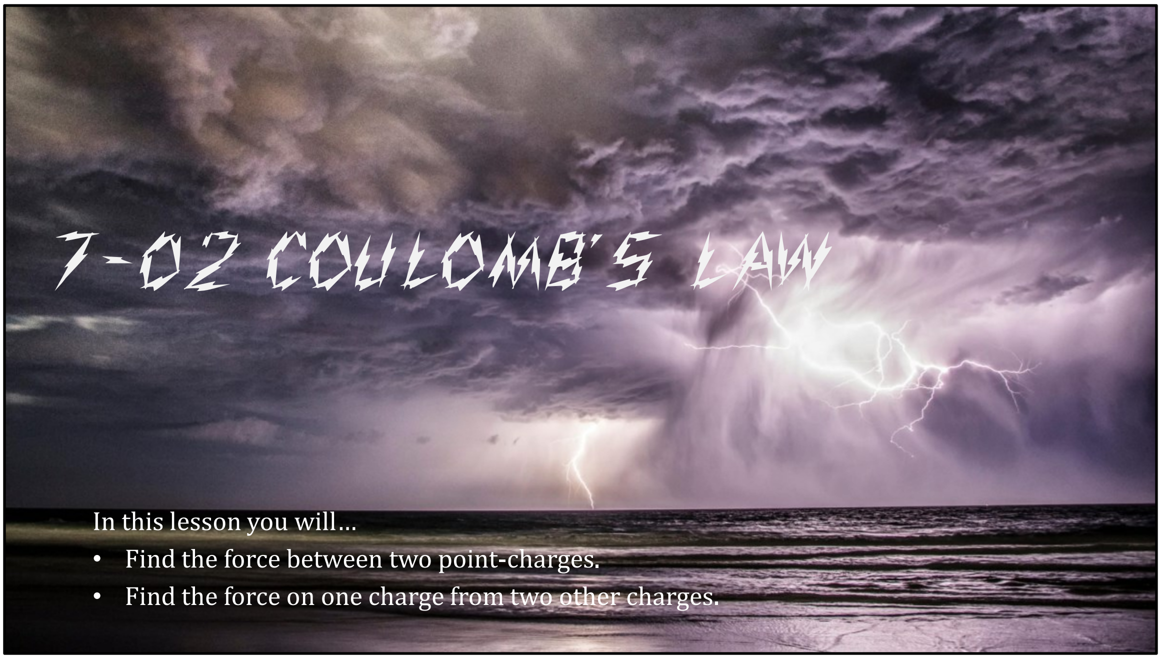
- Charge without touching
- Charged rod comes near neutral sphere
- The like charges are repelled to other sphere
- The spheres are separated
- The rod is removed
- Spheres are charged



07-01 Practice Work

- Try charging your way through these problems

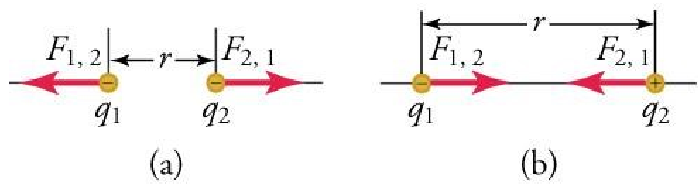
- Read
    - OpenStax College Physics 2e 18.3
    - OR
    - OpenStax High School Physics 18.2



OpenStax High School Physics 18.2
OpenStax College Physics 2e 18.3

7-02 Coulomb's Law

- Point charges exert force on each other
  - Related to the size of the charges and the distance between them
  - If the signs are same force repels
  - If the signs are opposite force attracts
  - Force of the first to the second is equal and opposite of the second to the first
    - Newton's Third Law



7-02 LAB

- Do the lab to observe properties of electric force

7-02 Coulomb's Law

- Coulomb's Law

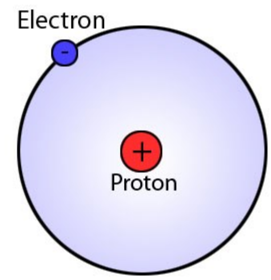
$$F = k\frac{|q_1 q_2|}{r^2}$$

- Where
  - F = electrostatic force
  - k = constant (8.99×10^9 Nm^2/C^2)
  - q = charge
  - r = distance between the charges

7-02 Coulomb's Law

- In a hydrogen atom, the electron ($q = -1.60 \times 10^{-19}$ C) is 5.29×10^{-11} m away from the proton of equal charge magnitude. Find the electrical force of attraction.

- $F = 8.22 \times 10^{-8}$ N



$$F = \frac{\left(8.99 \times 10^{9} \frac{Nm^2}{C^2}\right)\left((1.6 \times 10^{-19}\ C)(1.6 \times 10^{-19}\ C)\right)}{(5.29 \times 10^{-11}\ m)^2} = 8.22 \times 10^{-8}\ N$$

7-02 Coulomb's Law

- Coulomb's Law – other notes
  - Notice the similarity to Newton's Law of Universal Gravitation
  - Notice that $F \propto 1/r^2$
    - Distance increases by 4, force decreases by 16

7-02 Coulomb's Law

- Force on 1 charge by 2 others
  - Work in two parts
    - Find force of attraction by one of the points
    - Find force of attraction by the other point
    - Add the force vectors
      - REMEMBER!!!!! → you have to add the x and y components!!!!!

7-02 Coulomb's Law

- There are three charges in a straight line
- q_1 = +2μC at x = -0.1 m
- q_2 = −3 μC at x = 0 m
- q_3 = +5 μC at x = 0.3 m
- What is the force on q_2?

- F = −3.89 N

$F_{12} = 8.99 \times 10^9 \frac{Nm^2}{C^2} \frac{(2\times10^{-6}\ C)(3\times10^{-6}\ C)}{(0.1\ m)^2} = -5.39\ N$ (neg because pulling in – direction)

$F_{23} = 8.99 \times 10^9 \frac{Nm^2}{C^2} \frac{(5\times10^{-6}\ C)(3\times10^{-6}\ C)}{(0.3\ m)^2} = 1.50\ N$ (pos because pulling in + direction)

$F = F_{12} + F_{23} = -5.39\ N + 1.50\ N = -3.89\ N$

7-02 Practice Work

- Charge these problems to your grade
- Read
  - OpenStax College Physics 2e 18.4-18.5
  - OR
  - OpenStax High School Physics 18.3

OpenStax High School Physics 18.3
OpenStax College Physics 2e 18.4-18.5

7-03 Electric Field

- We can use a ***test charge*** to determine how the surrounding charges generate a force

- Pick a small test charge so it doesn't change the surrounding charge orientation

7-03 Electric Field

- A test charge ($q_0 = 1.0 \times 10^{-10}\ C$) experiences a force of $2 \times 10^{-9}\ N$ when placed near a charged sphere. Determine the Force per Coulomb that the charge experiences and predict the force on a $2\ C$ charge.

- $\frac{F}{q_0} = 20\ N/C$
- $F = 40\ N$

$$\frac{F}{q_0} = \frac{2 \times 10^{-9}\ N}{1 \times 10^{-10}\ C} = 20 \frac{N}{C}$$

$$F = 20 \frac{N}{C}\ (2\ C) = 40\ N$$

7-03 Electric Field

- Electric Field Definition

$$E = \frac{F}{q_0} = \frac{kq_1}{r^2}$$

  - Force per charge
  - Vector
    - Same direction as the force on a positive test charge
    - Remember to add them as vectors!!!!
  - Unit: N/C

The surrounding charges create the electric field at a given point
As we will see, the test charge does not affect the electric field

7-03 Electric Field

- Point Charges

$$E = \frac{F}{q_0}$$

$$F = \frac{kqq_0}{r^2}$$

$$E = \frac{\frac{kqq_0}{r^2}}{q_0}$$

$$E = \frac{kq}{r^2}$$

- Notice the q_0 does not affect the E-field

7-03 Electric Field

- There are two point charges of q_1 = 4 C and q_2 = 8 C and they are 10 m apart. Find point where E = 0 between them.

- d = 5.85 m from q_2 towards q_1

Pick the distance from the first as d and the distance from the second as 10 – d
Set E-fields equal to each other

$$\frac{k8\ C}{d^2} = \frac{k4\ C}{(10-d)^2}$$

$$\frac{8}{d^2} = \frac{4}{(10-d)^2}$$

$$8(10-d)^2 = 4d^2$$

$$2\sqrt{2}(10-d) = \pm 2d$$

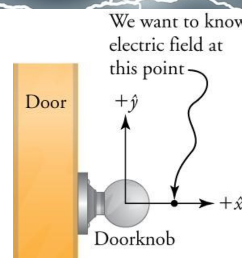
$$28.2 - 2.82d = \pm 2d$$

$$Take\ +:\ 28.2 - 2.82d = 2d \Diamond 28.2 = 4.82d \rightarrow d = 5.85$$

$$Take\ -:\ 28.2 - 2.82d = -2d \rightarrow 28.2 = 0.82\ d \rightarrow d = 34.39$$

Answer is 5.85

- A doorknob, which can be taken to be a spherical metal conductor, acquires a static electricity charge of $-1.5\ nC$ What is the electric field 1.0 cm in front of the doorknob? The diameter of the doorknob is 5.0 cm.



Like gravity, electric force and field are taken from the center of a sphere. So the distance *r* is the radius plus the 1 cm away from the surface.

$$r = 0.025\ m + 0.01\ m = 0.035\ m$$

$$E = \frac{kq}{r^2}$$

$$E = \frac{\left(8.99 \times 10^9 \frac{Nm^2}{C^2}\right)(1.5 \times 10^{-9}\ C)}{(0.035\ m)^2} = 1.10 \times 10^4 \frac{N}{C}$$

Positive charge at this location will be attracted towards the knob on the left, so the answer is $1.10 \times 10^4 \frac{N}{C}$ to the left.

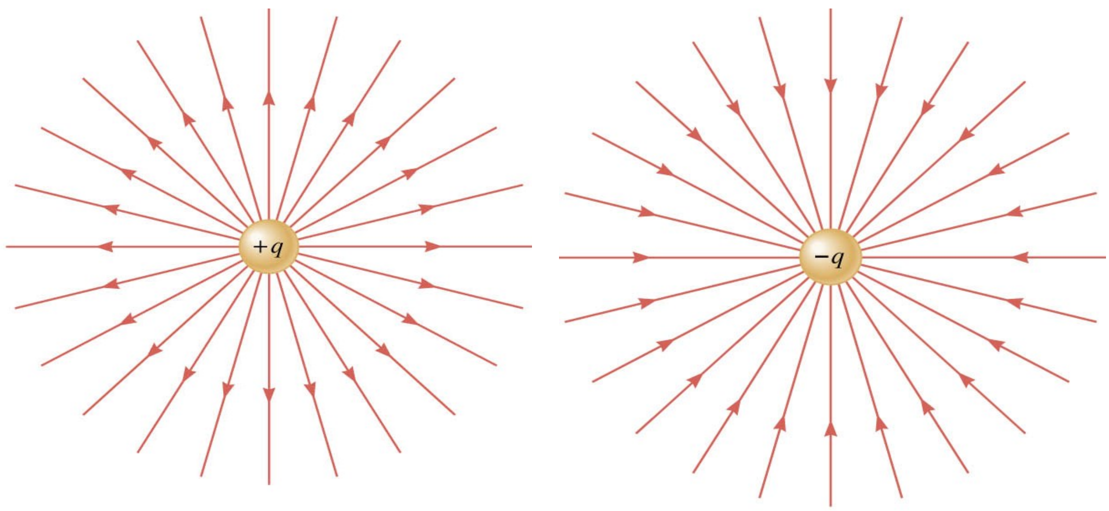
7-03 Electric Field

- It would be nice to have some kind of map to show the E-field in space
- Rules
  - Lines begin at positive charges only
  - Lines end at negative charges only
  - The number of lines entering or leaving a charge is proportional to the size of charge
  - Lines don't cross each other
  - Lines leave surfaces at 90 degrees

Spread out lines → weak E-field
Close lines → strong E-field

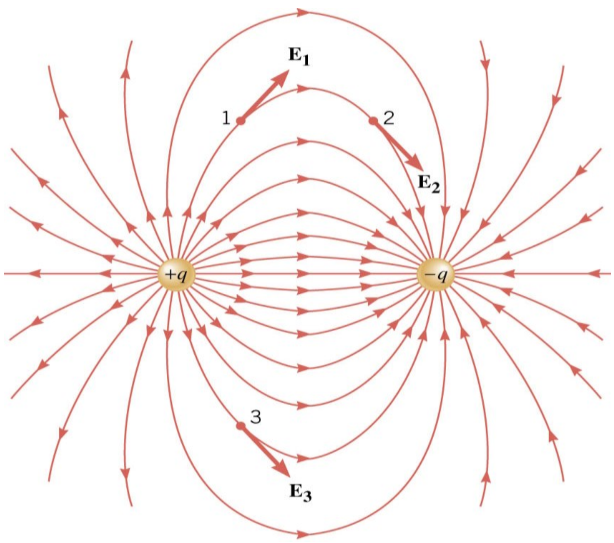
Lines don't cross because there is only one value of E at one point

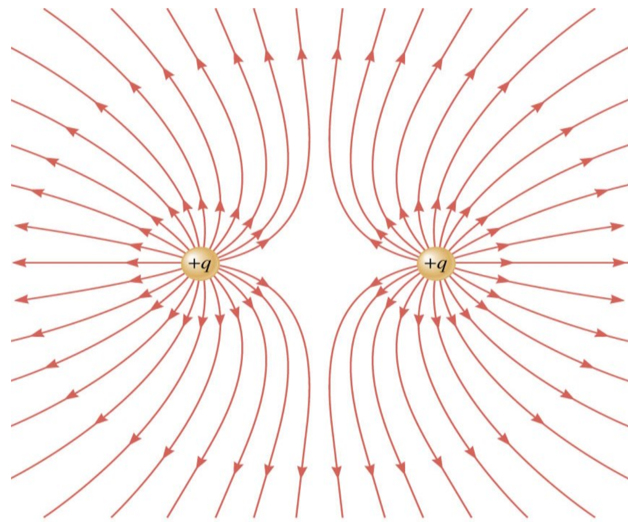
7-03 Electric Field



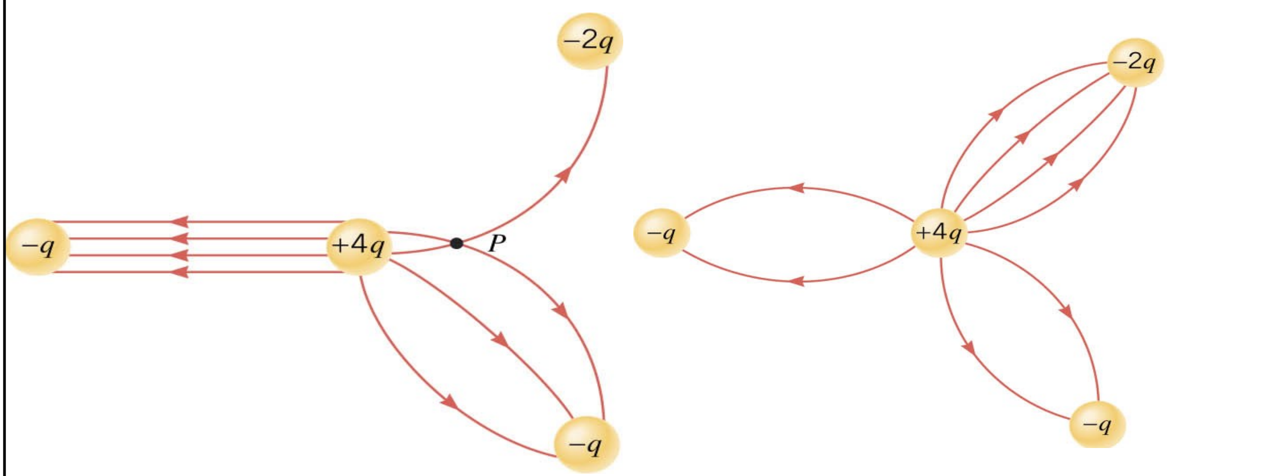
Made by putting test charge in points and seeing direction and strength of E-field

7-03 Electric Field





7-03 Electric Field



Lines on left should be curved→ as is the charge would constant between them, should depend on distance
Lines cross at point P
Number of lines should be proportional to charge 1:4:2:1 or 2:8:4:2 to make symmetry

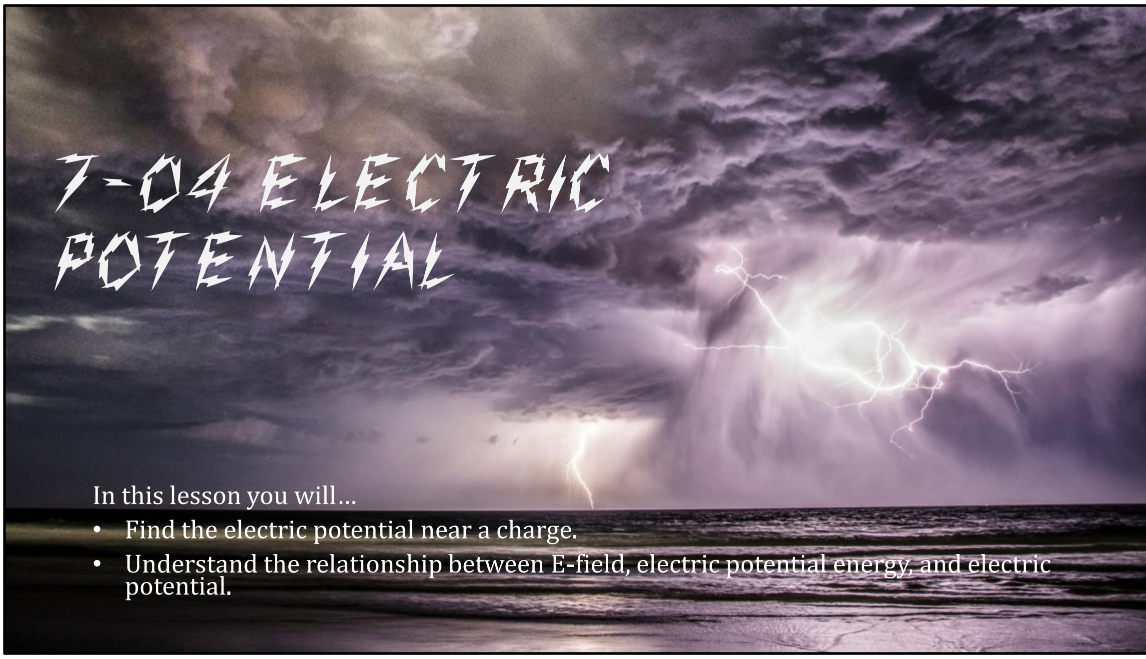
07-03 Lab

- Create your own electric field map

7-03 Practice Work

- Electrify your brain and answer these problems

- Read
  - OpenStax College Physics 2e 19.1-19.3
  - OR
  - OpenStax High School Physics 18.4



OpenStax High School Physics 18.4
OpenStax College Physics 2e 19.1-19.3

7-04 Electric Potential

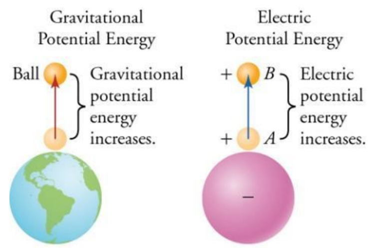
- Change in PE due to Gravity
  - Force of gravity is conservative
  - $W = mgh_0 - mgh_f = PE_0 - PE_f$
- Change in PE due to Electrical Force
  - Electrical Force is conservative
  - $W = PE_0 - PE_f$

$$F_G = G\frac{m_1 m_2}{r^2}$$

$$F_E = k\frac{q_1 q_2}{r^2}$$

7-04 Electric Potential

- For gravity (in a constant G-field)
  - $W = -\Delta PE$
  - $W = Fd$
  - $-\Delta PE = Fd$
  - $F = mg$
  - $W = -\Delta PE = mg(y_f - y_0)$
- For static electricity (in a constant E-field)
  - $W = -\Delta PE$
  - $W = Fd$
  - $-\Delta PE = Fd$
  - $F = q_0 E$
  - $W = -\Delta PE = q_0 E(x_f - x_0)$

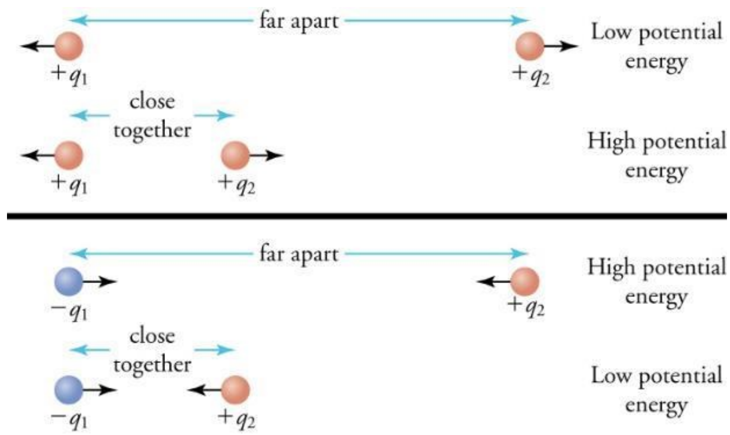


PE can only be differences because there is no absolute zero position

The sign is negative because the potential energy of the ball decreases as gravity does work to it (makes it come down).

7-04 Electric Potential

- If the field is not constant, then calculus is used.
- For point charges
  - $PE = q_0 E r$
  - $PE = q_0 \left(\frac{kq}{r^2}\right) r$
  - $PE = \frac{kqq_0}{r}$



7-04 Electric Potential

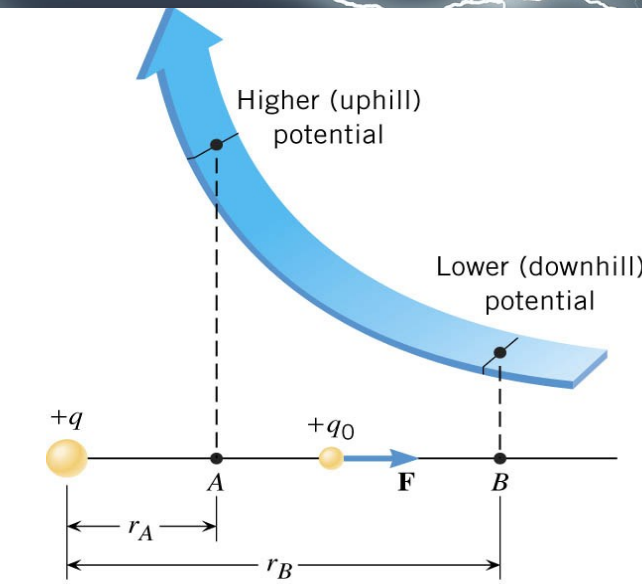
- E-field is $E = \frac{F}{q_0}$ and is a vector
- It might be nice to have a similar idea with energy which is not a vector

- Electric Potential (or Potential Difference)
  - $V = \frac{\Delta PE}{q_0}$
- For point charges
  - $V = \frac{kq}{r}$

7-04 Electric Potential

- Potential energy
  - PE
  - q_0V
  - Unit: J
- Electric potential
  - V
  - $\frac{\Delta PE}{q_0}$
  - Unit: J/C = V

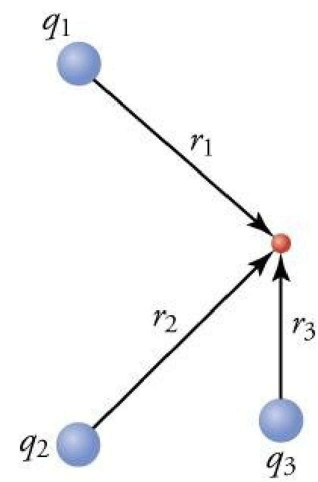
7-04 Electric Potential



- Charge at q
- Two points at distances rA and rB
- At both these points a small positive test charge is repelled by the force F = (kqq/r^2)
- This force does work to move the test charge from A to B
- Since r varies from A to B and the force varies also, so must use calculus integrals to find the work done
    - $W_{AB} = kqq_0/rA – kqq_0/rB$
- The potential difference can be found
    - $V_B – V_A = -W_{AB}/q_0 = kq/rB – kq/rA$
- If we make rB very large (infinite) then kq/rB = 0 and $V_B = 0$
- For convenience we always set $V_B = 0$ so
    - V = kq/r

7-04 Electric Potential

- To add potentials from several point charges, add the potentials at that point



7-04 Electric Potential

- Two point-charges lie on the *x*-axis with $q_1 = -2\ \mu C$ at 1 cm and $q_2 = 3\ \mu C$ at 9 cm. Where is the electric potential zero between them?

$$V = \frac{kq}{r}$$

$$V = \frac{k(-2 \times 10^{-6}\ C)}{x} + \frac{k(3 \times 10^{-6}\ C)}{8 - x} = 0$$

$$\frac{k(3 \times 10^{-6}\ C)}{8 - x} = \frac{k(2 \times 10^{-6}\ C)}{x}$$

Cancel *k* and *C* and cross multiply

$$(3 \times 10^{-6})x = (2 \times 10^{-6})(8 - x)$$

$$(3 \times 10^{-6})x = (16 \times 10^{-6}) - (2 \times 10^{-6})x$$

$$(5 \times 10^{-6})x = 16 \times 10^{-6}$$

$$x = 3.2\ cm$$

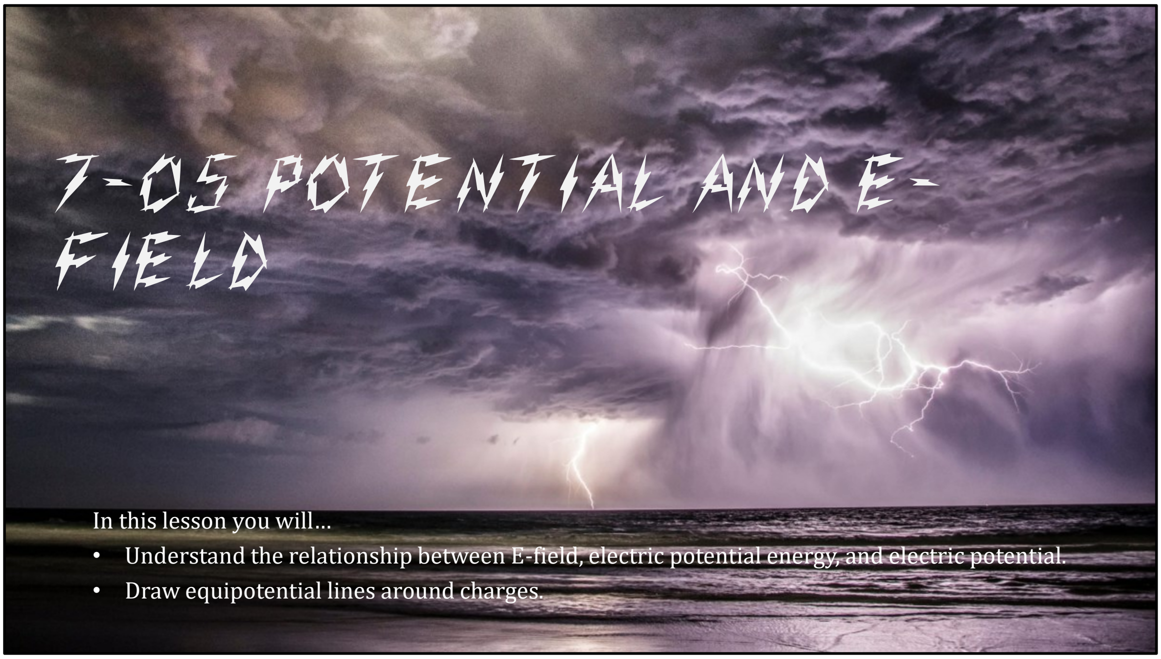
Add 1 cm because the *x* was measured from 1 cm.

V is 0 at the 4.2 cm point

7-04 Practice Work

- Electrify your brain and answer these problems

- Read
  - OpenStax College Physics 2e 19.4
  - OR
  - OpenStax High School Physics 18.4



OpenStax High School Physics 18.4
OpenStax College Physics 2e 19.4

7-05 Potential and E-field

- Electric Potential and E-field
- $\Delta V = \frac{\Delta PE}{q_0} = -E\left(x_f - x_0\right)$
- $W = -\Delta PE = q_0 E(x_f - x_0)$
- $\Delta V = -\frac{\Delta PE}{q_0} = \frac{q_0 E\left(x_f - x_0\right)}{q_0}$
- $\Delta V = E\left(x_f - x_0\right)$
- $E = \frac{\Delta V}{x_f - x_0}$

- E-field units
  - N/C
  - V/m
- It is easy to measure ΔV
  - To find E-field, divide ΔV and the distance between two points

7-05 Potential and E-Field

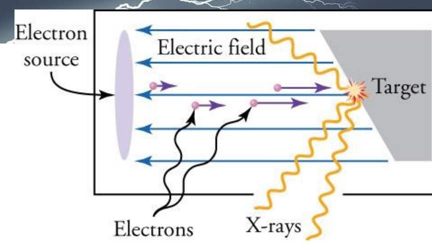
- What is the voltage difference between the positions, x = 11 m and x = 5.0 m in an electric field of 2.0 N/C?

$$E = \frac{\Delta V}{x_f - x_0}$$

$$2.0\,\frac{N}{C} = \frac{\Delta V}{11\ m - 5\ m}$$

$$\Delta V = 12\ V$$

7-05 Potential and E-Field



- X-ray tubes that generate X-rays contain an electron source separated by about 10 cm from a metallic target. The electrons are accelerated from the source to the target by a uniform electric field with a magnitude of about 100 kN/C. When the electrons hit the target, X-rays are produced. (a) What is the potential difference between the electron source and the metallic target? (b) What is the kinetic energy of the electrons when they reach the target, assuming that the electrons start at rest?

a. $E = \frac{\Delta V}{x_f - x_0}$

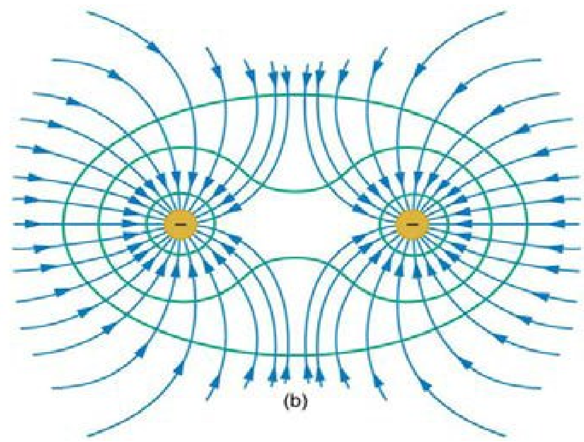
$$100{,}000 \frac{N}{C} = \frac{\Delta V}{0.1\text{ m}}$$
$$10{,}000\ V = \Delta V$$

b. $E_0 + W_{nc} = E_f$

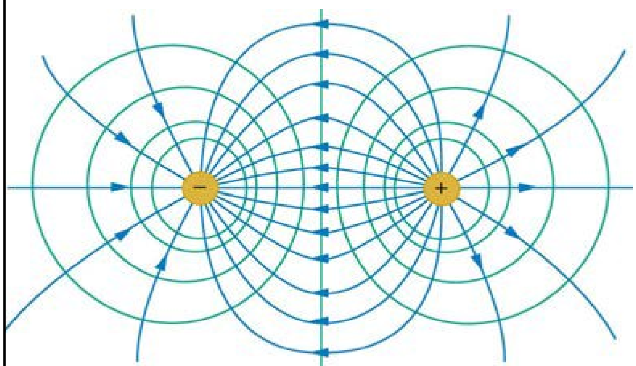
$$PE_0 + KE_0 = PE_f + KE_f$$
$$0 + 0 = q_0 V + KE_f$$
$$KE_f = -q_0 V$$
$$KE_f = -(-1.6 \times 10^{-19}\ C)(10000\ V) = 1.6 \times 10^{-15}\ J$$

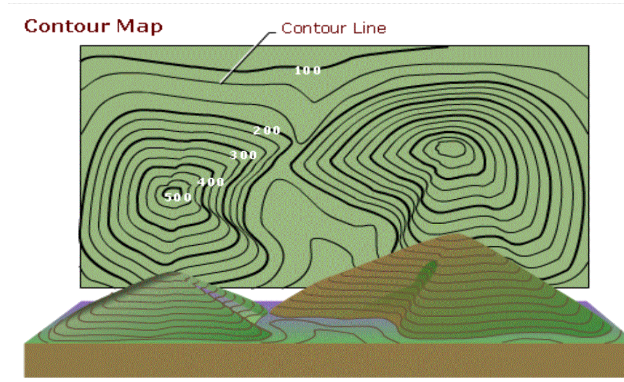
7-05 Potential and E-field

- Equipotential Lines
  - Lines where the electric potential is the same
  - Perpendicular to E-field
  - No work is required to move charge along equipotential line since $q\Delta V = 0$



7-05 Potential and E-Field

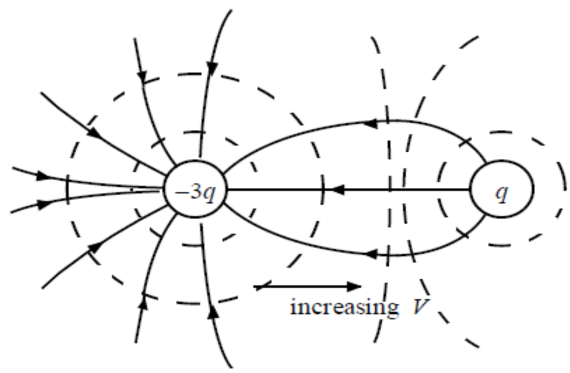




Field lines and equipotential lines like topographic map where altitudes are equipotential lines and slopes are like field lines

7-05 Practice Work

- Sketch the equipotential lines in the vicinity of two opposite charges, where the negative charge is three times as great in magnitude as the positive.



7-05 Potential and E-Field

- Let me charge you with this point:
  You can reach your potential.