Slide 1

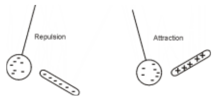
Electric Force and Electric Field

These lectures slides were prepared by
Dr. Danica Solina

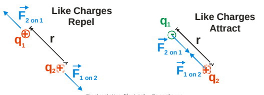
Text: Walker *et al.* (2021), *Halliday's Fundamentals of Physics – First Australian and New Zealand Edition*
John Wiley & Sons Australia (HW)

Slide 2

Electric Force



- Electric charge produces a force on another charge
- Like charges repel while unlike charges attract
- Between point charges the electric forces obey Newton's Third Law.



HW : Sec. 21.1

Slide 3

Coulomb's Law

Charles Augustin de Coulomb (1736 – 1806) studied point charges using a torsional balance (illustrated). He found:

$$\text{Electric Force} \propto \frac{1}{\text{Distance squared}} \text{ or } \frac{1}{r^2}$$

For two point charges q_1 and q_2

Electric Force

HW : Sec. 21.1
https://nationalmaglab.org/education/magnet-academy/history-of-electricity-magnetism/museum/torsion-balance-1785

SUMMARY

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Coulomb's Law

The magnitude of the electric force between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between them.

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

where $k = \frac{1}{4\pi\varepsilon_o} = 8.988\times10^9\ \text{N.m}^2/\text{C}^2 \cong 9.0\times10^9\ \text{N.m}^2/\text{C}^2$

and $\varepsilon_o = 8.854\times10^{-12}\ \text{C}^2/\text{N.m}$

HW : Sec. 21.1 Electrostatics, Electricity, Capacitance 4

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Important Points regarding Charge

Charge is quantised (restricted to certain values):

$$q = ne, \qquad n = \pm1, \pm2, \pm3, \ldots$$

Where e is the elementary charge and $e = 1.602 \times 10^{-19}$ C

Charge is Conserved where the PRINCIPLE OF CONSERVATION OF CHARGE is :

The algebraic sum of all electric charges in any closed system is conserved.

HW : Sec. 21.2 and 21.3 Electrostatics, Electricity, Capacitance 5

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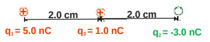
Example

In the diagram below, what is the electric force on q_3?



SOLUTION

HW : Sec. 21.1 Electrostatics, Electricity, Capacitance 6

SUMMARY

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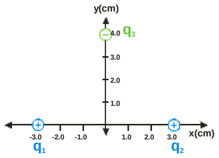
Example

In the diagram below, what is the electric force on q_3 given $q_1 = 2.0 \times 10^{-6}$ C, $q_2 = 2.0 \times 10^{-6}$ C and $q_3 = -4.0 \times 10^{-6}$ C?



HW : Sec. 21.1 Electrostatics, Electricity, Capacitance 7

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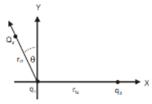
Example

Three charges q_1, q_2 and q_3 are arranged as shown where

$q_1 = -1.0\times10^{-6}$ C $q_2 = +3.0\times10^{-6}$ C $q_3 = -2.0\times10^{-6}$ C

$r_{12} = 0.15$ m $r_{13} = 0.10$ m $\theta = 30°$

What is the force on q_1 due to the other 2 charges?



HW : Sec. 21.1 Electrostatics, Electricity, Capacitance 8

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Example cont….

Three charges q_1, q_2 and q_3 are arranged as shown where

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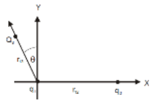

HW : Sec. 21.1 Electrostatics, Electricity, Capacitance 9

SUMMARY

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Electric Field and Electric Forces

How does a charge know the other is there?

>>> Electric Field

Imagine that somehow the charge that a body carries modifies the space around it. Then another body as a result of its charge senses this change. The second body responds by experiencing the force F_0 to this modification.

HW : Sec. 22.1 Electrostatics, Electricity, Capacitance 10

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The modification is the Electric Field (E).

"The electric force on a charged body is exerted by the electric field created by other charged bodies."

Electric field E is defined as the electric force F_0 experienced by a test charge q_0 given by:

$$\vec{E} = \frac{\vec{F}_0}{q_0}$$

Unit: N/C

HW : Sec. 22.1 Electrostatics, Electricity, Capacitance 11

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Rearranging:

$$\vec{F}_0 = \vec{E}q_0$$

If q_0 is positive, the force and field are in the same direction.
If q_0 is negative, the force and field are in opposite directions.
The electric field is directed from positive to negative.

This applies to point charges!!!

Now

$$F_0 = \frac{1}{4\pi\varepsilon_0}\frac{|qq_0|}{r^2} \Rightarrow E = \frac{F_0}{q_0} = \frac{1}{4\pi\varepsilon_0}\frac{|q|}{r^2}$$

HW : Sec. 22.2 Electrostatics, Electricity, Capacitance 12

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As a vector:

$$\overline{E} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}\hat{r}$$

Example

Determine the size of the electric field 2.0 m from a point charge of 3.0 μC.

HW : Sec. 22.2 Electrostatics, Electricity, Capacitance 13

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Example

Determine the electric field at (1.5 m, -2.0 m) from a point charge of q = - 5.0 μC at the origin.

HW : Sec. 22.2 Electrostatics, Electricity, Capacitance 14

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As with Newton's 2nd Law

$$\sum \vec{F} = m\vec{a}$$

$$\vec{F}_0 = \sum \vec{F} = \sum q_0 \vec{E} = q_0 \sum \vec{E}$$

You will see this as 'Principle of Superposition'

What this means is that the electric field owing to a number of charges is additive at a point.

HW : Sec. 22.2 Electrostatics, Electricity, Capacitance 15

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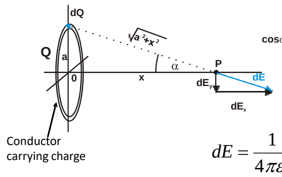
Field of a Ring of Charge

What is the field at point P?



$$\cos\alpha = \frac{x}{\sqrt{a^2+x^2}}$$

$$dE = \frac{1}{4\pi\varepsilon_0}\frac{dQ}{a^2+x^2}$$

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Field of a Ring of Charge

$$dE_x = dE\cos\alpha = \frac{1}{4\pi\epsilon_0}\frac{dQ}{a^2+x^2}\frac{x}{\sqrt{a^2+x^2}} = \frac{1}{4\pi\varepsilon_0}\frac{dQx}{\left(a^2+x^2\right)^{3/2}}$$

$$E_x = \int\frac{1}{4\pi\varepsilon_0}\frac{dQx}{\left(a^2+x^2\right)^{3/2}} = \frac{1}{4\pi\varepsilon_0}\frac{Qx}{\left(a^2+x^2\right)^{3/2}}$$

Giving

$$\overline{E} = E_x\hat{i} = \frac{1}{4\pi\varepsilon_0}\frac{Qx}{\left(a^2+x^2\right)^{3/2}}\hat{i}$$

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Electric Field Lines

Electric field lines are imaginary lines giving the direction of the electric-field vector at that point.

Their spacing gives an indication of the strength of the electric field at that point.

The direction is away from the positive charge and toward the negative charge.

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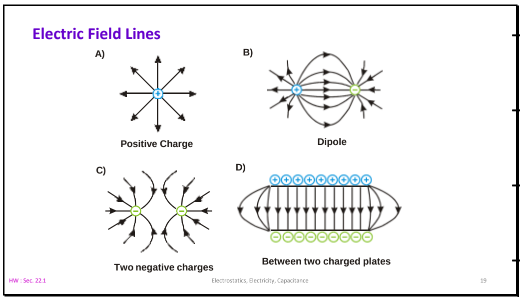

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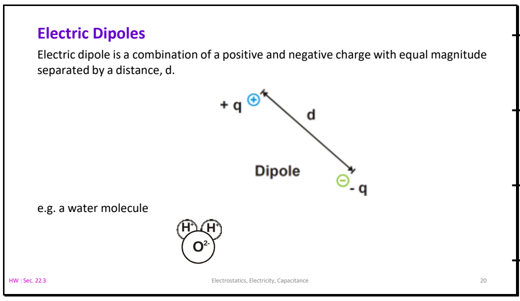

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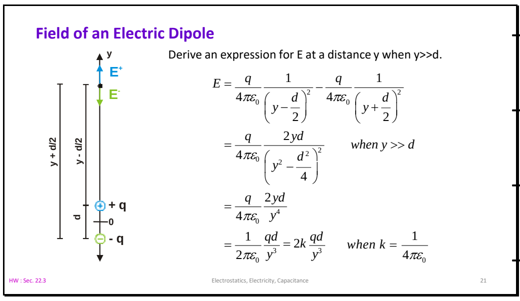

SUMMARY

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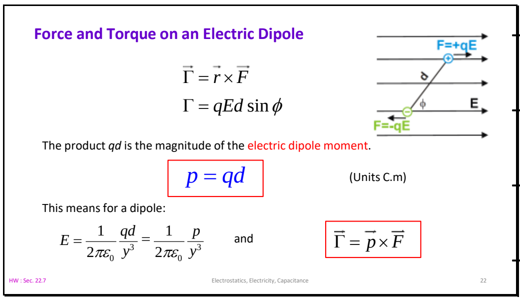

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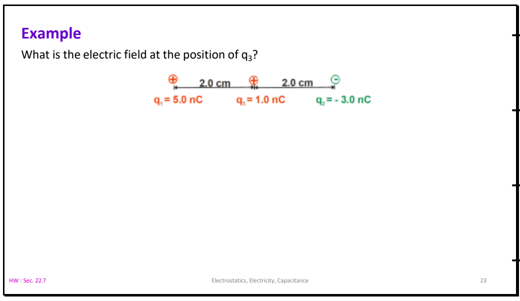

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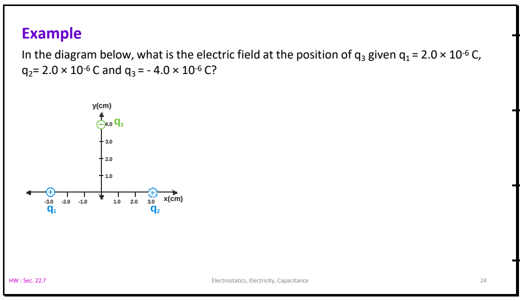

SUMMARY

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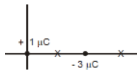
Example

Two charges of +1.00 μC and -3.00 μC are located on the *x*-axis. The positive charge is at the origin, while the negative charge is at *x* = 1.00 m. What is the magnitude and direction of the electric field due to these charges at a) *x*=0.50m and b) *x*=1.50m?



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Electric Potential

These lectures slides were prepared by
Dr. Danica Solina

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Review

First

$$W_{a\to b} = \int_a^b \vec{F}\bullet d\vec{l} = \int_a^b F\cos\phi\, dl$$

This is work done by a force.

Second

$$W_{a\to b} = U_a - U = -(U_b - U_a) = -\Delta U$$

For work done by a conservative force.

Third

$$K_a + U_a = K_b + U_b$$

Work-energy theorem when work is done by a conservative force i.e. total energy is conserved.

SUMMARY

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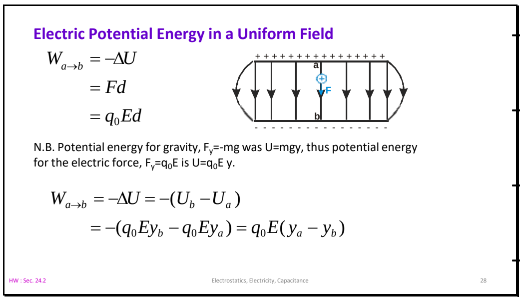

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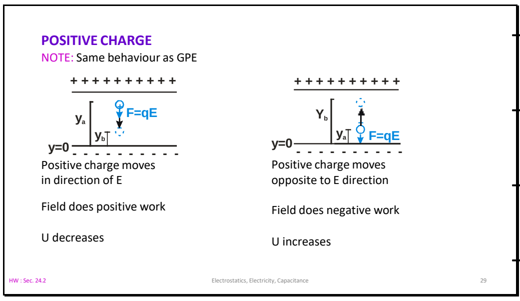

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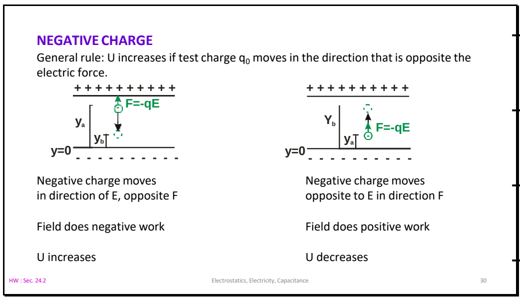

SUMMARY

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The presence of q and q_0!

Remember a field exists in the presence of a charge and the effect on another charge is an electric force $F_0=q_0E$.

The potential energy, U, when the test charge, q_0 is any distance r from q is then:

$$U = \frac{1}{4\pi\varepsilon_0}\frac{qq_0}{r}$$

Units: Joules (J)

HW : Sec. 24.7 Electrostatics, Electricity, Capacitance 31

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Electric Potential (V)

Potential is potential energy per unit charge.

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

Unit: Volt, V or J/C

Potential energy and charge are scalars, therefore potential is a scalar quantity.

N.B. Whereas potential is a property of the field, potential energy is the energy of a charged object in the field.

HW : Sec. 24.7 Electrostatics, Electricity, Capacitance 32

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Work done

Now work done by an electric force from a to b is $-\Delta U=-(U_b-U_a)$, then the work per unit charge is:

$$\frac{W_{a\to b}}{q_0} = \frac{-\Delta U}{q_0} = -\left(\frac{U_b}{q_0} - \frac{U_a}{q_0}\right) = -(V_b - V_a)$$

$$\frac{W_{a\to b}}{q_0} = V_a - V_b$$

This gives the potential of a w.r.t b.

Equals the work done to move a UNIT charge slowly from b to a against the electric force.

HW : Sec. 24.7 Electrostatics, Electricity, Capacitance 33

SUMMARY

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Calculating electric potential

Potential due to a point charge

$$V = \frac{U}{q_0} = \frac{1}{4\pi\varepsilon_0}\frac{q}{r} \quad or \quad V = \frac{F \times d}{q_0} = E \times d$$

Due to a collection of point charges

$$V = \frac{U}{q_0} = \frac{1}{4\pi\varepsilon_0}\sum \frac{q_i}{r_i}$$

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Some useful notes

Unit of electric field:

1 N/C = 1 V/m

Electron Volts (eV)

Uses magnitude of electron charge to define a useful unit of energy. If V_{ab}=1 V then:

$$U_a - U_b = qV_{ab} = 1.602\times10^{-19}\times1 = 1.602\times10^{-19}\,J$$
$$\Rightarrow \quad 1.602\times10^{-19}\,J = 1eV$$

THIS IS A UNIT OF ENERGY NOT POTENTIAL!!!!

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Example

Calculate the electric potential of a charge of 5.0 µC experiencing a force of 3.0 N over 2.0m.

SUMMARY

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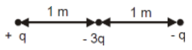
Example

Find the work done in assembling the charges as illustrated



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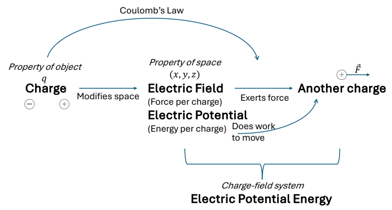

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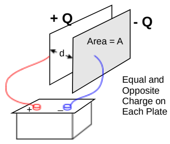
Capacitor

Used in a variety of electric circuits:

- to tune the frequency of the radio receivers,
- Slow a circuit response so it doesn't pick up noise,
- store short term energy for rapid release in electronic flash units.

Configuration:

Two parallel plates of area, A, are separated by a distance 'd'. In an electric circuit, plates are connected to the terminals of a battery. Electrons are pulled off one plate transferred through the battery and deposited on the other leaving it with charge – Q. Transfer stops when the potential difference is the same as that from the battery.



SUMMARY

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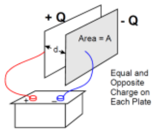
Capacitance, C, of a capacitor

Ratio of the magnitude of the charge on either conductor to the potential difference between the conductors:

$$C_0 = \frac{Q_0}{\Delta V_0} = \varepsilon_0 \frac{A}{d}$$



C = capacitance (farad (F)
= colomb per volt (C/V).
Q = charge (colombs, C)
ΔV = Potential Difference (volts, V)
ε_0 =permittivity of free space = 8.85×10^{-12} $C^2/N{\cdot}m^2$
A = area (m^2)
d = distance between the slides (m)

HW : Sec. 25.1 Electrostatics, Electricity, Capacitance 40

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Dielectric Material and the Dielectric Constant, κ

A dielectric is an insulating material. When it is inserted between the plates the capacitance increases and we have:

$$C = \kappa\varepsilon_0 \frac{A}{d} = \kappa \frac{Q_0}{\Delta V_0} = \kappa C_0$$

κ = relative permittivity of dielectric material between the plate

Material	Dielectric constant, κ	Material	Dielectric constant, κ
Air	1.00059	Pyrex® glass	5.6
Bakelite®	4.9	Silicone Oil	2.5
Fused Quartz	3.78	Strontium titanate	233
Neoprene rubber	6.7	Teflon®	2.1
Nylon	3.4	Vacuum	1.00000
Paper	3.7	Water	80
Polystyrene	2.56		

HW : Sec. 25.1 Electrostatics, Electricity, Capacitance 41

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Example

Nerve cell walls in the human body have a double layer of surface charge, with a layer of negative charge inside the wall and a layer of positive charge of equal magnitude on the outside. Assume that the surface area of the cell is 25 μm^2, the cell wall is 5.0×10^{-9} m thick with a dielectric constant of 6.
If the potential across the cell is 55 mV, calculate,

a) the magnitude of the electric field in the wall between the two charge layers

b) the capacitance of the cell wall

c) the charge on the cell wall

Electrostatics, Electricity, Capacitance 42

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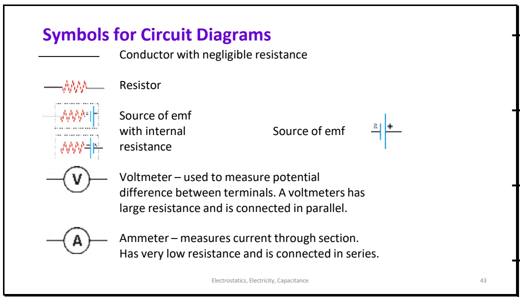

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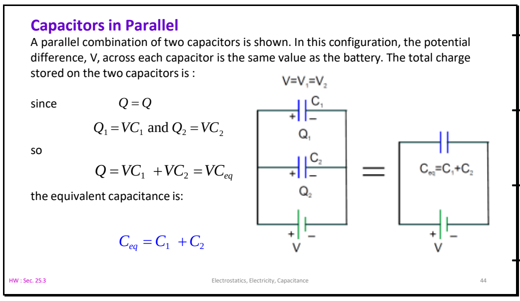

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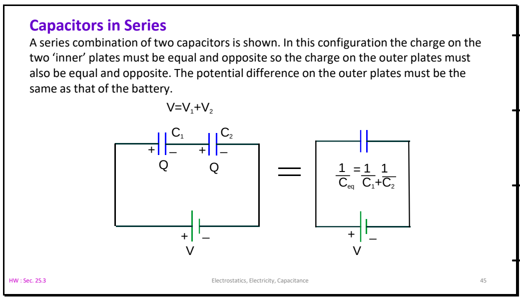

SUMMARY

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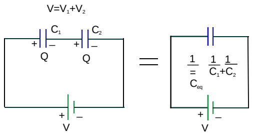
Capacitors in Series

Since

$$V_1 = \frac{Q}{C_1} \text{ and } V_2 = \frac{Q}{C_2}$$

then



$$V = V_1 + V_2 \text{ then } \frac{Q}{C_{eq}} = \frac{Q}{C_1} + \frac{Q}{C_2}$$

the equivalent capacitance, C_{eq}, can be found from:

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2}$$

HW : Sec. 25.3 Electrostatics, Electricity, Capacitance 46

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Summary Equivalent Capacitance:

The equivalent capacitance for capacitors in parallel is the sum of the individual capacitances:

$$C_{eq} = C_1 + C_2 + C_3 + ...$$

The equivalent capacitance for capacitors in parallel is always greater than any individual capacitance.

For capacitors in series, the INVERSE of the equivalent capacitance is the sum of the inverses of the individual capacitances:

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + ...$$

The equivalent capacitance for capacitors in series is always smaller than any individual capacitance.

HW : Sec. 25.3 Electrostatics, Electricity, Capacitance 47

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Example

Two capacitors of value 12.5 μF and 8.8 μF are connected a) in parallel and then b) in series. Calculate the effective capacitance of each arrangement, the charge and voltage drop on each capacitor when connected to a 16.0 V source.

HW : Sec. 25.4 Electrostatics, Electricity, Capacitance 48

SUMMARY

QUESTIONS NOTES

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Example cont…..

Two capacitors of value 12.5 μF and 8.8 μF are connected a) in parallel and then b) in series. Calculate the effective capacitance of each arrangement, the charge and voltage drop on each capacitor when connected to a 16.0 V source.

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Example

A potential difference of 300 V is applied to a 2.0 mF and an 8.0 mF capacitor in series. Find the charge and the potential difference for each capacitor.

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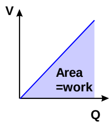
Stored Energy on a Capacitor

We know:

$$V = \frac{W}{Q} \Rightarrow W = VQ$$

Plotting V versus Q gives a straight line. The area under the line is the work done to fill the capacitor with charge or energy stored on the capacitor. It is a triangle.



Work: $\text{Area } \Delta = \frac{1}{2}\text{Base}\times\text{Height}$

$$W = \frac{1}{2}QV$$

SUMMARY

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Stored Energy on a Capacitor

From

$$W = \frac{1}{2}QV \quad \text{and} \quad V = \frac{Q}{C}$$

Energy stored:

$$Energy\ Stored = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{Q^2}{2C}$$

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Example

Three capacitors having capacitances of 10.0 µF, 10.0 µF, and 6.0 µF are connected in series across a 20-volt line.

a. Calculate the charge on the 6.0 µF capacitor.
b. Calculate the total energy of all three capacitors.

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Example cont….

The capacitors are disconnected from the line and reconnected in parallel with the positively charged plates connected together.

c. Calculate the voltage of the new combination.
d. Calculate the energy stored in the combination.

SUMMARY

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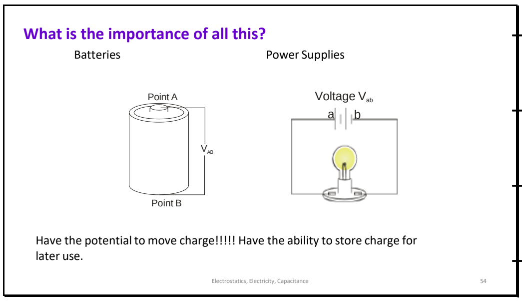

SUMMARY