Devil Physics
The Baddest Class on Campus

IB Physics

LSN 11-3: CAPACITANCE

Questions From Reading Activity?

Essential Idea:

- Capacitors can be used to store electrical energy for later use.

Nature Of Science:

- Relationships: Examples of exponential growth and decay pervade the whole of science. It is a clear example of the way that scientists use mathematics to model reality.
- This topic can be used to create links between physics topics but also to uses in chemistry, biology, medicine and economics.

International-Mindedness:

- Lightning is a phenomenon that has fascinated physicists from Pliny through Newton to Franklin. The charged clouds form one plate of a capacitor with other clouds or Earth forming the second plate. The frequency of lightning strikes varies globally, being particularly prevalent in equatorial regions. The impact of lightning strikes is significant, with many humans and animals being killed annually and huge financial costs to industry from damage to buildings, communication and power transmission systems, and delays or the need to reroute air transport.

Understandings:

- Capacitance
- Dielectric materials
- Capacitors in series and parallel
- Resistor-capacitor (RC) series circuits
- Time constant

Applications And Skills:

- Describing the effect of different dielectric materials on capacitance
- Solving problems involving parallel-plate capacitors
- Investigating combinations of capacitors in series or parallel circuits
- Determining the energy stored in a charged capacitor

Applications And Skills:

- Describing the nature of the exponential discharge of a capacitor
- Solving problems involving the discharge of a capacitor through a fixed resistor
- Solving problems involving the time constant of an RC circuit for charge, voltage and current

Guidance:

- Only single parallel-plate capacitors providing a uniform electric field, in series with a load, need to be considered (edge effect will be neglected)
- Problems involving the discharge of capacitors through fixed resistors need to be treated both graphically and algebraically
- Problems involving the charging of a capacitor will only be treated graphically
- Derivation of the charge, voltage and current equations as a function of time is not required

Data Booklet Reference:

- $C = \frac{q}{V}$
- $C_{parallel} = C_1 + C_2 + \cdots$
- $\frac{1}{C_{series}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots$
- $C = \varepsilon \frac{A}{d}$
- $E = \frac{1}{2} C V^2$
- $\tau = RC$
- $q = q_0 e^{-\frac{t}{\tau}}$
- $I = I_0 e^{-\frac{t}{\tau}}$
- $V = V_0 e^{-\frac{t}{\tau}}$

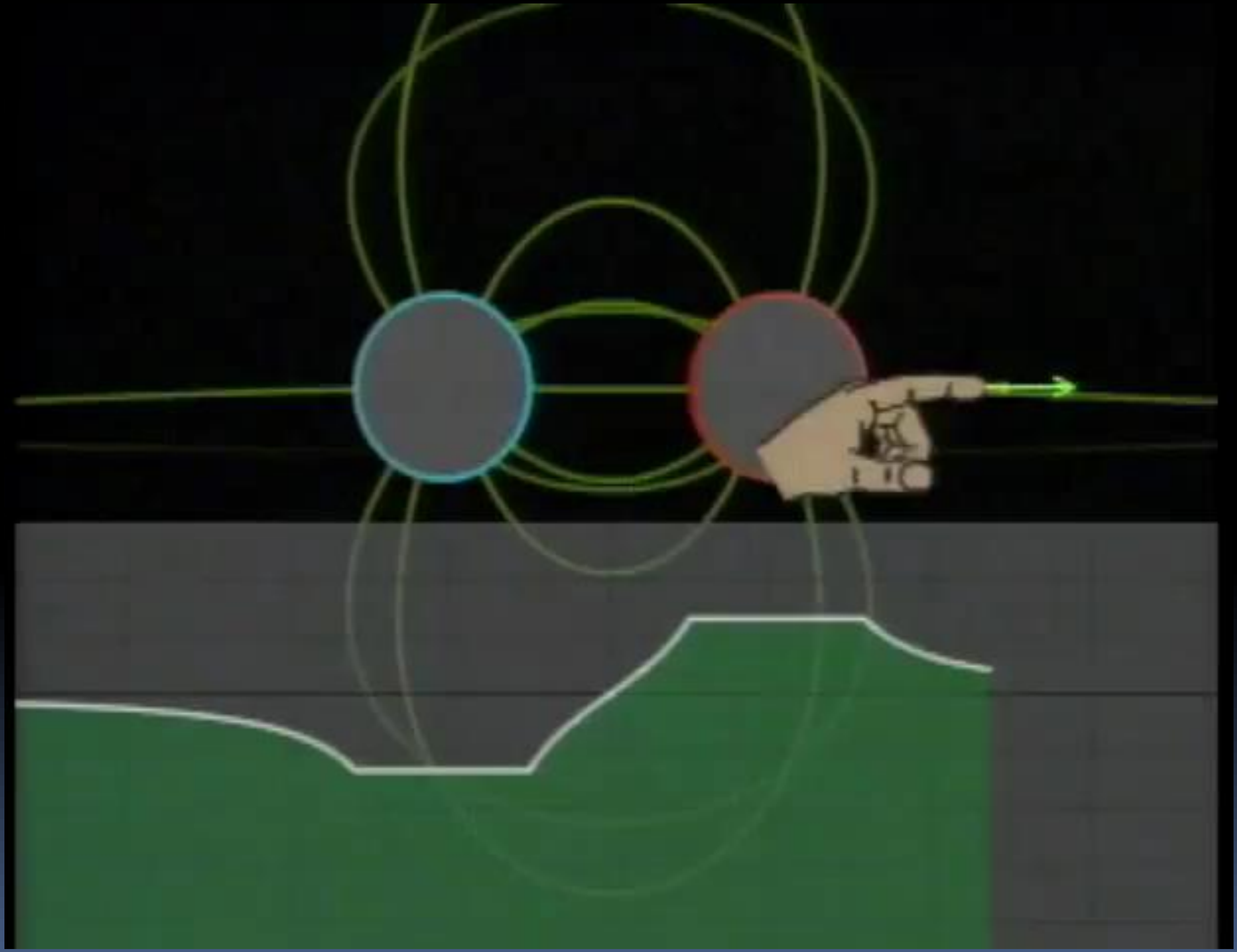
Utilization:

- The charge and discharge of capacitors obeys rules that have parallels in other branches of physics including radioactivity.

Aims:

- Aim 3: the treatment of exponential growth and decay by graphical and algebraic methods offers both the visual and rigorous approach so often characteristic of science and technology.
- Aim 6: experiments could include (but are not limited to): investigating basic RC circuits; using a capacitor in a bridge circuit; examining other types of capacitors; verifying time constant.

Introductory Video

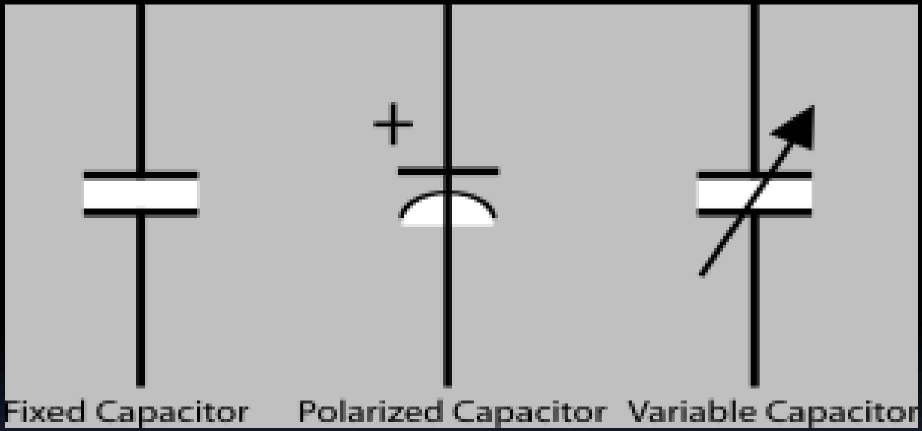


Capacitor

- Two conductors separated by a vacuum or by insulating material
- The reason why
  - When a camera stops whining, it is ready to release a really bright flash
  - Reason why a light stays on for a while then fades out after a device is turned off

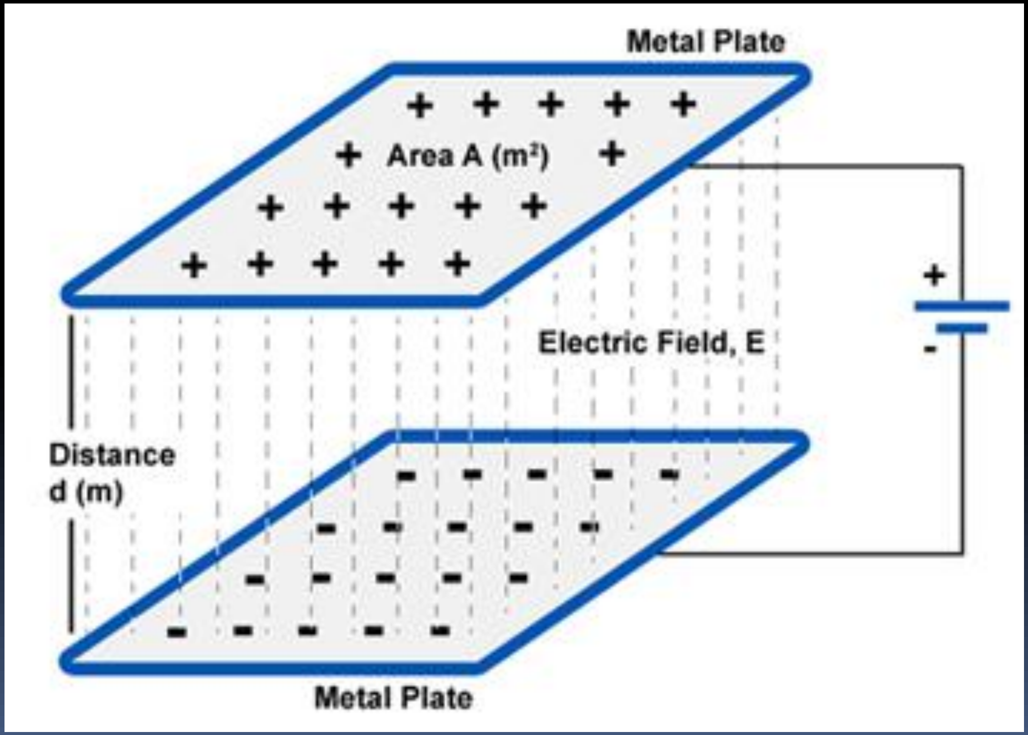
Capacitor

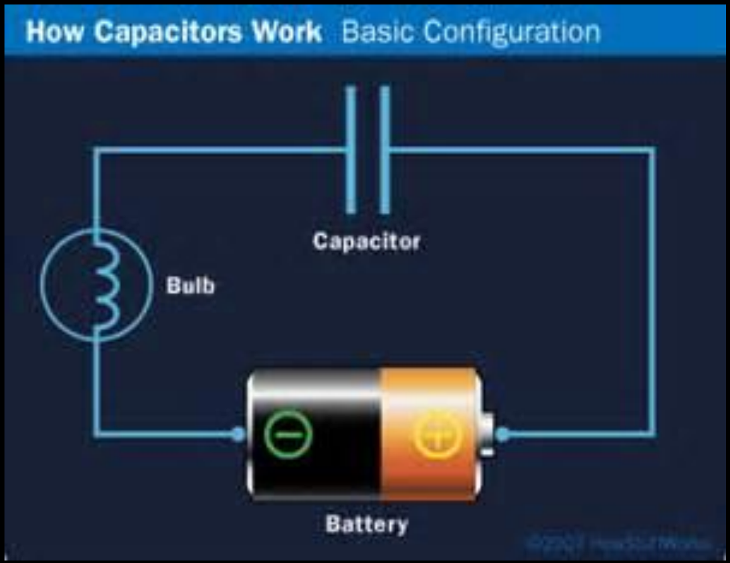
- Symbols and Forms



Capacitor

- Parallel Plate Capacitor





Capacitor

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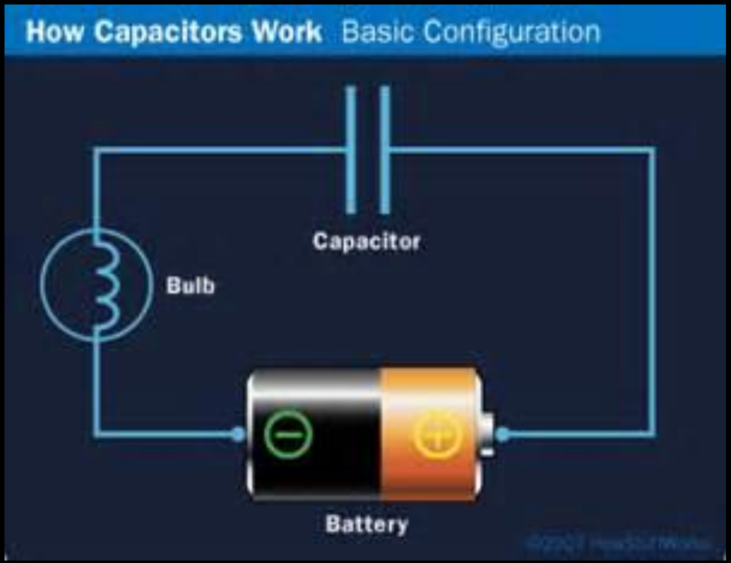
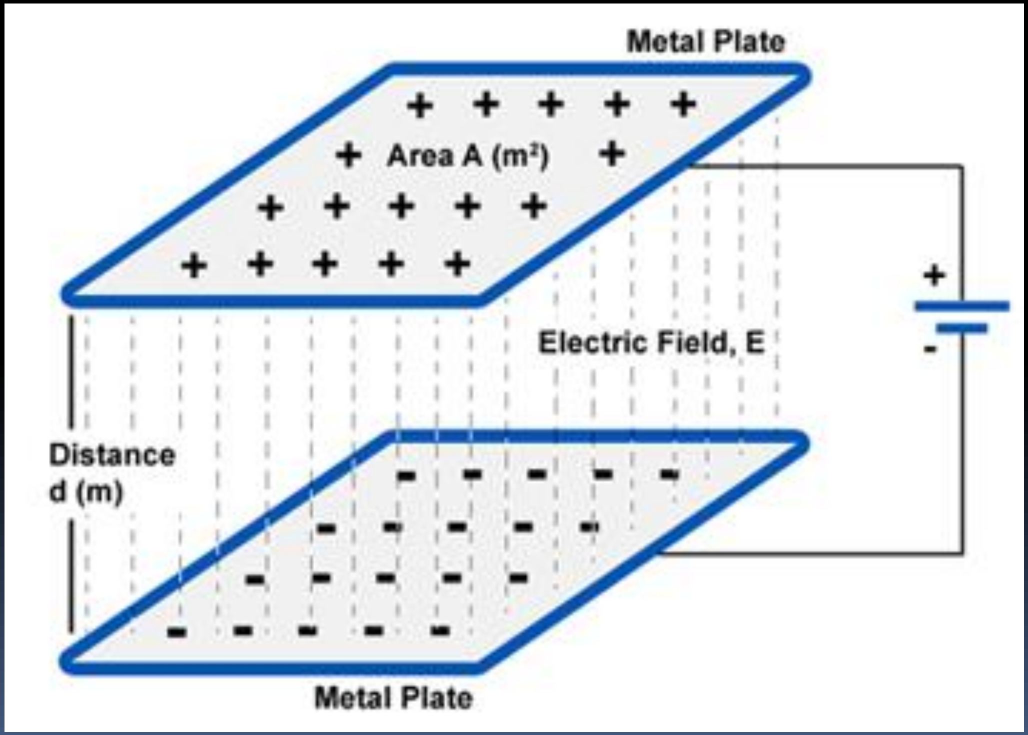


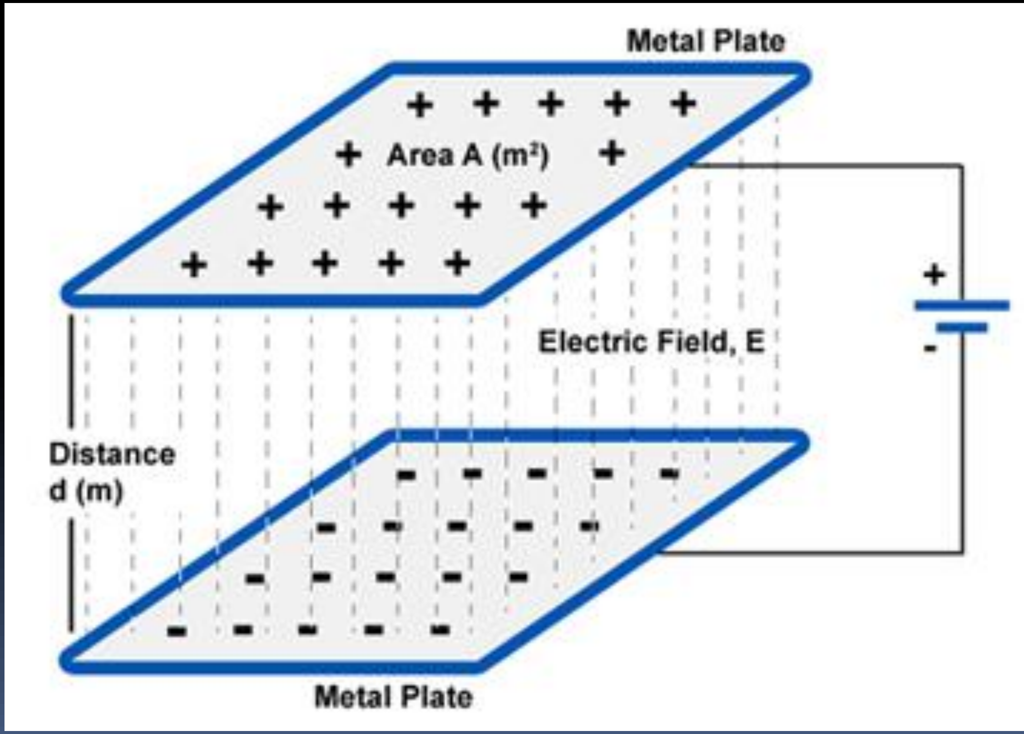


We assume the electric field between the plates is uniform with no edge effects.

Capacitor

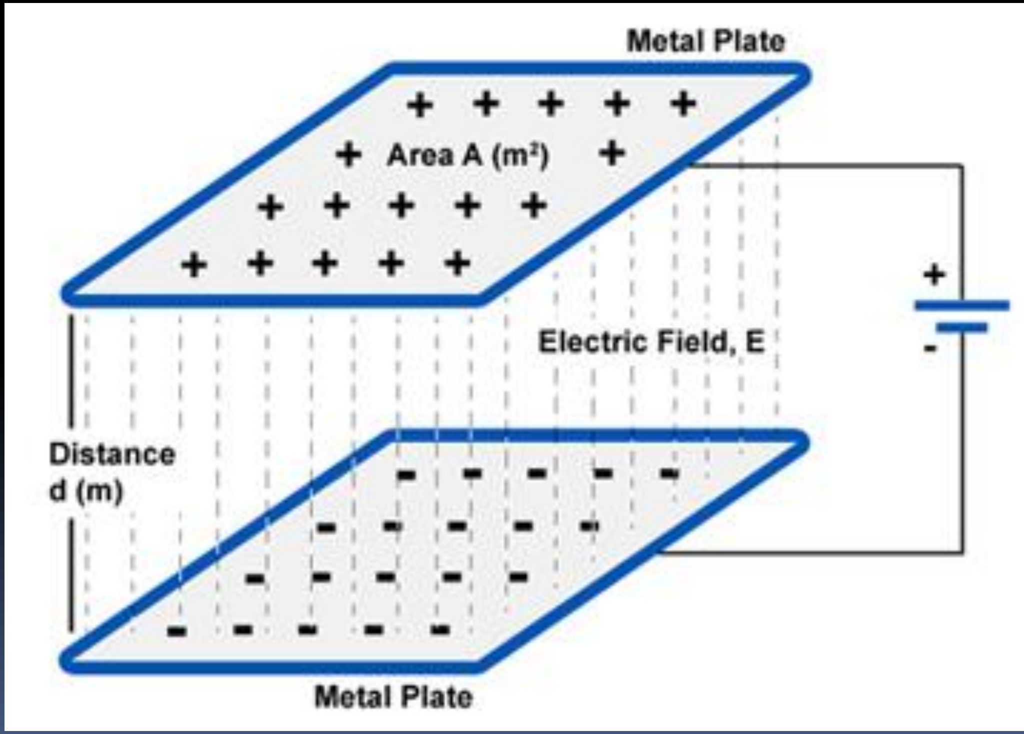
- Parallel Plate Capacitor

TOK Question: If we connect the capacitor to a 12-V battery, how much charge accumulates?



Capacitor

- Parallel Plate Capacitor



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TOK Answer: It depends

Capacitor

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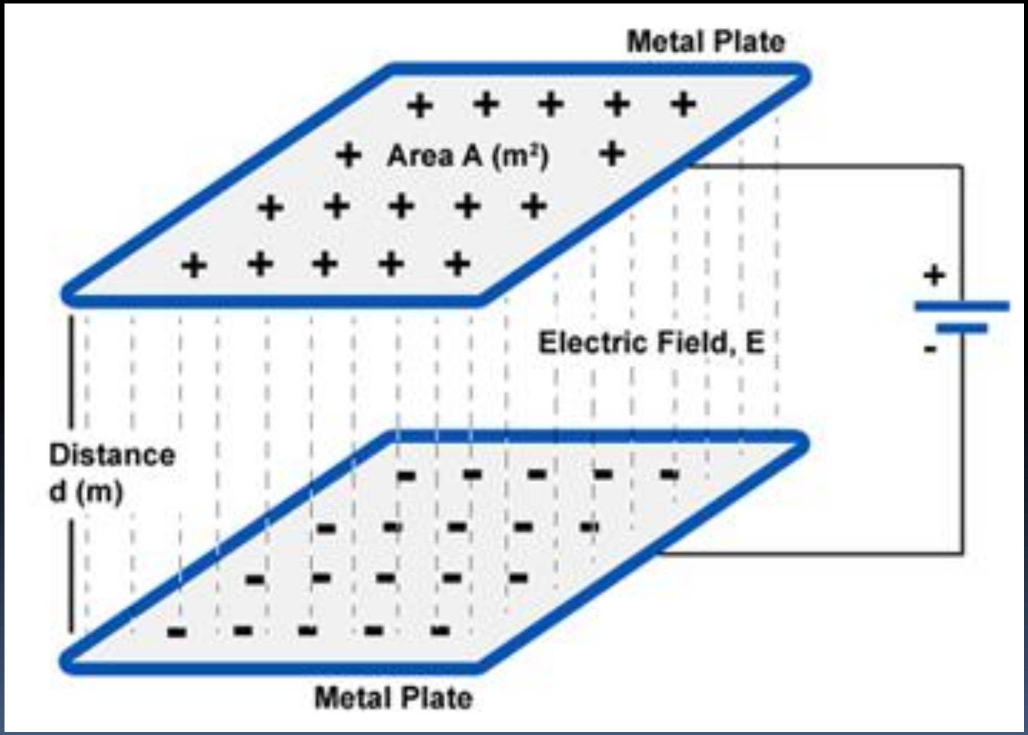

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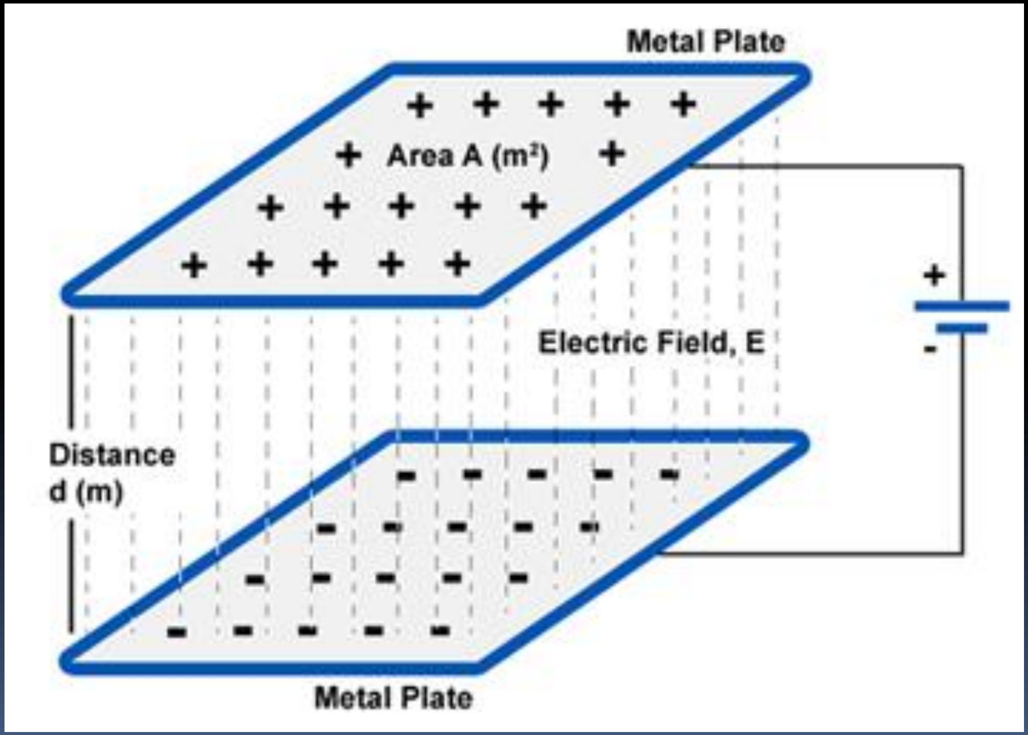
TOK Answer: It depends

Physics Question: On what?

Capacitor

- Parallel Plate Capacitor



TOK Question: If we connect the capacitor to a 12-V battery, how much charge accumulates?

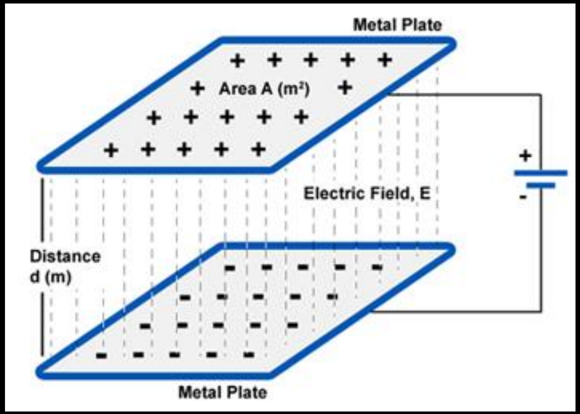
TOK Answer: It depends

Physics Question: On what?

Physics Answer: Capacitance

Capacitance

- Charge per unit voltage that can be stored on a capacitor



$$C = \frac{q}{V}$$

  - q = charge
  - V = potential difference between the plates
  - Unit is the farad, 1F = 1C/V

Capacitance

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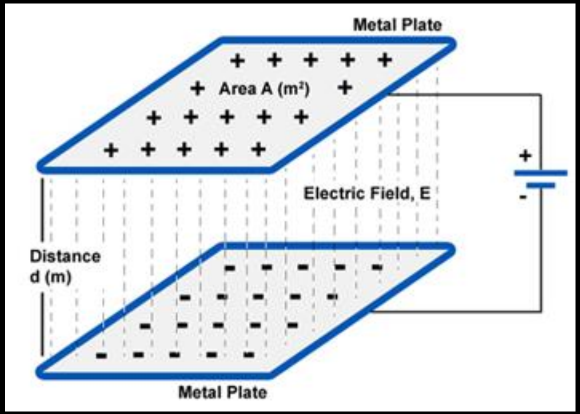

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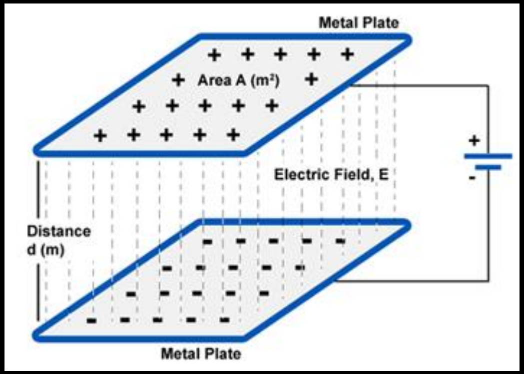
Capacitance

- Capacitance depends on the geometry of the capacitor

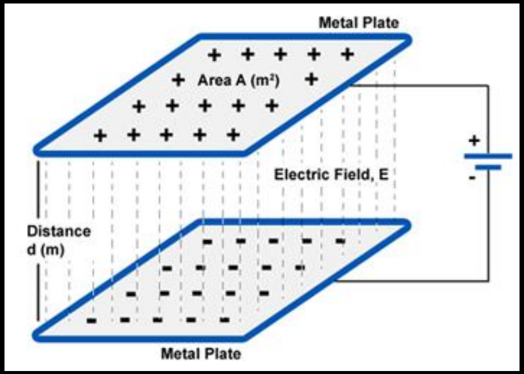


$$C = \epsilon \frac{A}{d}$$

  - ε = permittivity of the medium between the plates (for a vacuum, ε_o = 8.85 x 10^{-12} F/m)
  - *A* = area of ***one*** of the plates
  - *d* = separation of the plates

Capacitance

- Capacitance depends on the geometry of the capacitor



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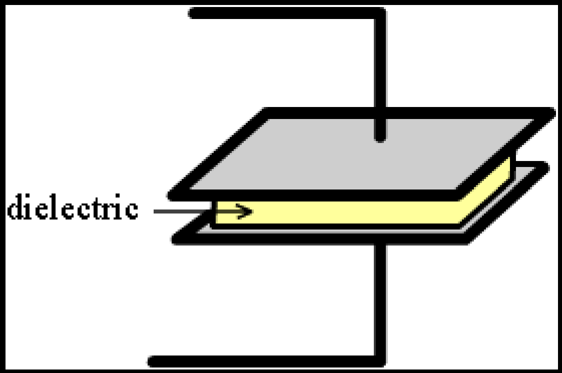
Effect of Dielectric

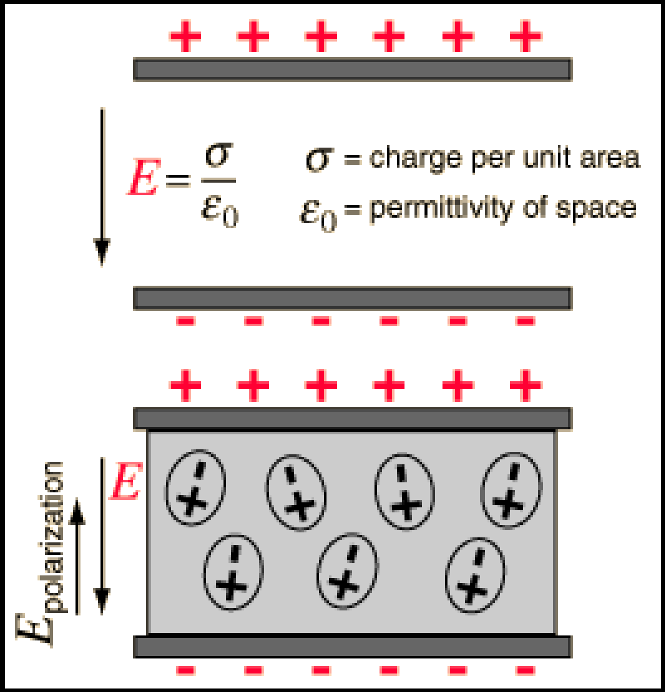
- Dielectric is an insulating material placed between the two plates
- Since the permittivity of an insulator is greater than that of a vacuum ($\varepsilon > \varepsilon_o$) the capacitance with a dielectric is greater than one with a vacuum



$$C = \epsilon \frac{A}{d}$$

Effect of Dielectric

- The electric field will cause ***charge polarization*** of the dielectric material
  - Unlike charges attract
- This creates a small electric field within the dielectric material that reduces the net field strength of the capacitor in comparison to the vacuum capacitor

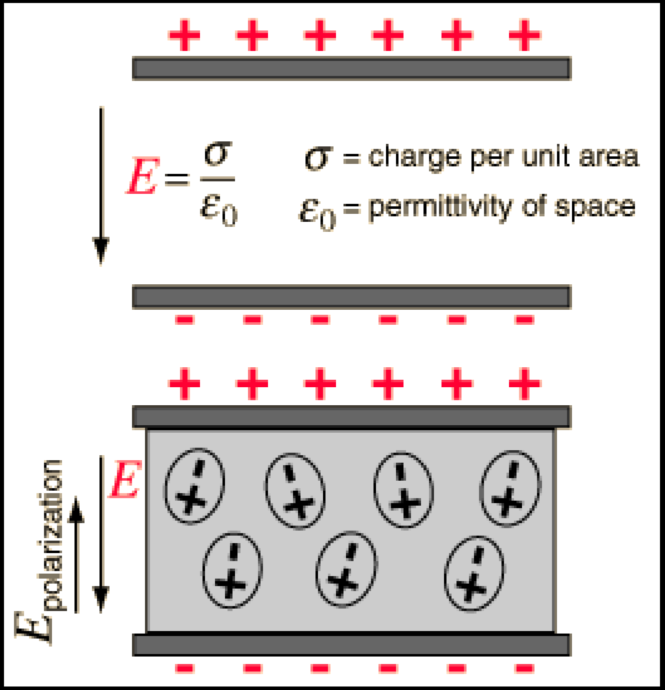


Effect of Dielectric

- Work done to move a charge ***q*** from one plate to another is,

$$W = Fd = qEd$$

  - Since ***E*** is reduced with a dielectric, work done is also reduced
  - Work is also, $W = qV$
  - This implies that potential, ***V***, also decreases with a dielectric

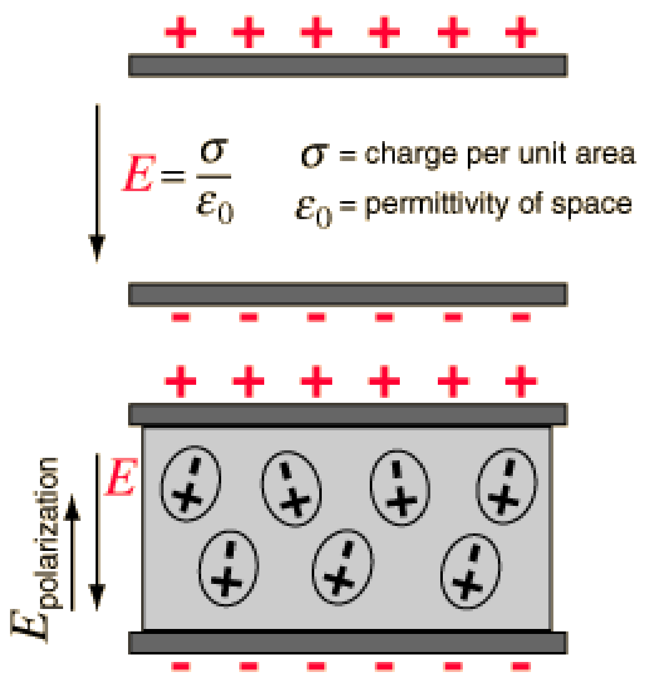


Effect of Dielectric

- Since potential, ***V***, decreases with a dielectric and

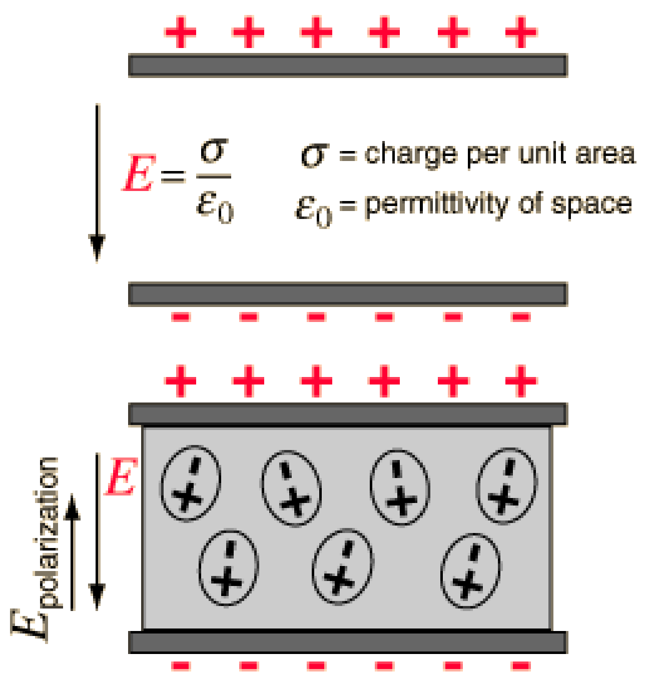
$$C = \frac{q}{V}$$

- Then capacitance increases



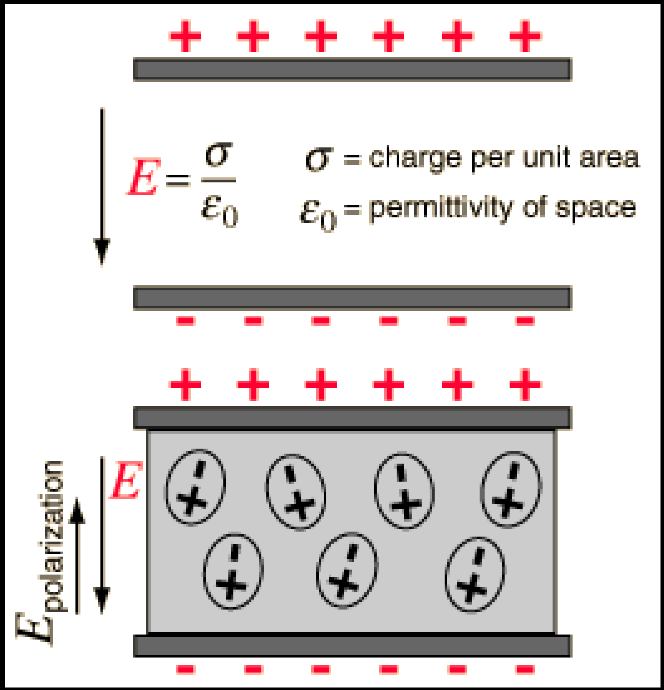
Effect of Dielectric

- Now consider a situation where the capacitors are connected to a power supply (like a battery) where the potential is constant
  - Since $W = qV$
  - Work is constant
  - Since $W = qEd$
  - The ***net*** electric fields must be equal



Effect of Dielectric

- Now consider a situation where the capacitors are connected to a power supply (like a battery) where the potential is constant
  - Since the dielectric capacitor has an increased charge ***q***, it follows that its capacitance is also increased



$$W = qV$$

$$C = \frac{q}{V}$$

$$W = qEd$$

Capacitors in Parallel

- If two of the same capacitors are wired in parallel and connected to a voltage source, V, then the voltage drop across each capacitor is the same

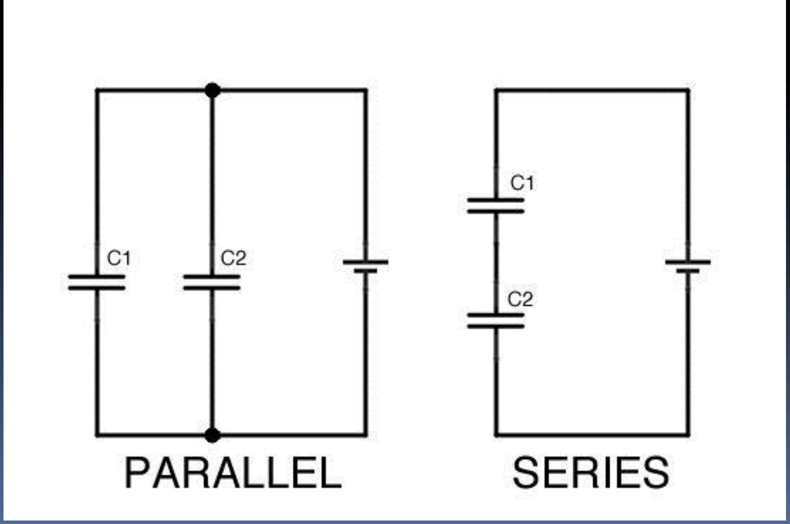
$$C = \frac{q}{V}$$

$$q_1 = C_1 V$$

$$q_2 = C_2 V$$

$$q = q_1 + q_2 = (C_1 + C_2)V$$

$$C_{parallel} = C_1 + C_2 + \ldots$$



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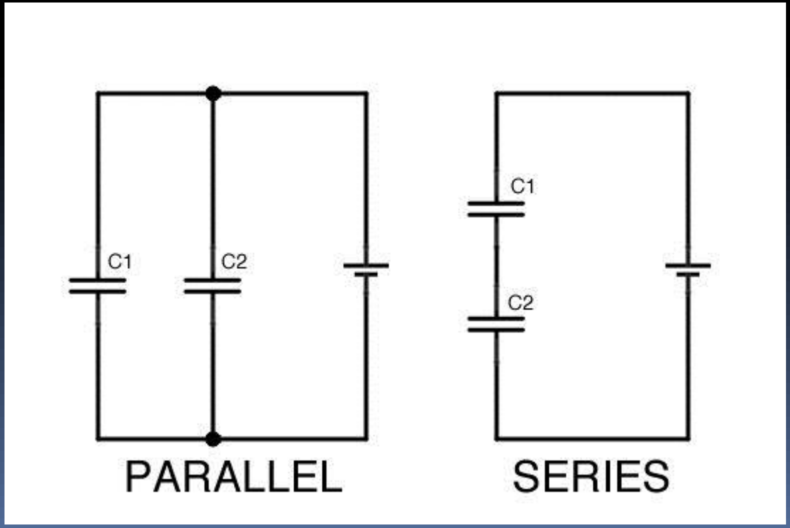
Just the opposite of resistors!



Capacitors in Series

- In a series circuit, the sum of the voltage drops across each component is equal to the voltage source

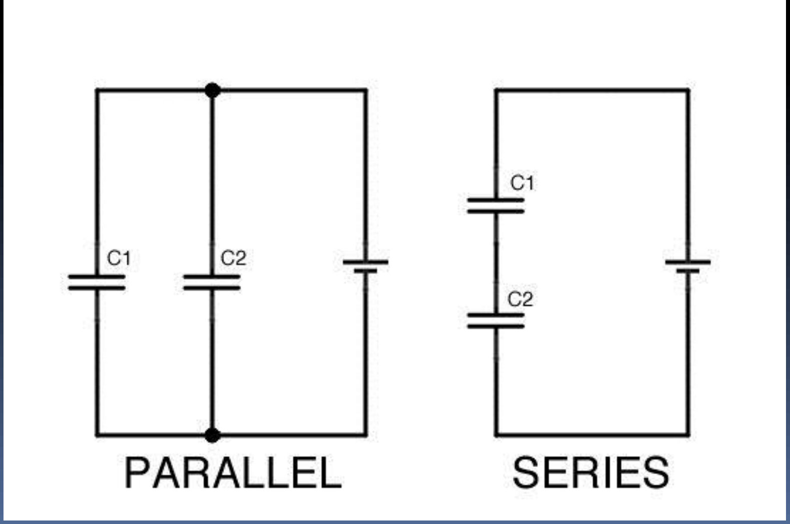
$$V = V_1 + V_2$$

$$C = \frac{q}{V}$$

$$V = \frac{q}{C}$$

$$V = \frac{q}{C_1} + \frac{q}{C_2} = q\left(\frac{1}{C_1} + \frac{1}{C_2}\right)$$

$$C_{series} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots$$



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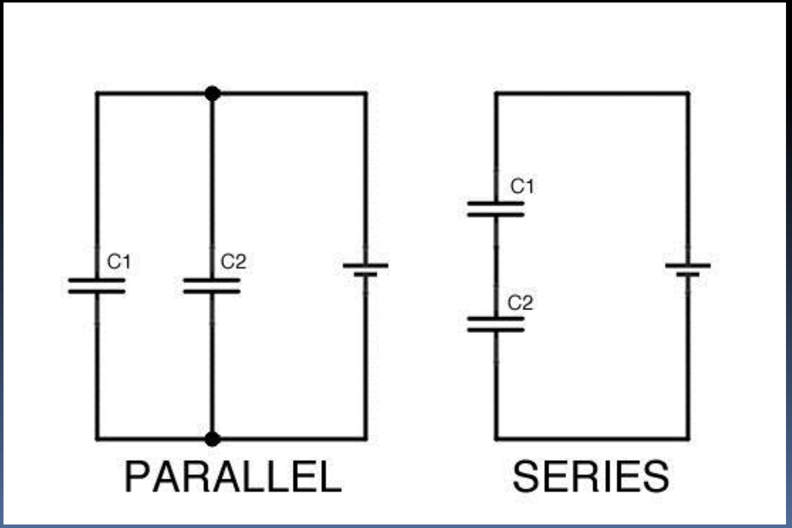

Energy Stored in a Capacitor

- Think of the energy stored in a capacitor as being equal to the work required to move a charge from one plate to the other
- Through calculus, this becomes

$$W = E = \frac{q^2}{2C} = \frac{1}{2}CV^2 = \frac{1}{2}qV$$

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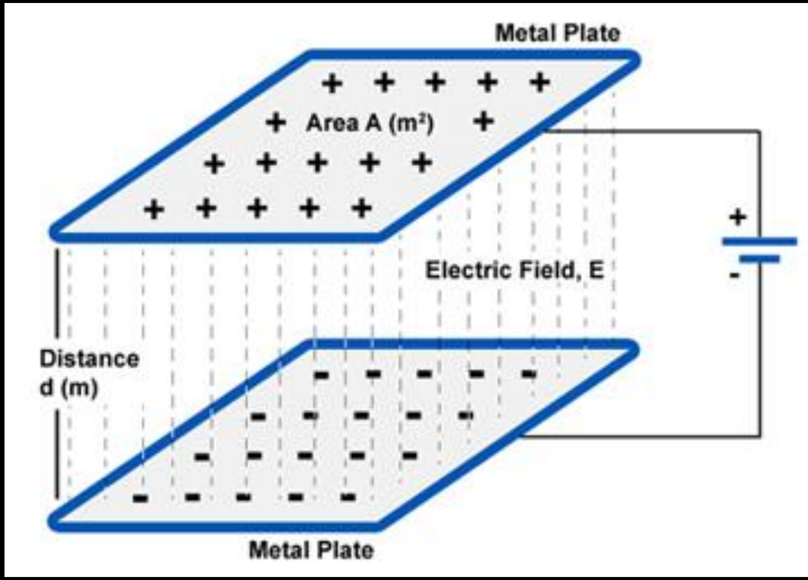
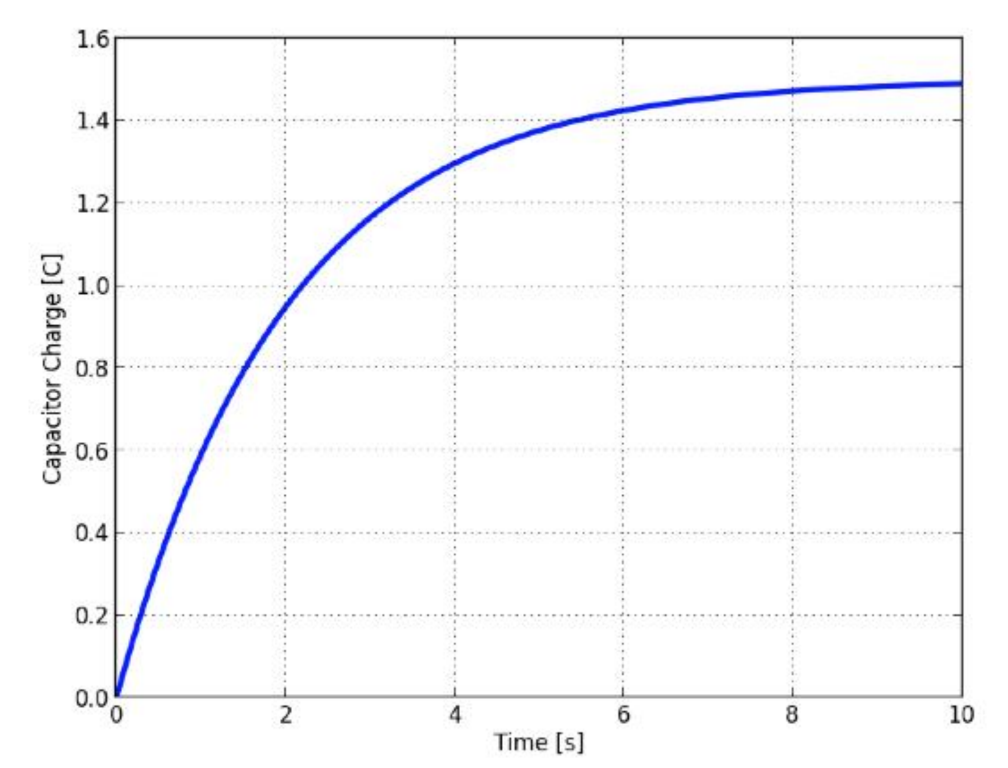
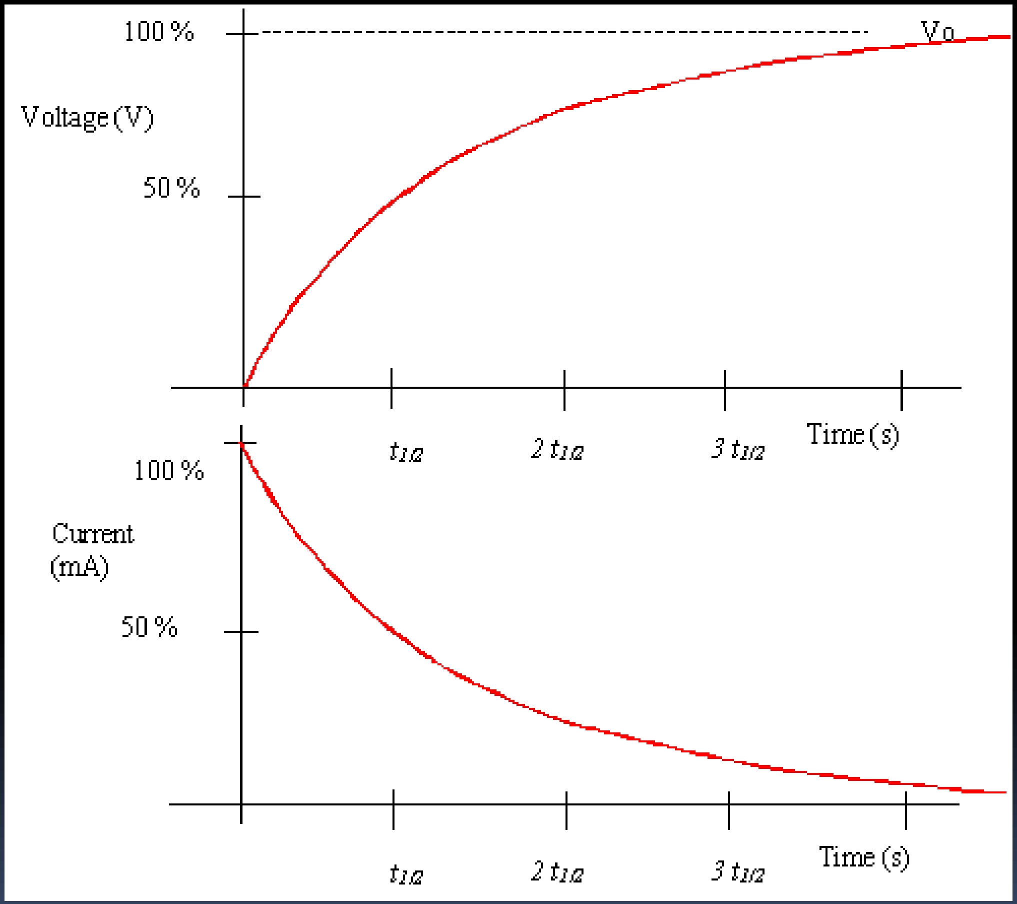
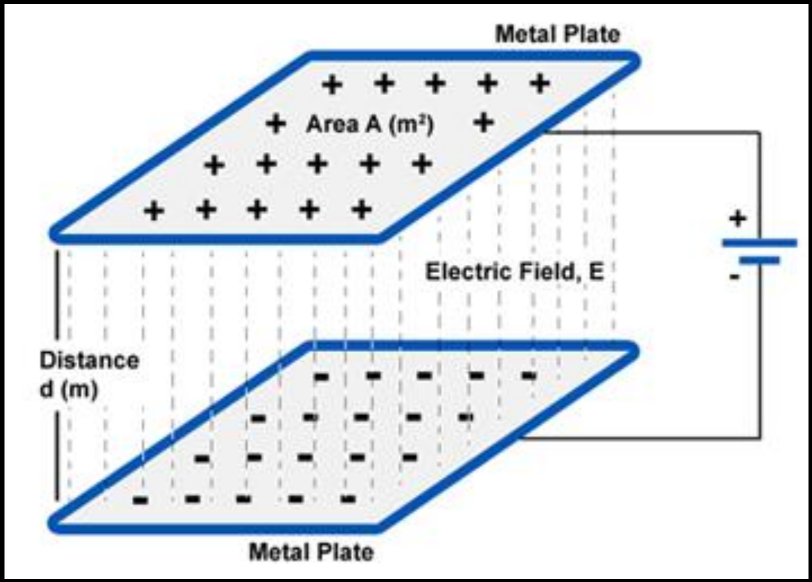
Charging a Capacitor

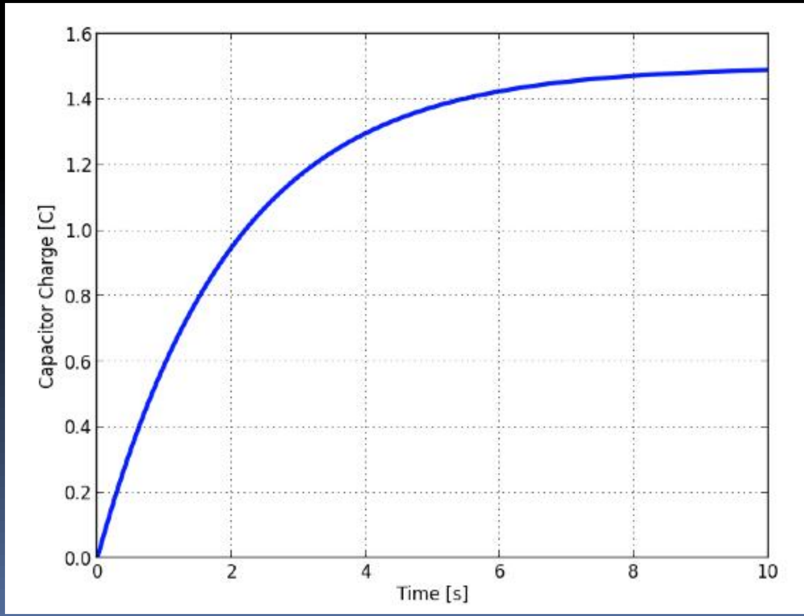




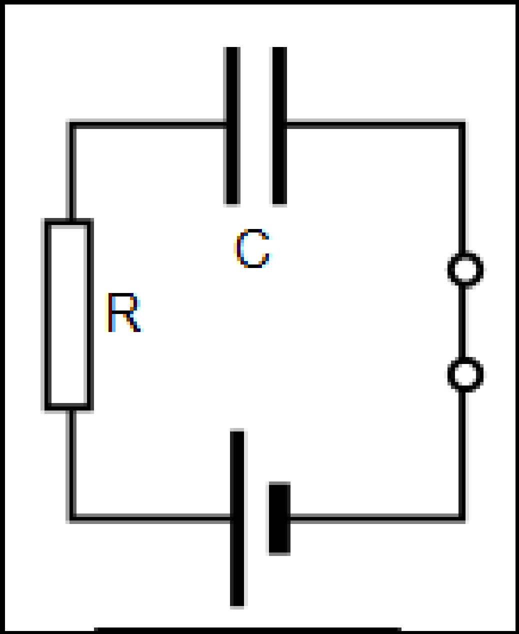
Charging a Capacitor







Discharging a Capacitor through a Resistor (RC circuit)

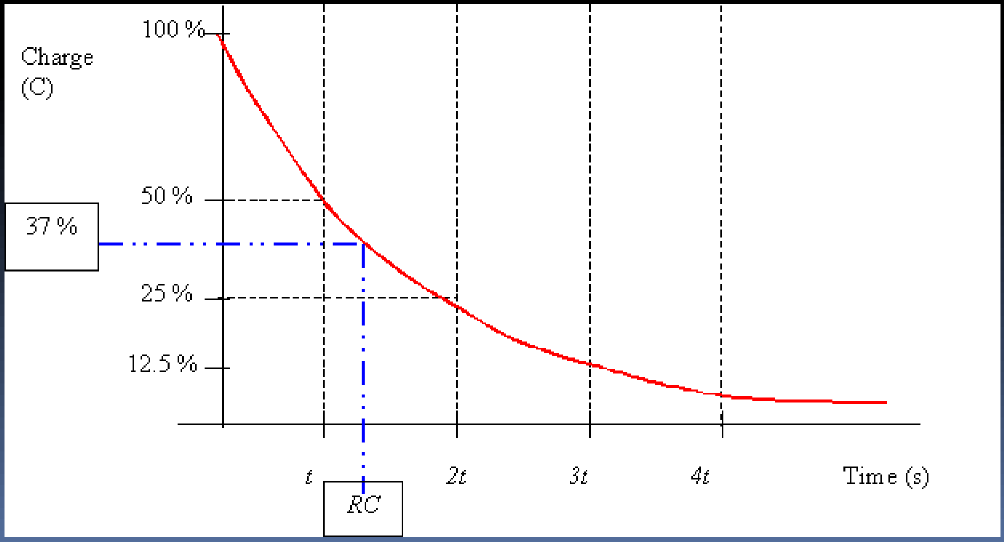


- As seen by the graph, the discharge rate is an exponential decay function represented by

$$q = q_0 e^{-\frac{t}{RC}}$$

$$V = V_0 e^{-\frac{t}{RC}}$$

  - ***R*** = resistance
  - ***C*** = capacitance



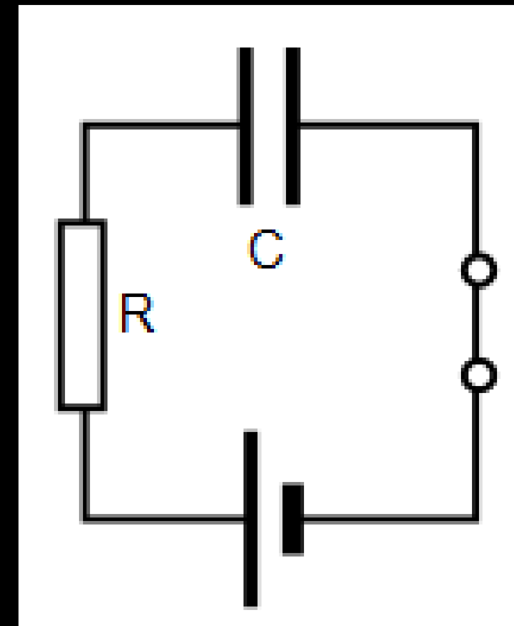
Discharging a Capacitor through a Resistor (RC circuit)

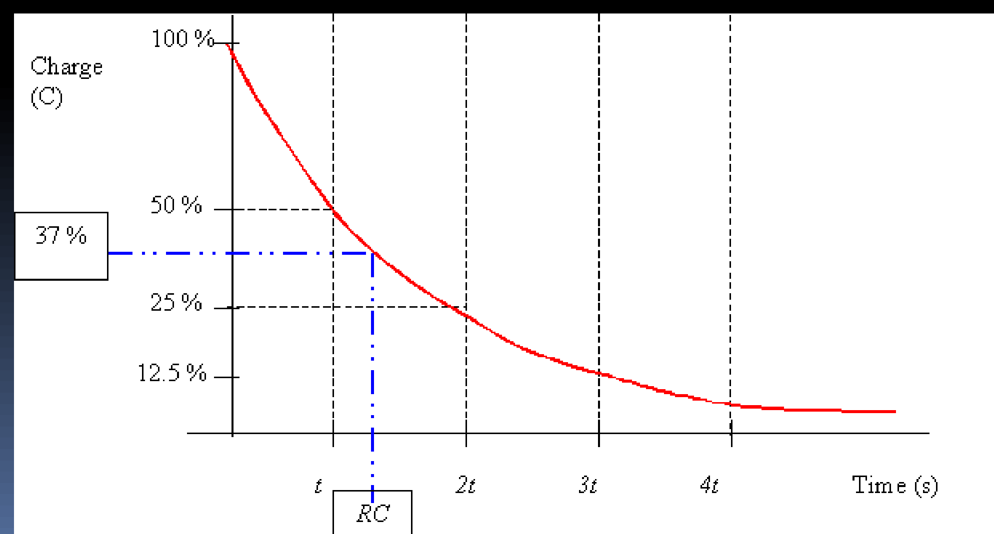
- The quantity ***RC*** is called the ***time constant*** and is given the variable ***τ***
- Time constant determines time scale for discharge
  - Large = long time
  - Small = short time

$$\tau = RC$$

$$q = q_0 e^{-\frac{t}{\tau}}$$

$$V = V_0 e^{-\frac{t}{\tau}}$$



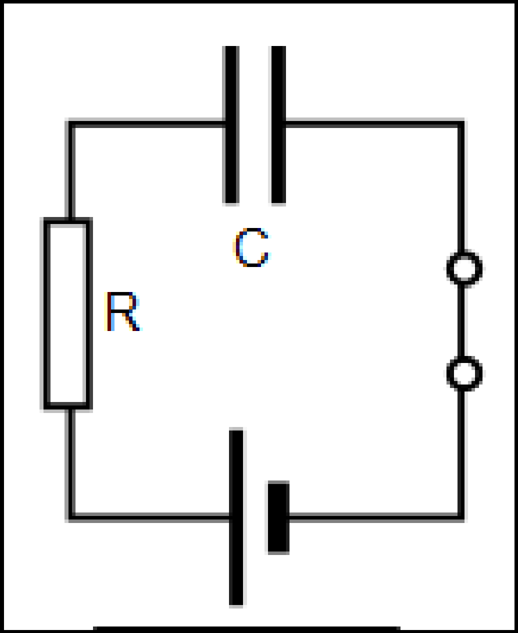


Discharging a Capacitor through a Resistor (RC circuit)

- It is called the time constant because when t = τ, the value of the charge will be 37% of its original charge

$$q = q_0 e^{-\frac{t}{\tau}}$$

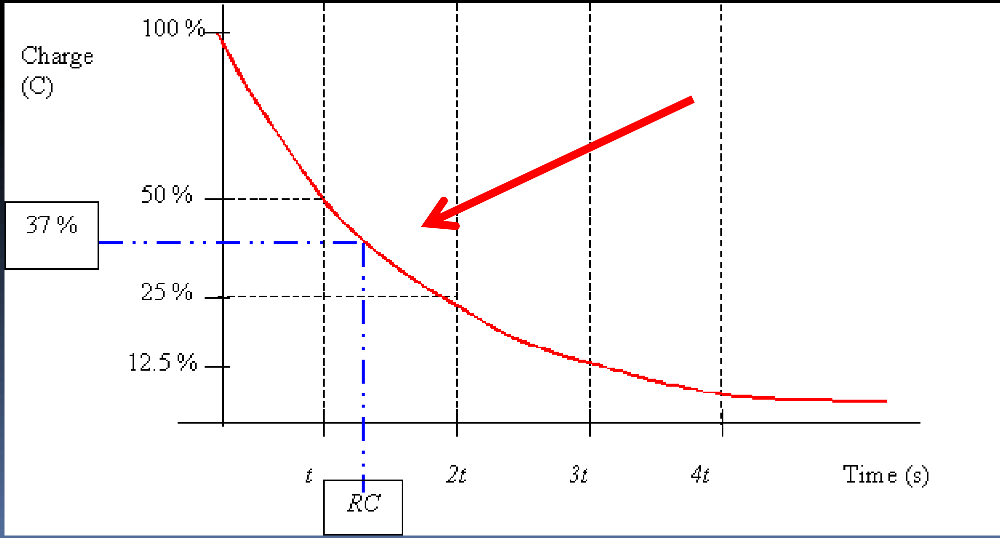
$$V = V_0 e^{-\frac{t}{\tau}}$$



$$q = q_0 e^{-\frac{t}{\tau}}$$

$$q = q_0 e^{-1}$$

$$q = \frac{q_0}{e} = 0.37 q_0$$

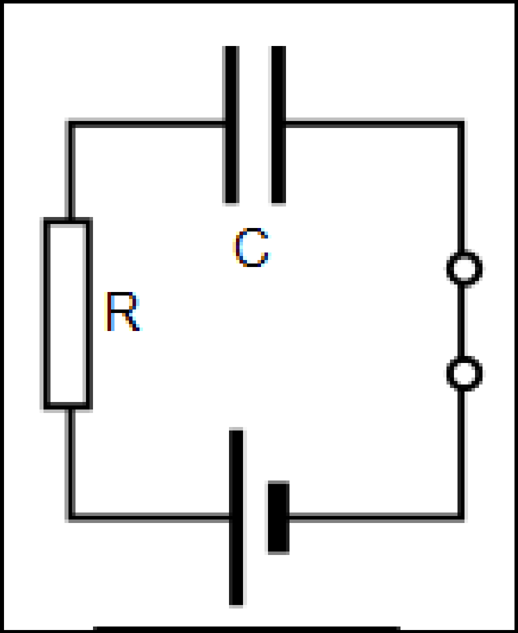


Discharging a Capacitor through a Resistor (RC circuit)

- Since current is proportional to voltage (V = IR), the same equation applies to current

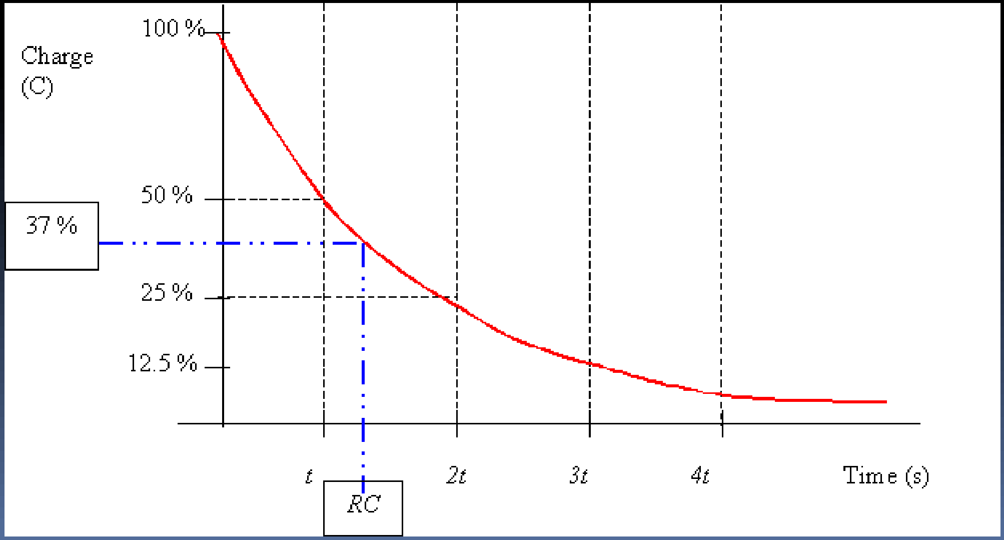
$$q = q_0 e^{-\frac{t}{\tau}}$$

$$V = V_0 e^{-\frac{t}{\tau}}$$



$$I = I_0 e^{-\frac{t}{\tau}}$$

$$I_0 = \frac{V}{R} = \frac{\varepsilon}{R}$$



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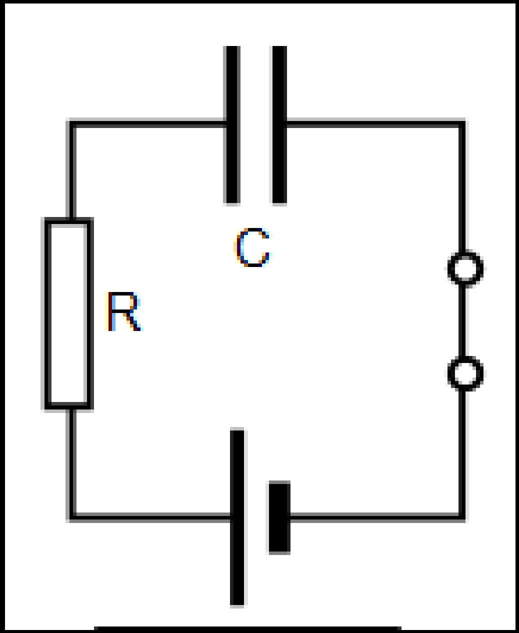

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$$q = q_0 e^{-\frac{t}{\tau}}$$

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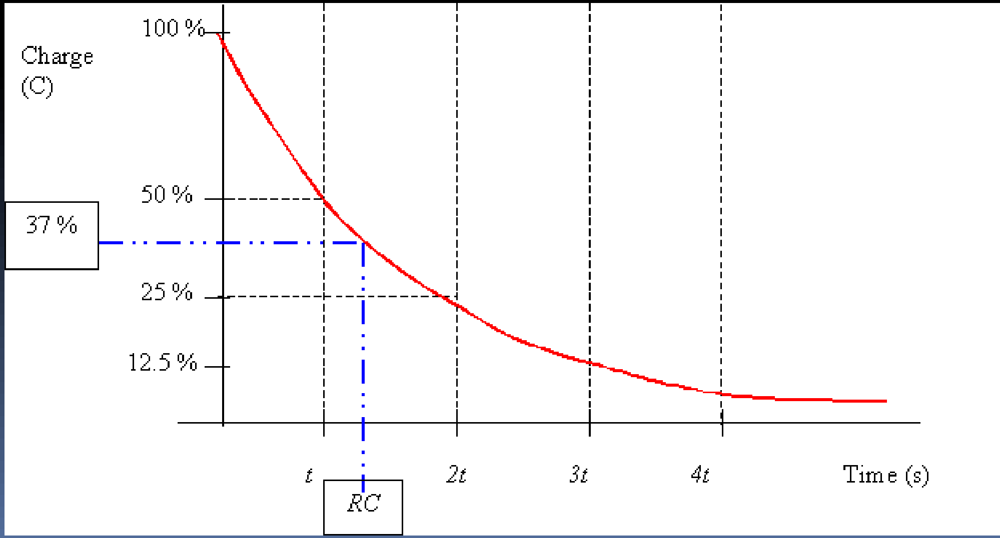


Discharging a Capacitor through a Resistor (RC circuit)

- ***When will the charge on the capacitor be half of its original charge ($q = \frac{1}{2} q_o$)?***

Discharging a Capacitor through a Resistor (RC circuit)

- ***When will the charge on the capacitor be half of its original charge ($q = ½\, q_o$)?***

$$q = q_0 e^{-\frac{t_{1/2}}{\tau}}$$

$$\frac{1}{2} q_0 = q_0 e^{-\frac{t_{1/2}}{\tau}}$$

$$\frac{1}{2} = e^{-\frac{t_{1/2}}{\tau}}$$

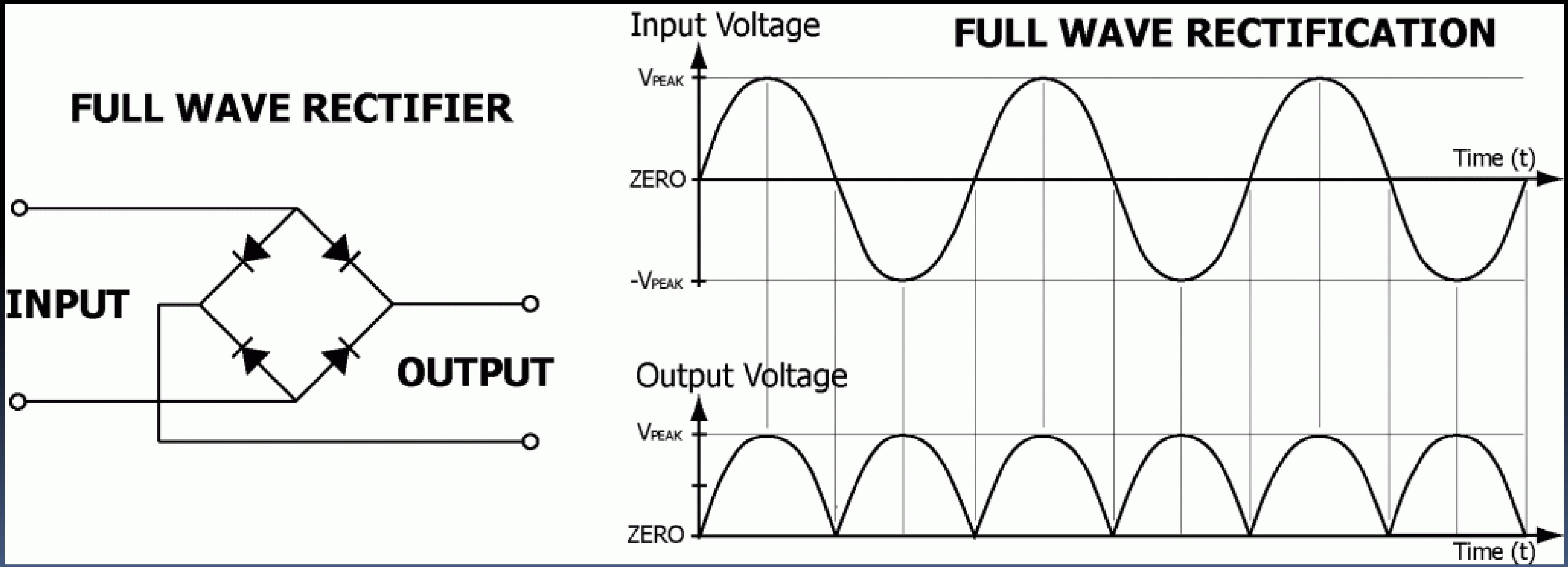
$$2 = e^{\frac{t_{1/2}}{\tau}}$$

$$\ln 2 = \frac{t_{1/2}}{\tau}$$

$$(\ln 2)\tau = t_{1/2}$$

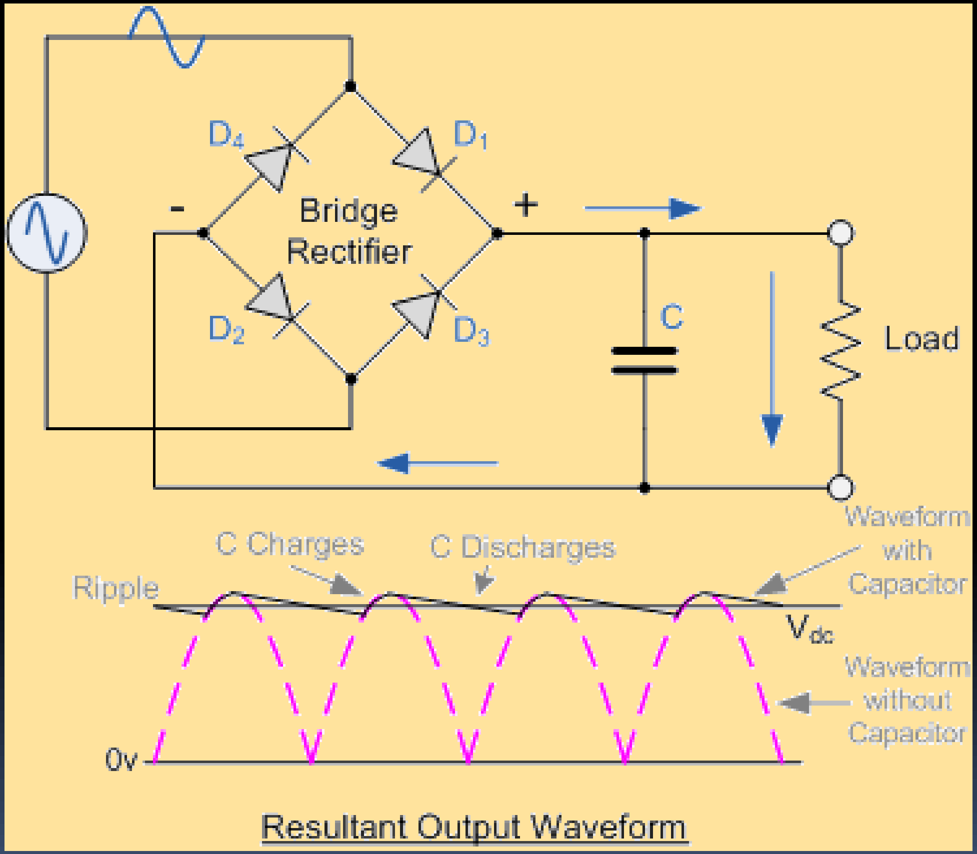
Capacitors in Rectification

- The output of a diode bridge is a direct current, but one that is not very ‘smooth’



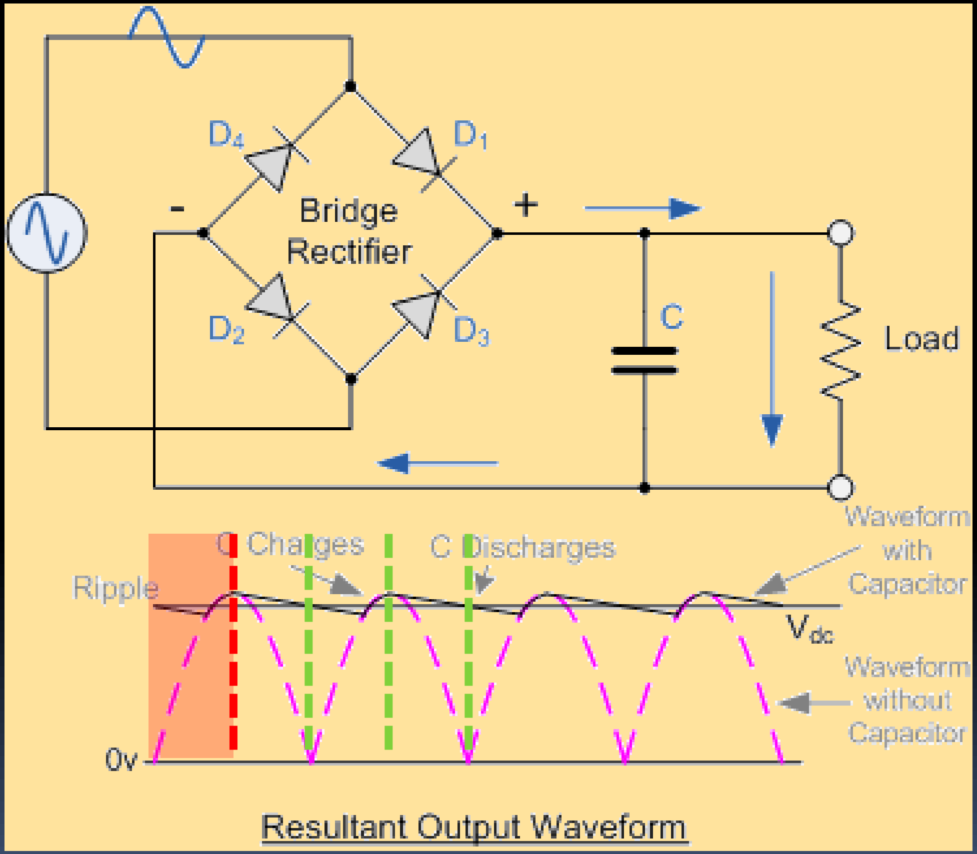
Capacitors in Rectification

- By adding a capacitor in parallel to the output load, the output is 'smoothed out'



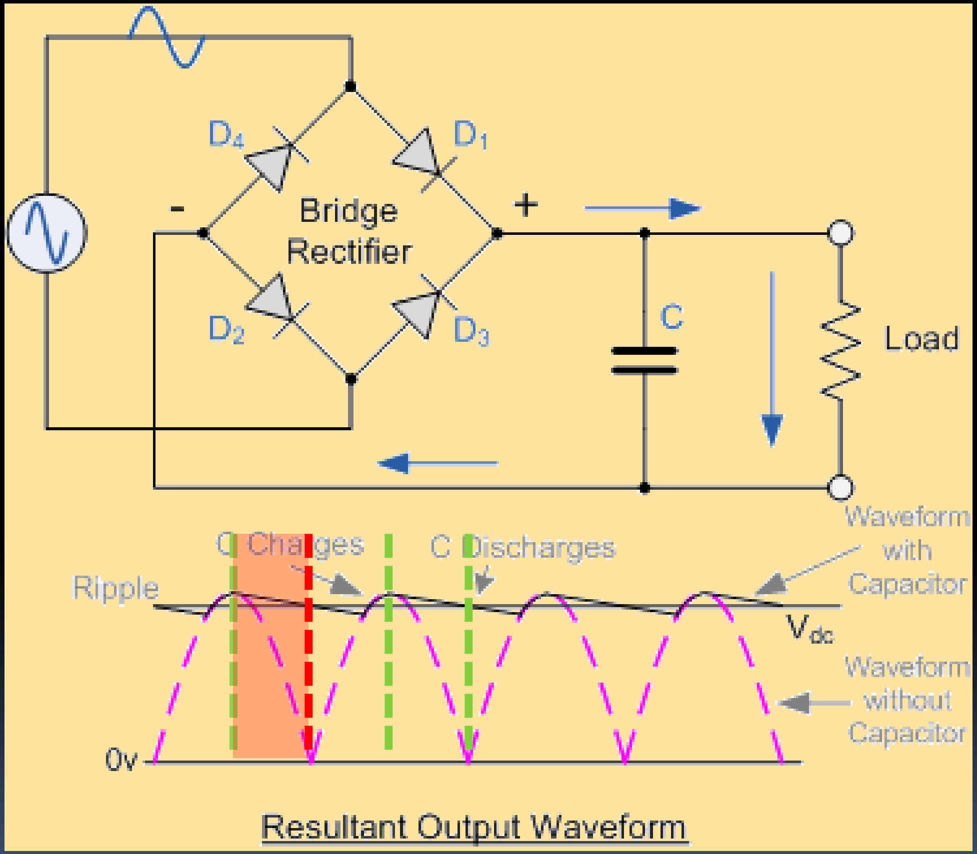
Capacitors in Rectification

- In the circuit, current flows clockwise thru the capacitor and resistor (load)
  - The first quarter-cycle charges the capacitor and the potential on the top plate reaches a maximum



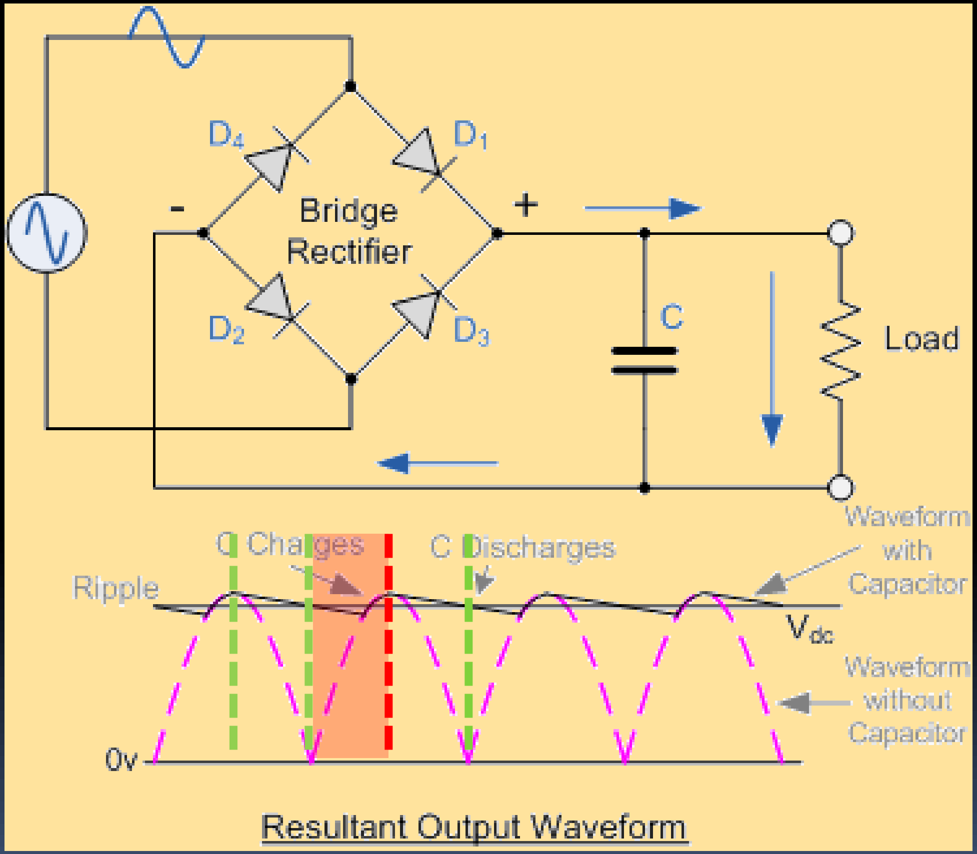
Capacitors in Rectification

- In the circuit, current flows clockwise thru the capacitor and resistor (load)
  - In the second quarter-cycle, as the potential decreases, the capacitor discharges because of its higher top-plate potential



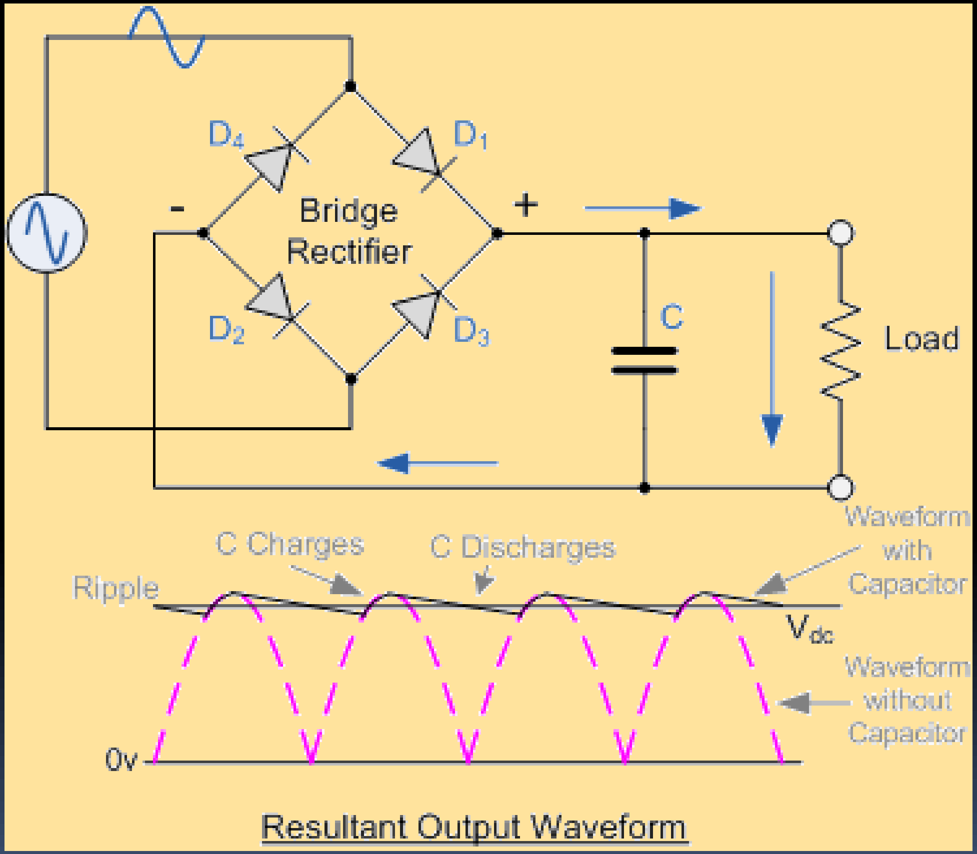
Capacitors in Rectification

- In the circuit, current flows clockwise thru the capacitor and resistor (load)
  - In the third quarter-cycle, as the potential increases, the capacitor discharge rate decreases and then starts charging



Capacitors in Rectification

- The ‘ripple effect’ is thus reduced



Understandings:

- Capacitance
- Dielectric materials
- Capacitors in series and parallel
- Resistor-capacitor (RC) series circuits
- Time constant

Applications And Skills:

- Describing the effect of different dielectric materials on capacitance
- Solving problems involving parallel-plate capacitors
- Investigating combinations of capacitors in series or parallel circuits
- Determining the energy stored in a charged capacitor

Applications And Skills:

- Describing the nature of the exponential discharge of a capacitor
- Solving problems involving the discharge of a capacitor through a fixed resistor
- Solving problems involving the time constant of an RC circuit for charge, voltage and current

Data Booklet Reference:

- $C = \frac{q}{V}$
- $C_{parallel} = C_1 + C_2 + \cdots$
- $\frac{1}{C_{series}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots$
- $C = \varepsilon \frac{A}{d}$
- $E = \frac{1}{2} CV^2$
- $\tau = RC$
- $q = q_0 e^{-\frac{t}{\tau}}$
- $I = I_0 e^{-\frac{t}{\tau}}$
- $V = V_0 e^{-\frac{t}{\tau}}$

Essential Idea:

- Capacitors can be used to store electrical energy for later use.

QUESTIONS?

Homework

#22-35