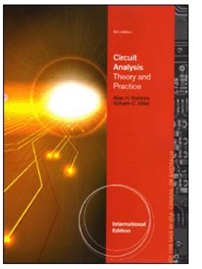
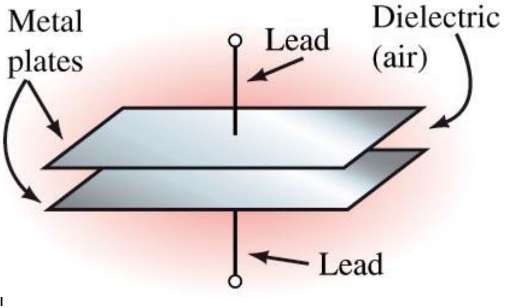


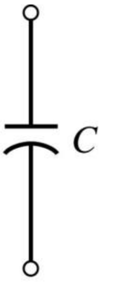
Chapter 10

Capacitors and Capacitance

Capacitance

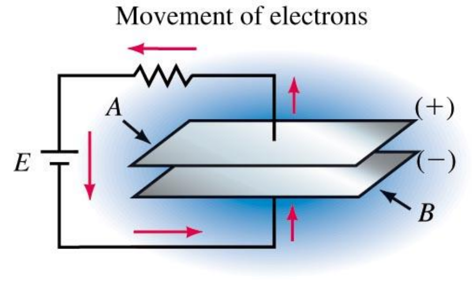
- Capacitor
  - **Two conductive plates separated by insulator**
  - **Insulating material** called **dielectric**
  - Conductive plates can become charged with opposite charges

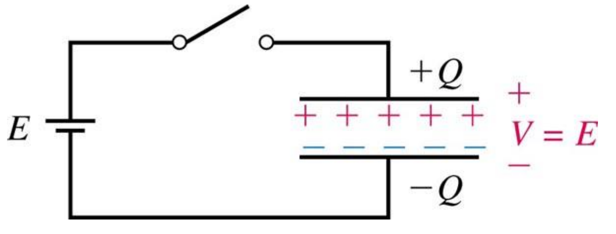




Capacitance

- Capacitor can **store charge**





Definition of Capacitance

- Amount of charge Q that a capacitor can store depends on applied voltage by

  $Q = CV$ or $C = Q/V$ (Similar to Ohm's Law)

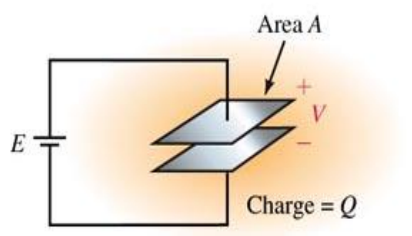
  - C is capacitance of the capacitor and unit is the **farad (F)**
  - **One farad** if it **stores one coulomb of charge**
  - When the voltage across its terminals is one volt
- **Factors affecting capacitance**

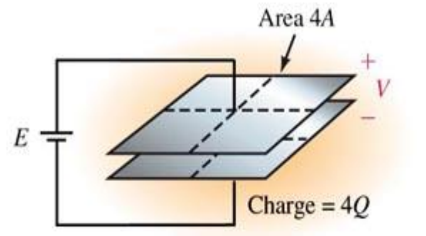
  Area *A*, spacing *d*, and dielectric ε

Effect of Area

Capacitance is directly proportional to amount of charge , $C \propto Q$

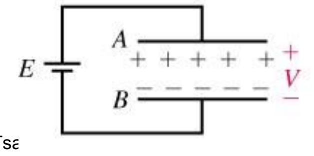
- **Capacitance is <u>directly proportional</u> to plate area , $C \propto A$**
- Larger plate will be able to hold more charge
- If plate area is doubled, capacitance is doubled

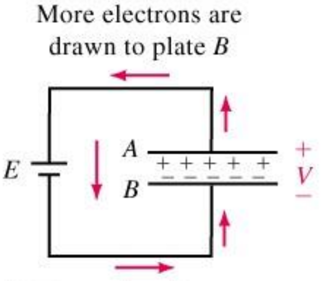




Effect of Spacing

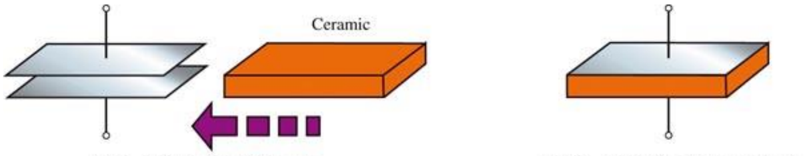
- **Capacitance <u>inversely proportional</u> to distance between plates , $C \propto 1/d$**
- As plates are moved closer together
  - Force of attraction between opposite charges is greater
- Double the distance between plates
  - Capacitance becomes half as much





Effect of Dielectric

- The capacitance increases if the dielectric constant or relative permittivity is large
- If a dielectric other than air is used between the plates, more charge can build up on the plates
- Permittivity represented by **ε** (Greek letter epsilon)
  - How easy it is to establish electric flux in a material



(a) C = 200 pF with air dielectric

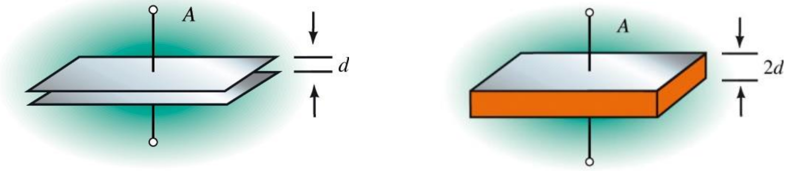
(b) C = 1.5 μF with high permittivity ceramic dielectric

Capacitance of a Parallel-Plate Capacitor

- Directly proportional to plate area ***A***
- Inversely proportional to plate separation ***d***
- Dependent on dielectric ∈

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

- $\in = \in_r \in_0$, $\in_0 = 8.854 \times 10^{-12} \mathrm{F/m}$
- A farad is a very large unit
  - **μF** or **pF**



(a) C = 24 pF with air dielectric

(b) C = 66 pF

Dielectric Constants

$\in = \in_r \in_o$ $\qquad$ $C = \in_r C_o$

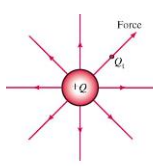
Material	$\in_r$ (Nominal Values)
Vacuum	1
Air	1.0006
Ceramic	30–7500
Mica	5.5
Mylar	3
Oil	4
Paper (dry)	2.2
Polystyrene	2.6
Teflon	2.1

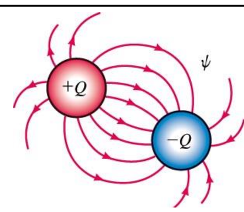
Example

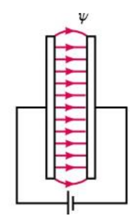
Compute the capacitance of a parallel-plate capacitor with plates 10cm by 20cm, separation of 5mm, and a **mica** dielectric.

Electric Fields

- Regions in which forces between charges exists
- Electric flux
  - **Electric field lines** are indicated by ψ (Greek letter psi)
- Direction of this field is direction of force on a positive test charge
- Field lines never cross
- Density of lines indicate field strength





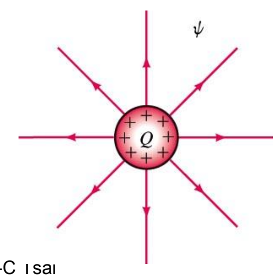


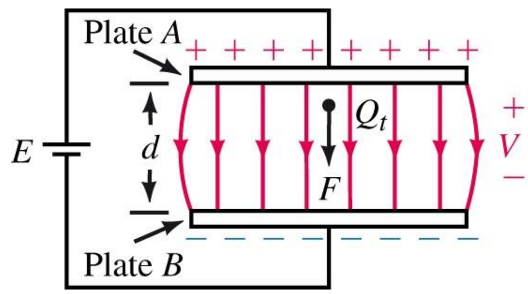
Electric Field strength

- Strength of an electric field is force that field exerts on a small test charge
  - $E = F / Q$
- Electric flux density = total flux/area
  - $D = \psi / A$
- Flux is due to the charge Q
- The number of flux lines coming from a charge is equal to the charge itself
  - $\psi = Q$

Field of a Parallel-Plate Capacitor

- To move a charge from the negative plate to the positive plate requires work
- Work = Force × distance, *W = F × S*
- Voltage = Work/charge, *E = W/Q*
- ***E = V/d***





Voltage Breakdown

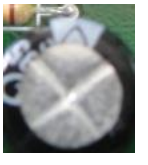
High voltage causes the dielectric breakdown of a capacitor

- Force on electrons becomes very great
- Electrons are torn from orbit
- For air, breakdown occurs at a voltage gradient of 3 kV/mm

Capacitor Voltage Rating

Capacitors rated for maximum operating voltage (**working voltage dc**)

- Rating is necessary due to dielectric breakdown



Non-ideal Effects

Leakage current:

- Property of real capacitors
- Eventual discharge
- Small amount of charge “leaks” through dielectric
- Effect of leakage is modeled by a resistor

Equivalent Series Resistance (ESR)

- Property of real capacitors
- Sources of resistance
  - Resistance of leads
  - Contact connections between leads and plates
  - ac losses in the dielectric
- **Can be modeled as a resistance in series with the capacitor**
- ESR is so small it can be neglected for many types
- Can be a problem with electrolytic capacitors
- **Cannot be measured with an ohmmeter**
  - Need specialized test instruments

Dielectric Absorption

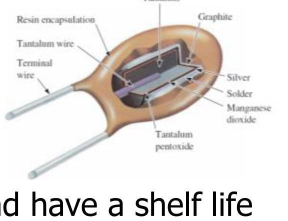
- Residual charge from remaining polarized atoms:
  - Cause residual voltage after discharge
- **Shorting resistor** may need to **be put back on to complete the discharge**

Temperature Coefficient

- Positive temperature coefficient
  - Capacitance increases with increasing temperature
- Negative temperature coefficient
  - Capacitance decreases with increasing temperature
- Zero temperature coefficient
  - Capacitance remains constant

Types of Capacitors

- Fixed capacitors, often identified by their dielectrics:
  - Ceramic, Plastic, Mica, Aluminum
  - <u>Tantalum</u> oxide



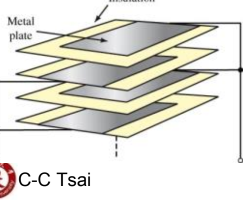
- Electrolytic capacitors
  - **Large capacitance** at low cost and have a shelf life
- Surface mount capacitors
  - Soldered directly onto printed circuit boards
  - Extremely small: High packaging density
- Variable capacitors
- **Supercapacitors**

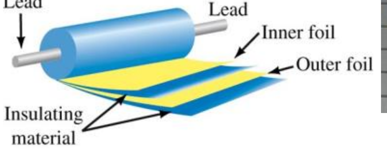
Standard Capacitor Values

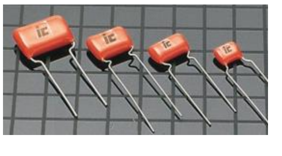
- Capacitors manufactured in specific standard sizes
  - 0.1 μF, 0.22 μF, 0.47 μF, etc.
  - Multiples and submultiples of above values
    0.1 pF, 0.22 pF, 0.47 pF, etc.

Fixed Capacitors

- **Ceramic** Capacitors
  - Permittivity varies widely
  - Values change little with temperature, voltage, or aging
- **Plastic Film** Capacitors
- **Mica** Capacitors
  - Low cost, low leakage, good stability
- **Electrolytic** Capacitors
  - Large capacitance at low cost
  - Polarized
- **Surface Mount** Capacitors

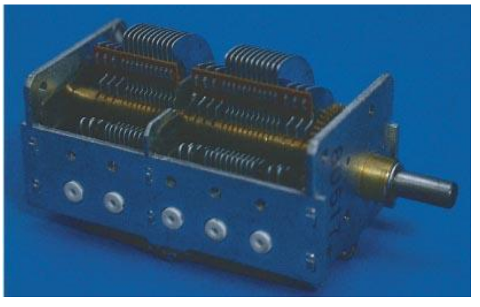






Variable Capacitors

- Used to **tune a radio**
- Stationary plates and movable plates
  - Combined and mounted on a shaft
- A trimmer or padder capacitor is used to make fine adjustments on a circuit



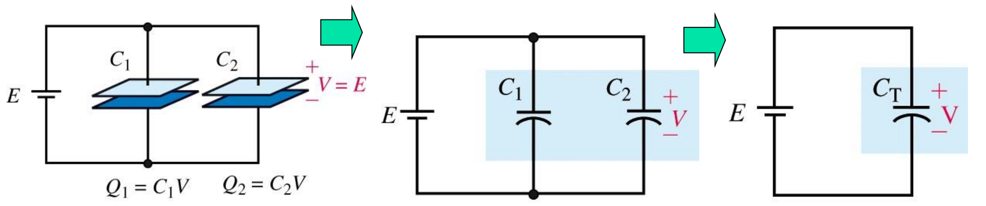
Supercapacitors

- Devices with enormous capacitance values
  - Values extend into the hundreds of farads and beyond
  - Also known as **ultracapacitors**
  - **Used in power sources**, GPS systems, PDAs, medical equipment, security systems
- Voltage rating typically only a few volts

Capacitors in Parallel

- Total charge on capacitors is sum of all charges
  $Q = CV$
  $C_T E = C_1 V_1 + C_2 V_2 + C_3 V_3$
- **All voltages are equal** $E = V_1 = V_2 = V_3$
- Total capacitance of capacitors in parallel
  - Sum of their capacitances (like resistors in series)

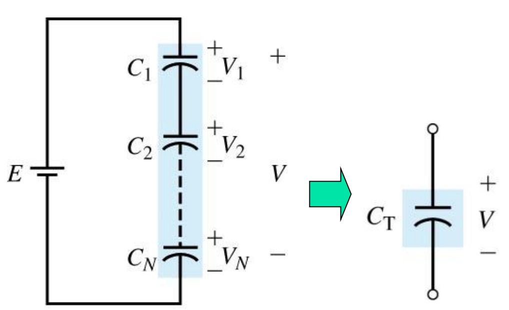
$C_T = C_1 + C_2 + C_3$



(a) Parallel capacitors (b) $C_T = C_1 + C_2$ (c) Equivalent

Capacitors in Series

- **Same charge** appears on all capacitors $Q = Q_1 = Q_2 = Q_3$
- Total V: Sum of individual voltages (like resistors in parallel)
  $E = V = V_1 + V_2 + V_3$
- **$C_T = 1 / (1/C_1 + 1/C_2 + 1/C_3)$**



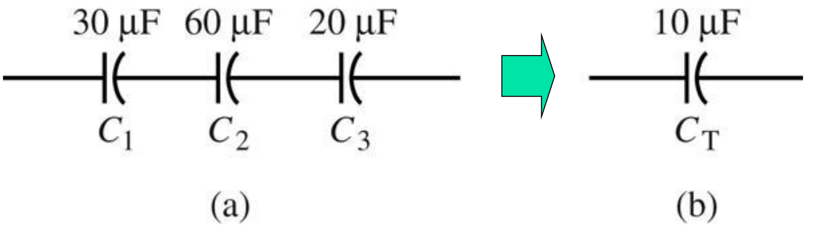
(a) Series connection (b) Equivalent

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

$$\frac{Q}{C_T} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$$

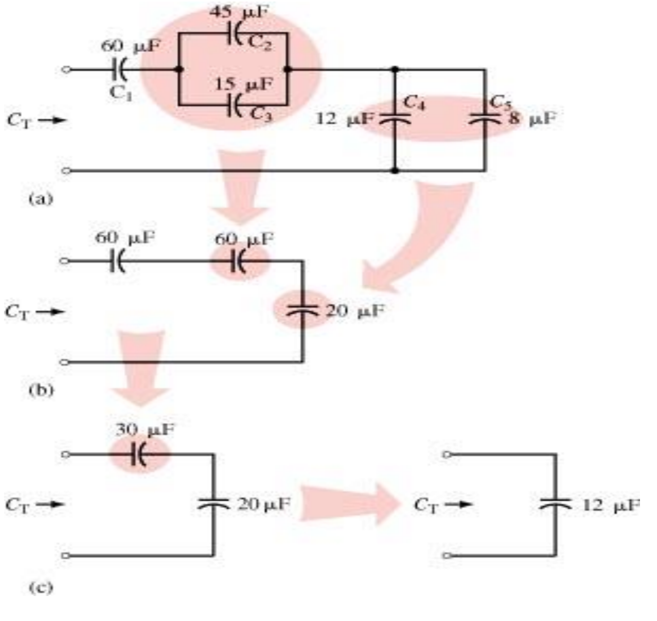
$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Example: Capacitors in Series



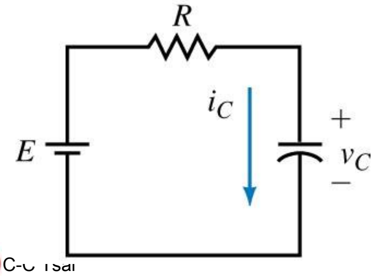
C_T = 1/(1/30μ+1/60μ+1/20μ) = 10μF

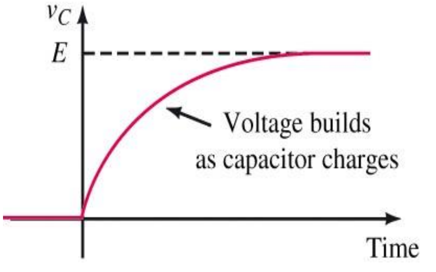
Example: Capacitors in Series



Capacitor Voltage During Charging

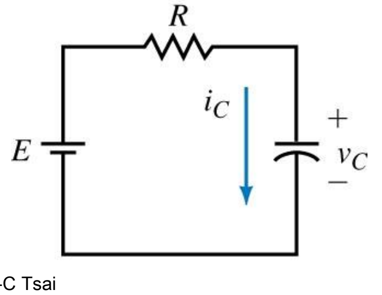
- **Voltage across a capacitor** **does not change instantaneously**
- **Voltage begins at zero and** **gradually climbs to full voltage** (or source voltage)
- May range from nanoseconds to milliseconds
  - Depending on the resistance and capacitance

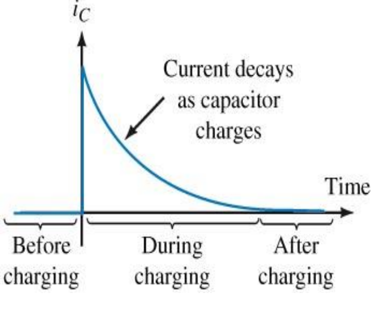




Capacitor Current During Charging

- During charging
  - **Electrons move from one plate to another**
- Current lasts only until capacitor is charged
- Current
  - **Large initial spike to zero**





Capacitor *v*-*i* Relationship

$$q = Cv_C$$

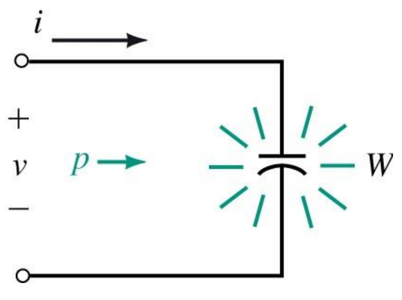
$$i_C = \frac{dq}{dt} = \frac{d}{dt}(Cv_C)$$

$$i_C = C\frac{dv_C}{dt} \quad \text{(A)}$$

$$i_C = C\frac{\Delta v_C}{\Delta t} = C\frac{\text{rise}}{\text{run}} = C \times \text{slope of the line}$$

Energy Stored by a Capacitor

- **A capacitor does not dissipate power**
- **Stored energy**: When power is transferred to a capacitor



$$\text{Energy} = \frac{1}{2}CV^2$$

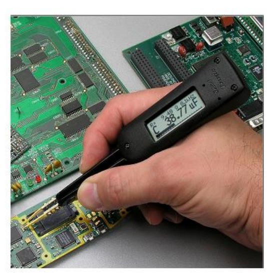
$$W = \int_0^t p\,dt = C\int_0^t v\frac{dv}{dt}\,dt = C\int_0^V v\,dv = \frac{1}{2}CV^2$$

Capacitor Failures and Troubleshooting

- Reasons for capacitor's failure
  - **Excessive voltage, current,** or **temperature,** or **aging**
- Test with an ohmmeter
  - **Good capacitor will read low**, then **gradually increase to infinity**
- Capacitor **short**
  - Meter resistance will **stay low**
- If capacitor is **leaky**
  - Reading will be **lower than normal**
- If capacitor is **open**
  - **Stays at infinity**

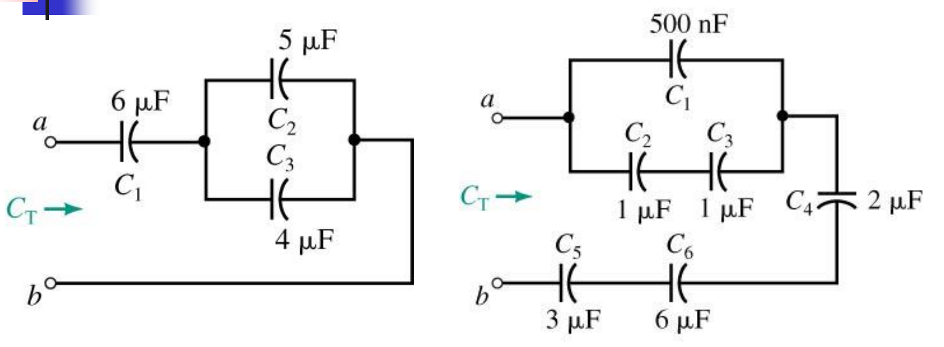
Limitation of Capacitor Testers

- **Ohmmeter testing of limited usefulness**
  - Does not evaluate capacitor quality issues: Such as ESR (Equivalent Series Resistance)
- Smart Tweezers™ device for testing surface mount components

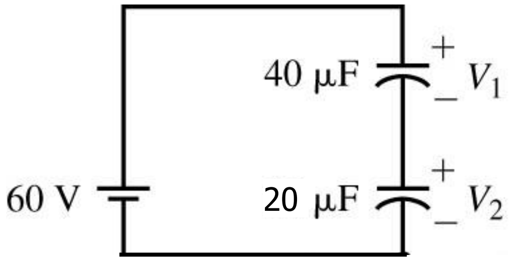


- **LCR/ESR component tester**

Problem: Determine C_T



Problem: Find V_1 and V_2



Problem: Find V_1, V_2, and V_3