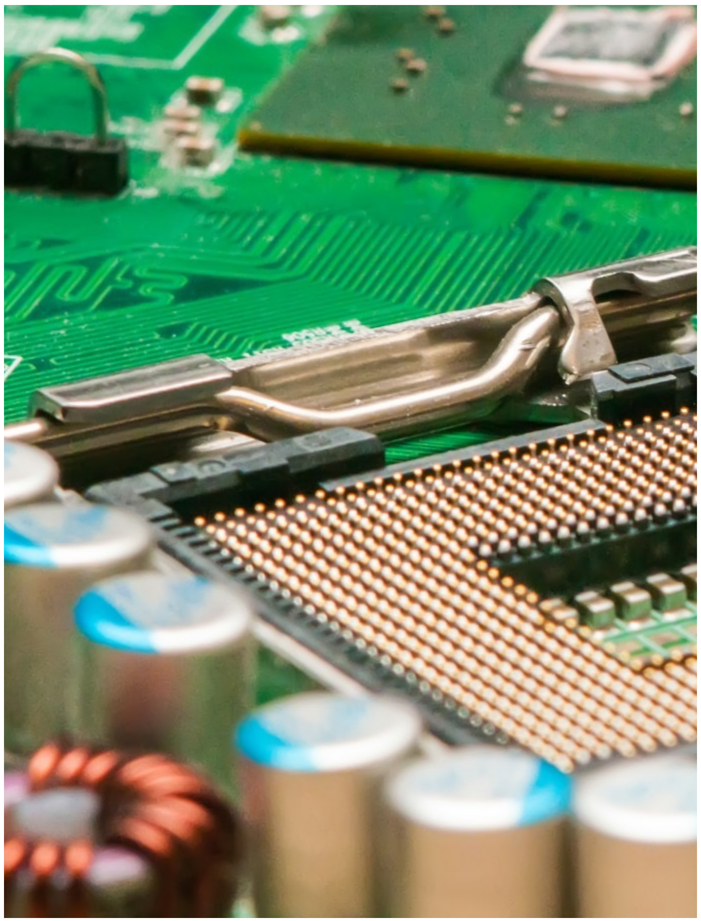
Fundamentals of Electrical & Electronic Engineering

Prof. John G. Breslin, Electrical & Electronic Engineering



Lecture 9

Capacitors

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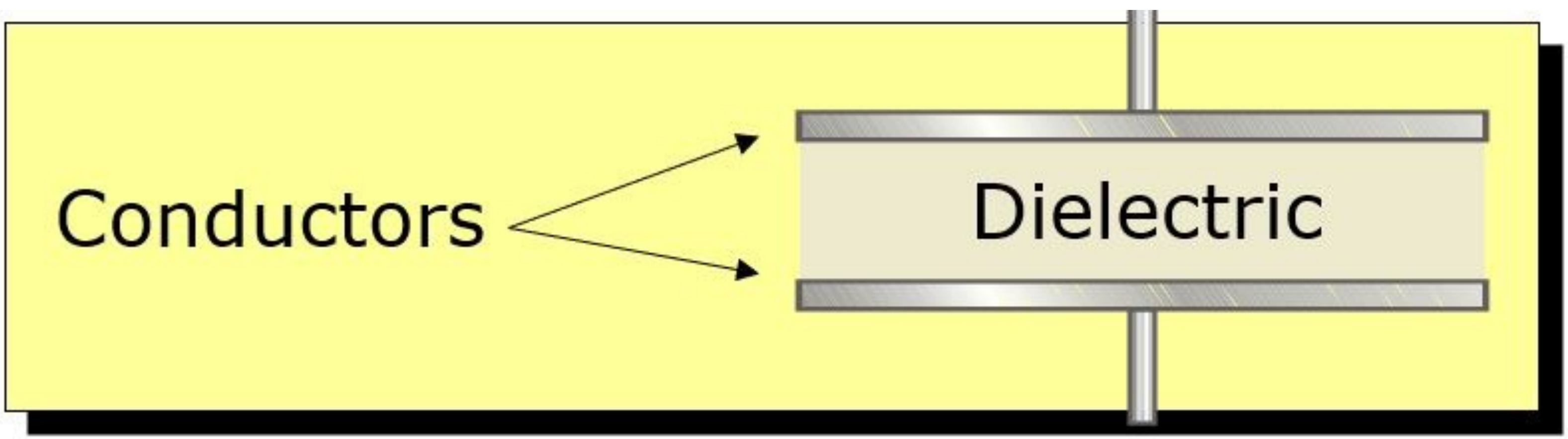
Summary (1 of 34)

The Basic Capacitor

Capacitors are one of the fundamental passive components. In its most basic form, it is composed of two plates separated by an insulating material or dielectric.

The ability to store charge is the definition of **capacitance**.



Summary (2 of 34)

The Basic Capacitor

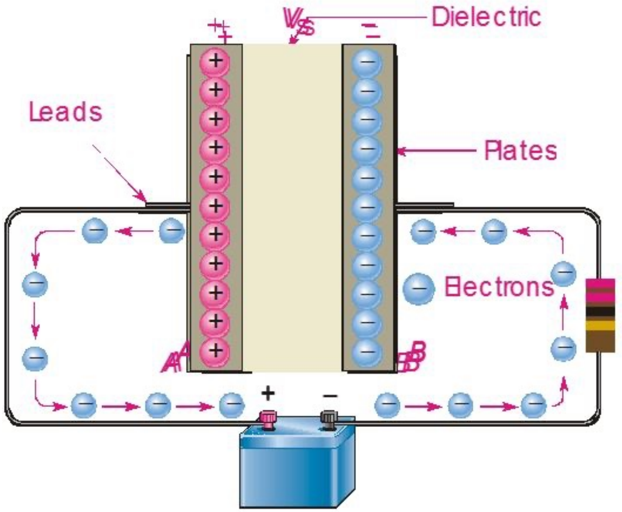
The charging process ◡

Initially uncharged

Charging

Fully charged

Source removed



A capacitor with stored charge can act as a temporary source of electrical energy.

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Capacitance

Capacitors have a maximum voltage that cannot be exceeded before breakdown. Dielectric strength is expressed as the maximum voltage per mil that a material can withstand. Some common dielectric materials and their dielectric strengths are:

MATERIAL	DIELECTRIC STRENGTH (V/MIL)
Air	80
oil	375
Ceramic	1,000
Paper (paraffined)	1,200
Teflon®	1,500
Mica	1,500
Glass	2,000

Summary (4 of 34)

Capacitance

Capacitance is the ratio of charge to voltage

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

Rearranging, the amount of charge on a capacitor is determined by the size of the capacitor (C) and the voltage (V).

$$Q = CV$$

Example

If a $22\,\mu\text{F}$ capacitor is connected to a 10 V source, the charge is $220\,\mu\text{C}$.

Summary (5 of 34)

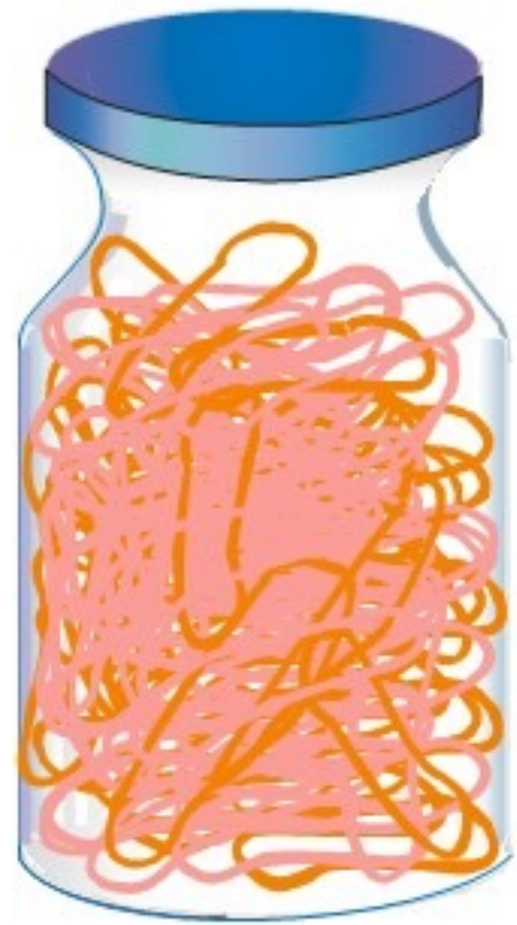
Capacitance

An analogy:

Imagine you store rubber bands in a bottle that is nearly full.

You could store more rubber bands (like charge or Q) in a bigger bottle (capacitance or C) *or* if you push them in more (voltage or V). Thus,

$$Q = CV$$



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Capacitance

A capacitor stores energy in the form of an electric field that is established by the opposite charges on the two plates. The energy of a charged capacitor is given by the equation

$$W = \frac{1}{2}CV^2$$

Where

$W =$ the energy in joules

$C =$ the capacitance in farads

$V =$ the voltage in volts

Example

How much energy is stored in a $10{,}000\ \mu\text{F}$ capacitor charged to 24 V? 2.88 J

Summary (7 of 34)

Capacitance

The capacitance of a capacitor depends on three physical characteristics.

$$C = 8.85 \times 10^{-12}\,\mathrm{F/m}\left(\frac{\varepsilon_r A}{d}\right)$$

C is directly proportional to the **relative dielectric constant** and the **plate area**.

C is inversely proportional to the **distance** between the plates

Capacitance

Example Find the capacitance of a 4.0 cm diameter sensor immersed in oil if the plates are separated by 0.25 mm. $\left(\varepsilon_r = 4.0 \text{ for oil}\right)$

$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{\varepsilon_r A}{d}\right)$$

The plate area is $A = \pi r^2 = \pi\left(0.02\ \text{m}^2\right) = 1.26\times10^{-3}\,\text{m}^2$

The distance between the plates is 0.25×10^{-3} m

$$C = 8.85\times10^{-12}\,\text{F/m}\left(\frac{(4.0)(1.26\times10^{-3}\ \text{m}^2)}{0.25\times10^{-3}\ \text{m}}\right) = 178\ \text{pF}$$

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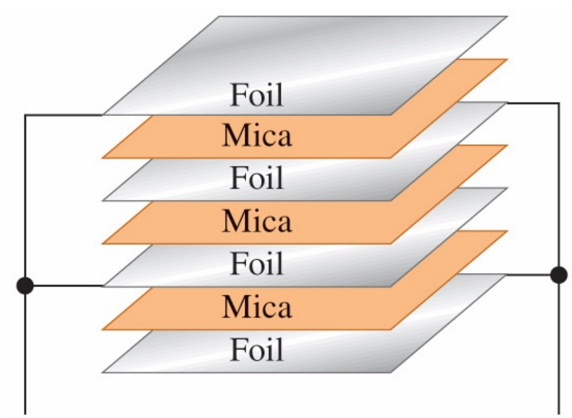
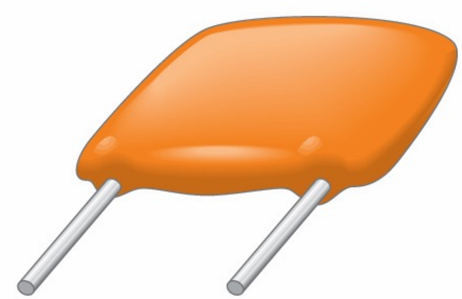
Capacitor Types

Mica

Mica capacitors are small with high working voltage. The **working voltage** is the voltage limit that must not be exceeded without damaging the part.





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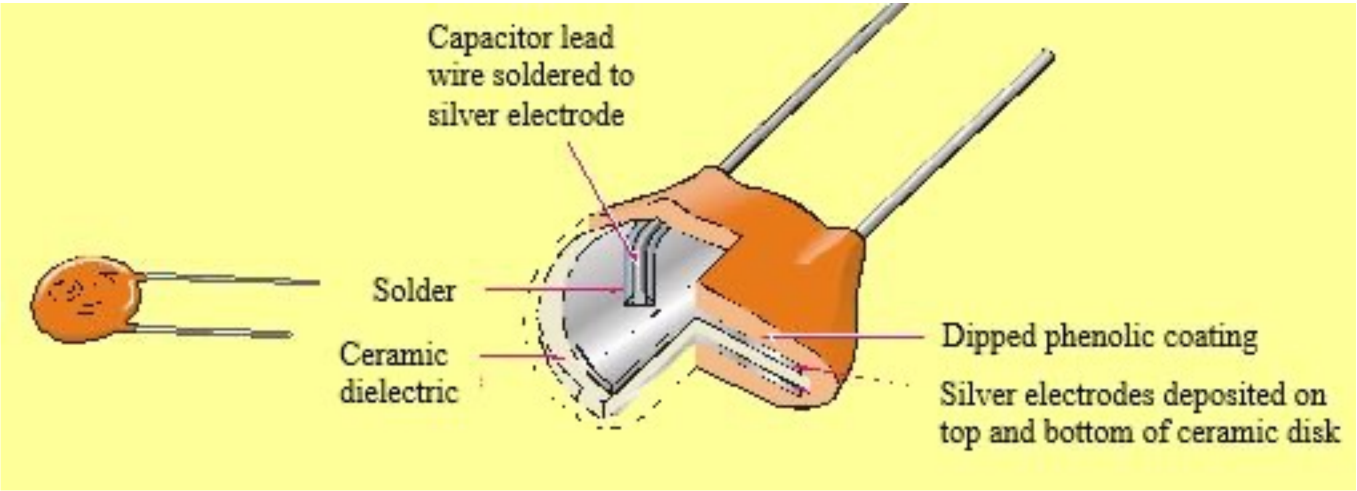
Capacitor Types

Ceramic disk

Ceramic disks are small nonpolarized capacitors They have relatively high capacitance due to high ε_r



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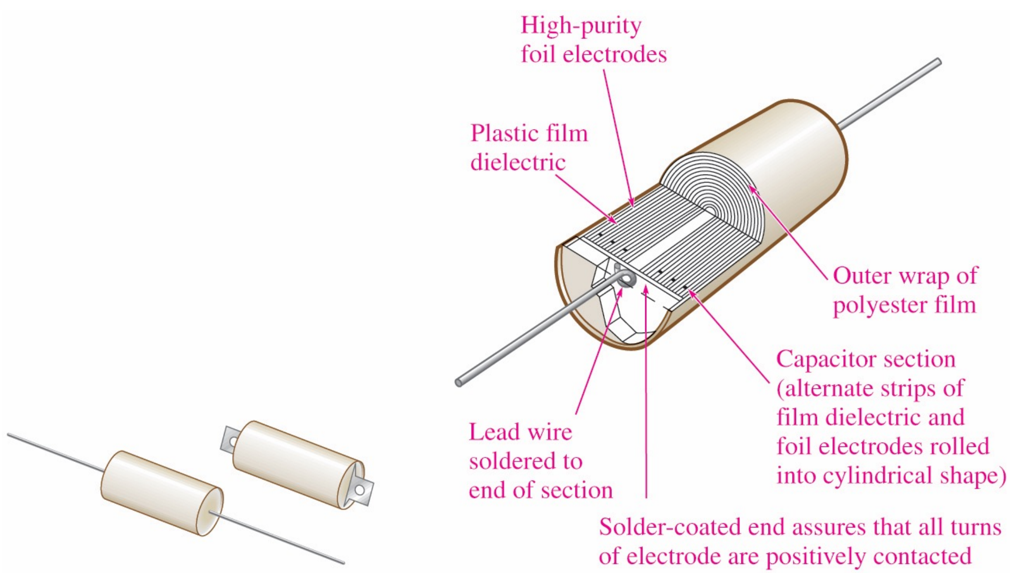
Capacitor Types

Plastic Film

Plastic film capacitors are small and nonpolarized. They have relatively high capacitance due to larger plate area.



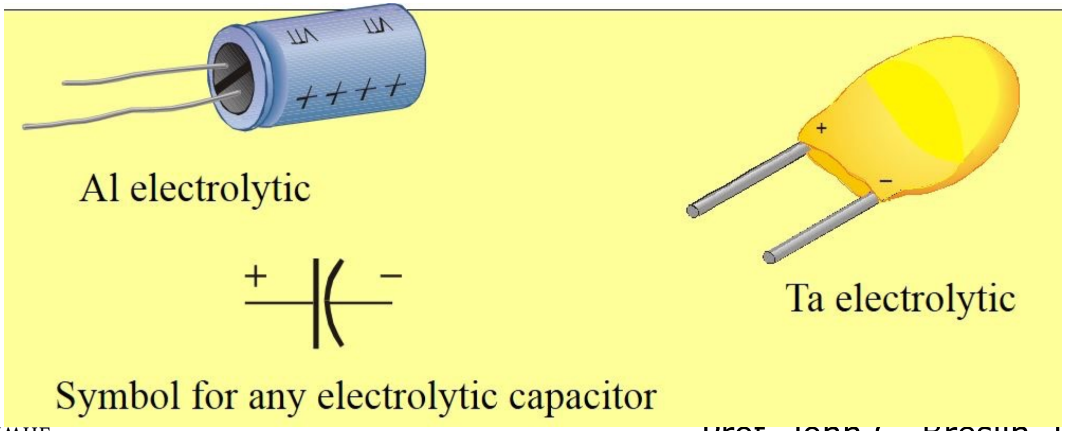
(a) Typical capacitors (b) Construction view

Summary (12 of 34)

Capacitor Types

Electrolytic

Aluminum (Al) and tantalum (Ta) electrolytic capacitors have high capacitance but they are not as precise as other types and generally have more leakage current. All electrolytic types are polarized.



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Capacitor Types

Electrolytic

A type of electrolytic capacitor that differs from standard Al and Ta electrolytics is the polymer type. Polymer electrolytics use a solid conductive polymer electrolyte rather than the liquid or gel used in other electrolytic capacitors. An advantage to the polymer electrolytic type is they have very low equivalent series resistance (ESR), an advantage in certain applications like power supplies.

There are also new much larger value electrolytic capacitors sometimes called super capacitors with capacitances of hundreds of farads. These capacitors are useful for battery backup and for applications like small motor starters that require a very large capacitance.

A flat polymer electrolytic capacitor

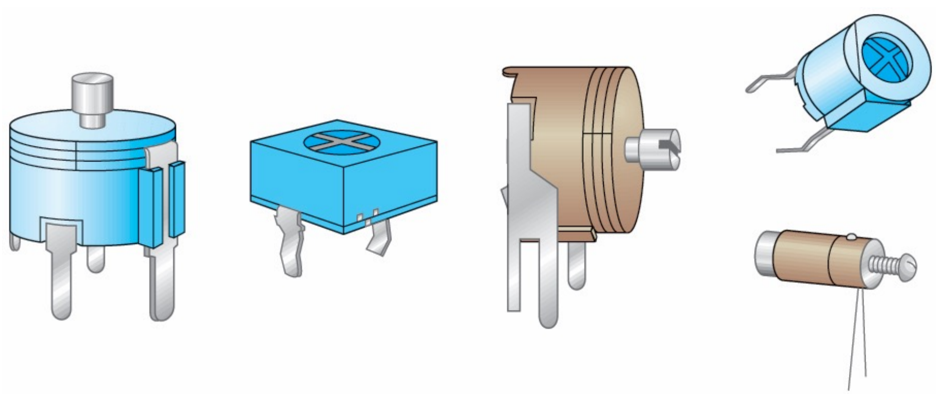
Summary (14 of 34)

Capacitor Types

Variable

Variable capacitors typically have small capacitance values and are usually adjusted manually.

A solid-state device that is used as a variable capacitor is the varactor diode; it is adjusted with an electrical signal.



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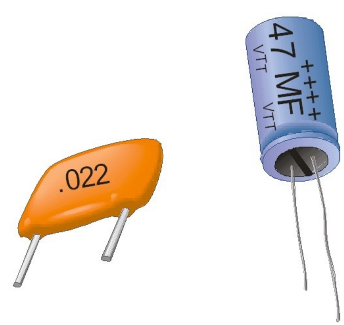
Capacitor Labeling

Capacitors use several labeling methods. Small capacitors values are frequently stamped on them such as .001 or .01, which have units of microfarads.

Electrolytic capacitors have larger values, so are read as μF.

The unit is usually stamped as μF, but some older ones may be shown as MF or MMF).



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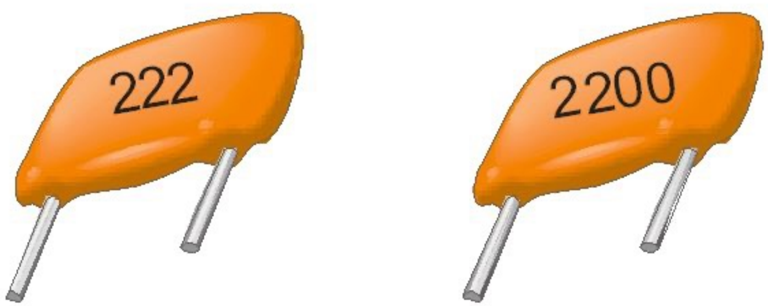
Capacitor Labeling

A label such as 103 or 104 is read as 10×10^3 (10,000 pF) or 10×10^4 (100,000 pF) respectively. (Third digit is the power of ten of the multiplier.)

When values are marked as 330 or 6800, the units are picofarads



Example

a. What is the value of each capacitor? Both are 2200 pF.

b. What is the value of a capacitor marked 682? 6800 pF.

Summary

Series Capacitors

When capacitors are connected in series, the total capacitance is smaller than the smallest one. The general equation for capacitors in series is:

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

The total capacitance of two series capacitors is: $C_T = \dfrac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$

This reduces to the product-over-sum rule: $C_T = \dfrac{C_1 C_2}{C_1 + C_2}$

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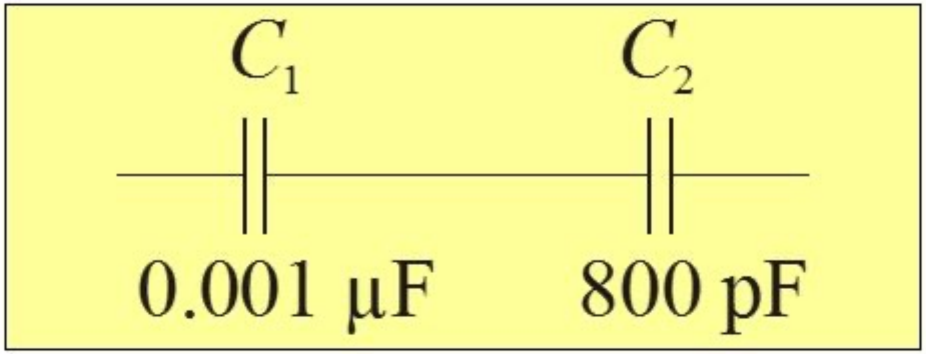
Series Capacitors

Example If a 0.001 μF capacitor is connected in series with an 800 pF capacitor, the total capacitance is 444 pF.



Follow-up: If another 0.001 μF capacitor is connected in series with the capacitors, the total capacitance is 308 pF.

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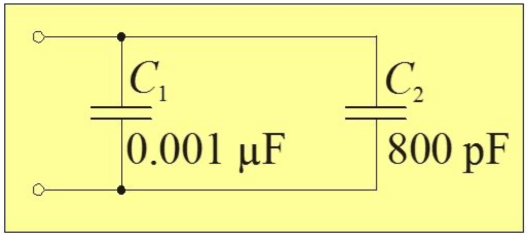
Parallel Capacitors

When capacitors are connected in parallel, the total capacitance is the sum of the individual capacitors. The general equation for capacitors in parallel is

$$C_T = C_1 + C_2 + C_3 + \ldots + C_n$$

Example If a 0.001 μF capacitor is connected in parallel with an 800 pF capacitor, the total capacitance is 1800 pF.



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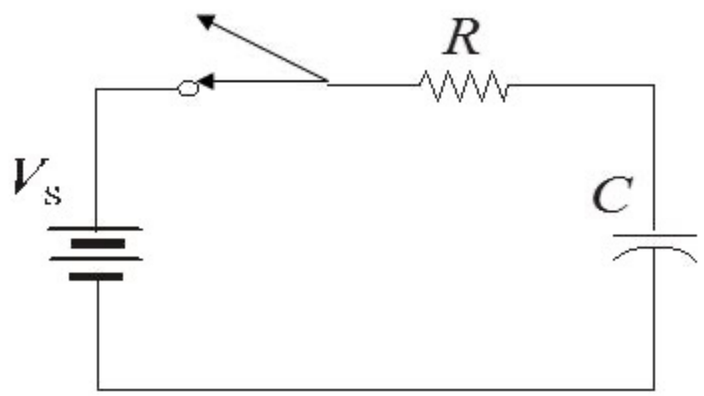
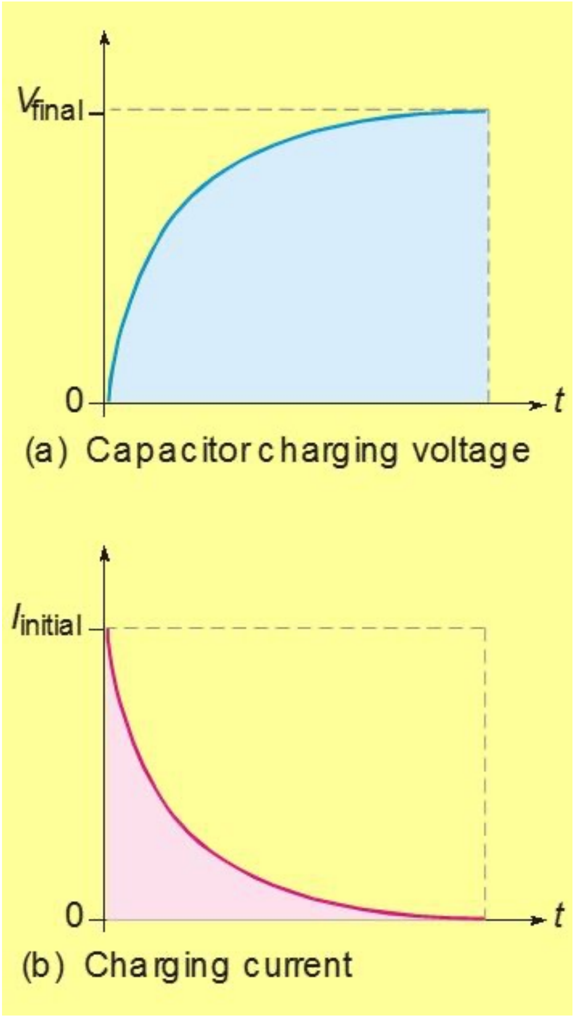
The *RC* Time Constant

When a capacitor is charged through a series resistor and dc source, the charging curve is exponential.





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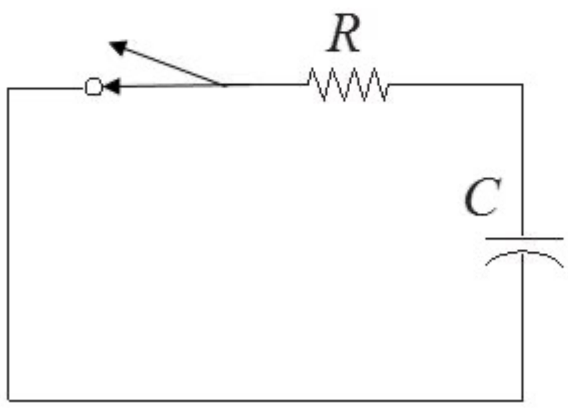
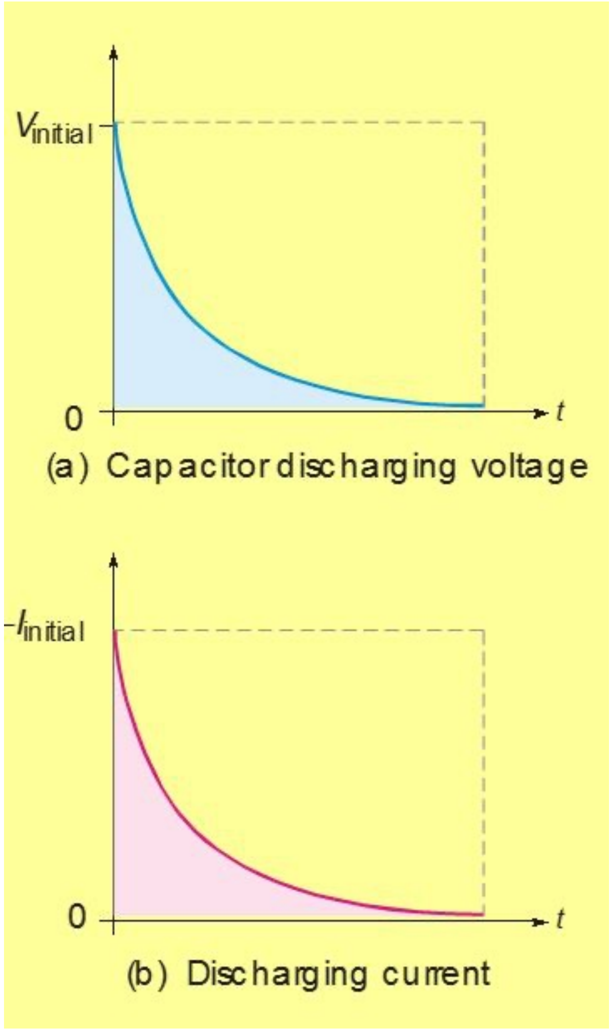
The *RC* Time Constant

When a capacitor is discharged through a resistor, the discharge curve is also an exponential. (Note that the current is negative.)





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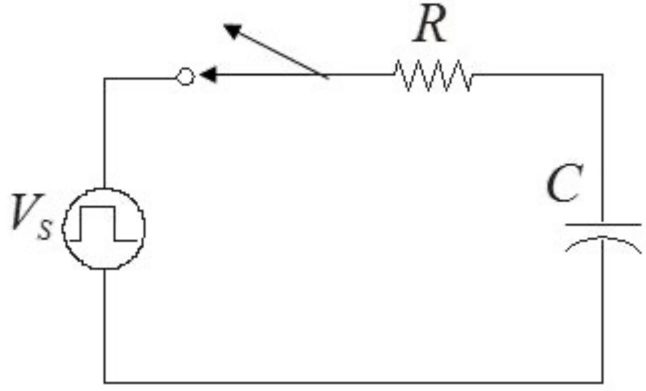
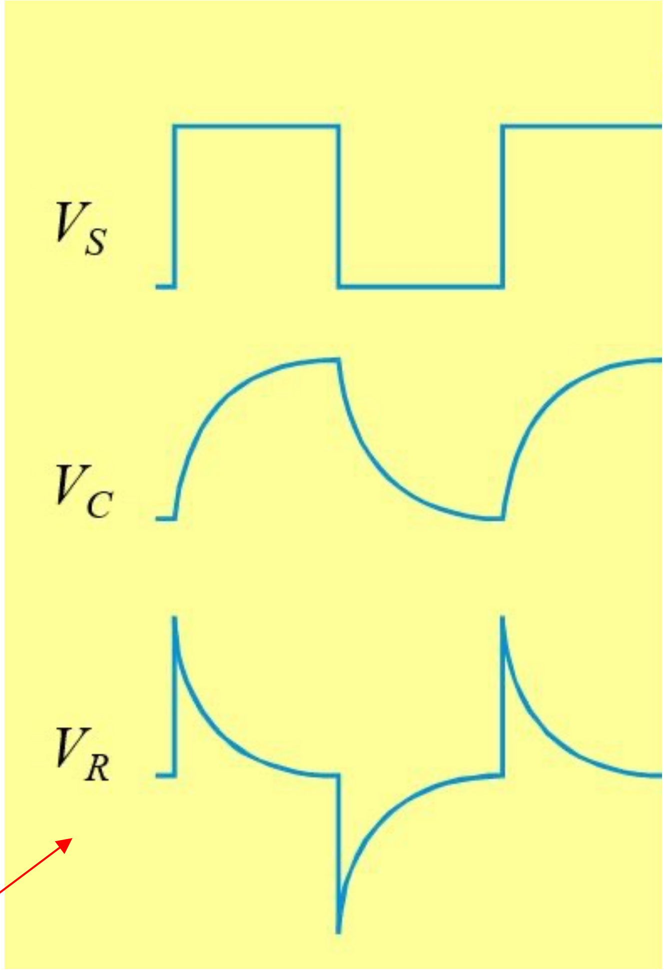
The *RC* Time Constant

The same shape curves are seen if a square wave is used for the source.

Question What is the shape of the current curve?





The current has the same shape as V_R.

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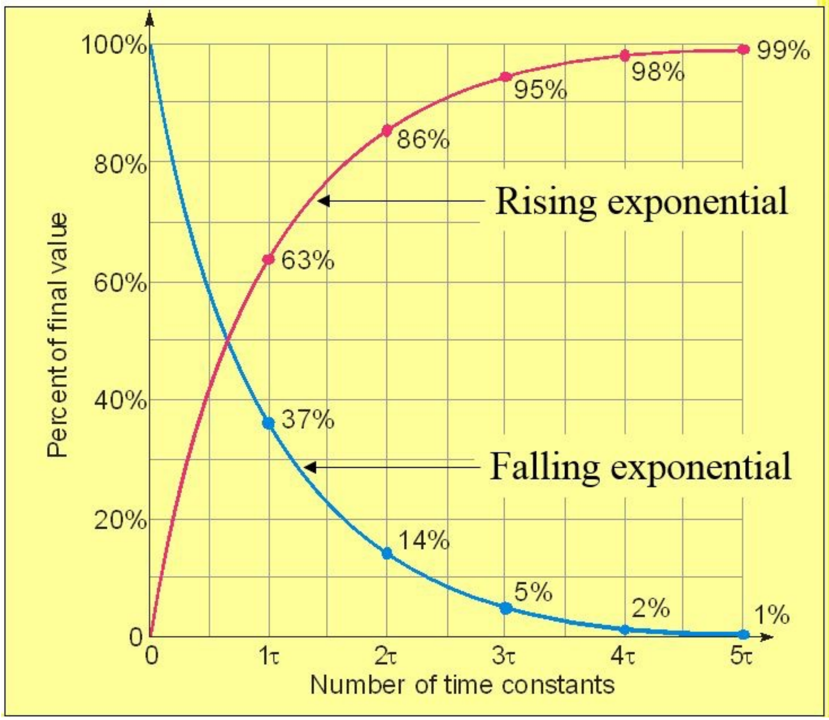
Universal Exponential Curves

Specific values for current and voltage can be read from a universal curve. For an *RC* circuit, the time constant is

$$\tau = RC$$

For the rising exponential, 5τ is typically considered to be 100%. For the falling exponential, 5τ is typically considered to be 0%.



Universal Exponential Curves

The universal curves can be applied to general formulas for the voltage (or current) curves for *RC* circuits. The general voltage formula is

$$v = V_F + (V_i - V_F)e^{-t/RC}$$

$$V_F = \text{final value of voltage}$$

$$V_i = \text{initial value of voltage}$$

$$v = \text{instantaneous value of voltage}$$

The final capacitor voltage is greater than the initial voltage when the capacitor is charging, or less that the initial voltage when it is discharging.

Capacitive Reactance

Capacitive reactance is the opposition to ac by a capacitor. The equation for capacitive reactance is

$$X_C = \frac{1}{2\pi fC}$$

Example The reactance of a $0.047\ \mu\text{F}$ capacitor when a frequency of 15 kHz is applied is 226 Ω.

Capacitive Reactance

When capacitors are in series, the total reactance is the sum of the individual reactances. That is,

$$X_{C(tot)} = X_{C1} + X_{C2} + X_{C3} + \ldots + X_{Cn}$$

Example Assume three $0.033\ \mu\text{F}$ capacitors are in series with a 2.5 kHz ac source. What is the total reactance?

Solution: The reactance of each capacitor is

$$X_C = \frac{1}{2\pi fc} = \frac{1}{2\pi(2.5\ \text{kHz})(0.033\ \mu\text{F})} = 1.93\ \text{k}\Omega$$

$$X_{C(tot)} = X_{C1} + X_{C2} + X_{C3}$$
$$= 1.93\ \text{k}\Omega + 1.93\ \text{k}\Omega + 1.93\ \text{k}\Omega = 5.79\ \text{k}\Omega$$

Summary (27 of 34)

Capacitive Reactance

When capacitors are in parallel, the total reactance is the reciprocal of the sum of the reciprocals of the individual reactances. That is,

$$X_{C(tot)} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}} + \ldots + \frac{1}{X_{Cn}}}$$

Example If the three $0.033\ \mu F$ capacitors from the last example are placed in parallel with the 2.5 kHz ac source, what is the total reactance?

Solution: The reactance of each capacitor is $1.93\ k\Omega$

$$X_{C(tot)} = \frac{1}{\frac{1}{X_{C1}} + \frac{1}{X_{C2}} + \frac{1}{X_{C3}}} = \frac{1}{\frac{1}{1.93\ k\Omega} + \frac{1}{1.93\ k\Omega} + \frac{1}{1.93\ k\Omega}} = 643\ \Omega$$

Capacitive Voltage Divider

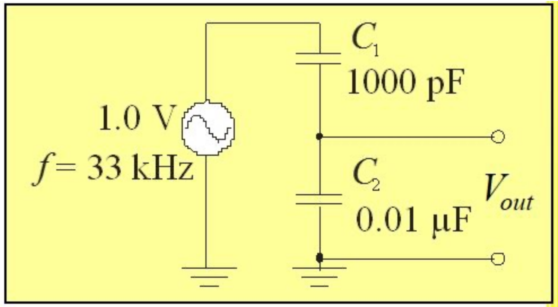
Two capacitors in series are commonly used as a capacitive voltage divider. The capacitors split the output voltage in proportion to their reactance (and inversely proportional to their capacitance).

Example What is the output voltage for the capacitive voltage divider?

Solution:

$$X_{C1} = \frac{1}{2\pi f c_1} = \frac{1}{2\pi(33\,\text{kHz})(1000\,\text{pF})} = 4.82\,\text{k}\Omega$$

$$X_{C2} = \frac{1}{2\pi f c_2} = \frac{1}{2\pi(33\,\text{kHz})(0.01\,\mu\text{F})} = 482\,\Omega$$



$$X_{c(tot)} = X_{C1} + X_{C2}$$

$$= 4.82\,\text{k}\Omega + 482\,\Omega = 5.31\,\text{k}\Omega$$

$$V_{out} = \left(\frac{X_{C2}}{X_{C(tot)}}\right) V_s = \left(\frac{482\,\Omega}{5.31\,\text{k}\Omega}\right) 1.0\text{ V} = 90.9\text{ mV}$$

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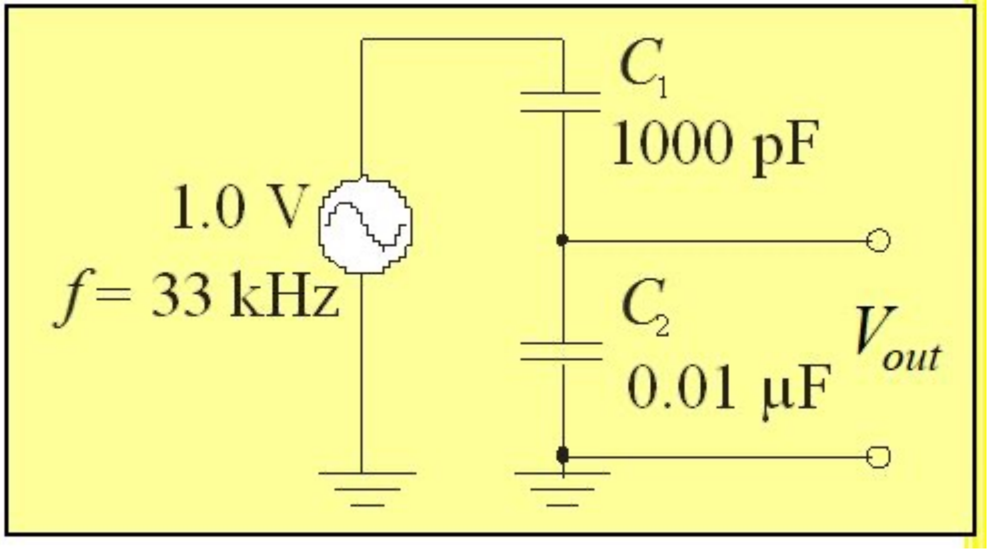
Capacitive Voltage Divider

Instead of using a ratio of reactances in the capacitor voltage divider equation, you can use a ratio of the total series capacitance to the output capacitance (multiplied by the input voltage). The result is the same. For the problem presented in the last slide,

90.9 mV



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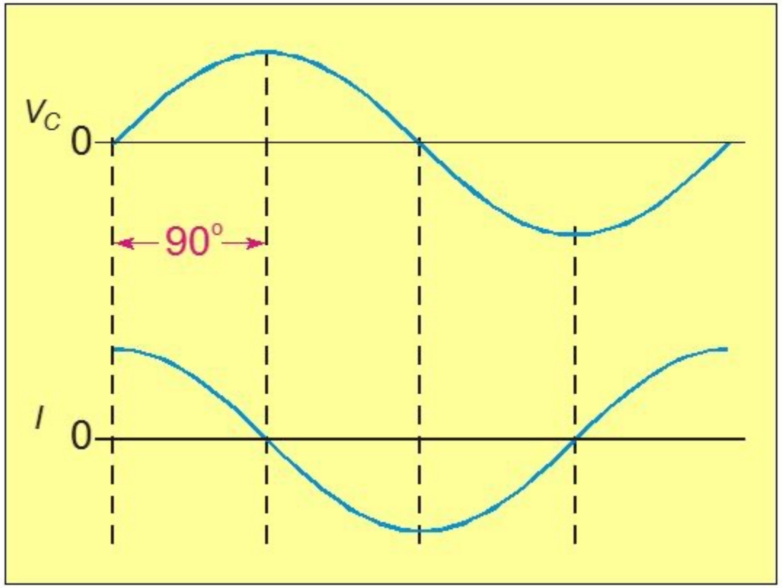
Capacitive Phase Shift

When a sine wave is applied to a capacitor, there is a phase shift between voltage and current such that current always leads the voltage by $90°$.



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Power in a Capacitor

Energy is stored by the capacitor during a portion of the ac cycle and returned to the source during another portion of the cycle.

Voltage and current are always 90° out of phase. For this reason, no true power is dissipated by a capacitor, because stored energy is returned to the circuit.

The rate at which a capacitor stores or returns energy is called **reactive power**. The unit for reactive power is the VA R (volt-ampere reactive).

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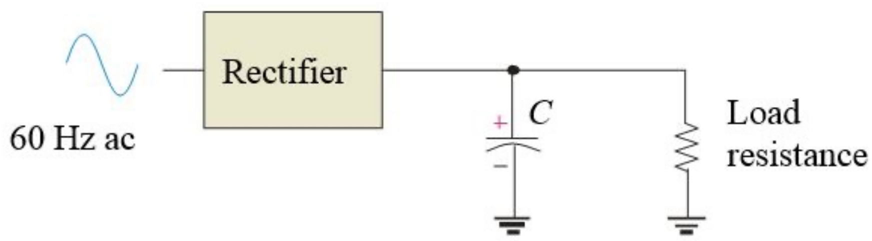
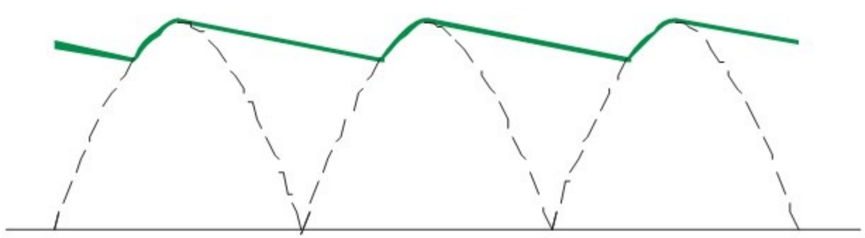
Power Supply Filtering

There are many applications for capacitors. One is in filters, such as the power supply filter shown here.





The filter smooths the pulsating dc from the rectifier.

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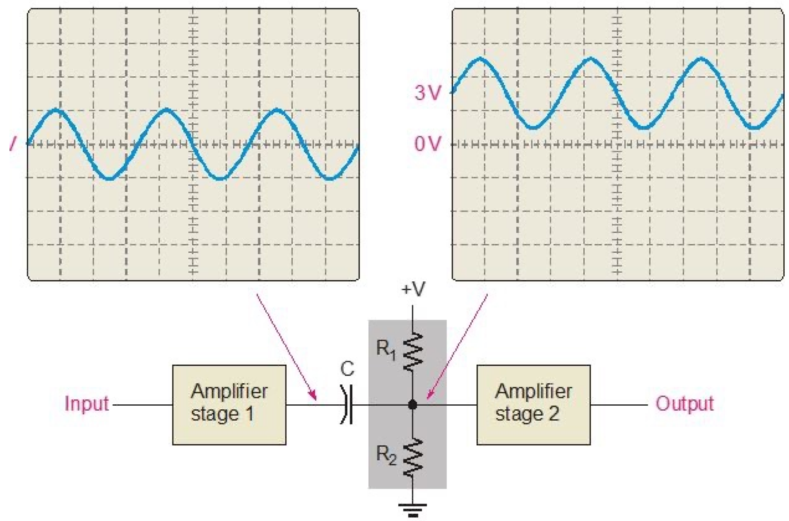
Coupling Capacitors

Coupling capacitors are used to pass an ac signal from one stage to another while blocking dc.



The capacitor isolates dc between the amplifier stages, preventing dc in one stage from affecting the other stage.

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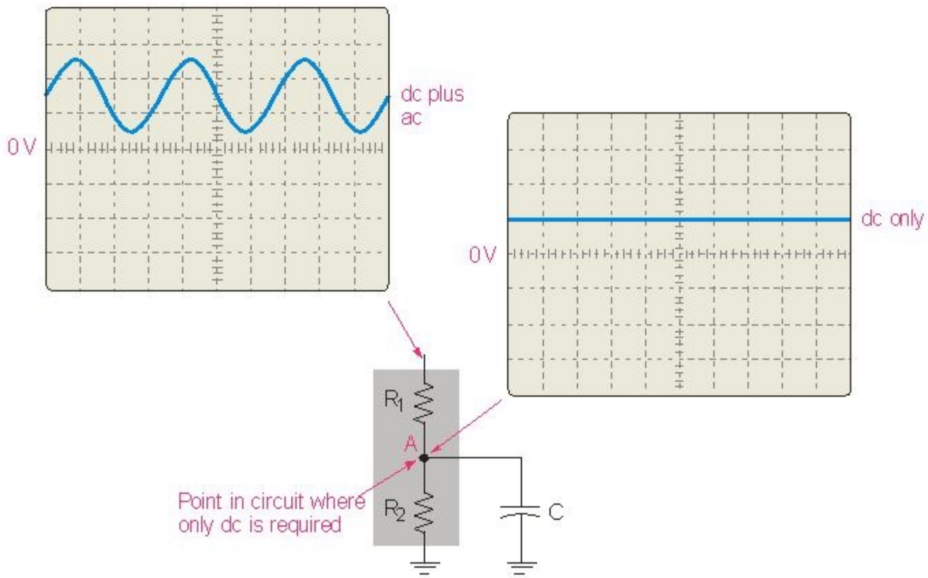
Bypass Capacitors

Another application is to **bypass** an ac signal to ground but retain a dc value. This is widely done to affect gain in amplifiers.



The bypass capacitor places point *A* at ac ground, keeping only a dc value at point *A*.

Selected Key Terms (1 of 2)

Capacitor An electrical device consisting of two conductive plates separated by an insulating material and possessing the property of capacitance.

Dielectric The insulating material between the conductive plates of a capacitor.

Farad The unit of capacitance.

RC time constant A fixed time interval set by the R and C values, that determine the time response of a series RC circuit. It equals the product of the resistance and the capacitance.

Selected Key Terms (2 of 2)

Capacitive reactance	The opposition of a capacitor to sinusoidal current. The unit is the ohm.
Instantaneous power (p)	The value of power in a circuit at a given instant of time.
True power (P_{true})	The power that is dissipated in a circuit usually in the form of heat.
Reactive power(P_r)	The rate at which energy is alternately stored and returned to the source by a capacitor. The unit is the VAR.
VAR *(volt-ampere reactive)*	The unit of reactive power.

Quiz (1 of 11)

1. The capacitance of a capacitor will be larger if

    a. the spacing between the plates is increased.

    b. air replaces oil as the dielectric.

    c. the area of the plates is increased.

    d. all of the above.

Quiz (2 of 11)

2. The major advantage of a mica capacitor over other types is

   a. they have the largest available capacitances.

   b. their voltage rating is very high.

   c. they are polarized.

   d. all of the above.

Quiz (3 of 11)

3. Electrolytic capacitors are useful in applications where

   a. a precise value of capacitance is required.
   b. low leakage current is required.
   c. large capacitance is required.
   d. all of the above.

Quiz (4 of 11)

4. If a $0.015\ \mu F$ capacitor is in series with a 6800 pF capacitor, the total capacitance is

   a. 1568 pF.

   b. 4679 pF.

   c. 6815 pF.

   d. $0.022\ \mu F$.

Quiz (5 of 11)

5. Two capacitors that are initially uncharged are connected in series with a dc source. Compared to the larger capacitor, the smaller capacitor will have

   a. the same charge.

   b. more charge.

   c. less voltage.

   d. the same voltage.

Quiz (6 of 11)

6. When a capacitor is connected through a resistor to a dc voltage source, the charge on the capacitor will reach 50% of its final charge in

   a. less than one time constant.

   b. exactly one time constant.

   c. greater than one time constant.

   d. answer depends on the amount of voltage.

Quiz (7 of 11)

7. When a capacitor is connected through a series resistor and switched to a dc voltage source, the voltage across the resistor after the switch is closed has the shape of

   a. a straight line.

   b. a rising exponential.

   c. a falling exponential.

   d. none of the above.

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Quiz (8 of 11)

8. The capacitive reactance of a $100\ \mu\text{F}$. capacitor to 60 Hz is

   a. $6.14\ \text{k}\Omega$.

   b. $265\ \Omega$.

   c. $37.7\ \Omega$.

   d. $26.5\ \Omega$.

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Quiz (9 of 11)

9. If an sine wave from a function generator is applied to a capacitor, the current will

   a. lag voltage by 90°.

   b. lag voltage by 45°.

   c. be in phase with the voltage.

   d. none of the above.

Quiz (10 of 11)

10. The rate at which a capacitor stores or returns energy is called its

    a. instantaneous power.
    b. reactive power.
    c. true power.
    d. apparent power.

Quiz (11 of 11)

Answers:

1. c	6. a
2. b	7. c
3. c	8. d
4. b	9. d
5. a	10. b

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