MPC Microcontroller SIG

13 June 2018 – Presentation - John Macey

The Mysteries of CAPACITORS

In response to requests

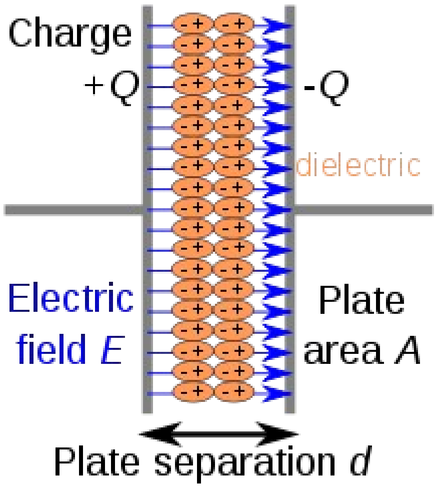
A brief introduction,
for electronics newcomers

With a few examples of their application

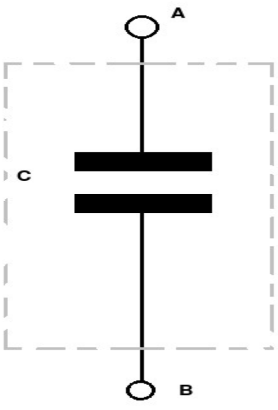
this presentation will be posted on our website

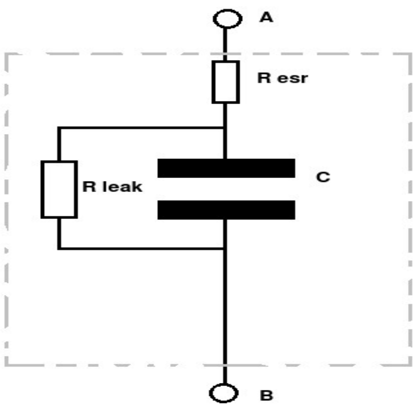
Capacitors are used in just about every electronic device.

All are basically 2 conducting (metal) plates separated by a dielectric material :-



This is the usual circuit symbol on the left and the reality of a “real” capacitor on the right including leakage and series resistive losses





They come in many forms

2 basic types of capacitors

Polarised (with semi-liquid paste dielectric)

- Aluminium (electrolytic)
- Tantalum (electrolytic)
- Super Capacitors (very high capacity)

(mainly used in power applications at low-modest (DC – kHz) frequencies)

Non-Polarised (with dielectrics of) :-

- paper (older technology, now rare)
- glass (older technology, now rare)
- silver mica (older technology, now rare)
- polycarbonate (Mylar) – now rare
- polypropylene
- polyester or polyester film
- ceramic (several sub-types)
- air (radio tuning capacitors)

(used at mid-high frequencies (kHz-MHz) for AC coupling, DC blocking, filtering and tuning purposes)

The choice of the correct capacitor type for an application is important.
A circuit may not work correctly if a wrong type of capacitor is used.

Electrolytic capacitor: Electrolytic capacitors are a type of capacitor that is polarised. They are able to offer high capacitance values - typically 1-10,000μF, and are most widely used in low frequency applications - power supplies, decoupling and audio coupling applications as they have a frequency limit of around 100 kHz.

Tantalum capacitor: Like electrolytic capacitors, tantalum capacitors are also polarised and offer a very high capacitance level for their volume. However this type of capacitor is very intolerant of being reverse biased, often exploding when placed under stress. This type of capacitor must also not be subject to high ripple currents or voltages above their working voltage. They are available in both leaded and surface mount formats. Relatively expensive.

Supercap: Also known as a supercapacitor, these capacitors have very large values of capacitance, of up to several thousand Farads. They find uses for providing a memory hold-up power supply and also some automotive applications. Rarely encountered.

Silver Mica Capacitor: Silver mica capacitors are not so widely used these days, but they still offer very high levels of stability, low loss and accuracy where space is not an issue. They are primarily used for RF applications and are limited to maximum values of 1000 pF or so.

Polycarbonate capacitor: Used in applications where reliability and performance are critical. Very stable and high tolerance which will hold their capacitance value over time. Also they have a low dissipation factor and they remain stable over a wide temperature range. They are expensive and these days, cheaper alternatives are available.

Polypropylene Capacitor: Used when an application requires a higher tolerance than polyester capacitors can provide. There is very little change of capacitance with time and voltage applied. This type of capacitor is also used for low frequencies, with 100 kHz or so being the upper limit. They are generally only available as leaded electronics components.

Polyester Film Capacitor: Polyester film capacitors are used where cost is a consideration as they do not offer tight tolerances. Most polyester film capacitors have a tolerance of 5% or 10%, which is adequate for many applications. They are generally only available as leaded electronics components. Very common.

Metallised Polyester Film Capacitor: This type of capacitor is a essentially a form of polyester film capacitor where the polyester films themselves are metallised. The advantage of using this process is that because their electrodes are thin, the overall capacitor can be contained within a relatively small package. The metallised polyester film capacitors are generally only available as leaded electronics components.

Ceramic capacitor: Used in many applications from audio to RF. Values range from a few picofarads to around 0.1 microfarads. By far the most commonly used type of capacitor being cheap and reliable and their loss factor is particularly low. The 1000pF value is very commonly used on PCBs for power bus noise filtering. Available in both leaded and surface mount formats and a variety of electrical/temperature characteristics.

Values and Markings

Capacity (C) is measured in Farads
C = Q/V
where Q = charge in coulombs and V = voltage in Volts
1 coulomb = charge delivered by 1 Ampere for 1 second

A Farad is an uncommonly encountered big unit!
Most common capacitor values are designated in:-
µF (10^-6 F) = F/1,000,000)
or nF (10^-9 F) = F/1,000,000,000
or pF (10^-12 F) = F/1,000,000,000,000

Larger sized capacitors are usually marked with their capacitance value (and voltage rating) printed in text.

Smaller sizes employ a 3 digit code with the value (in pF) in the first 2 digits and the number of zeros in the 3rd digit. eg. 104= 100,000 pF = 100nF = .1 µF

Small values are marked directly as 1 or 2 digits (in pF)

Charging and Discharging

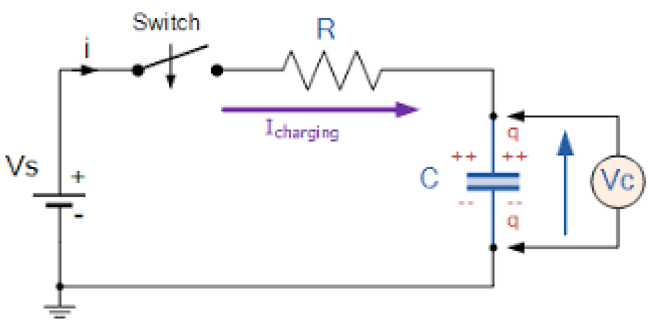
When capacitor is charged from 0 Volts by a voltage V (Volts) through a source with resistance R (Ohms) it's voltage rises quickly at first, then at a slower and slower rate until it eventually reaches full charge at the charging voltage V.

Charging/discharging rates are a function of the circuit's time-constant (T(secs) = RC).

[it's worth remembering,1MΩ and 1µF → RC = 1 sec]

It charges to about 63% of it's final voltage in 1 time-constant and takes about 4 time-constants to reach 99% full charge.

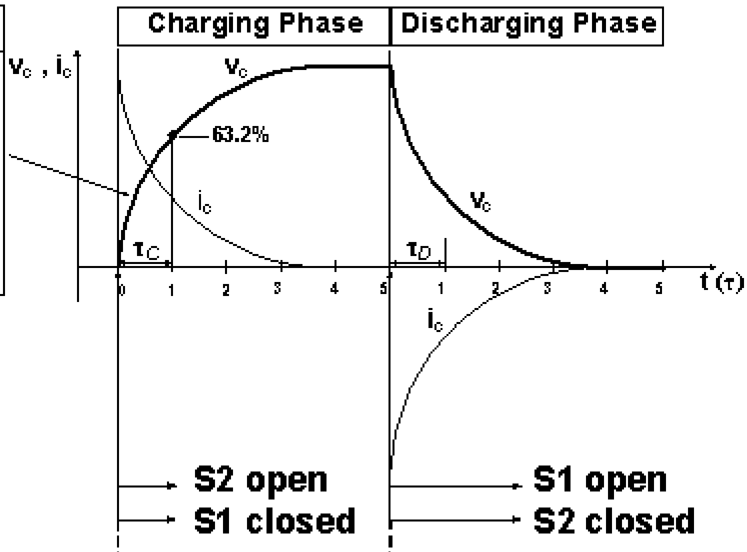
Conversely, a fully charged capacitor discharges to about 37% of it's initial voltage in 1 time-constant and to within 1% of zero volts in about 4 time-constants



This is what the charge and discharge curves look like

Charging Phase
v_c versus τ_c

τ_C	Magnitude (V)
0	0%
1 τ_C	63.2%
2 τ_C	86.5%
3 τ_C	95%
4 τ_C	98.2%
5 τ_C	100%



Charging phase:

$\tau_C = R_C \times C$

$v_c = V(1 - e^{-t/\tau_C})$

$i_c = V / R_C \, e^{-t/\tau_C}$

Discharging phase:

$\tau_D = R_D \times C$

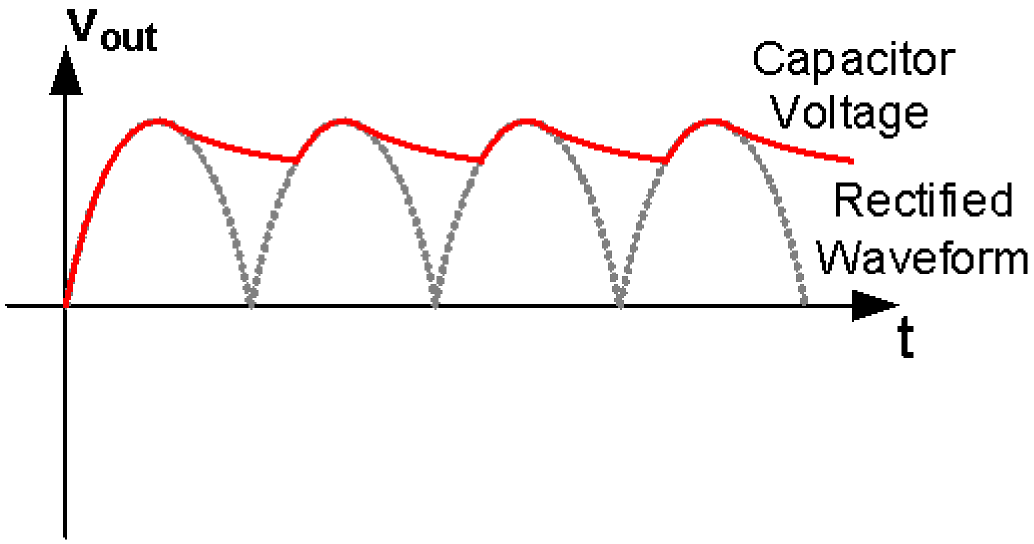
$v_c = V \, e^{-t/\tau_D}$

$i_c = -(V / R_D) \, e^{-t/\tau_D}$

Charge Storage/ Power Supply Filtering

Universally used to reduce the ripple voltage on the DC output of power supplies.

The circuits exploit the fact that power supply rectifier circuits have much lower source resistance than the resistance of the load they are feeding.



So the filter capacitor charges up to the design voltage very quickly from the low resistance supply source but discharges much slower to the higher resistance load.

This reduces the raw output ripple very substantially.

Even better ripple reduction can be obtained by inserting a series inductance between the source and the shunt capacitor.

Filtering

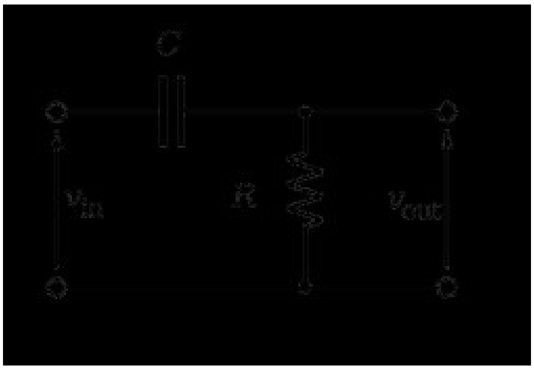
Capacitors (C in Farads) have a Reactance (Xc in Ohms) which varies with the applied frequency (F in Hz)

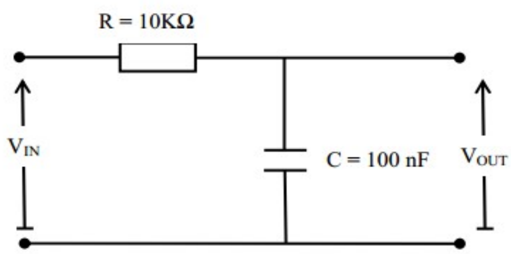
$$X_c = 1/\ (2\pi FC)$$

(Reactance resists current flow, somewhat like the effect of a resistor resisting current flow)

DC (F=0Hz) is completely blocked by a capacitor. Low-medium frequencies suffer some resistance, reducing to very little resistance at higher frequencies

So, a capacitor in series in a circuit acts as a high-pass filter, passing higher frequencies and resisting lower frequencies (completely blocking DC).

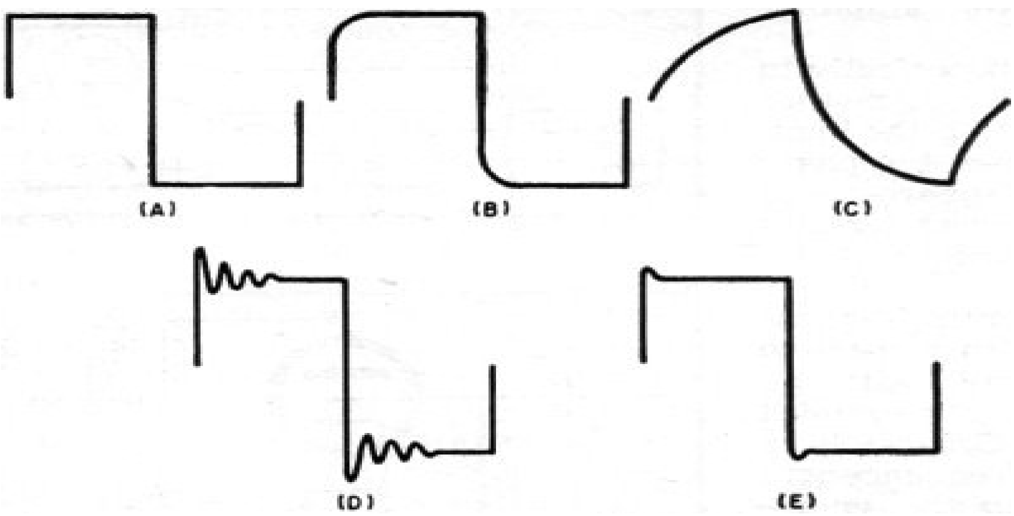




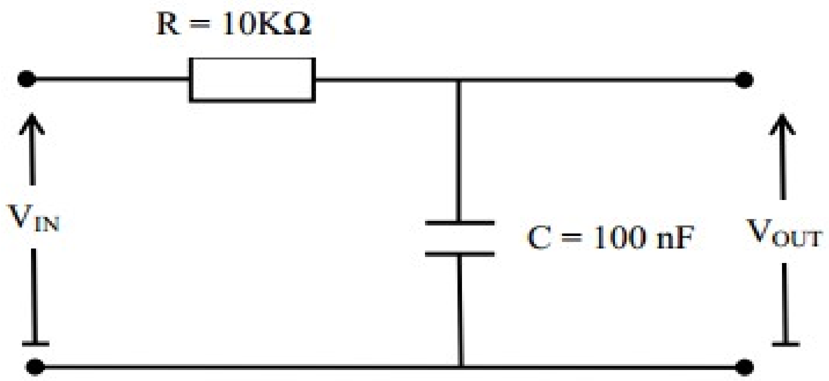
Conversely, a capacitor connected in shunt (eg. to ground) in a circuit, acts as a low-pass filter, passing DC and lower frequencies with no/little attenuation, but shunting higher frequencies away to ground

This low-pass filter effect is used in many applications to reduce high-frequency noise and eliminate unwanted voltage spikes.

Here are some examples:-
Square waves (A) are frequently generated/found with overshoot and undershoot spikes (D), caused by fast-rising/falling leading and trailing edges (which contain high frequency, harmonic components).

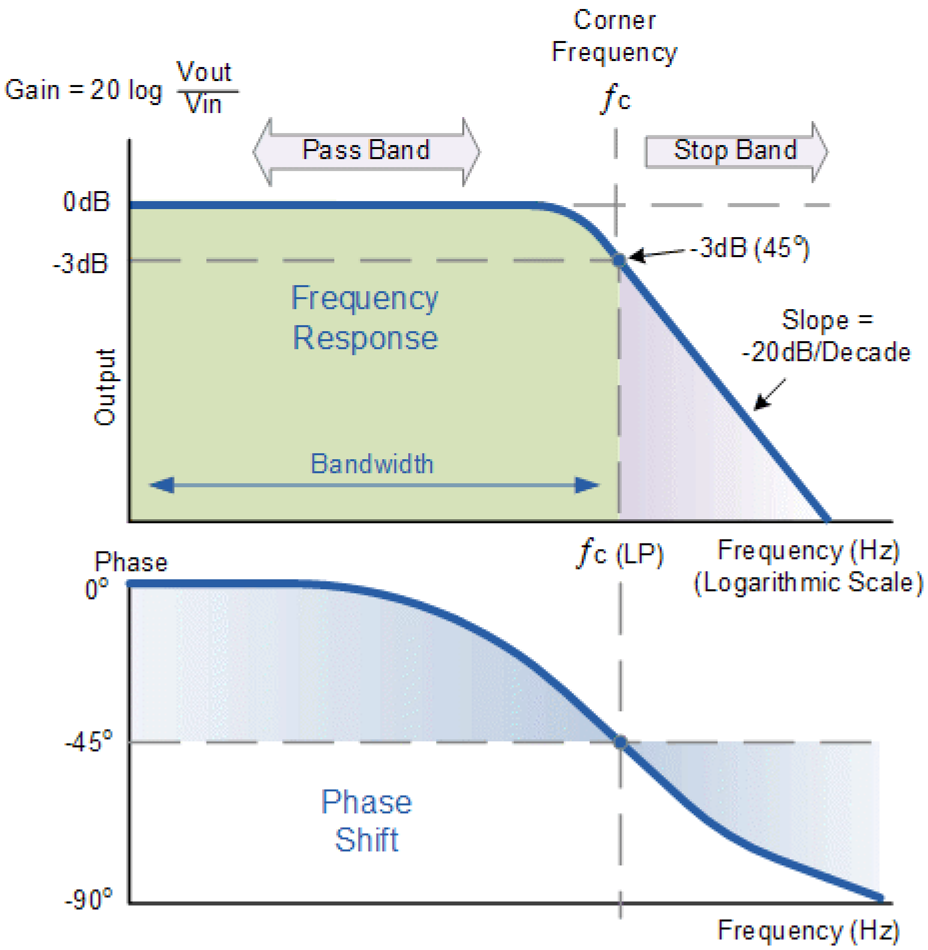


A low-pass filter circuit like below with an RC time constant of (10,000 x 100/1,000,000,000) = .001 will reduce the power of frequencies present at 1/2πRC ≈ 160Hz by ½. and reduce higher frequencies by a further ½ for every doubling of frequency (E).
[50% power ≈ 70% voltage] … other RC combinations with RC=.001 would behave the same.



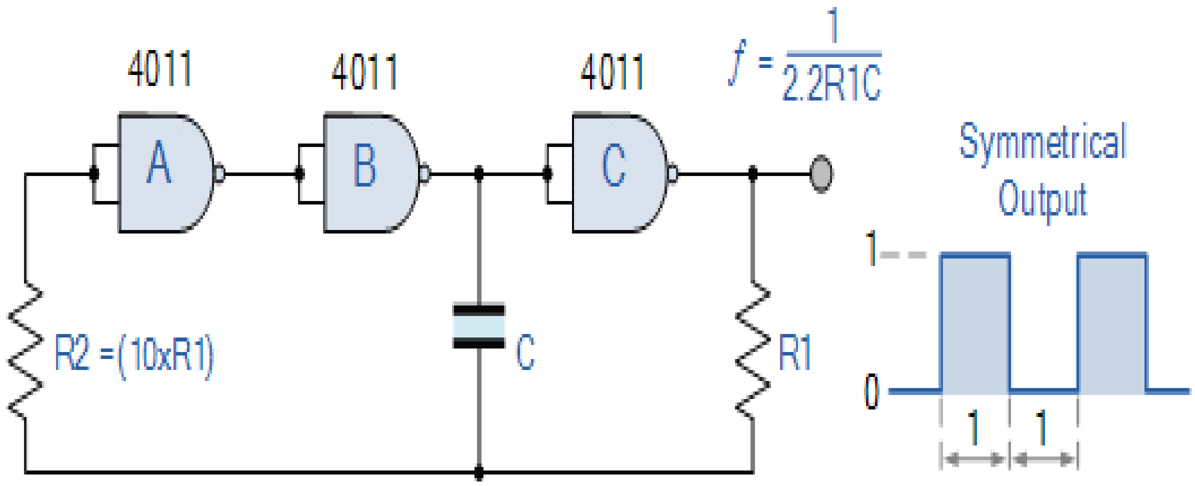
Higher values of RC will cause rounding of leading and trailing edges (B). Even higher RC values will result in an output like (C).

This simple RC filter response looks like this

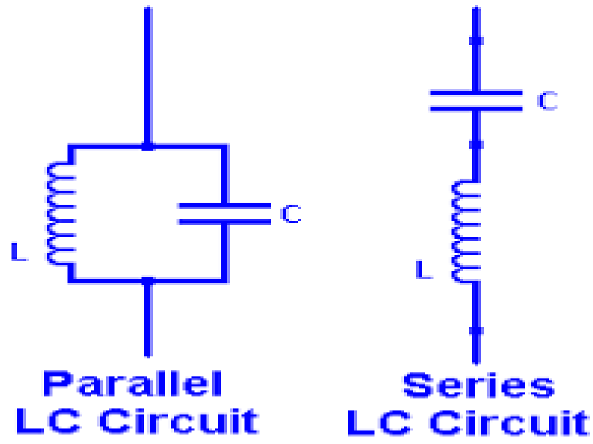


Tuning, Setting Clock Frequencies

An RC combination can be used to produce a clock generator using IC gates in a circuit like this :-



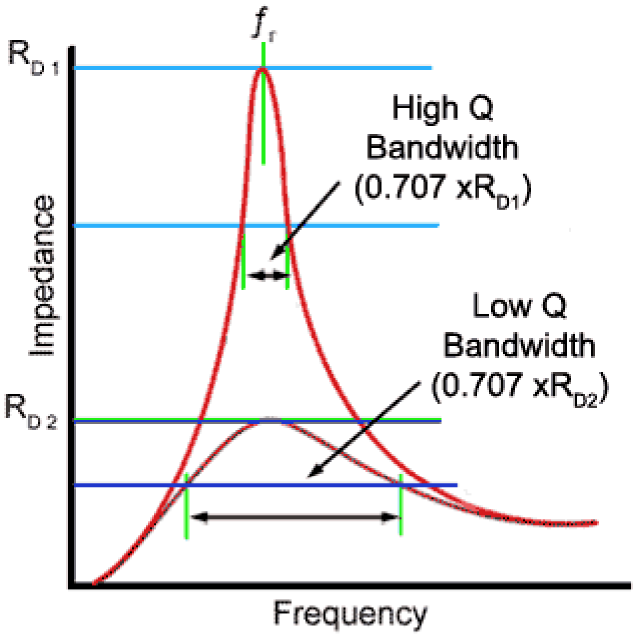
Or a combination of an inductance and a capacitor



acts as a relatively sharp (narrow bandwidth) tuned circuit. Resonant at:-

$$f_0 \equiv \frac{1}{2\pi\sqrt{LC}}$$

The sharpness of the circuit's resonance depends on the loss resistances associated with the capacitor (series resistance and leakage resistance) and the series resistance loss in the inductor. The smaller these losses, the higher the “quality” Q and the narrower the bandwidth.

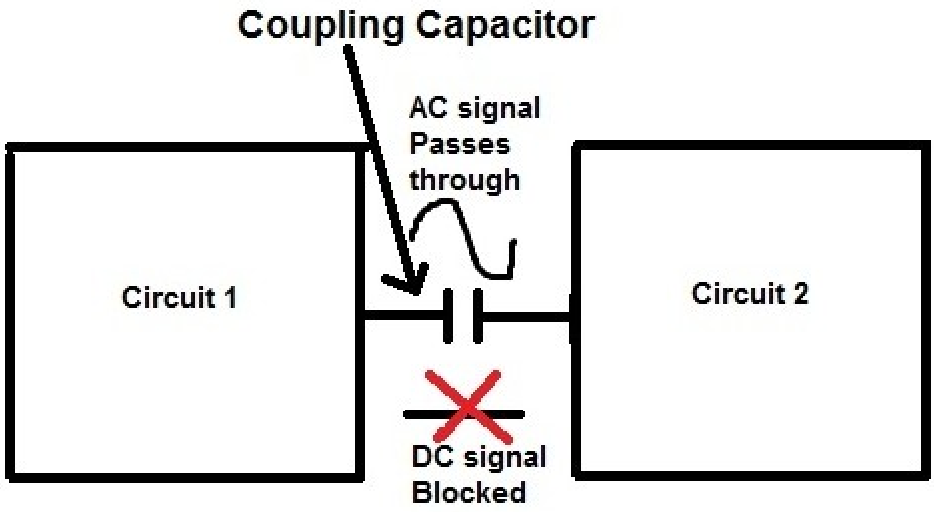


Typically, these oscillator/clock circuits would use high stability plastic capacitors or ceramic capacitors at low-mid frequencies and ceramic capacitors at RF frequencies (1MHz and up).
At lower frequencies (a few Hz) RC circuits may use electrolytic capacitors, where temperature stability, long-term stability and frequency precision are not necessary characteristics.
A simple delay circuit using a 470KHz resistor and a good 1000 µF capacitor (RC= 470) could produce a square- wave with a period of about 4 minutes.

By making one of the components above adjustable, a variable frequency device can be built.

Capacitive Coupling

Capacitive coupling allows the transfer of alternating electrical signals from one segment of a circuit to another. The coupling provides a series capacitor connection for the AC signals while blocking the DC energy.



Here is a typical application:-

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