OSCILLATORS

Objectives

- Describe the basic concept of an oscillator
- Discuss the basic principles of operation of an oscillator
- Describe the operation of Phase-Shift Oscillator, Wien Bridge Oscillator, Crystal Oscillator and Relaxation Oscillator

Introduction

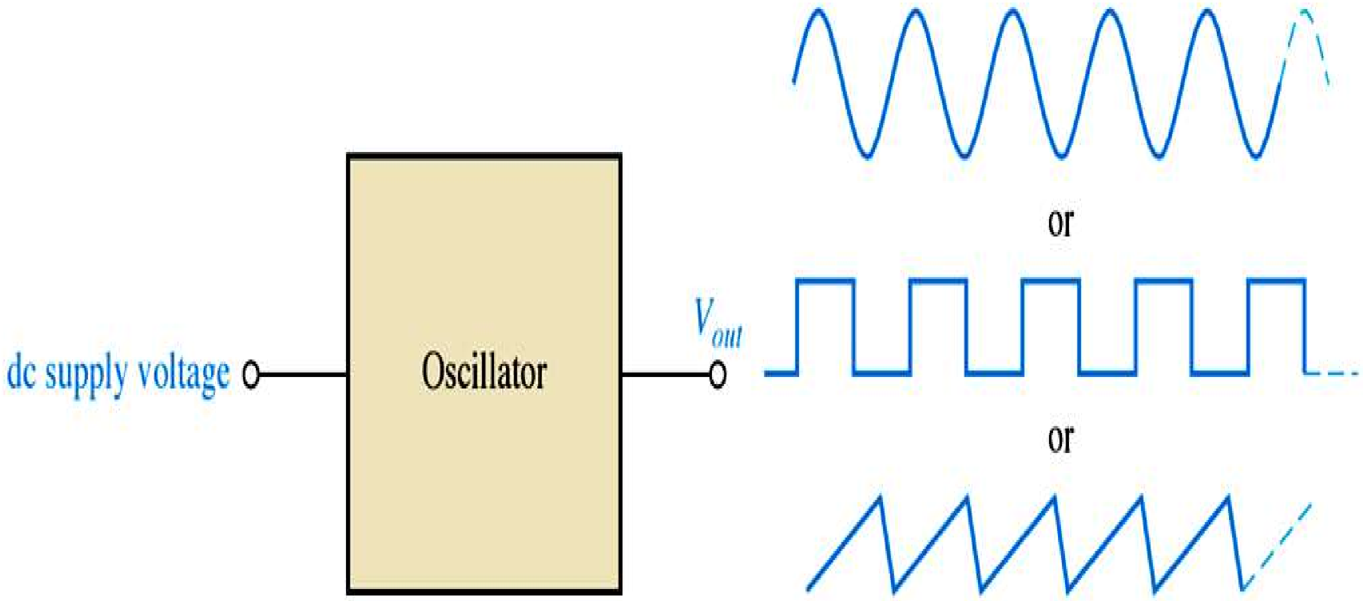
Oscillators are circuits that produce a continuous signal of some type without the need of an input.

These signals serve a variety of purposes such as communications systems, digital systems (including computers), and test equipment

The Oscillator

- ❖ An oscillator is a circuit that produces a repetitive signal from a dc voltage.
- ❖ The **feedback oscillator** relies on a **positive feedback** of the output to maintain the oscillations.
- ❖ The **relaxation oscillator** makes use of an RC timing circuit to generate a non-sinusoidal signal such as square wave.

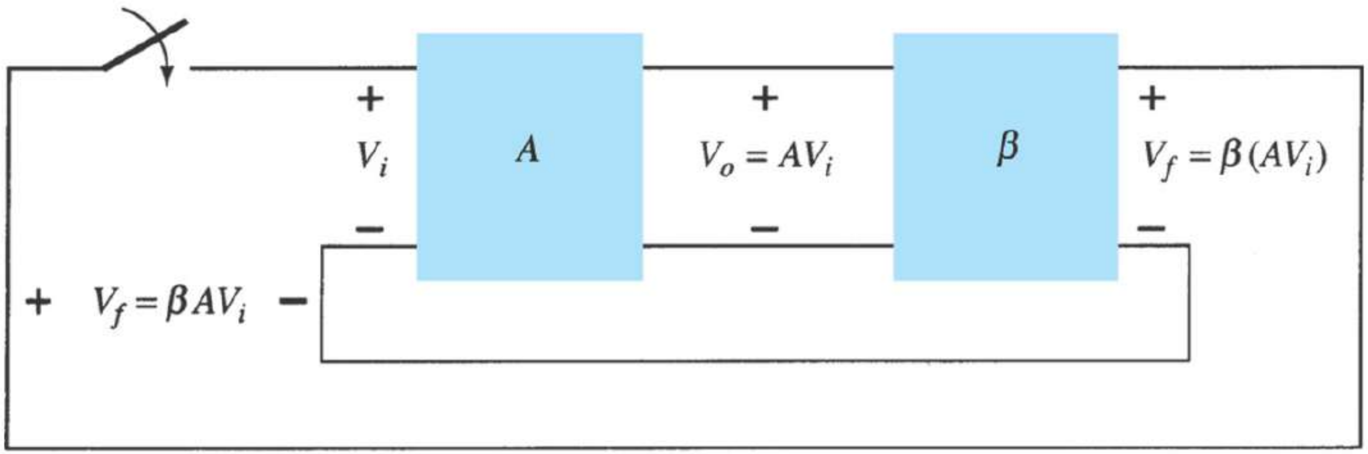
The Oscillator



Types of Oscillator

1. RC Oscillator - Wien Bridge Oscillator
   - Phase-Shift Oscillator
2. LC Oscillator - Crystal Oscillator
3. Relaxation Oscillator

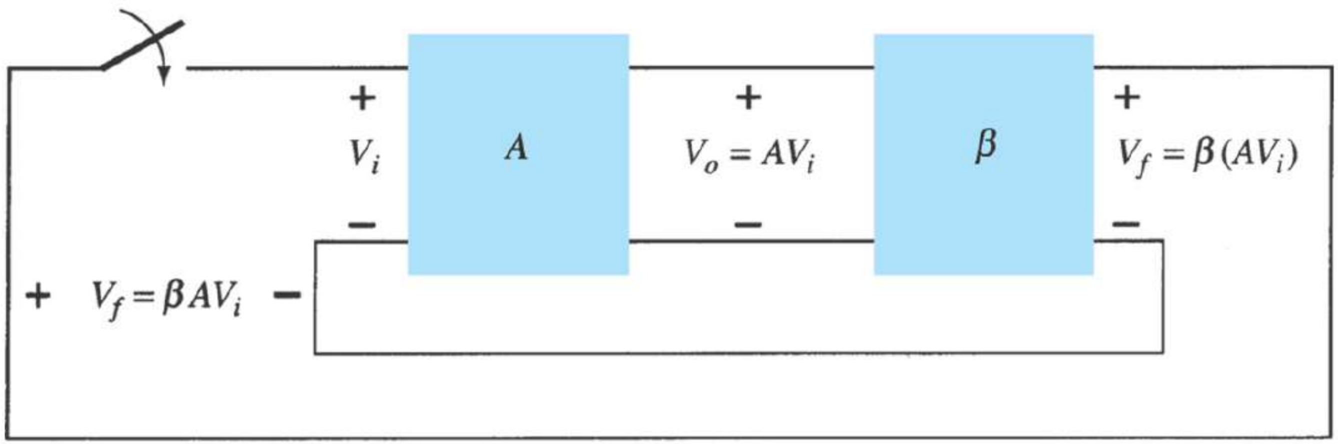
Feedback Oscillator Principles



Positive feedback circuit used as an oscillator

- When switch at the amplifier input is open, no oscillation occurs.
- Consider $V_{i,}$, results in $V_o = AV_i$ (after amplifier stage) and $V_f = \beta(AV_i)$ (after feedback stage)
- Feedback voltage $V_f = \beta(AV_i)$ where βA is called the **loop gain**.
- In order to maintain $\mathbf{V_f = V_i}$, **βA** must be in the **correct magnitude** and **phase**.

Feedback Oscillator Principles

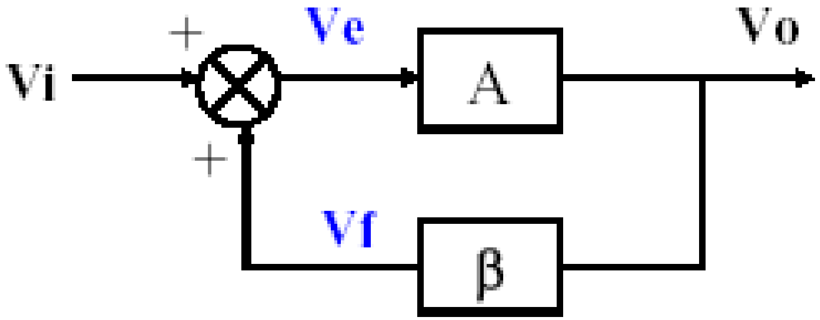


Positive feedback circuit used as an oscillator

- When the switch is closed and **V_i is removed**, the circuit **will continue operating** since the feedback voltage is sufficient to drive the amplifier and feedback circuit, resulting in proper input voltage to sustain the loop operation.

Feedback Oscillator Principles

- An oscillator is an amplifier with **positive feedback**.



$V_e = V_i + V_f$ (1)

$V_o = AV_e$ (2)

$V_f = \beta(AV_e) = \beta V_o$ (3)

From (1), (2) and (3), we get

$$A_f \equiv \frac{V_o}{V_s} = \frac{A}{(1 - A\beta)}$$

where βA is loop gain

Feedback Oscillator Principles

In general A and β are functions of frequency and thus may be written as;

$$A_f(s) = \frac{V_o}{V_s}(s) = \frac{A(s)}{1 - A(s)\beta(s)}$$

$A(s)\beta(s)$ is known as **loop gain**

Feedback Oscillator Principles

Writing $T(s) = A(s)\beta(s)$ the loop gain becomes;

$$A_f(s) = \frac{A(s)}{1 - T(s)}$$

Replacing s with $j\omega$;

$$A_f(j\omega) = \frac{A(j\omega)}{1 - T(j\omega)}$$

and $T(j\omega) = A(j\omega)\beta(j\omega)$

Feedback Oscillator Principles

At a specific frequency f_0;

$$T(j\omega_0) = A(j\omega_0)\beta(j\omega_0) = 1$$

At this frequency, the closed loop gain;

$$A_f(j\omega_0) = \frac{A(j\omega_0)}{1 - A(j\omega_0)\beta(j\omega_0)} = \frac{A(j\omega_0)}{(1-1)} = \infty$$

will be infinite, i.e. the circuit will have finite output for zero input signal – thus we have oscillation

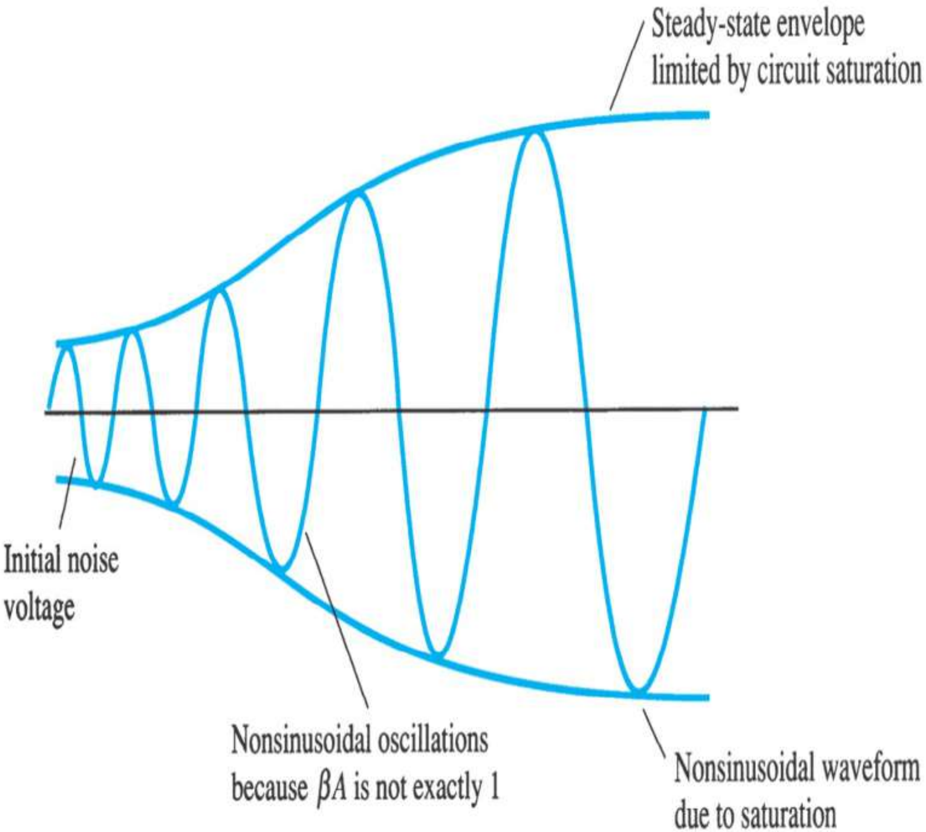
Design Criteria for oscillators

1) **|Aβ|** equal to **unity** or slightly larger at the desired oscillation frequency.

   - **Barkhaussen criterion**, **|Aβ|=1**

2) Total **phase shift,ϕ** of the loop gain must be **0°** or 360°.

Build-up of steady- state oscillations



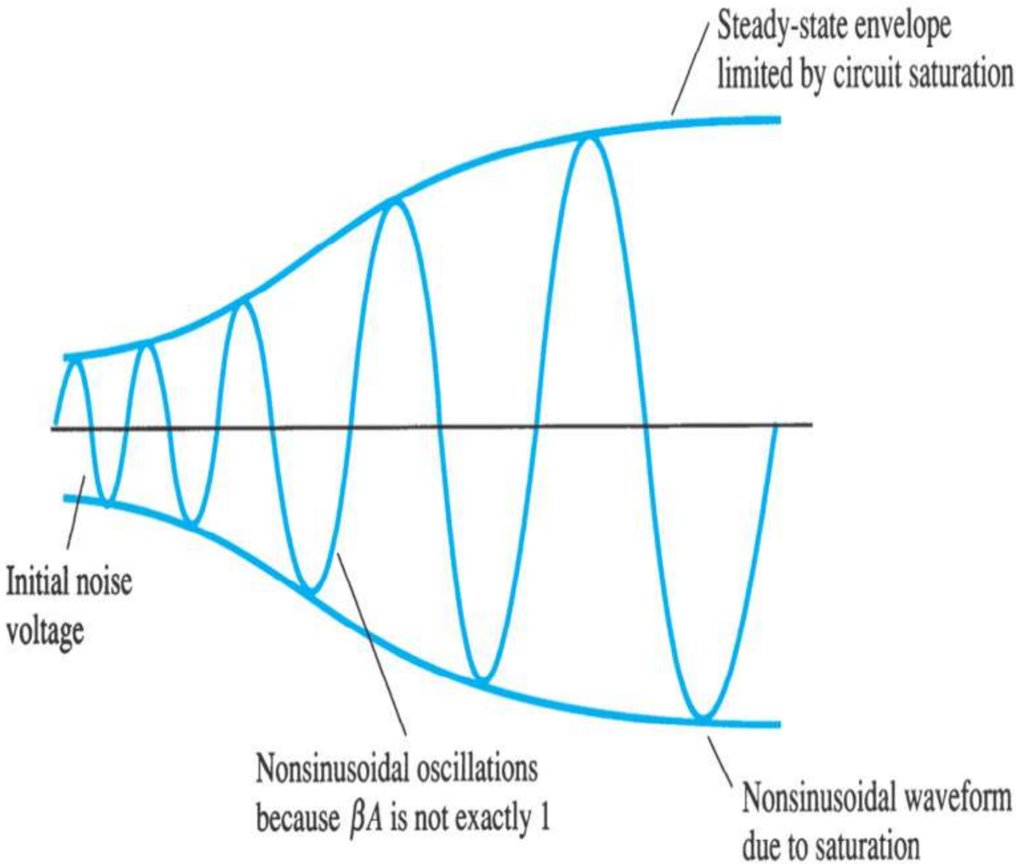
Build-up of steady-state oscillations

❖ The unity gain condition must be met for oscillation to be sustained

❖ In practice, for oscillation to **begin**, the voltage gain around the positive feedback loop must be **greater than 1** so that the amplitude of the output can build up to the desired value.

❖ If the overall gain is greater than 1, the oscillator eventually saturates.

Build-up of steady- state oscillations



Buildup of steady-state oscillations

- ❖Then voltage gain decreases to 1 and maintains the desired amplitude of waveforms.
- ❖ The resulting waveforms are never exactly sinusoidal.
- ❖ However, the closer the value βA to 1, the more nearly sinusoidal is the waveform.

Factors that determine the frequency of oscillation

- ❖Oscillators can be classified into many types depending on the feedback components, amplifiers and circuit topologies used.

- ❖RC components generate a sinusoidal waveform at a few Hz to kHz range.

- ❖LC components generate a sine wave at frequencies of 100 kHz to 100 MHz.

- ❖Crystals generate a square or sine wave over a wide range,i.e. about 10 kHz to 30 MHz.

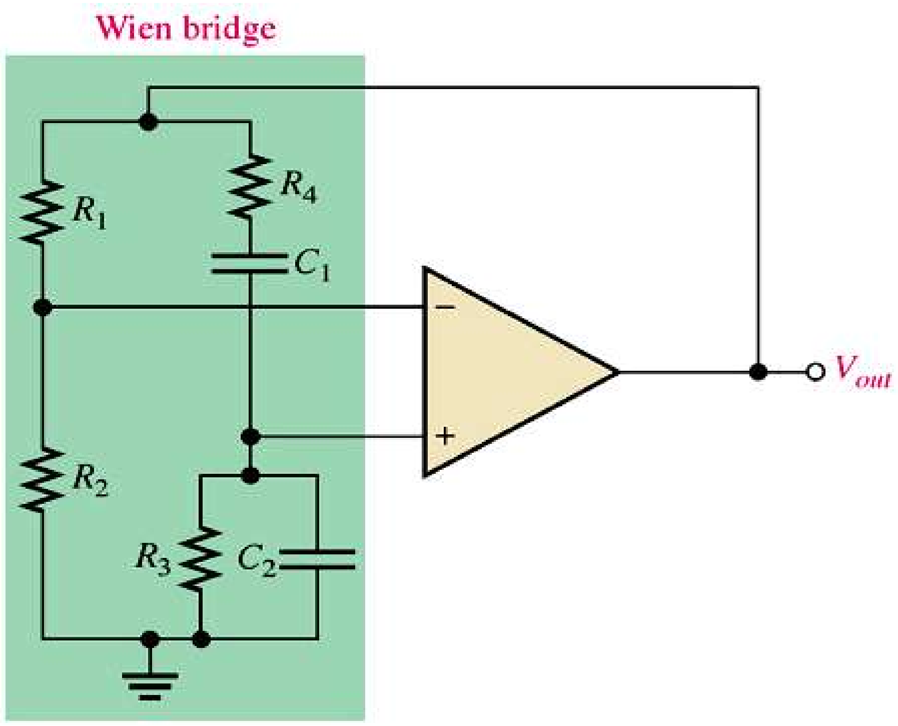
1. RC Oscillators

1. RC Oscillators

- RC feedback oscillators are generally limited to frequencies of 1MHz or less
- The types of RC oscillators that we will discuss are the Wien-Bridge and the Phase Shift

Wien-Bridge Oscillator

- It is a low frequency oscillator which ranges from a few kHz to 1 MHz.
- Structure of this oscillator is



Wien-Bridge Oscillator

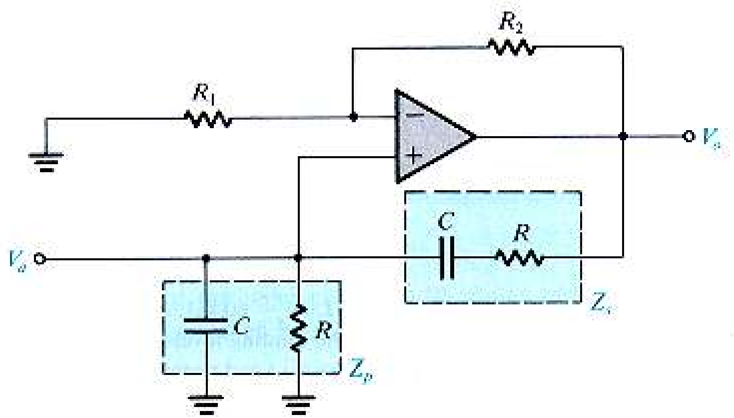
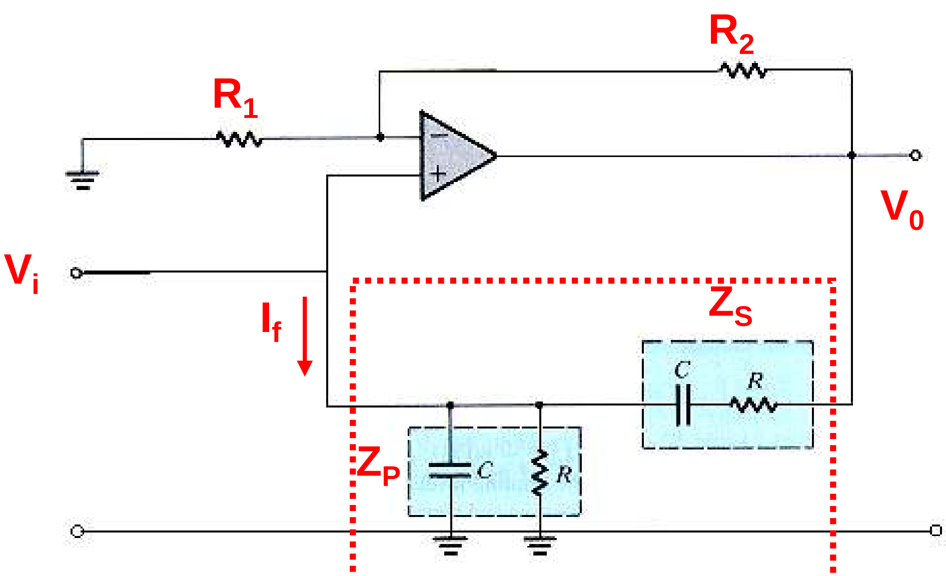
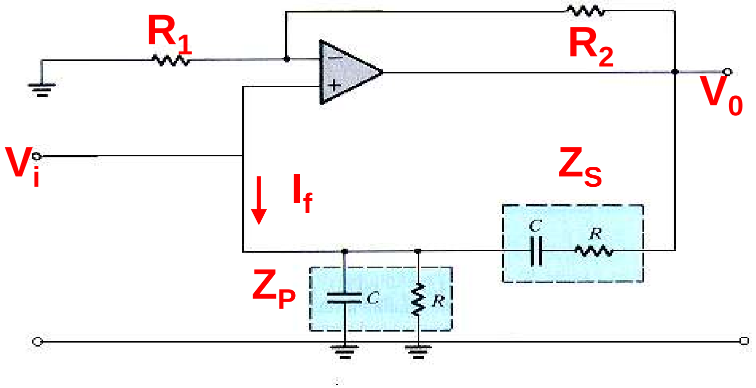


Fig. 12.4 Wien-bridge oscillator without amplitude stabilization.



- Based on op amp
- Combination of R's and C's in feedback loop so feedback factor β_f has a frequency dependence.
- Analysis assumes op amp is ideal.
  - Gain A is very large
  - Input currents are negligibly small (I_+ ⍰ $I\_$ ⍰ 0).
  - Input terminals are virtually shorted (V_+ ⍰ $V\_$).
- Analyze like a normal feedback amplifier.
  - Determine input and output loading.
  - Determine feedback factor.
  - Determine gain with feedback.
- Shunt-shunt configuration.

Wien Bridge Oscillator



Define

$$Z_S = R + Z_C = R + \frac{1}{sC} = \frac{1 + sRC}{sC}$$

$$Z_P = R \| Z_C = \left(\frac{1}{R} + \frac{1}{Z_C}\right)^{-1} = \left(\frac{1}{R} + sC\right)^{-1}$$

$$= \frac{R}{1 + sCR}$$

Wien-Bridge Oscillator

Oscillation condition

Phase of $\beta_f A_r$ equal to 180°. It already is since $\beta_f A_r < 0$.

Then need only $\left|\beta_f A_r\right| = \left(1+\frac{R_2}{R_1}\right)\frac{sCR}{sCR+(1+sCR)^2} = 1$

Rewriting

$$\left|\beta_f A_r\right| = \left(1+\frac{R_2}{R_1}\right)\frac{sCR}{sCR+(1+sCR)^2}$$

$$= \left(1+\frac{R_2}{R_1}\right)\frac{sCR}{sCR+\left(1+2sCR+s^2C^2R^2\right)}$$

$$= \left(1+\frac{R_2}{R_1}\right)\frac{sCR}{1+3sCR+s^2C^2R^2} = \left(1+\frac{R_2}{R_1}\right)\frac{1}{3+\frac{1}{sCR}+sCR}$$

$$= \left(1+\frac{R_2}{R_1}\right)\frac{1}{3+j\left(\omega CR-\frac{1}{\omega CR}\right)}$$

Then imaginary term $= 0$ at the oscillation frequency

$$\omega = \omega_o = \frac{1}{RC}$$

Then, we can get $\left|\beta_f A_r\right| = 1$ by selecting the resistors R_1 and R_2 appropriately using

$$\left(1+\frac{R_2}{R_1}\right)\frac{1}{3} = 1 \quad or \quad \frac{R_2}{R_1} = 2$$

Wien-Bridge Oscillator

Multiply the top and bottom by $j\omega C_{1,}$ we get

$$\frac{V_1}{V_o} = \frac{j\omega C_1 R_2}{(1 + j\omega C_1 R_1)(1 + j\omega C_2 R_2) + j\omega C_1 R_2}$$

Divide the top and bottom by C_1 R_1 C_2 R_2

$$\frac{V_1}{V_o} = \frac{j\omega}{R_1 C_2 \left(\frac{1}{R_1 C_1 R_2 C_2} + j\omega \left(\frac{R_1 C_1 + R_2 C_2 + R_2 C_1}{R_1 C_1 R_2 C_2} \right) - \omega^2 \right)}$$

Wien-Bridge Oscillator

Now the amp gives

$$\frac{V_0}{V_1^{'}} = K$$

Furthermore, for steady state oscillations, we want the feedback V_1 to be exactly equal to the amplifier input, V_1'. Thus

$$\frac{V_1^{'}}{V_o} = \frac{1}{K} = \frac{V_1}{V_o}$$

Wien-Bridge Oscillator

Hence $$\frac{1}{K} = \frac{j\omega}{R_1C_2\left(\frac{1}{R_1C_1R_2C_2} + j\omega\left(\frac{R_1C_1 + R_2C_2 + R_2C_1}{R_1C_1R_2C_2}\right) - \omega^2\right)}$$

$$\frac{j\omega K}{R_1C_2} = \left(\frac{1}{R_1C_1R_2C_2} + j\omega\left(\frac{R_1C_1 + R_2C_2 + R_2C_1}{R_1C_1R_2C_2}\right) - \omega^2\right)$$

Equating the real parts,

$$\frac{1}{R_1C_1R_2C_2} - \omega^2 = 0 \qquad K = \frac{R_1C_1 + R_2C_2 + R_2C_1}{R_2C_1}$$

Wien-Bridge Oscillator

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$

$$K = 3$$

A_{cl}

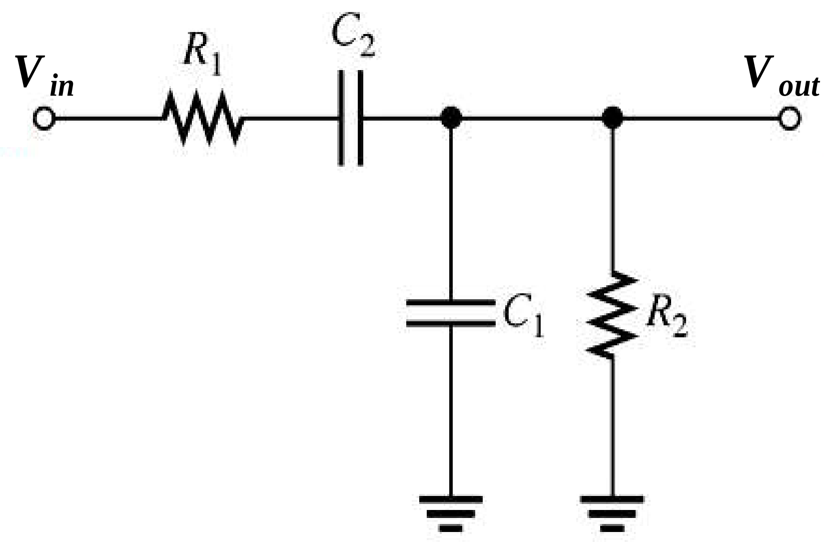
$$\omega = \frac{1}{RC}$$

$$f_r = \frac{1}{2\pi RC}$$

- Gain > 3 : growing oscillations
- Gain < 3 : decreasing oscillations

K = 3 ensured the loop gain of unity - oscillation

Wien-Bridge Oscillator

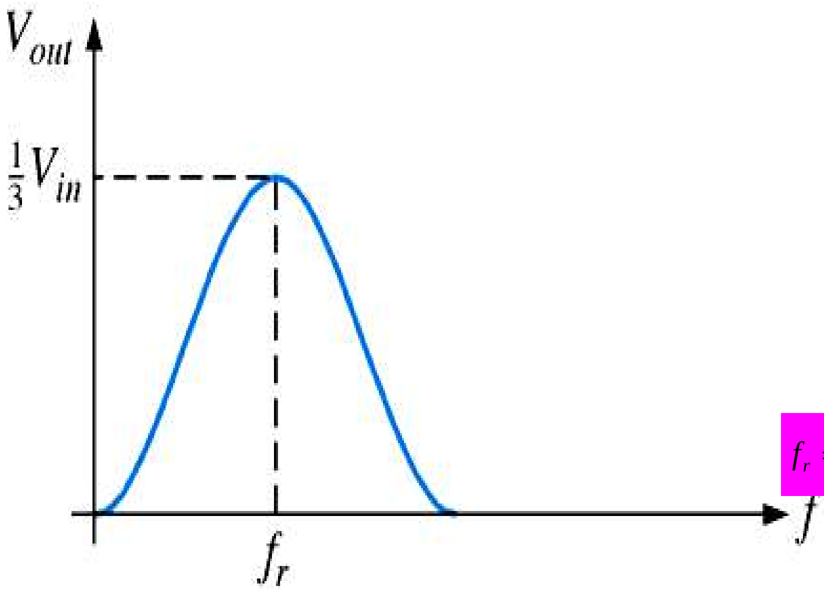


A lead-lag circuit

❖ The fundamental part of the Wien-Bridge oscillator is a lead-lag circuit.

❖ It is comprise of R_1 and C_1 is the ***lag*** portion of the circuit, R_2 and C_2 form the ***lead*** portion

Wien-Bridge Oscillator

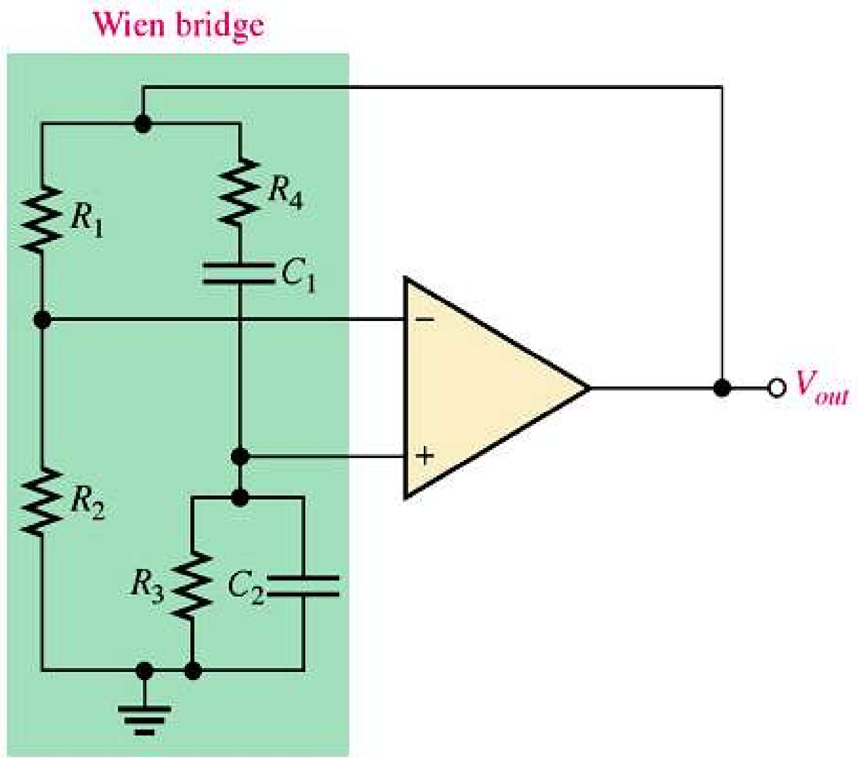


Response Curve

- The lead-lag circuit of a Wien-bridge oscillator **reduces** the input signal by 1/3 and yields a response curve as shown.
- The response curve indicate that the output voltage peaks at a frequency is called **frequency resonant.**
- The frequency of resonance can be determined by the formula below.

$$f_r = \frac{1}{2\pi RC}$$

Wien-Bridge Oscillator

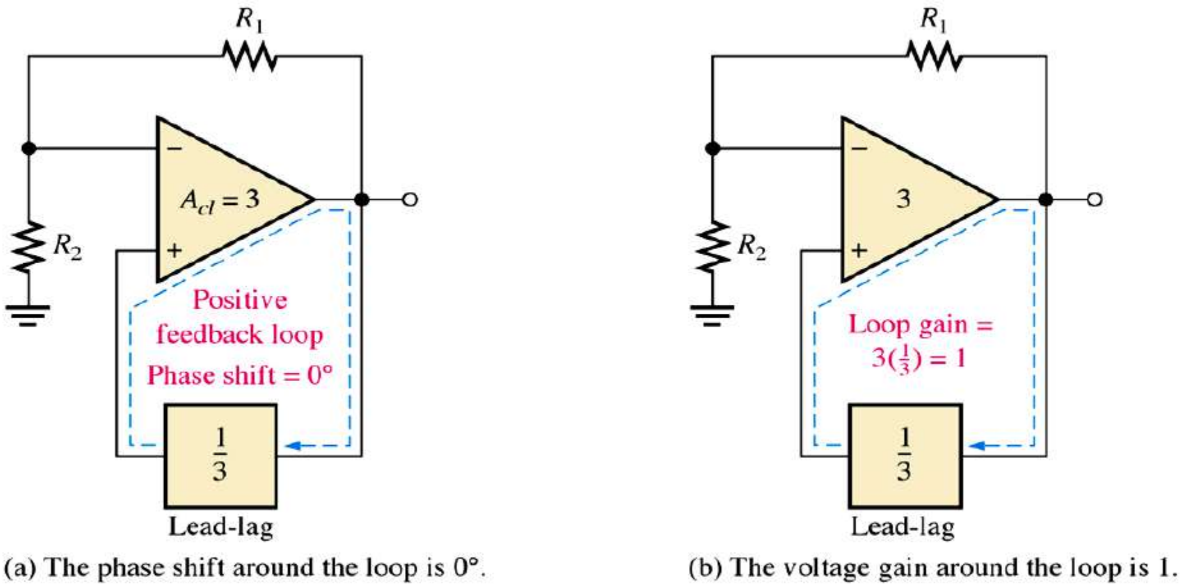


(b) Wien bridge circuit combines a voltage divider and a lead-lag circuit.

Basic circuit

- ❖ The lead-lag circuit is in the positive feedback loop of Wien-bridge oscillator.
- ❖ The **voltage divider limits gain (determines the closed-loop gain)**. The lead lag circuit is basically a band-pass with a narrow bandwidth.
- ❖The Wien-bridge oscillator circuit can be viewed as a noninverting amplifier configuration with the input signal fed back from the output through the lead-lag circuit.

Wien-Bridge Oscillator



Conditions for sustained oscillation

- ❖ The 0º phase-shift condition is met when the frequency is f_r because the phase-shift through the lead lag circuit is 0º
- ❖ The unity gain condition in the feedback loop is met when $A_{cl} = 3$

Wien-Bridge Oscillator

❖ Since there is a loss of about 1/3 of the signal in the positive feedback loop, the **voltage-divider ratio** must be adjusted such that a positive feedback loop gain of **1** is produced.

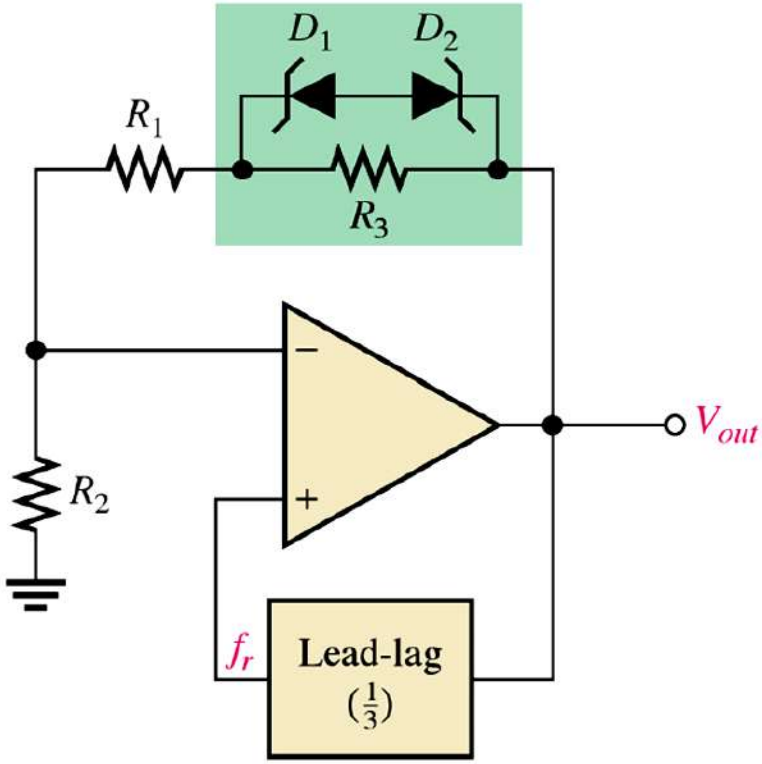
❖This requires a closed-loop gain of 3.

❖The ratio of R_1 and R_2 can be set to achieve this. In order to achieve a closed loop gain of 3, $R_1 = 2R_2$

$$\frac{R_1}{R_2} = 2$$

To ensure oscillation, the ratio R_1/R_2 must be slightly greater than 2.

Wien-Bridge Oscillator



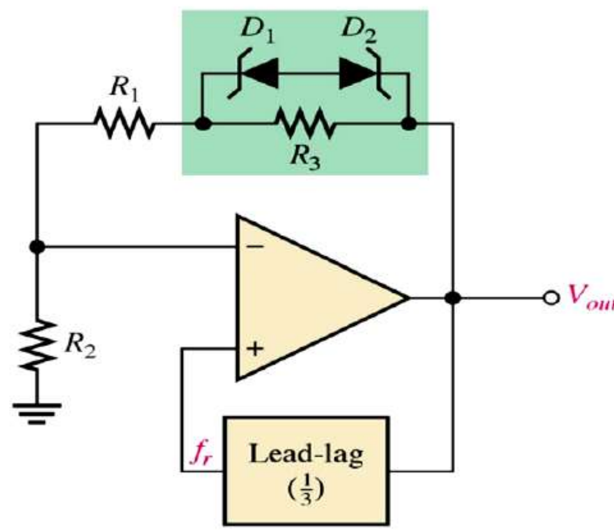
- To start the oscillations an initial gain greater than 1 must be achieved.
- The back-to-back zener diode arrangement is one way of achieving this with additional resistor R_3 in parallel.
- When dc is first applied the zeners appear as opens. This places R_3 in series with R_1, thus increasing the closed loop gain of the amplifier.

Self-starting Wien-bridge oscillator using back-to-back Zener diodes

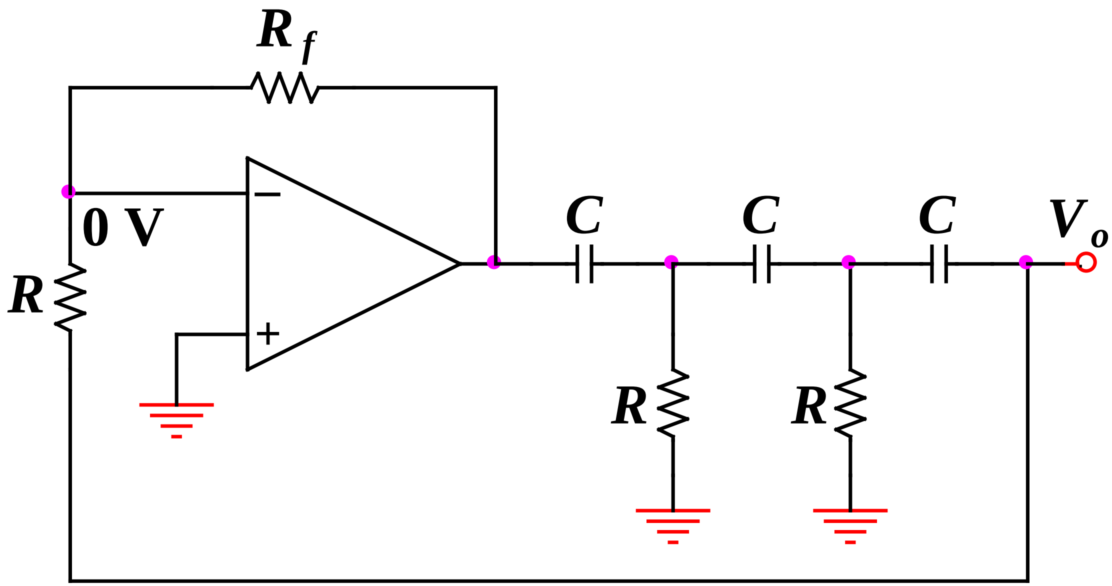
Wien-Bridge Oscillator

❖ The lead-lag circuit permits only a signal with a frequency equal to f_r to appear in phase on the noninverting input. The feedback signal is amplified and continually reinforced, resulting in a buildup of the output voltage.

❖ When the output signal reaches the zener breakdown voltage, the zener conduct and short R_3. The amplifier's closed loop gain lowers to 3. At this point, the total loop gain is 1 and the oscillation is sustained.



Phase-Shift Oscillator



Phase-shift oscillator

❖ The phase shift oscillator utilizes **three RC circuits** to provide 180º phase shift that when coupled with the 180º of the op-amp itself provides the necessary feedback to sustain oscillations.

❖ The frequency for this type is similar to any RC circuit oscillator :

$$f = \frac{1}{2\pi RC\sqrt{6}}$$

where $\beta = 1/29$ and the phase-shift is 180^o

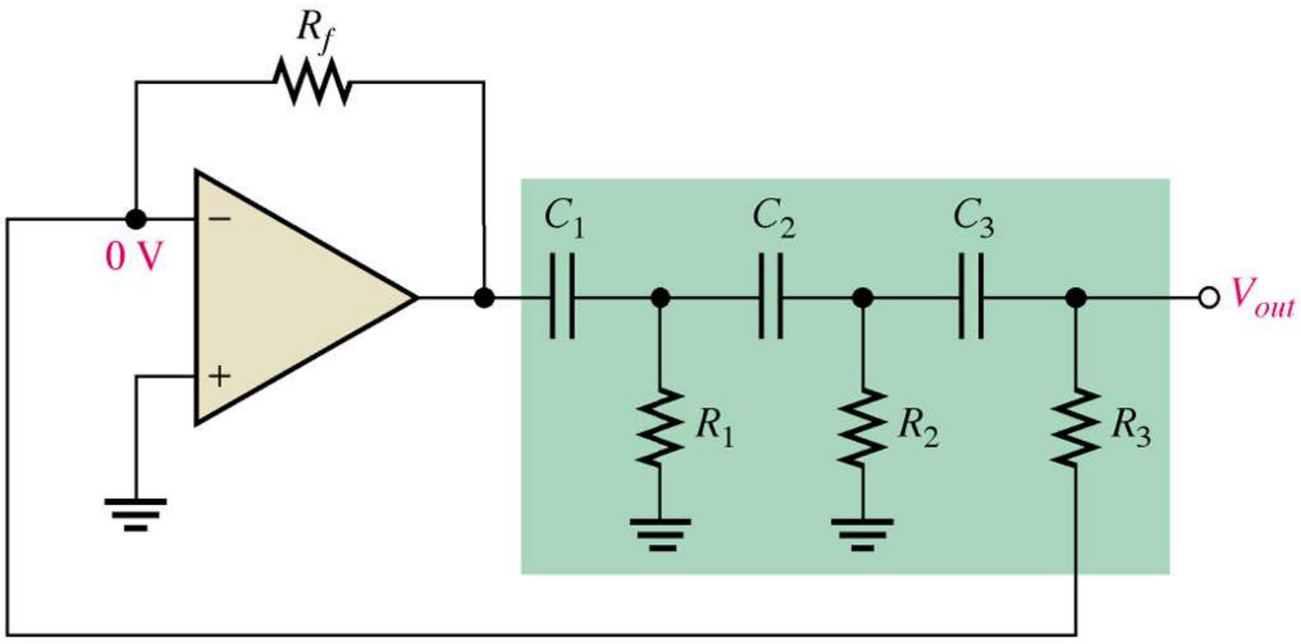
❖ For the loop gain βA to be greater than unity, the gain of the amplifier stage must be greater than 29.

❖ If we measure the phase-shift per RC section, each section would not provide the same phase shift (although the overall phase shift is 180^o).

❖ In order to obtain exactly 60^o phase shift for each of three stages, emitter follower stages would be needed for each RC section.

The gain must be at least 29 to maintain the oscillation

Phase-Shift Oscillator



The transfer function of the RC network is

$$\mathbf{TF} = \frac{\mathbf{Vin}}{\mathbf{Vo}} = \frac{1}{(SRC)^3 + 5(SRC)^2 + 6(SRC) + 1}$$

Phase-Shift Oscillator

If the gain around the loop equals 1, the circuit oscillates at this frequency. Thus for the oscillations we want,

$$K(TF) = 1$$

or $$(SRC)^3 + 5(SRC)^2 + 6(SRC) + 1 - K = 0$$

Putting s=jω and equating the real parts and imaginary parts, we obtain

$$-j\omega^3 (RC)^3 + 6 j\omega RC = 0 \quad \ldots.. (1) \qquad \text{(Imaginary Part)}$$

$$-5 \omega^2 (RC)^2 + 1 - K = 0 \quad \ldots.. (2) \qquad \text{(Real Part)}$$

Phase-Shift Oscillator

From equation (1) ;

$$-\omega^2 (RC)^2 + 6 = 0$$

$$\omega = \frac{\sqrt{6}}{(RC)}$$

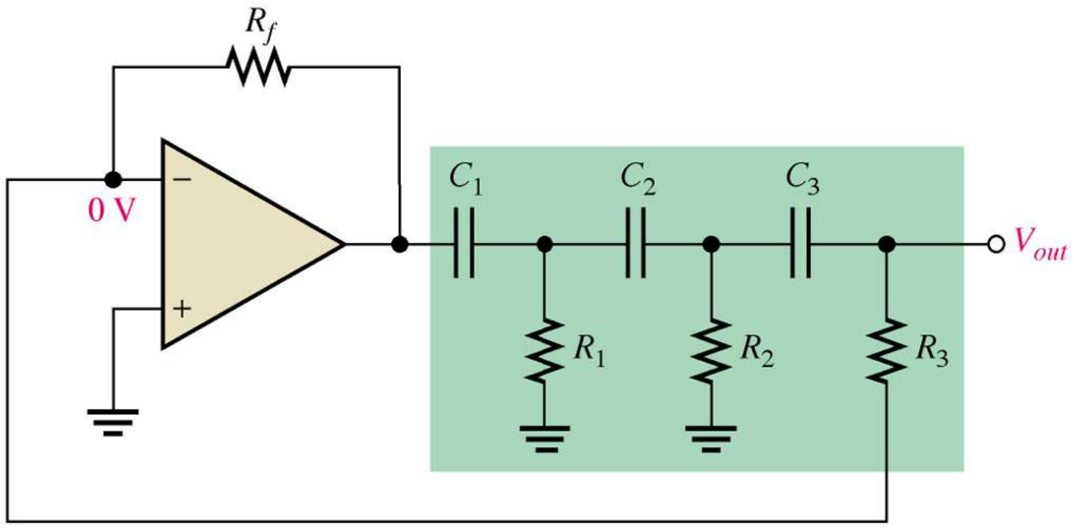
Substituting into equation (2) ;

$$-5\left[\frac{6}{(RC)^2}\right](RC)^2 + 1 = K$$

$$\Rightarrow \qquad K = -29$$

The gain must be at least 29 to maintain the oscillations.

Phase Shift Oscillator – Practical



The last R has been incorporated into the summing resistors at the input of the inverting op-amp.

$$f_r = \frac{1}{2\pi\sqrt{6}RC}$$

$$K = \frac{-R_f}{R_3} = -29$$

2. LC Oscillators

Oscillators With LC Feedback Circuits

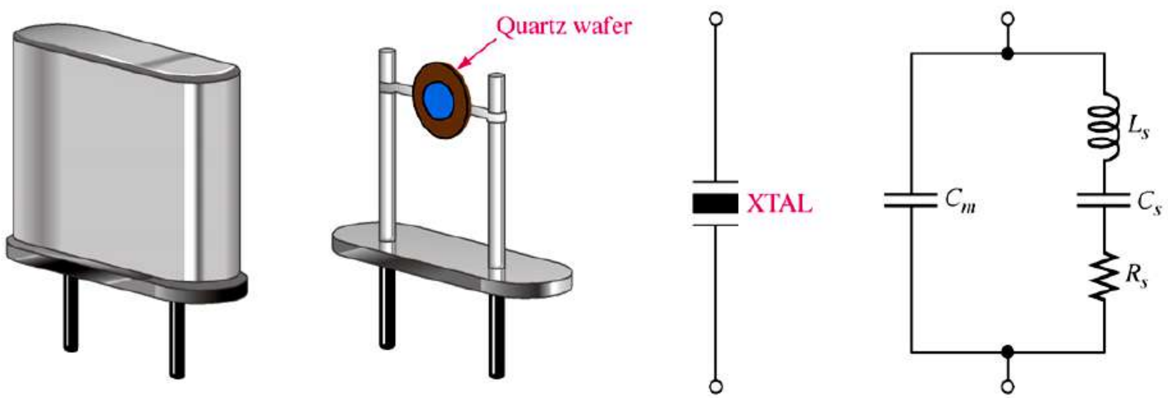
❖ For frequencies above 1 MHz, LC feedback oscillators are used.

❖ We will discuss the **crystal-controlled** oscillators.

❖ Transistors are used as the active device in these types.

Crystal Oscillator

The crystal-controlled oscillator is the most stable and accurate of all oscillators. A crystal has a natural frequency of resonance. Quartz material can be cut or shaped to have a certain frequency. We can better understand the use of a crystal in the operation of an oscillator by viewing its electrical equivalent.



(a) Typical packaged crystal (b) Basic construction (without case) (c) Symbol (d) Electrical equivalent

Crystal Oscillator

The crystal appears as a resonant circuit (tuned circuit oscillator).

The crystal has two resonant frequencies:

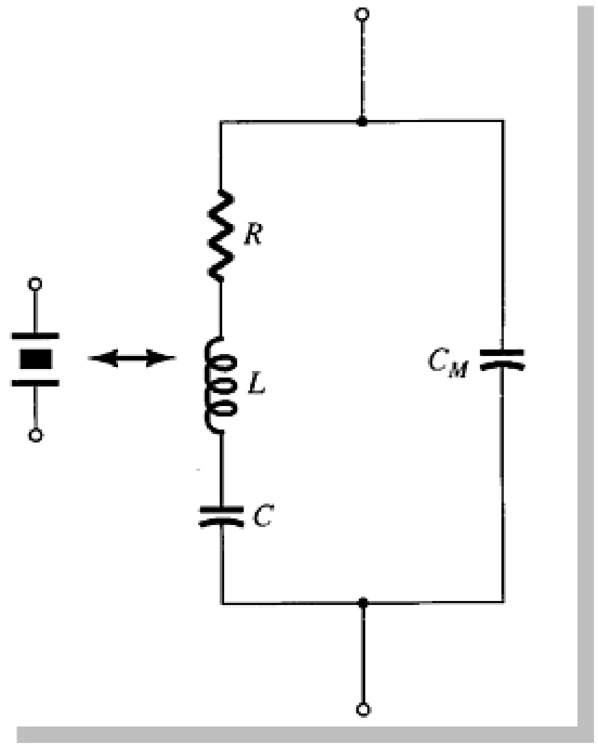
Series resonant condition

- RLC determine the resonant frequency
- The crystal has a low impedance

Parallel resonant condition

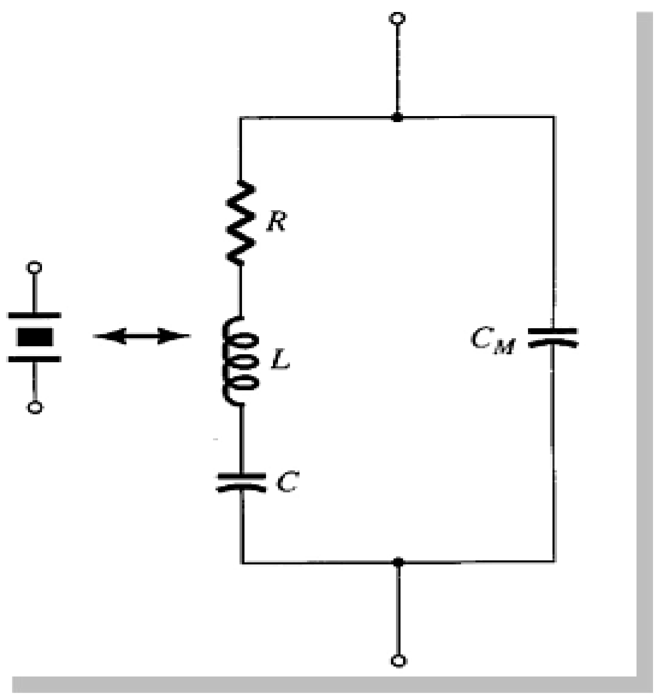
- RLC and C_M determine the resonant frequency
- The crystal has a high impedance

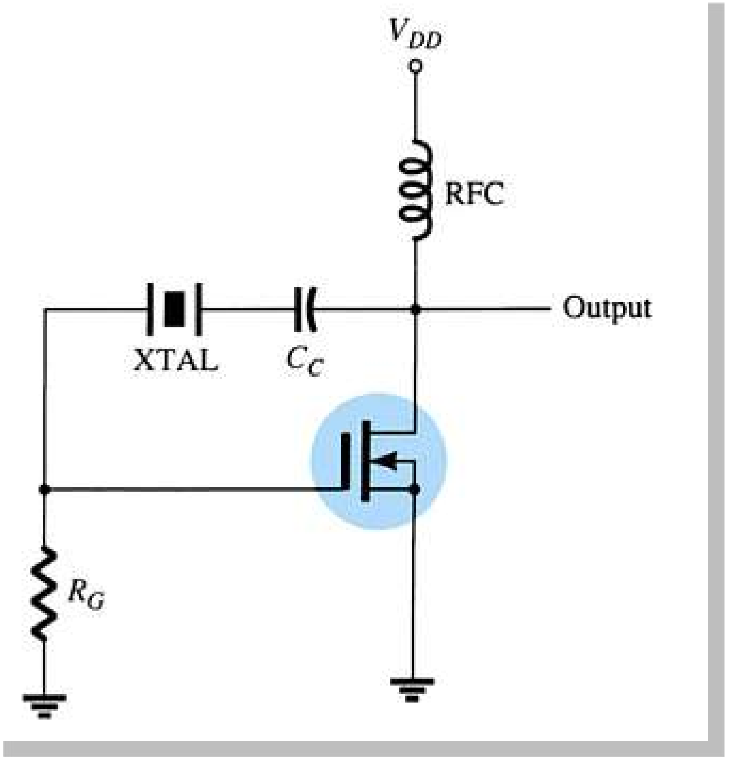
The series and parallel resonant frequencies are very close, within 1% of each other.



Series-Resonant Crystal Oscillator

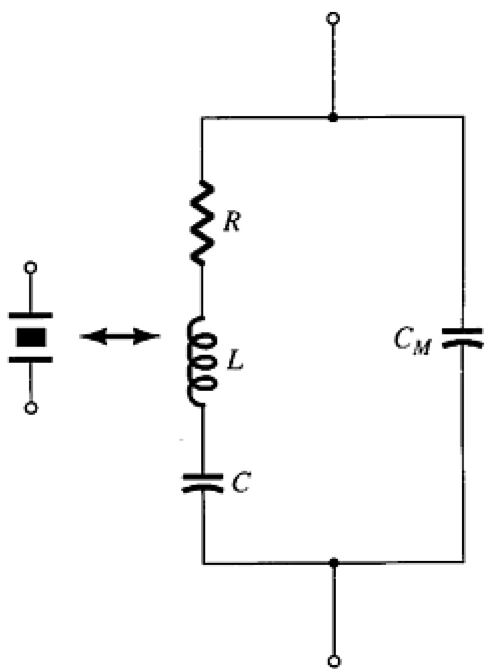
- RLC determine the resonant frequency
- The crystal has a low impedance at the series resonant frequency

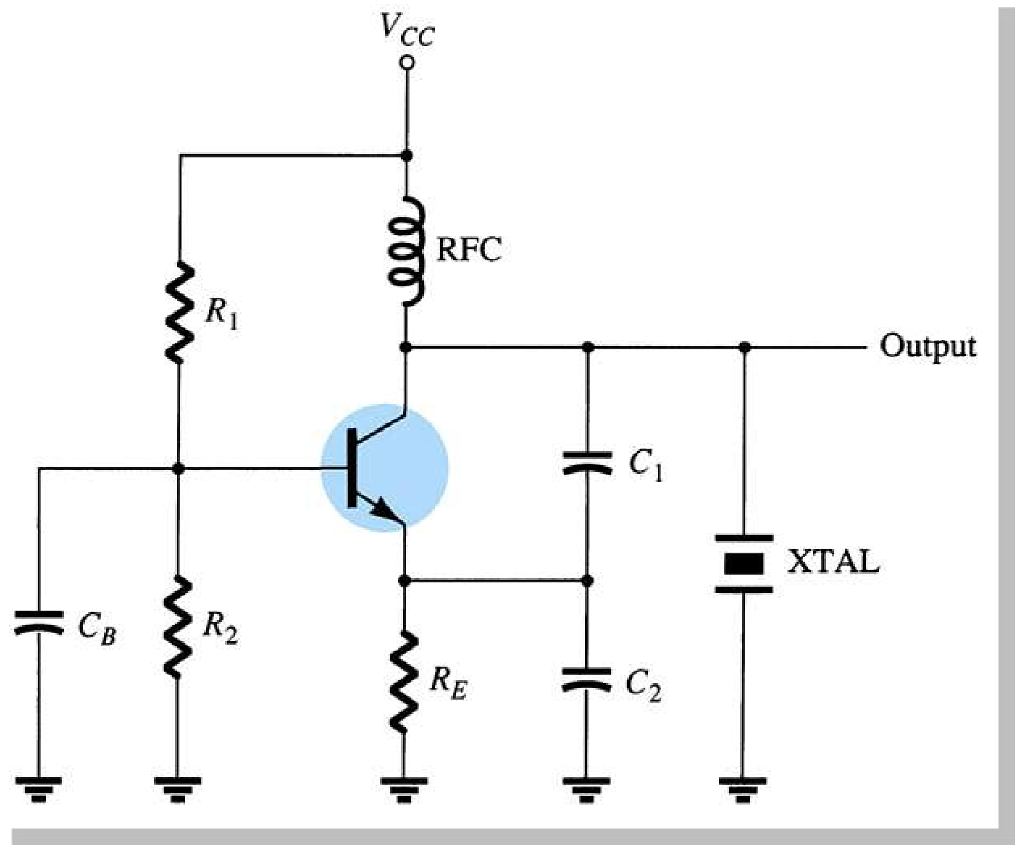




Parallel - Resonant Crystal Oscillator

- RLC and C_M determine the resonant frequency
- The crystal has a high impedance at parallel resonance





3. Relaxation Oscillators

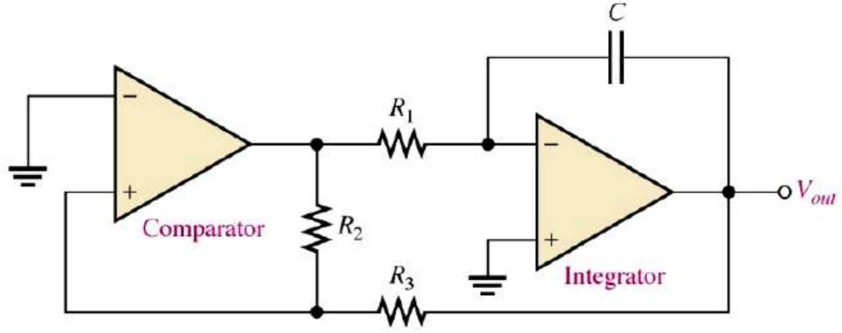
Relaxation Oscillator

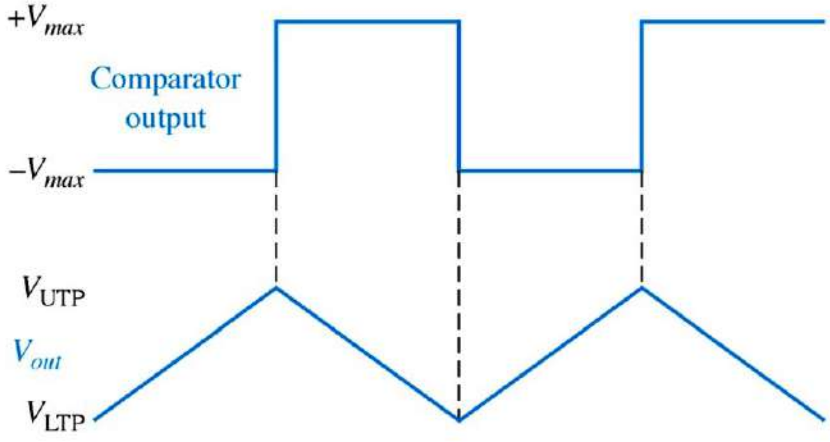
Relaxation oscillators make use of an RC timing and a device that changes states to generate a periodic waveform (non-sinusoidal) such as:

1. Triangular-wave
2. Square-wave
3. Sawtooth

Triangular-wave Oscillator

Triangular-wave oscillator circuit is a combination of a comparator and integrator circuit.





$$f_r = \frac{1}{4CR_1}\left(\frac{R_2}{R_3}\right)$$

$$V_{UTP} = +V_{\max}\left(\frac{R_3}{R_2}\right)$$

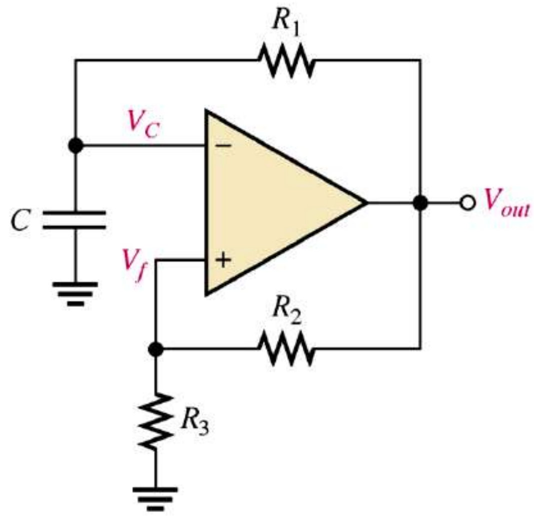
$$V_{LTP} = -V_{\max}\left(\frac{R_3}{R_2}\right)$$

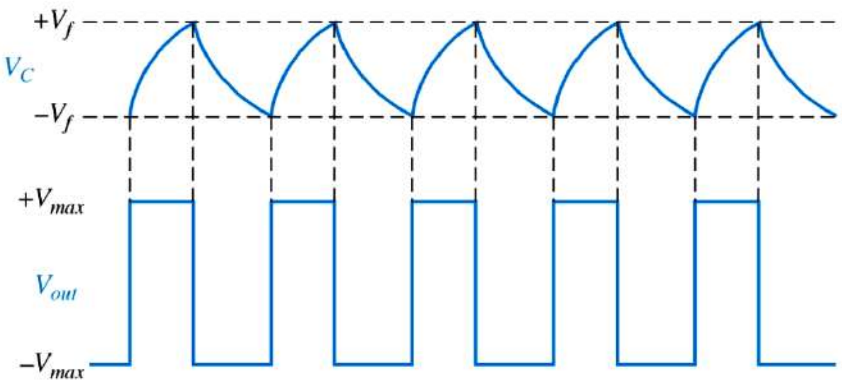
Square-wave Oscillator

❖ A square wave relaxation oscillator is like the Schmitt trigger or Comparator circuit.

❖ The charging and discharging of the capacitor cause the op-amp to switch states rapidly and produce a square wave.

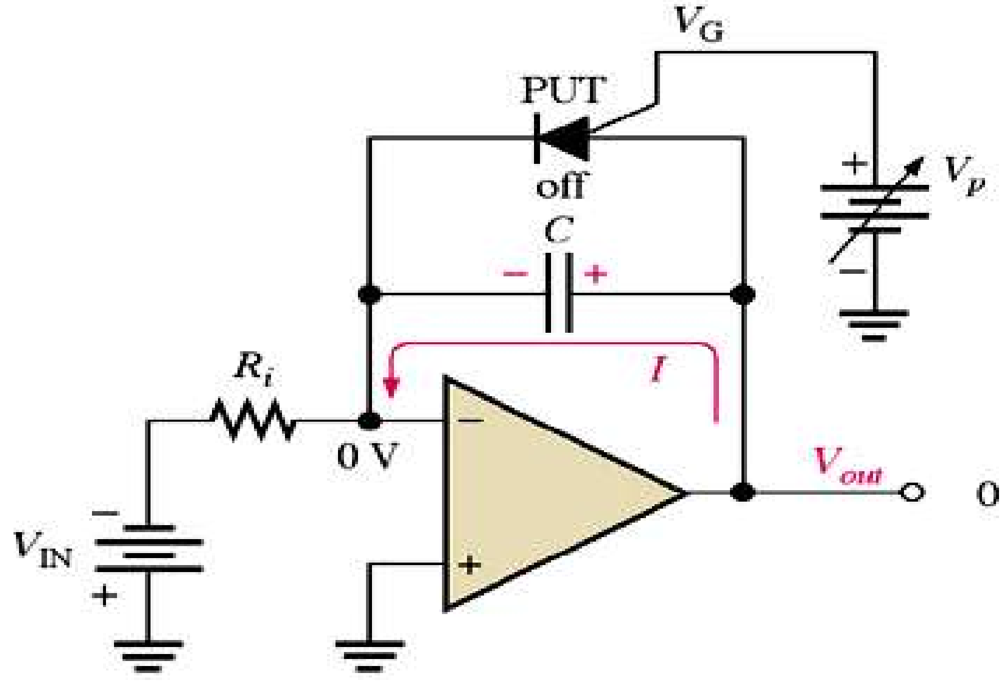
❖ The RC time constant determines the frequency.





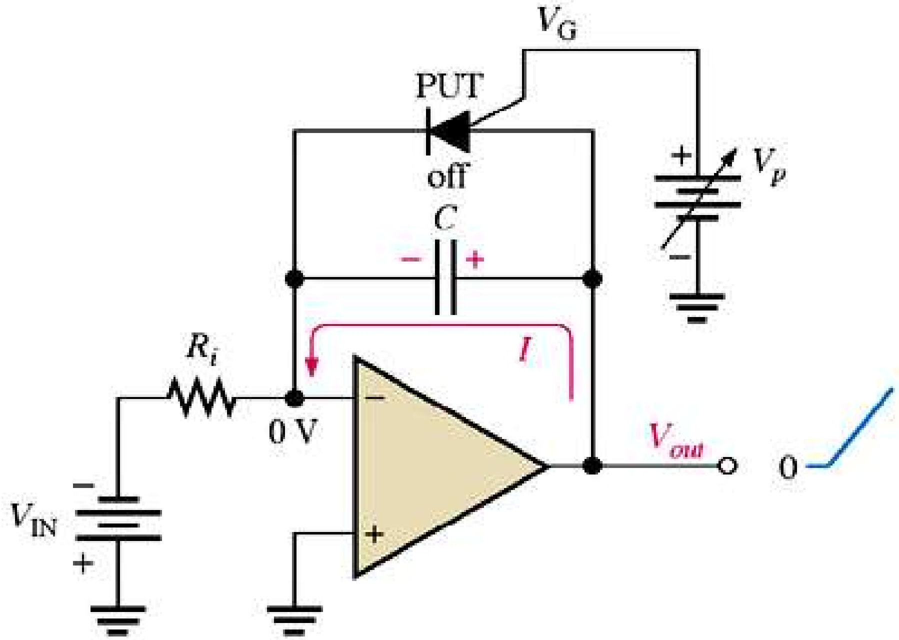
Sawtooth Voltage-Controlled Oscillator (VCO)

Sawtooth VCO circuit is a combination of a Programmable Unijunction Transistor (PUT) and integrator circuit.



Sawtooth Voltage-Controlled Oscillator (VCO)

Operation



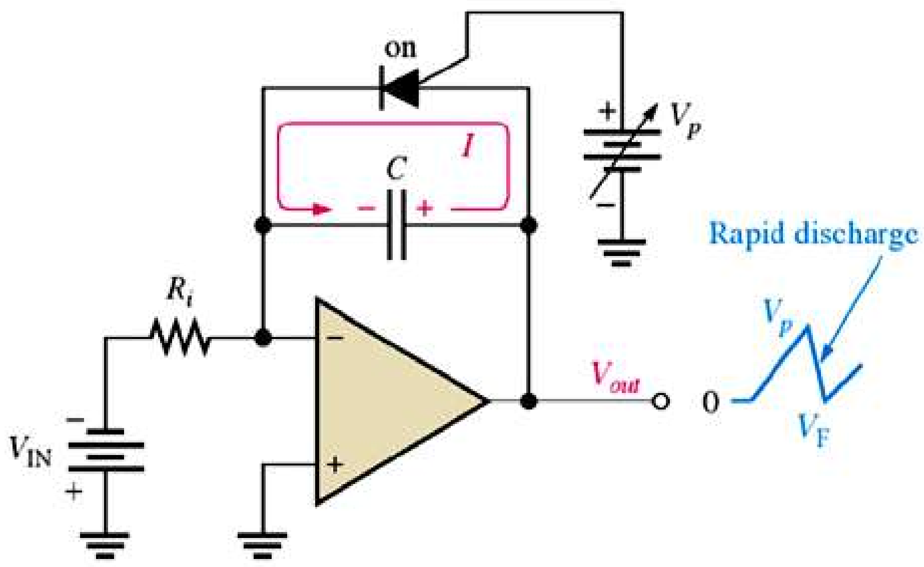
(a) Initially, the capacitor charges, the output ramp begins, and the PUT is off.

Initially, dc input = $-V_{IN}$

- Volt = 0V, $V_{anode} < V_G$
- The circuit is like an integrator.
- Capacitor is charging.
- Output is increasing positive going ramp.

Sawtooth Voltage-Controlled Oscillator (VCO)

Operation



(b) The capacitor rapidly discharges when the PUT momentarily turns on.

When $V_{out} = V_P$

- $V_{anode} > V_G$, PUT turn 'ON'
- The capacitor rapidly discharges.
- V_{out} drop until $V_{out} = V_F$.
- $V_{anode} < V_G$, PUT turn 'OFF'

V_P-maximum peak value

V_F-minimum peak value

Sawtooth Voltage-Controlled Oscillator (VCO)

Oscillation frequency is

$$f = \frac{V_{IN}}{R_i C}\left(\frac{1}{V_P - V_F}\right)$$

Summary

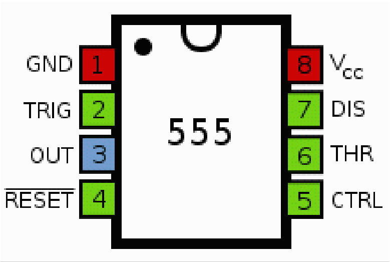
- Sinusoidal oscillators operate with positive feedback.
- Two conditions for oscillation are 0º feedback phase shift and feedback loop gain of 1.
- The initial startup requires the gain to be momentarily greater than 1.
- RC oscillators include the Wien-bridge and phase shift.
- LC oscillators include the Crystal Oscillator.

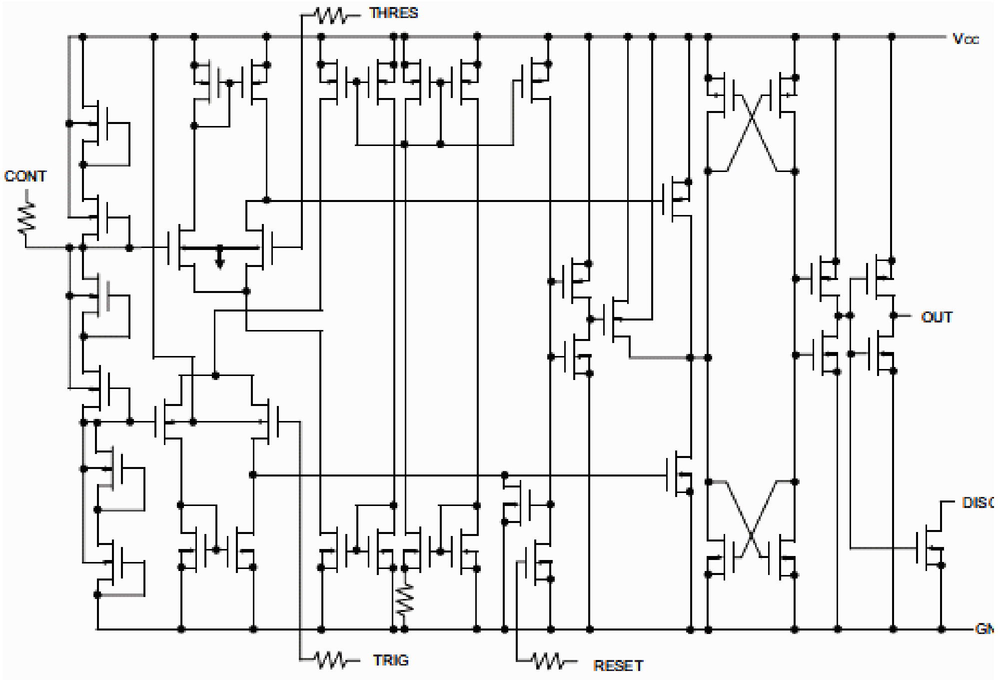
Summary

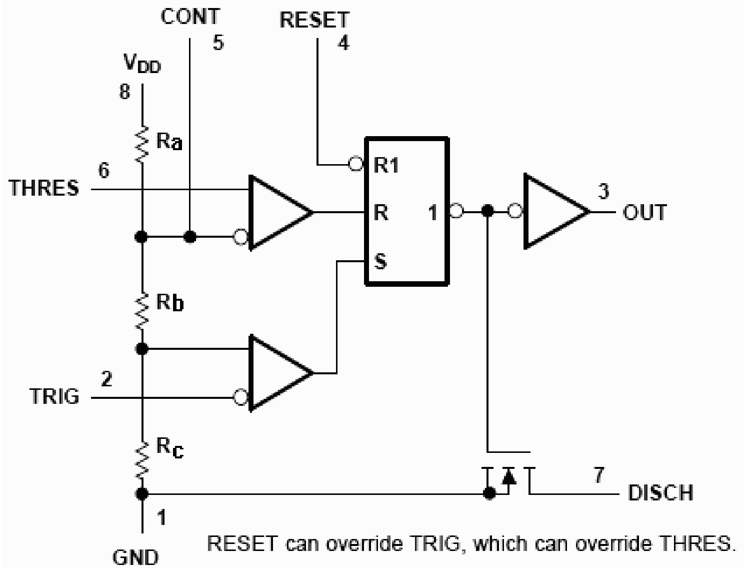
- The crystal actually uses a crystal as the LC tank circuit and is very stable and accurate.
- A voltage controlled oscillator’s (VCO) frequency is controlled by a dc control voltage.

LM/TLC 555 Timer

The TLC555C Chip (in your kit)







RESET can override TRIG, which can override THRES.

LM555 Timer Chip (TTL)
TLC555C Timer Chip (CMOS)

- An integrated chip that is used in a wide variety of circuits to generate square wave and triangular shaped single and periodic pulses.
  - Examples in your home are
    - high efficiency LED and fluorescence light dimmers and
    - temperature control systems for electric stoves
    - tone generators for appliance “beeps”
  - The Application Notes section of the datasheets for the TLC555 and LM555 timers have a number of other circuits that are in use today in various communications and control circuits.

Terms you may see in 555 circuits:

- **Astable** – a circuit that can not remain in one state.
- **Monostable** – a circuit that has one stable state. When perturbed, the circuit will return to the stable state.
- **One Shot** – Monostable circuit that produces one pulse when triggered.
- **Flip Flop** – a digital circuit that flips or toggles between two stable states (bistable). The Flip Flop inputs decide which of the two states its output will be.
- **Multivibrator** – a circuit used to implement a simple two-state system, which may be astable, monostable, or bistable.
- **CMOS** – complimentary Mosfet logic. CMOS logic dominates the digital industry because the power requirements and component density are significantly better than other technologies.

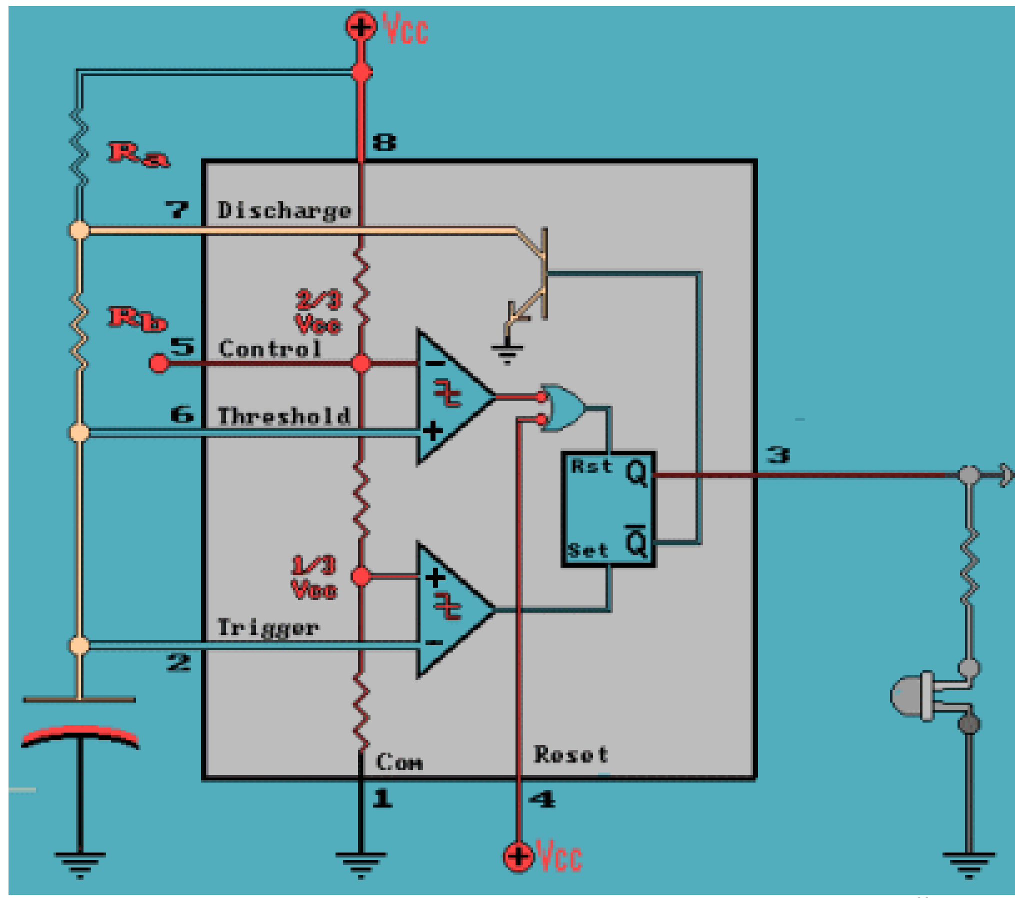
Two Types of 555 Multivibrators

- Monostable
  - A single pulse is outputted when an input voltage attached to the trigger pin of the 555 timer equals the voltage on the threshold pin.
- Astable
  - A periodic square wave is generated by the 555 timer.
    - The voltage for the trigger and threshold pins is the voltage across a capacitor that is charged and discharged through two different RC networks.

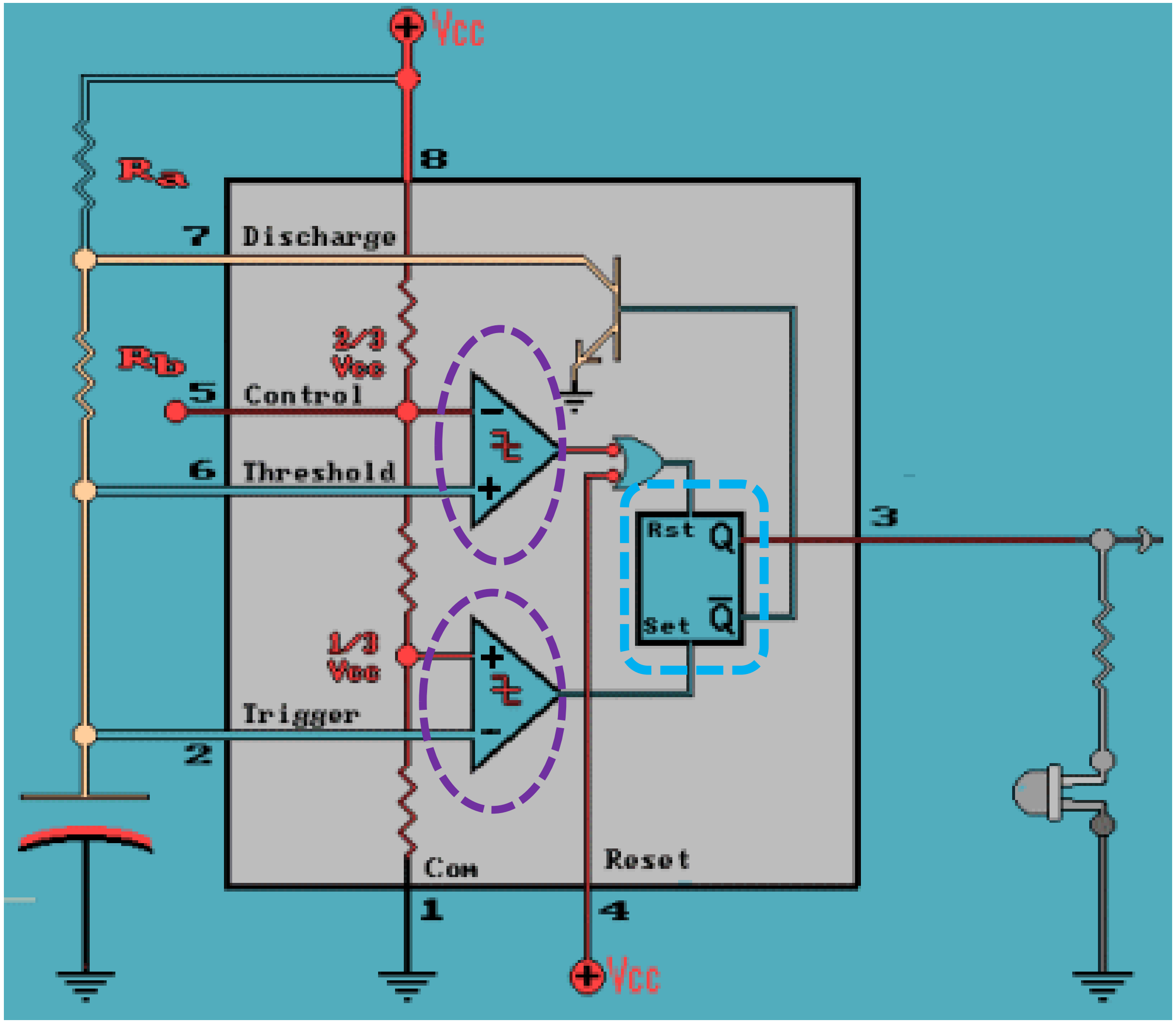
I know – who comes up with these names?

How a 555 Timer Works

- We will operate the 555 Timer as an Astable Multivibrator in the circuit for the metronome.



http://www.williamson-labs.com/480_555.htm



The components that make up a 555 timer are shown within the gray box.

Internal resistors form a voltage divider that provides ⅓V_{CC} and ⅔ V_{CC} reference voltages.

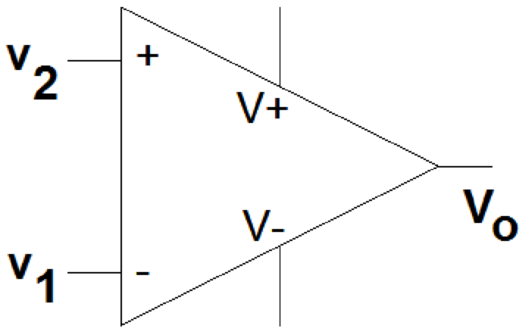
Two internal **voltage comparators** determine the state of a **D flip-flop**.

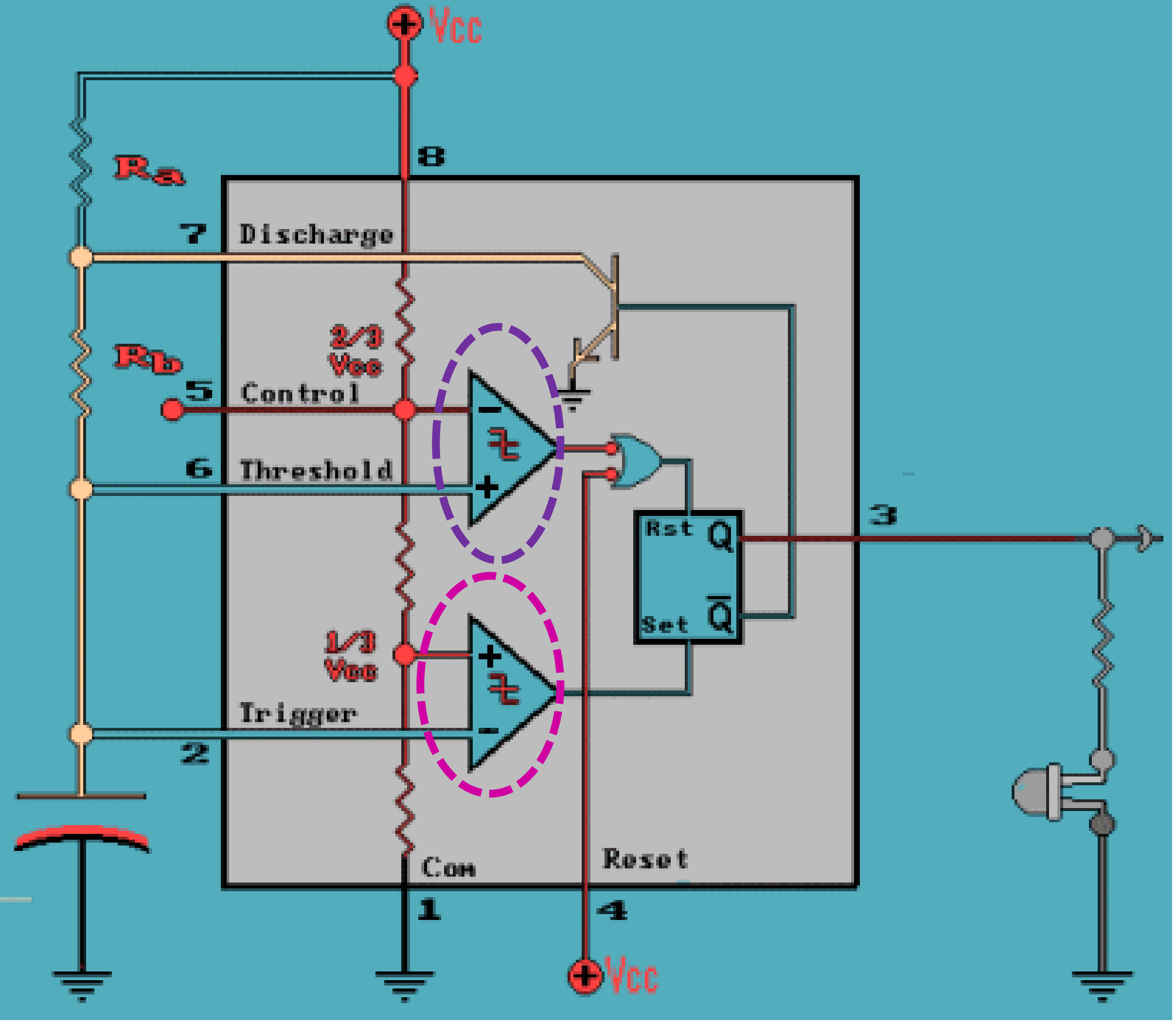
The flip-flop output controls a transistor switch.

http://www.williamson-labs.com/480_555.htm

Voltage Comparator

- As a reminder, an Op Amp without a feedback component is a voltage comparator.
  - Output voltage changes to force the negative input voltage to equal the positive input voltage.
    - A maximum output voltage (V_o) is against the positive supply rail (V+) if the positive input voltage (v_2) is greater than negative input voltage (v_1) .
    - A minimum output voltage (V_o) is is against the negative supply rail (V-) if the negative input voltage (v_1) is greater than the positive input voltage (v_2).





http://www.williamson-labs.com/480_555.htm

The voltage comparators use the internal voltage divider to keep the capacitor voltage (V_C) between ⅓V_{CC} and ⅔V_{CC}.

The output of the lower voltage comparator will be high (Vcc) when V_C < ⅓V_{CC}, and low (0 V) when V_C > ⅓V_{CC}

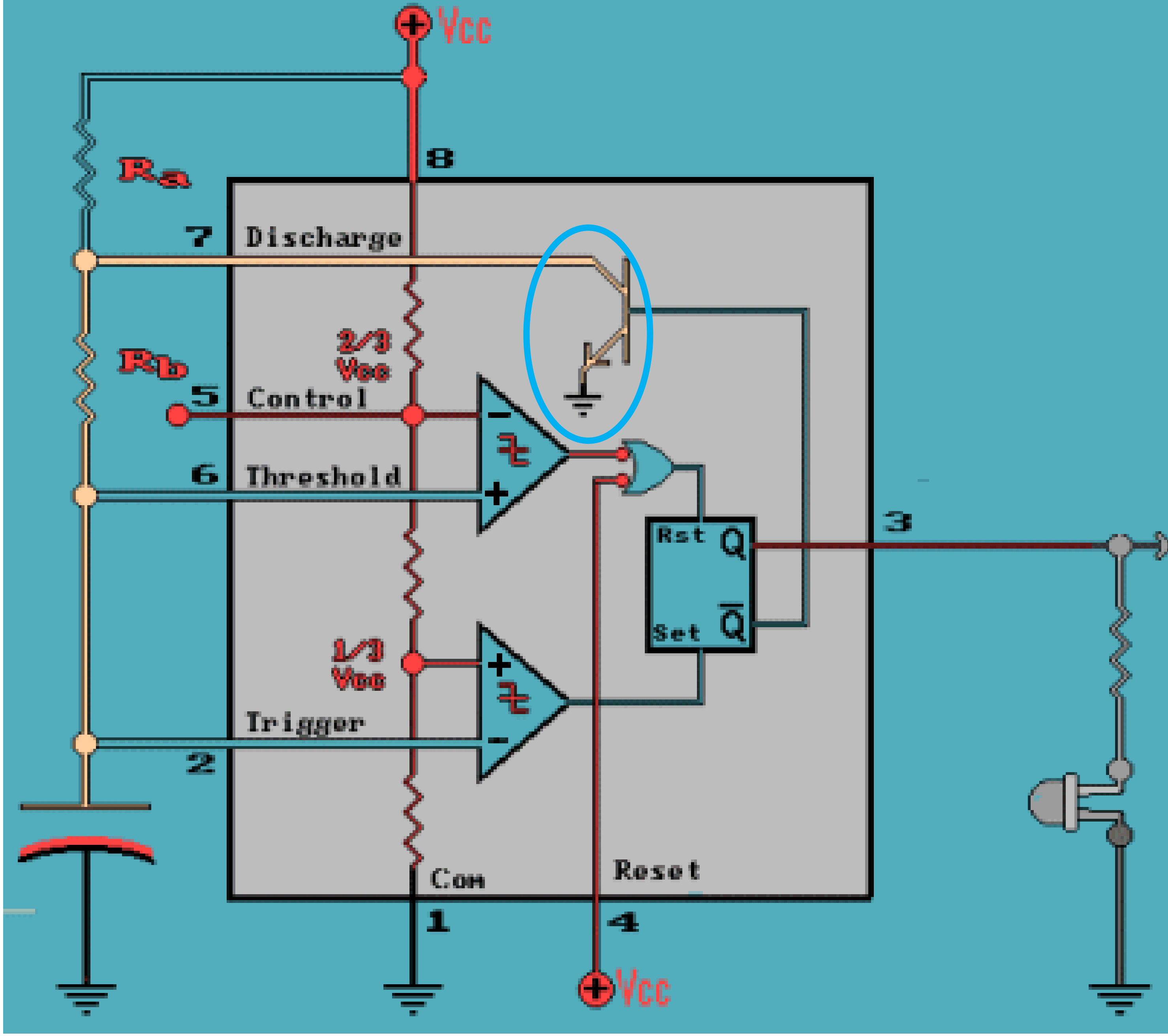
(⅓V_{CC} = the voltage across the lower resistor in the internal voltage divider).

The output of the **upper voltage comparator** will be low (0 V) when V_C < ⅔V_{CC}, and high (Vcc) when V_C > ⅔V_{CC}

(⅔V_{CC} = the voltage across the two lower resistors in the internal voltage divider).

The bipolar transistor (BJT) acts as a switch.

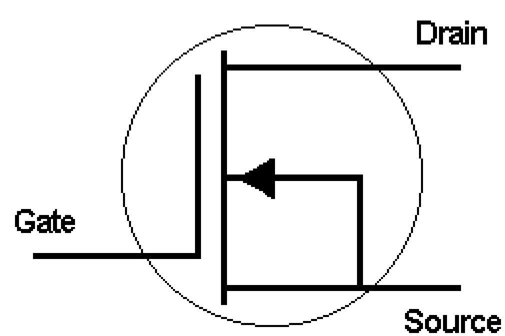
NOTE: Your kit TLC555 uses a MOSFET instead of a BJT.

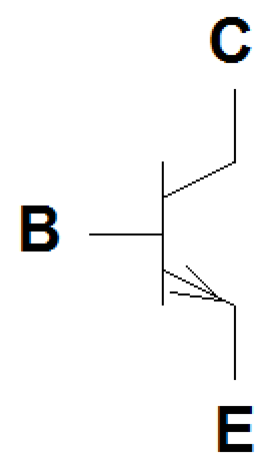


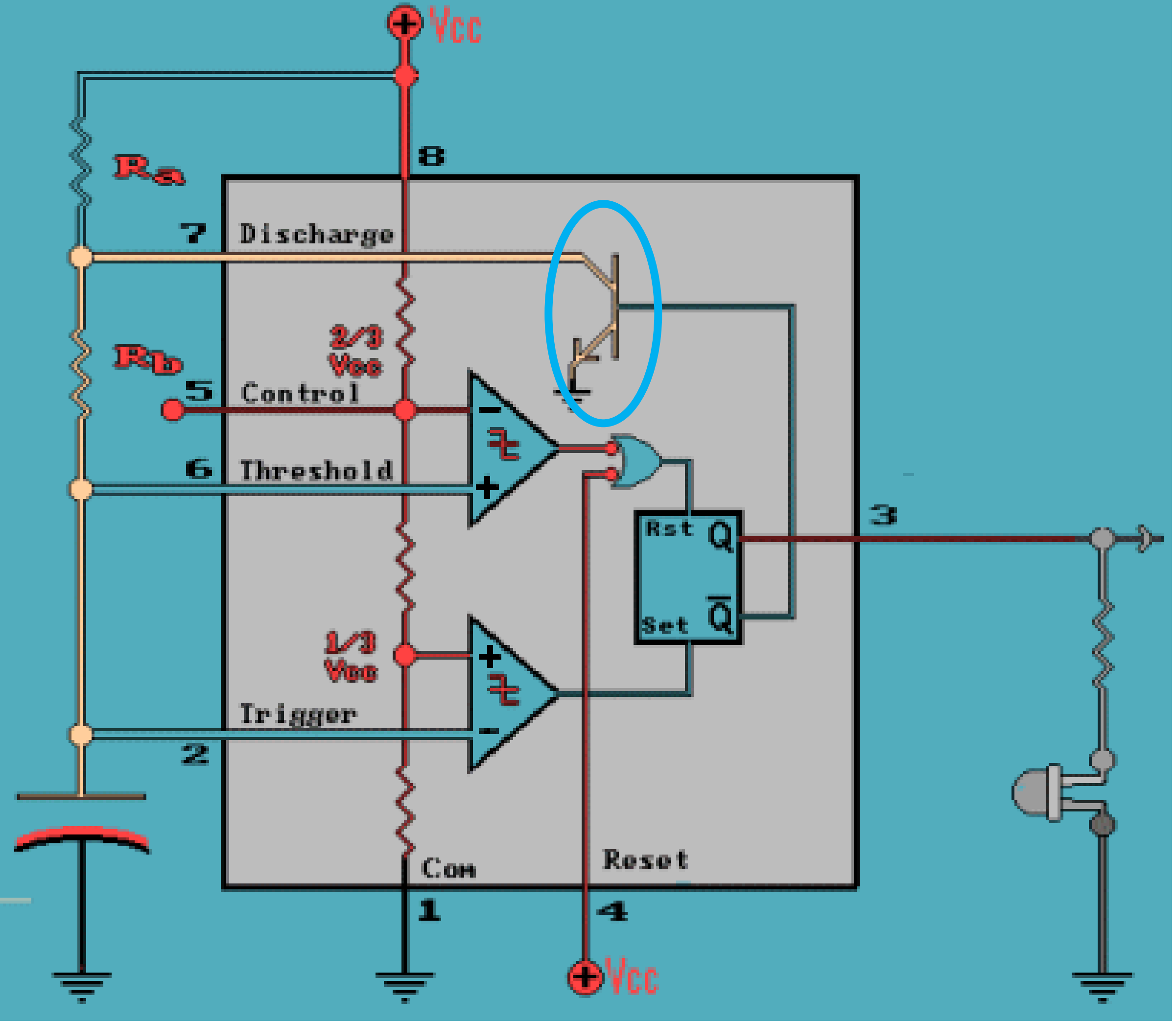
http://www.williamson-labs.com/480_555.htm

Transistor

- As you will learn in ECE 2204, a BJT or MOSFET transistor can be connected to act like a switch.
  - When a positive voltage is applied to the base or gate, the transistor acts like there is a very small resistor is between the collector and the emitter, or the drain and the source.
  - When ground is applied to the base or gate, the transistor acts like there is a an open circuit between the collector and the emitter, or the drain and the source.







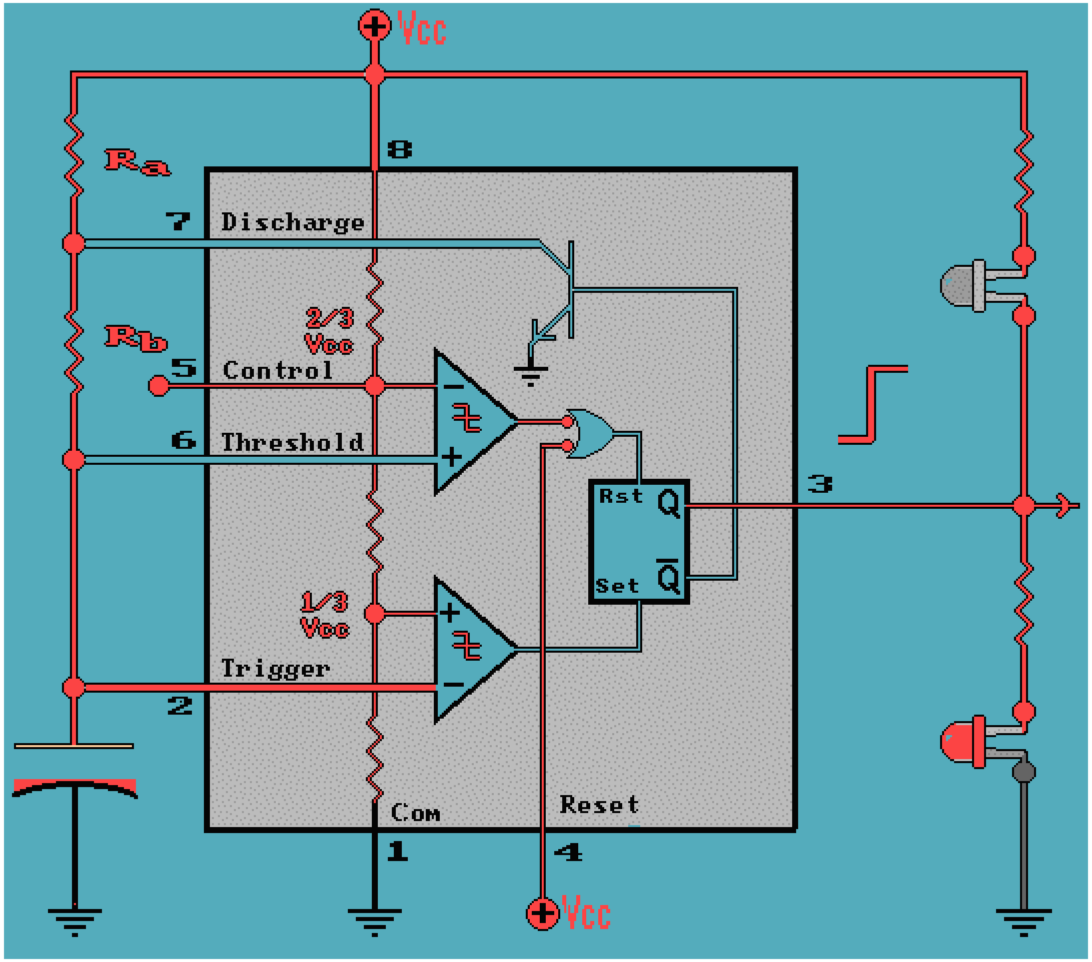
http://www.williamson-labs.com/480_555.htm

The **transistor** inside the 555 switches the discharge pin (7) to ground (or very close to 0 V), when Qbar (the Q with a line over it) of the D flip-flop is high ($V_{Qbar} \approx V_{CC}$).

The transistor grounds the node between external timing resistors R_a and R_b. The capacitor discharges through R_b to ground through the transistor. *Current through R_a also goes to ground through the transistor.*

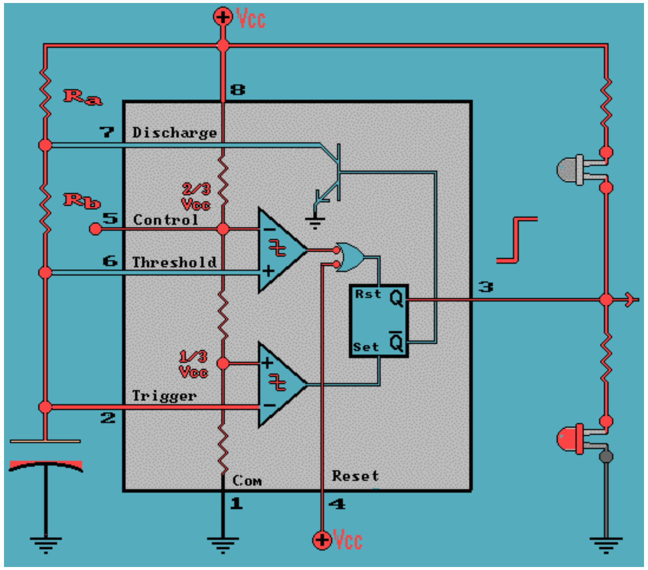
When the transistor is switched off, it acts like an open circuit. V_{CC} now charges the capacitor through R_a and R_b.

When you first apply power to the 555



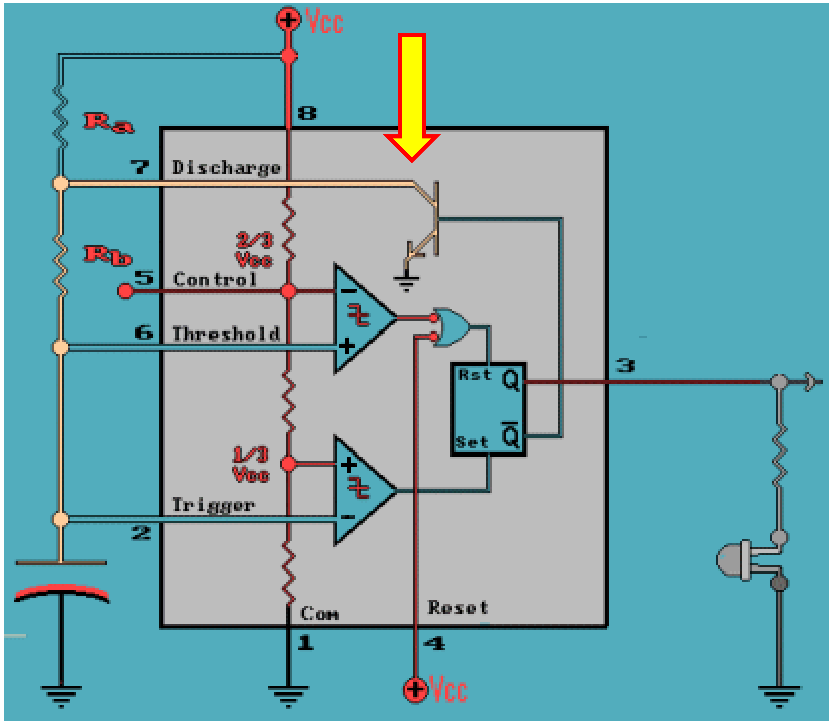
- The capacitor charges through R_A and R_B.
  - Because V_C started 0 V, the first timing period will be longer than the periods that follow.

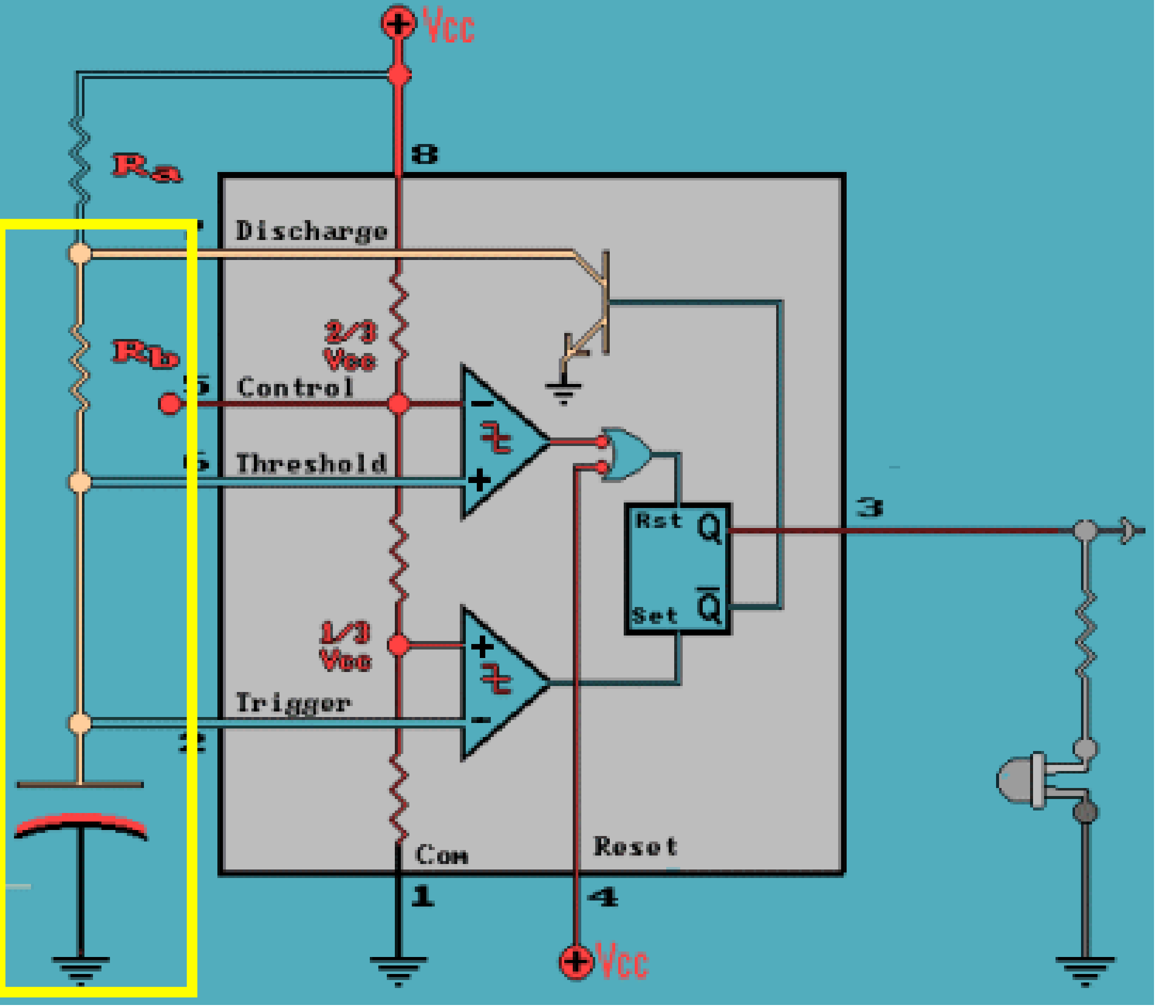
Charging



- The capacitor charges through R_a and R_b until $V_C = ⅔V_{CC}$.

- When V_C reaches $⅔V_{CC}$, the output of the upper voltage comparator changes and resets the D flip-flop, Qbar switches to high ($\approx V_{CC}$), and the transistor switches on.
- The capacitor then begins discharging through R_b & the transistor to ground.





Discharging:

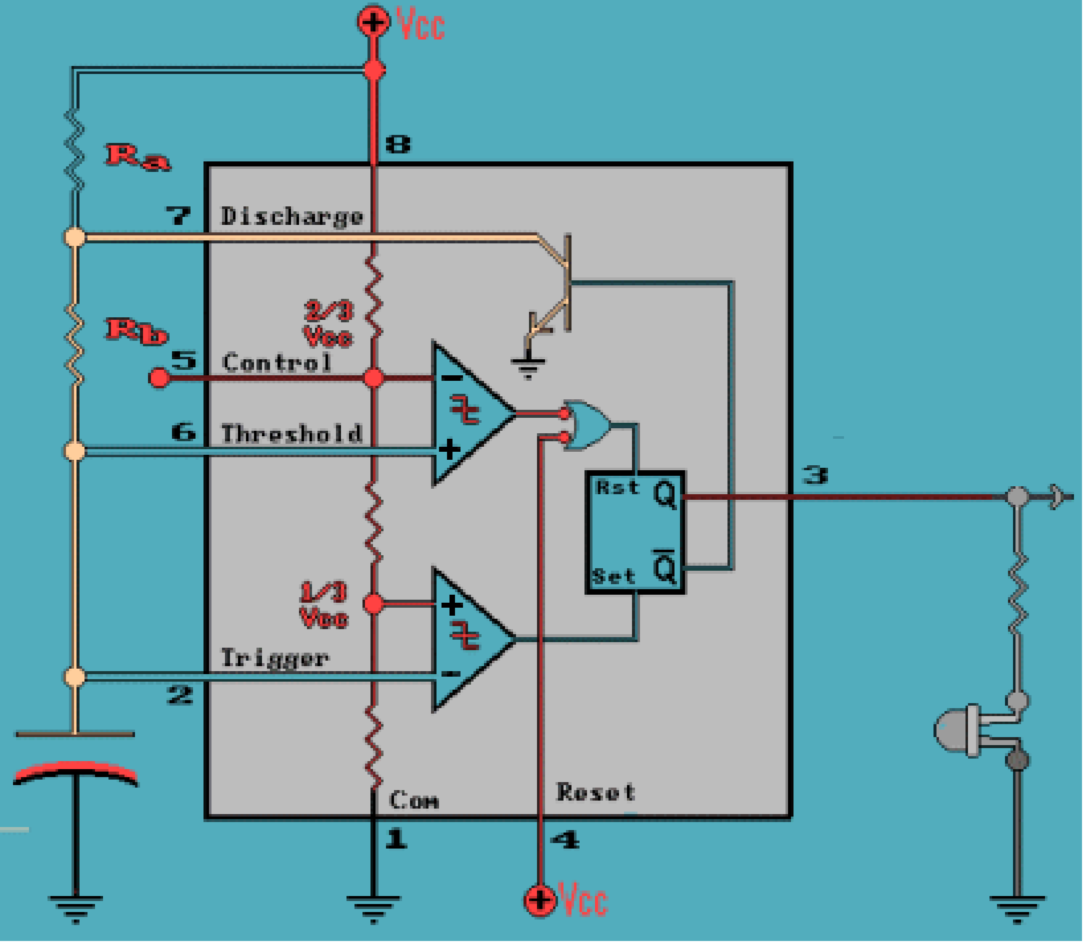
The capacitor discharges through R_b and the transistor to ground.

Current through R_a is also grounded by the transistor.

- When V_C reaches ⅓V_{CC}, the output of the lower voltage comparator changes and sets the D flip-flop, Qbar switches to low (≈ 0 V), and the transistor switches off.
- The capacitor then begins charging through R_a and R_b.

http://www.williamson-labs.com/480_555.htm

Thus, the voltage of the capacitor can be no more than ⅔V_{CC} and no less than ⅓V_{CC} if all of the components internal and external to the 555 are ideal.



http://www.williamson-labs.com/480_555.htm

The output of the 555 timer, pin 3, is Q on the D flip-flop.

- When Qbar is 5 V and the capacitor is charging, Q is 0 V.
- When Qbar is 0 V and the capacitor is discharging, Q is 5 V.

Thus, the output of a 555 timer is a continuous square wave function (0 V to 5 V) where:

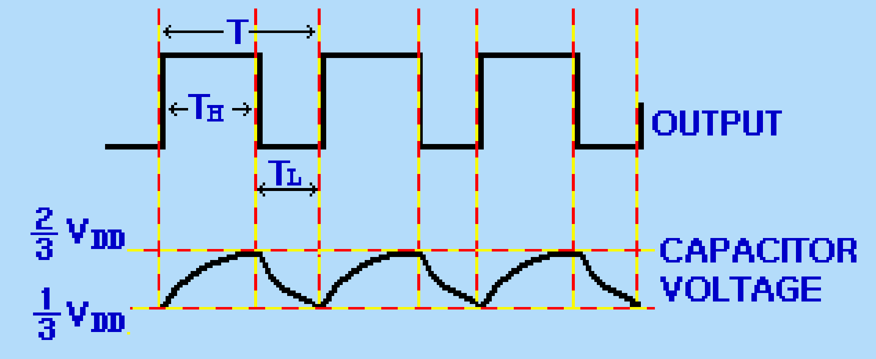
- the period is dependent the sum of the time it takes to charge the capacitor to ⅔V_{CC} and the time that it takes to discharge the capacitor to ⅓V_{CC}.
- In this circuit, the only time that the duty cycle (the time that the output is at 0 V divided by the period) will be 0.5 (or 50%) is when Ra = 0 W, which should not be allowed to occur as that would connect Vcc directly to ground when the transistor switches on.

Astable Multivibrator - Waveforms

- T_H is the time it takes C to charge from ⅓V_{CC} to ⅔V_{CC}
  - $T_H = (R_a + R_b)*C*[-\ln(½)]$ (from solving for the charge time between voltages)

- T_L is the time it takes C to discharge from ⅔V_{CC} to ⅓V_{CC}
  - $T_{Low} = R_b*C*[-\ln(½)]$ (from solving for the charge time between voltages)

- The duty cycle (% of the time the output is high) depends on the resistor values.



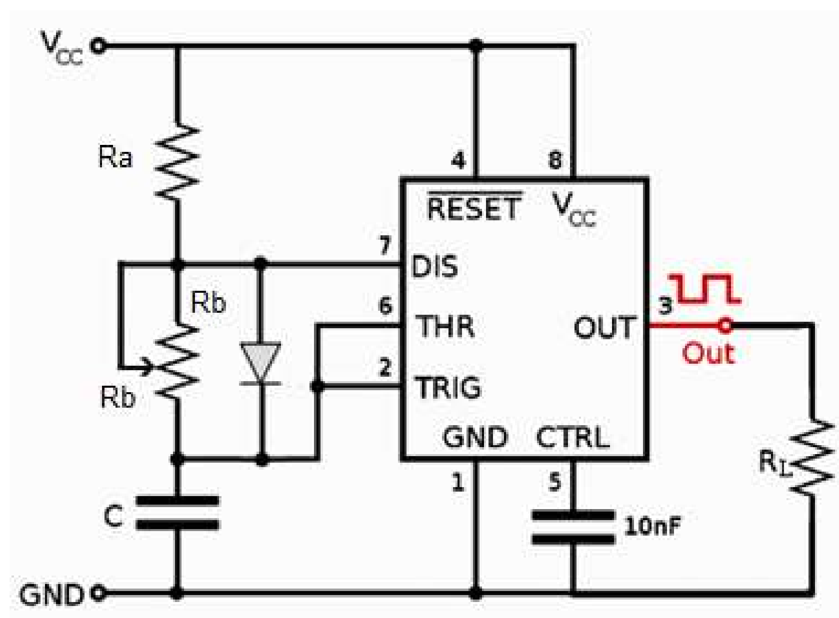
- Williamson Labs [555 astable circuit waveform animation]

Shortening the Astable Duty Cycle

- The duty cycle of the standard 555 timer circuit in Astable mode must be greater than 50%.
  - $T_{high} = 0.693(R_a + R_b)C$ [C charges through R_a and R_a from V_{CC}]
  - $T_{low} = 0.693R_bC$ [C discharges through R_b into pin 7]
  - R_1 must have a resistance value greater than zero to prevent the discharge pin from directly shorting V_{DD} to ground.
  - Duty cycle = $T_{high} / (T_{high} + T_{low}) = (R_a + R_b) / (R_a + 2R_b) > 50\%$ if $R_a \neq 0$

- **Adding a diode across R_b** allows the capacitor to charge directly through R_a.

This sets $T_{high} \approx 0.693R_aC$
$T_{low} = 0.693R_bC$ (unchanged)



Useful 555 Timer Chip Resources

- TI Data Sheets and design info
  - Data Sheet (pdf)
  - Design Calculator (zip)
- Williamson Labs **http://www.williamson-labs.com/480_555.htm**
  - Timer tutorials with a 555 astable circuit waveform animation.
  - Philips App Note AN170 (pdf)
- Wikipedia - 555 timer IC
- NE555 Tutorials http://www.unitechelectronics.com/NE-555.htm
- Doctronics 555 timer tips http://www.doctronics.co.uk/555.htm
- The Electronics Club http://www.kpsec.freeuk.com/555timer.htm
- 555 Timer Circuits http://www.555-timer-circuits.com
- 555 Timer Tutorial http://www.sentex.net/~mec1995/gadgets/555/555.html
- Philips App Note AN170 http://www.doctronics.co.uk/pdf_files/555an.pdf

Equations

- Time constants of two different resistor-capacitor networks determine the length of time the timer output, t_1 and t_2, is at 5V and 0V, respectively.

$$t_1 = 0.693(R_a + R_b)C$$

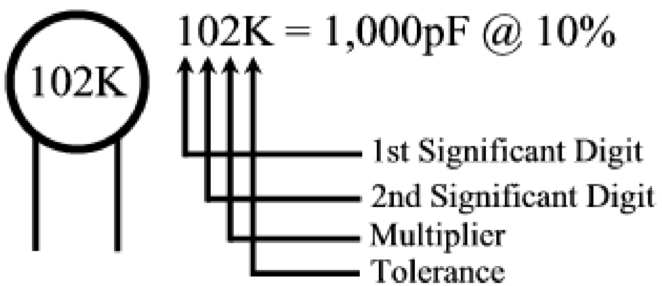
$$t_2 = 0.693(R_b)C$$

Types of Capacitors

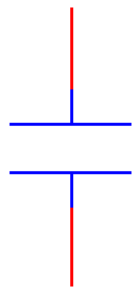
- Fixed Capacitors
  - Nonpolarized
    - May be connected into circuit with either terminal of capacitor connected to the high voltage side of the circuit.
      - Insulator: Paper, Mica, Ceramic, Polymer
  - Electrolytic
    - The negative terminal must always be at a lower voltage than the positive terminal
      - Plates or Electrodes: Aluminum, Tantalum

Nonpolarized

- It's difficult to make nonpolarized capacitors that store a large amount of charge or operate at high voltages.
  - Tolerance on capacitance values is very large
    - +50%/-25% is not unusual



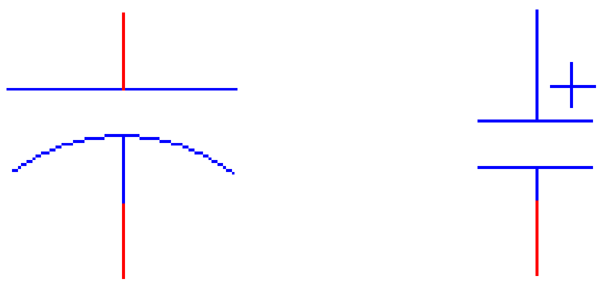
PSpice Symbol



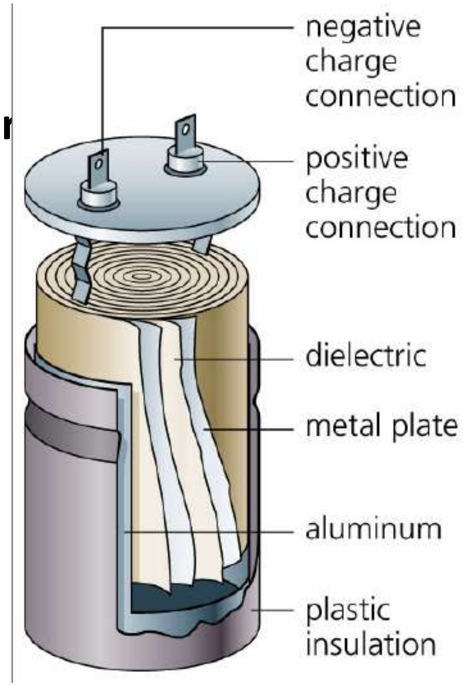
http://www.marvac.com/fun/ceramic_capacitor_codes.aspx

Electrolytic

Pspice Symbols



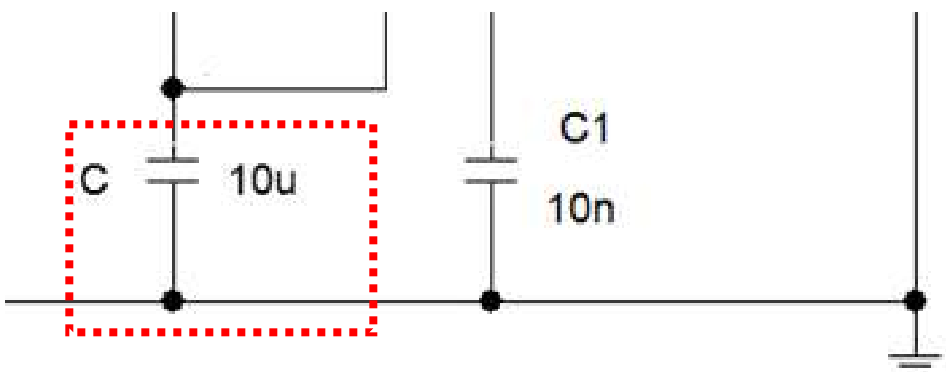
Fabr



http://www.digitivity.com/articles/2008/11/choosing-the-right-capacitor.html

Electrolytic Capacitors

- The negative electrode must always be at a lower voltage than the positive electrode.
  - So in your circuit, the negative electrode must be grounded.



Frequency and Duty Cycle

$$f = \frac{1}{t_1 + t_2} = \frac{1.44}{(R_a + 2R_b)C}$$

$$D = \frac{t_2}{t_1 + t_2} = \frac{R_b}{R_a + 2R_b}$$

When the output of the 555 timer changes from 5V to 0V, a pulse current will flow through the speaker, causing the speaker to create a click sound. You will change the frequency of the pulses to the speaker by changing the value of R_a. Since Ra is usually much larger than R_b, the frequency of the pulses are linearly proportional to the value of R_a and the duty cycle of the pulse waveform will be very short.

Active Filters

Introduction

- Filters are circuits that are capable of *passing signals within a band* of frequencies while *rejecting or blocking* signals of frequencies *outside this band*. This property of filters is also called “frequency selectivity”.

- Filter can be passive or active filter.

Passive filters: The circuits built using RC, RL, or RLC circuits.

Active filters : The circuits that employ one or more op-amps in the design an addition to resistors and capacitors

Advantages of Active Filters over Passive Filters

- Active filters can be designed to provide required gain, and hence no attenuation as in the case of passive filters
- No loading problem, because of high input resistance and low output resistance of op-amp.
- Active Filters are cost effective as a wide variety of economical op-amps are available.

Applications

- Active filters are mainly used in communication and signal processing circuits.
- They are also employed in a wide range of applications such as entertainment, medical electronics, etc.

Active Filters

- There are 4 basic categories of active filters:

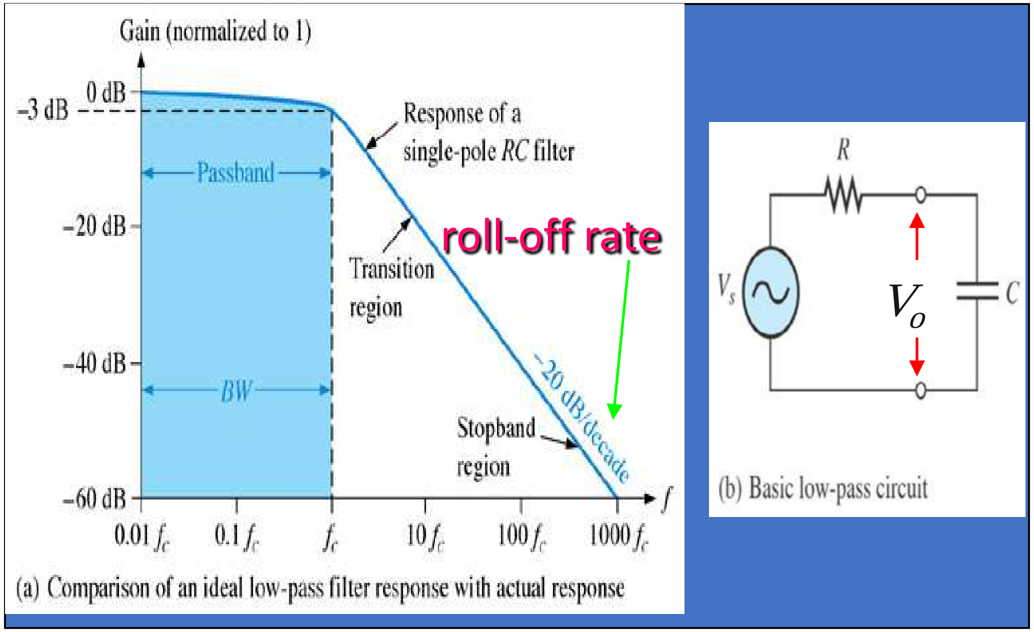
1. **Low-pass filters**
2. **High-pass filters**
3. **Band-pass filters**
4. **Band-reject filters**

- Each of these filters can be built by using op-amp as the active element combined with RC, RL or RLC circuit as the passive elements.

BASIC FILTER RESPONSES

Low-Pass Filter Response

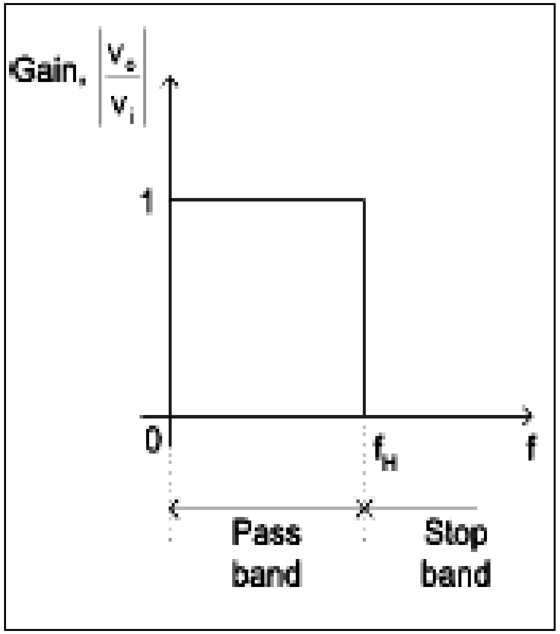
➢ A **low-pass filter** is a filter that passes frequencies from 0Hz to critical frequency, f_c and significantly attenuates all other frequencies.



(a) Comparison of an ideal low-pass filter response with actual response

(b) Basic low-pass circuit

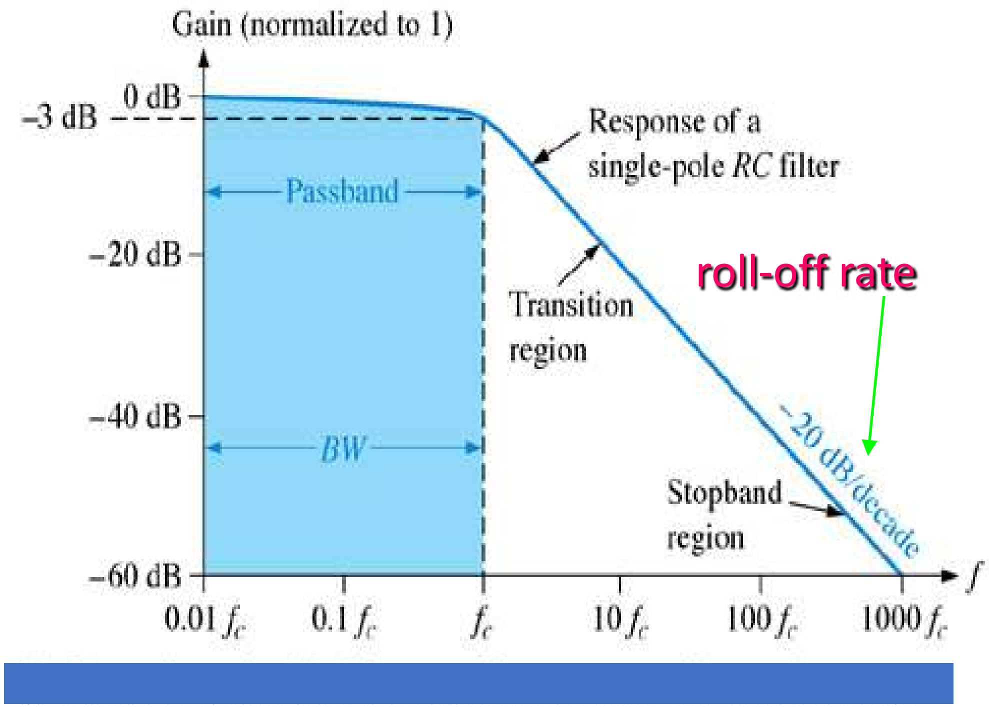
Actual response



Ideal response

➢ Ideally, the response drops abruptly at the critical frequency, f_H

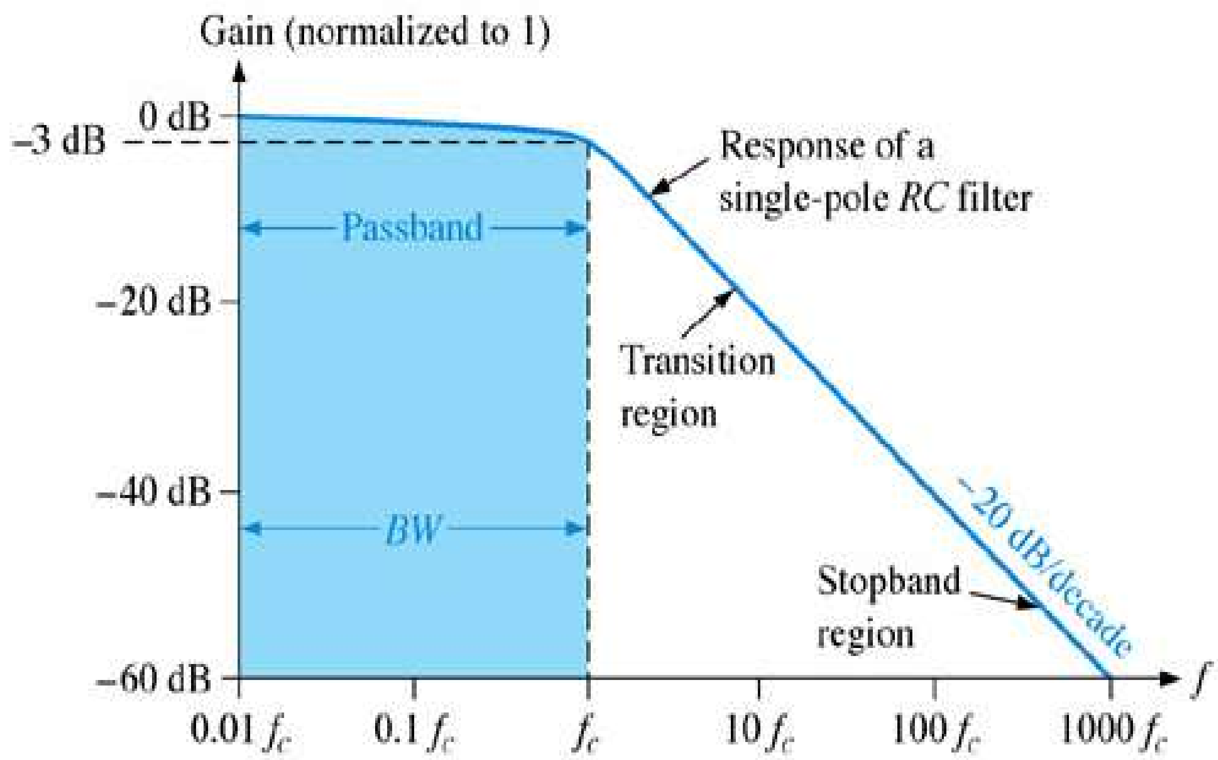
Passband of a filter is the range of frequencies that are allowed to pass through the filter with minimum attenuation (usually defined as less than -3 dB of attenuation).



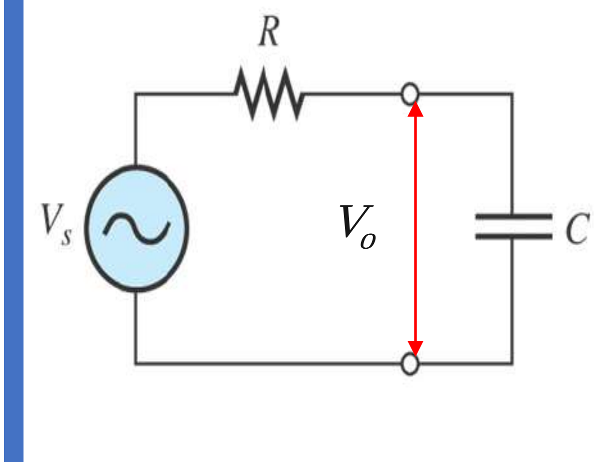
Transition region shows the area where the fall-off occurs.

Stopband is the range of frequencies that have the most attenuation.

Critical frequency, **f_c**, (also called the cutoff frequency) defines the end of the passband and normally specified at the point where the response drops – 3 dB (70.7%) from the passband response.



(a) Comparison of an ideal low-pass filter response with actual response



(b) Basic low-pass circuit

- ➢ At low frequencies, X_C is very high and the capacitor circuit can be considered as open circuit. Under this condition, V_o = V_{in} or A_V = 1 (unity).

- ➢ At very high frequencies, X_C is very low and the V_o is small as compared with V_{in}. Hence the gain falls and drops off gradually as the frequency is increased.

- The **bandwidth** of an **ideal** low-pass filter is equal to f_c:

$$BW = f_c$$

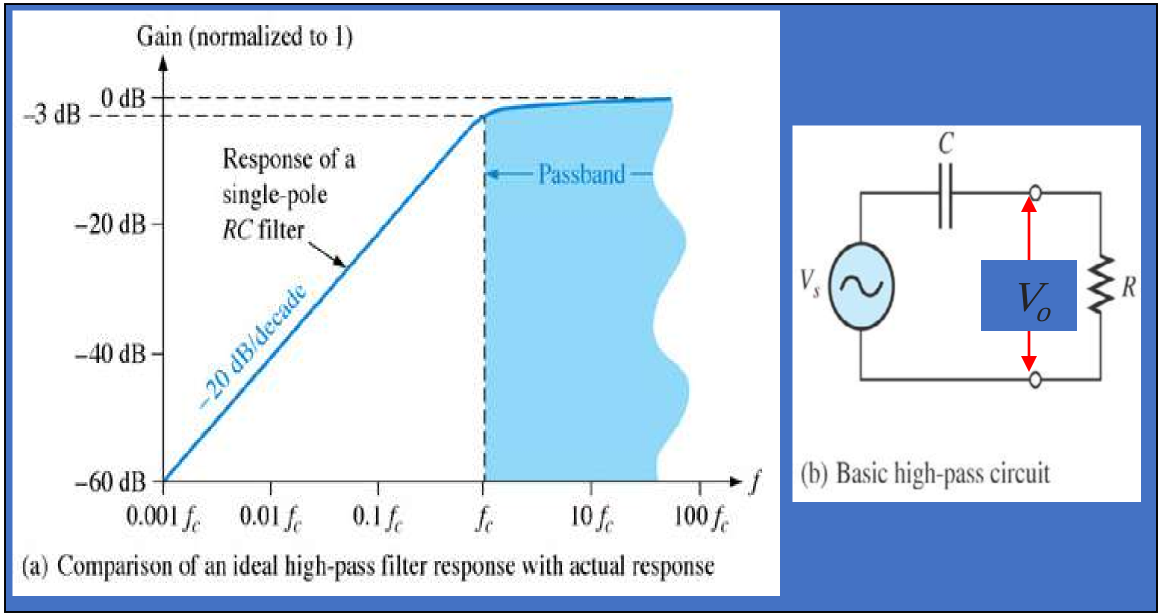
- The critical frequency of a low-pass RC filter occurs when **$X_C = R$** and can be calculated using the formula below:

$$f_c = \frac{1}{2\pi RC}$$

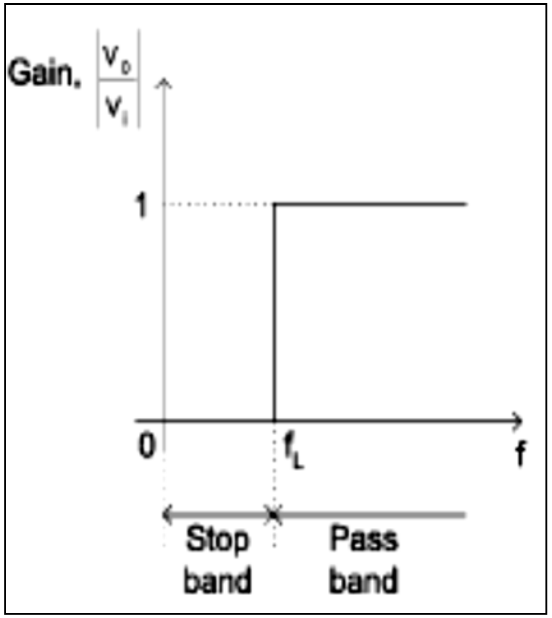
High-Pass Filter Response

- A **high-pass filter** is a filter that significantly attenuates or rejects all frequencies **below** f_c and passes all frequencies **above** f_c.

- The passband of a high-pass filter is all frequencies above the critical frequency.



Actual response



Ideal response

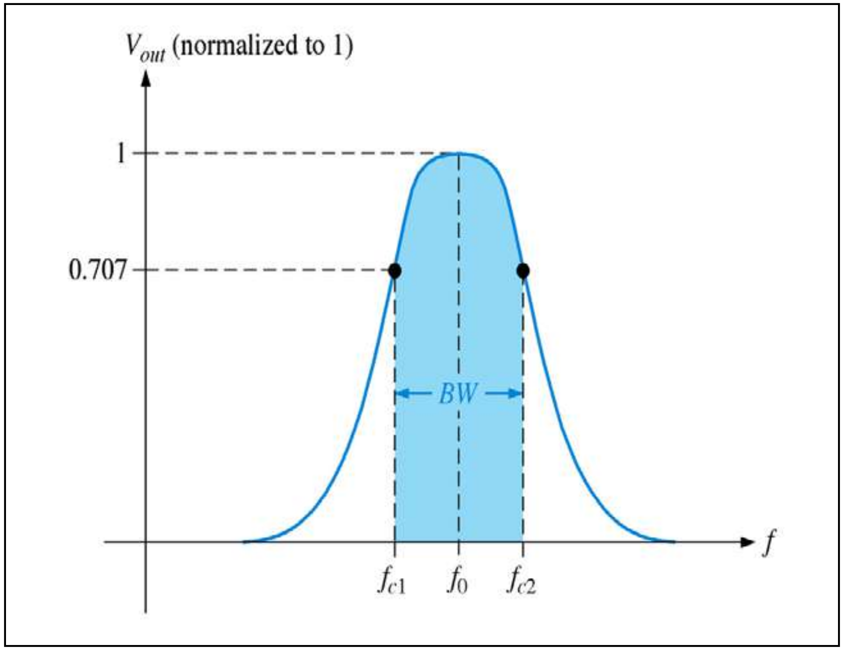
- Ideally, the response rises abruptly at the critical frequency, f_L

- The critical frequency of a high-pass RC filter occurs when **$X_C = R$** and can be calculated using the formula below:

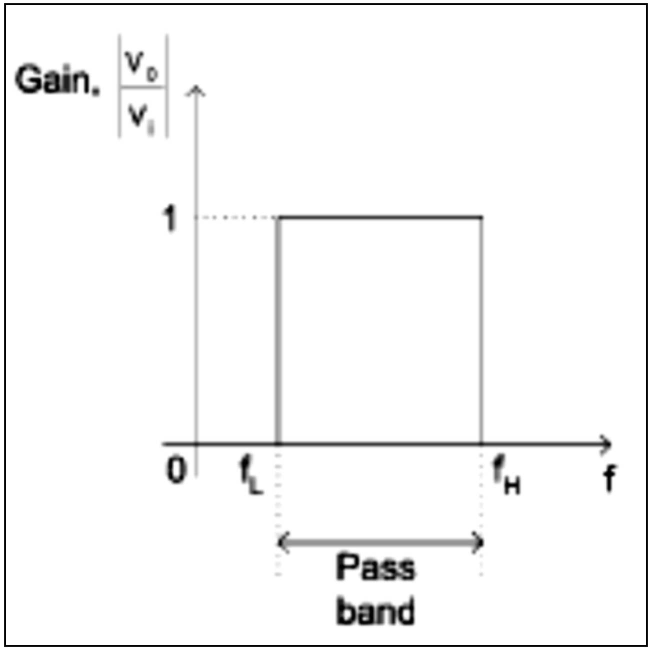
$$f_c = \frac{1}{2\pi RC}$$

Band-Pass Filter Response

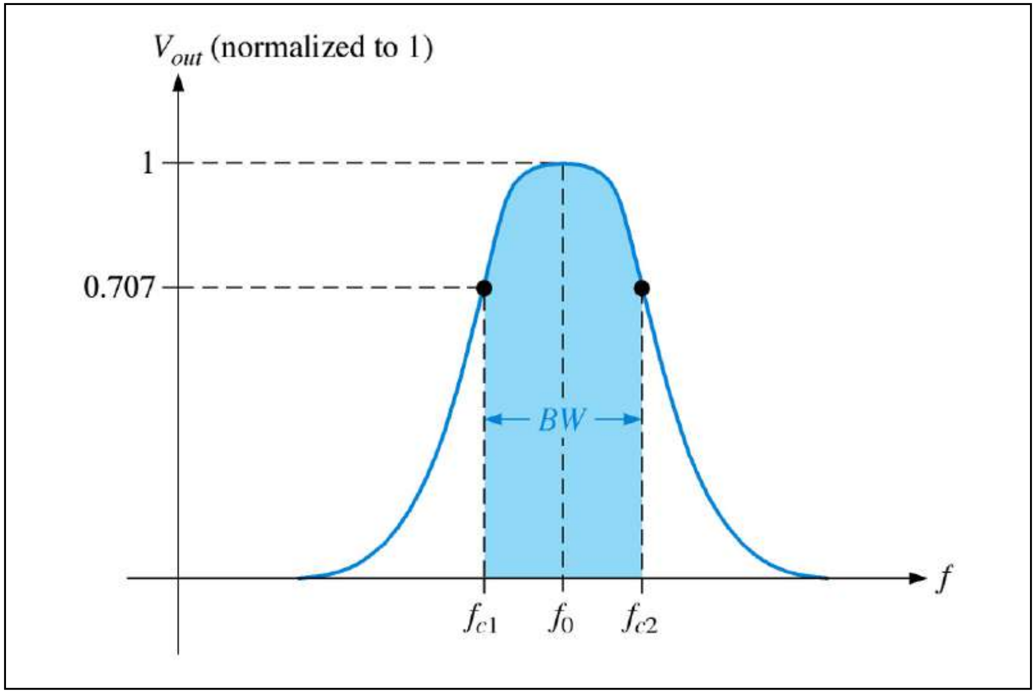
➢ A band-pass filter passes all signals lying within a band between a lower-frequency limit and upper-frequency limit and essentially rejects all other frequencies that are outside this specified band.



Actual response



Ideal response



➢ The bandwidth (BW) is defined as the difference between the upper critical frequency (f_{c2}) and the lower critical frequency (f_{c1}).

$$BW = f_{c2} - f_{c1}$$

- The frequency about which the pass band is centered is called the ***center frequency***, f_o and defined as the geometric mean of the critical frequencies.

$$f_o = \sqrt{f_{c1} f_{c2}}$$

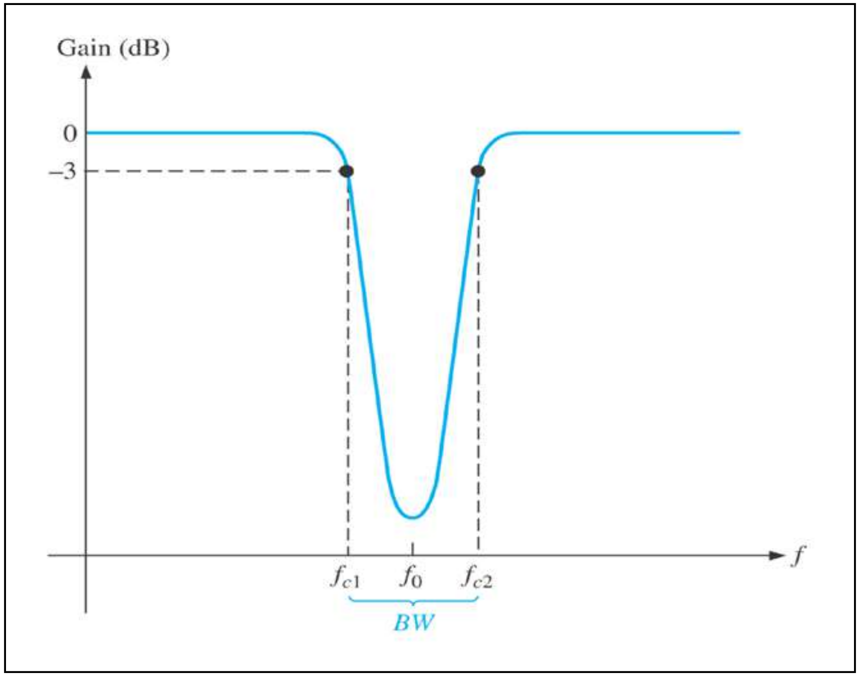
- The ***quality factor (Q)*** of a band-pass filter is the ratio of the center frequency to the bandwidth.

$$Q = \frac{f_o}{BW}$$

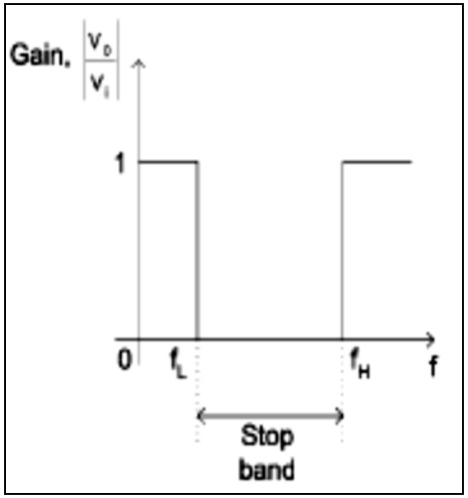
- The higher value of Q, the narrower the bandwidth and the better the selectivity for a given value of f_o.
- (Q>10) as a narrow-band or (Q<10) as a wide-band
- The quality factor (Q) can also be expressed in terms of the damping factor (DF) of the filter as :

$$Q = \frac{1}{DF}$$

Band-Stop Filter Response



Actual response



Ideal response

- Band-stop filter is a filter which its operation is opposite to that of the band-pass filter because the frequencies within the bandwidth are rejected, and the frequencies above f_{c1} and f_{c2} are passed.
- For the band-stop filter, the bandwidth is a band of frequencies between the 3 dB points, just as in the case of the band-pass filter response.

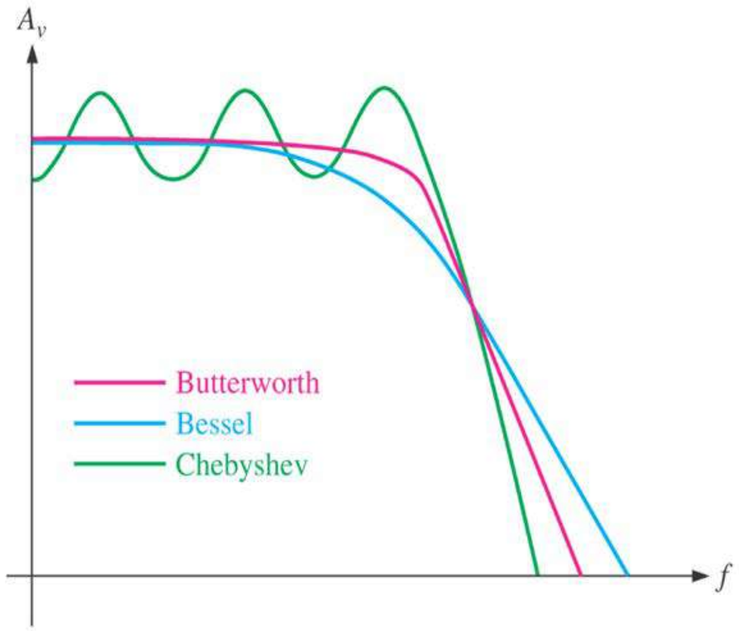
FILTER RESPONSE CHARACTERISTICS

- There are **3** characteristics of filter response :

i) **Butterworth** characteristic

ii) **Chebyshev** characteristic

iii) **Bessel** characteristic.

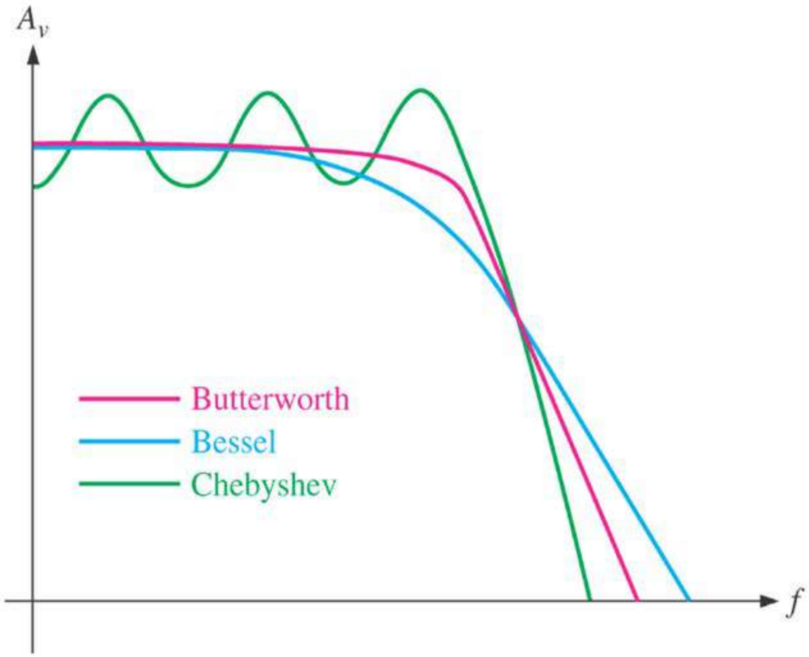


Comparative plots of three types of filter response characteristics.

- Each of the characteristics is identified by the shape of the response curve

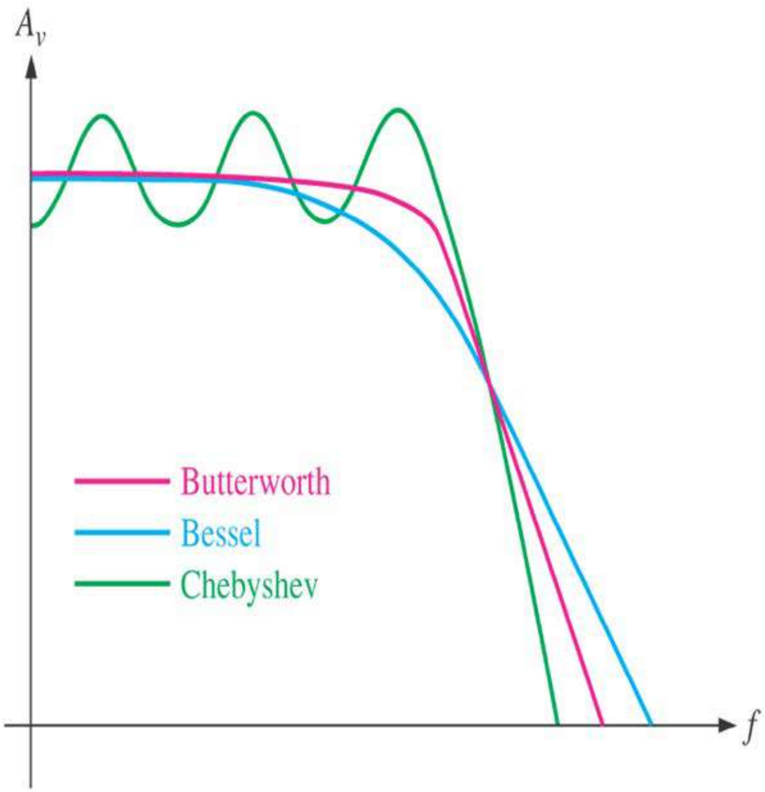
Butterwoth Characteristic

- Filter response is characterized by flat amplitude response in the passband.
- Provides a roll-off rate of -20 dB/decade/pole.
- Filters with the Butterworth response are normally used when all frequencies in the passband must have the ***same gain***.



Chebyshev Characteristic

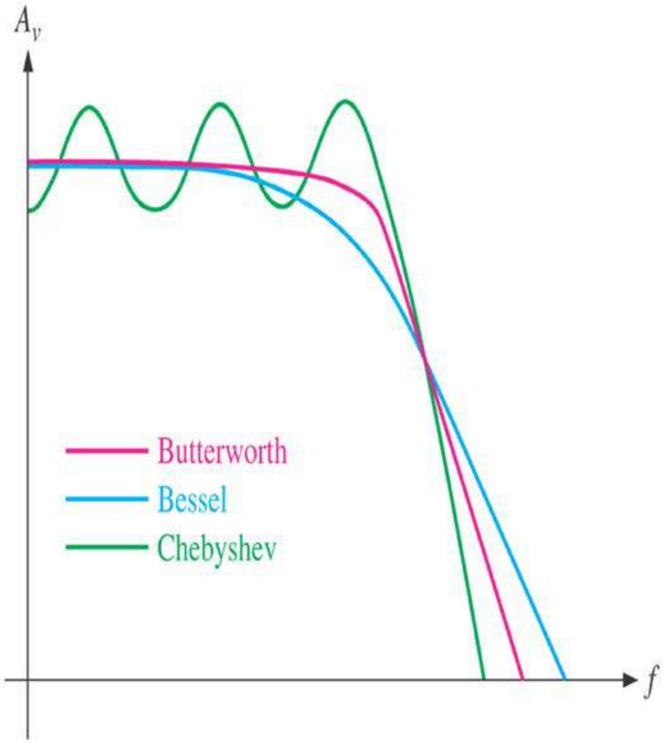
- Filter response is characterized by overshoot or ripples in the passband.
- Provides a roll-off rate greater than -20 dB/decade/pole.
- Filters with the Chebyshev response can be implemented with fewer poles and less complex circuitry for a given roll-off rate



Bessel Characteristic

- Filter response is characterized by a linear characteristic, meaning that the phase shift increases linearly with frequency.

- Filters with the Bessel response are used for filtering pulse waveforms without distorting the shape of waveform.



DAMPING FACTOR

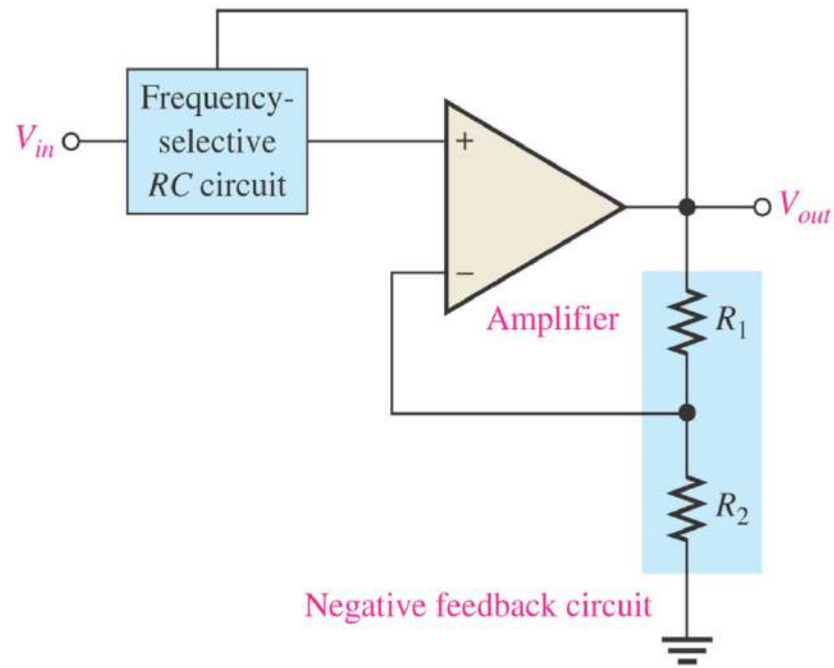
- The damping factor (DF) of an active filter determines which response characteristic the filter exhibits.

- This active filter consists of an amplifier, a negative feedback circuit and RC circuit.

- The amplifier and feedback are connected in a non-inverting configuration.

- DF is determined by the negative feedback and defined as :

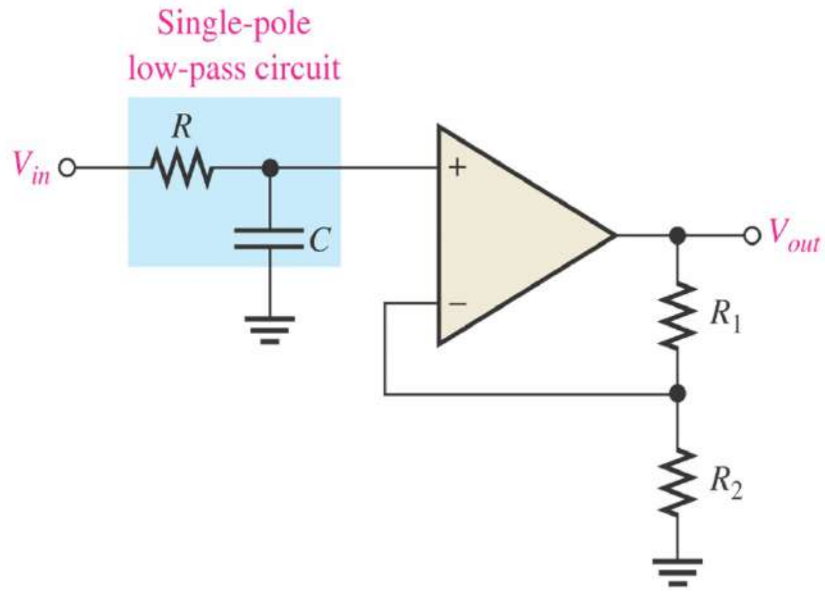
$$DF = 2 - \frac{R_1}{R_2}$$



General diagram of active filter

- The value of DF required to produce a desired response characteristics depends on order (number of poles) of the filter.
- A pole (single pole) is simply one resistor and one capacitor.
- The more poles filter has, the faster its roll-off rate

CRITICAL FREQUENCY AND ROLL-OFF RATE



One-pole (first-order) low-pass filter.

- The critical frequency, f_c is determined by the values of **R** and **C** in the frequency-selective RC circuit.
- Each RC set of filter components represents a pole.
- Greater roll-off rates can be achieved with more poles.
- Each pole represents a -20dB/decade increase in roll-off.

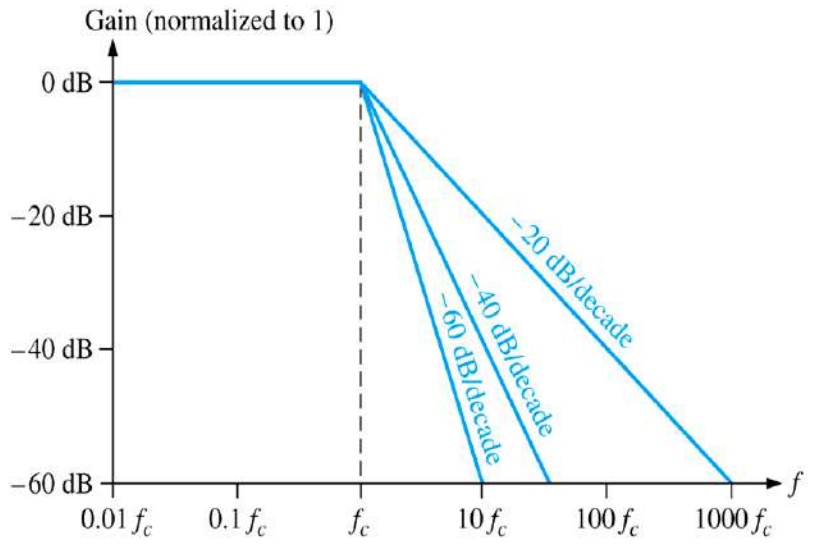
- For a single-pole (first-order) filter, the critical frequency is :

$$f_c = \frac{1}{2\pi RC}$$

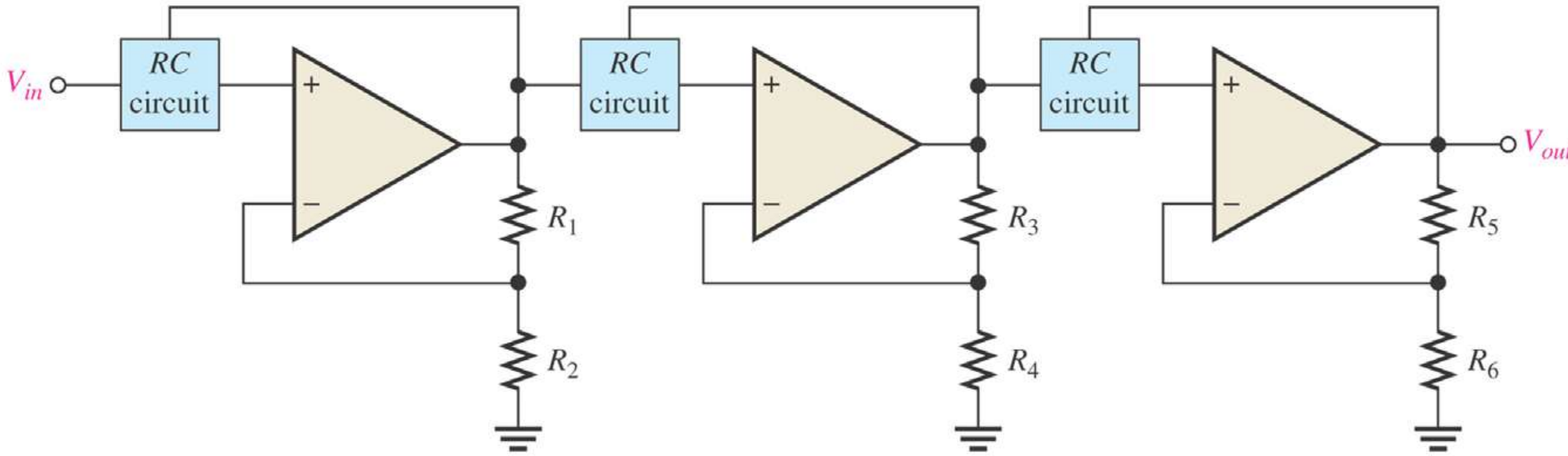
- The above formula can be used for both low-pass and high-pass filters.

➢ The number of poles determines the roll-off rate of the filter. For example, a Butterworth response produces -20dB/decade/pole. This means that:

- **One-pole (first-order)** filter has a roll-off of -20 dB/decade
- **Two-pole (second-order)** filter has a roll-off of -40 dB/decade
- **Three-pole (third-order)** filter has a roll-off of -60 dB/decade



- The number of filter poles can be increased by ***cascading***. To obtain a filter with three poles, cascade a two-pole with one-pole filters.



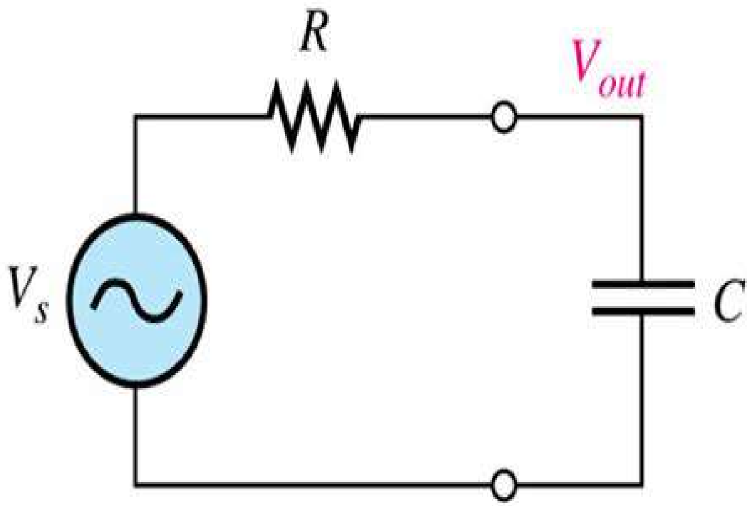
Three-pole (third-order) low-pass filter.

ACTIVE LOW-PASS FILTERS

Advantages of active filters over passive filters (R, L, and C elements only):

1. By containing the op-amp, active filters can be designed to provide required gain, and hence **no signal attenuation** as the signal passes through the filter.
2. **No loading problem**, due to the high input impedance of the op-amp prevents excessive loading of the driving source, and the low output impedance of the op-amp prevents the filter from being affected by the load that it is driving.
3. **Easy to adjust over a wide frequency range** without altering the desired response.

- Figure below shows the basic Low-Pass filter circuit



(b) Basic low-pass circuit

At critical frequency,

Resistance = Capacitance

$$R = X_c$$

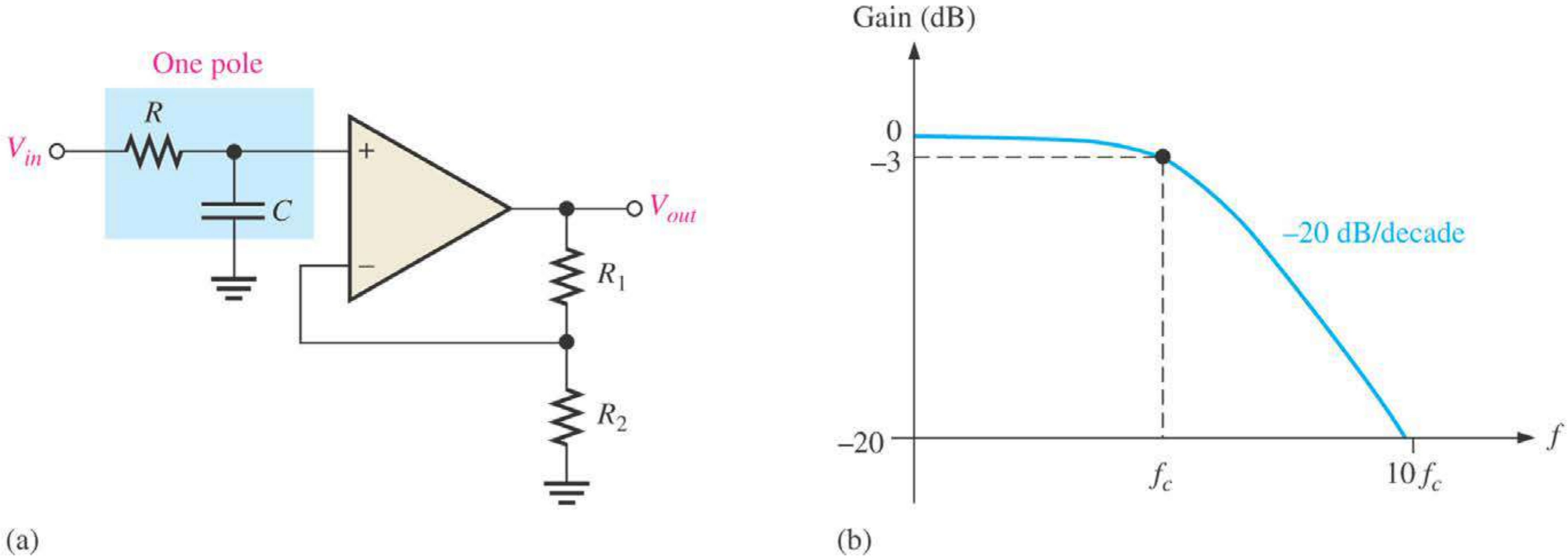
$$R = \frac{1}{\omega_c C}$$

$$R = \frac{1}{2\pi f_c C}$$

So, critical frequency ;

$$f_c = \frac{1}{2\pi RC}$$

Single-Pole Filter



Single-pole active low-pass filter and response curve.

➢ This filter provides a roll-off rate of -20 dB/decade above the critical frequency.

- The op-amp in single-pole filter is connected as a noninverting amplifier with the closed-loop voltage gain in the passband is set by the values of R_1 and R_2 :

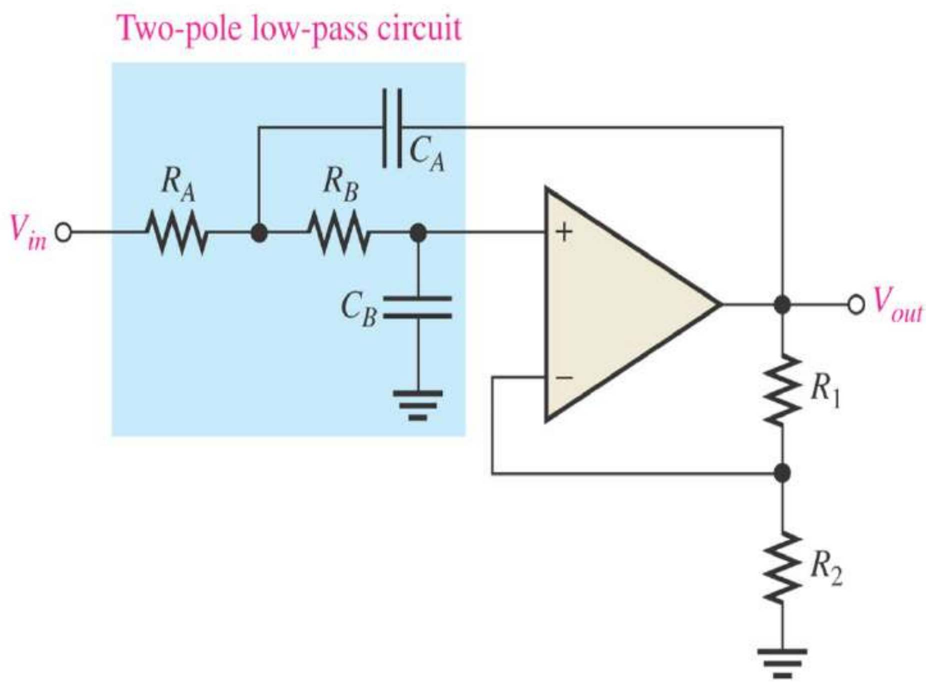
$$A_{cl(NI)} = \frac{R_1}{R_2} + 1$$

- The critical frequency of the single-pole filter is :

$$f_c = \frac{1}{2\pi RC}$$

Sallen-Key Low-Pass Filter

➢ Sallen-Key is one of the most common configurations for a second order (two-pole) filter.



Basic Sallen-Key low-pass filter.

➢ There are two low-pass RC circuits that provide a roll-off of -40 dB/decade above f_c (assuming a Butterworth characteristics).

➢ One RC circuit consists of R_A and C_A, and the second circuit consists of R_B and C_B.

- The critical frequency for the Sallen-Key filter is :

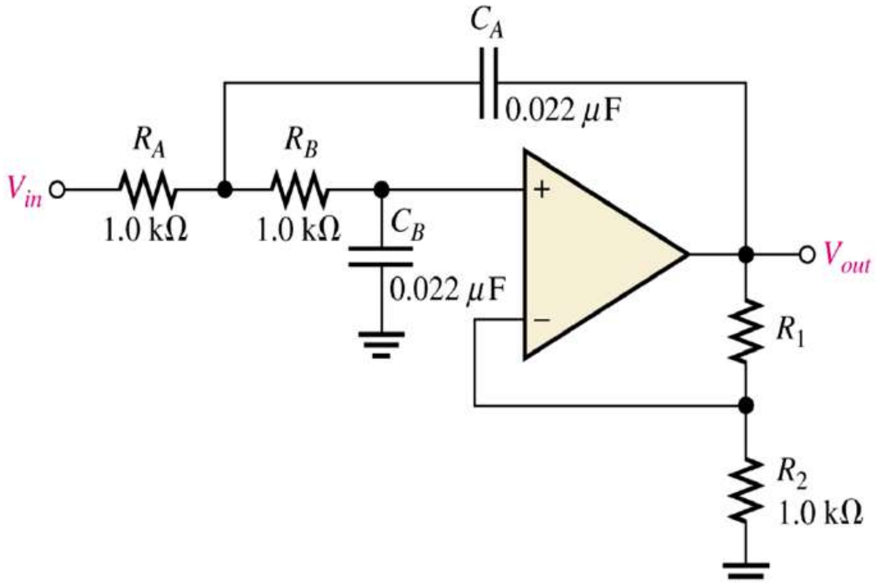
$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$

- For $R_A = R_B = R$ and $C_A = C_B = C$, thus the critical frequency :

$$f_c = \frac{1}{2\pi RC}$$

Example :

- Determine critical frequency
- Set the value of R_1 for Butterworth response by giving that Butterworth response for second order is 0.586



- Critical frequency

$$f_c = \frac{1}{2\pi RC} = 7.23kHz$$

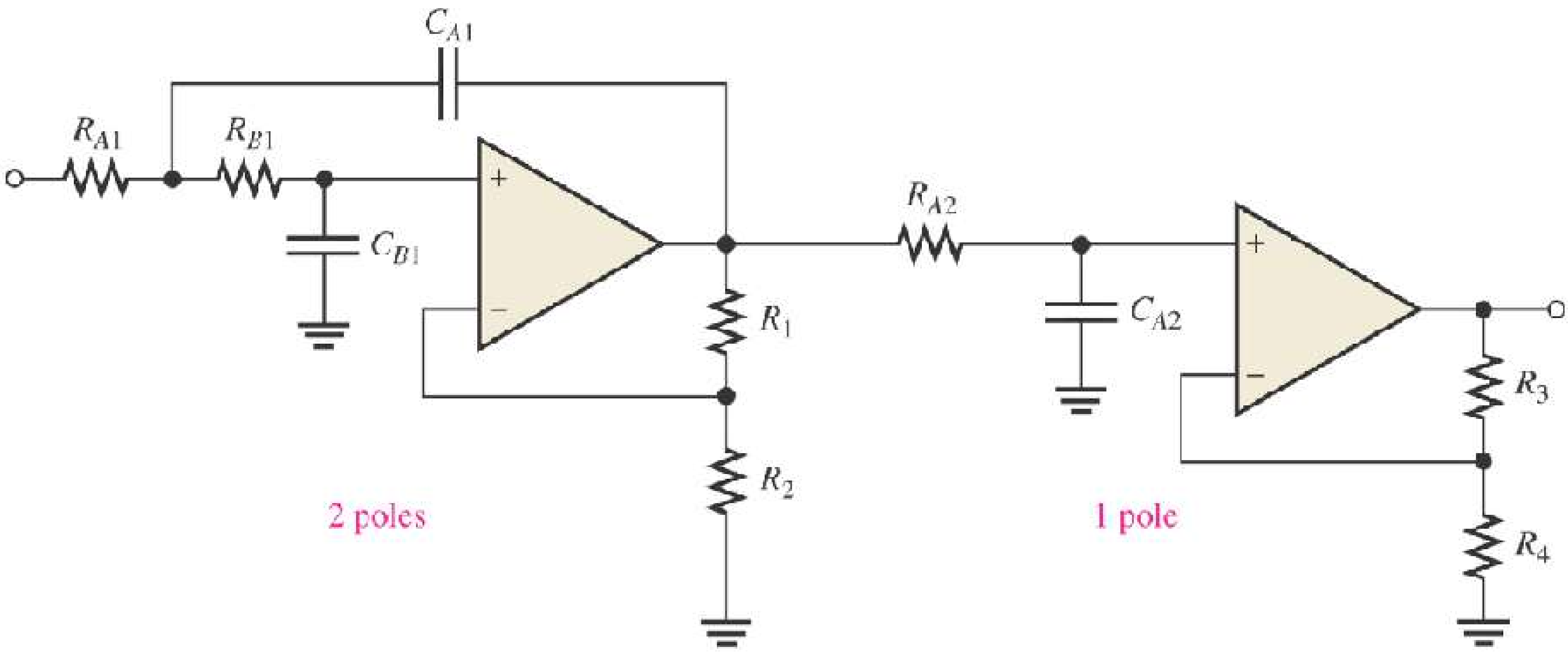
- Butterworth response given $R_1/R_2 = 0.586$

$$R_1 = 0.586 R_2$$

$$R_1 = 586k\Omega$$

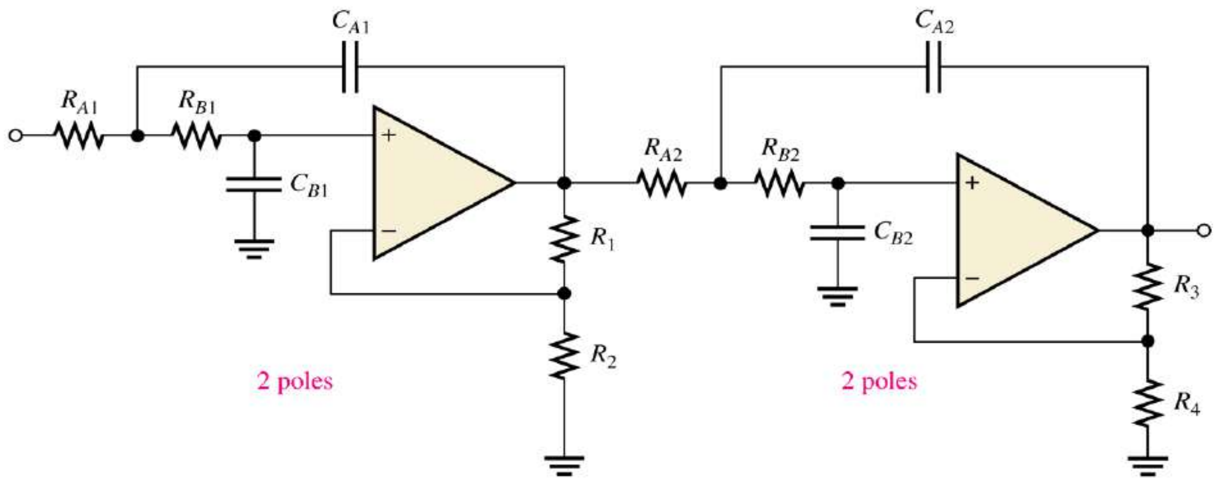
Cascading Low-Pass Filter

➢ A three-pole filter is required to provide a roll-off rate of -60 dB/decade. This is done by cascading a two-pole Sallen-Key low-pass filter and a single-pole low-pass filter.



Cascaded low-pass filter: third-order configuration.

➢ A four-pole filter is required to provide a roll-off rate of -80 dB/decade. This is done by cascading a two-pole Sallen-Key low-pass filter and a two-pole Sallen-Key low-pass filter.

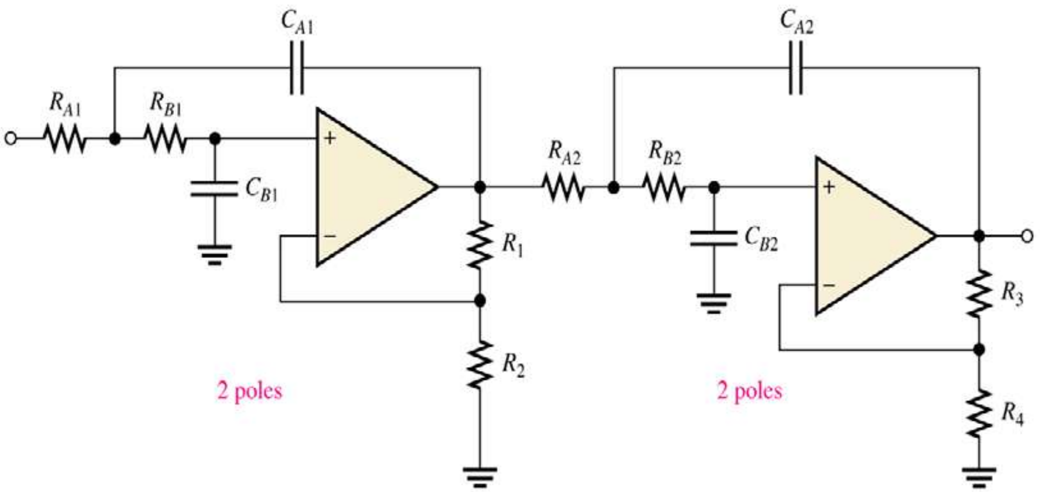


(b) Fourth-order configuration

Cascaded low-pass filter: fourth-order configuration.

Example :

- Determine the capacitance values required to produce a critical frequency of 2680 Hz if all resistors in RC low pass circuit is 1.8kΩ



(b) Fourth-order configuration

$$f_c = \frac{1}{2\pi RC}$$

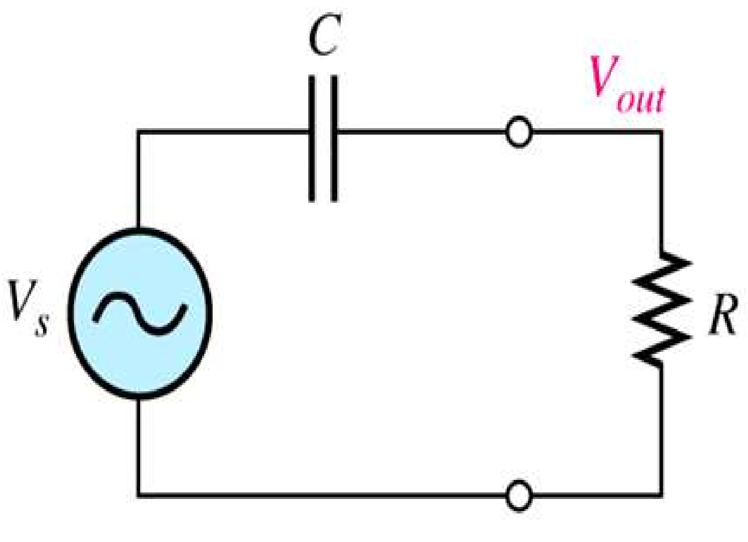
$$C = \frac{1}{2\pi f_c R} = 0.033\mu F$$

$$C_{A1} = C_{B1} = C_{A2} = C_{B2} = 0.033\mu f$$

- Both stages must have the same f_c. Assume equal-value of capacitor

ACTIVE HIGH-PASS FILTERS

➢ Figure below shows the basic High-Pass filter circuit :



(b) Basic high-pass circuit

At critical frequency,

Resistance = Capacitance

$$R = X_c$$

$$R = \frac{1}{\omega_c C}$$

$$R = \frac{1}{2\pi f_c C}$$

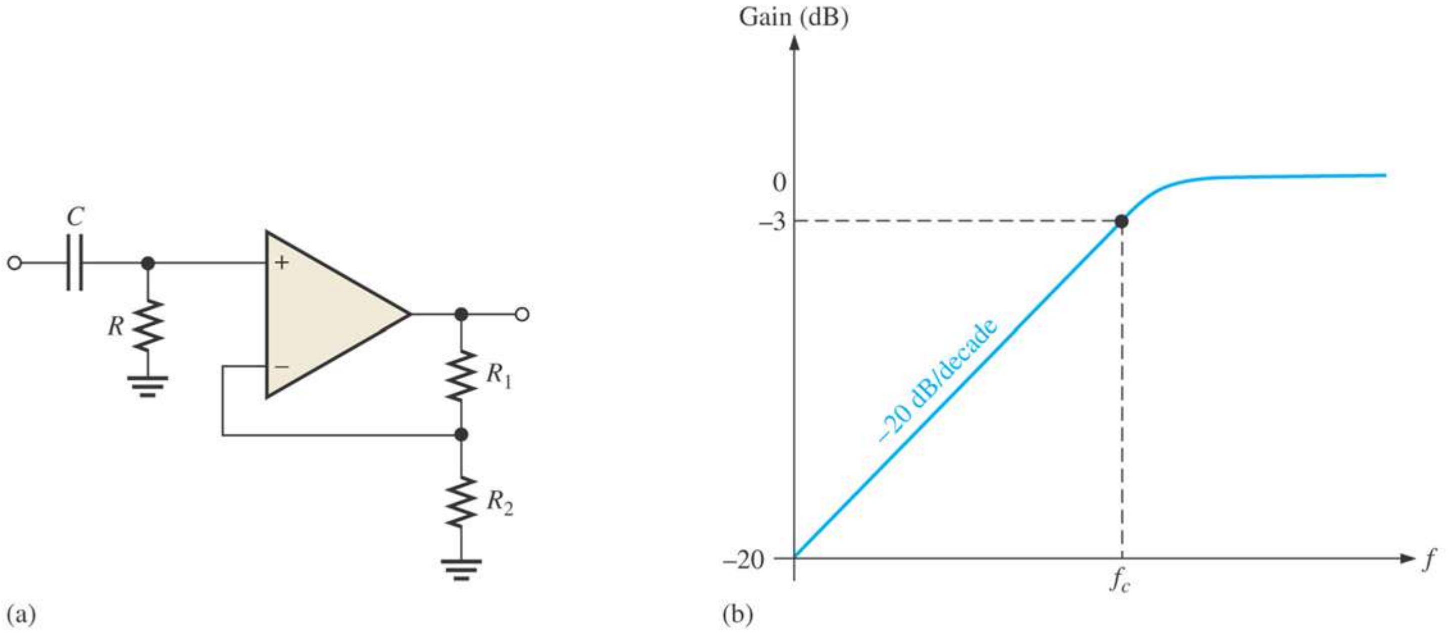
So, critical frequency ;

$$f_c = \frac{1}{2\pi RC}$$

Single-Pole Filter

- In high-pass filters, the roles of the capacitor and resistor are reversed in the RC circuits as shown from Figure (a). The negative feedback circuit is the same as for the low-pass filters.

- Figure (b) shows a high-pass active filter with a -20dB/decade roll-off



Single-pole active high-pass filter and response curve.

- The op-amp in single-pole filter is connected as a noninverting amplifier with the closed-loop voltage gain in the passband is set by the values of R_1 and R_2 :

$$A_{cl(NI)} = \frac{R_1}{R_2} + 1$$

- The critical frequency of the single-pole filter is :

$$f_c = \frac{1}{2\pi RC}$$

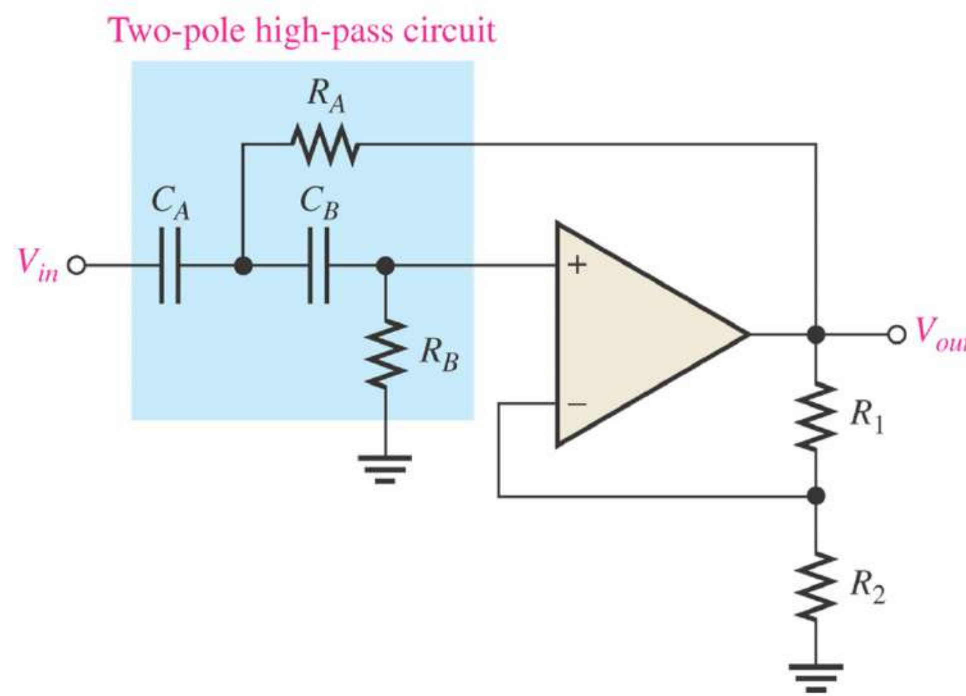
Sallen-Key High-Pass Filter

- Components R_A, C_A, R_B, and C_B form the **second order** (two-pole) frequency-selective circuit.

- The position of the resistors and capacitors in the frequency-selective circuit are **opposite** in low pass configuration.

- There are two high-pass RC circuits that provide a **roll-off of -40 dB/decade above fc**

- The **response characteristics** can be optimized by proper selection of the **feedback resistors**, R_1 and R_2.



Basic Sallen-Key high-pass filter.

- The critical frequency for the Sallen-Key filter is :

$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$

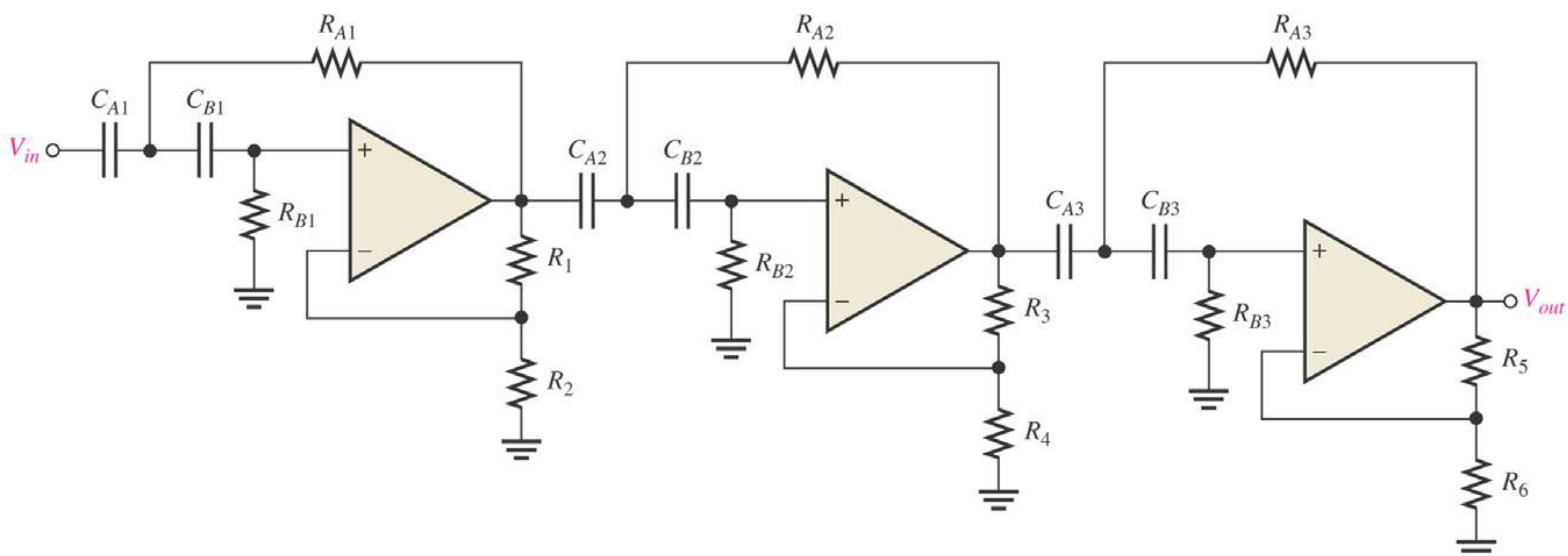
- For $R_A = R_B = R$ and $C_A = C_B = C$, thus the critical frequency :

$$f_c = \frac{1}{2\pi RC}$$

Cascading High-Pass Filter

➢ As with the low-pass filter, first- and second-order high-pass filters can be cascaded to provide three or more poles and thereby create faster roll-off rates.

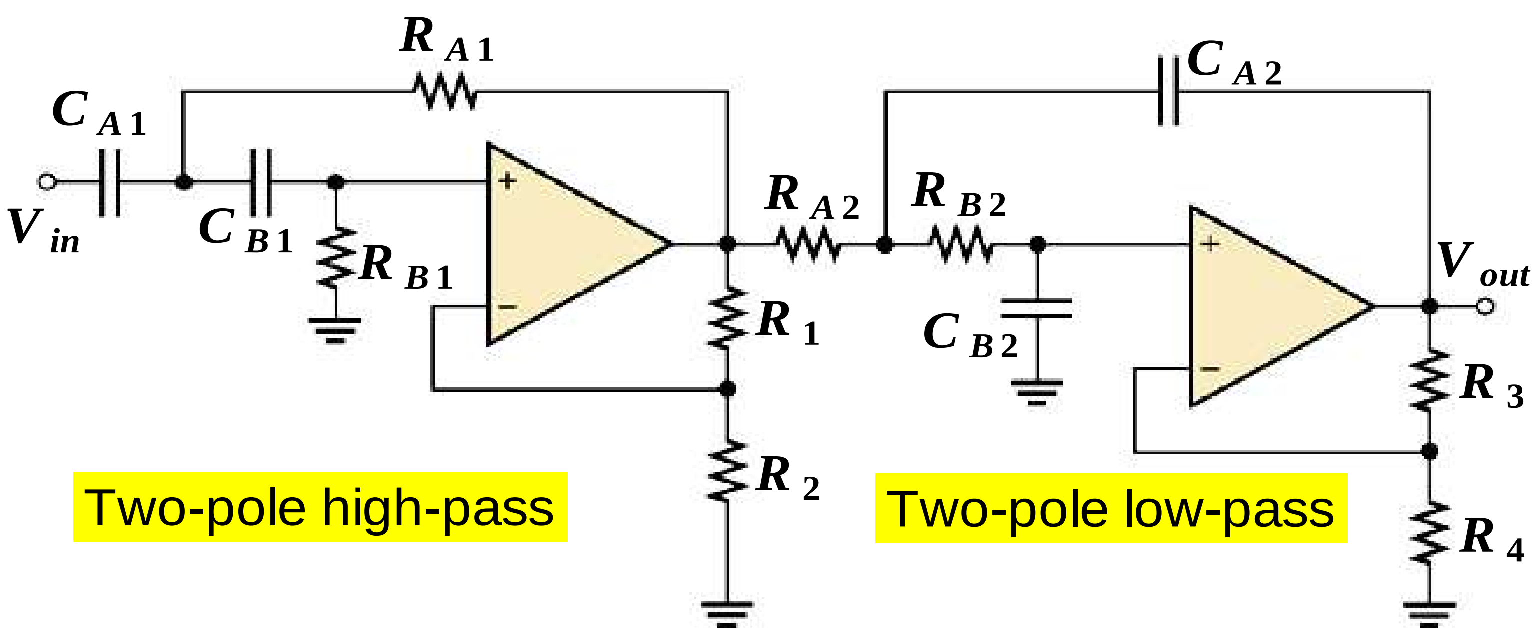
➢A six-pole high-pass filter consisting of three Sallen-Key two-pole stages with the roll-off rate of -120 dB/decade.



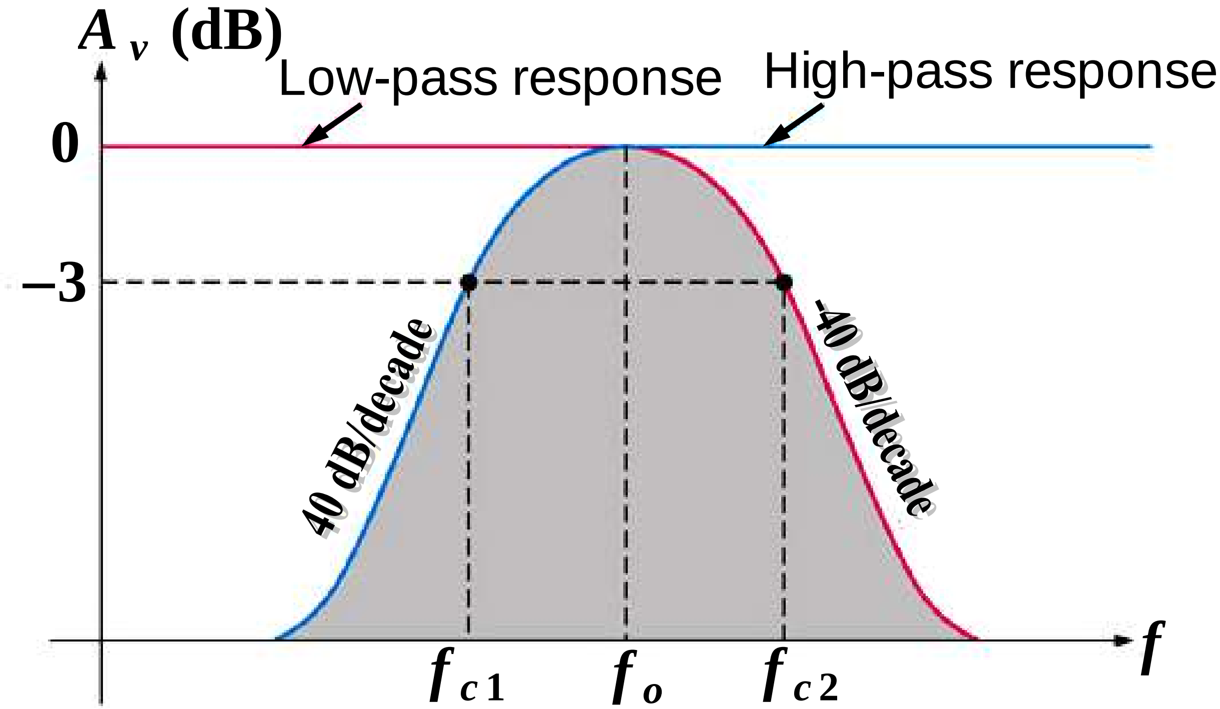
Sixth-order high-pass filter

ACTIVE BAND-PASS FILTERS

Cascaded Low-Pass and High-Pass Filters

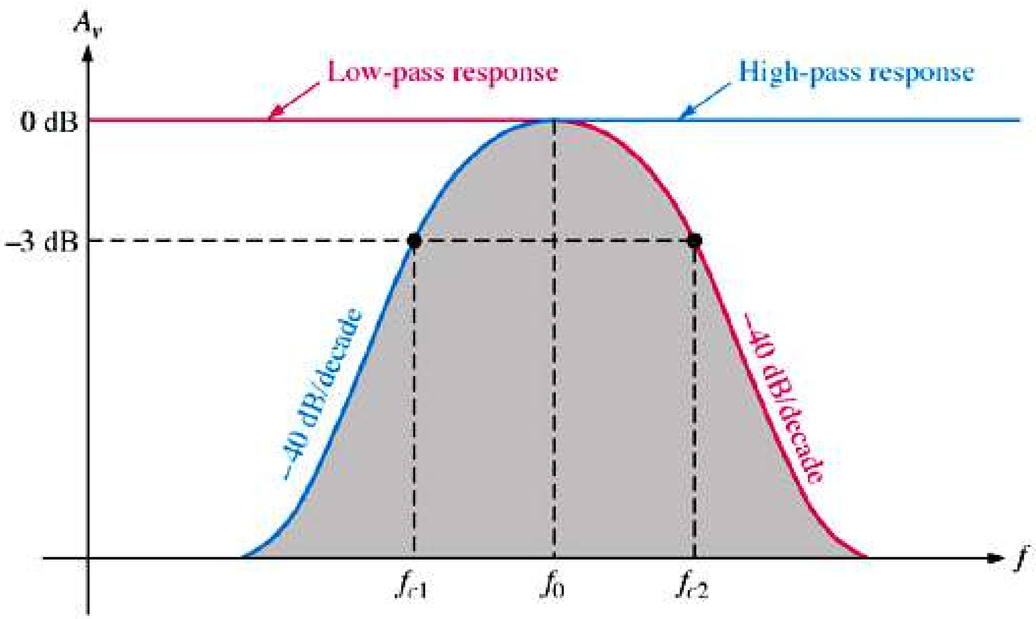


- ➢ Band-pass filter is formed by cascading a two-pole high-pass and two pole low-pass filter.
- ➢ Each of the filters shown is Sallen-Key Butterworth configuration, so that the roll-off rate are -40dB/decade.



➢ The lower frequency f_{c1} of the passband is the critical frequency of the high-pass filter.

➢ The upper frequency f_{c2} of the passband is the critical frequency of the low-pass filter.



➢ The following formulas express the three frequencies of the band-pass filter.

$$f_{c1} = \frac{1}{2\pi\sqrt{R_{A1}R_{B1}C_{A1}C_{B1}}}$$

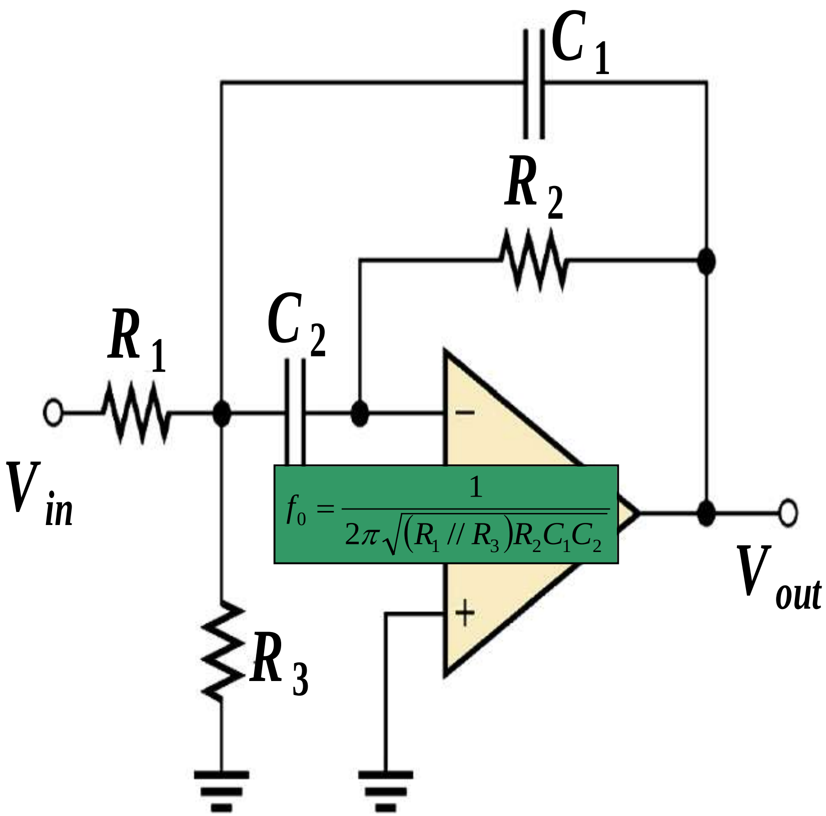
$$f_{c2} = \frac{1}{2\pi\sqrt{R_{A2}R_{B2}C_{A2}C_{B2}}}$$

$$f_0 = \sqrt{f_{c1} f_{c2}}$$

➢ If equal-value components are used in implementing each filter,

$$f_c = \frac{1}{2\pi RC}$$

Multiple-Feedback Band-Pass Filter



$$f_0 = \frac{1}{2\pi\sqrt{(R_1 // R_3)R_2C_1C_2}}$$

- The low-pass circuit consists of R_1 and C_1.
- The high-pass circuit consists of R_2 and C_2.
- The feedback paths are through C_1 and R_2.
- Center frequency;

- By making C1 = C2 =C, yields

$$f_0 = \frac{1}{2\pi C}\sqrt{\frac{R_1 + R_3}{R_1 R_2 R_3}}$$

- The resistor values can be found by using following formula

$$R_1 = \frac{Q}{2\pi f_o C A_o}$$

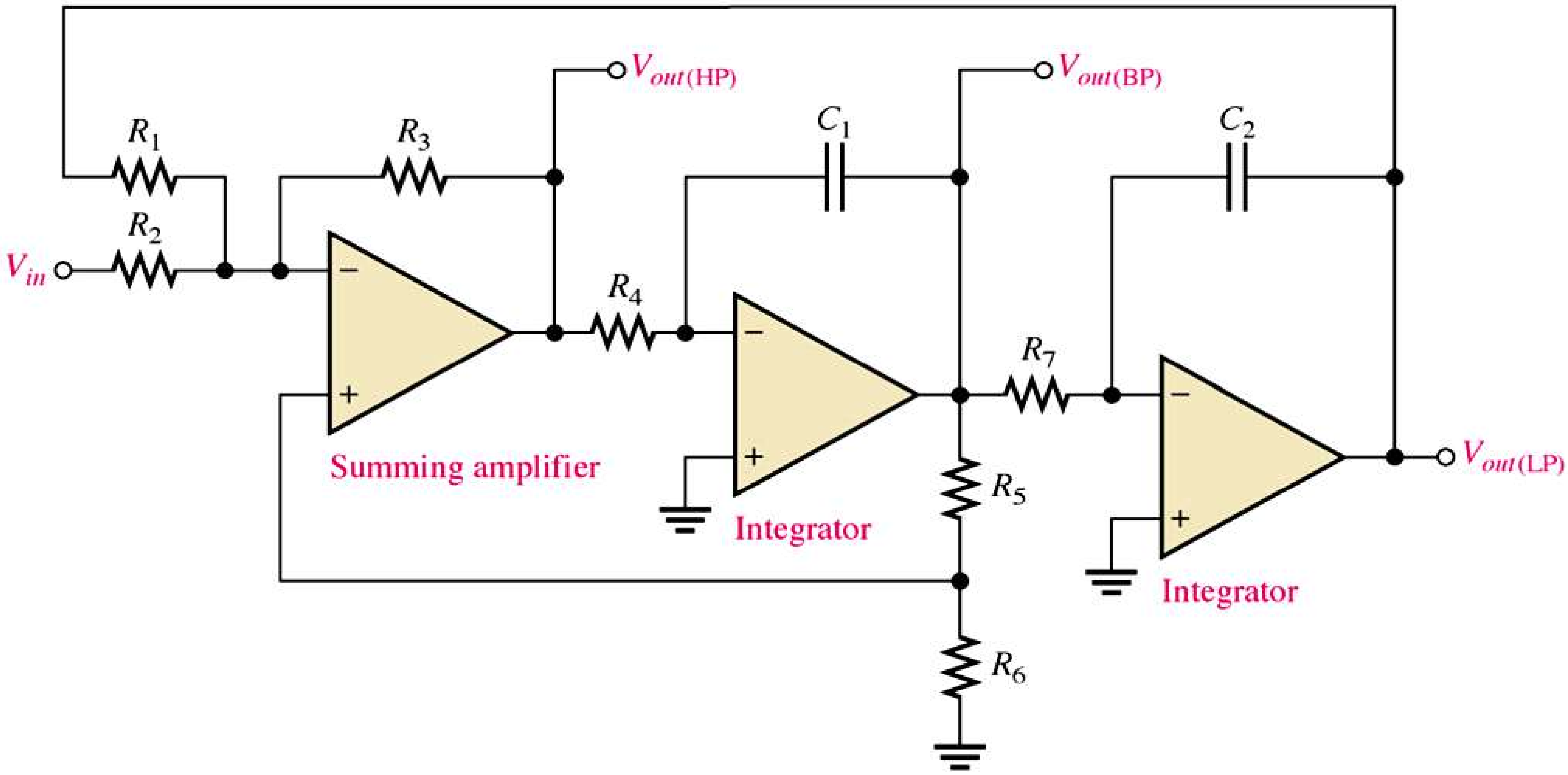
$$R_2 = \frac{Q}{\pi f_o C}$$

$$R_3 = \frac{Q}{2\pi f_o C(2Q^2 - A_o)}$$

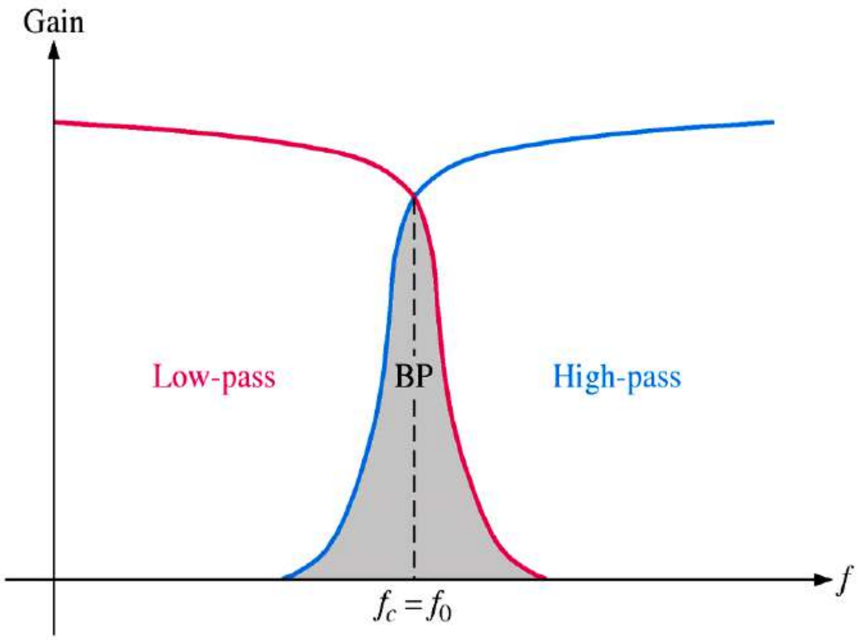
- The maximum gain, A_o occurs at the center frequency.

State-Variable Filter

- State-Variable BPF is widely used for band-pass applications.



- It consists of a summing amplifier and two integrators.
- It has outputs for low-pass, high-pass, and band-pass.
- The center frequency is set by the integrator RC circuits.
- The critical frequency of the integrators usually made equal
- R_5 and R_6 set the Q (bandwidth).



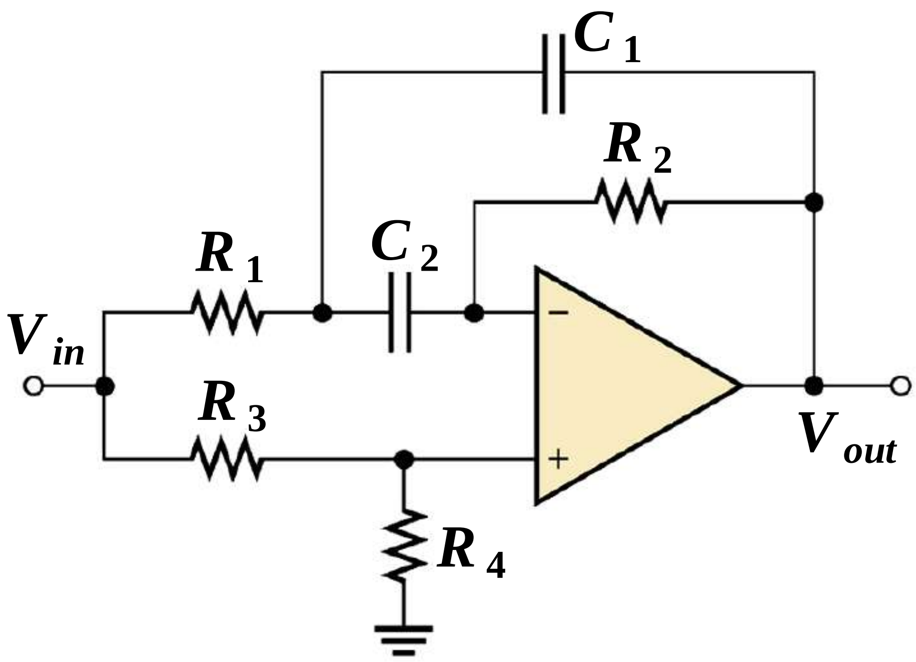
- The band-pass output peaks sharply the center frequency giving it a high Q.

- The Q is set by the feedback resistors R_5 and R_6 according to the following equations :

$$Q = \frac{1}{3}\left(\frac{R_5}{R_6} + 1\right)$$

ACTIVE BAND-STOP FILTERS

Multiple-Feedback Band-Stop Filter



- The configuration is similar to the band-pass version BUT R_3 has been moved and R_4 has been added.
- The BSF is opposite of BPF in that it blocks a specific band of frequencies

FILTER RESPONSE MEASUREMENT

- Measuring frequency response can be performed with typical bench-type equipment.
- It is a process of setting and measuring frequencies both outside and inside the known cutoff points in predetermined steps.
- Use the output measurements to plot a graph.
- More accurate measurements can be performed with sweep generators along with an oscilloscope, a spectrum analyzer, or a scalar analyzer.

SUMMARY

- The bandwidth of a low-pass filter is the same as the upper critical frequency.
- The bandwidth of a high-pass filter extends from the lower critical frequency up to the inherent limits of the circuit.
- The band-pass passes frequencies between the lower critical frequency and the upper critical frequency.

- A band-stop filter rejects frequencies within the upper critical frequency and upper critical frequency.
- The Butterworth filter response is very flat and has a roll-off rate of –20 B
- The Chebyshev filter response has ripples and overshoot in the passband but can have roll-off rates greater than –20 dB

- The Bessel response exhibits a linear phase characteristic, and filters with the Bessel response are better for filtering pulse waveforms.

- A filter pole consists of one RC circuit. Each pole doubles the roll-off rate.
  The Q of a filter indicates a band-pass filter’s selectivity. The higher the Q the narrower the bandwidth.

- The damping factor determines the filter response characteristic.