BENHA UNIVERSITY
FACULTY OF ENGINEERING AT SHOUBRA

ECE-322
Electronic Circuits (B)

Lecture #5
Active Filters

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SPRING 2015

Agenda

- Basic Filter Responses
- Filter Response Characteristics
- Active LPF, HPF, BPF & BSF
- Filter Response Measurements

BASIC FILTER RESPONSES

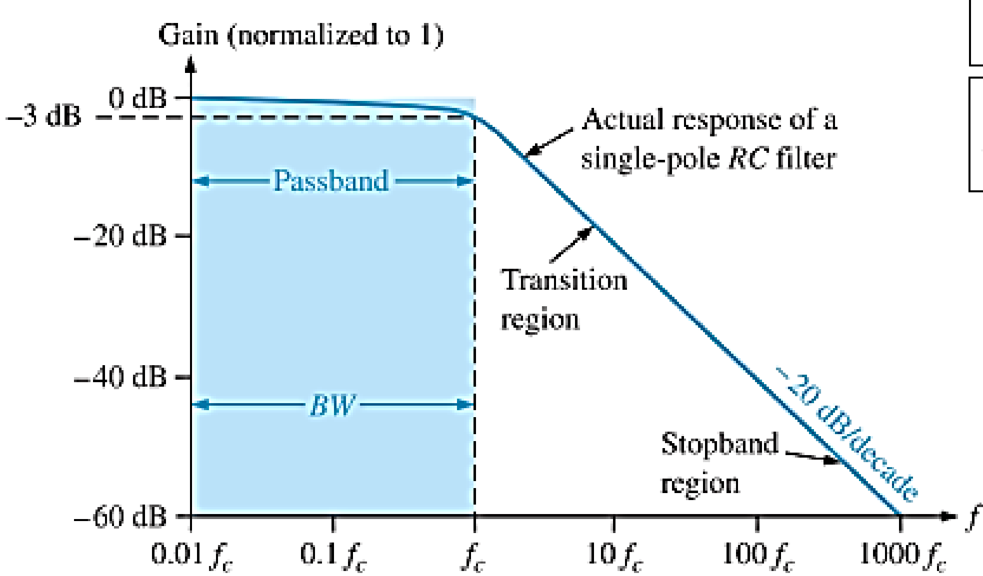
Intro.

- **Filters** are circuits that are capable of **passing** signals with certain selected **frequencies** while **rejecting** signals with **other** frequencies.
- This property is called **selectivity**.
- **Active** filters use **transistors** or **op-amps** combined with passive RC, RL, or RLC circuits.

- The **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 of attenuation).
- The **critical frequency**, (also called the **cutoff frequency**) defines the **end of the passband** and is normally specified at the point where the response drops (**70.7%**) from the passband response.
- Following the passband is a region called the **transition region** that leads into a region called the **stopband**.
- There is **no precise point** between the transition region and the stopband.

Basic Filter Responses

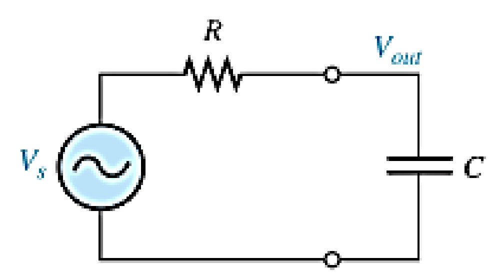
- **Low-Pass Filter Response**
  - Actual filter responses depend on the **number of poles**, a term used with filters to describe the **number of RC circuits** contained in the filter.
  - The -20 dB/decade **roll-off** rate for the gain of a basic RC filter means that at a frequency of $10 f_c$, the output will be -20dB (10%) of the input.
  - This roll-off rate is **not a good filter characteristic** because too much of the unwanted frequencies (beyond the passband) are allowed through the filter.



(a) Comparison of an ideal low-pass filter response (blue area) with actual response. Although not shown on log scale, response extends down to $f_c = 0$.

$$BW = f_c$$

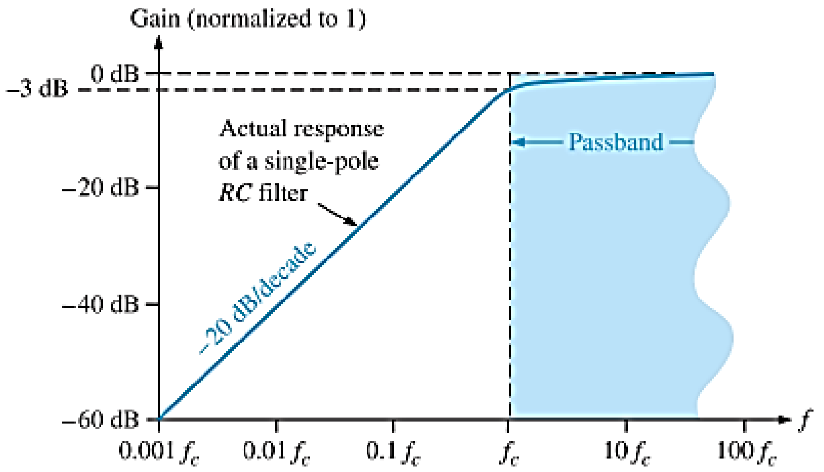
$$f_c = \frac{1}{2\pi RC}$$



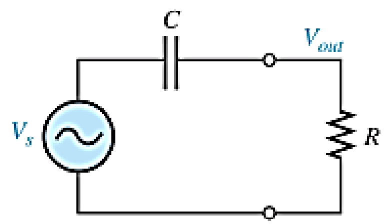
(b) Basic low-pass circuit

Basic Filter Responses..

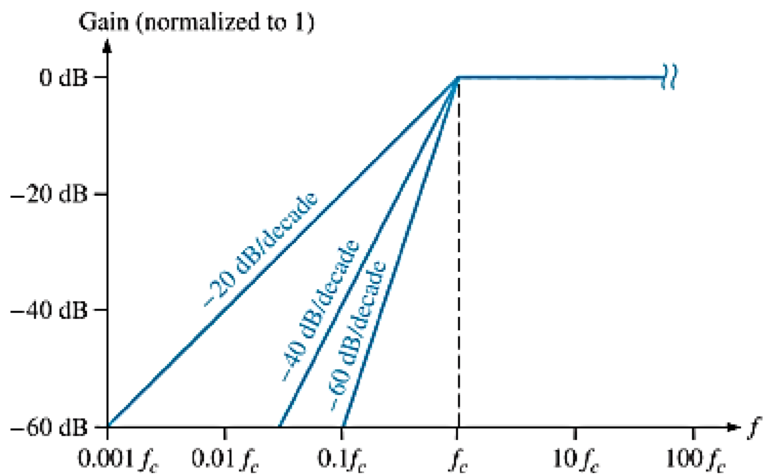
- **High-Pass Filter Response**



(a) Comparison of an ideal high-pass filter response (blue area) with actual response



(b) Basic high-pass circuit



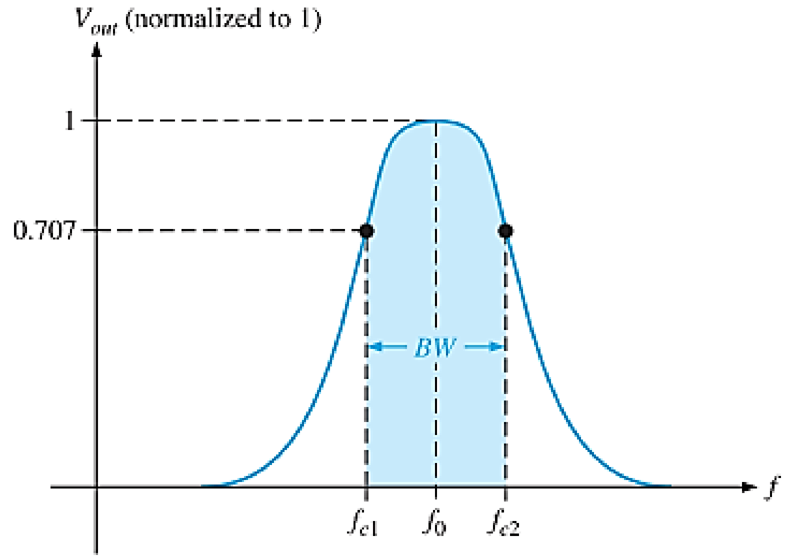
$$f_c = \frac{1}{2\pi RC}$$

Basic Filter Responses...

- **Band-Pass Filter Response**

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

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



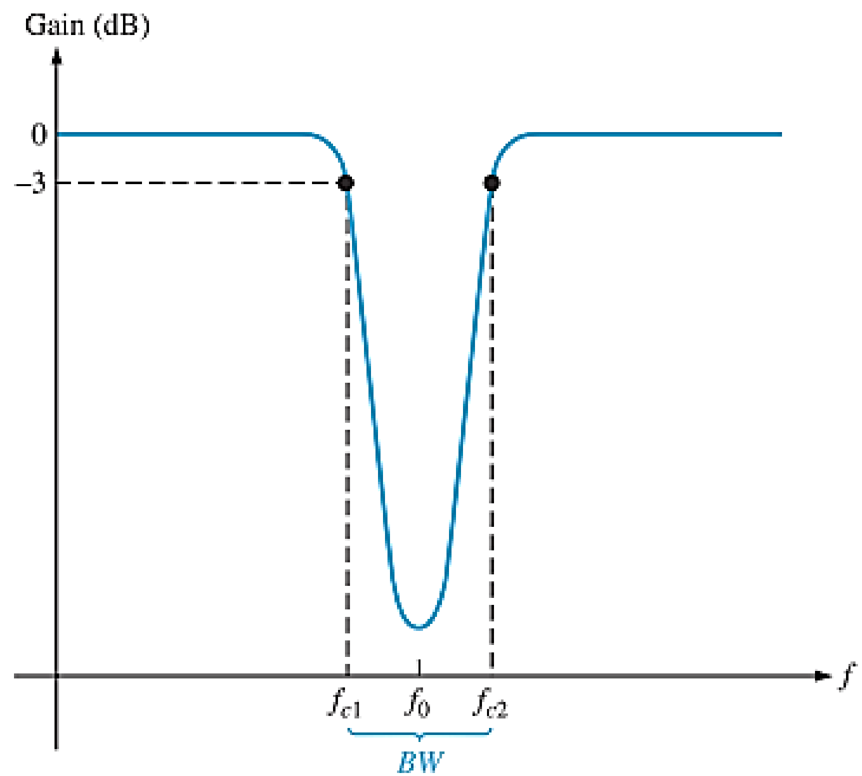
- The **quality factor** (Q) of a band-pass filter is the ratio of the center frequency to the bandwidth.
- The higher the value of Q, the narrower the bandwidth and the better the selectivity for a given value of f_0.
- Band-pass filters are sometimes classified as **narrow-band** (Q>10) or **wide-band** (Q<10).
- The quality factor (Q) can also be expressed in terms of the **damping factor** (DF) of the filter

$$Q = \frac{f_0}{BW} \qquad Q = \frac{1}{DF}$$

Basic Filter Responses....

- **Band-Stop Filter Response**

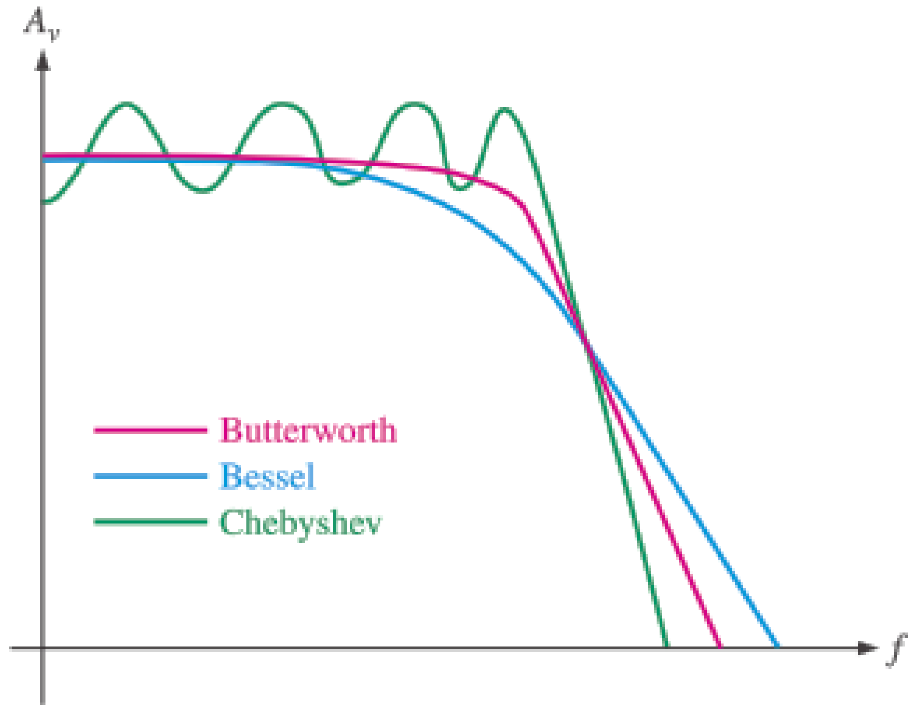
  also known as notch, band-reject, or band-elimination filter.



FILTER RESPONSE CHARACTERISTICS

FILTER RESPONSE CHARACTERISTICS

- Each type of filter response (low-pass, high-pass, band-pass, or band-stop) can be tailored by ***circuit component values*** to have either a
  - **Butterworth,**
  - **Chebyshev, or**
  - **Bessel** characteristic.
- Each of these characteristics is identified by the **shape of the response curve**, and each has an advantage in certain applications.



The Butterworth Characteristic

- The Butterworth characteristic provides a **very flat amplitude response** in the passband and a roll-off rate of -20 dB/decade/pole.
- The **phase response is not linear**, and the phase shift (thus, time delay) of signals passing through the filter varies nonlinearly with frequency.
- Therefore, a **pulse** applied to a Butterworth filter will **cause overshoots** on the output because each frequency component of the pulse's rising and falling edges experiences a different time delay.

FILTER RESPONSE CHARACTERISTICS..

The Chebyshev Characteristic

- Filters with the Chebyshev response characteristic are useful when a **rapid roll-off** is required because it provides a roll-off rate greater than -20 dB/decade/pole.
- This is a **greater rate** than that of the Butterworth, so filters can be implemented with the Chebyshev response with **fewer poles** and **less complex** circuitry for a given roll-off rate.
- This type of filter response is characterized by overshoot or **ripples in the passband** (depending on the number of poles) and an even **less linear phase response** than the Butterworth.

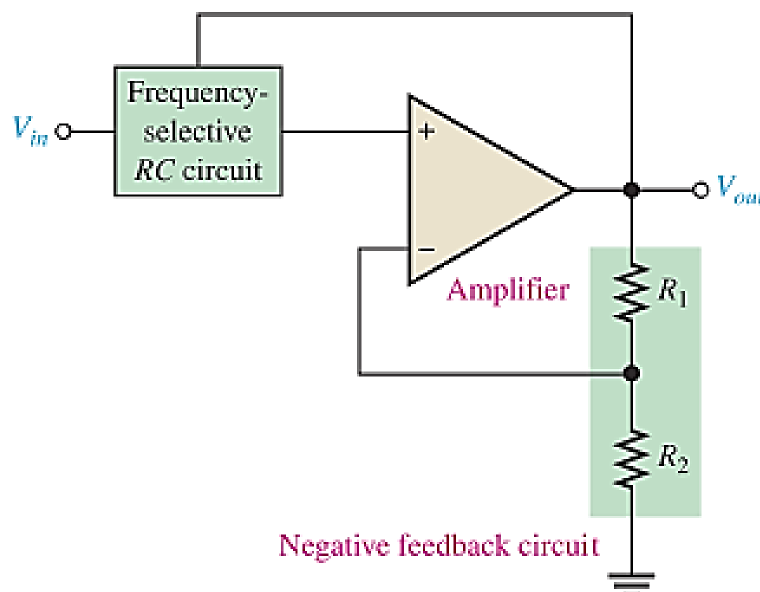
The Bessel Characteristic

- The Bessel response exhibits a **linear phase characteristic**, meaning that the phase shift increases linearly with frequency.
- The result is almost **no overshoot on the output** with a pulse input.
- It has the **slowest roll-off** rate.

The Damping Factor

- The damping factor (**DF**) of an active filter circuit determines which **response characteristic** the filter exhibits.
- It affects the filter response by **negative feedback action**.
- Any attempted increase or decrease in the output voltage is offset by the **opposing effect** of the negative feedback.
- This **tends to** make the **response** curve **flat** in the passband of the filter if the value for the damping factor is precisely set.

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



- The **value of the damping factor** required to produce a desired response characteristic **depends on the order** (number of poles) of the filter.
- ***<u>Example</u>:*** 2nd order → DF=1.4

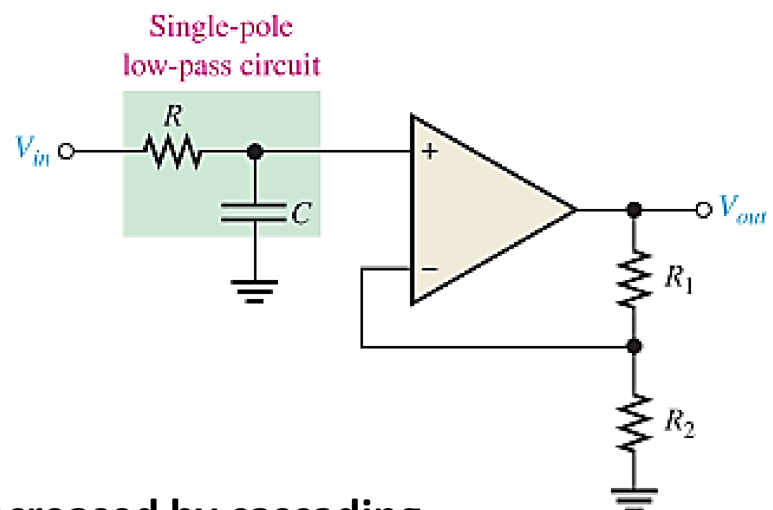
$$\frac{R_1}{R_2} = 2 - DF = 2 - 1.414 = 0.586$$

Values for the Butterworth response

ORDER	ROLL-OFF DB/DECADE	1ST STAGE POLES	1ST STAGE DF	1ST STAGE R_1/R_2	2ND STAGE POLES	2ND STAGE DF	2ND STAGE R_3/R_4	3RD STAGE POLES	3RD STAGE DF	3RD STAGE R_5/R_6
1	−20	1	Optional							
2	−40	2	1.414	0.586						
3	−60	2	1.00	1	1	1.00	1			
4	−80	2	1.848	0.152	2	0.765	1.235			
5	−100	2	1.00	1	2	1.618	0.382	1	0.618	1.382
6	−120	2	1.932	0.068	2	1.414	0.586	2	0.518	1.482

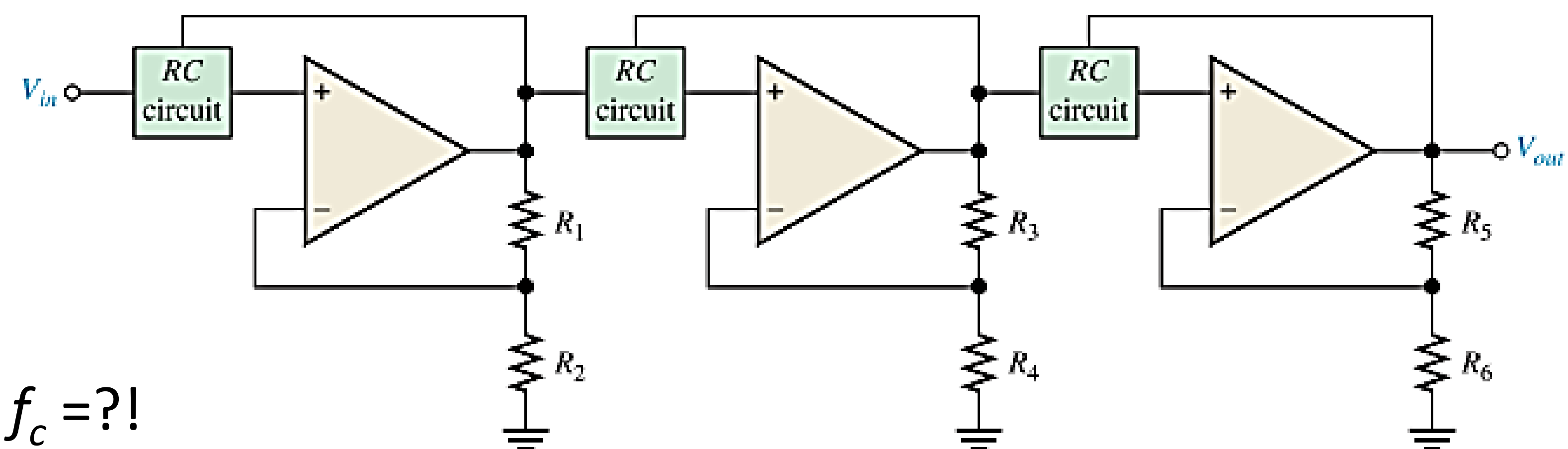
Critical Frequency and Roll-Off Rate

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



- The number of filter **poles** can be **increased by cascading**.

Example: Third-order (three-pole) filter



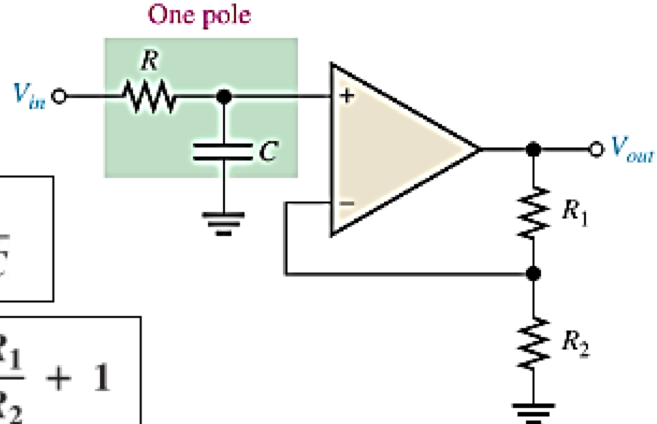
f_c =?!

ACTIVE LOW-PASS FILTERS

Advantages of Op-Amp Active Filters

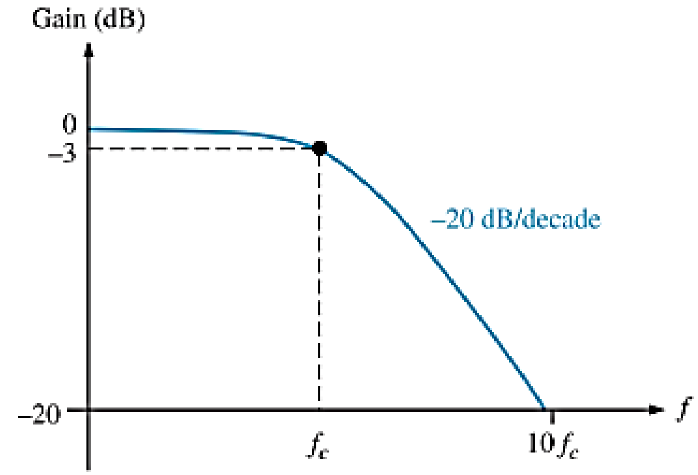
- Filters that use **op-amps** as the **active element** provide several **advantages** over passive filters (R, L, and C elements only).
  - The op-amp provides **gain**, so the **signal is not attenuated** as it passes through the filter.
  - The high input impedance of the op-amp **prevents excessive loading of the driving source**.
  - The low output impedance of the op-amp **prevents the filter from being affected by the load** that it is driving.
  - Active filters are also **easy to adjust over a wide frequency range** without altering the desired response.

Single-Pole LPF



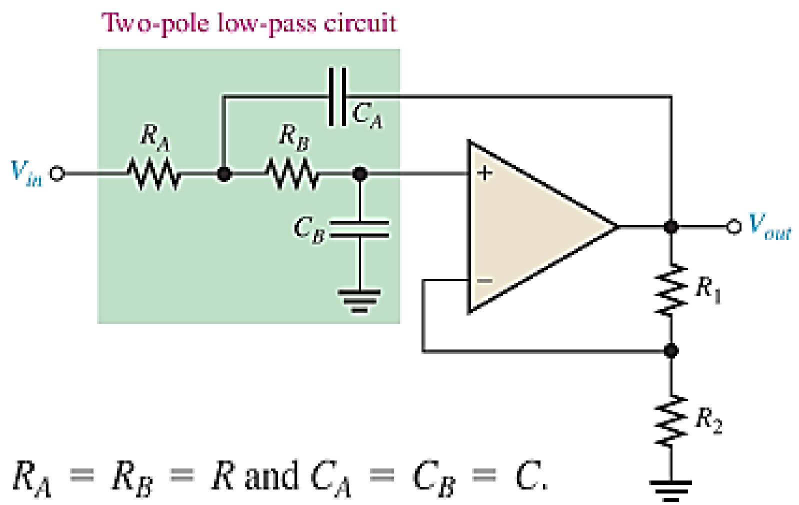
$$f_c = \frac{1}{2\pi RC}$$

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



The Sallen-Key LPF (2nd Order)

- It is used to provide **very high Q factor and passband gain without the use of inductors**.
- It is also known as a **VCVS** (voltage-controlled voltage source) filter.

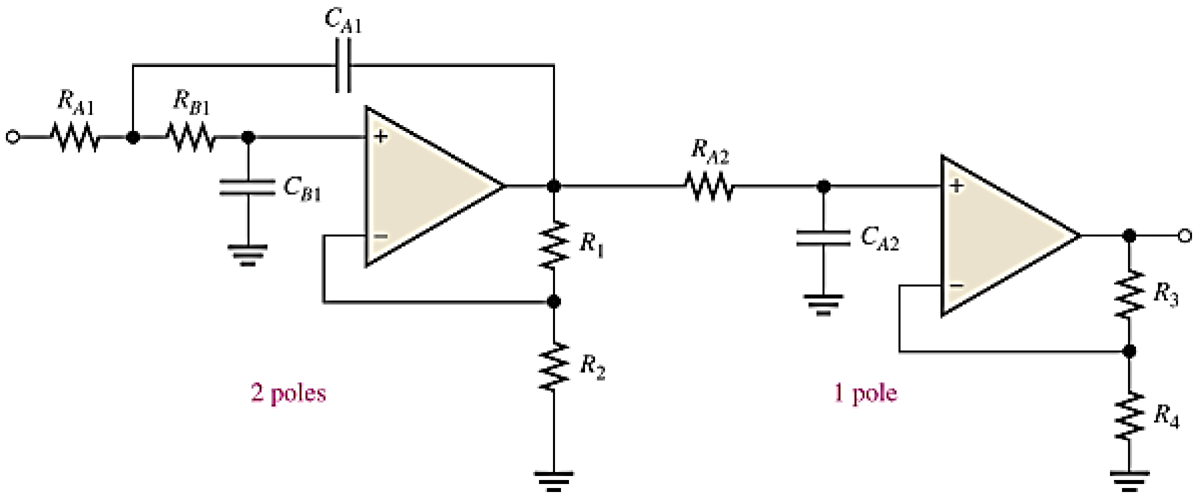


$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$

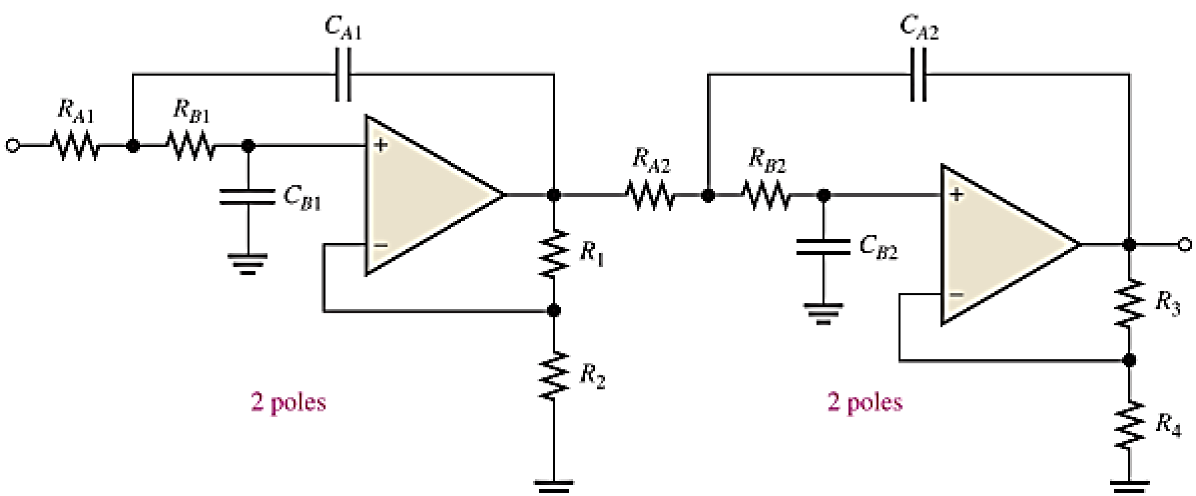
$$f_c = \frac{1}{2\pi RC}$$ @ $R_A = R_B = R$ and $C_A = C_B = C$.

Cascaded LPF

- A **three-pole** filter is required to get a **third-order** low-pass response.
- A **four-pole** filter is **preferred** because it uses the same number of op-amps to achieve a faster roll-off.



(a) Third-order configuration

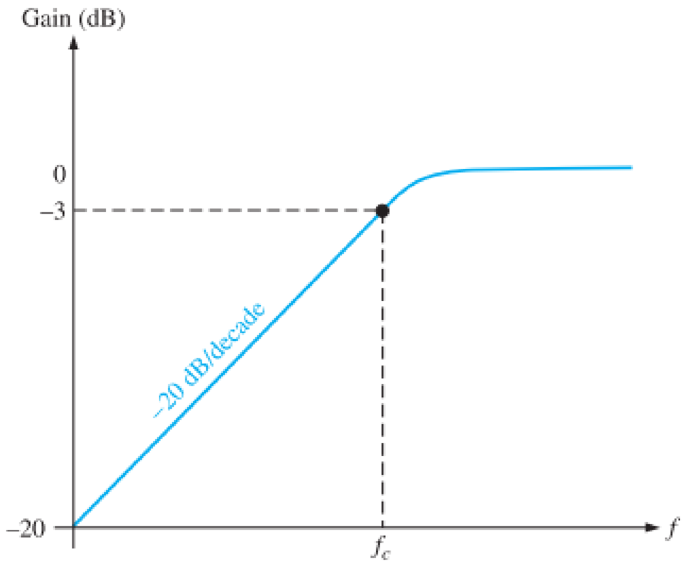


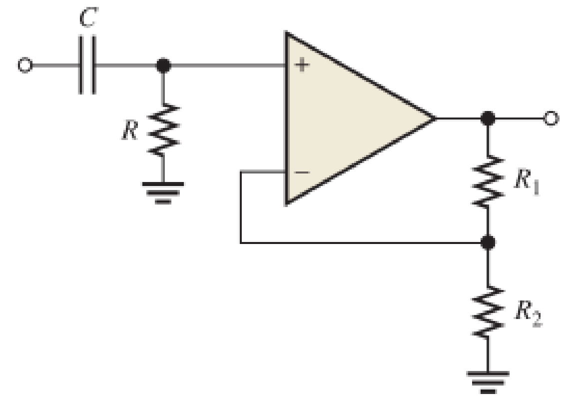
(b) Fourth-order configuration

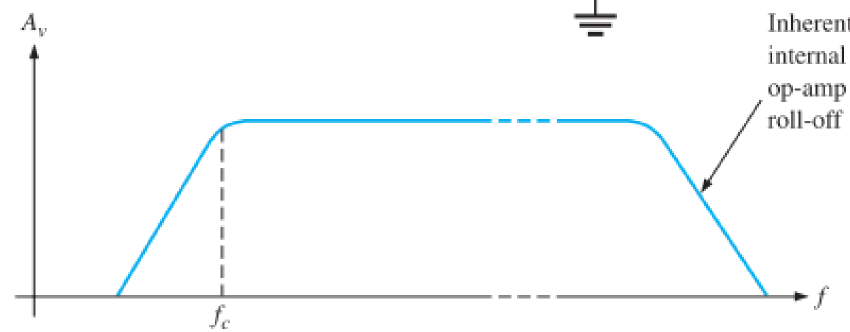
In high-pass filters, the roles of the capacitor and resistor are reversed in the RC circuits.

ACTIVE HIGH-PASS FILTERS

Single Pole HPF

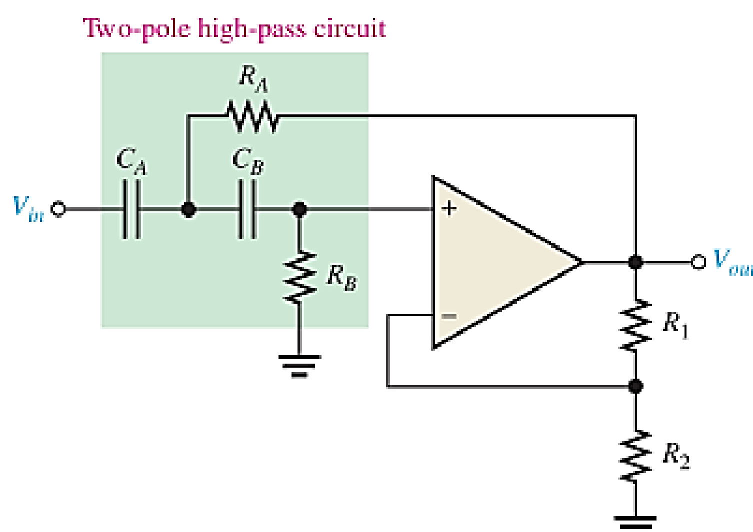




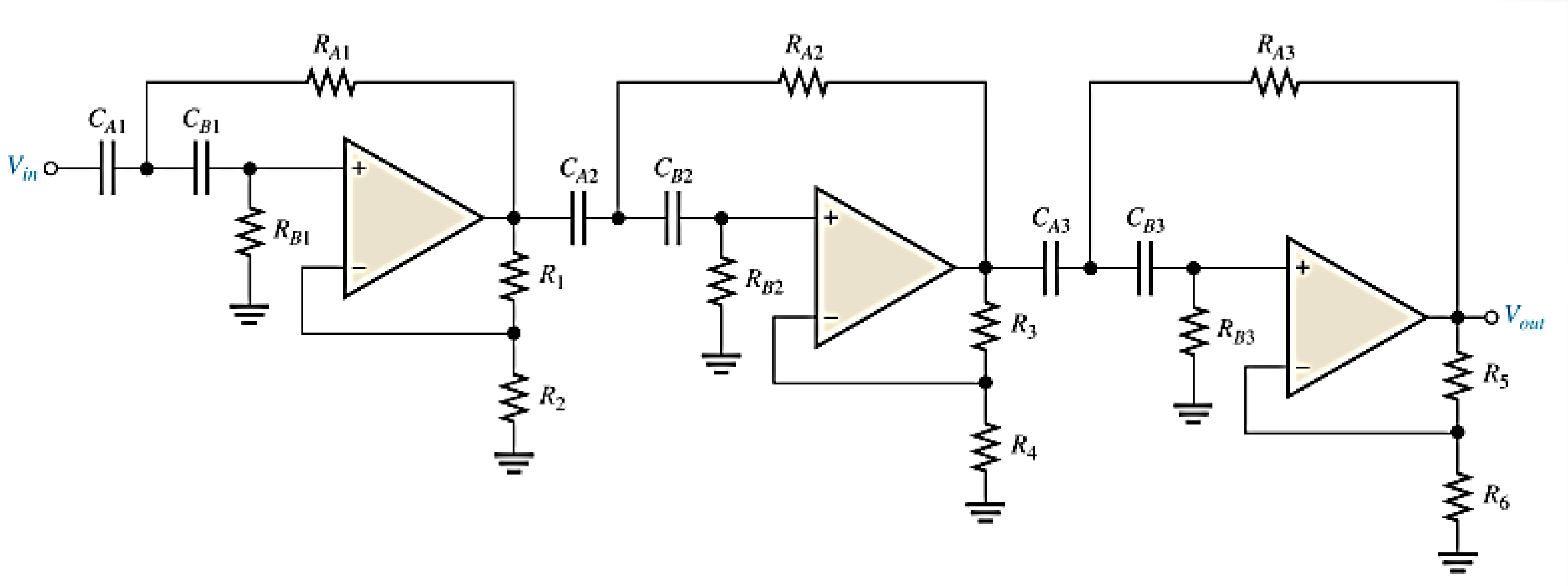


(b) Nonideal

Sallen-Key HPF



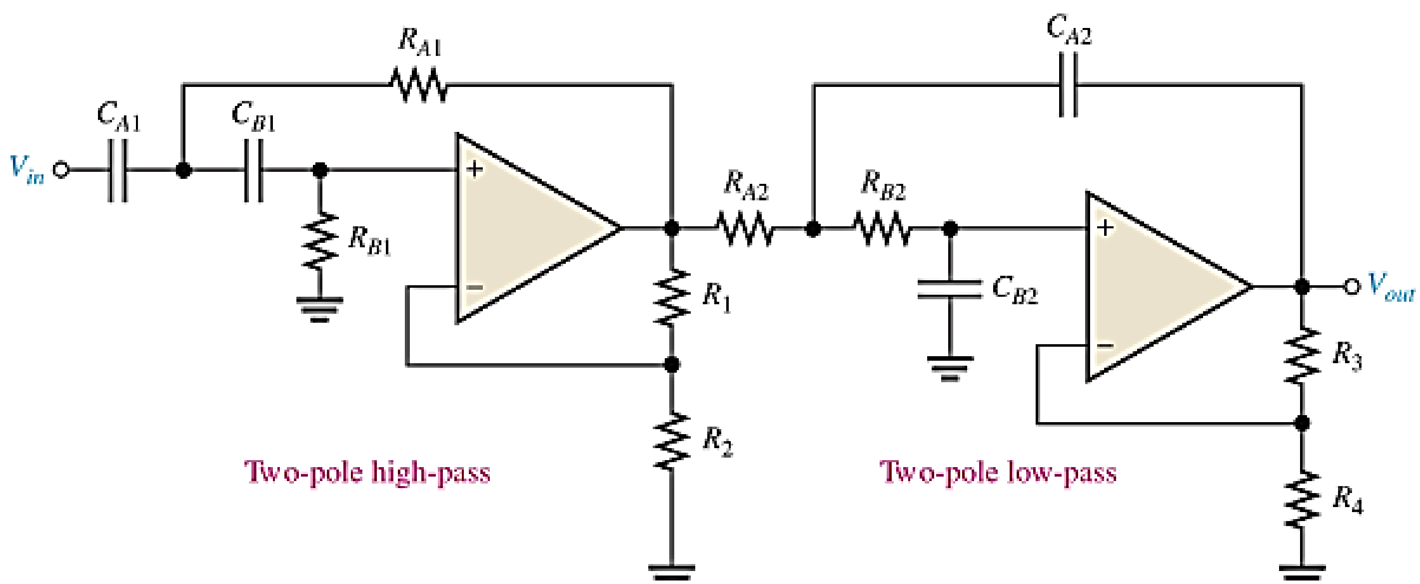
Cascaded HPF



Order = ?
roll-off = ?

ACTIVE BAND-PASS FILTERS

Cascaded Low-Pass and High-Pass Filters



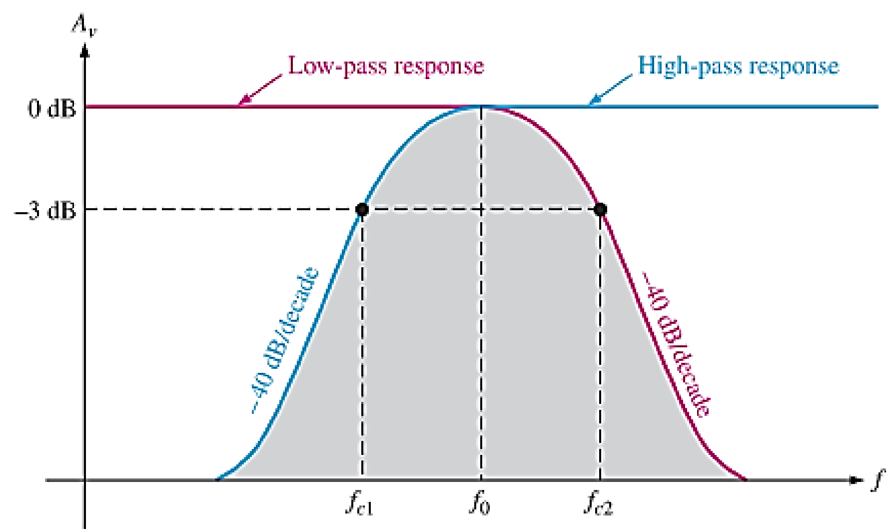
$$f_{c1} = \frac{1}{2\pi\sqrt{R_{A1}R_{B1}C_{A1}C_{B1}}}$$

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

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

If equal components:

$$f_c = 1/(2\pi RC).$$



Multiple-Feedback Band-Pass Filter

- The center frequency expression is:

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

- A value for the capacitors is chosen and then the three resistor values are calculated using the expressions:

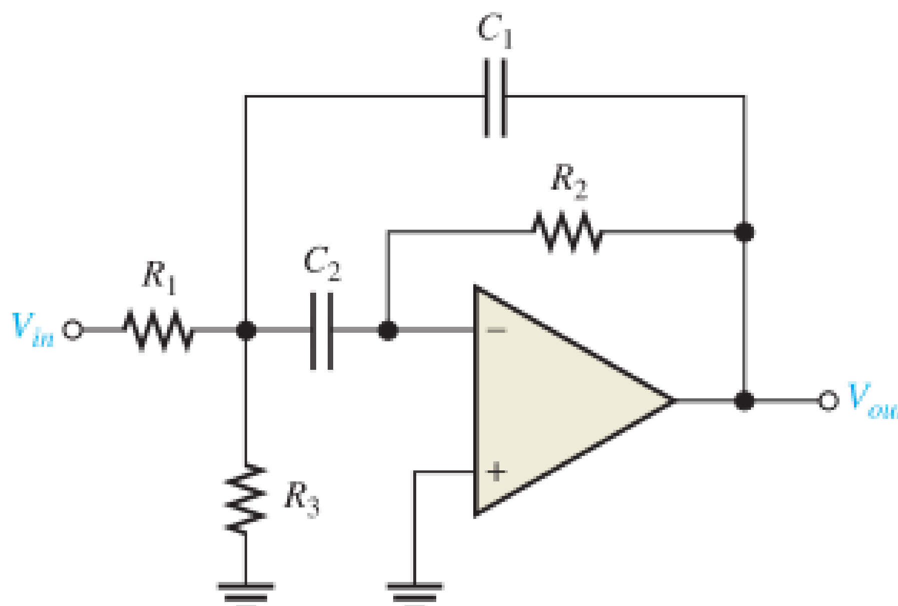
$$R_1 = \frac{Q}{2\pi f_0 C A_0}$$

$$R_2 = \frac{Q}{\pi f_0 C}$$

$$R_3 = \frac{Q}{2\pi f_0 C(2Q^2 - A_0)}$$

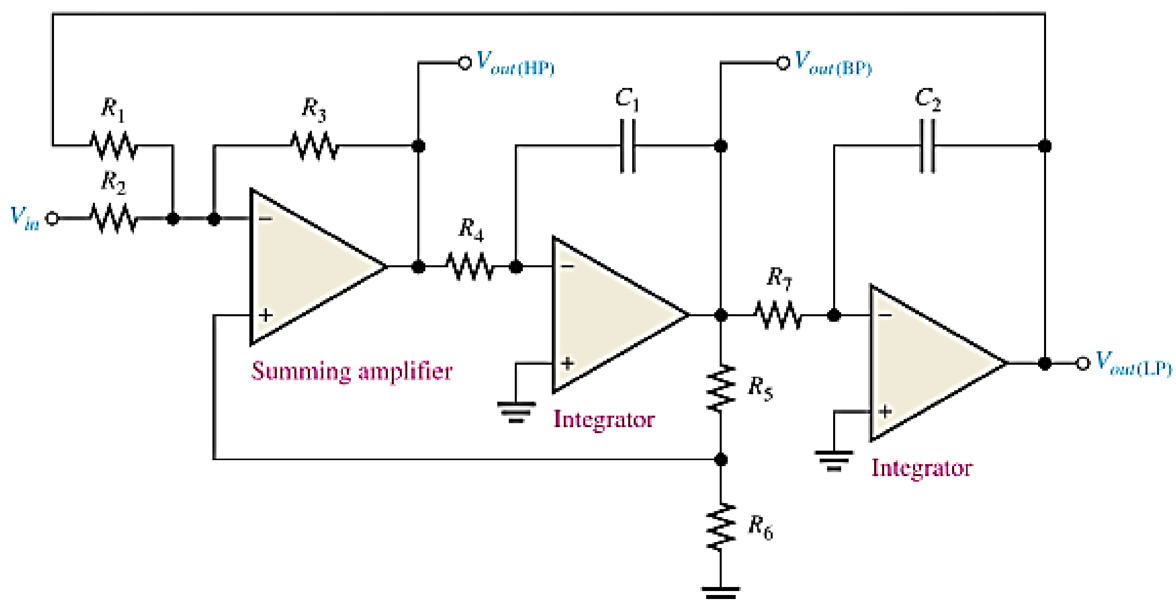
- The gain expression

$$A_0 = \frac{R_2}{2R_1}$$



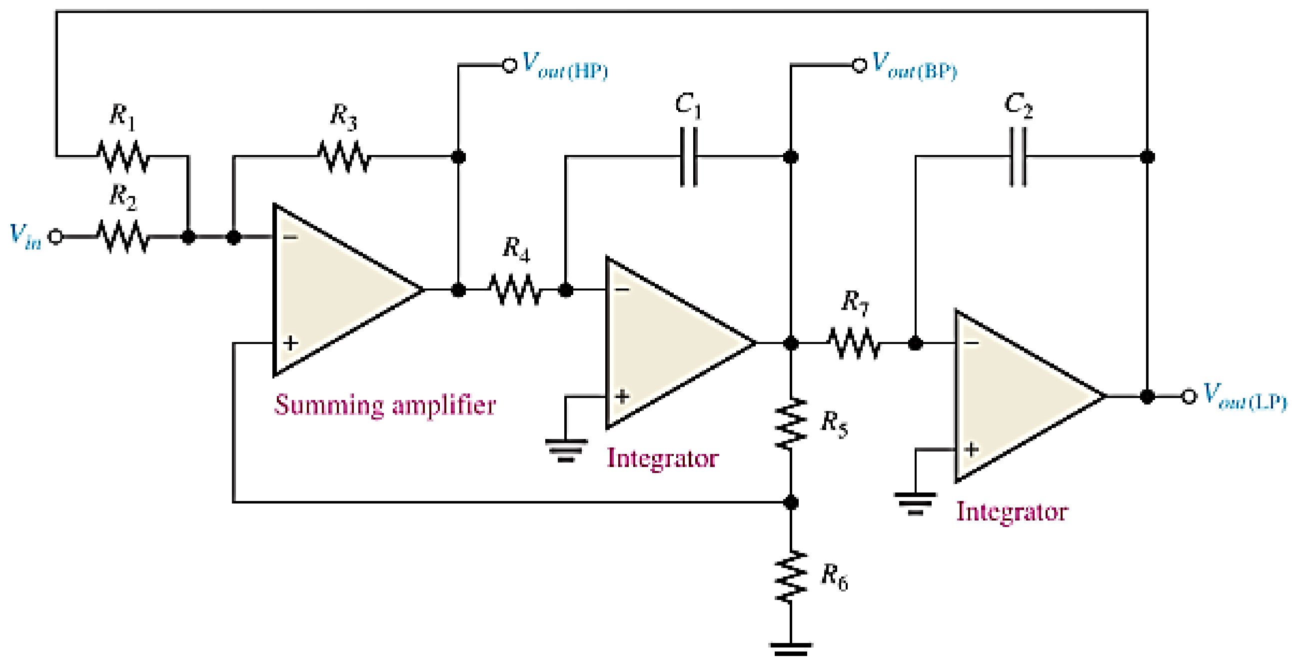
State-Variable Filter **(universal active filter)**

- It consists of **one or more integrators**, connected in some feedback configuration.
- It realizes the ***state-space model*** with n state variables for an n^{th} order system.
- The **instantaneous output** voltage of one of the integrators **corresponds to one of** the state-space model's **state variables**.
- The **center frequency** is set by the **RC** circuits in both **integrators**.



State-Variable Filter..

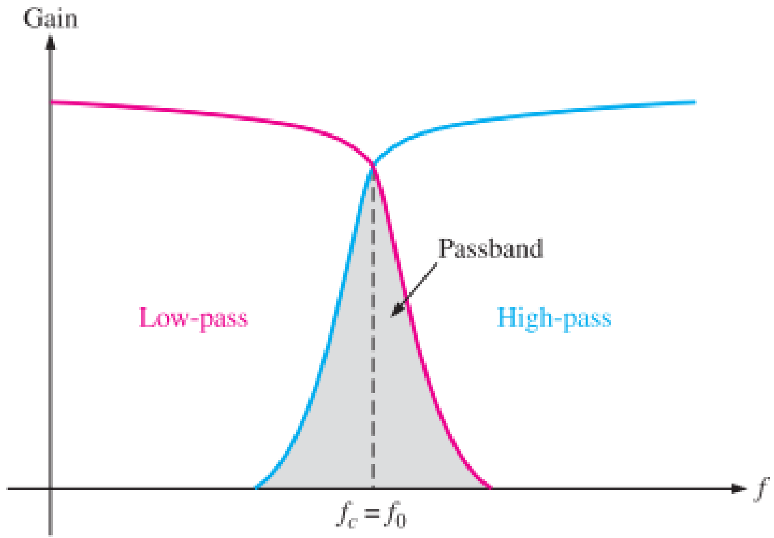
- At **<u>f < f$_c$</u>**, the input signal passes through the summing amplifier and integrators and is **fed back 180º** out of phase. Thus, the feedback signal and **input signal cancel** for all frequencies < fc.
- As the **low-pass response of the integrators rolls off**, the feedback signal diminishes, thus **allowing the input to pass** through to the band-pass output.
- **<u>Above f$_c$</u>**, the **low-pass response disappears**, thus preventing the input signal from passing through the integrators.
- As a **<u>result</u>**, the band-pass filter output **peaks sharply at f$_c$**.



State-Variable Filter…

- Stable **Qs** up to 100 can be obtained with this type of filter.

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



- The state-variable filter **cannot be optimized for low-pass, high-pass, and narrow band-pass performance simultaneously**.
- To optimize for a low-pass or a high-pass Butterworth response, DF must equal 1.414. Since Q = 1/DF, a Q of 0.707 will result.
- Such a low Q provides a very wide band-pass response (large BW and poor selectivity).
- For optimization as a narrow band-pass filter, the Q must be set high.

Biquad Filter

Report:
Simulate the State Variable & Biquad Filters.
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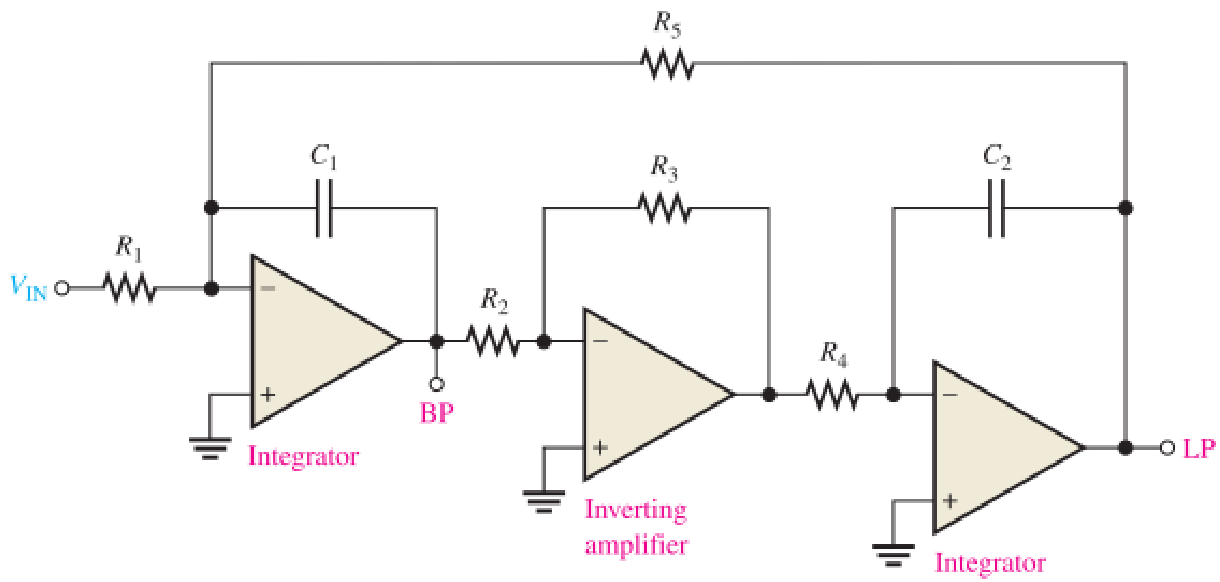
D.L. : Monday 06-04-2015 @ 11:59 PM

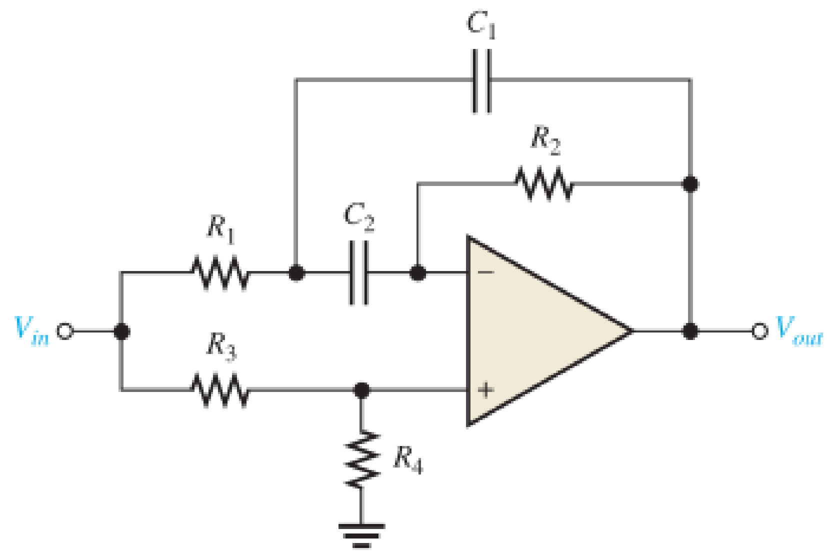
- "Biquad" is an abbreviation of "**biquadratic**", which refers to the fact that in the Z domain, its **transfer function** is the ratio of two quadratic functions.



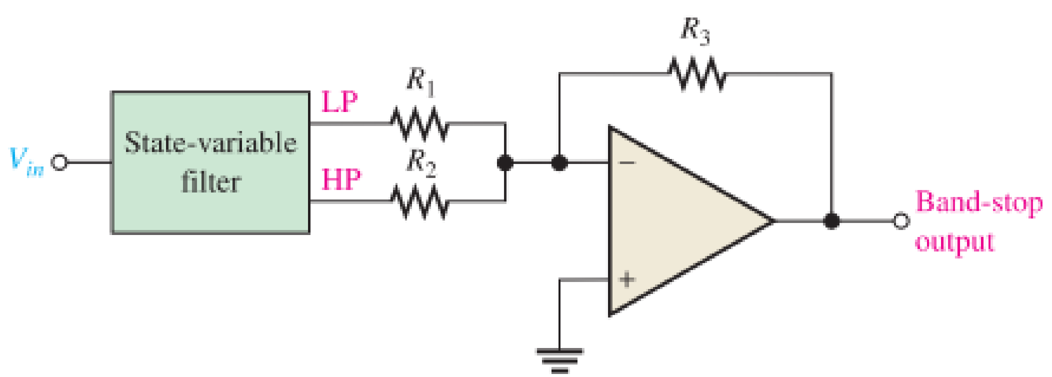
State-Variable Filter	Biquad Filter
Sum. Amp. → Integrator → Integrator	Integrator →Inv. Amp. → Integrator
very high Q value	very high Q value
B.W. depends on f_c	B.W. independent on f_c
Q independent on f_c	Q depends on f_c
HP, BP & LP outputs	BP & LP outputs

ACTIVE BAND-STOP FILTERS

Multiple-Feedback Band-Stop Filter



State-Variable Band-Stop Filter

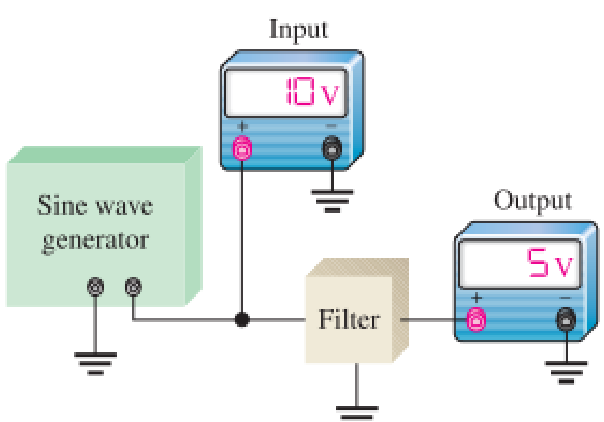


FILTER RESPONSE MEASUREMENTS

Discrete Point Measurement

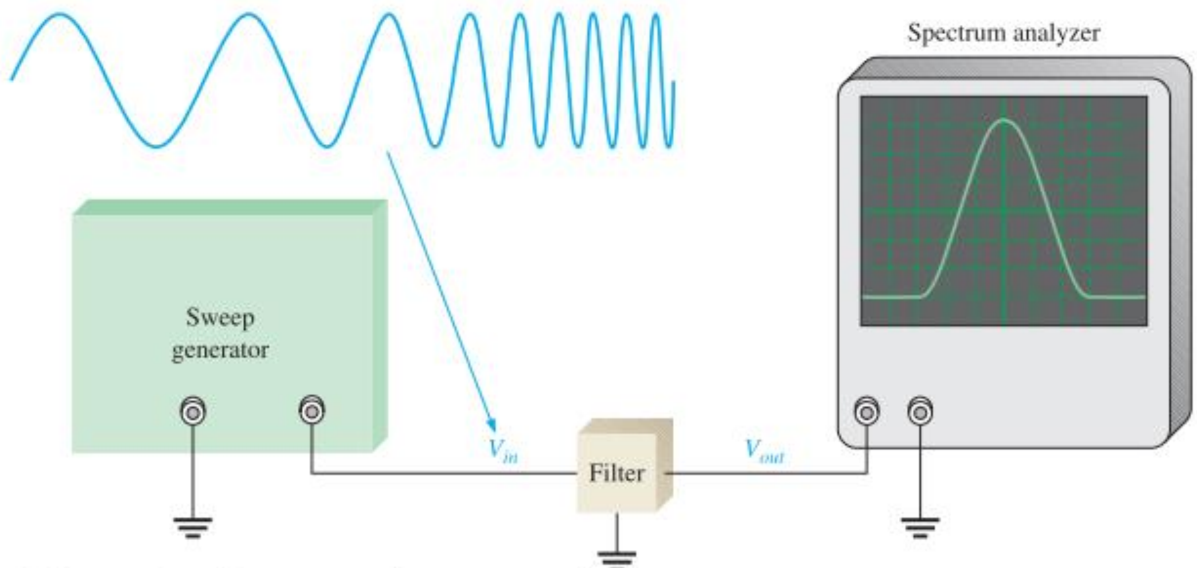
The **general procedure** is as follows:

1. **Set the amplitude** of the sine wave generator to a desired voltage level.
2. **Set the frequency** of the sine wave generator to a value well below the expected critical frequency of the filter under test.
    - For a **low-pass** filter, set the frequency as near as possible to **0 Hz**.
    - For a **band-pass** filter, set the frequency well **below the expected lower** critical frequency.
3. **Increase the frequency** in predetermined **steps** sufficient to allow enough data points for an accurate response curve.
4. **Maintain** a **constant input** voltage **amplitude** while **varying** the **frequency**.
5. **Record** the **output voltage** at each value of frequency.
6. After recording a sufficient number of points**, plot a graph** of output voltage versus frequency.

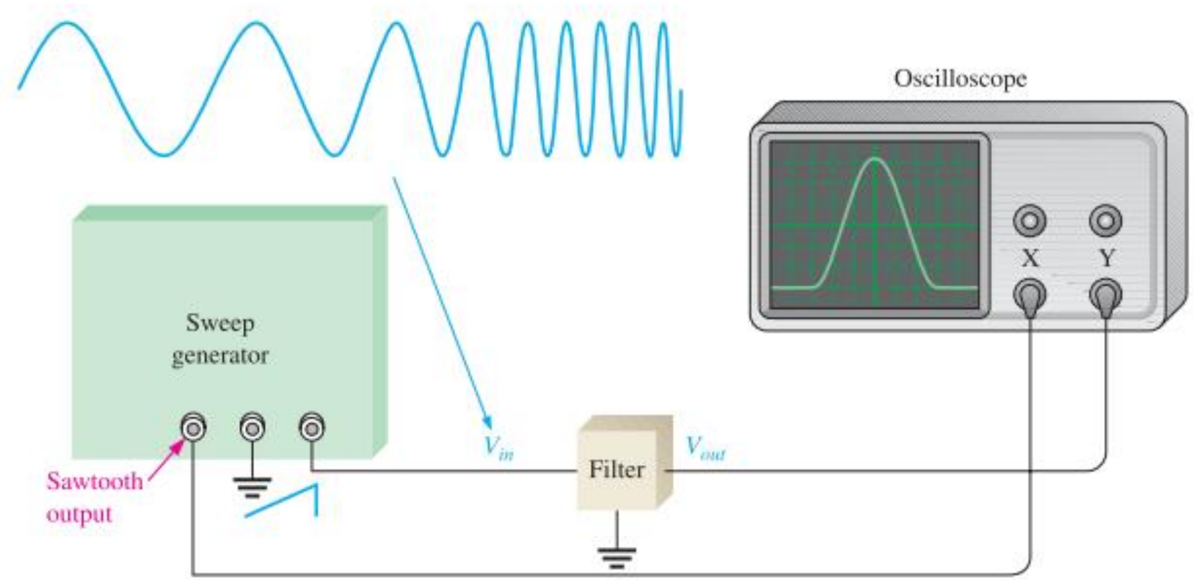


Swept Frequency Measuremen

- requires more elaborate test equipment
- but it is much more efficient



(a) Test setup for a filter response using a spectrum analyzer



(b) Test setup for a filter response using an oscilloscope. The scope is placed in X-Y mode. The sawtooth waveform from the sweep generator drives the X-channel of the oscilloscope.

- For more details, refer to:
  - Chapter 15, T. Floyd, **Electronic Devices**, 9th edition.
- The lecture is available online at:
  - http://bu.edu.eg/staff/ahmad.elbanna-courses/12135
- For inquires, send to:
  - ahmad.elbanna@feng.bu.edu.eg