Misr International University
جامعة مصر الدولية

Faculty of Engineering
Department of Electronics and Communications

GEE336
Electronic Circuits II

Lecture #7
Active Filters

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Agenda

- Basic Filter Responses
- Filter Response Characteristics
- Active LPF, HPF, BPF & BSF
- Active Filters Based on Two-Integrators Loop
- Active Filters Based Upon Inductor replacement

BASIC FILTER RESPONSES

Intro.

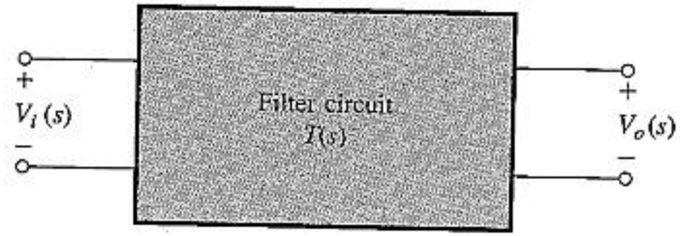
- **Filters** are circuits that are capable of **passing** signals with certain selected **frequencies** while **rejecting** signals with **other** frequencies.
- This property is called **selectivity**.
- **Active** filters use **transistors** or **op-amps** combined with passive RC, RL, or RLC circuits.

- The **passband** of a filter is the range of frequencies that are allowed to pass through the filter with **minimum attenuation**.
- 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.

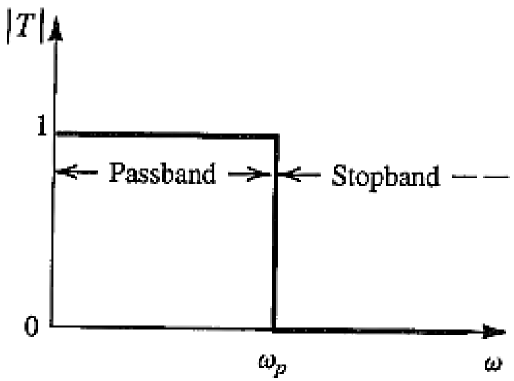
Basic Filter Responses

- **Ideal Response**

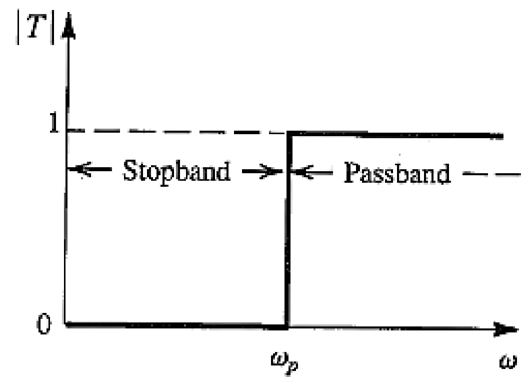


Filter transfer function

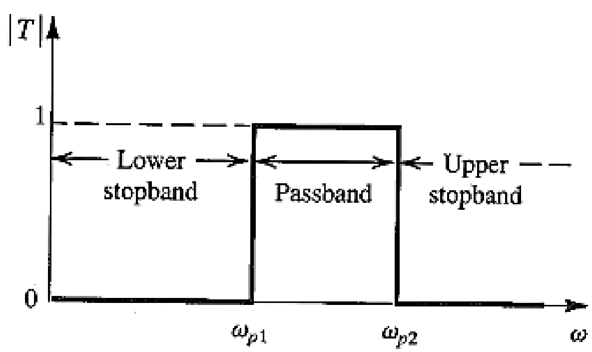
$$T(s) \equiv \frac{V_o(s)}{V_i(s)}$$



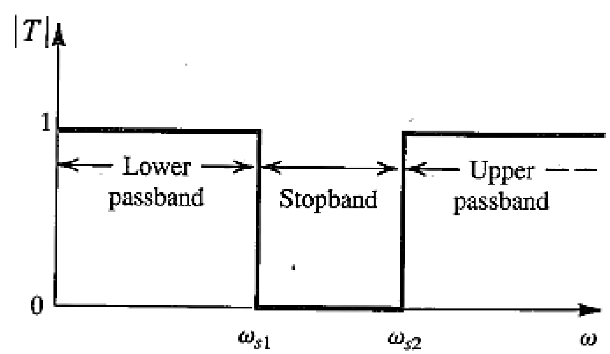
(a) Low-pass (LP)



(b) High-pass (HP)



(c) Bandpass (BP)



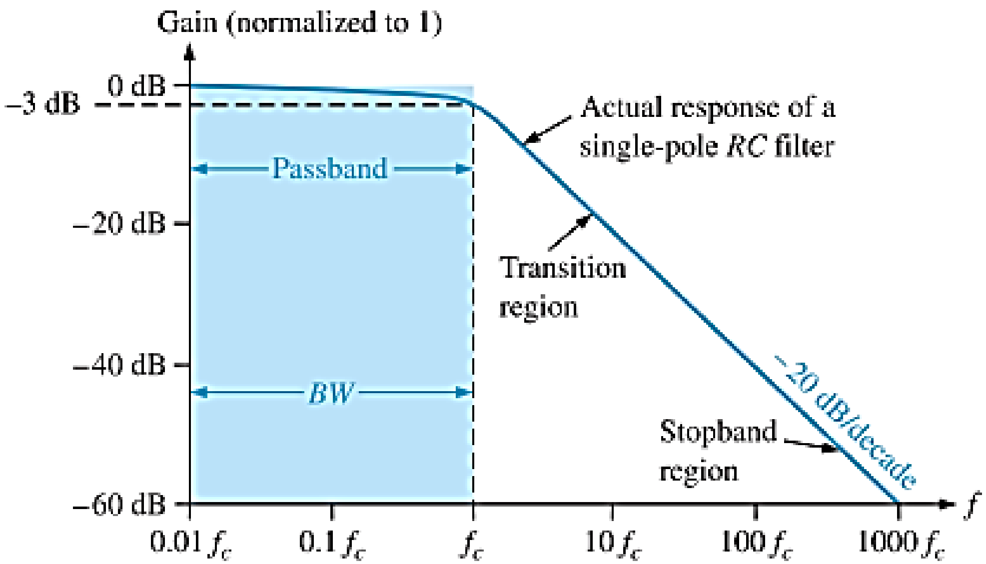
(d) Bandstop (BS)

Basic Filter Responses

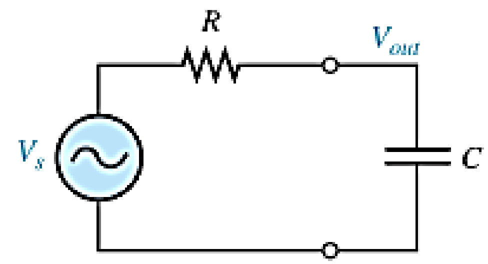
- Actual filter responses depend on the **number of poles**, a term used with filters to describe the **number of RC circuits** contained in the filter.
- The -20 dB/decade **roll-off** rate for the gain of a basic RC filter means that at a frequency of $10\,f_c$, the output will be -20dB (10%) of the 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.

Basic Filter Responses

- **Low-Pass Filter Response**



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



(b) Basic low-pass circuit

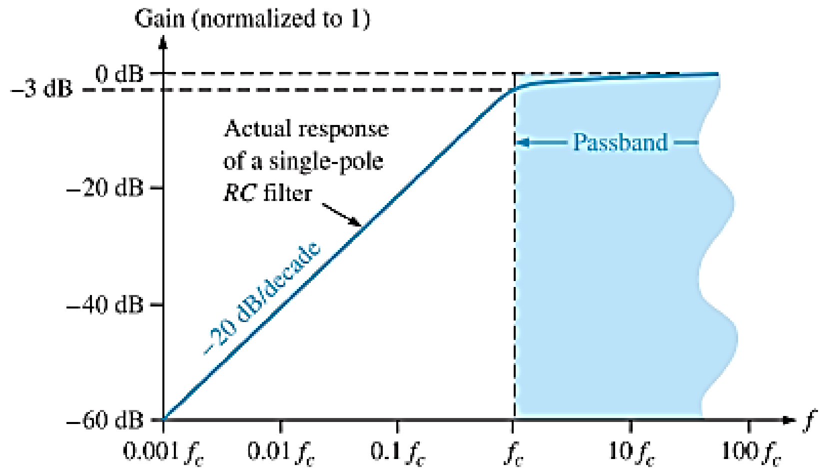
$$BW = f_c$$

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

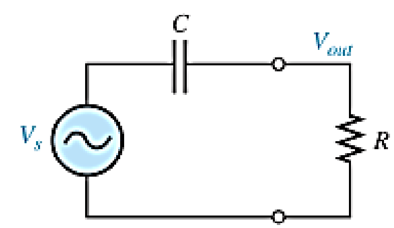
$$T(s) = \frac{V_o(s)}{V_i(s)} = \frac{1/sc}{R + 1/sc} = \frac{1}{1 + scR}$$

Basic Filter Responses..

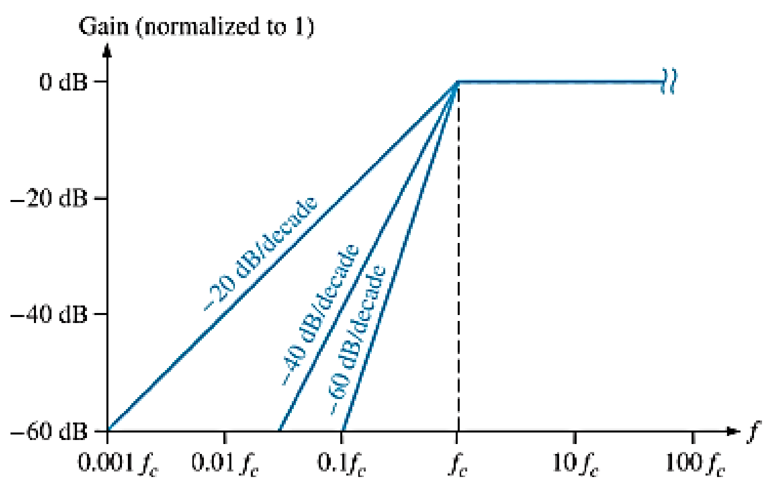
- **High-Pass Filter Response**



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



(b) Basic high-pass circuit



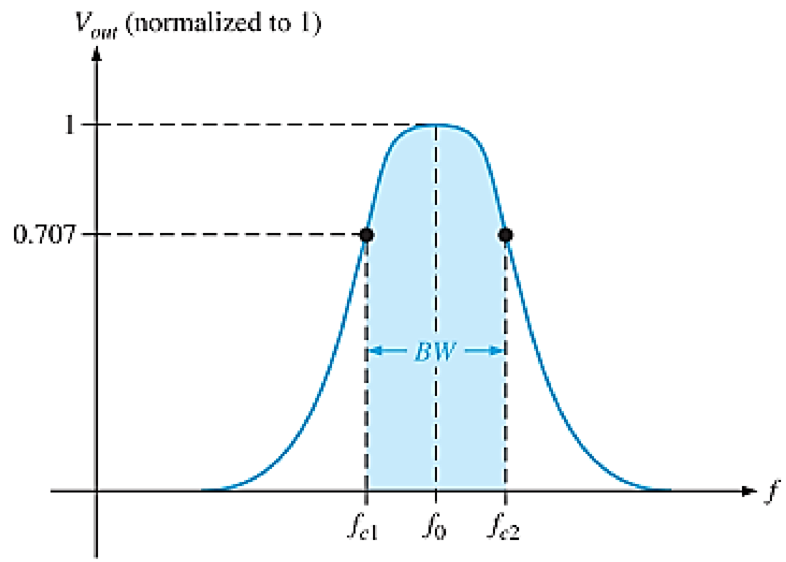
$$f_c = \frac{1}{2\pi RC}$$

Basic Filter Responses...

- **Band-Pass Filter Response**

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

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



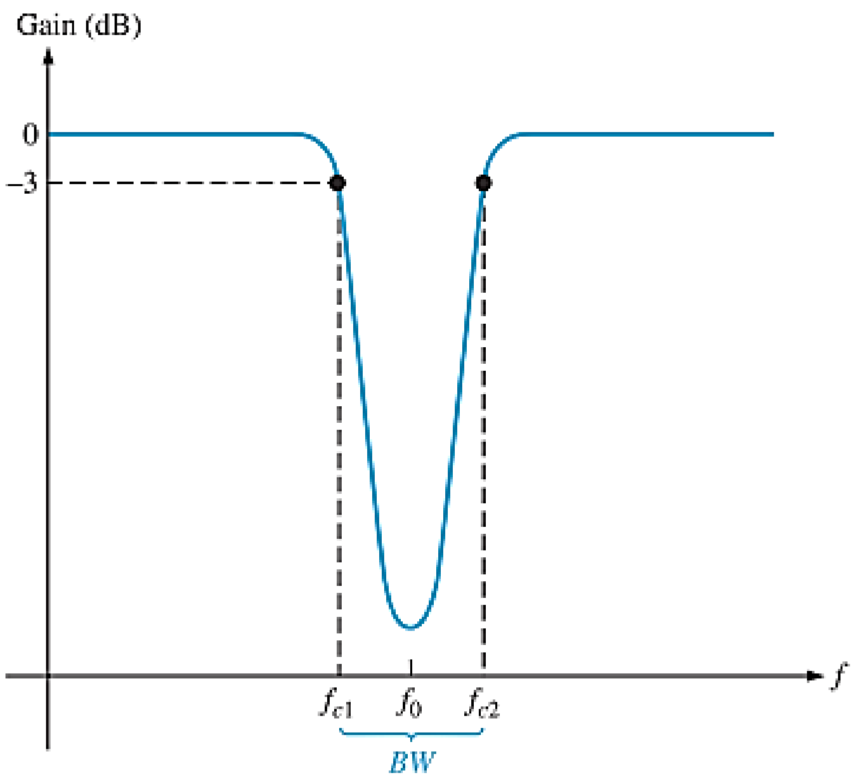
- The **quality factor** (Q) of a band-pass filter is the ratio of the center frequency to the bandwidth.
- The higher the value of Q, the narrower the bandwidth and the better the selectivity for a given value of f_0.
- Band-pass filters are sometimes classified as **narrow-band** (Q>10) or **wide-band**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

$$Q = \frac{f_0}{BW}$$

Basic Filter Responses....

- **Band-Stop Filter Response**

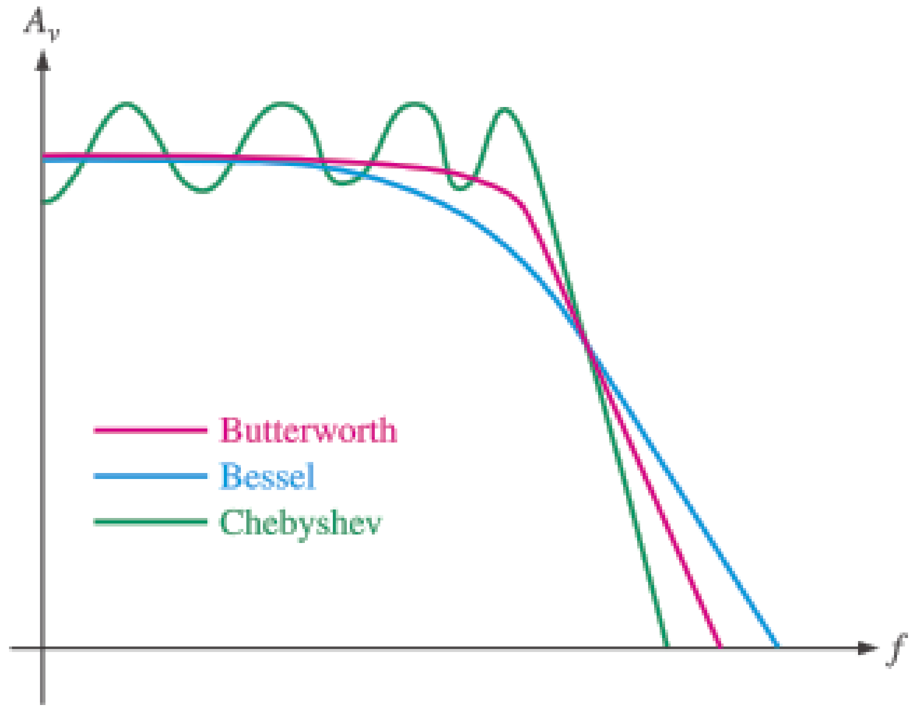
  also known as notch, band-reject, or band-elimination filter.



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

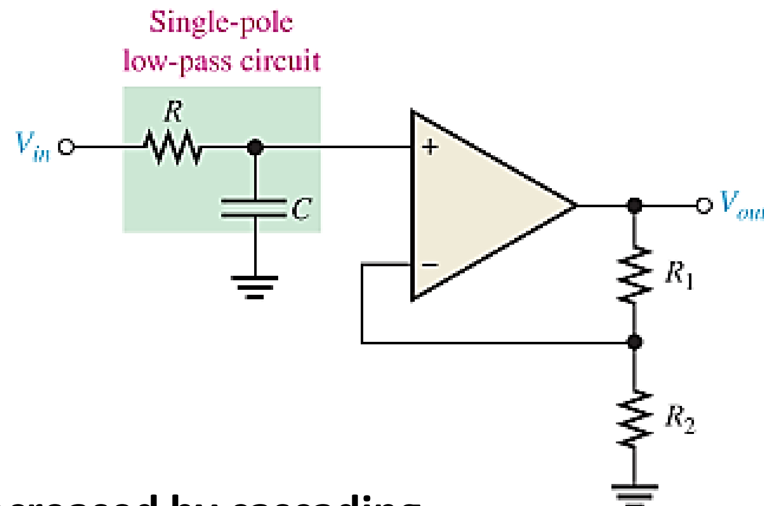
- Filters with the Chebyshev response characteristic are useful when a **rapid roll-off** is required because it provides a roll-off rate greater than -20 dB/decade/pole.
- This is a **greater rate** than that of the Butterworth, so filters can be implemented with the Chebyshev response with **fewer 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.

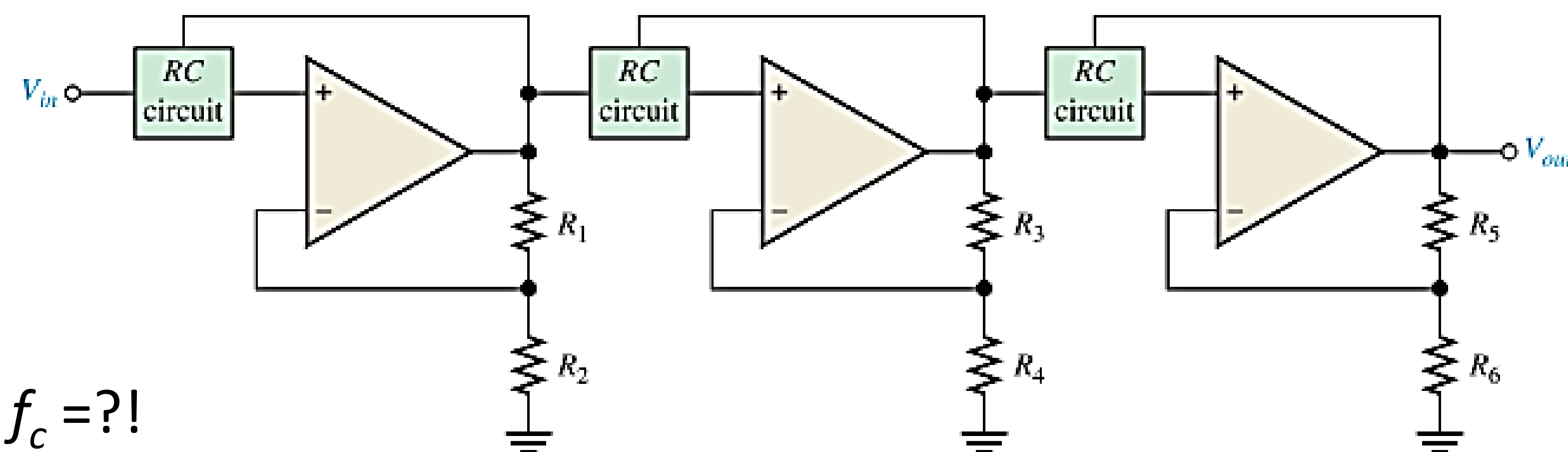
Critical Frequency and Roll-Off Rate

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



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

Example: Third-order (three-pole) filter



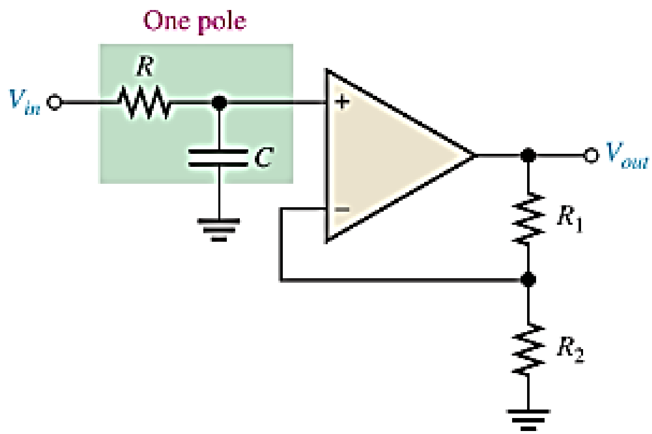
f_c =?!

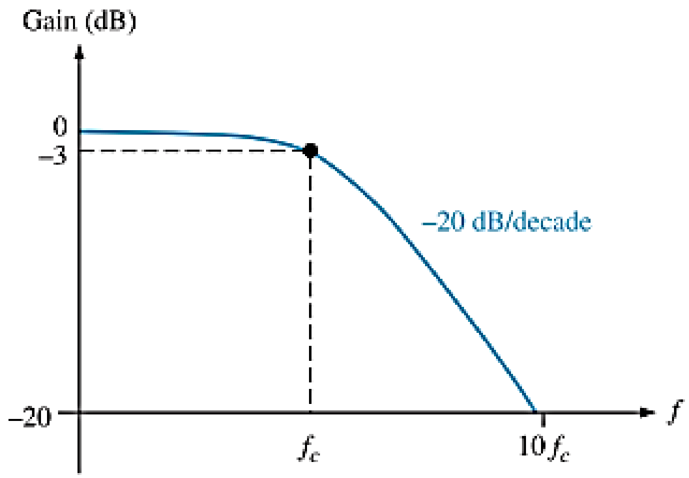
ACTIVE LOW-PASS FILTERS

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



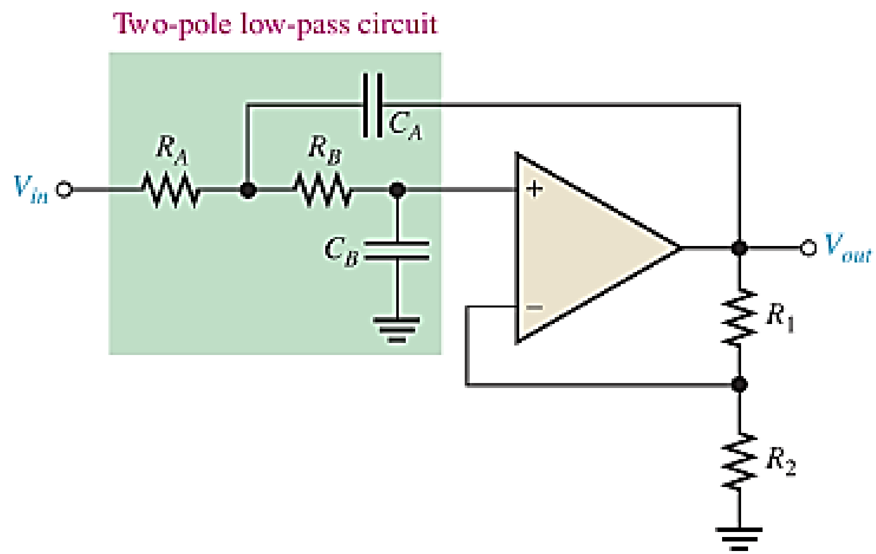


$$A_{cl(NI)} = \frac{R_1}{R_2} + 1$$

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

2-Pole LPF
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.



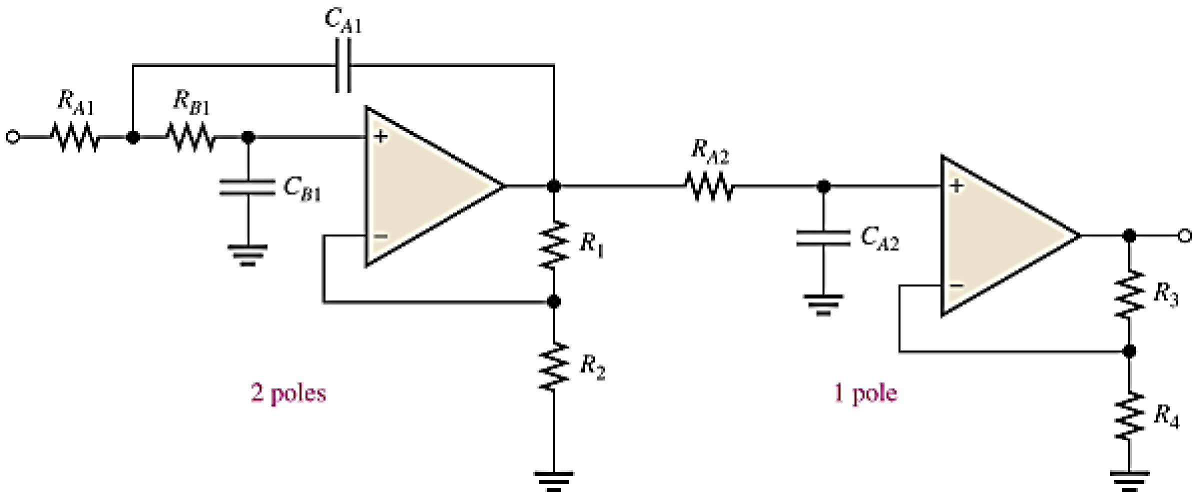
$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$

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

<u>Assignment:</u>
Derive the f_c equation.

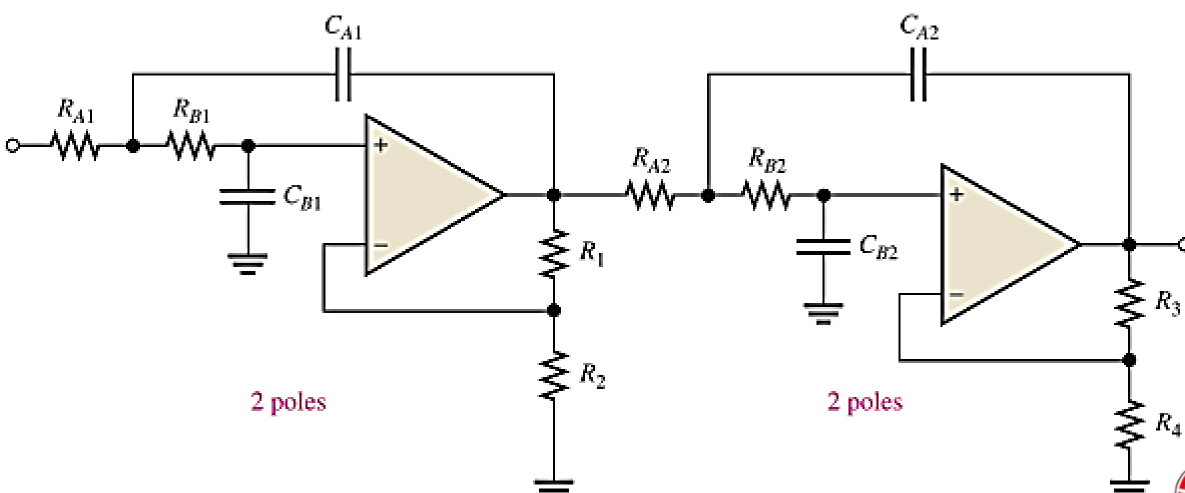
Cascaded LPF

- A **three-pole** filter is required to get a **third-order** low-pass response.



(a) Third-order configuration

- A **four-pole** filter is **preferred** because it uses the same number of op-amps to achieve a faster roll-off.

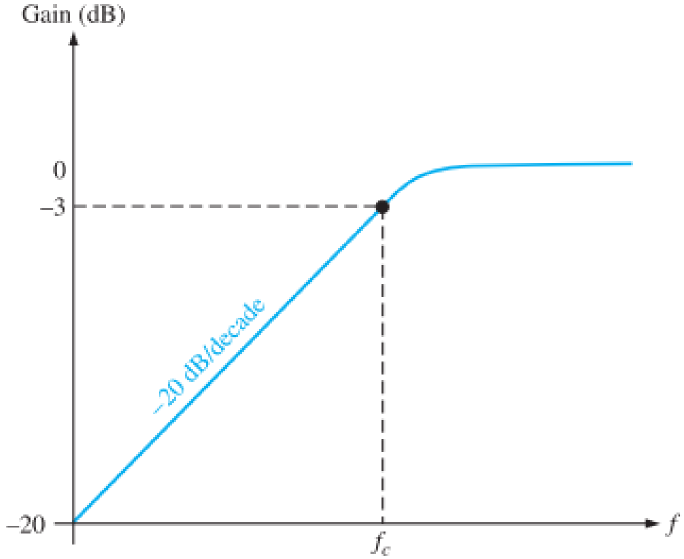


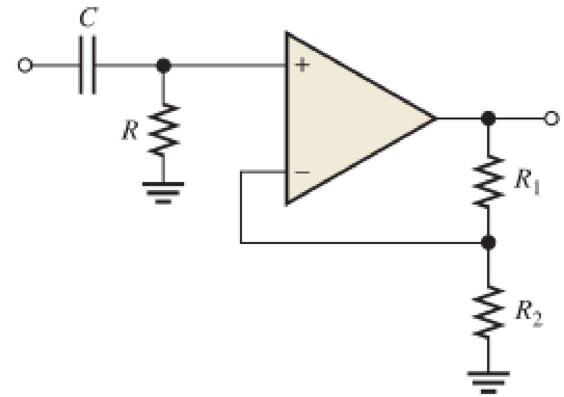
(b) Fourth-order configuration

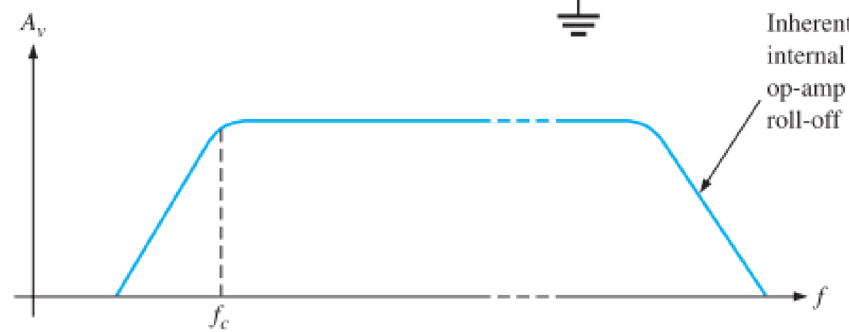
In high-pass filters, the roles of the capacitor and resistor are reversed in the RC circuits.

ACTIVE HIGH-PASS FILTERS

Single Pole HPF

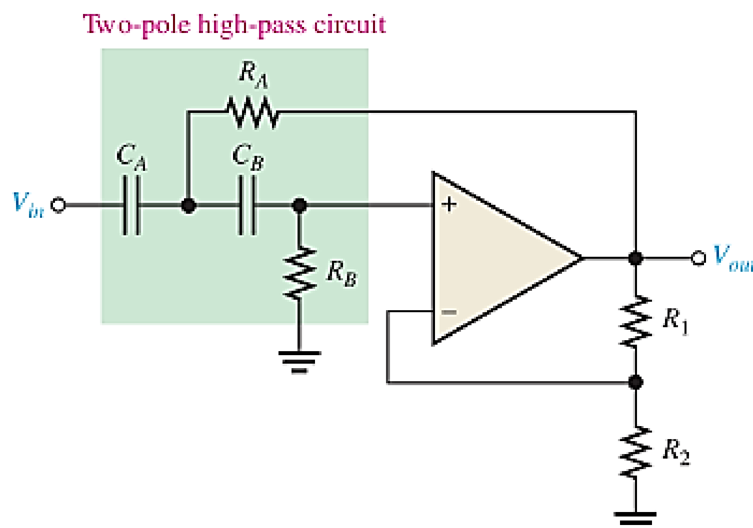




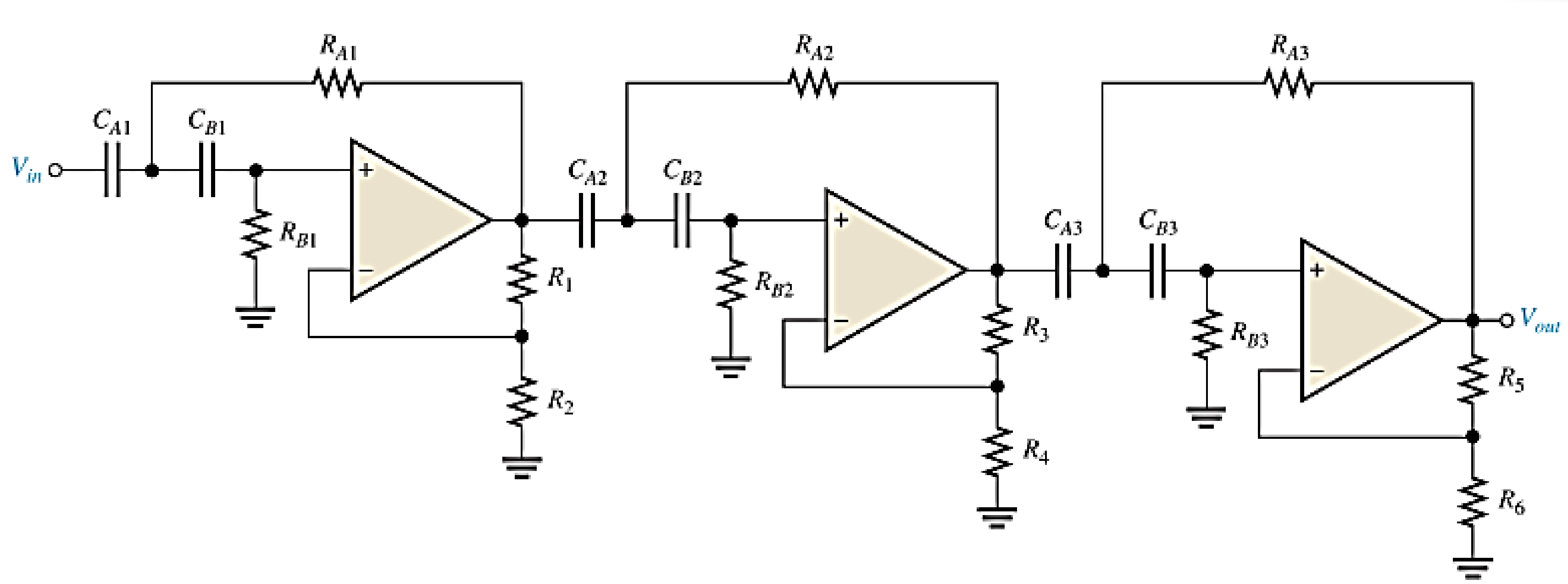


(b) Nonideal

Sallen-Key HPF



Cascaded HPF

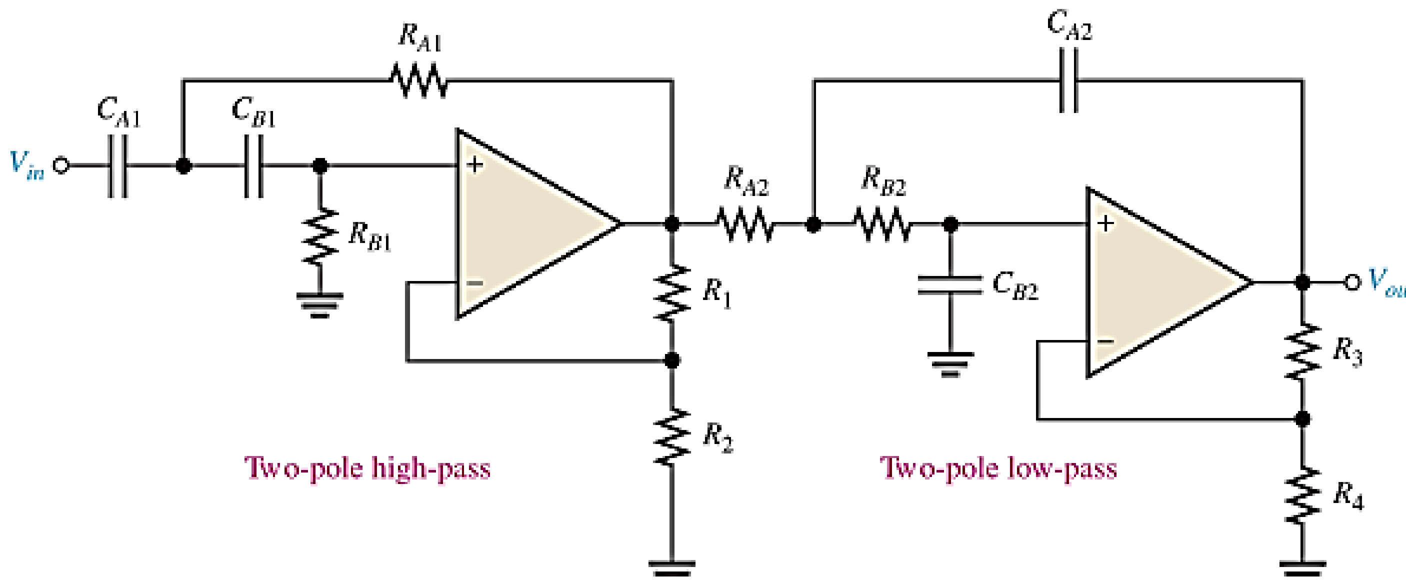


Order = ?

roll-off = ?

ACTIVE BAND-PASS FILTERS

Cascaded Low-Pass and High-Pass Filters



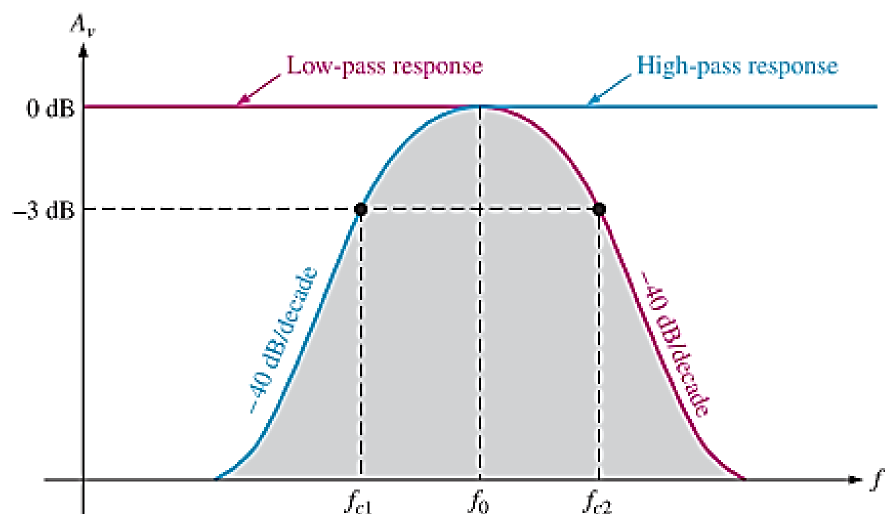
$$f_{c1} = \frac{1}{2\pi\sqrt{R_{A1}R_{B1}C_{A1}C_{B1}}}$$

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

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

If equal components,

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



ACTIVE FILTERS BASED ON TWO-INTEGRATORS LOOP

Biquad Filter

(Two-Integrators Loop biquadratic circuit)

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

- To derive the biquad circuit, consider the 2nd order high pass transfer function

$$\frac{V_{hp}}{V_i} = \frac{Ks^2}{s^2 + s(\omega_0/Q) + \omega_0^2}$$

Cross multiply and reform,

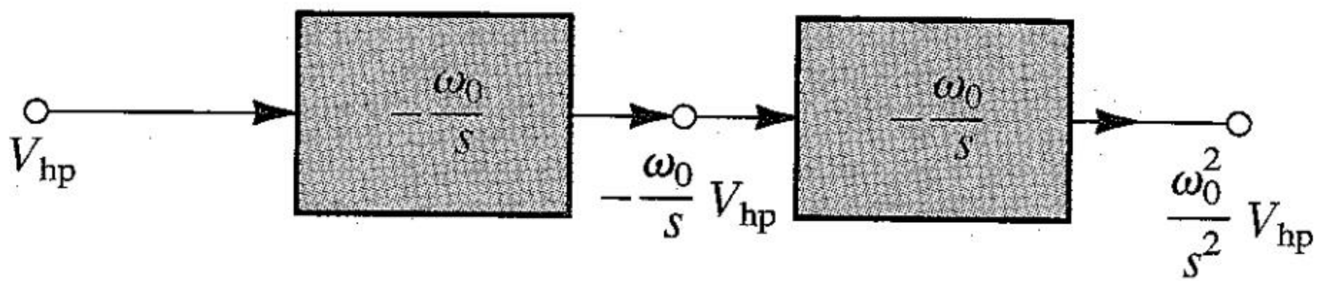
$$V_{hp} + \frac{1}{Q}\left(\frac{\omega_0}{s}V_{hp}\right) + \left(\frac{\omega_0^2}{s^2}V_{hp}\right) = KV_i$$

$$V_{hp} = KV_i - \frac{1}{Q}\frac{\omega_0}{s}V_{hp} - \frac{\omega_0^2}{s^2}V_{hp}$$

Biquad Filter ..

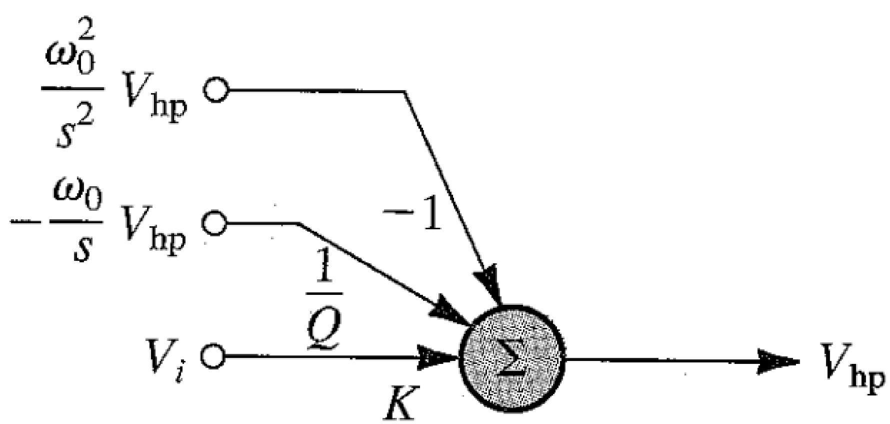
- Derivation of a block diagram realization of the two-integrator loop biquad

$$V_{hp} + \frac{1}{Q}\left(\frac{\omega_0}{s}V_{hp}\right) + \left(\frac{\omega_0^2}{s^2}V_{hp}\right) = KV_i$$



(a)

$$V_{hp} = KV_i - \frac{1}{Q}\frac{\omega_0}{s}V_{hp} - \frac{\omega_0^2}{s^2}V_{hp}$$



(b)

Biquad Filter …

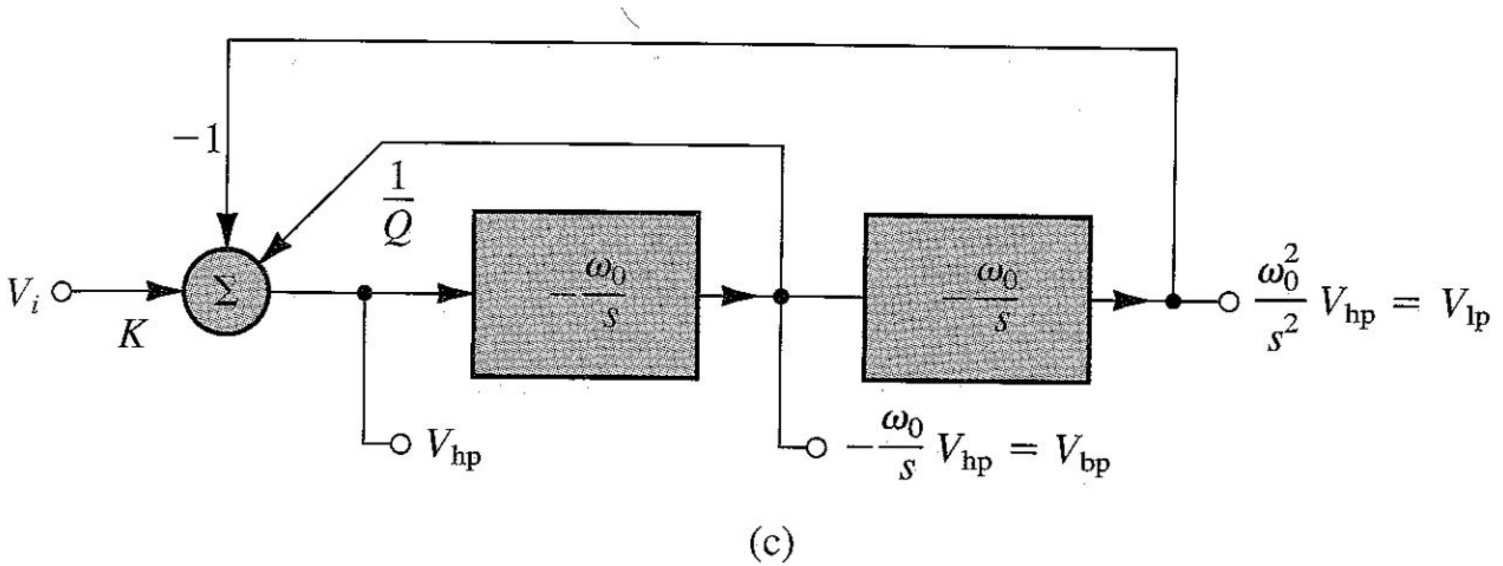


FIGURE 12.23 Derivation of a block diagram realization of the two-integrator-loop biquad.

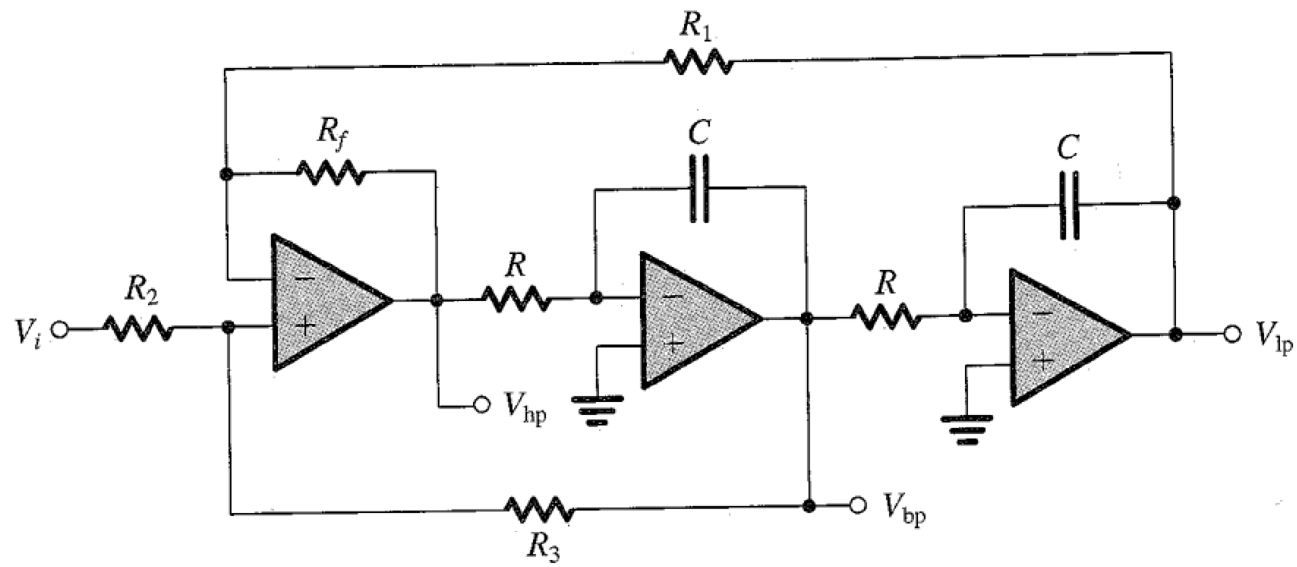
$$\frac{(-\omega_0/s)V_{hp}}{V_i} = -\frac{K\omega_0 s}{s^2 + s(\omega_0/Q) + \omega_0^2} = T_{bp}(s)$$

$$V_{hp} = KV_i - \frac{1}{Q}\frac{\omega_0}{s}V_{hp} - \frac{\omega_0^2}{s^2}V_{hp}$$

$$\frac{(\omega_0^2/s^2)V_{hp}}{V_i} = \frac{K\omega_0^2}{s^2 + s(\omega_0/Q) + \omega_0^2} = T_{lp}(s)$$

Biquad Filter ….

(Universal Circuit)



$$V_{hp} = \frac{R_3}{R_2+R_3}\left(1+\frac{R_f}{R_1}\right)V_i + \frac{R_2}{R_2+R_3}\left(1+\frac{R_f}{R_1}\right)\left(-\frac{\omega_0}{s}V_{hp}\right) - \frac{R_f}{R_1}\left(\frac{\omega_0^2}{s^2}V_{hp}\right)$$

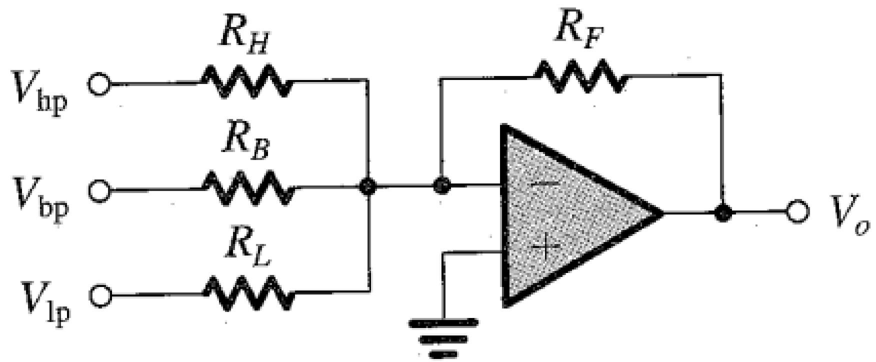
$R_f/R_1 = 1$

$R_3/R_2 = 2Q-1$

$K = 2-(1/Q)$

Biquad Filter ….

- To obtain notch and all-pass function, the three outputs of the biquad are summed with appropriate weights



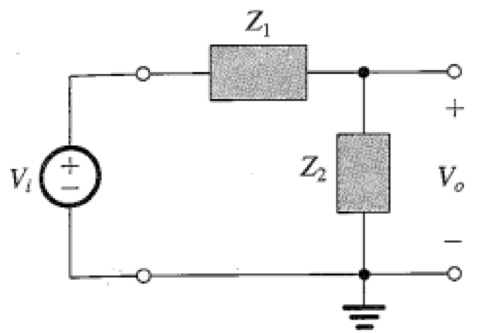
$$\frac{V_o}{V_i} = -K\frac{(R_F/R_H)s^2 - s(R_F/R_B)\omega_0 + (R_F/R_L)\omega_0^2}{s^2 + s(\omega_0/Q) + \omega_0^2}$$

Notch filter as example, use

$$R_B = \infty \qquad \frac{R_H}{R_L} = \left(\frac{\omega_n}{\omega_0}\right)^2$$

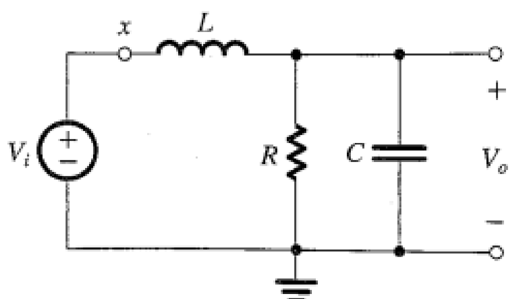
ACTIVE FILTERS BASED UPON INDUCTOR REPLACEMENT

2^{nd} order LCR Resonator



(a) General structure

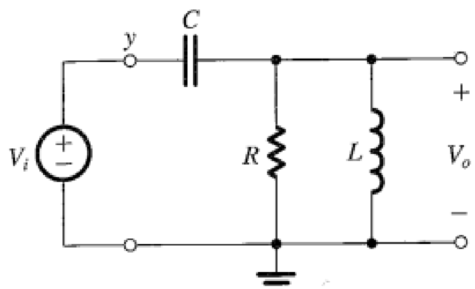
$$T(s) = \frac{V_o(s)}{V_i(s)} = \frac{Z_2(s)}{Z_1(s)+Z_2(s)}$$



(b) LP

$$T(s) \equiv \frac{V_o}{V_i} = \frac{Z_2}{Z_1+Z_2} = \frac{Y_1}{Y_1+Y_2} = \frac{1/sL}{(1/sL)+sC+(1/R)}$$

$$= \frac{1/LC}{s^2+s(1/CR)+(1/LC)}$$

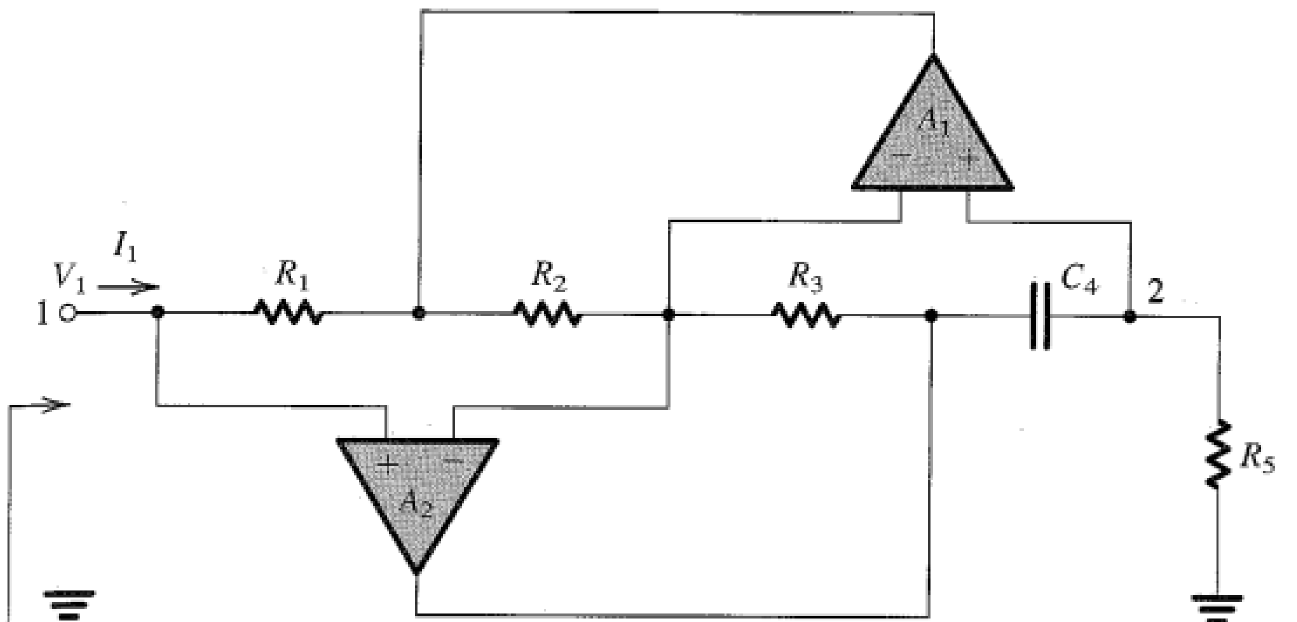


(c) HP

$$T(s) \equiv \frac{V_o}{V_i} = \frac{a_2 s^2}{s^2+s(\omega_0/Q)+\omega_0^2}$$

2nd order Active Filter based on inductor replacement

The Antoniou Inductance-Simulation Circuit



$$Z_{in} \equiv \frac{V_1}{I_1} = sC_4R_1R_3R_5/R_2$$

(a)

$$L = C_4R_1R_3R_5/R_2$$

selecting $R_1 = R_2 = R_3 = R_5 = R$ and $C_4 = C$,

$$L = CR^2.$$

2nd order Active Filter based on inductor replacement ..

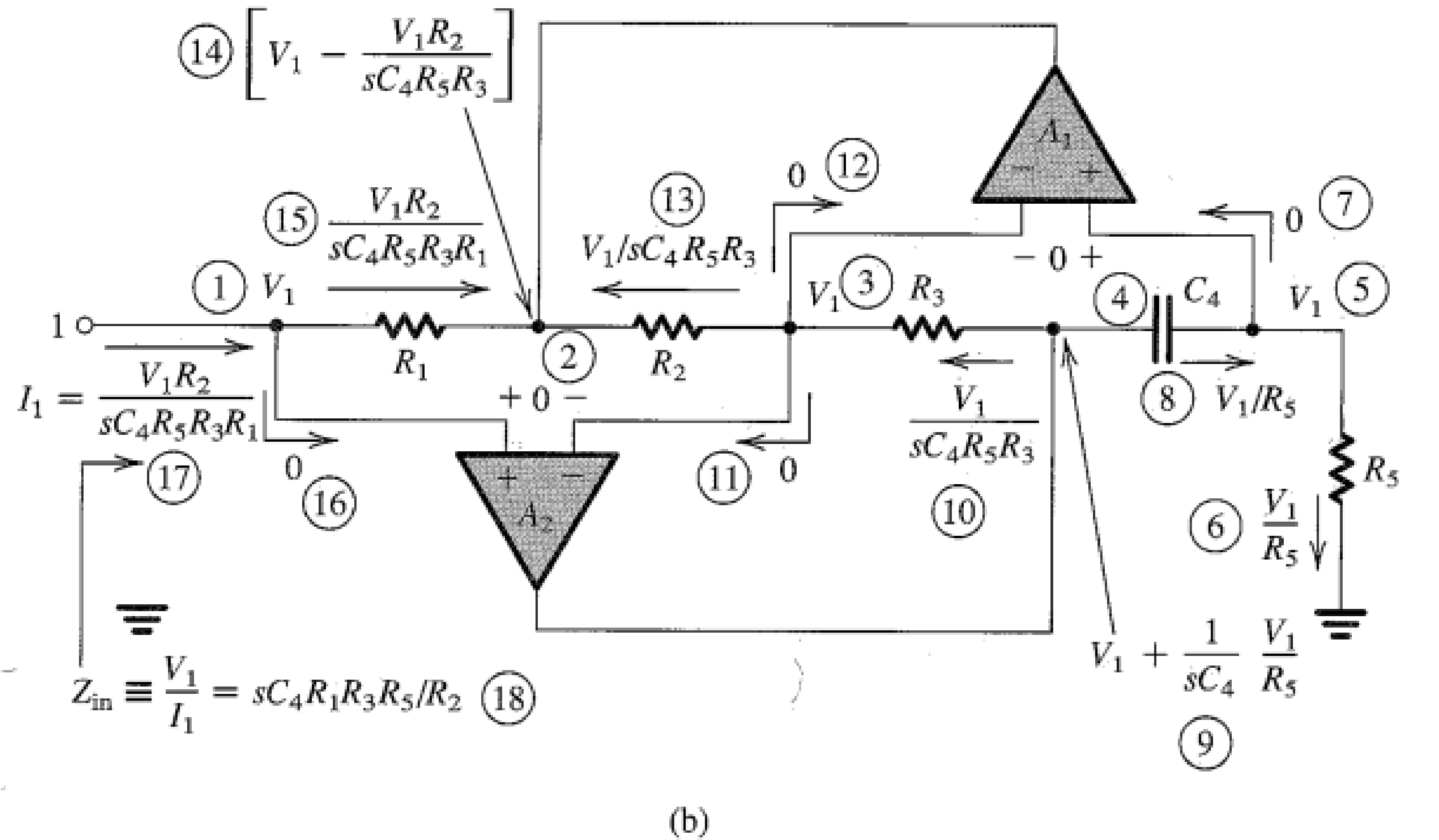
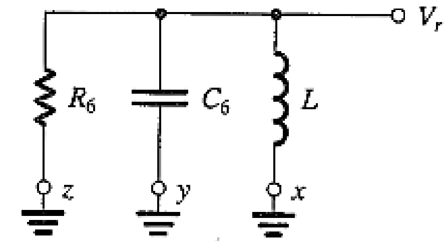


FIGURE 12.20 (a) The Antoniou inductance-simulation circuit. (b) Analysis of the circuit assuming ideal op amps. The order of the analysis steps is indicated by the circled numbers.

2^{nd} order Active Filter based on inductor replacement …

The Op Amp–RC Resonator



(a)

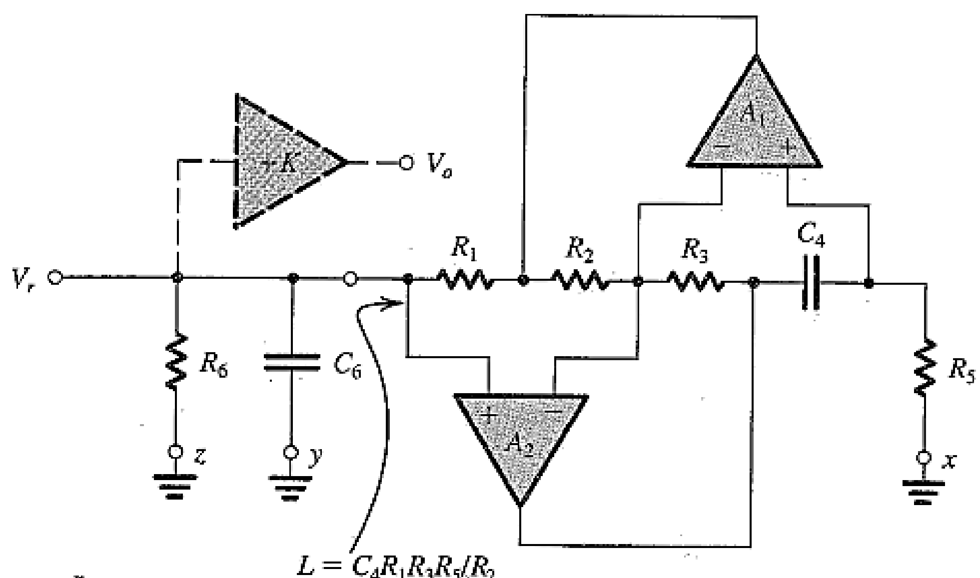
$$\omega_0 = 1/\sqrt{LC_6} = 1/\sqrt{C_4 C_6 R_1 R_3 R_5 / R_2}$$

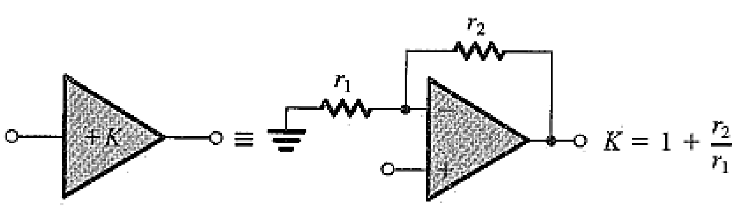
$$Q = \omega_0 C_6 R_6 = R_6 \sqrt{\frac{C_6}{C_4} \frac{R_2}{R_1 R_3 R_5}}$$

$$C_4 = C_6 = C \text{ and } R_1 = R_2 = R_3 = R_5 = R$$

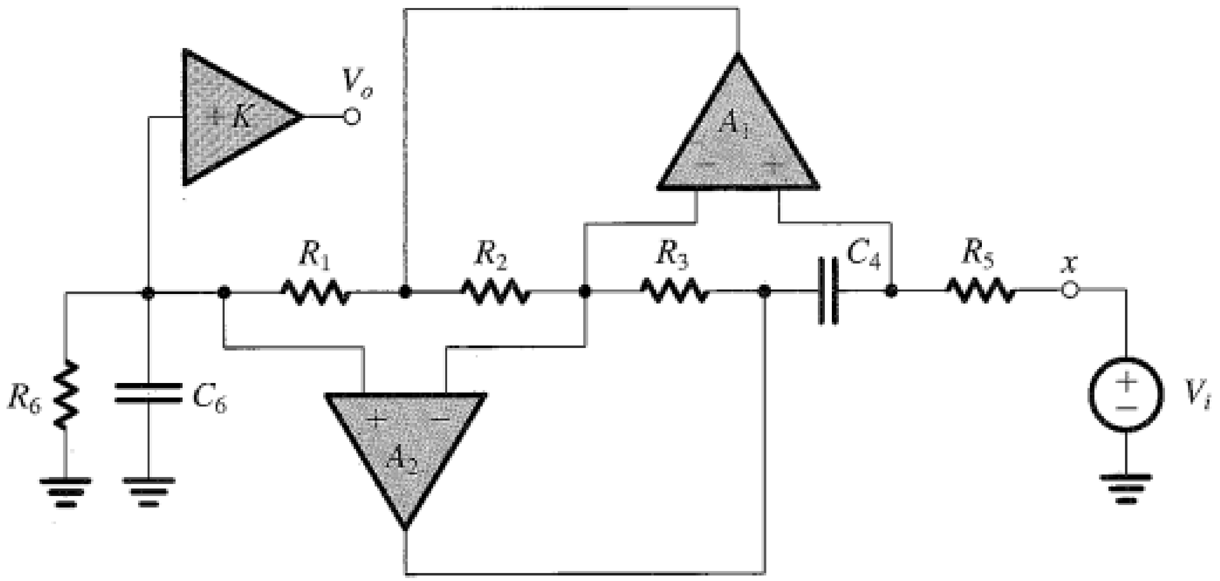
$$\omega_0 = 1/CR$$

$$Q = R_6/R$$





LPF
with inductor replacement circuit



(a) LP

$$T(s) = \frac{KR_2/C_4C_6R_1R_3R_5}{s^2 + s\frac{1}{C_6R_6} + \frac{R_2}{C_4C_6R_1R_3R_5}}$$

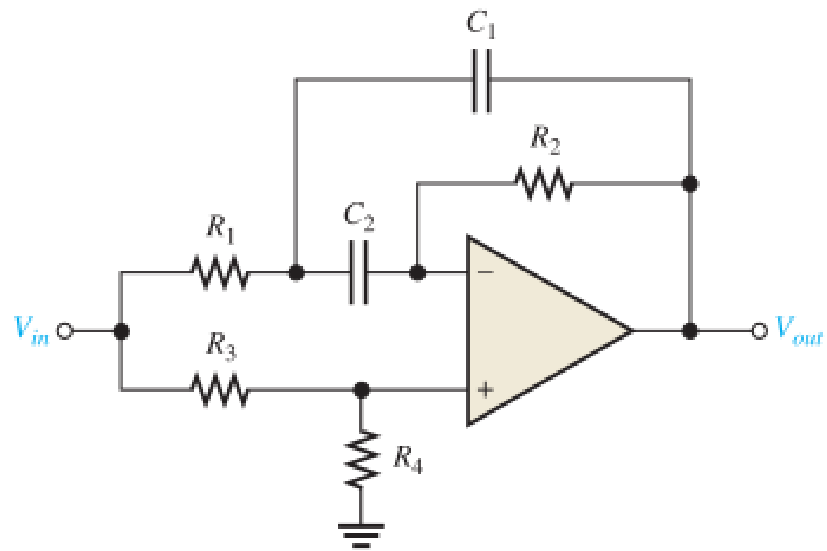
K = DC gain

$$\omega_0 = 1/\sqrt{LC_6} = 1/\sqrt{C_4C_6R_1R_3R_5/R_2}$$

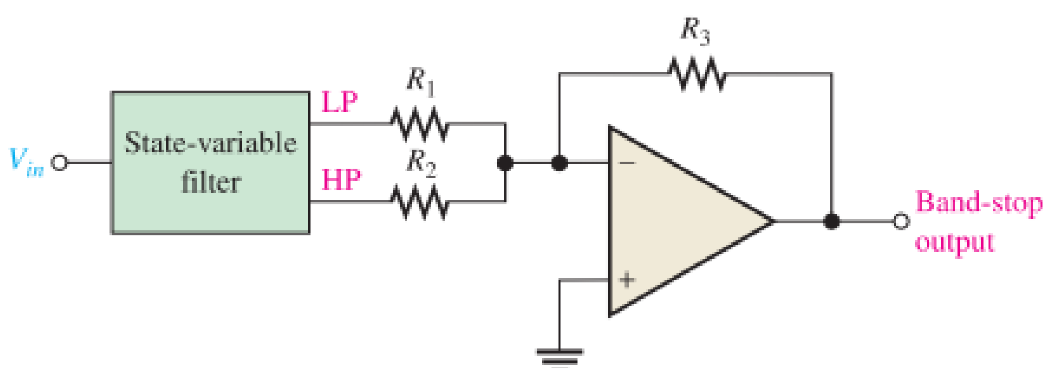
$$Q = \omega_0 C_6 R_6 = R_6\sqrt{\frac{C_6}{C_4}\frac{R_2}{R_1R_3R_5}}$$

ACTIVE BAND-STOP FILTERS

Multiple-Feedback Band-Stop Filter



State-Variable Band-Stop Filter



- For more details, refer to:
  - Chapter 15 at T. Floyd, **Electronic Devices**,9th edition.
  - Chapter 12 at Sedra & Smith, **Microelectronic Circuits**, 5th edition.
- The lecture is available online at:
  - http://bu.edu.eg/staff/ahmad.elbanna-courses/12884
- For inquires, send to:
  - ahmad.elbanna@feng.bu.edu.eg