EE 254

Electronic Instrumentation

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Lecture Note #07

Content (Brief)

2. Op-Amp Applications

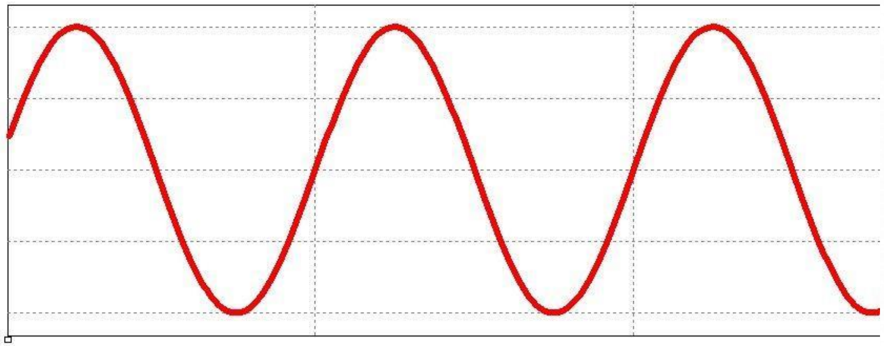
- Linear Applications
  - Inverting amplifiers
  - Noninverting amplifiers
  - Differential amplifiers
  - Summing amplifiers
  - Integrators
  - Differentiators
  - Low/ High pass filters
  - Instrumentational amplifiers
- Nonlinear Applications
  - Precision rectifiers
  - Peak detectors
  - Schmitt-trigger comparator
  - Logarithmic amplifiers

Low-Pass and High-Pass Filters

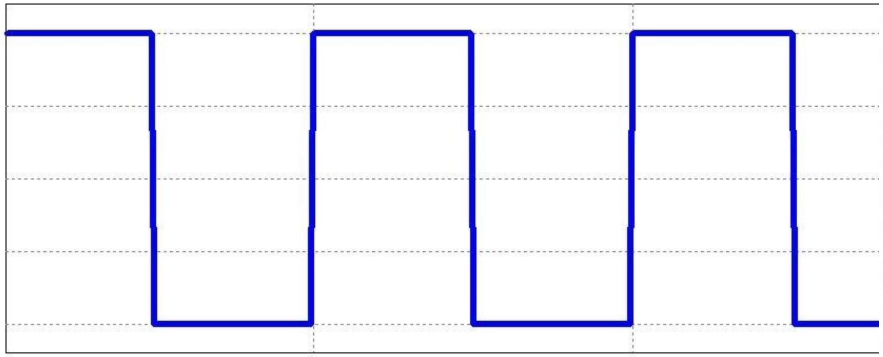
Basic Idea

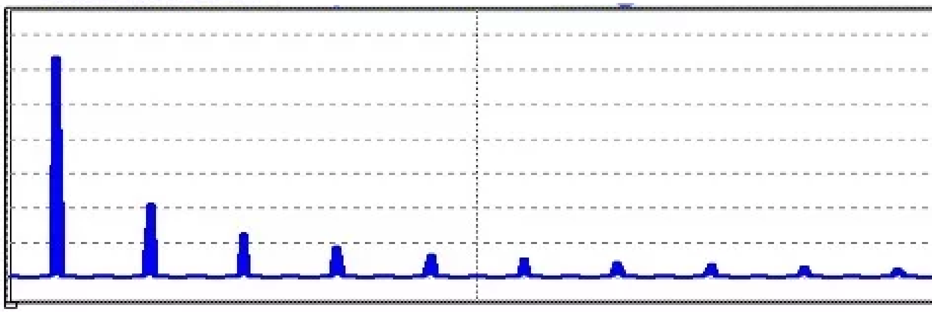
Time Domain and Frequency Domain

Vsine

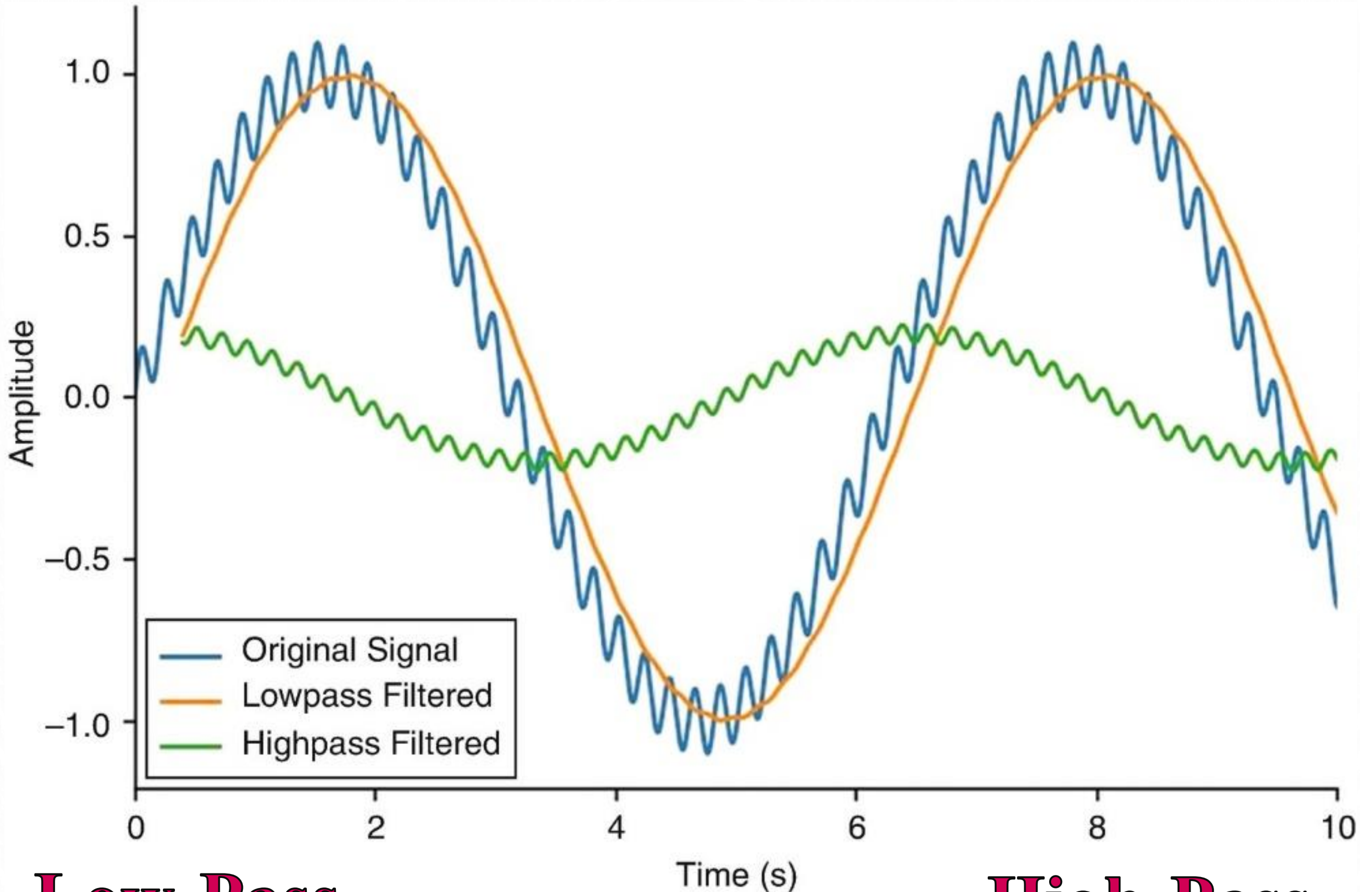


Vsquare

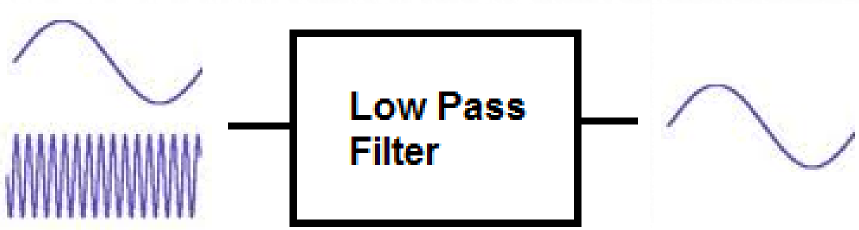




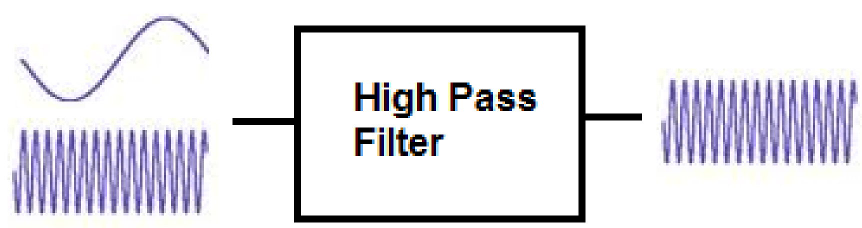
Basic Idea



Low-Pass



High-Pass



Introduction to Filters - *General*

- **An electrical filter** can be defined as a **network or system** that transforms an input signal in some specified way to yield an output signal with desired characteristics.
- Filter is a **frequency-selective device**, and its frequency response has significant values only in **certain bands along the frequency axis**.
- Filters are used extensively in electronic devices. For instance, telephone, radio, telegraph, television, radar, sonar, and space vehicles utilize filters in one form or another.
- Filters may be either **analog** or **digital**. Here we consider only analog filters. The components of an analog filter may be **passive circuit elements** like RLC circuits.
- Alternatively, it may be an **active one**; RLC circuit with operational amplifiers.

Filter Classifications

Depending on the type of element used in their construction, filters are classified into two types, such as:

1. **Passive Filters**:

   A passive filter is built with passive components such as resistors, capacitors and inductors.

2. **Active Filters**:

   An active filter makes use of active elements such as transistors, op-amps in addition to resistor and capacitors.

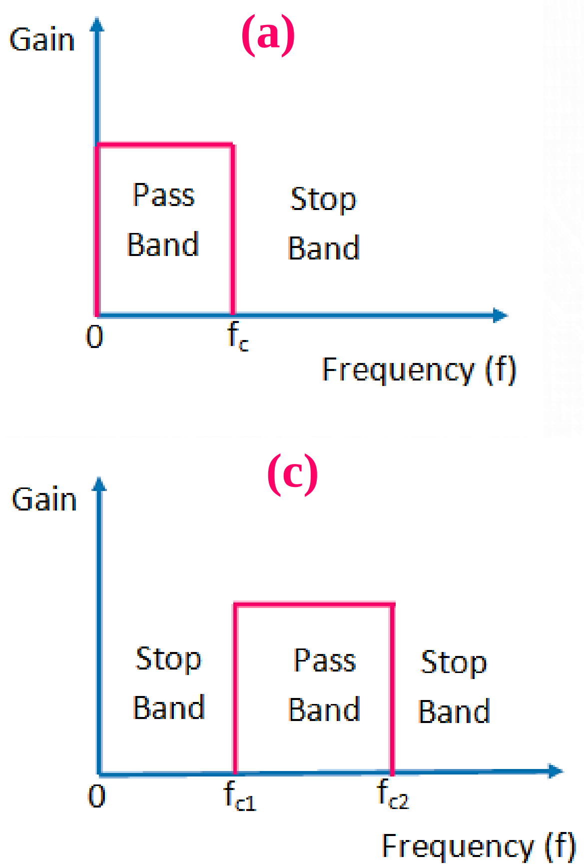
Filter Classifications

- Process the signals in order to enhance certain frequency components and to reject certain others.
- For example, if a signal consists of a **low-frequency** information-bearing portion and a **high-frequency noise portion**, we can employ a filter to **reject the high frequencies** and thus remove the noise.
- We will look at four kinds of filters:

1. Low-pass filters
2. High-pass filters
3. Band-pass filters
4. Band-stop filters

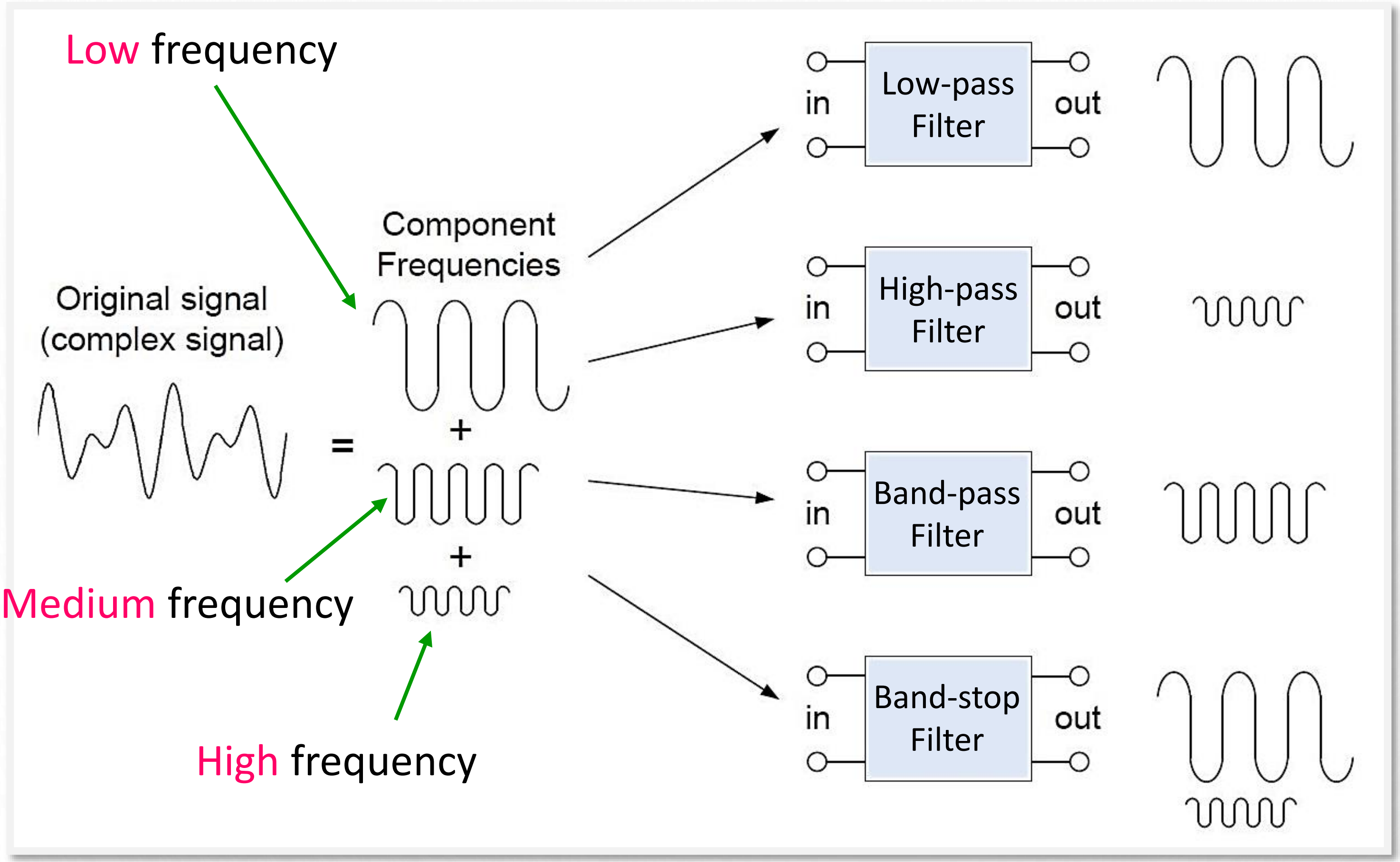
Filter Classifications

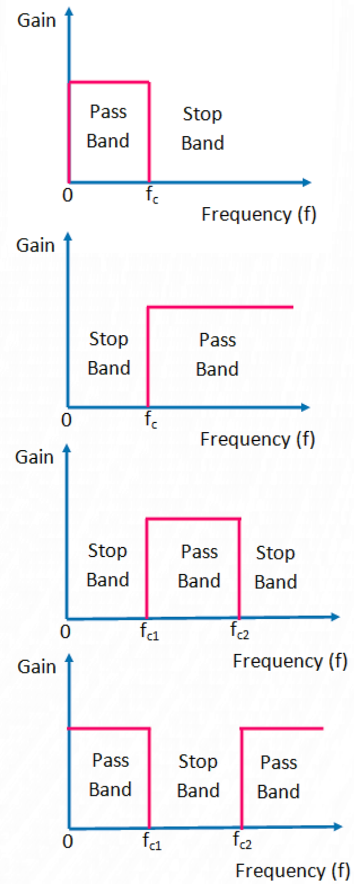
Filters can be classified on the basis of their frequency response: (a) low-pass, (b) high-pass, (c) band-pass, (d) band-stop filters.



- These are **ideal filters**
- There are several way to show that the ideal filter is **not realizable**.

How Filters Work?





Active Filters

Advantages over Passive Filters

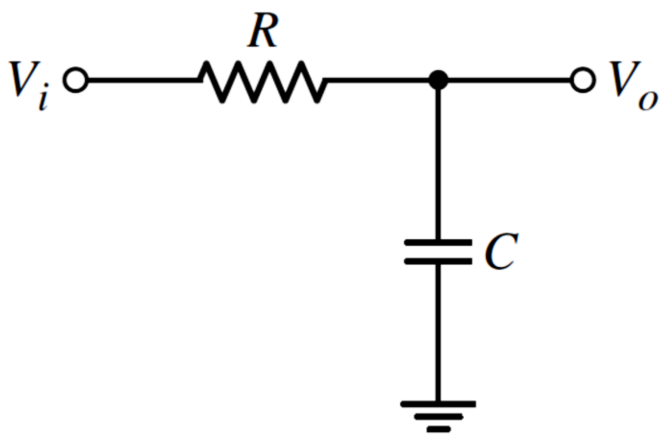
- The **maximum gain** or the maximum value of the transfer function may be greater than unity.
- The **loading effect is minimal**, which means that the output response of the filter is essentially independent of the load driven by the filter.

Passive Low-Pass Filter *(Review – Passive Filters)*

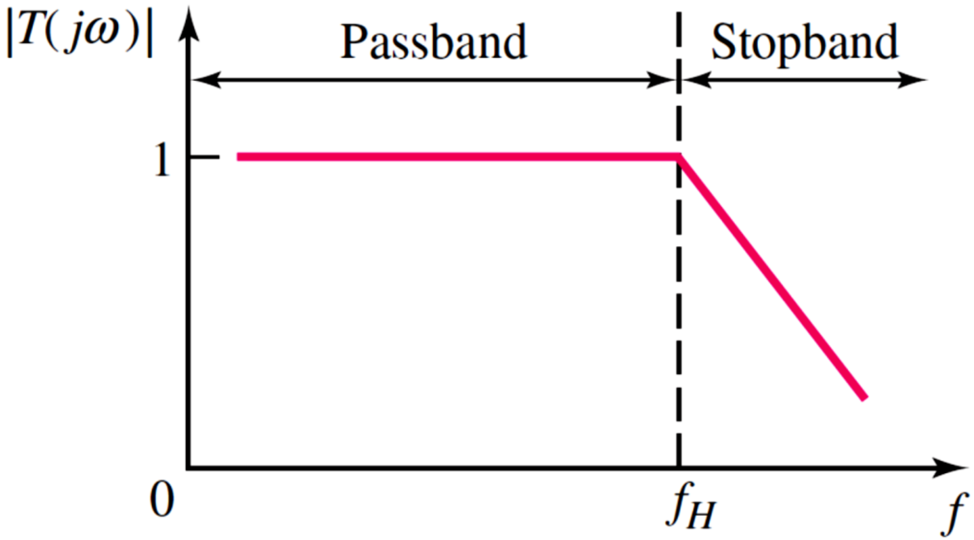
- The voltage transfer function

$$T(s) = \frac{V_o(s)}{V_i(s)} = \frac{\frac{1}{sC}}{\frac{1}{sC} + R} = \frac{1}{1 + sRC}$$

Low-pass Filter

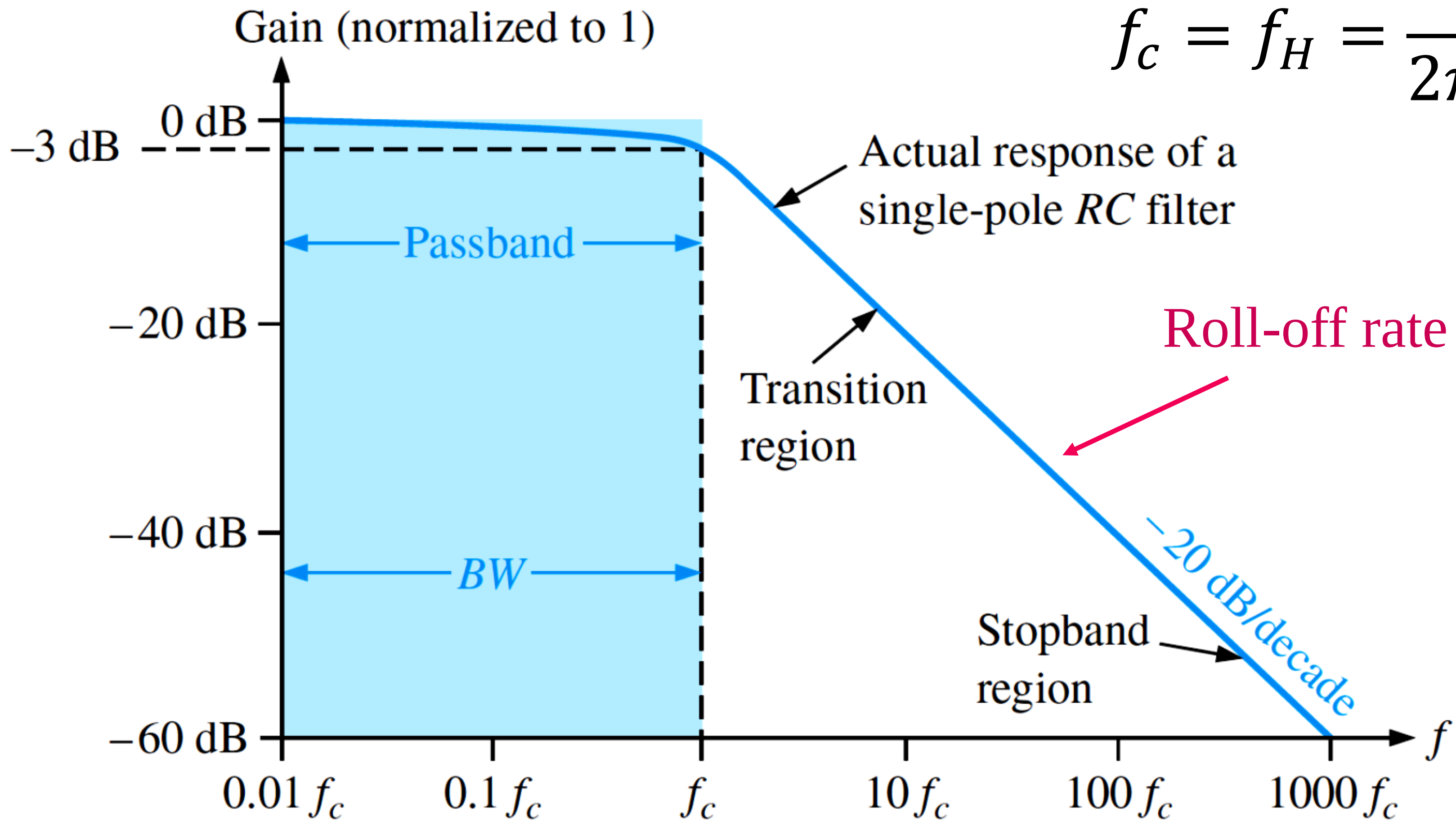


The Bode plot of the voltage gain magnitude $|T(j\omega)|$



Passive Low-Pass Filter *(Review – Passive Filters)*

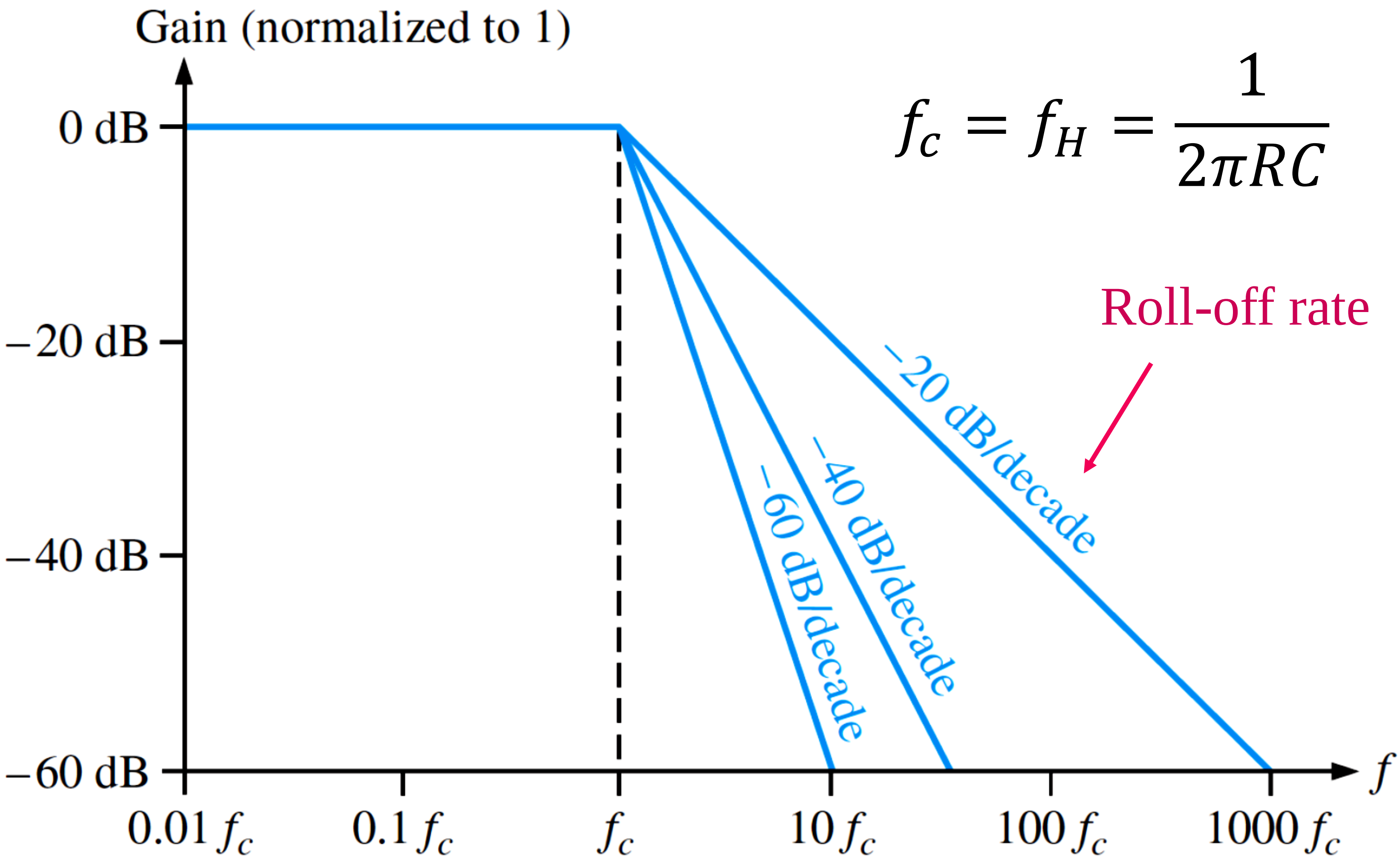
$$f_c = f_H = \frac{1}{2\pi RC}$$



Comparison of an ideal low-pass filter response (blue area) with actual response.

Passive Low-Pass Filter *(Review – Passive Filters)*

Idealized filter responses

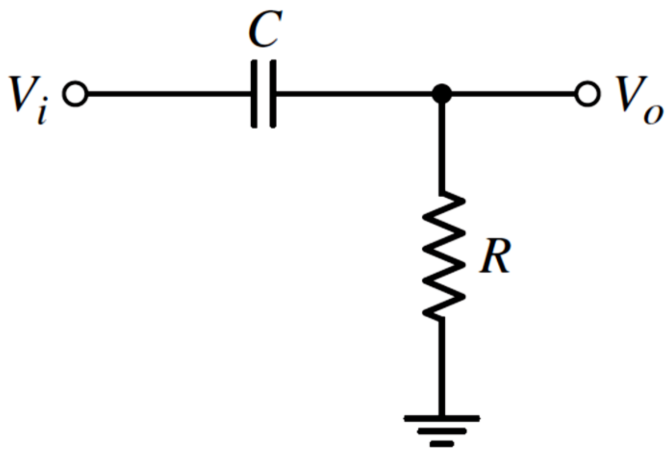


$$f_c = f_H = \frac{1}{2\pi RC}$$

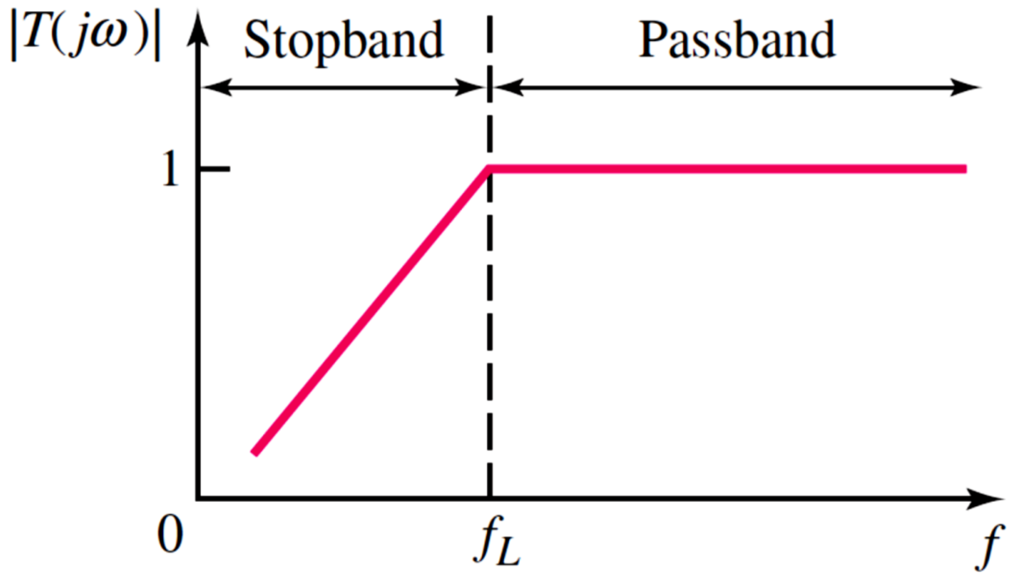
Passive High-Pass Filter *(Review – Passive Filters)*

- RC network is a filter.
- The voltage transfer function

High-pass Filter



$$T(s) = \frac{V_o(s)}{V_i(s)} = \frac{R}{R + \frac{1}{sC}} = \frac{sRC}{1 + sRC}$$

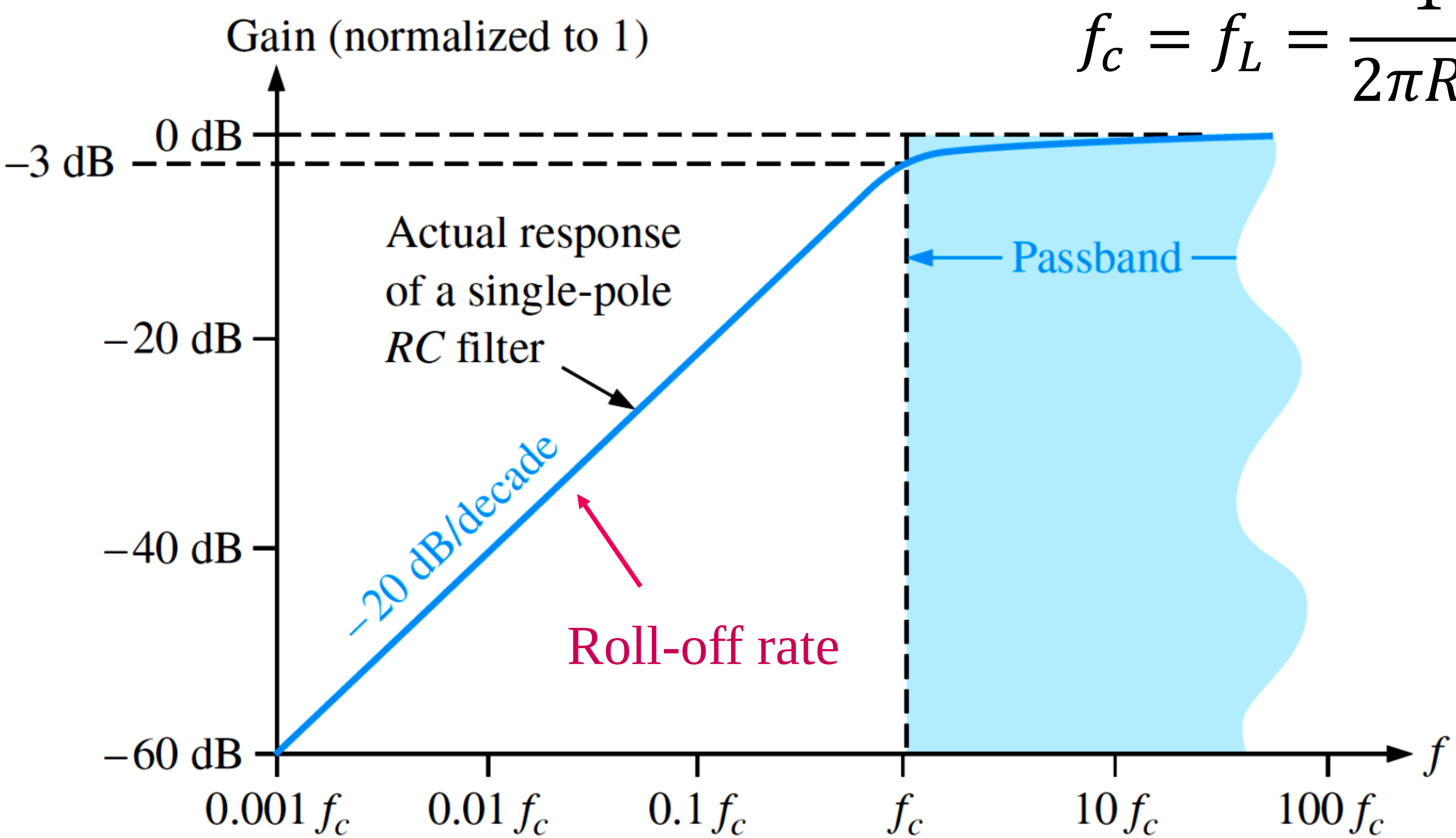


The Bode plot of the voltage gain magnitude $|T(j\omega)|$

Passive High-Pass Filter *(Review – Passive Filters)*

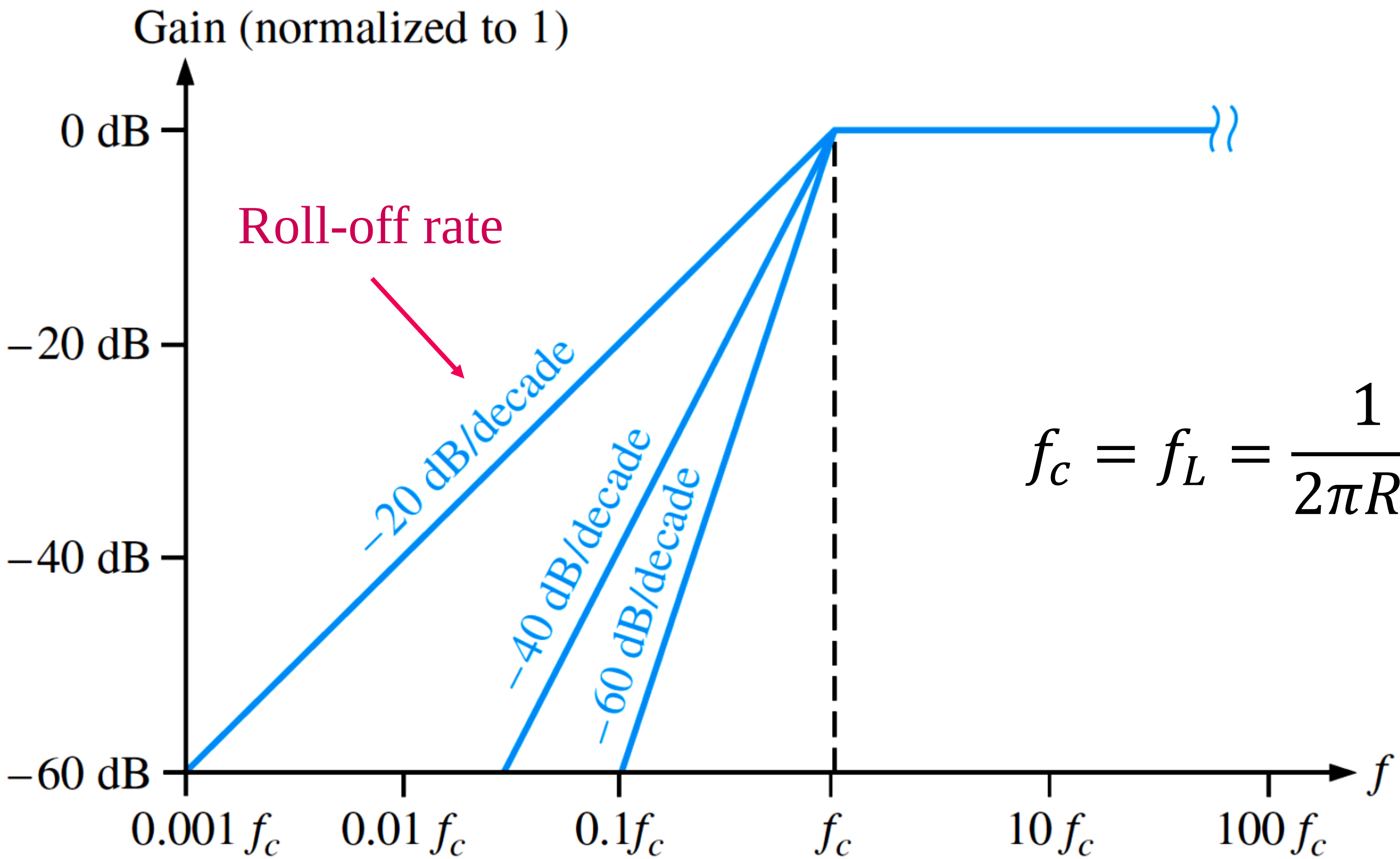
Comparison of an **ideal high-pass filter** response (blue area) with **actual response**

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



Passive High-Pass Filter *(Review – Passive Filters)*

Idealized Filter Responses

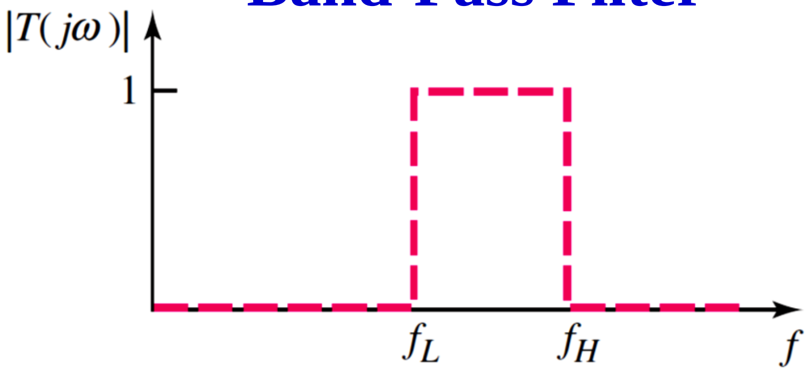


$$f_c = f_L = \frac{1}{2\pi RC}$$

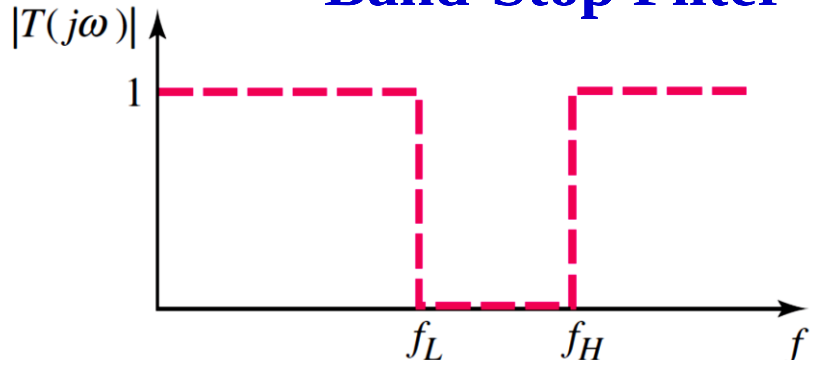
Band-Pass and Band-Reject Filters (Review – Passive Filters)

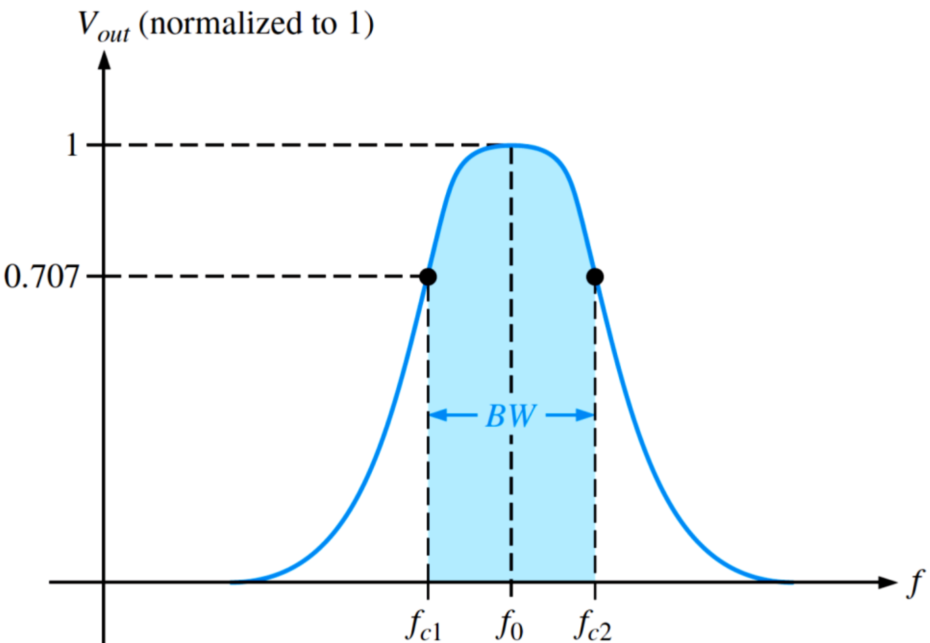
Ideal frequency characteristics

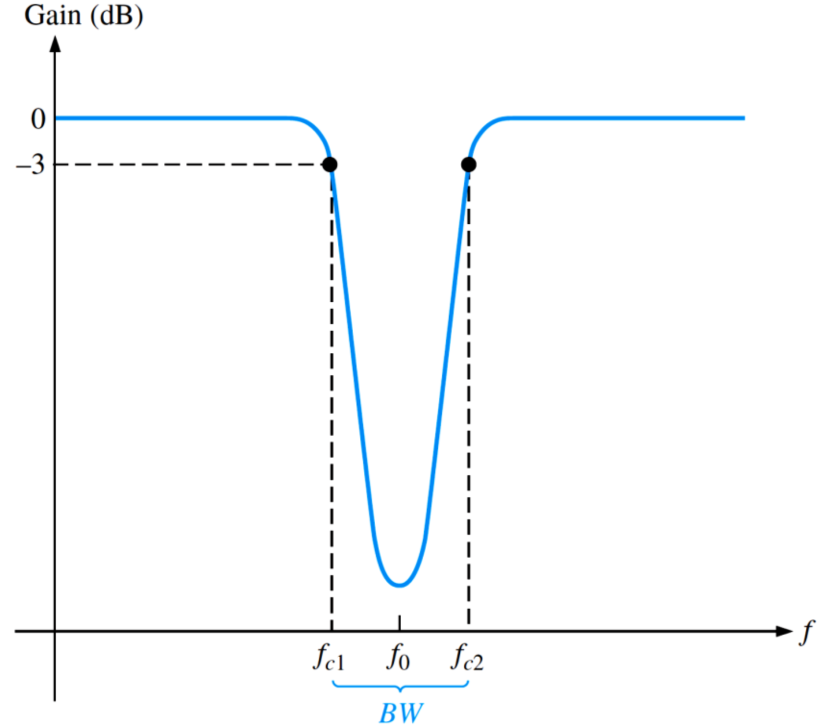
Band-Pass Filter



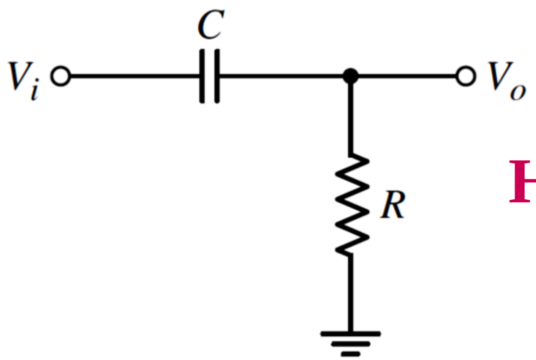
Band-Stop Filter





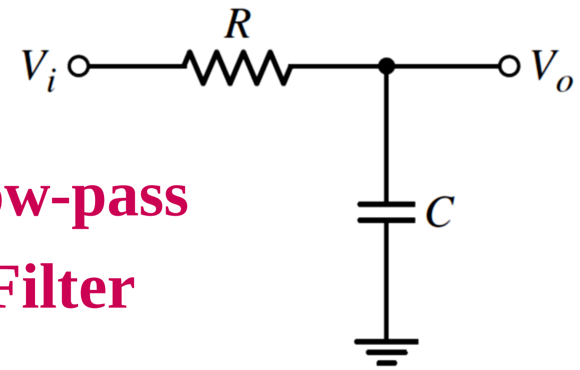


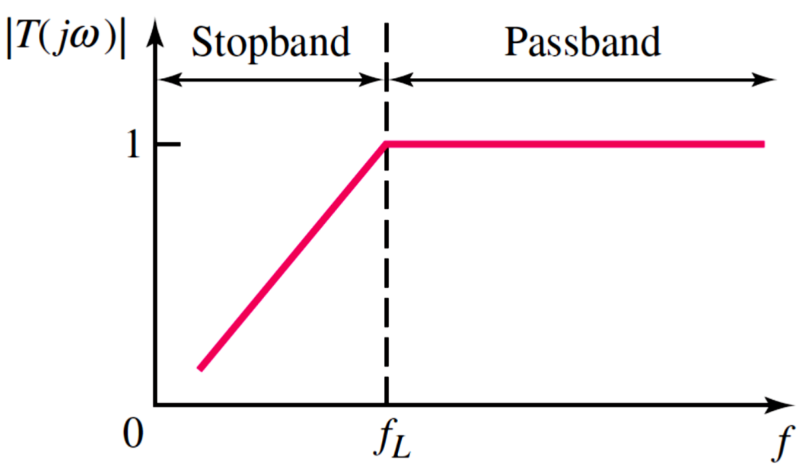
Comparison of Low and High-Pass Filters (Review)

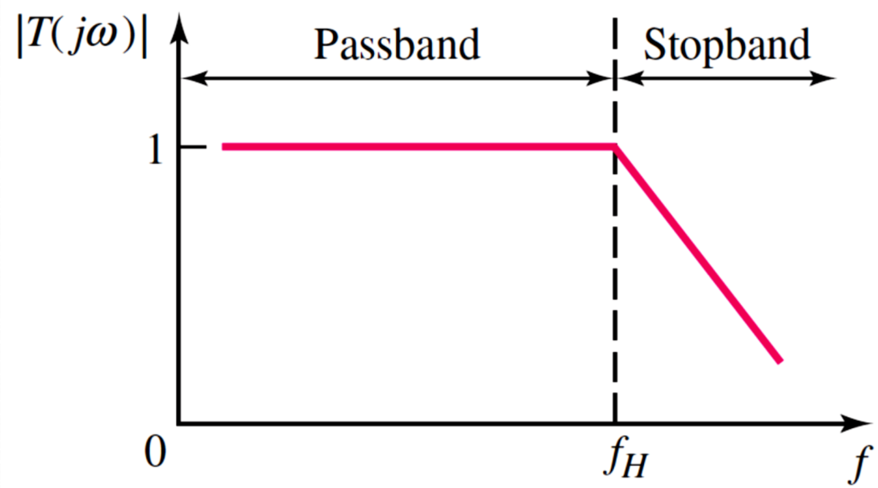


High-pass Filter

Low-pass Filter



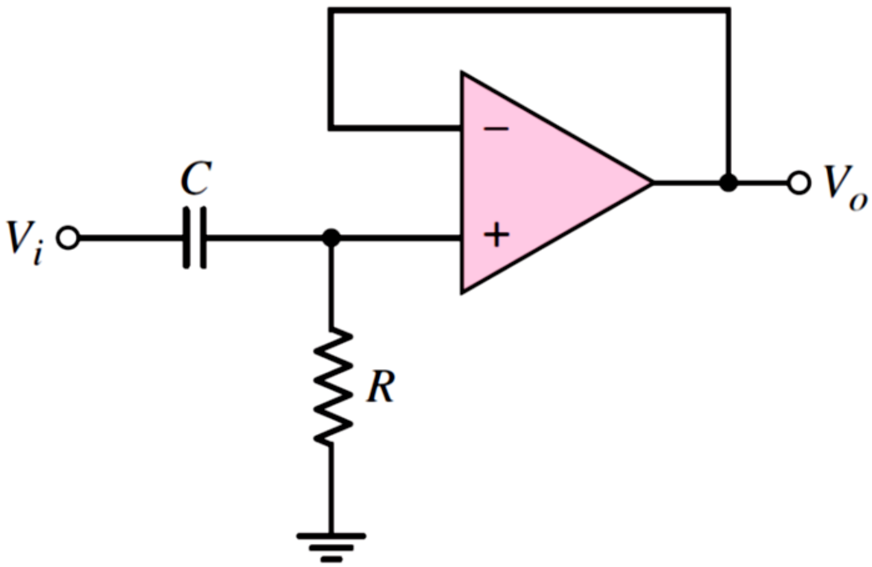


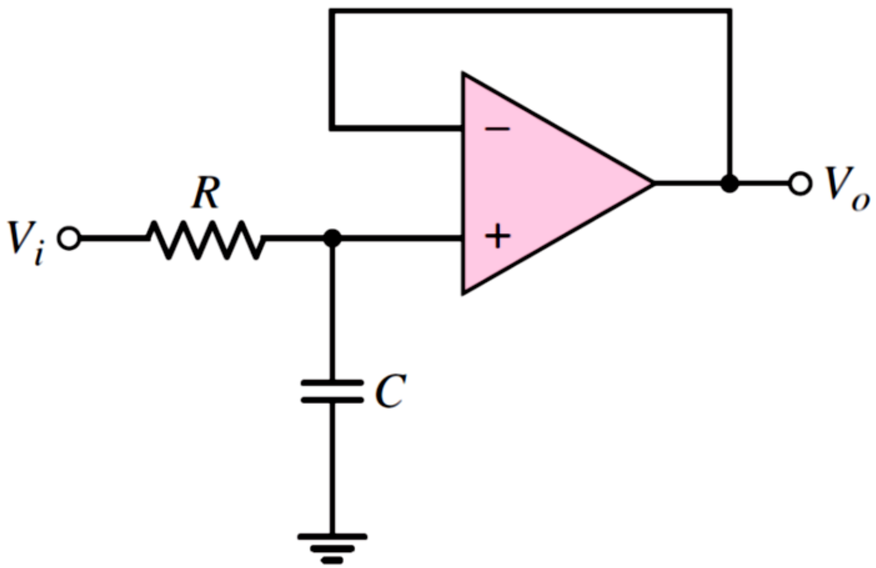


- When a load is connected, these may suffer from **Loading Effect** and substantially **reducing the maximum gain**
- Cutoff frequencies f_L and f_H may change when load is connected

Eliminating Loading Effect

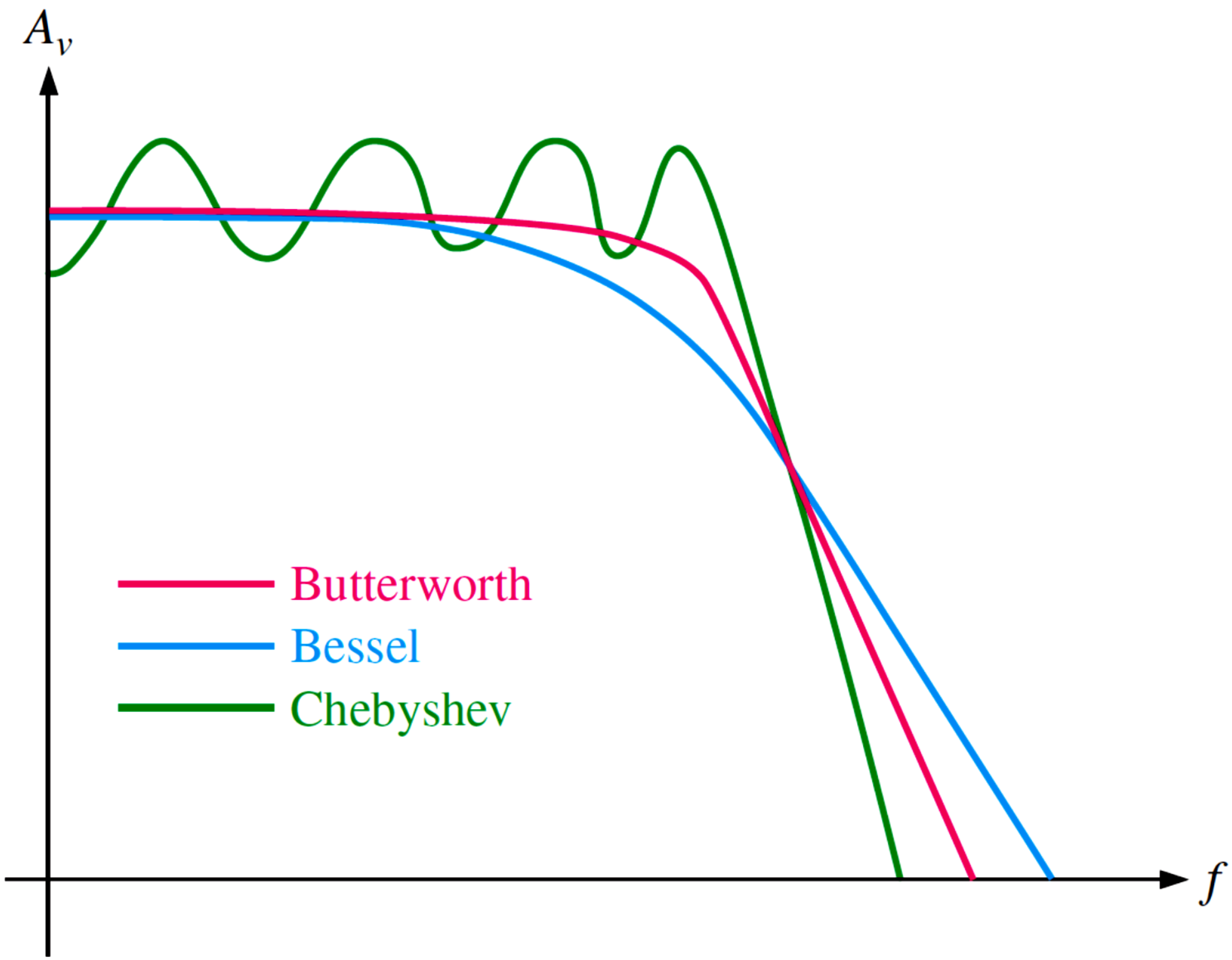
Filters with voltage followers





- **Loading effect** can be eliminated with **voltage followers**
- **Noninverting amplifier** can be incorporated to increase the gain

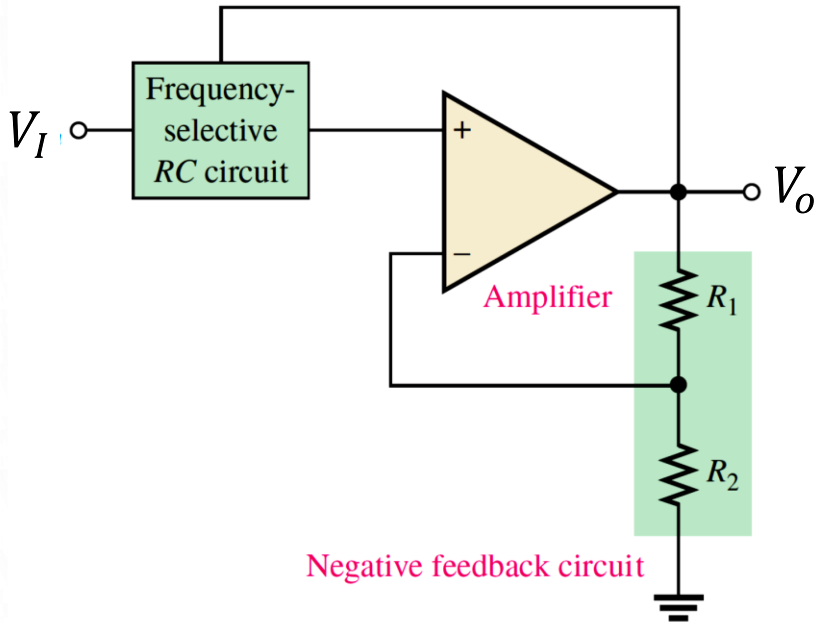
Active Filters - *examples*

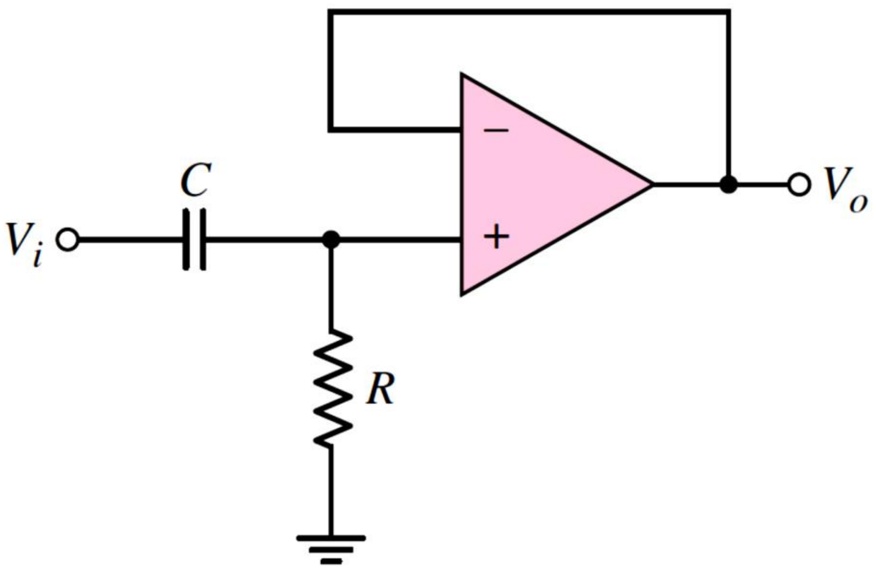


- These filters can be realized by proper selection of certain component values for Active filters.

Active Filters

- We can have different configurations with op-amps





With negative feedback circuit

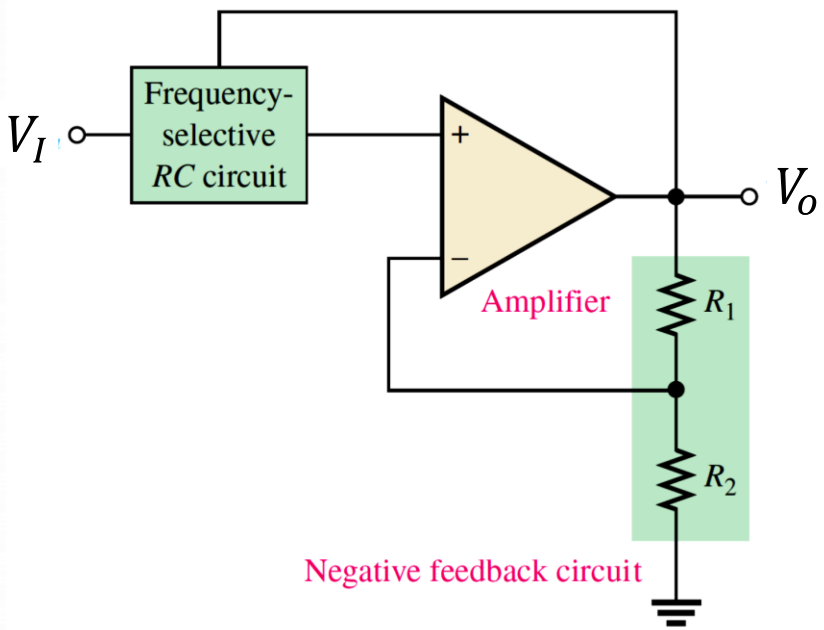
With voltage follower circuit

Active Filters (with negative feedback)

- An active filter can be designed to have either a **Butterworth, Chebyshev, or Bessel response characteristic** regardless of whether it is a **low-pass, high-pass, band-pass, or band-stop** type.

- The **Damping Factor (DF)** of an active filter circuit determines which response characteristic the filter exhibits **from above three**.

- The damping factor is determined by the **negative feedback circuit** and is defined by the following equation.



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

Active Filters (with negative feedback)

- The value of the **damping factor** required to produce a desired response characteristic depends on the **order**.
- With more poles, the filter **roll-off rate** becomes fast.
- For example, for a **second-order Butterworth** filter, the DF must be 1.414.

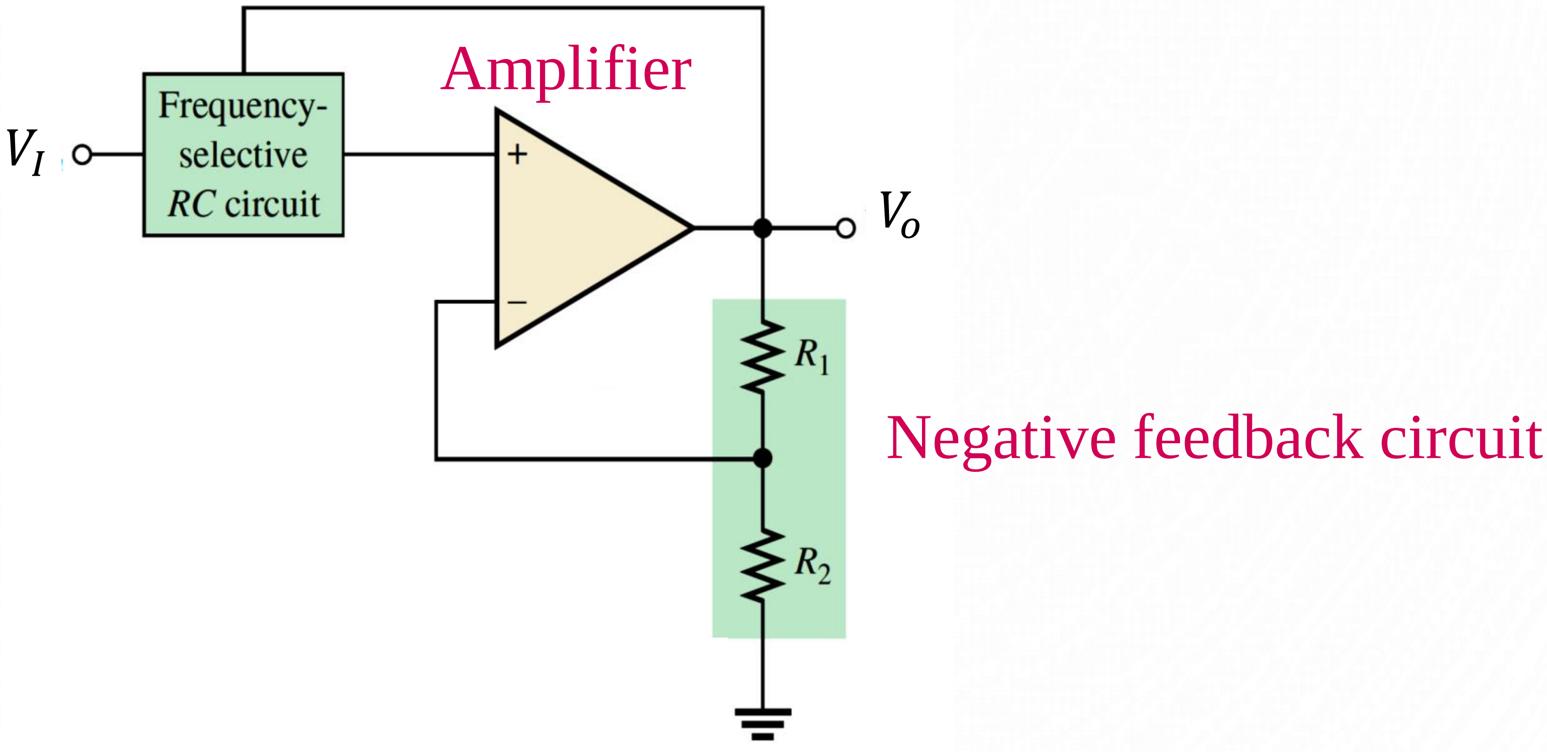
$$\frac{R_1}{R_2} = 2 - DF = 2 - 1.414 = 0.586$$

- The closed-loop gain becomes

$$A_{cl(\mathrm{NI})} = \frac{1}{B} = \frac{1}{R_2/(R_1 + R_2)} = \frac{R_1 + R_2}{R_2} = \frac{R_1}{R_2} + 1 = 0.586 + 1 = 1.586$$

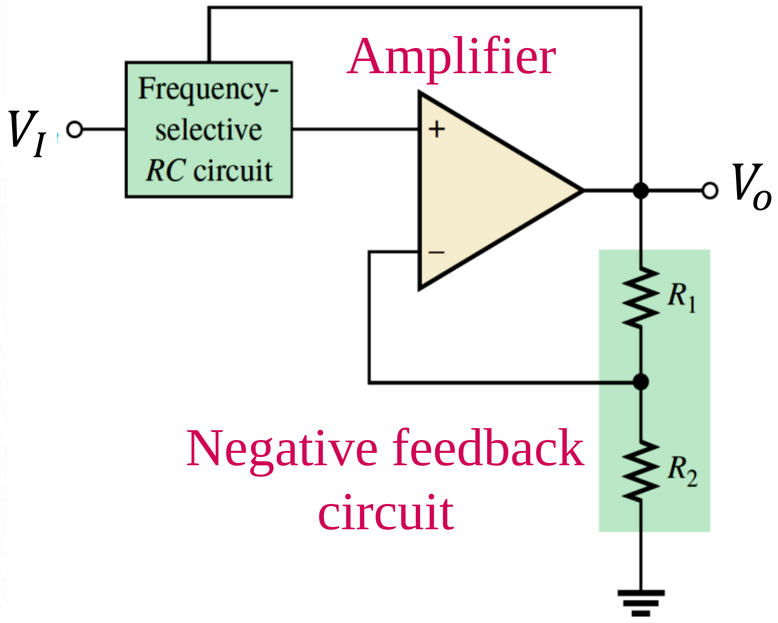
Ex. 01: Active Single-pole Filter

If resistor R_2 in the feedback circuit of an active single-pole filter of the type in Figure below is $10k\Omega$ what value must R_1 be to obtain a maximally flat Butterworth response?



Ex. 01: Active Single-pole Filter

Solution:



As stated before;

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

$$\frac{R_1}{R_2} = 0.586$$

$$R_1 = 0.586 \times R_2 = 0.586\,(10k\Omega)$$

$$R_1 = 5.86\;k\Omega$$

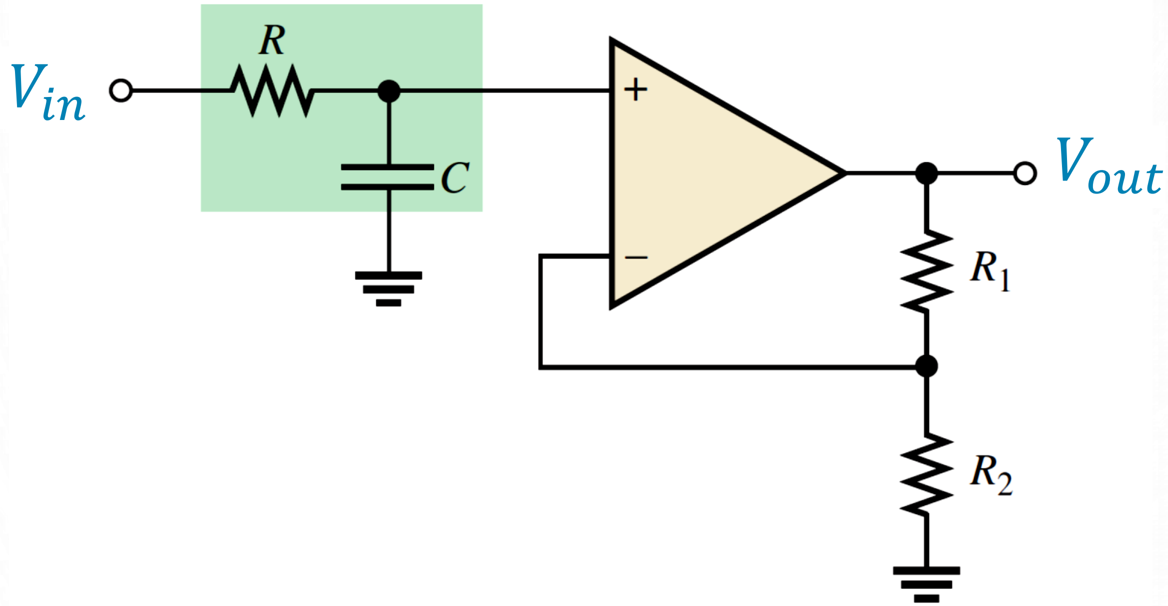
Using the nearest standard 5 percent value of will get very close to the ideal Butterworth response.

Critical Frequency and Roll-Off Rate

- The critical frequency is determined by the values of the resistors and capacitors in the frequency-selective RC circuit.

Single-pole low-pass circuit

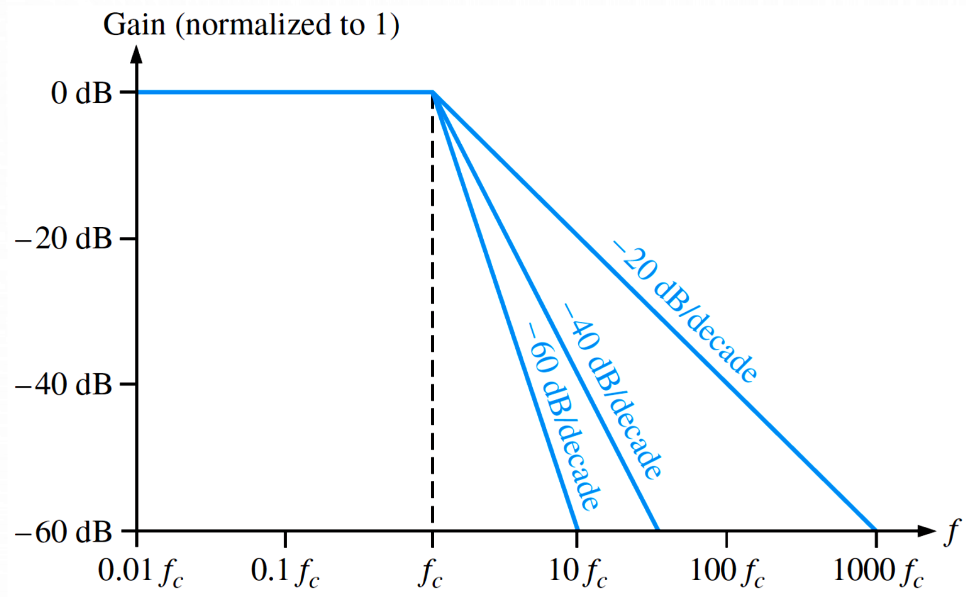
$$f_c = \frac{1}{2\pi RC}$$

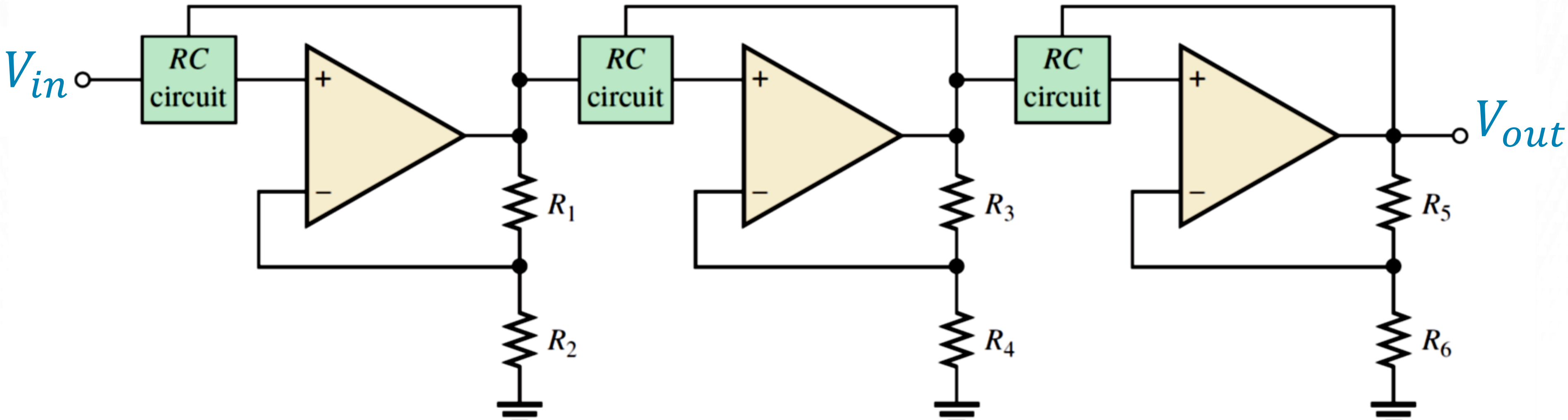


- The number of poles determines the roll-off rate of the filter.

Critical Frequency and Roll-Off Rate

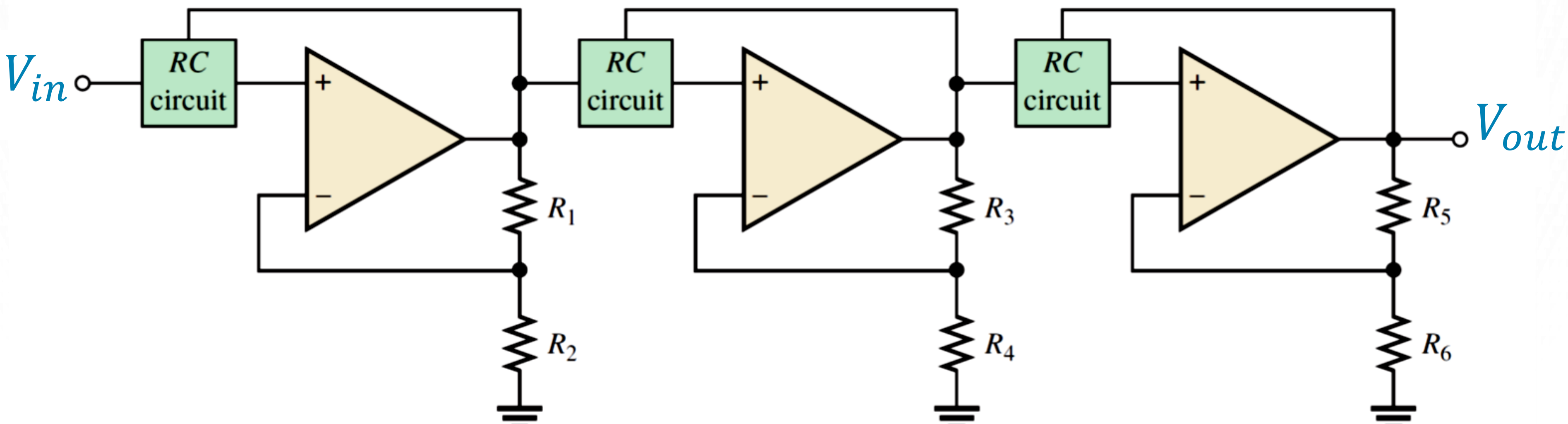
- Generally, to obtain a filter with three poles or more, one-pole or two-pole filters are cascaded.





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

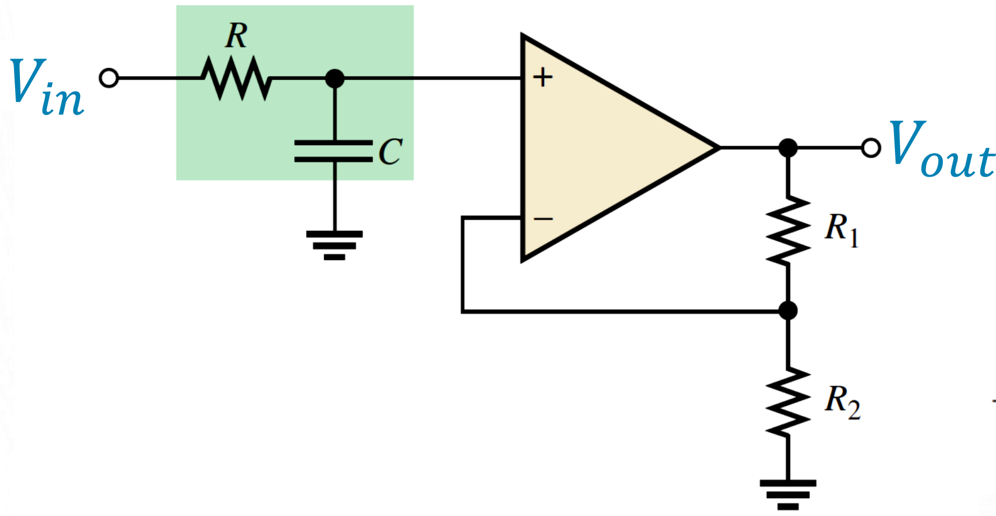


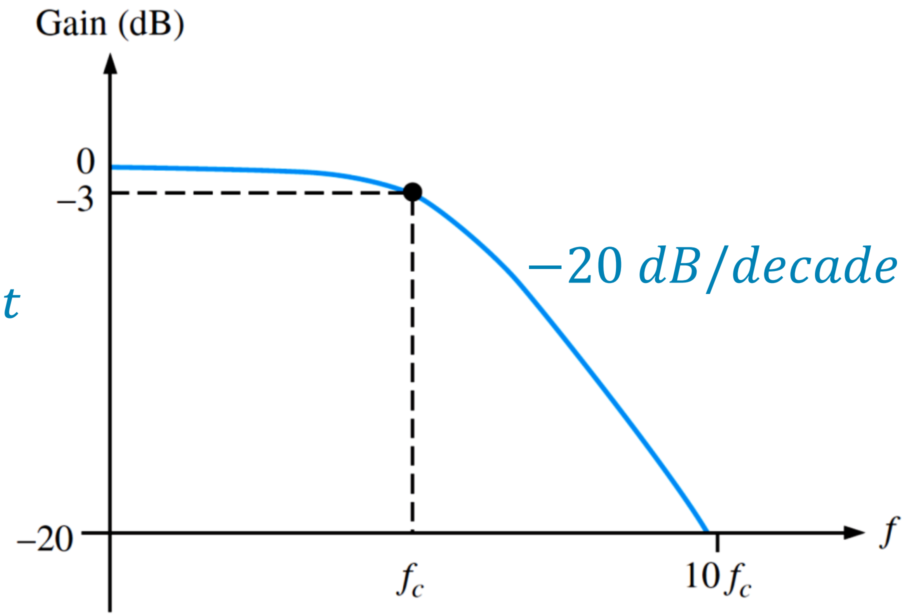
A Single-Pole Low-Pass Filter

- The closed-loop voltage gain

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

One pole



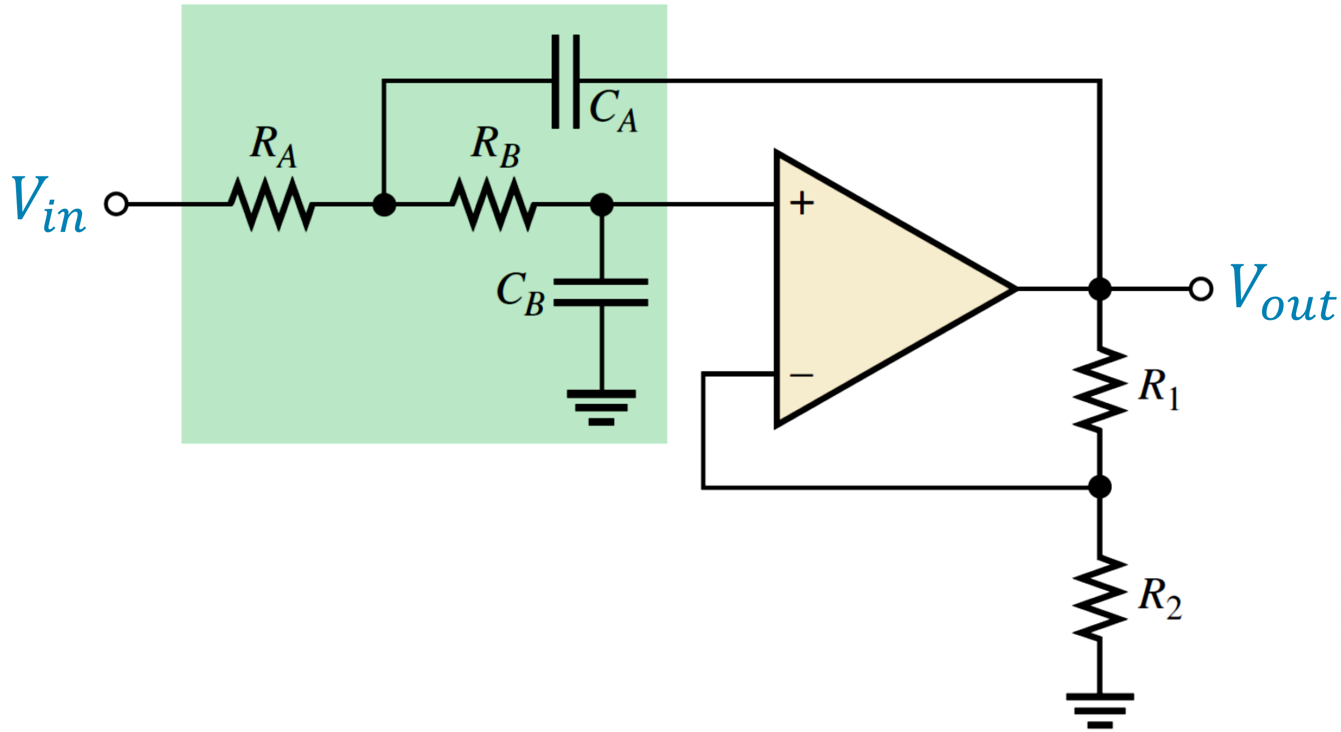


A Second-Order (Two Poles) Low-Pass Filter

- The capacitor C_A provides feedback for shaping the response near the edge of the passband.

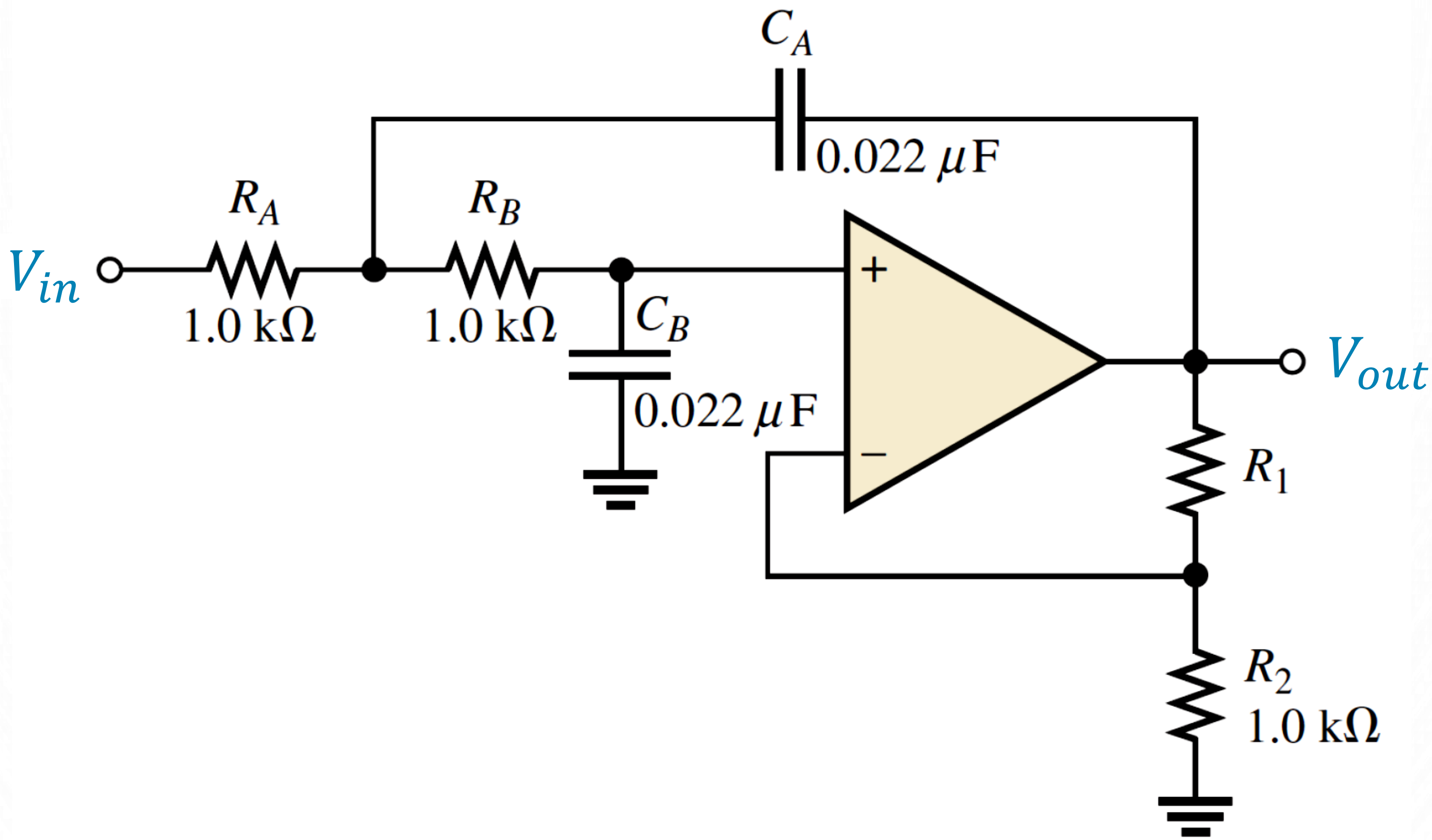
$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$

Two-pole low-pass circuit



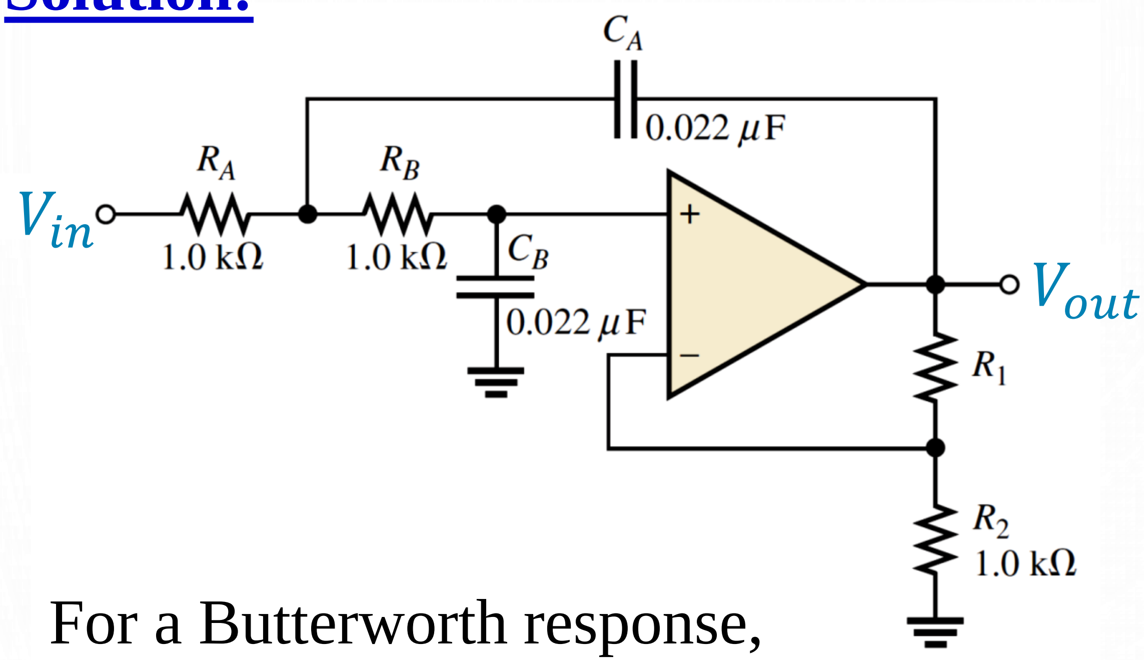
Ex. 02: Second-Order Low-Pass Filter

Determine the critical frequency of the second-order low-pass filter in Figure, and set the value of R_1 for an approximate Butterworth response



Ex. 02: Second-Order Low-Pass Filter

Solution:



Since;

$$R_A = R_B = R = 1.0\ k\Omega$$

And

$$C_A = C_B = C = 0.022\ \mu F$$

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

$$= \frac{1}{2\pi(1\times 10^3)(0.022\times 10^{-6})}$$

For a Butterworth response,

$$\frac{R_1}{R_2} = 0.586$$

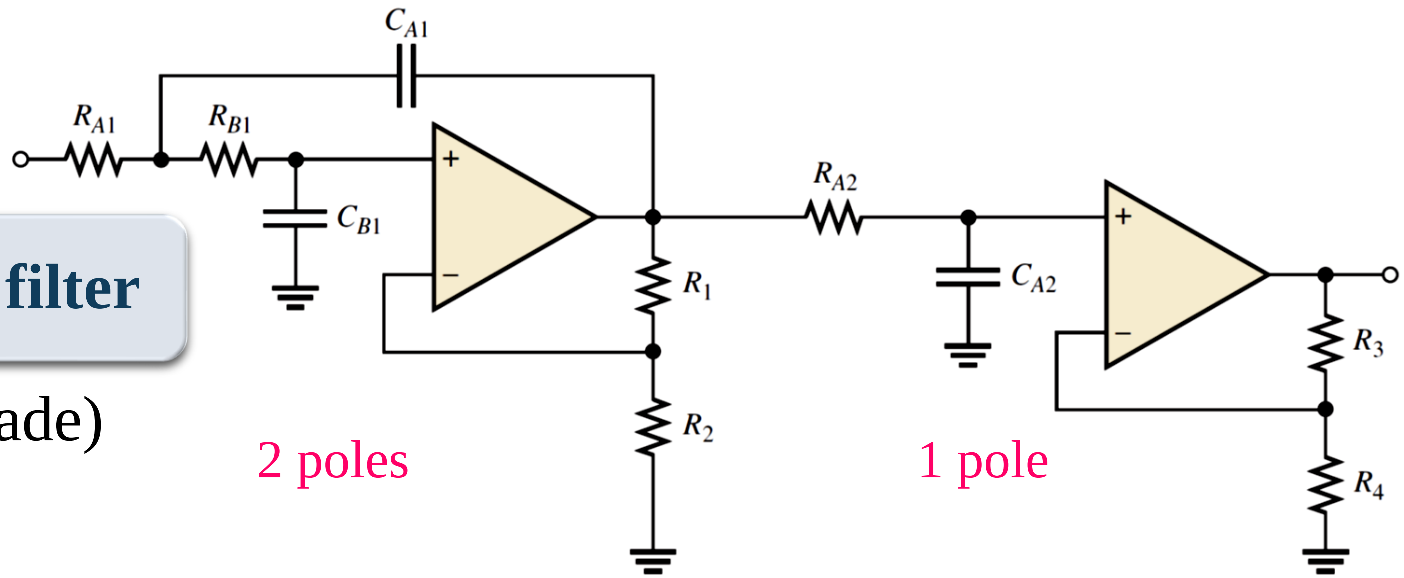
Then, $R_1 = 0.586 \times R_2 = 0.586(1.0\times 10^3) = 586\ \Omega$

Select a standard value as near as possible to this calculated value.

Cascaded Low-Pass Filters

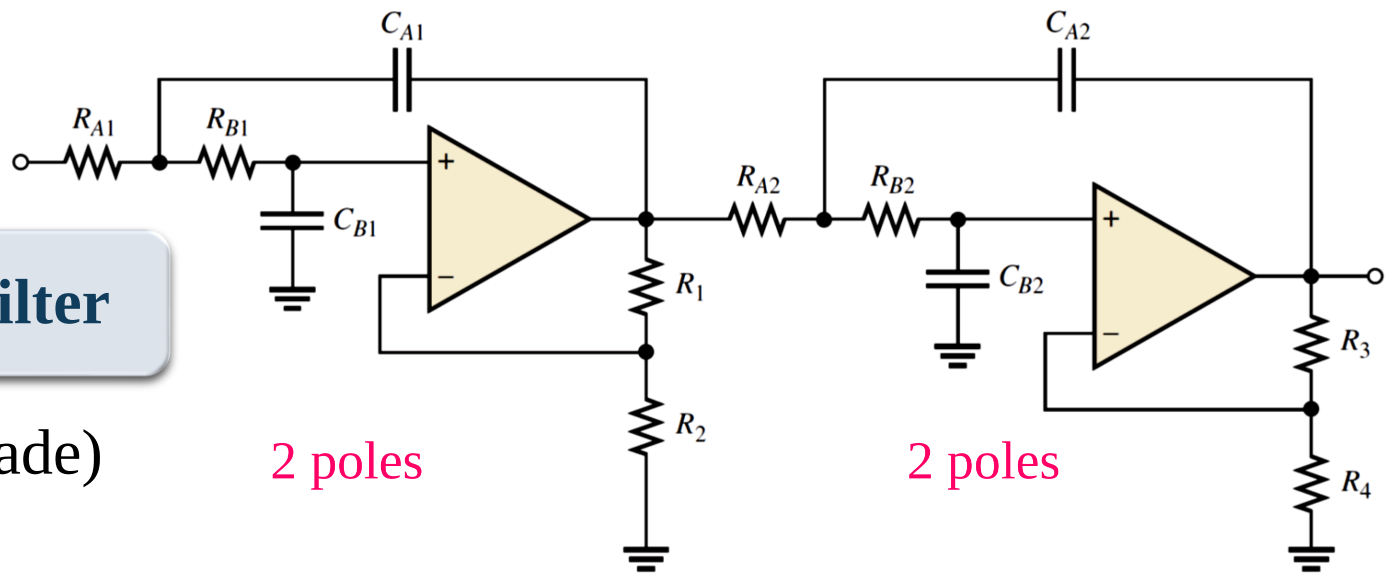
A three-pole filter

(-60 dB/decade)



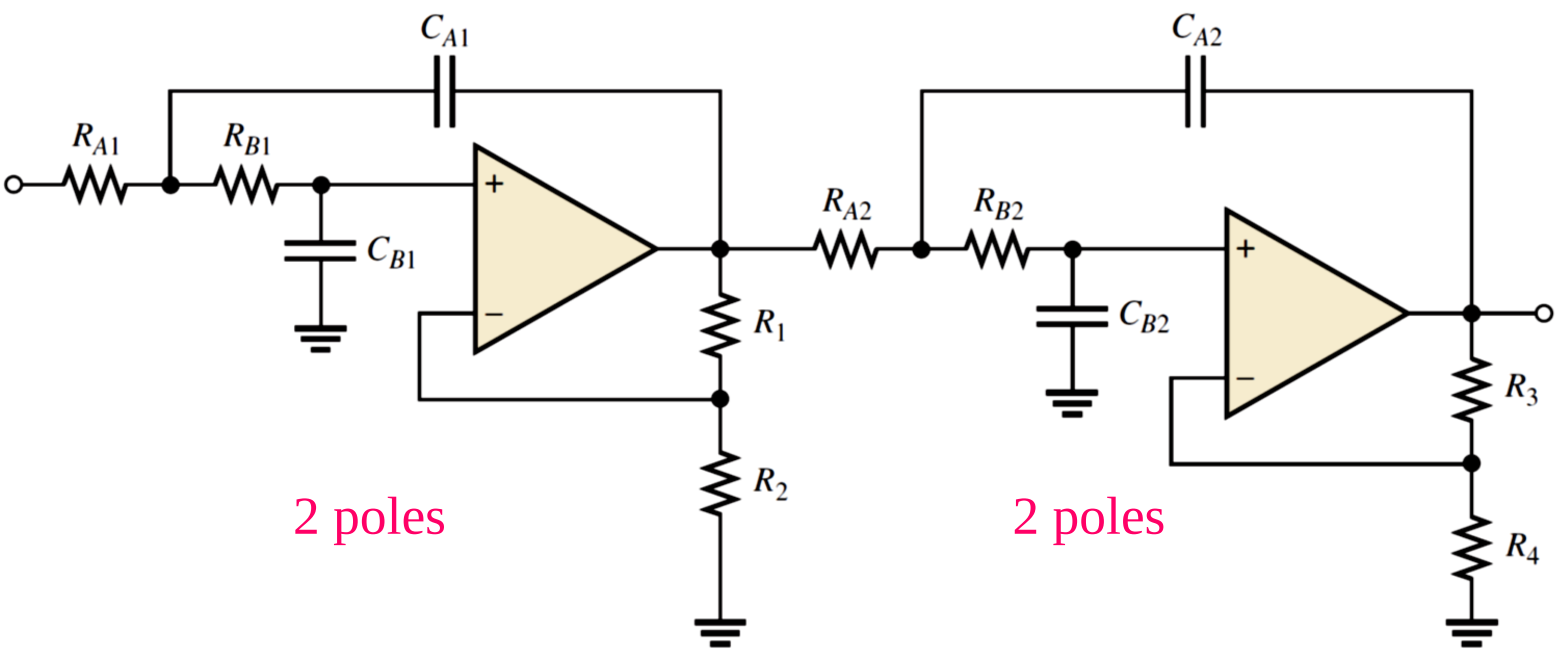
A four-pole filter

(-80 dB/decade)



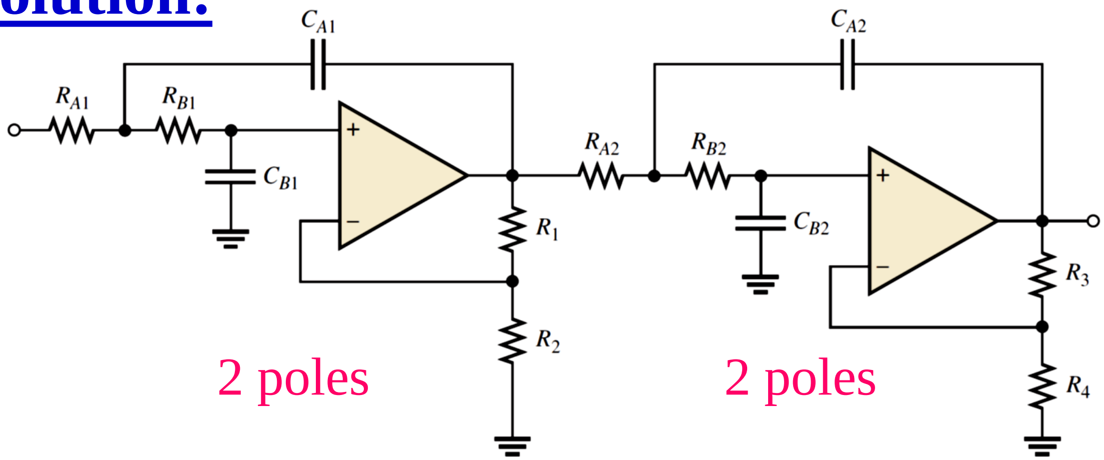
Ex. 03: Four-Pole Low Pass Filter

For the four-pole filter in Figure, determine the capacitance values required to produce a critical frequency of 2680 Hz if all the resistors in the RC low-pass circuits are $1.8k\Omega$. Also select values for the feedback resistors to get a Butterworth response.



Ex. 03: Four-Pole Low Pass Filter

Solution:



Both stages must have the same f_c. Assuming equal-value capacitors:

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

$$C = \frac{1}{2\pi R f_c} = \frac{1}{2\pi(1.8k\Omega)(2680Hz)} = \mathbf{0.033\ \mu F}$$

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

Also select $\boldsymbol{R_2 = R_4 = 1.8\ k\Omega}$ for simplicity.

- Select the values for ***DF*** and $\boldsymbol{R_1/R_2}$ and $\boldsymbol{R_3/R_4}$ from the table for a **Butterworth response**.
- The filter has four poles and two stages.

Ex. 03: Four-Pole Low Pass Filter

Solution: For a Butterworth filter, Selected: $R_2 = R_4 = 1.8\ k\Omega$

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

In the first stage: $DF = 1.848$ and $R_1/R_2 = 0.152$

$$R_1 = 0.152 \times R_2 = 0.152(1.8 \times 10^3) = \mathbf{274\ \Omega}$$

Choose: $\boldsymbol{R_1 = 270\ \Omega}$

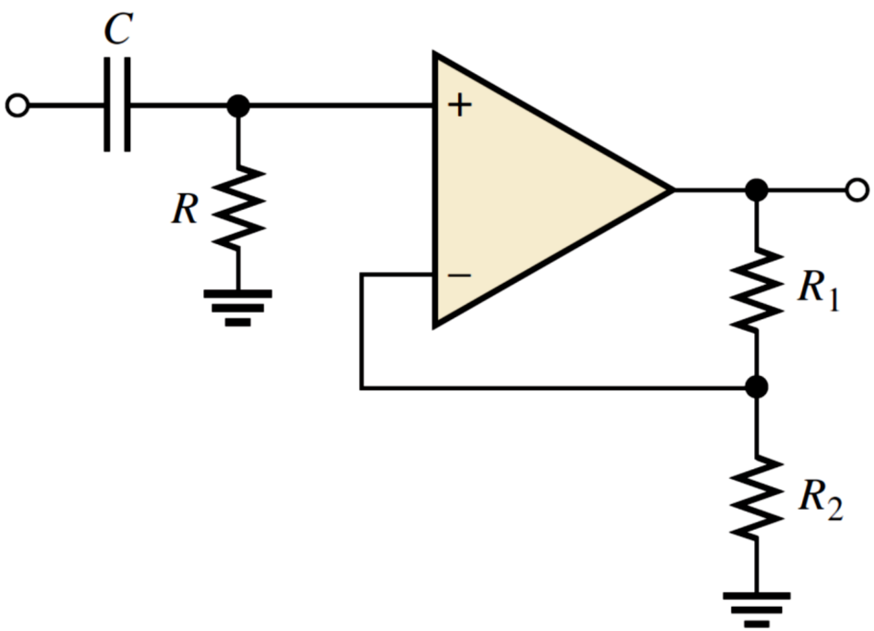
In the second stage: $DF = 0.765$ and $R_3/R_4 = 1.235$

$$R_3 = 1.235 \times R_4 = 0.152(1.8 \times 10^3) = \mathbf{2.22\ k\Omega}$$

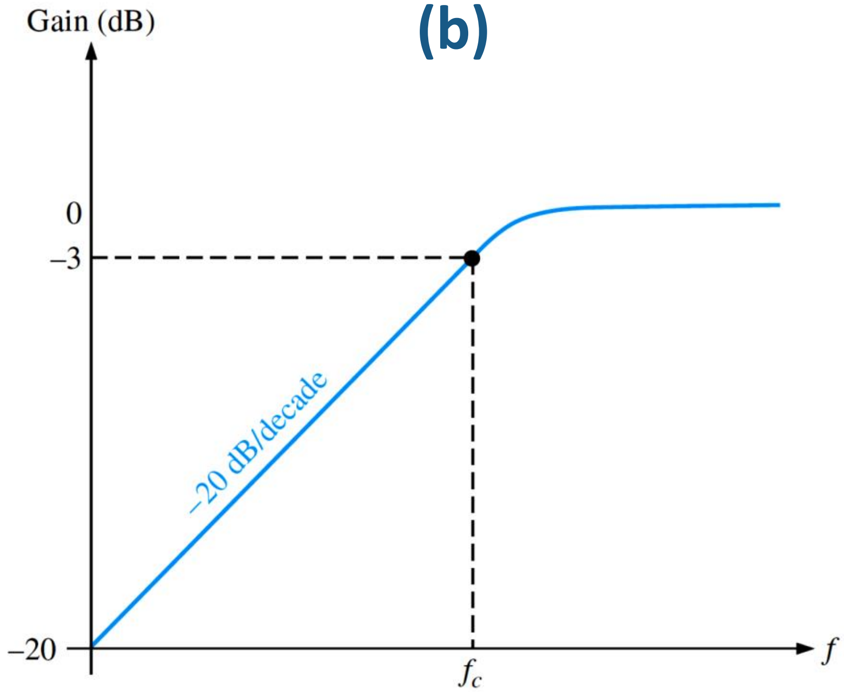
Choose: $\boldsymbol{R_3 = 2.2\ k\Omega}$

A Single-Pole High-Pass Filter

(a)



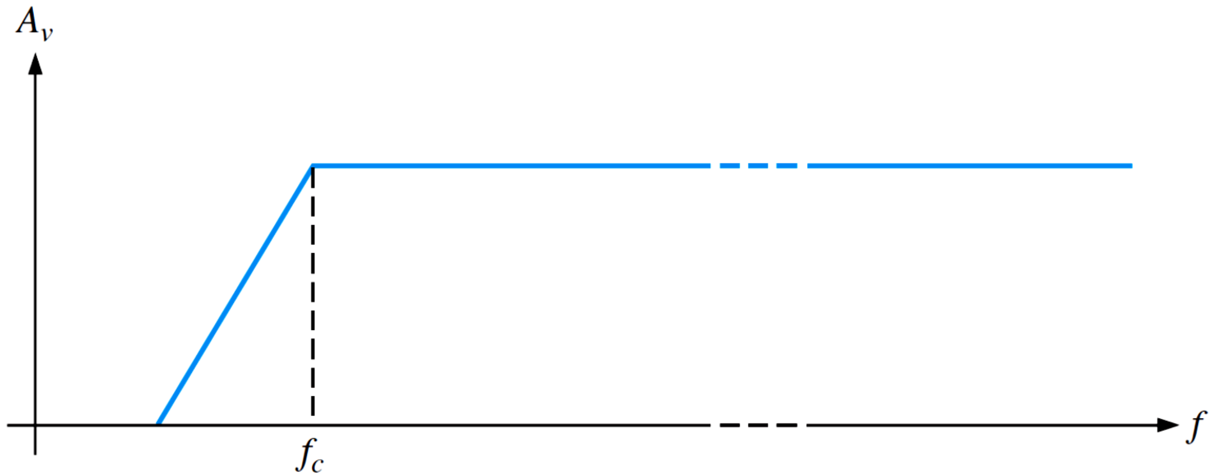
(b)



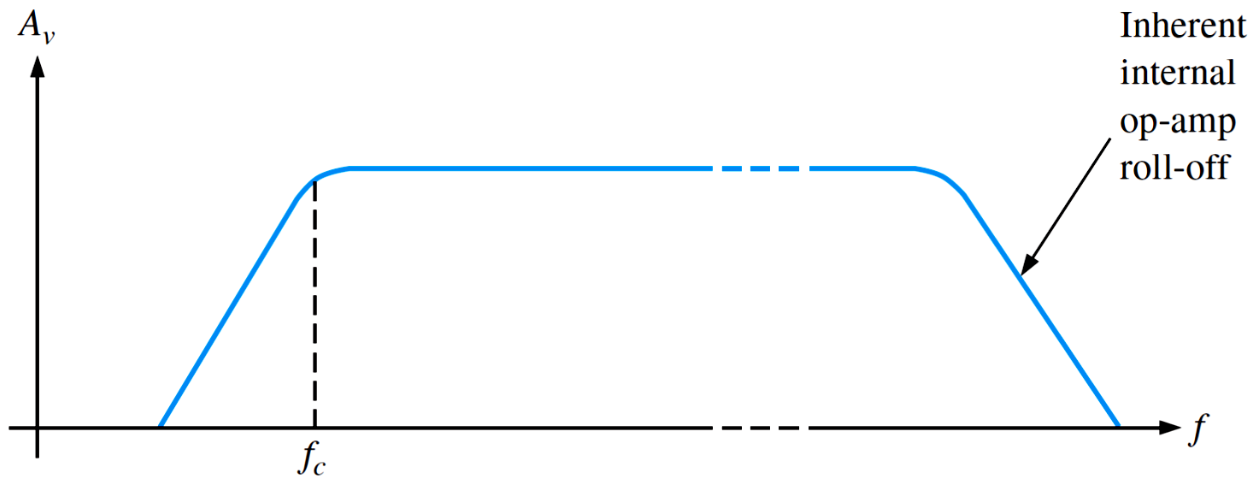
- Ideally, a high-pass filter passes all frequencies above without limit.
- But in practice, all op-amps inherently have internal RC circuits that limit the amplifier’s response at high frequencies.

A Single-Pole High-Pass Filter

Ideal

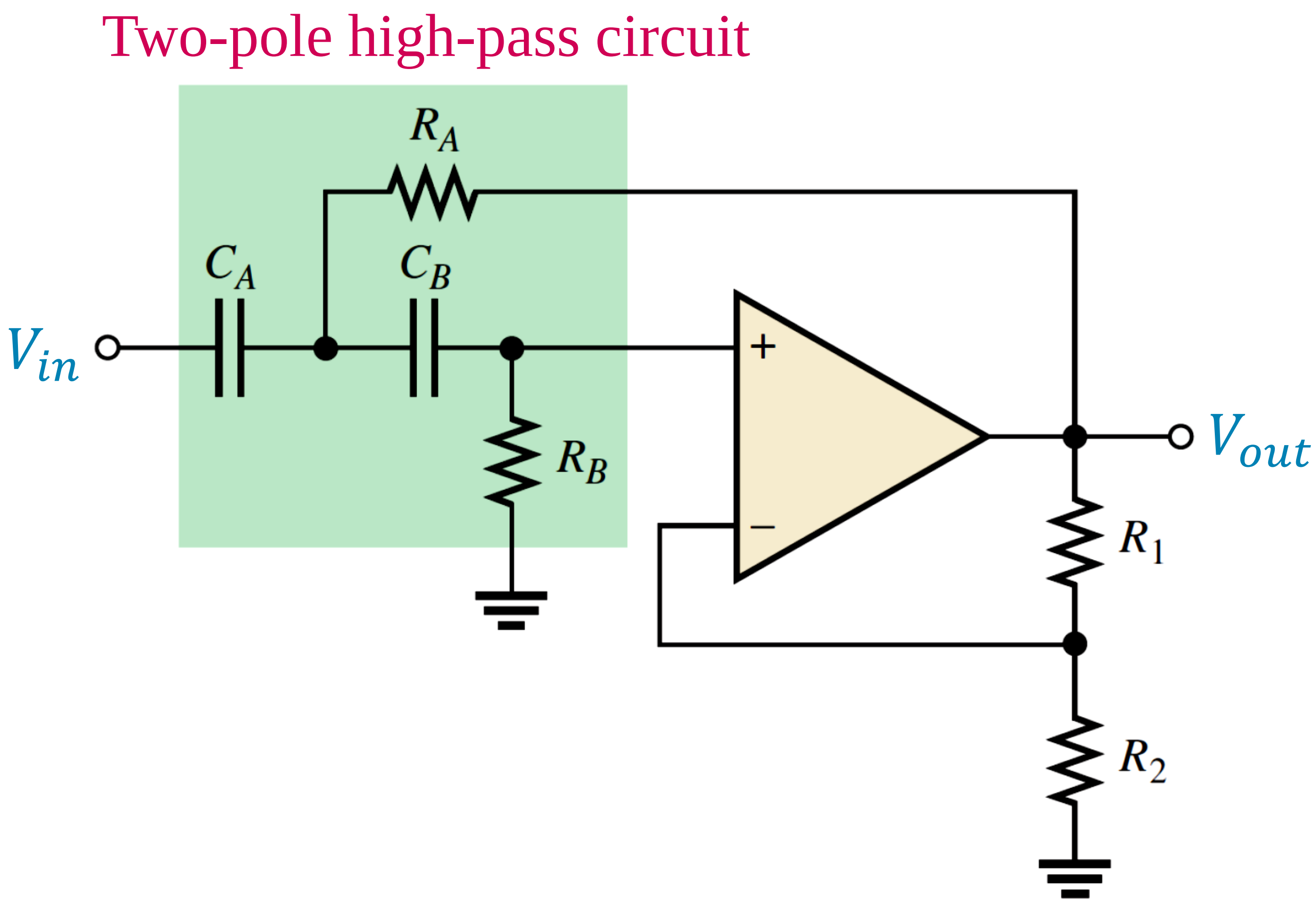


Non-ideal



- In some applications, discrete transistors are used for the gain element to increase the **high-frequency limitation** beyond that realizable with available op-amps.

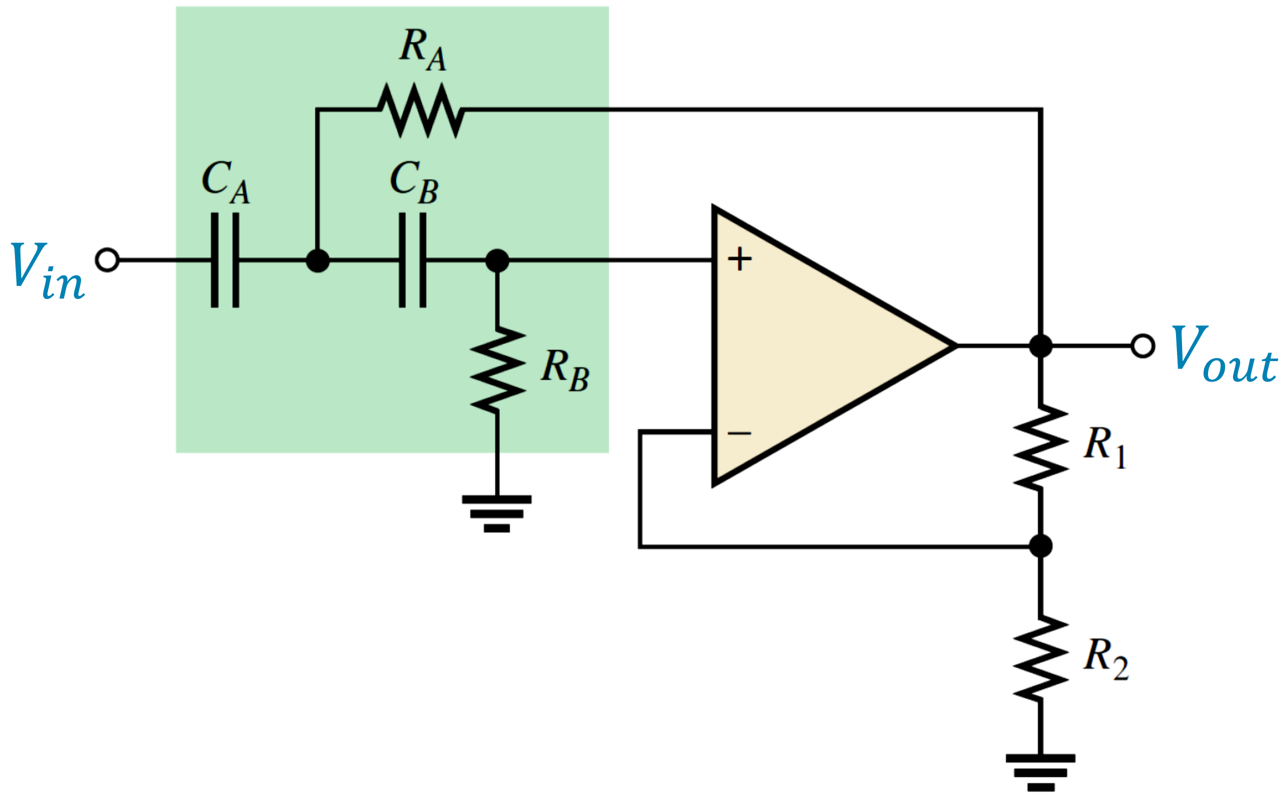
Two-Pole High-Pass Filter



Ex. 04: Two-Pole High-Pass Filter

Choose values for the two-pole high-pass filter in Figure to implement an equal-value second-order Butterworth response with a critical frequency of approximately 10 kHz.

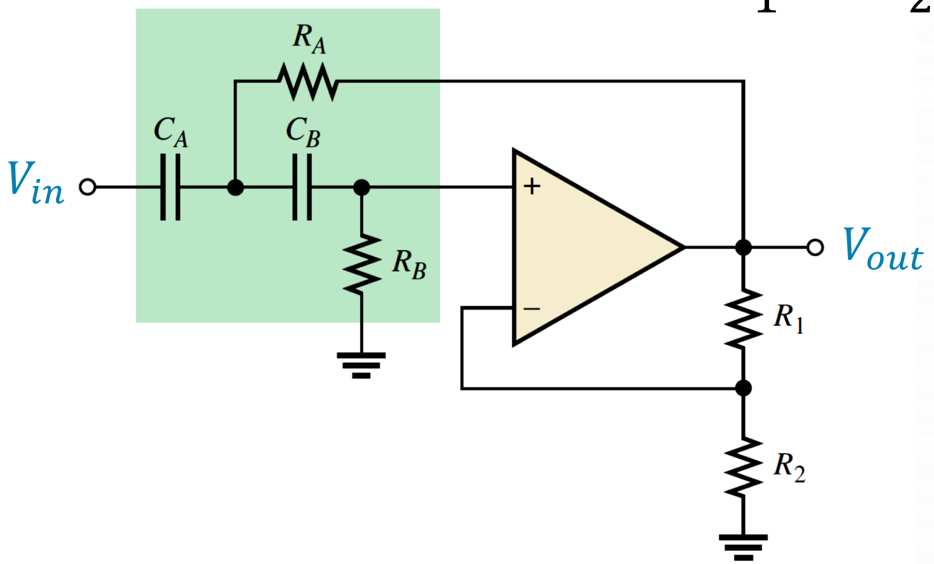
Two-pole high-pass circuit



Ex. 04: Two-Pole High-Pass Filter

Solution: Select the values for R_A and R_B

Two-pole high-pass circuit



R_1 or R_2 can also be the same value as R_A

$$R_A = R_B = R_2 = 3.3\ k\Omega$$

Calculate the capacitance

$$C_A = C_B = \frac{1}{2\pi R f_c} = \frac{1}{2\pi(3.3 \times 10^3)(10)}$$

$$C_A = C_B = \mathbf{0.0048\ \mu F}$$

For a Butterworth filter; $DF = 1.414$ and $R_1/R_2 = 0.586$

$$R_1 = 0.586 \times R_2 = 0.586(3.3 \times 10^3) = \mathbf{1.93\ k\Omega}$$

If you have chosen $R_1 = 3.3k\Omega$

$$R_2 = \frac{R_1}{0.586} = 3.3 \times \frac{10^3}{0.586} = \mathbf{5.63k\Omega}$$

Cascading High-Pass Filters

Sixth-order high-pass filter (-120 dB/decade)