Electronics

Lect. #14

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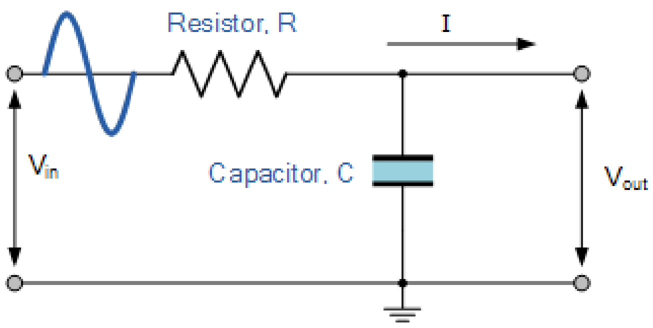
Filters

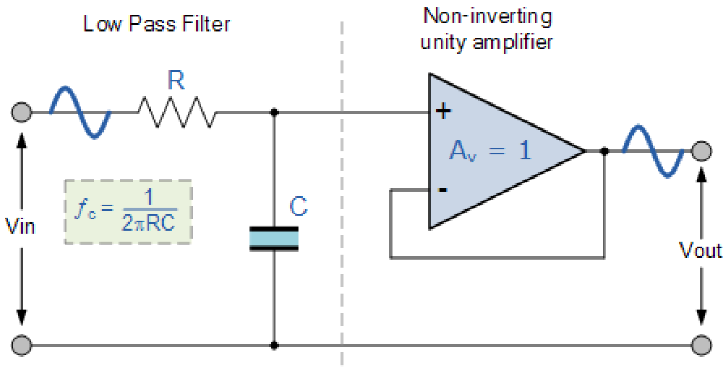
- A filter is an electronic circuit or system that selects specific frequencies of a signal and attenuates (reduces) others. In other words, filters allow certain frequency ranges to pass while blocking unwanted frequencies, shaping the signal according to the required application.
- Filters are used in almost every electronic and communication system. The main applications, can be summarized as follows:

  - Noise Reduction: Removes unwanted high-frequency or low-frequency noise from signals.
  - Communication Systems: Selects desired channels and rejects interference.
  - Power Supplies: Smooths DC output by removing AC ripple.
  - Medical Instruments: Filters ECG/EEG signals to remove noise.
  - Digital Signal Processing: Shapes signals in image, audio, and speech processing.
  - Radio Receivers: Allow only a specific frequency band to pass.

Filters Categories

- **Passive filter:** is an electronic network constructed exclusively from passive components such as resistors, inductors, and capacitors. It operates without any external power source and relies just on the inherent impedance characteristics of its components to shape or control the frequency content of a signal. Passive filters cannot provide amplification; therefore, their output amplitude is always less than or equal to the input.
- **Active filter:** is a frequency-selective electronic circuit that incorporates active components, typically operational amplifiers, along with resistors and capacitors. Active filters require an external power supply and can provide signal amplification, improved selectivity, and greater control over filter parameters.





Low-Pass Filter

- **Low-Pass Filter:** is a circuit that allows low frequencies to pass through and blocks or reduces high frequencies.
- The passband is the range of frequencies that can pass through the filter with almost no loss.
- The critical (cutoff) frequency, *fc* is the point where the output drops to 70.7% (−3 dB) of the original signal. This marks the end of the passband.
  - The −3 dB is a standard engineering criterion used to define the cutoff frequency of a filter and to calculate bandwidth.
  - Because at −3 dB the power becomes exactly half, which is a natural physical reference.
  - It gives a clear and uniform way to define bandwidth and filter limits.

$$P \propto V^2$$

$$\frac{1}{\sqrt{2}} = 0.707$$

$$(0.707)^2 = 0.5$$

$$\text{dB} = 10\log\left(\frac{P_{out}}{P_{in}}\right)$$

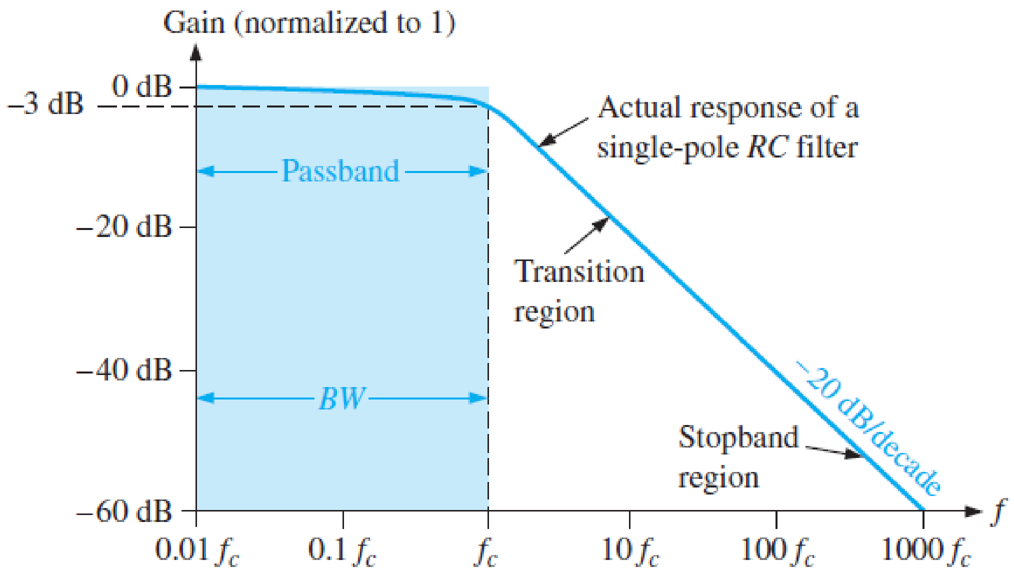
$$\text{dB} = 20\log\left(\frac{V_{out}}{V_{in}}\right)$$

Plot Type	Cutoff Definition
Gain in dB vs frequency	Look for –3 dB
Gain (voltage ratio) vs frequency	Look for 0.707 × max gain
Power gain vs frequency	Look for 0.5 × max power

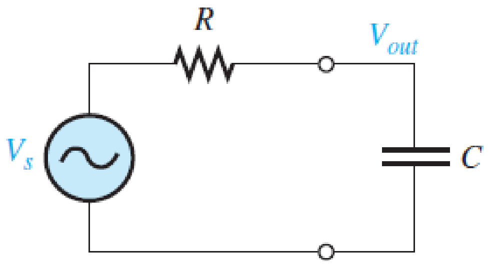
Low-Pass Filter

- After the passband, the signal enters the transition region, where the filter starts reducing the signal.
- Beyond that is the stopband, where the filter strongly blocks the frequencies.
- A low-pass filter lets low frequencies (from DC up to fc) pass and reduces high frequencies.
- In an ideal low-pass filter, everything below fc passes perfectly, and everything above it is completely blocked, this is called a brick-wall response.
- The bandwidth of an ideal low-pass filter is simply the cutoff frequency fc.

Frequency	Increase	Attenuation
fc = 1 kHz	—	−3 dB
10× fc = 10 kHz	1 decade	−20 dB
100× fc = 100 kHz	2 decades	−40 dB
1000× fc = 1 MHz	3 decades	−60 dB



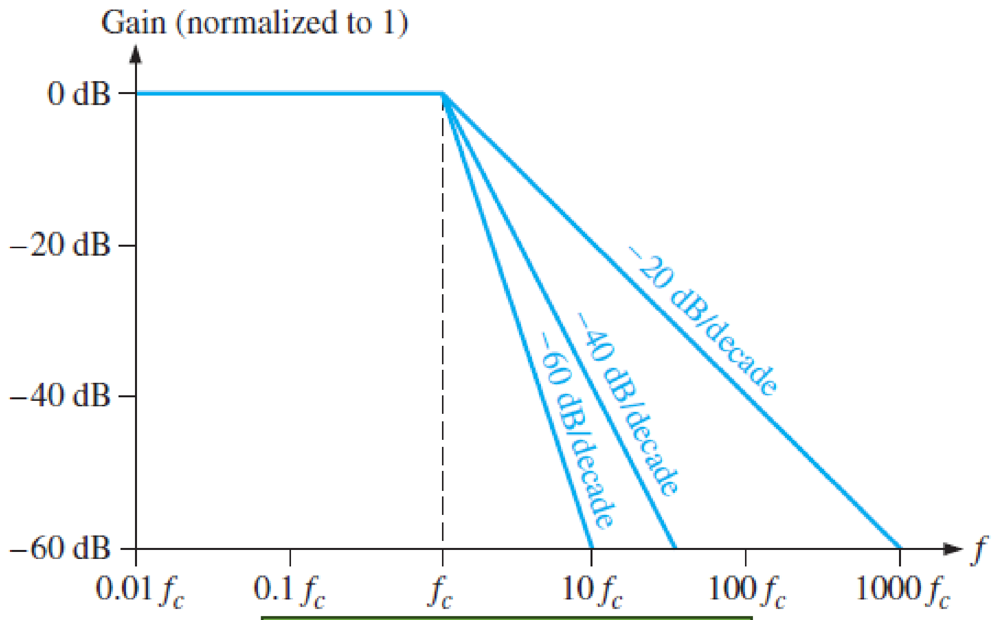
(a) Comparison of an ideal low-pass filter response (blue area) with actual response. Although not shown on log scale, response extends down to $f_c = 0$.



(b) Basic low-pass circuit

Low-Pass Filter

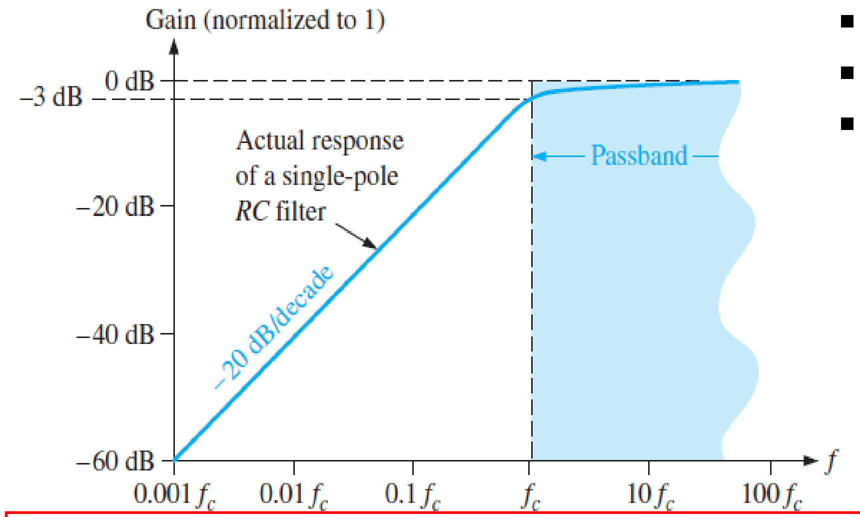
- A decade in electronics means, A 10× (ten-fold) increase or decrease in frequency, for example:
  - From 1 kHz to 10 kHz → one decade
  - From 10 kHz to 100 kHz → one decade
  - From 100 kHz to 1 MHz → one decade
  - From 2 MHz to 20 MHz → one decade
- The −20 dB/decade roll-off means for every 10× increase in frequency, the output of the filter decreases by 20 dB.



Ideal Response

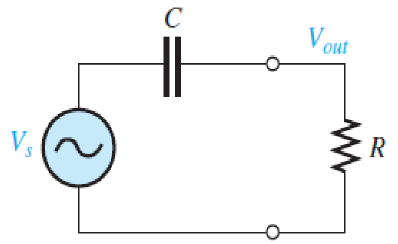
High-Pass Filter

- A high-pass filter blocks or attenuates low frequencies and passes high frequencies.
- At frequencies below fc, the filter provides strong attenuation.
- At frequencies above fc, the filter allows signals to pass.
- The ideal high-pass filter would have a sharp, instantaneous cutoff at fc, but this is not possible in real circuits.
- In reality, the filter response increases gradually, not instantly.

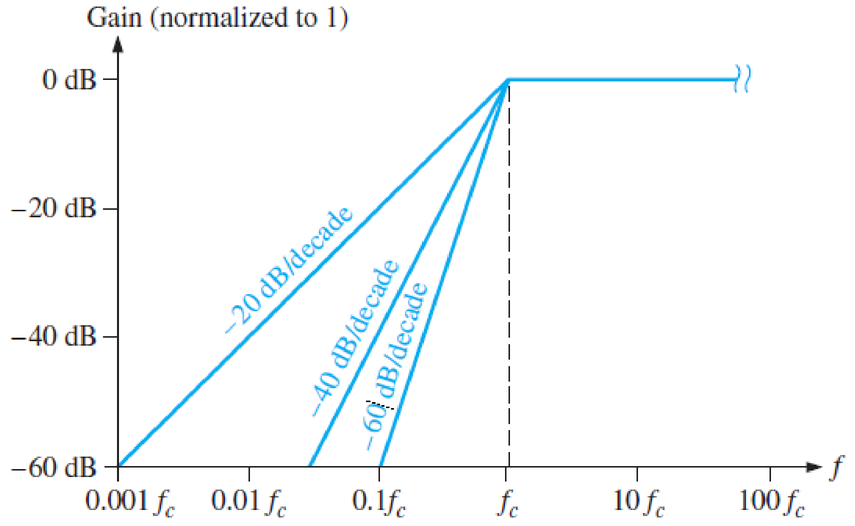


(a) Comparison of an ideal high-pass filter response (blue area) with actual response

- At 0.1 fc, attenuation ≈ −20 dB
- At 0.01 fc, attenuation ≈ −40 dB
- At 0.001 fc, attenuation ≈ −60 dB



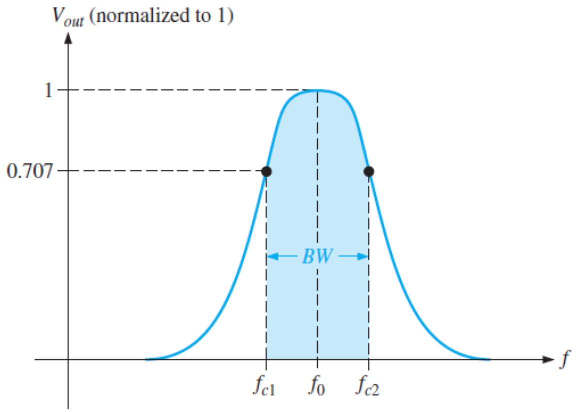
(b) Basic high-pass circuit



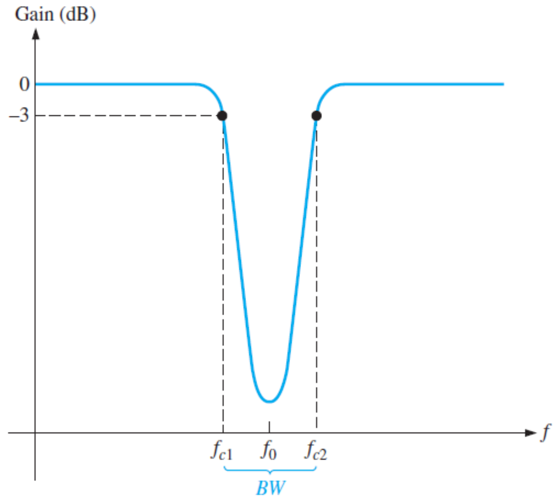
Ideal Response

Band-Pass and Band-Stop Filters

- A band-pass filter is an electronic circuit that passes only the frequencies within a specific range, called the passband, and attenuates all frequencies below and above that range.

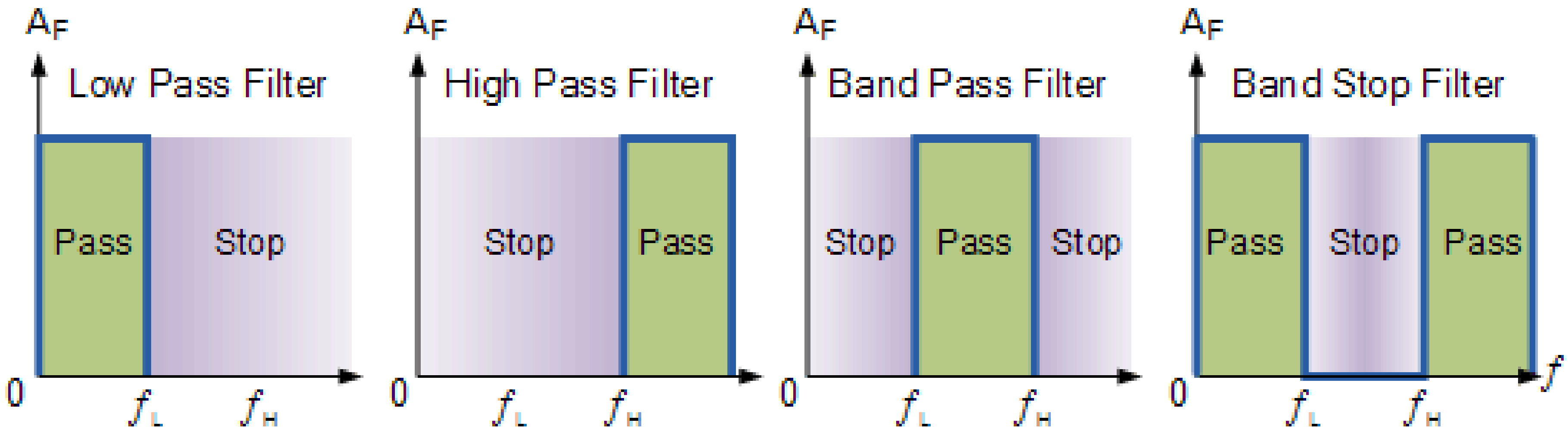


- A band-stop filter (also called a band-reject or notch filter) is an electronic circuit that attenuates or rejects a specific band of frequencies while allowing frequencies below and above that band to pass with little or no attenuation.



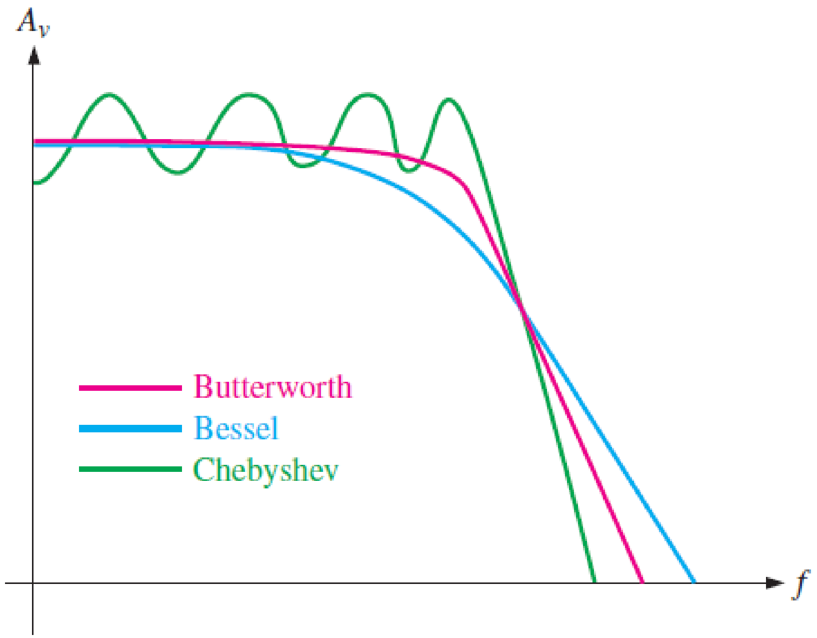
Band-Pass and Band-Stop Filters

Ideal Filters



Filter response characteristics

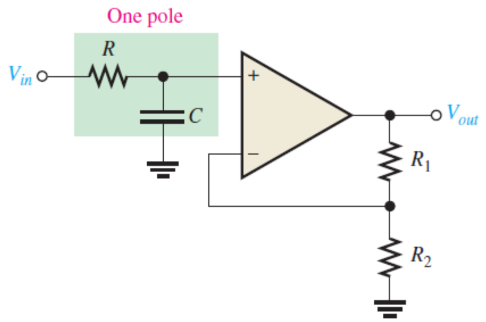
- The Butterworth characteristic provides a maximally flat amplitude response in the passband, meaning there is no ripple and the gain is very smooth up to the cutoff frequency. Its roll-off rate is –20 dB/decade per pole.
- The Bessel characteristic provides the most linear phase response and therefore the best time-domain behavior. It minimizes signal distortion, preserves waveform shape, and avoids overshoot or ringing. Its roll-off is slower than Butterworth or Chebyshev.
- The Chebyshev characteristic achieves a faster roll-off by allowing ripple either in the passband (Type I) or stopband (Type II).

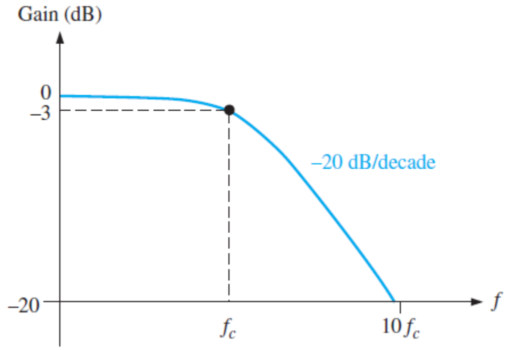


Filter Type	Passband	Roll-Off	Phase Response	Notes
Butterworth	Flat (no ripple)	Medium	Moderate	Most common, smooth response
Bessel	Flat	Slow (shallow)	**Best** (linear phase)	Best for preserving waveform shape
Chebyshev	Ripple	**Fastest**	Worst ***t + Δt***	Sharp cutoff, but wavy response

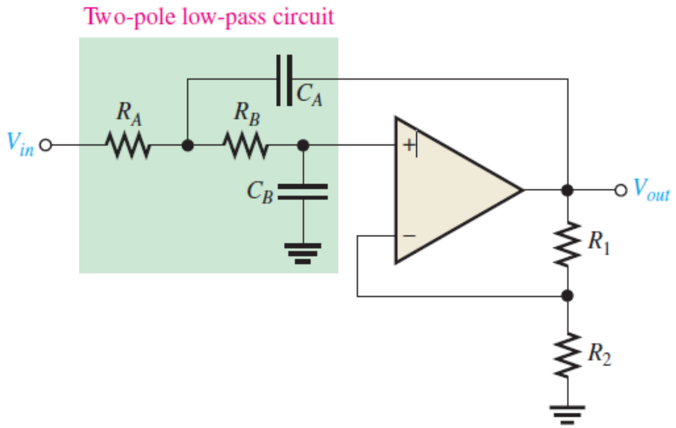
Active Low-Pass Filters

- A single-pole (1st Order) active low-pass filter is a filter that uses a single RC network to establish a low-pass cutoff frequency and an operational amplifier to provide voltage gain in the passband. It has one pole, which produces a roll-off of −20 dB per decade beyond the cutoff frequency. The op-amp is typically configured as a non-inverting amplifier, and its closed-loop gain is determined by the feedback resistors.





- A Sallen-Key low-pass filter is a widely used second-order (two-pole) active filter configuration that uses an operational amplifier and two RC networks to achieve sharper frequency selectivity, it provides a −40 dB/decade roll-off above the cutoff frequency, which is twice as steep as a single-pole filter.



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

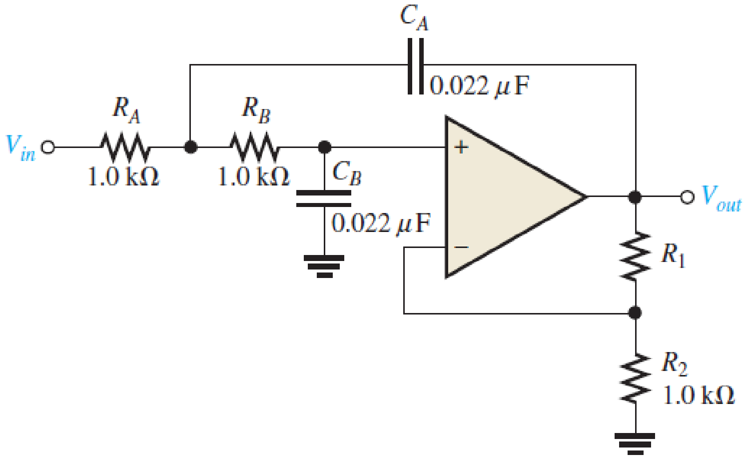
$$f_c = \frac{1}{2\pi RC}$$

For:

$$R_A = R_A = R$$
$$C_A = C_B = C$$

Example #1:

Determine the critical (cutoff) frequency f_c of the Sallen–Key low-pass filter shown in the figure below. Then choose the value of R_1 to obtain an approximate Butterworth response.



❑ For the Sallen–Key low-pass filter in the shown figure:

- $R_A = R_B = R_2 = 2.2\ k\Omega$
- $C_A = C_B = 0.01\quad \mu\text{F}$

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

$$f_c = \frac{1}{2\pi(2.2\times 10^3)(0.01\times 10^{-6})}$$

$$f_c \approx 7.23\text{ kHz}$$

❑ For a Butterworth characteristic with this Sallen–Key configuration, the design condition is:

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

$$R_1 = 586\ \Omega$$


Thanks for listening...
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