EE101: Op Amp circuits (Part 6)

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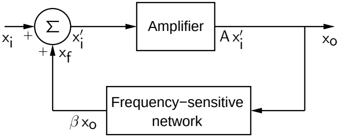
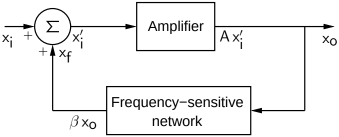


Consider an amplifier with feedback.



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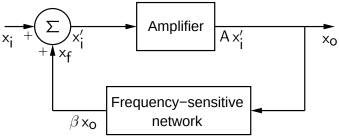

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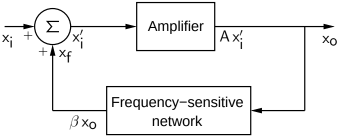

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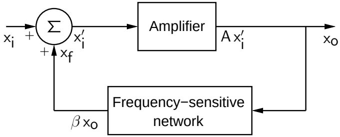
Since A and β will generally vary with ω, we re-write A_f as,

$\rightarrow A_f(j\omega) = \dfrac{A\,(j\omega)}{1 - A\,(j\omega)\,\beta\,(j\omega)}$.



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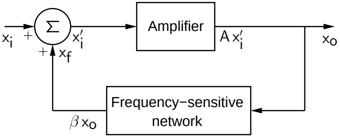

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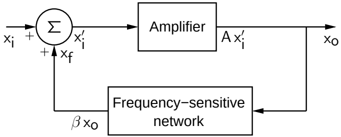
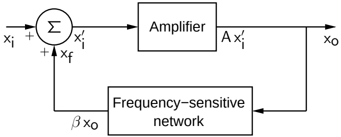
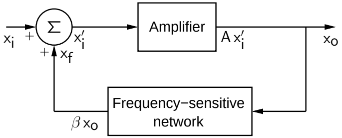
In other words, we can remove x_i and still get a non-zero x_o. This is the basic principle behind sinusoidal oscillators.


Σ
Amplifier
Frequency−sensitive network
x_i
+
x'_i
+
x_f
$A\,x'_i$
x_o
$\beta\,x_o$



* The condition, $A(j\omega)\,\beta(j\omega) = 1$, for a circuit to oscillate spontaneously (i.e., without any input), is known as the Barkhausen criterion.



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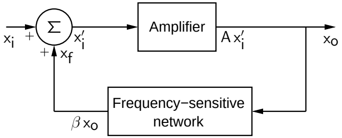

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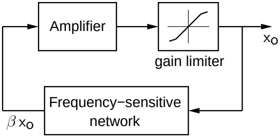
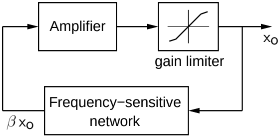
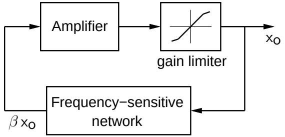
* For the circuit to oscillate at $\omega = \omega_0$, the β network is designed such that the Barkhausen criterion is satisfied only for ω_0, i.e., all components except ω_0 get attenuated to zero.
* The output x_o will therefore have a frequency ω_0 ($\omega_0/2\pi$ in Hz), but what about the amplitude?

Sinusoidal oscillators

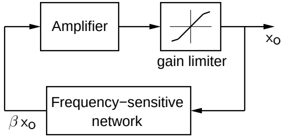




* A gain limiting mechanism is required to limit the amplitude of the oscillations.



* A gain limiting mechanism is required to limit the amplitude of the oscillations.
* Amplifier clipping can provide a gain limiter mechanism. For example, in an Op Amp, the output voltage is limited to $\pm V_{\mathrm{sat}}$, and this serves to limit the gain as the magnitude of the output voltage increases.



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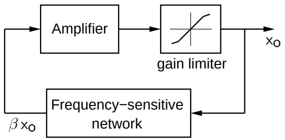
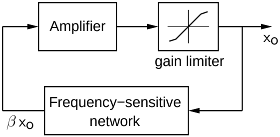
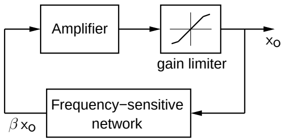
* For a more controlled output with low distortion, diode-resistor networks are used for gain limiting, as we shall see.


Amplifier
gain limiter
xo
Frequency−sensitive network
β xo



* Up to about 100 kHz, an Op Amp based amplifier and a β network of resistors and capacitors can be used.



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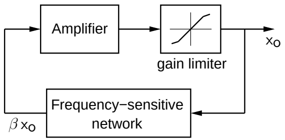

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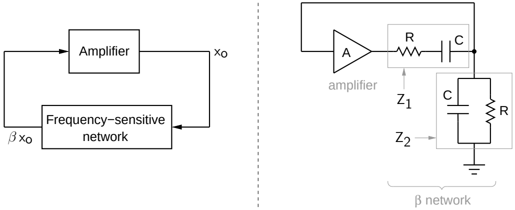
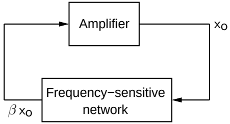
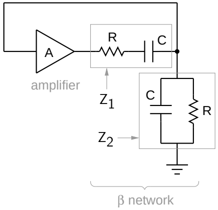
* For high frequencies, transistor amplifiers are used, and LC tuned circuits or piezoelectric crystals are used in the β network.

Wien bridge oscillator

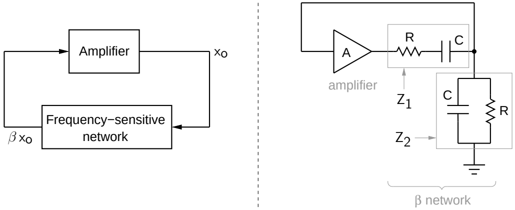






Assuming $R_{\text{in}} \rightarrow \infty$ for the amplifier, we get

$$A(s)\,\beta(s) = A\,\frac{Z_2}{Z_1 + Z_2} = A\,\frac{R \parallel (1/sC)}{R + (1/sC) + R \parallel (1/sC)} = A\,\frac{sRC}{(sRC)^2 + 3sRC + 1}.$$



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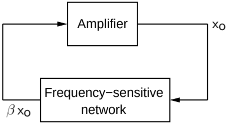
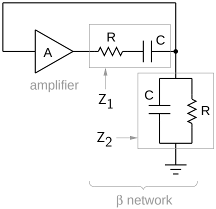
For $A\,\beta = 1$ (and with A equal to a real positive number),

$$\frac{j\omega RC}{-\omega^2(RC)^2+3j\omega RC+1} \text{ must be real and equal to } 1/A.$$





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$$\rightarrow \boxed{\omega = \frac{1}{RC},\ A = 3}$$

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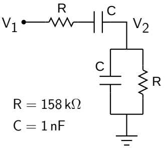

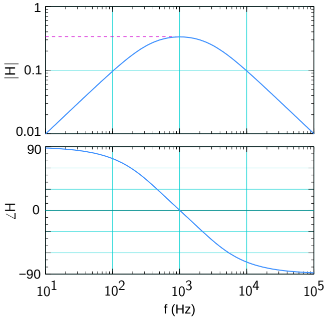

$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{j\omega RC}{-\omega^2 (RC)^2 + 3j\omega RC + 1}.$$

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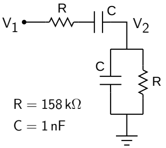

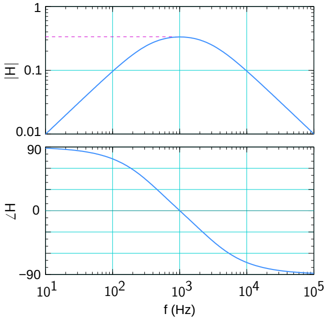

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Note that the condition $\angle H = 0$ is satisfied only at one frequency, $\omega_0 = 1/RC$, i.e., $f_0 = 1\,\text{kHz}$.

At this frequency, $|H| = 0.33$, i.e., $\beta(j\omega) = 1/3$.

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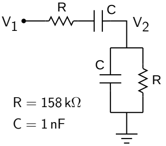

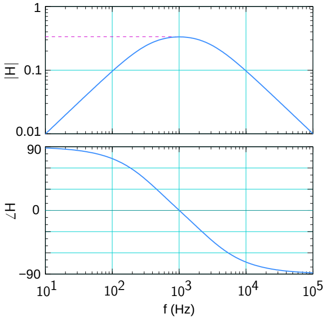

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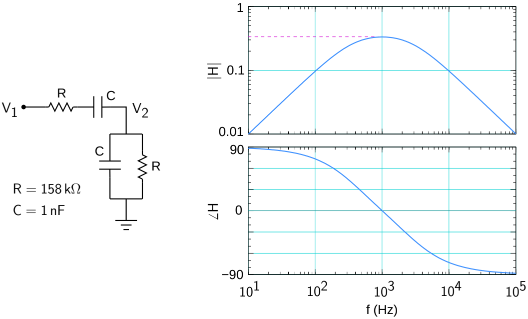

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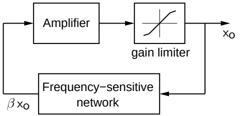
Wien bridge oscillator

Block diagram



Ref.: S. Franco, "Design with Op Amps and analog ICs"

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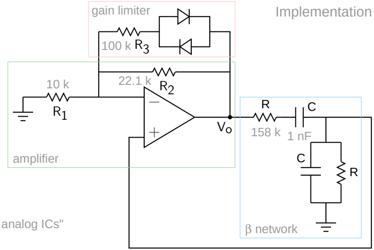
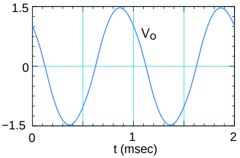
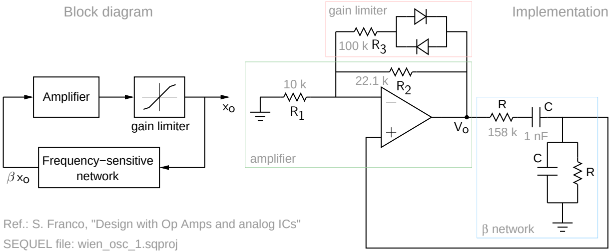
Implementation



Output voltage



Wien bridge oscillator



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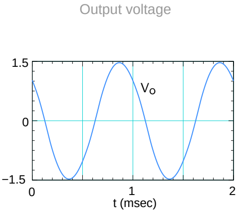
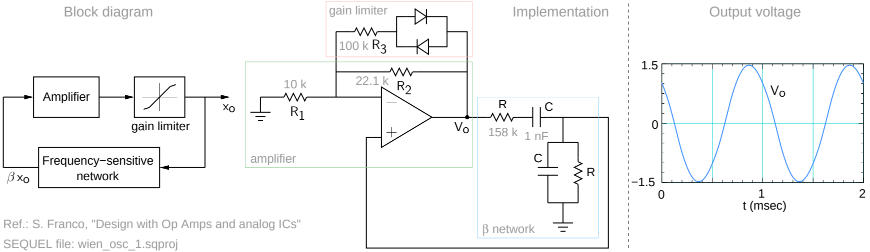


* $\omega_0 = \dfrac{1}{RC} = \dfrac{1}{(158\,\text{k}) \times (1\,\text{nF})} \rightarrow f_0 = 1\,\text{kHz}.$



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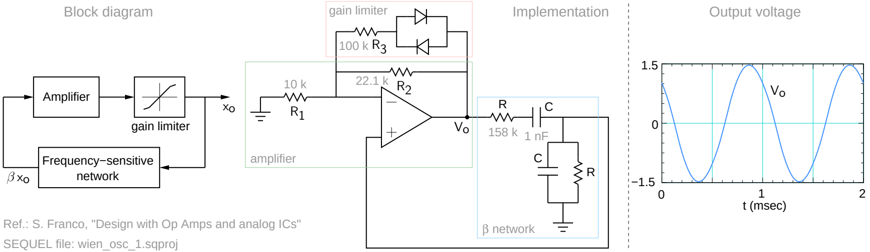
Wien bridge oscillator



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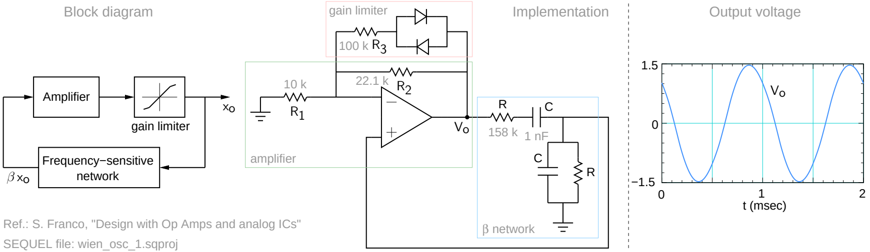
Wien bridge oscillator



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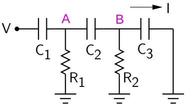
* Note that there was no need to consider loading of the β network by the amplifier because of the large input resistance of the Op Amp. That is why β could be computed independently.

Phase-shift oscillator



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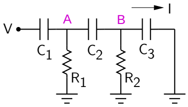
Phase-shift oscillator



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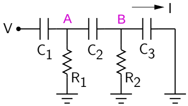
Let $R_1 = R_2 = R = 10\,\text{k}$, $G = 1/R$, and $C_1 = C_2 = C_3 = C = 16\,\text{n}F$.



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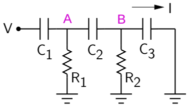
Using nodal analysis,

$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \qquad (1)$$

$$sC(V_B - V_A) + GV_B + sCV_B = 0 \qquad (2)$$

Phase-shift oscillator



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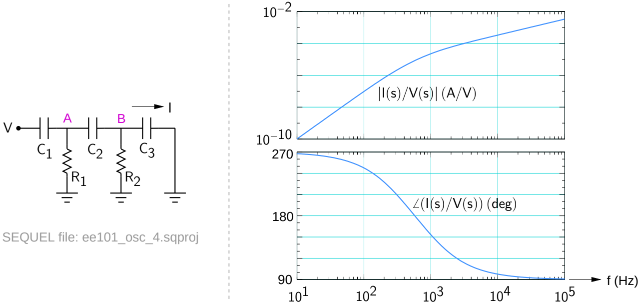
$$sC(V_B - V_A) + GV_B + sCV_B = 0 \qquad (2)$$

Solving (1) and (2),

$$I = \frac{1}{R}\,\frac{(sRC)^3}{3\,(sRC)^2 + 4\,sRC + 1}\,V\,.$$



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Let $R_1 = R_2 = R = 10\,\text{k}$, $G = 1/R$, and $C_1 = C_2 = C_3 = C = 16\,\text{n}F$.

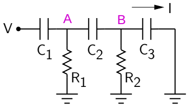
Using nodal analysis,

$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \qquad (1)$$

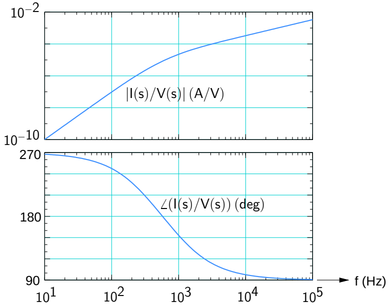
$$sC(V_B - V_A) + GV_B + sCV_B = 0 \qquad (2)$$

Solving (1) and (2),

$$I = \frac{1}{R}\,\frac{(sRC)^3}{3\,(sRC)^2 + 4\,sRC + 1}\,V\,.$$



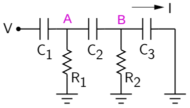
SEQUEL file: ee101_osc_4.sqproj



$(R_1 = R_2 = R = 10\,\text{k, and } C_1 = C_2 = C_3 = C = 16\,\text{n}F.)$

$$\beta(j\omega) = \frac{I(j\omega)}{V(j\omega)} = \frac{1}{R}\,\frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\,j\omega RC + 1}.$$

Phase-shift oscillator



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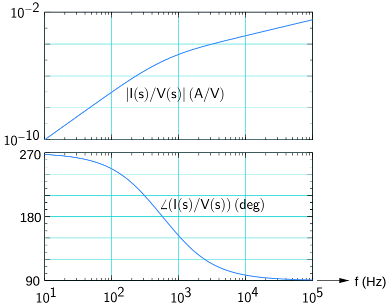

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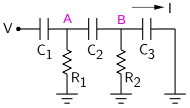
For $\beta(j\omega)$ to be a real number, the denominator must be purely imaginary.

$$\rightarrow 3(\omega RC)^2 + 1 = 0, \text{ i.e., } 3(\omega RC)^2 = 1 \rightarrow \omega \equiv \omega_0 = \frac{1}{\sqrt{3}}\,\frac{1}{RC} \rightarrow f_0 = 574\,\text{Hz}\,.$$

Phase-shift oscillator



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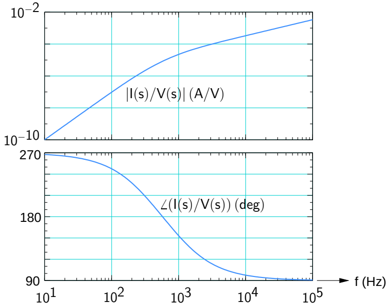

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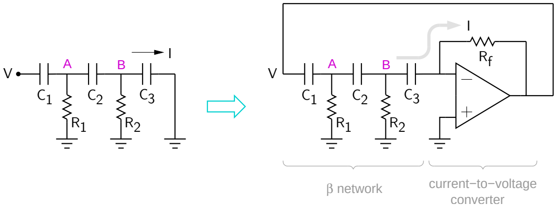
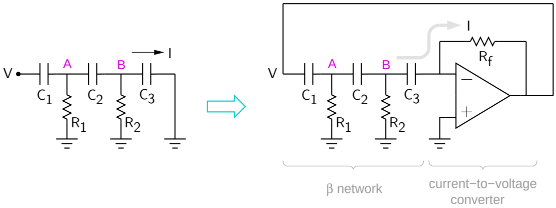
Note that, at $\omega = \omega_0$,

$$\beta(j\omega_0) = \frac{1}{R}\,\frac{(j/\sqrt{3})^3}{4\,j/\sqrt{3}} = -\frac{1}{12\,R} = -8.33 \times 10^{-6}.$$

Phase-shift oscillator



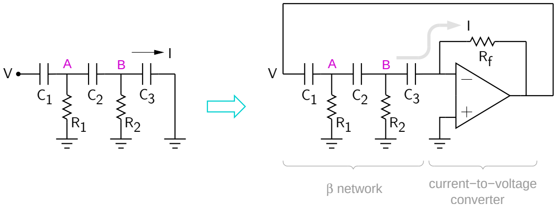
Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the Op Amp.



Note that the functioning of the β network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the Op Amp.

$$V(j\omega) = -R_f I(j\omega) \rightarrow A\beta(j\omega) = -R_f \frac{I(j\omega)}{V(j\omega)} = -\frac{R_f}{R} \frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4\, j\omega RC + 1}.$$

Phase-shift oscillator



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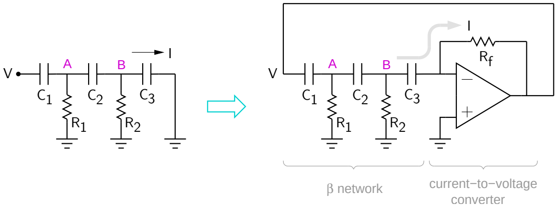

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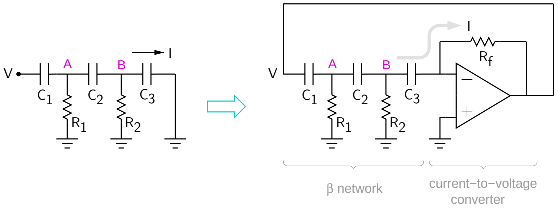
For the circuit to oscillate, we need $A\beta = 1 \rightarrow R_f(1/12\, R) = 1$, i.e., $\boxed{R_f\ = 12\, R}$

Phase-shift oscillator



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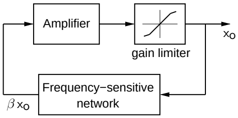
In addition, we employ a gain limiter circuit to complete the oscillator design.

Phase-shift oscillator

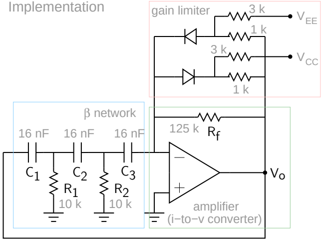
Block diagram



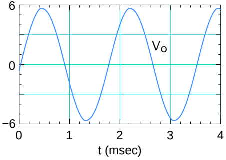
Ref.: Sedra and Smith, "Microelectronic circuits"

SEQUEL file: phase_shift_osc_1.sqproj

Implementation

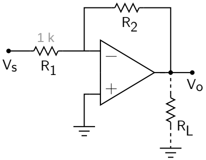


Output voltage



$$\omega_0 = \frac{1}{\sqrt{3}}\,\frac{1}{RC} \rightarrow f_0 = 574\ \text{Hz}, \quad T = 1.74\ \text{ms}\,.$$

Inverting amplifier, revisited



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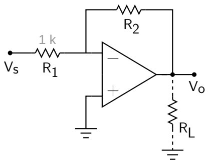
Inverting amplifier, revisited



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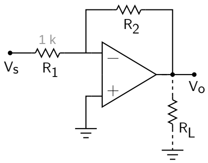
* As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.

Inverting amplifier, revisited



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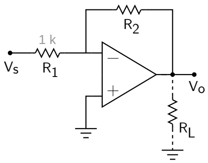

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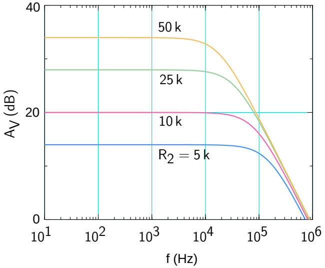

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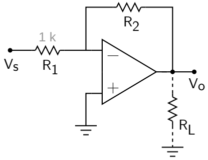

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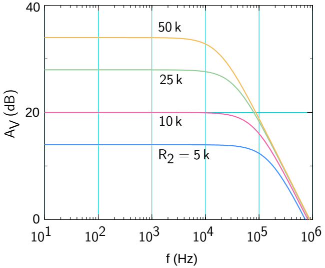

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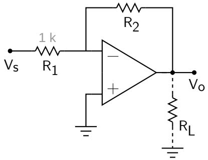

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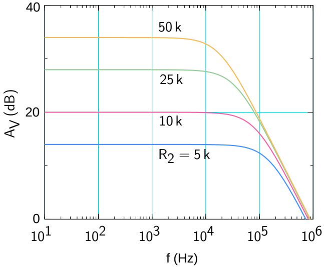
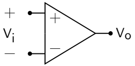
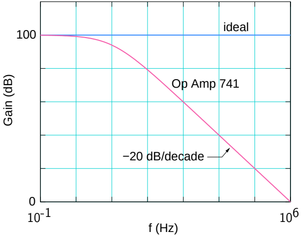


* As seen earlier, $A_V = -R_2/R_1 \rightarrow |A_V|$ should be independent of the signal frequency.
* However, a measurement with a real Op Amp will show that $|A_V|$ starts reducing at higher frequencies.
* If $|A_V|$ is increased, the gain "roll-off" starts at lower frequencies.
* This behaviour has to do with the frequency response of the Op Amp which we have not considered so far.

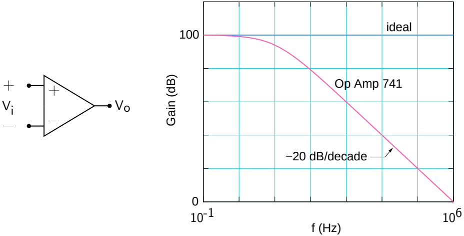
Frequency response of Op Amp 741





The gain of the 741 Op Amp starts falling at rather low frequencies, with $f_c \simeq 10\,\text{Hz}$!

Frequency response of Op Amp 741



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The 741 Op Amp (and many others) are *designed* with this feature to ensure that, in typical amplifier applications, the overall circuit is stable (and not oscillatory).

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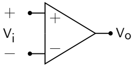

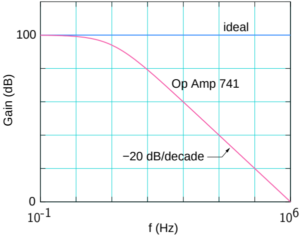

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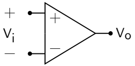
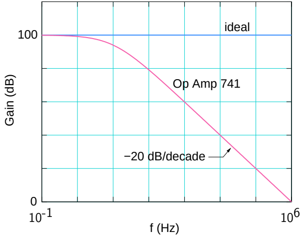
In other words, the Op Amp has been *internally compensated* for stability.





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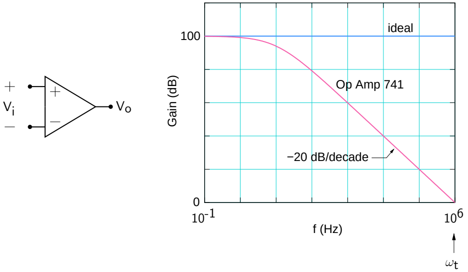
The gain of the 741 Op Amp can be represented by,

$$A(s) = \frac{A_0}{1 + s/\omega_c},$$

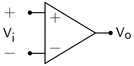
with $A_0 \approx 10^5$ (i.e., 100 dB), $\omega_c \approx 2\pi \times 10\,\text{rad/s}$.

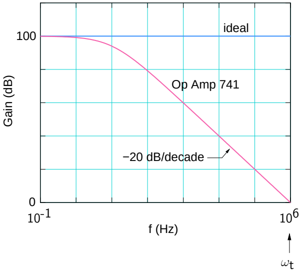
Frequency response of Op Amp 741



$$A(j\omega) = \frac{A_0}{1 + j\omega/\omega_c}.$$

For $\omega \gg \omega_c$, we have $A(j\omega) \approx \dfrac{A_0}{j\omega/\omega_c}$.





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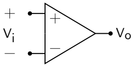
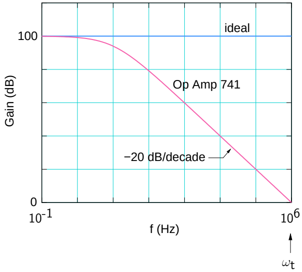
Frequency response of Op Amp 741





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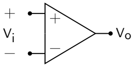
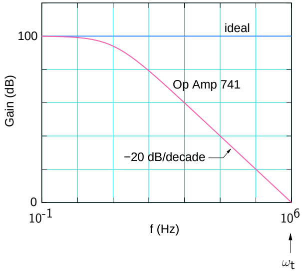
$|A(j\omega)|$ becomes 1 when $A_0 = \omega/\omega_c$, i.e., $\omega = A_0\omega_c$.

This frequency, $\omega_t = A_0\omega_c$, is called the unity-gain frequency.

For the 741 Op Amp, $f_t = A_0 f_c \approx 10^5 \times 10 = 10^6$ Hz.

Frequency response of Op Amp 741





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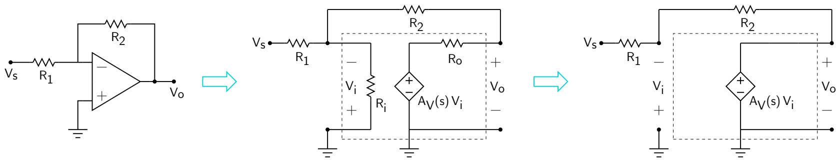
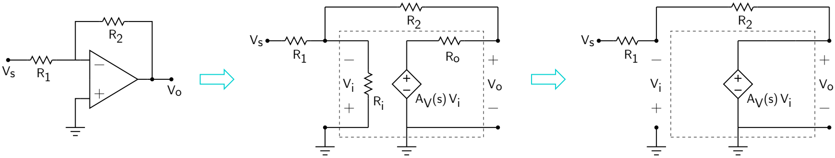
Let us see how the frequency response of the 741 Op Amp affects the gain of an inverting amplifier.

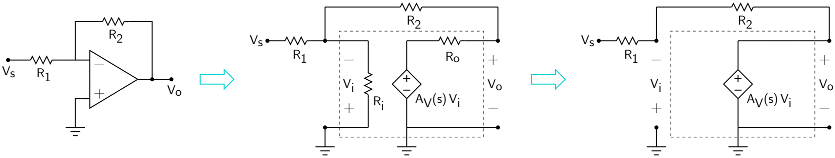
Inverting amplifier, revisited





Assuming R_i to be large and R_o to be small, we get

$$-V_i(s) = V_s(s)\,\frac{R_2}{R_1 + R_2} + V_o(s)\,\frac{R_1}{R_1 + R_2}.$$



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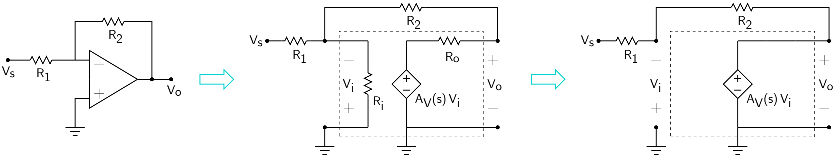
Using $V_o(s) = A_V(s)\,V_i(s)$,

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{\left[1+\left(\dfrac{R_1+R_2}{R_1}\right)\dfrac{1}{A_0}\right]+\left(\dfrac{R_1+R_2}{R_1A_0}\right)\dfrac{s}{\omega_c}}$$

Inverting amplifier, revisited



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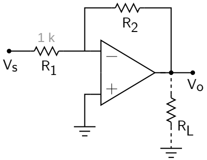
Using $V_o(s) = A_V(s)\,V_i(s)$,

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{\left[1+\left(\dfrac{R_1+R_2}{R_1}\right)\dfrac{1}{A_0}\right]+\left(\dfrac{R_1+R_2}{R_1A_0}\right)\dfrac{s}{\omega_c}}$$

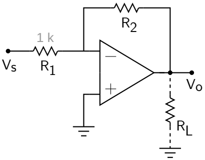
$$\approx -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'}, \quad \text{with } \omega_c' = \frac{\omega_c A_0}{1+R_2/R_1} = \frac{\omega_t}{1+R_2/R_1}.$$

Inverting amplifier, revisited



SEQUEL file: inv_amp_ac.sqproj

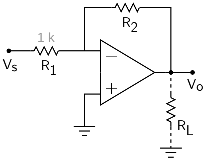
Inverting amplifier, revisited



SEQUEL file: inv_amp_ac.sqproj

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited

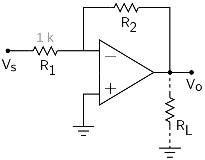


SEQUEL file: inv_amp_ac.sqproj

R_2	gain (dB)	f_c' (kHz)
5 k	14	167

$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\mathrm{MHz}).$$

Inverting amplifier, revisited



SEQUEL file: inv_amp_ac.sqproj

R_2	gain (dB)	f_c' (kHz)
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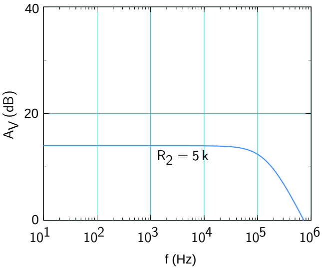
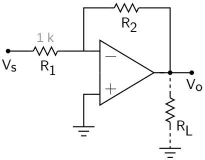


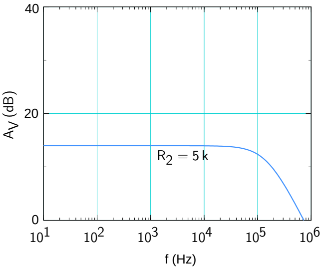
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited



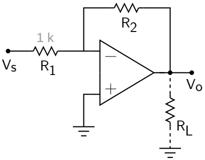
SEQUEL file: inv_amp_ac.sqproj

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91



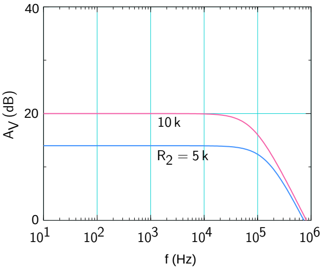
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$

Inverting amplifier, revisited



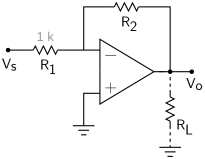
SEQUEL file: inv_amp_ac.sqproj

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91



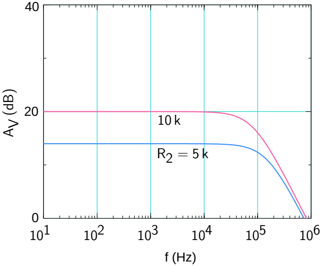
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\mathrm{MHz}).$$

Inverting amplifier, revisited



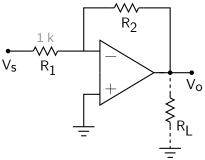
SEQUEL file: inv_amp_ac.sqproj

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38



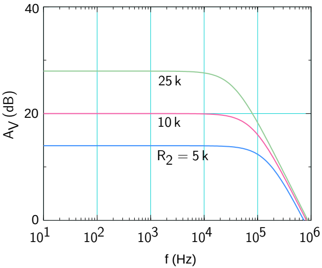
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\mathrm{MHz}).$$

Inverting amplifier, revisited

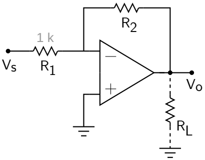


SEQUEL file: inv_amp_ac.sqproj

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38

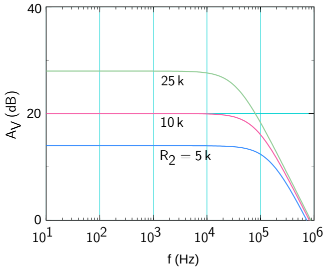


$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\mathrm{MHz}).$$

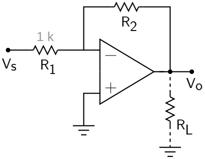


SEQUEL file: inv_amp_ac.sqproj

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38
50 k	34	19.6

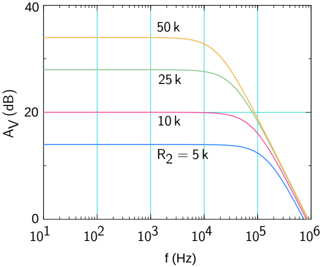


$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\mathrm{MHz}).$$



SEQUEL file: inv_amp_ac.sqproj

R_2	gain (dB)	f_c' (kHz)
5 k	14	167
10 k	20	91
25 k	28	38
50 k	34	19.6



$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1}\,\frac{1}{1+s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1+R_2/R_1}, \quad (f_t = 1\,\text{MHz}).$$