

## EE101: Op Amp circuits (Part 6)

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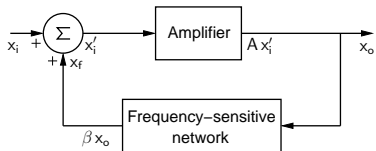
**M. B. Patil**

[mbpatil@ee.iitb.ac.in](mailto:mbpatil@ee.iitb.ac.in)

[www.ee.iitb.ac.in/~sequel](http://www.ee.iitb.ac.in/~sequel)

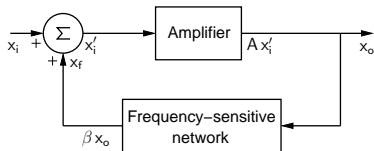
Department of Electrical Engineering  
Indian Institute of Technology Bombay

# Sinusoidal oscillators



Consider an amplifier with feedback.

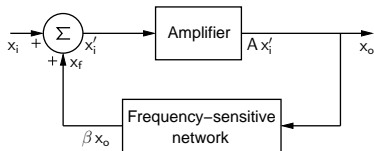
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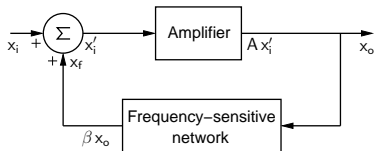


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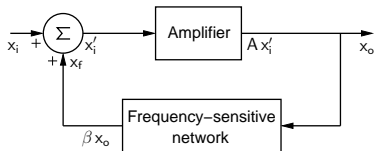
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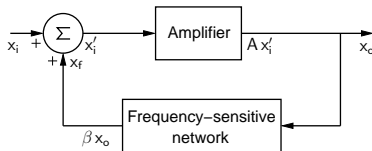
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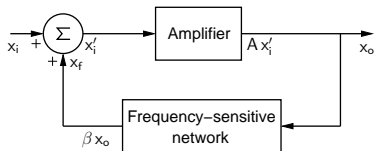
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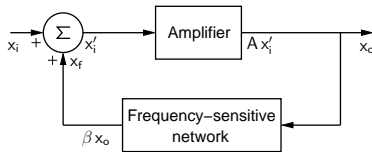
In other words, we can remove  $x_i$  and still get a non-zero  $x_o$ . This is the basic principle behind sinusoidal oscillators.

# Sinusoidal oscillators



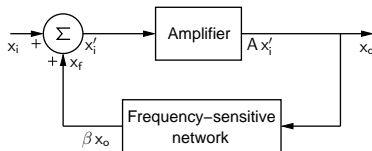


## Sinusoidal oscillators



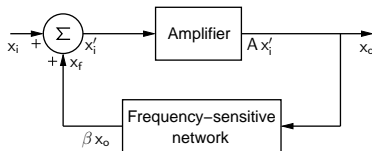
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# Sinusoidal oscillators



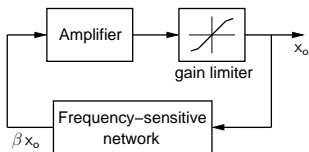
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# Sinusoidal oscillators

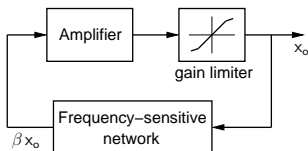


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- \* The output  $x_o$  will therefore have a frequency  $\omega_0$  ( $\omega_0/2\pi$  in Hz), but what about the amplitude?

# Sinusoidal oscillators

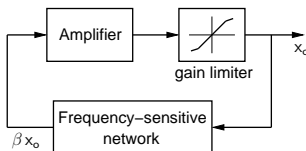


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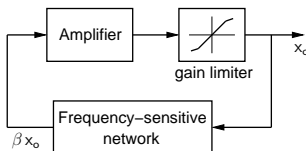
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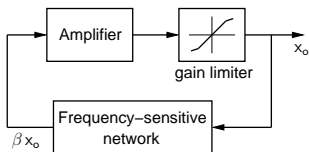
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- \* Amplifier clipping can provide a gain limiter mechanism. For example, in an Op Amp, the output voltage is limited to  $\pm V_{\text{sat}}$ , and this serves to limit the gain as the magnitude of the output voltage increases.

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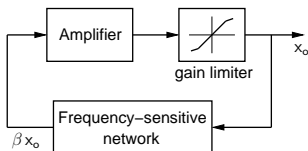
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- \* For a more controlled output with low distortion, diode-resistor networks are used for gain limiting, as we shall see.

# Sinusoidal oscillators



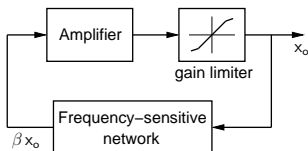


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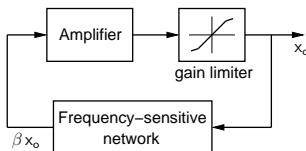
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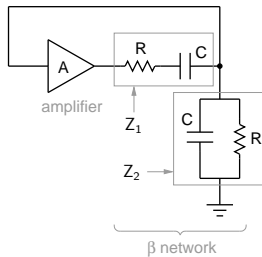
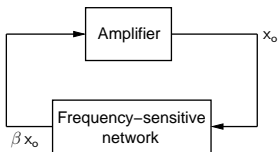
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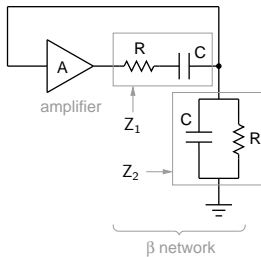
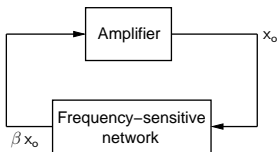


- \* Up to about 100 kHz, an Op Amp based amplifier and a  $\beta$  network of resistors and capacitors can be used.
- \* At higher frequencies, an Op Amp based amplifier is not suitable because of frequency response and slew rate limitations of Op Amps.
- \* For high frequencies, transistor amplifiers are used, and  $LC$  tuned circuits or piezoelectric crystals are used in the  $\beta$  network.

# Wien bridge oscillator



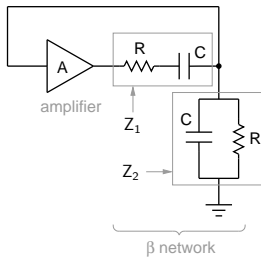
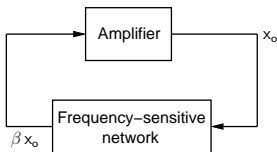
## Wien bridge oscillator



Assuming  $R_{in} \rightarrow \infty$  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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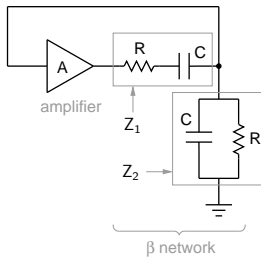
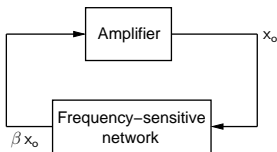
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For  $A\beta = 1$  (and with  $A$  equal to a real positive number),

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

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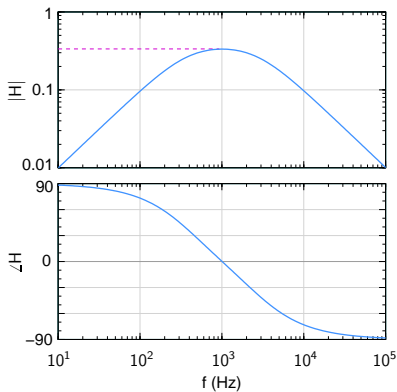
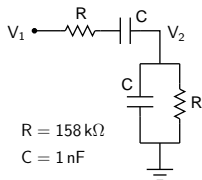
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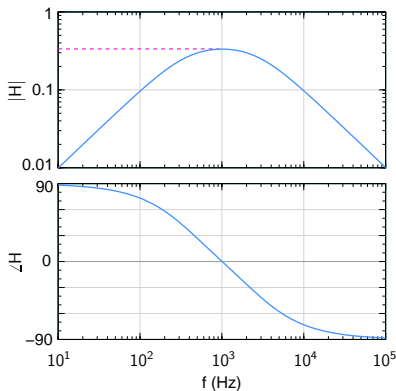
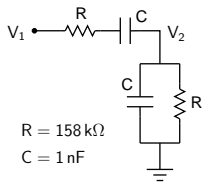
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$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{j\omega RC}{-\omega^2(RC)^2 + 3j\omega RC + 1}$$



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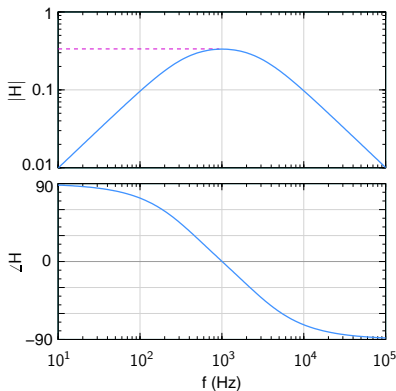
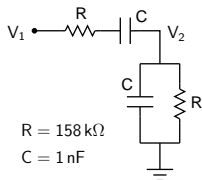


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At this frequency,  $|H| = 0.33$ , i.e.,  $\beta(j\omega) = 1/3$ .

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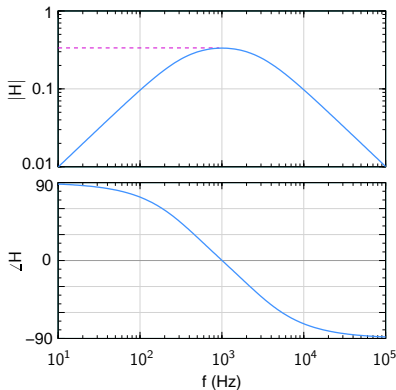
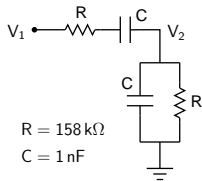
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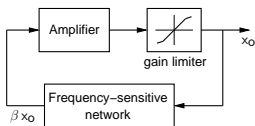
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SEQUEL file: ee101\_osc.1.sqproj

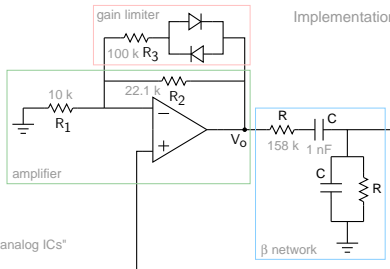
# Wien bridge oscillator

Block diagram

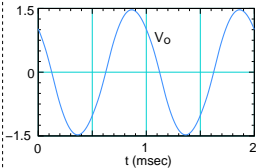


Ref.: S. Franco, "Design with Op Amps and analog ICs"  
SEQUEL file: wien\_osc\_1.sqproj

Implementation

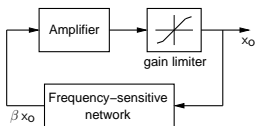


Output voltage



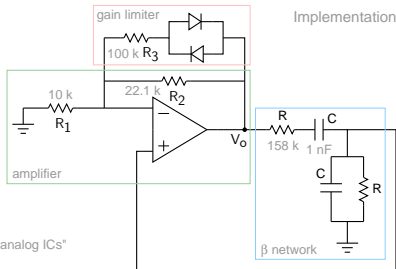
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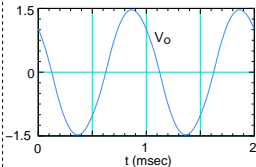
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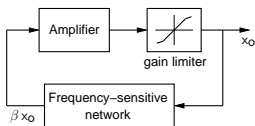
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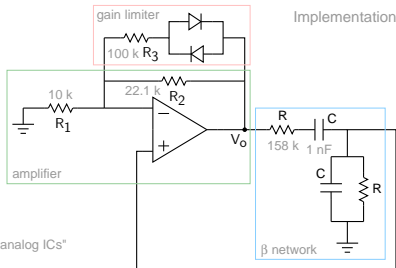
$$* \omega_0 = \frac{1}{RC} = \frac{1}{(158 \text{ k}) \times (1 \text{ nF})} \rightarrow f_0 = 1 \text{ kHz.}$$

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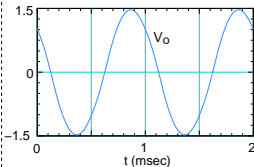


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Implementation

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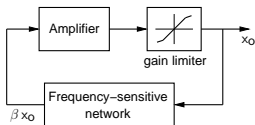


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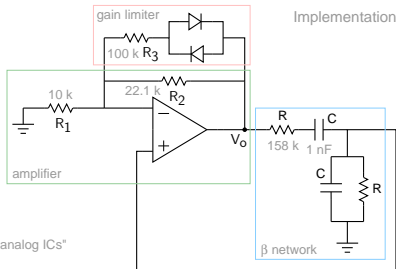
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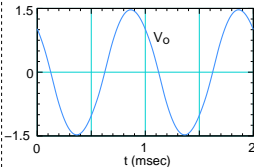
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Implementation

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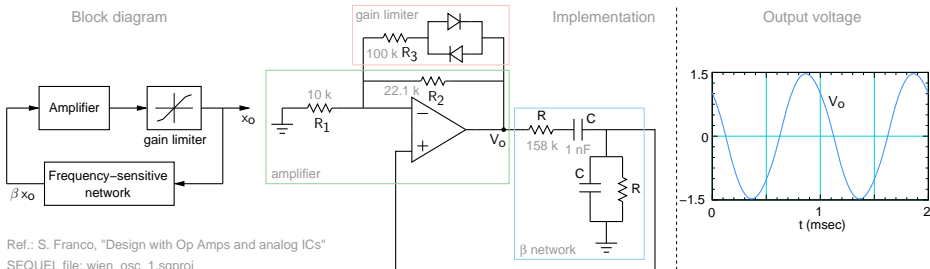


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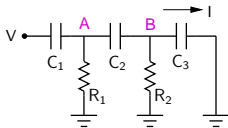


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- \* For gain limiting, diodes have been used. With one of the two diodes conducting,  $R_2 \rightarrow R_2 \parallel R_3$ , and the gain reduces.
- \* Note that there was no need to consider loading of the  $\beta$  network by the amplifier because of the large input resistance of the Op Amp. That is why  $\beta$  could be computed independently.

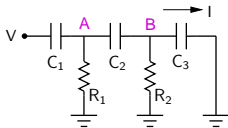


## Phase-shift oscillator



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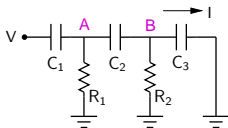
## Phase-shift oscillator



SEQUEL file: ee101\_osc\_4.sqproj

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

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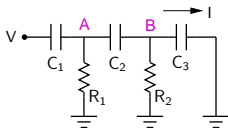
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Using nodal analysis,

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

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

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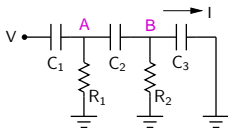
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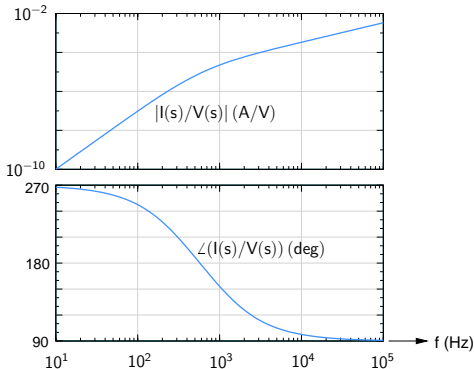
Solving (1) and (2),

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

# Phase-shift oscillator



SEQUEL file: ee101\_osc\_4.sqproj



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

Using nodal analysis,

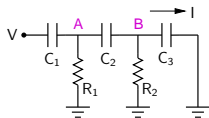
$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \quad (1)$$

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

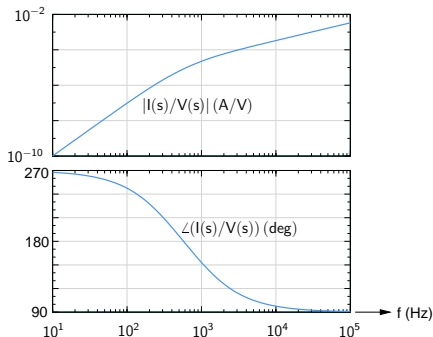
Solving (1) and (2),

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

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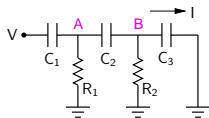
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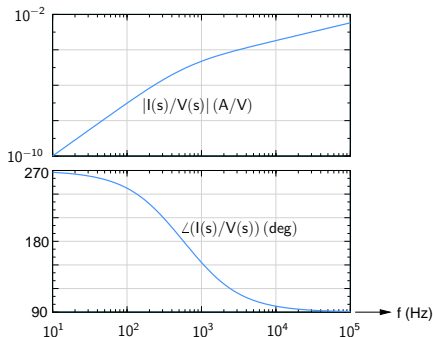
( $R_1 = R_2 = R = 10\text{ k}$ , and  $C_1 = C_2 = C_3 = C = 16\text{ nF}$ .)

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

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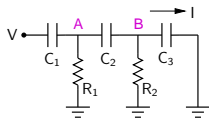
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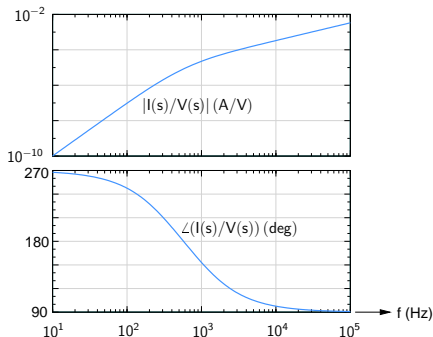
For  $\beta(j\omega)$  to be a real number, the denominator must be purely imaginary.

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

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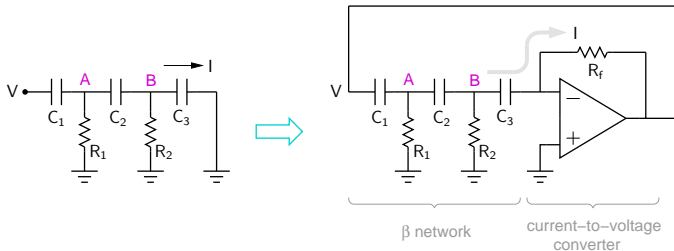
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Note that, at  $\omega = \omega_0$ ,

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

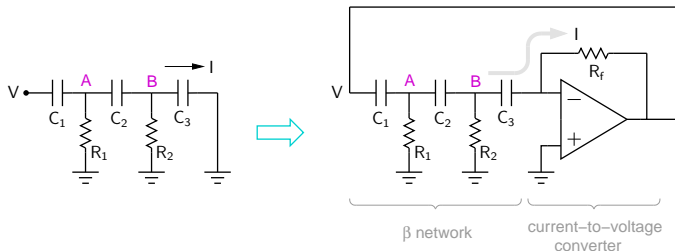


## Phase-shift oscillator



Note that the functioning of the  $\beta$  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.

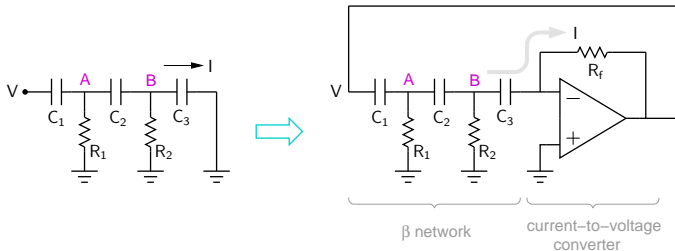
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$$V(j\omega) = -R_f I(j\omega) \rightarrow A\beta(j\omega) = -R_f \frac{I(j\omega)}{V(j\omega)} = -\frac{R_f}{R} \frac{(j\omega RC)^3}{3(j\omega RC)^2 + 4j\omega RC + 1}.$$

## Phase-shift oscillator

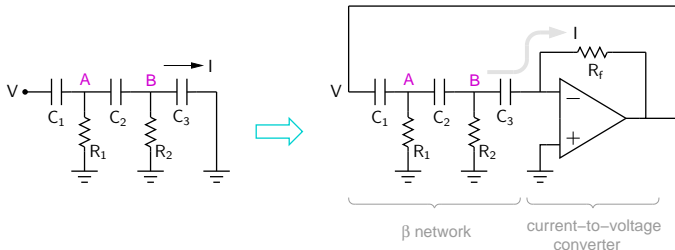


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As seen before, at  $\rightarrow \omega = \omega_0 = \frac{1}{\sqrt{3}} \frac{1}{RC}$ , we have  $\frac{I(j\omega)}{V(j\omega)} = -\frac{1}{12R}.$

## Phase-shift oscillator



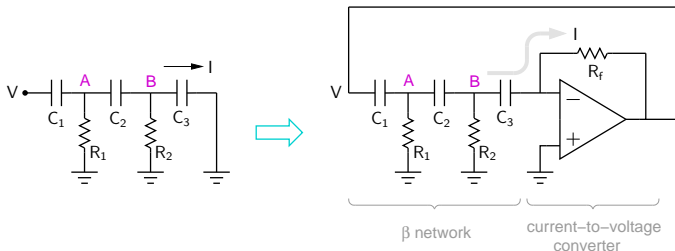
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For the circuit to oscillate, we need  $A\beta = 1 \rightarrow R_f(1/12R) = 1$ , i.e.,  $R_f = 12R$

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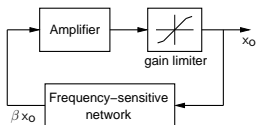
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In addition, we employ a gain limiter circuit to complete the oscillator design.

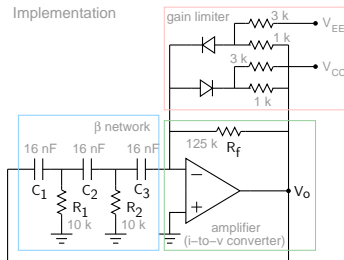
# Phase-shift oscillator

Block diagram

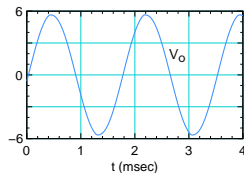


Ref.: Sedra and Smith, "Microelectronic circuits"  
 SEQUEL file: phase\_shift\_osc\_1.sqproj

Implementation

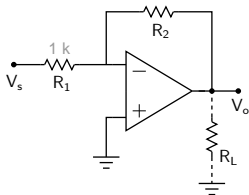


Output voltage



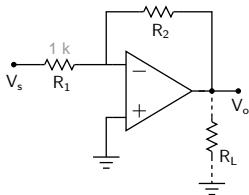
$$\omega_0 = \frac{1}{\sqrt{3}} \frac{1}{RC} \rightarrow f_0 = 574 \text{ Hz}, T = 1.74 \text{ ms}.$$

## Inverting amplifier, revisited



SEQUEL file: inv\_amp\_ac.sqproj

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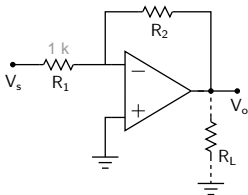


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- \* As seen earlier,  $A_V = -R_2/R_1 \rightarrow |A_V|$  should be independent of the signal frequency.



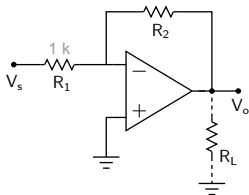
## Inverting amplifier, revisited



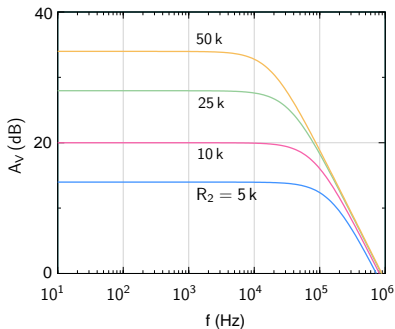
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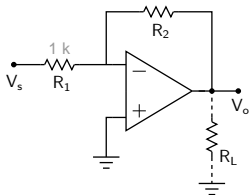


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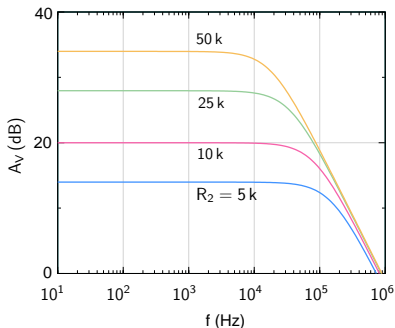


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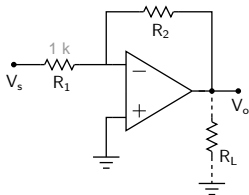


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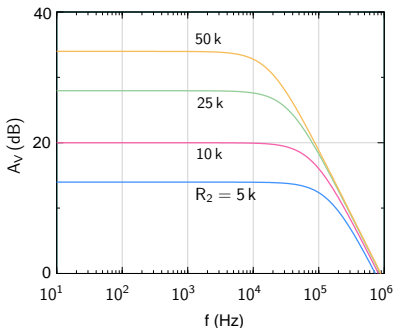


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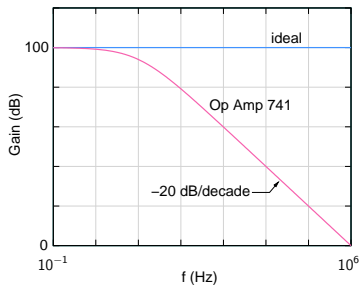
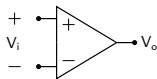


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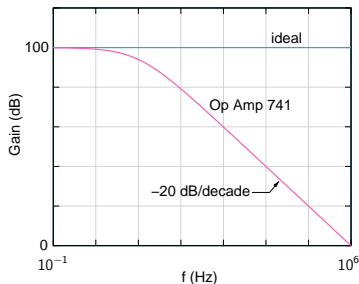
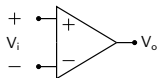
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- \* If  $|A_V|$  is increased, the gain “roll-off” starts at lower frequencies.
- \* This behaviour has to do with the frequency response of the Op Amp which we have not considered so far.

## Frequency response of Op Amp 741



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

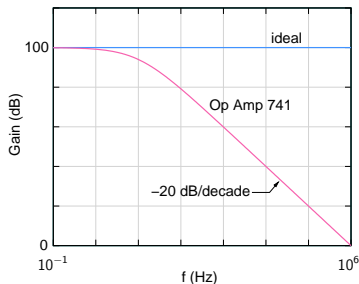
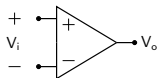
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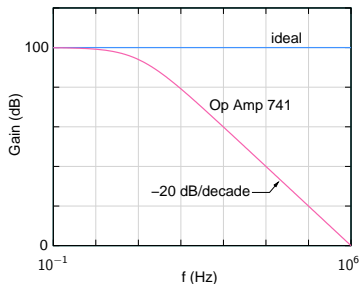
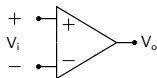


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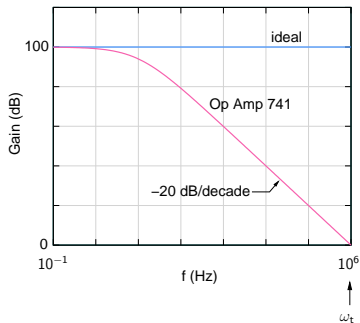
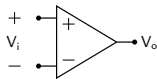
The gain of the 741 Op Amp can be represented by,

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

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



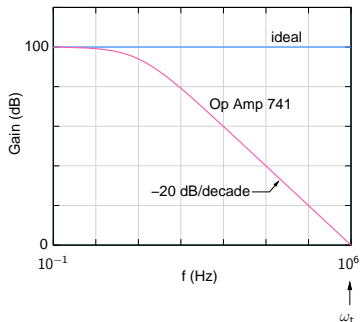
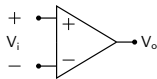
## Frequency response of Op Amp 741



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

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

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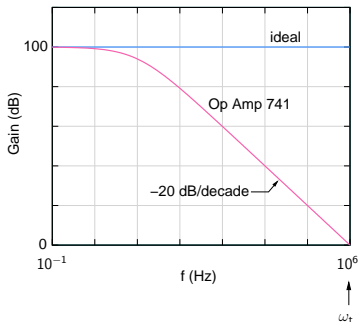
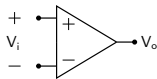


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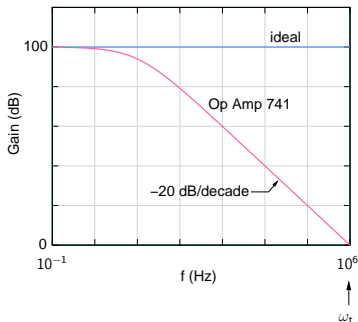
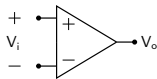
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$|A(j\omega)|$  becomes 1 when  $A_0 = \omega/\omega_c$ , i.e.,  $\omega = A_0\omega_c$ .

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

For the 741 Op Amp,  $f_t = A_0f_c \approx 10^5 \times 10 = 10^6$  Hz.

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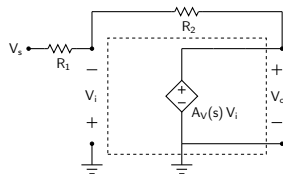
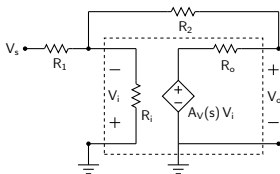
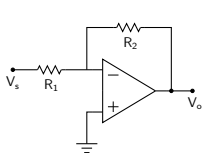
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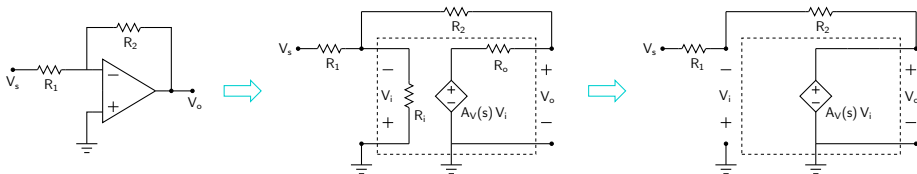
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Let us see how the frequency response of the 741 Op Amp affects the gain of an inverting amplifier.

## Inverting amplifier, revisited



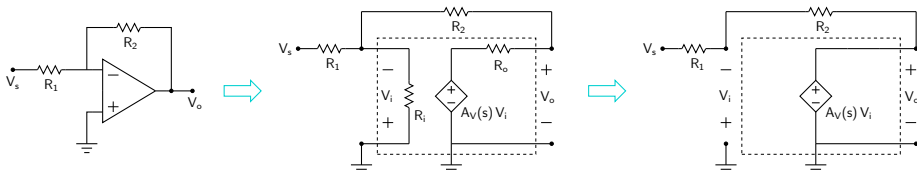
# Inverting amplifier, revisited



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

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

## Inverting amplifier, revisited



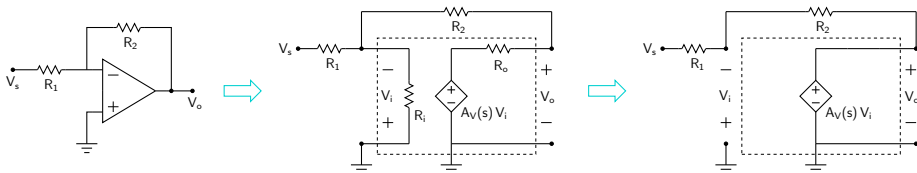
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Using  $V_o(s) = A_V(s) V_i(s)$ ,

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

## Inverting amplifier, revisited



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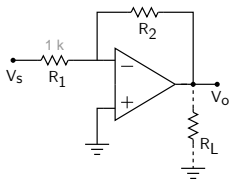
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Using  $V_o(s) = A_V(s) V_i(s)$ ,

$$\begin{aligned} \frac{V_o(s)}{V_s(s)} &= -\frac{R_2}{R_1} \frac{1}{\left[1 + \left(\frac{R_1 + R_2}{R_i}\right) \frac{1}{A_0}\right] + \left(\frac{R_1 + R_2}{R_i A_0}\right) \frac{s}{\omega_c}} \\ &\approx -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c}, \quad \text{with } \omega'_c = \frac{\omega_c A_0}{1 + R_2/R_1} = \frac{\omega_t}{1 + R_2/R_1}. \end{aligned}$$

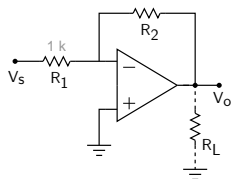


## Inverting amplifier, revisited



SEQUEL file: inv\_amp\_ac.sqproj

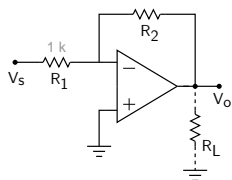
## Inverting amplifier, revisited



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

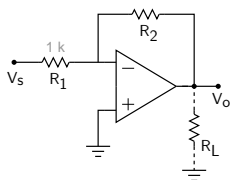


$R_2$	gain (dB)	$f_c'$ (kHz)
5 k	14	167

SEQUENCE file: inv\_amp\_ac.sqproj

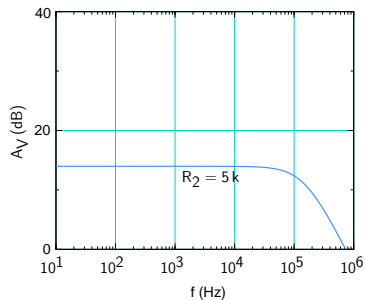
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



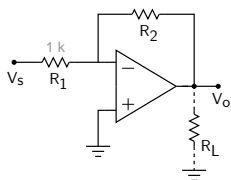
$R_2$	gain (dB)	$f_c'$ (kHz)
5 k	14	167

SEQUEL file: inv\_amp\_ac.sqproj



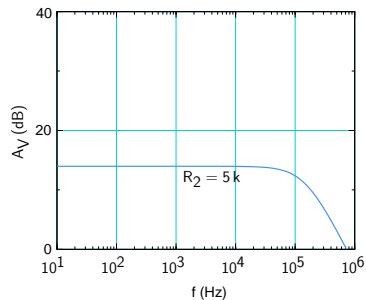
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



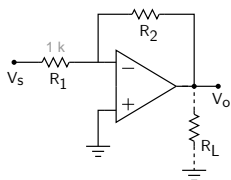
$R_2$	gain (dB)	$f_c'$ (kHz)
5 k	14	167
10 k	20	91

SEQUEL file: inv\_amp\_ac.sqproj



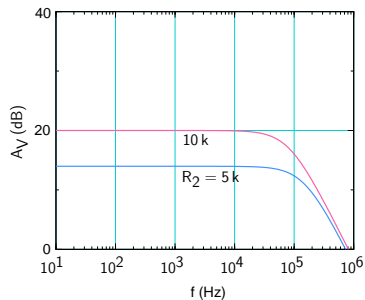
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



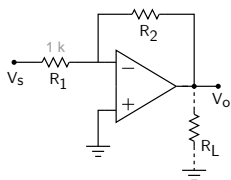
$R_2$	gain (dB)	$f_c'$ (kHz)
5 k	14	167
10 k	20	91

SEQUEL file: inv\_amp\_ac.sqproj



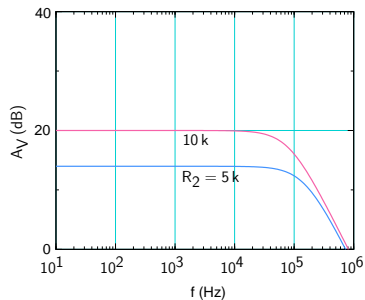
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



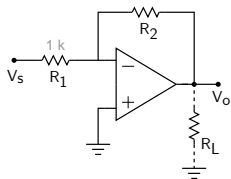
$R_2$	gain (dB)	$f_c'$ (kHz)
5 k	14	167
10 k	20	91
25 k	28	38

SEQUEL file: inv\_amp\_ac.sqproj



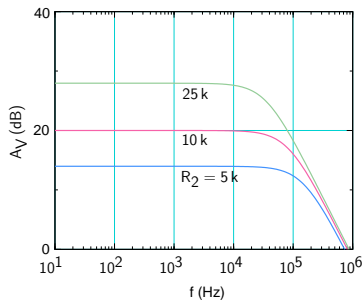
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

## Inverting amplifier, revisited



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

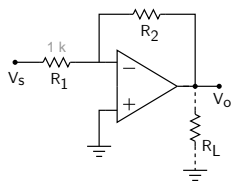
SEQUEL file: inv\_amp\_ac.sqproj



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

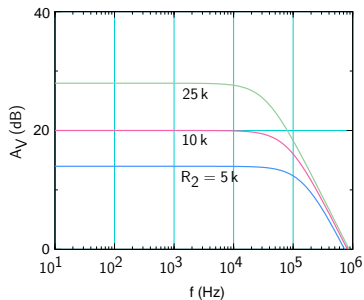


## Inverting amplifier, revisited



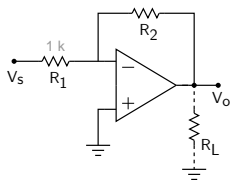
$R_2$	gain (dB)	$f_c'$ (kHz)
5 k	14	167
10 k	20	91
25 k	28	38
50 k	34	19.6

SEQUEL file: inv\_amp\_ac.sqproj



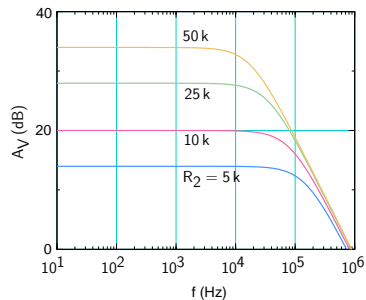
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



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

SEQUEL file: inv\_amp\_ac.sqproj



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