

## EE101: Op Amp circuits (Part 6)

---

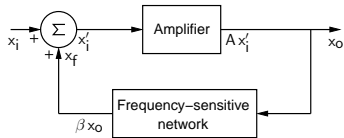


**M. B. Patil**

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

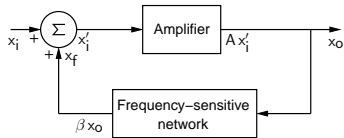
Department of Electrical Engineering  
Indian Institute of Technology Bombay

# Sinusoidal oscillators



Consider an amplifier with feedback.

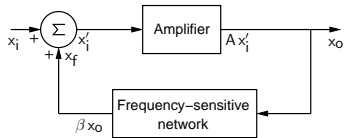
# Sinusoidal oscillators



Consider an amplifier with feedback.

$$x_o = A x'_i = A(x_i + x_f) = A(x_i + \beta x_o)$$

# Sinusoidal oscillators

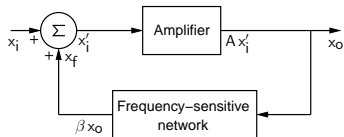


Consider an amplifier with feedback.

$$x_o = Ax_i' = A(x_i + x_f) = A(x_i + \beta x_o)$$

$$\rightarrow A_f \equiv \frac{x_o}{x_i} = \frac{A}{1 - A\beta}$$

# Sinusoidal oscillators



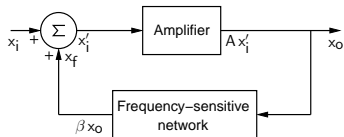
Consider an amplifier with feedback.

$$x_o = A x_i' = A(x_i + x_f) = A(x_i + \beta x_o)$$

$$\rightarrow A_f \equiv \frac{x_o}{x_i} = \frac{A}{1 - A\beta}$$

Since  $A$  and  $\beta$  will generally vary with  $\omega$ , we re-write  $A_f$  as,

$$\rightarrow A_f(j\omega) = \frac{A(j\omega)}{1 - A(j\omega)\beta(j\omega)}$$



Consider an amplifier with feedback.

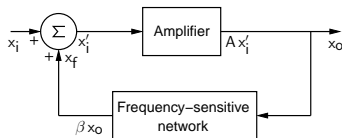
$$x_o = A x_i' = A(x_i + x_f) = A(x_i + \beta x_o)$$

$$\rightarrow A_f \equiv \frac{x_o}{x_i} = \frac{A}{1 - A\beta}$$

Since  $A$  and  $\beta$  will generally vary with  $\omega$ , we re-write  $A_f$  as,

$$\rightarrow A_f(j\omega) = \frac{A(j\omega)}{1 - A(j\omega)\beta(j\omega)}$$

As  $A(j\omega)\beta(j\omega) \rightarrow 1$ ,  $A_f(j\omega) \rightarrow \infty$ , and we get a finite  $x_o$  even if  $x_i = 0$ .



Consider an amplifier with feedback.

$$x_o = A x_i' = A(x_i + x_f) = A(x_i + \beta x_o)$$

$$\rightarrow A_f \equiv \frac{x_o}{x_i} = \frac{A}{1 - A\beta}.$$

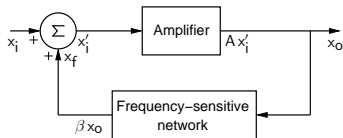
Since  $A$  and  $\beta$  will generally vary with  $\omega$ , we re-write  $A_f$  as,

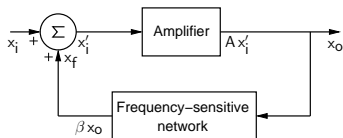
$$\rightarrow A_f(j\omega) = \frac{A(j\omega)}{1 - A(j\omega)\beta(j\omega)}.$$

As  $A(j\omega)\beta(j\omega) \rightarrow 1$ ,  $A_f(j\omega) \rightarrow \infty$ , and we get a finite  $x_o$  even if  $x_i = 0$ .

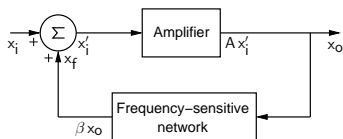
In other words, we can remove  $x_i$  and still get a non-zero  $x_o$ . This is the basic principle behind sinusoidal oscillators.

# Sinusoidal oscillators

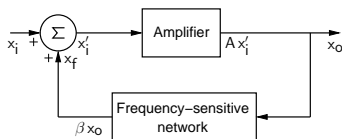




- \* The condition,  $A(j\omega)\beta(j\omega) = 1$ , for a circuit to oscillate spontaneously (i.e., without any input), is known as the Barkhausen criterion.

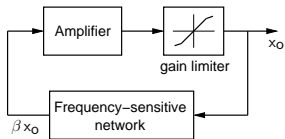


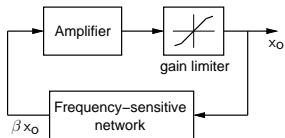
- \* The condition,  $A(j\omega)\beta(j\omega) = 1$ , for a circuit to oscillate spontaneously (i.e., without any input), is known as the Barkhausen criterion.
- \* For the circuit to oscillate at  $\omega = \omega_0$ , the  $\beta$  network is designed such that the Barkhausen criterion is satisfied only for  $\omega_0$ , i.e., all components except  $\omega_0$  get attenuated to zero.



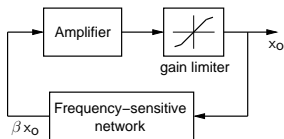
- \* The condition,  $A(j\omega)\beta(j\omega) = 1$ , for a circuit to oscillate spontaneously (i.e., without any input), is known as the Barkhausen criterion.
- \* For the circuit to oscillate at  $\omega = \omega_0$ , the  $\beta$  network is designed such that the Barkhausen criterion is satisfied only for  $\omega_0$ , i.e., all components except  $\omega_0$  get attenuated to zero.
- \* The output  $x_o$  will therefore have a frequency  $\omega_0$  ( $\omega_0/2\pi$  in Hz), but what about the amplitude?

# Sinusoidal oscillators

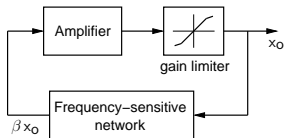




- \* A gain limiting mechanism is required to limit the amplitude of the oscillations.

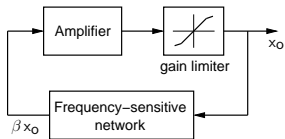


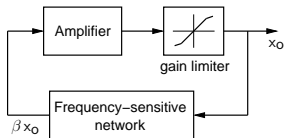
- \* A gain limiting mechanism is required to limit the amplitude of the oscillations.
- \* Amplifier clipping can provide a gain limiter mechanism. For example, in an Op Amp, the output voltage is limited to  $\pm V_{\text{sat}}$ , and this serves to limit the gain as the magnitude of the output voltage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



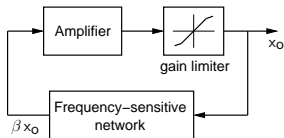
- \* A gain limiting mechanism is required to limit the amplitude of the oscillations.
- \* Amplifier clipping can provide a gain limiter mechanism. For example, in an Op Amp, the output voltage is limited to  $\pm V_{\text{sat}}$ , and this serves to limit the gain as the magnitude of the output voltage increases.
- \* For a more controlled output with low distortion, diode-resistor networks are used for gain limiting, as we shall see.

# Sinusoidal oscillators

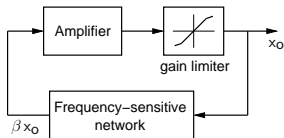




- \* Up to about 100 kHz, an Op Amp based amplifier and a  $\beta$  network of resistors and capacitors can be used.

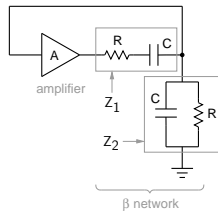
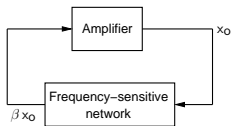


- \* Up to about 100 kHz, an Op Amp based amplifier and a  $\beta$  network of resistors and capacitors can be used.
- \* At higher frequencies, an Op Amp based amplifier is not suitable because of frequency response and slew rate limitations of Op Amps.

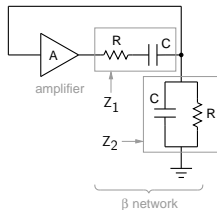
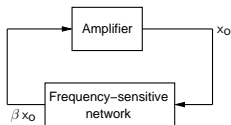


- \* Up to about 100 kHz, an Op Amp based amplifier and a  $\beta$  network of resistors and capacitors can be used.
- \* At higher frequencies, an Op Amp based amplifier is not suitable because of frequency response and slew rate limitations of Op Amps.
- \* For high frequencies, transistor amplifiers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

# Wien bridge oscillator



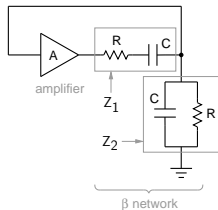
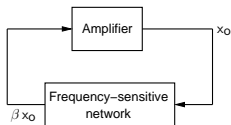
# Wien bridge oscillator



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

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

# Wien bridge oscillator



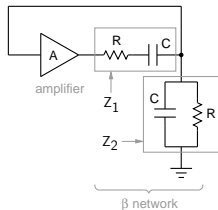
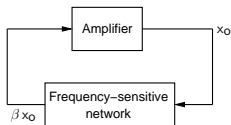
Assuming  $R_{in} \rightarrow \infty$  for the amplifier, we get

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

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

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

# Wien bridge oscillator



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

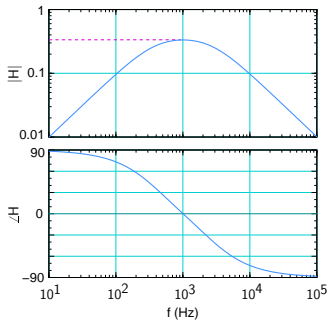
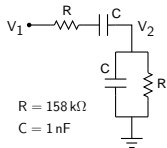
$$A(s)\beta(s) = A \frac{Z_2}{Z_1 + Z_2} = A \frac{R \parallel (1/sC)}{R + (1/sC) + R \parallel (1/sC)} = A \frac{sRC}{(sRC)^2 + 3sRC + 1}.$$

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

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

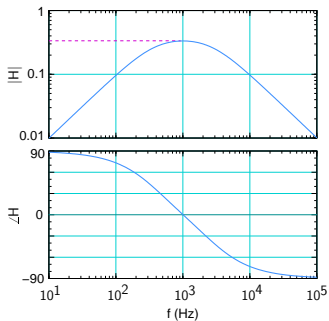
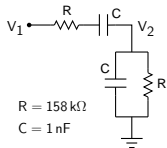
$$\rightarrow \boxed{\omega = \frac{1}{RC}, A = 3}$$

# Wien bridge oscillator



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

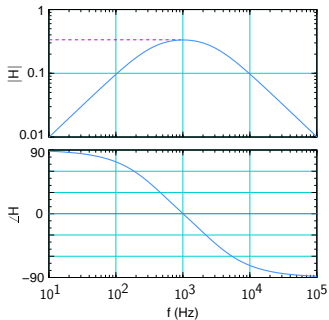
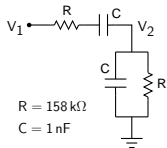
# Wien bridge oscillator



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

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.,  $\beta(j\omega) = 1/3$ .

# Wien bridge oscillator



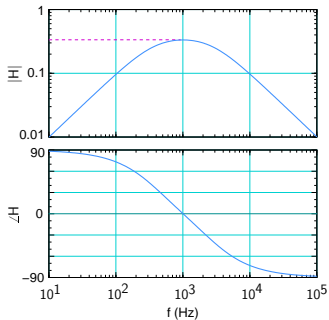
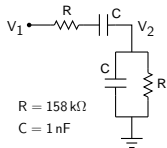
$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{j\omega RC}{-\omega^2(RC)^2 + 3j\omega RC + 1}$$

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.,  $\beta(j\omega) = 1/3$ .

For  $A\beta = 1 \rightarrow A = 3$ , as derived analytically.

# Wien bridge oscillator



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

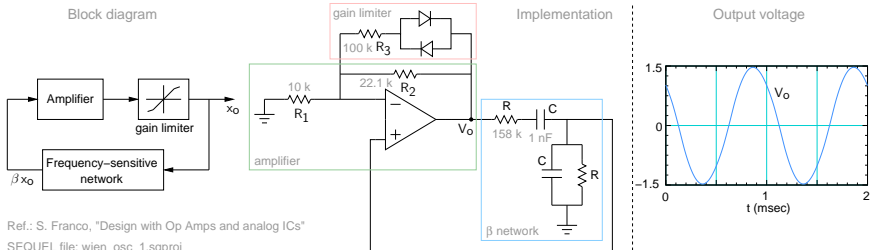
Note that the condition  $\angle H = 0$  is satisfied only at one frequency,  $\omega_0 = 1/RC$ , i.e.,  $f_0 = 1 \text{ kHz}$ .

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

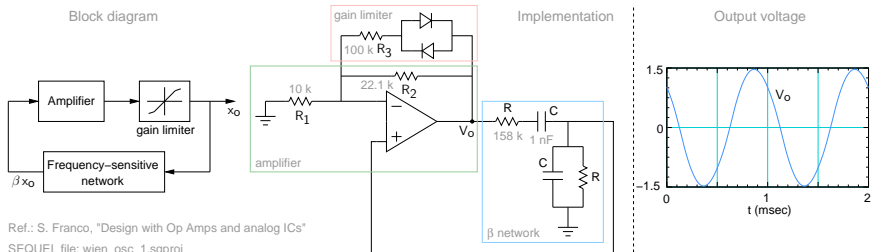
For  $A\beta = 1 \rightarrow A = 3$ , as derived analytically.

SEQUEL file: ee101\_osc.1.sqproj

# Wien bridge oscillator



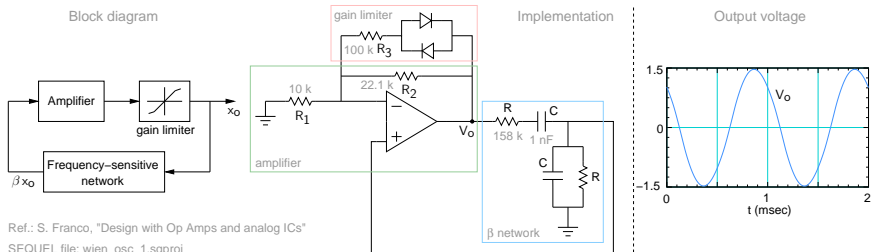
# Wien bridge oscillator



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

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

# Wien bridge oscillator

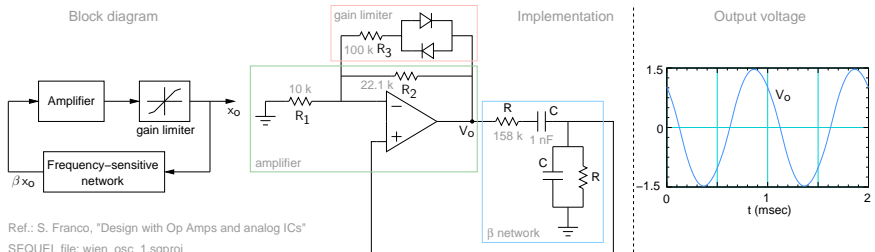


Ref.: S. Franco, "Design with Op Amps and analog ICs"  
SEQUEL file: wien\_osc\_1.sqproj

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

$$* \text{ Since the amplifier gain is required to be } A = 3, \text{ we must have } 1 + \frac{R_2}{R_1} = 3 \rightarrow R_2 = 2 R_1.$$

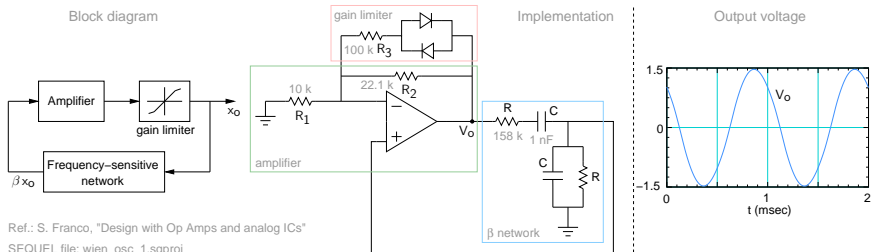
# Wien bridge oscillator



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

- \*  $\omega_0 = \frac{1}{RC} = \frac{1}{(158 \text{ k}) \times (1 \text{ nF})} \rightarrow f_0 = 1 \text{ kHz}.$
- \* Since the amplifier gain is required to be  $A = 3$ , we must have  $1 + \frac{R_2}{R_1} = 3 \rightarrow R_2 = 2 R_1.$
- \* 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.

# Wien bridge oscillator

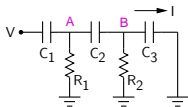


Ref.: S. Franco, "Design with Op Amps and analog ICs"

SEQUEL file: wien\_osc\_1.sqproj

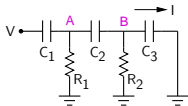
- \*  $\omega_0 = \frac{1}{RC} = \frac{1}{(158 \text{ k}) \times (1 \text{ nF})} \rightarrow f_0 = 1 \text{ kHz}.$
- \* Since the amplifier gain is required to be  $A = 3$ , we must have  $1 + \frac{R_2}{R_1} = 3 \rightarrow R_2 = 2 R_1.$
- \* For gain limiting, diodes have been used. With one of the 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



SEQUEL file: ee101\_osc\_4.sqproj

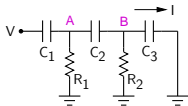
## Phase-shift oscillator



SEQUEL file: ee101\_osc\_4.sqproj

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

# Phase-shift oscillator



SEQUEL file: ee101\_osc\_4.sqproj

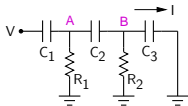
Let  $R_1 = R_2 = R = 10\text{ k}$ ,  $G = 1/R$ , and  $C_1 = C_2 = C_3 = C = 16\text{ nF}$ .

Using nodal analysis,

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

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

# 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,

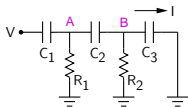
$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \quad (1)$$

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

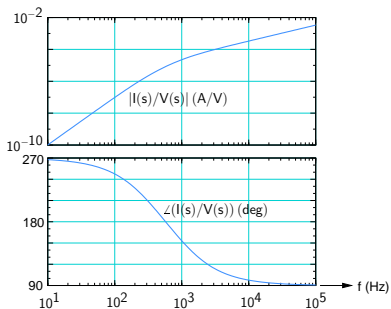
Solving (1) and (2),

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

# 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,

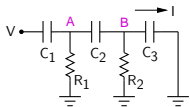
$$sC(V_A - V) + GV_A + sC(V_A - V_B) = 0 \quad (1)$$

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

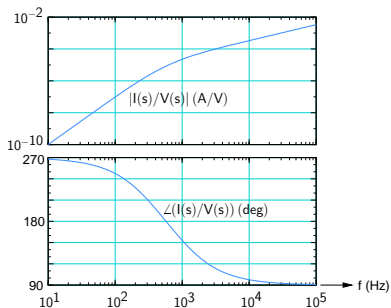
Solving (1) and (2),

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

# Phase-shift oscillator



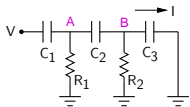
SEQUEL file: ee101\_osc\_4.sqproj



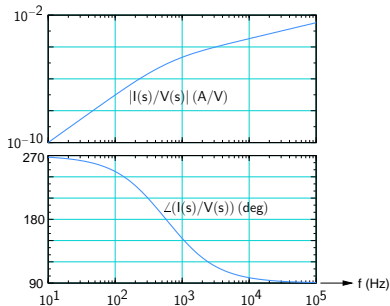
( $R_1 = R_2 = R = 10 \text{ k}$ , and  $C_1 = C_2 = C_3 = C = 16 \text{ nF}$ .)

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

# Phase-shift oscillator



SEQUEL file: ee101\_osc\_4.sqproj



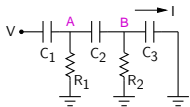
( $R_1 = R_2 = R = 10 \text{ k}$ , and  $C_1 = C_2 = C_3 = C = 16 \text{ nF}$ .)

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

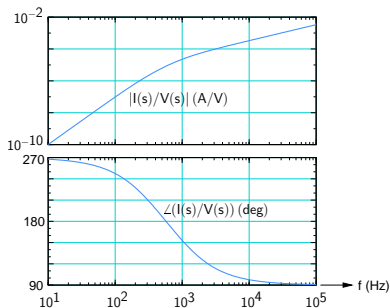
For  $\beta(j\omega)$  to be a real number, the denominator must be purely imaginary.

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

# Phase-shift oscillator



SEQUEL file: ee101\_osc\_4.sqproj



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

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

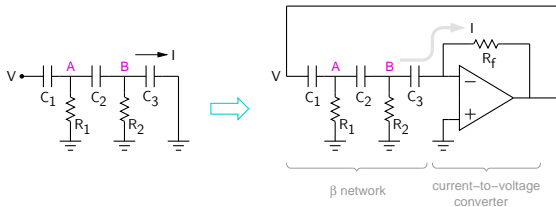
For  $\beta(j\omega)$  to be a real number, the denominator must be purely imaginary.

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

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

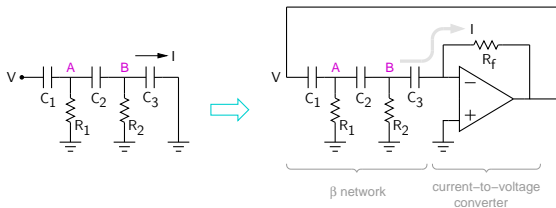
$$\beta(j\omega_0) = \frac{1}{R} \frac{(j/\sqrt{3})^3}{4j/\sqrt{3}} = -\frac{1}{12R} = -8.33 \times 10^{-6}.$$

## Phase-shift oscillator



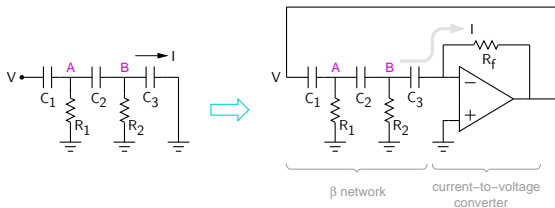
Note that the functioning of the  $\beta$  network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the Op Amp.

## 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.

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

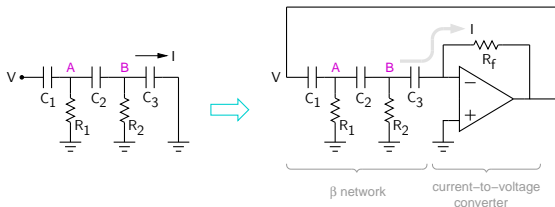


Note that the functioning of the  $\beta$  network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the Op Amp.

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

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

## Phase-shift oscillator

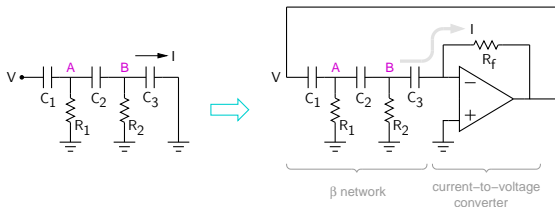


Note that the functioning of the  $\beta$  network as a stand-alone circuit (left figure) and as a feedback block (right figure) is the same, thanks to the virtual ground provided by the Op Amp.

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

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

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



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.

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

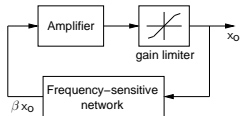
As seen before, at  $\omega = \omega_0 = \frac{1}{\sqrt{3} RC}$ , we have  $\frac{I(j\omega)}{V(j\omega)} = -\frac{1}{12R}$ .

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

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

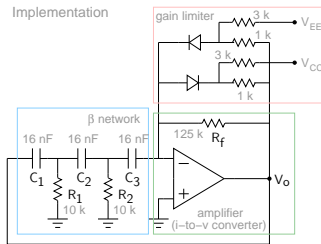
# Phase-shift oscillator

Block diagram

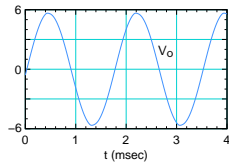


Ref.: Sedra and Smith, "Microelectronic circuits"  
SEQUEL file: phase\_shift\_osc\_1.sqproj

Implementation

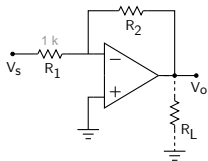


Output voltage



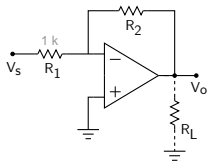
$$\omega_0 = \frac{1}{\sqrt{3}} \frac{1}{RC} \rightarrow f_0 = 574 \text{ Hz}, T = 1.74 \text{ ms}.$$

## Inverting amplifier, revisited



SEQUEL file: inv\_amp\_ac.sqproj

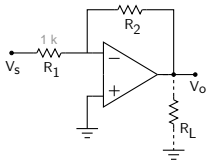
## Inverting amplifier, revisited



SEQUEL file: inv\_amp\_ac.sqproj

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

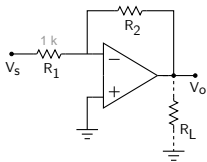
## Inverting amplifier, revisited



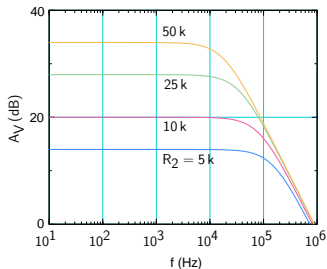
SEQUEL file: inv\_amp\_ac.sqproj

- \* 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.

## Inverting amplifier, revisited

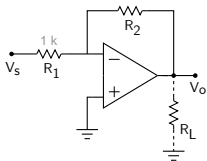


SEQUEL file: inv\_amp\_ac.sqproj

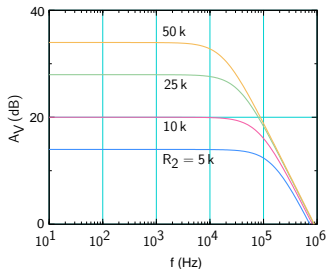


- \* As seen earlier,  $A_V = -R_2/R_1 \rightarrow |A_V|$  should be independent of the signal frequency.
- \* However, a measurement with a real Op Amp will show that  $|A_V|$  starts reducing at higher frequencies.

## Inverting amplifier, revisited

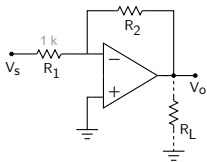


SEQUEL file: inv\_amp\_ac.sqproj

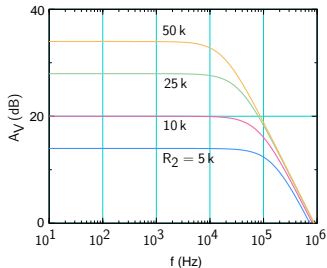


- \* As seen earlier,  $A_V = -R_2/R_1 \rightarrow |A_V|$  should be independent of the signal frequency.
- \* However, a measurement with a real Op Amp will show that  $|A_V|$  starts reducing at higher frequencies.
- \* If  $|A_V|$  is increased, the gain “roll-off” starts at lower frequencies.

## Inverting amplifier, revisited

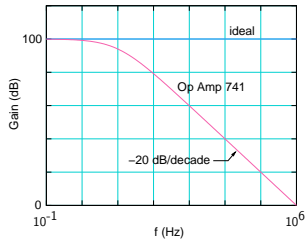
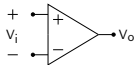


SEQUEL file: inv\_amp\_ac.sqproj



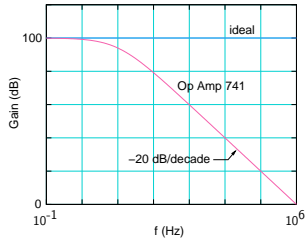
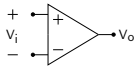
- \* As seen earlier,  $A_V = -R_2/R_1 \rightarrow |A_V|$  should be independent of the signal frequency.
- \* However, a measurement with a real Op Amp will show that  $|A_V|$  starts reducing at higher frequencies.
- \* If  $|A_V|$  is increased, the gain “roll-off” starts at lower frequencies.
- \* 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  $f_c \simeq 10$  Hz!

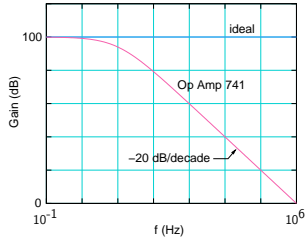
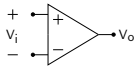
# Frequency response of Op Amp 741



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

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).

# Frequency response of Op Amp 741

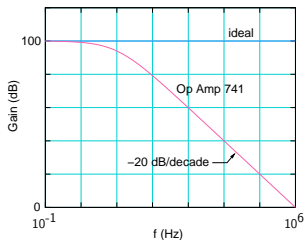
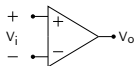


The gain of the 741 Op Amp starts falling at rather low frequencies, with  $f_c \simeq 10$  Hz!

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).

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

# 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!

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).

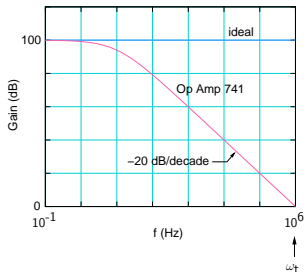
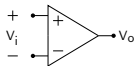
In other words, the Op Amp has been *internally compensated* for stability.

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.

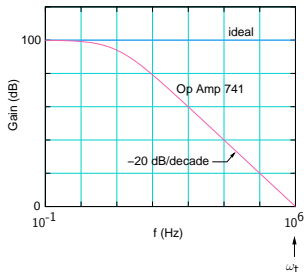
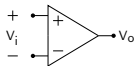
# Frequency response of Op Amp 741



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

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

# Frequency response of Op Amp 741

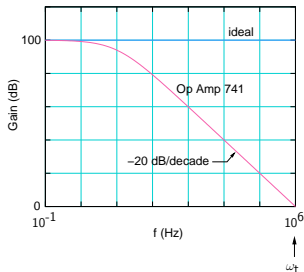
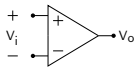


$$A(j\omega) = \frac{A_0}{1 + j\omega/\omega_c}$$

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

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

## Frequency response of Op Amp 741



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

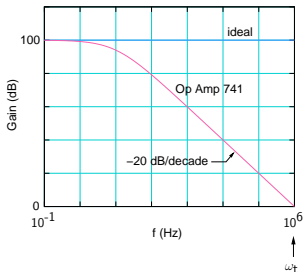
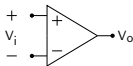
For  $\omega \gg \omega_c$ , we have  $A(j\omega) \approx \frac{A_0}{j\omega/\omega_c}$ .

$|A(j\omega)|$  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



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

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

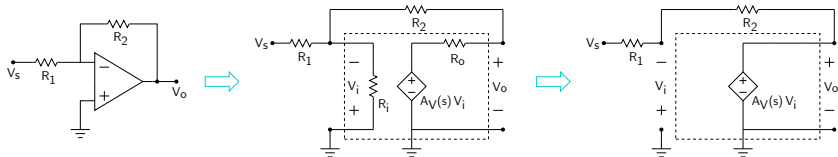
$|A(j\omega)|$  becomes 1 when  $A_0 = \omega/\omega_c$ , i.e.,  $\omega = A_0\omega_c$ .

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

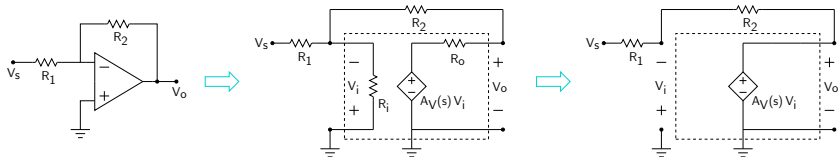
For the 741 Op Amp,  $f_t = A_0 f_c \approx 10^5 \times 10 = 10^6$  Hz.

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

# Inverting amplifier, revisited



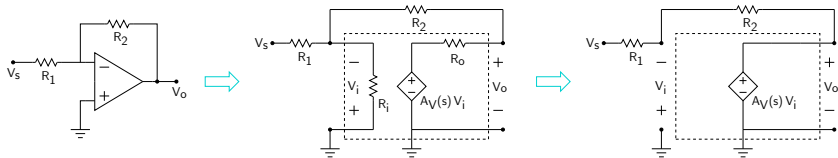
## Inverting amplifier, revisited



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



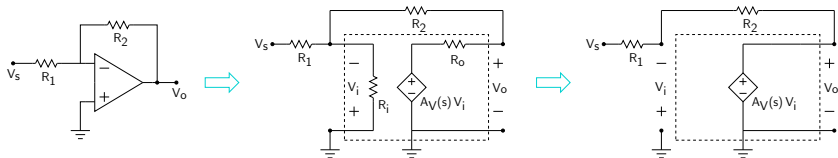
Assuming  $R_i$  to be large and  $R_o$  to be small, we get

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

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

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

## Inverting amplifier, revisited



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

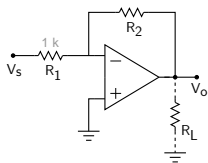
$$-V_i(s) = V_s(s) \frac{R_2}{R_1 + R_2} + V_o(s) \frac{R_1}{R_1 + R_2}.$$

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

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

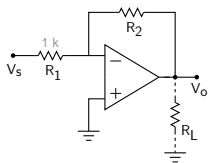
$$\approx -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c}, \quad \text{with } \omega'_c = \frac{\omega_c A_0}{1 + R_2/R_1} = \frac{\omega_t}{1 + R_2/R_1}.$$

## Inverting amplifier, revisited



SEQUEL file: inv\_amp\_ac.sqproj

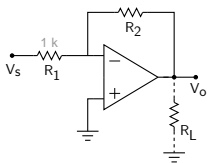
## Inverting amplifier, revisited



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

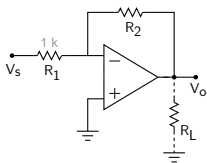


SEQUEL file: inv\_amp\_ac.sqproj

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

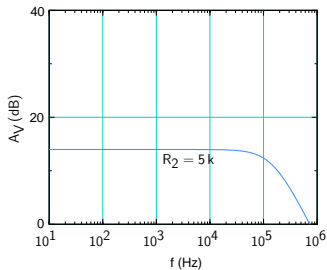
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega_c'} \quad \omega_c' = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



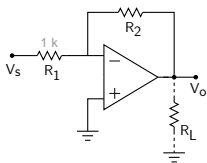
SEQUEL file: inv\_amp\_ac.sqproj

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



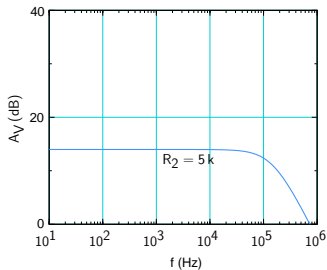
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



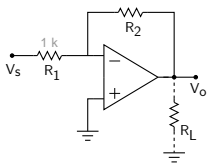
SEQUEL file: inv\_amp\_ac.sqproj

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



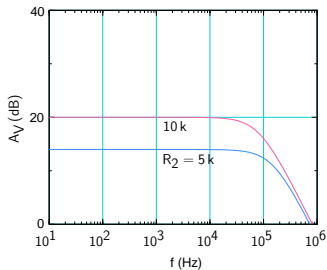
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



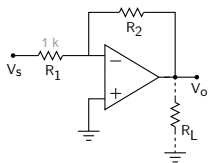
SEQUEL file: inv\_amp\_ac.sqproj

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



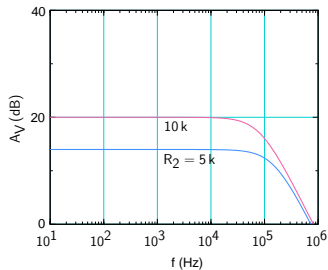
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



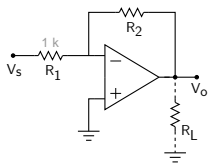
SEQUEL file: inv\_amp\_ac.sqproj

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



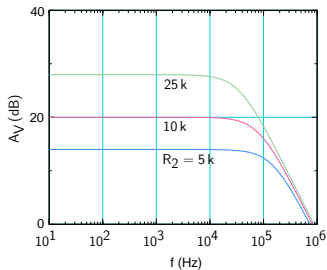
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



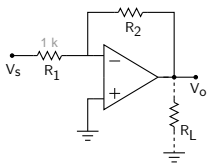
SEQUEL file: inv\_amp\_ac.sqproj

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



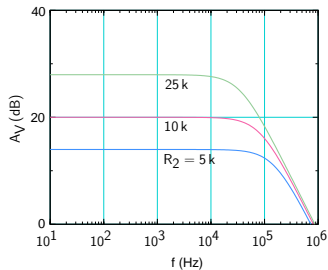
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# Inverting amplifier, revisited



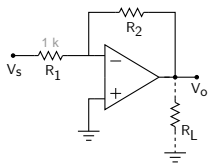
SEQUEL file: inv\_amp\_ac.sqproj

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



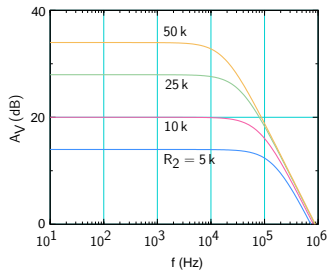
$$\frac{V_o(s)}{V_s(s)} = -\frac{R_2}{R_1} \frac{1}{1 + s/\omega'_c} \quad \omega'_c = \frac{\omega_t}{1 + R_2/R_1}, \quad (f_t = 1 \text{ MHz}).$$

# 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           |
| 50 k  | 34        | 19.6         |



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