CHAPTER 11

Exercises

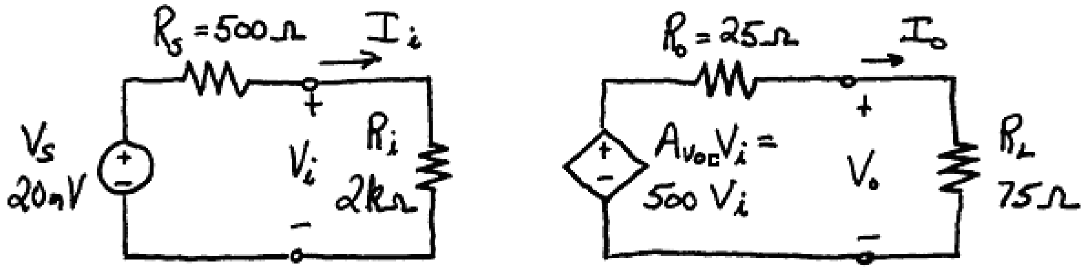
E11.1 (a) A noninverting amplifier has positive gain. Thus

$$v_o(t) = A_v v_i(t) = 50 v_i(t) = 5.0\sin(2000\pi t)$$

(b) An inverting amplifier has negative gain. Thus

$$v_o(t) = A_v v_i(t) = -50 v_i(t) = -5.0\sin(2000\pi t)$$

E11.2



$$A_v = \frac{V_o}{V_i} = A_{oc}\frac{R_L}{R_o + R_L} = 500\frac{75}{25+75} = 375$$

$$A_{vs} = \frac{V_o}{V_s} = \frac{R_i}{R_s + R_i} A_{oc}\frac{R_L}{R_o + R_L} = \frac{2000}{500+2000} 500 \frac{75}{25+75} = 300$$

$$A_i = \frac{I_o}{I_i} = A_v\frac{R_i}{R_L} = 375 \times \frac{2000}{75} = 10^4$$

$$G = A_v A_i = 3.75 \times 10^6$$

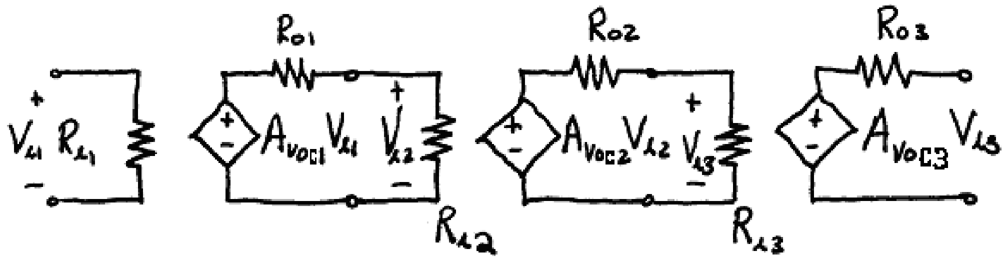
E11.3 Recall that to maximize the power delivered to a load from a source with fixed internal resistance, we make the load resistance equal to the internal (or Thévenin) resistance. Thus we make $R_L = R_o = 25\ \Omega$. Repeating the calculations of Exercise 11.2 with the new value of R_L, we have

$$A_v = \frac{V_o}{V_i} = A_{oc}\frac{R_L}{R_o + R_L} = 500\frac{25}{25+25} = 250$$

$$A_i = \frac{I_o}{I_i} = A_v\frac{R_i}{R_L} = 250 \times \frac{2000}{25} = 2 \times 10^4$$

$$G = A_v A_i = 5 \times 10^6$$

E11.4



By inspection, $R_i = R_{i1} = 1000\ \Omega$ and $R_o = R_{o3} = 30\ \Omega$.

$$A_{voc} = \frac{V_{o3}}{V_{i1}} = A_{voc1}\frac{R_{i2}}{R_{o1}+R_{i2}}A_{voc2}\frac{R_{i3}}{R_{o2}+R_{i3}}A_{voc3}$$

$$A_{voc} = \frac{V_{o3}}{V_{i1}} = 10\frac{2000}{100+2000}20\frac{3000}{200+3000}30 = 5357$$

E11.5 Switching the order of the amplifiers of Exercise 11.4 to 3-2-1, we have

$$R_i = R_{i3} = 3000\ \Omega \text{ and } R_o = R_{o1} = 100\ \Omega$$

$$A_{voc} = \frac{V_{o1}}{V_{i3}} = A_{voc3}\frac{R_{i2}}{R_{o3}+R_{i2}}A_{voc2}\frac{R_{i1}}{R_{o2}+R_{i1}}A_{voc1}$$

$$A_{voc} = \frac{V_{o1}}{V_{i3}} = 30\frac{2000}{300+2000}20\frac{1000}{200+1000}10 = 4348$$

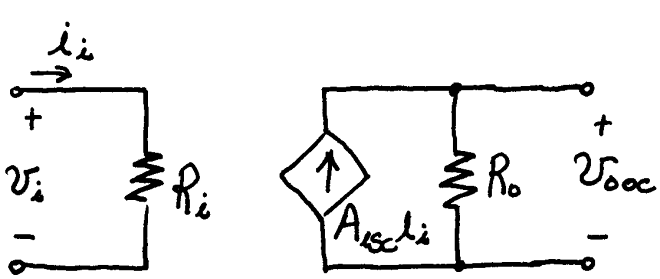
E11.6

$$P_s = (15\ \text{V})\times(1.5\ \text{A}) = 22.5\ \text{W}$$

$$P_d = P_s + P_i - P_o = 22.5 + 0.5 - 2.5 = 20.5\ \text{W}$$

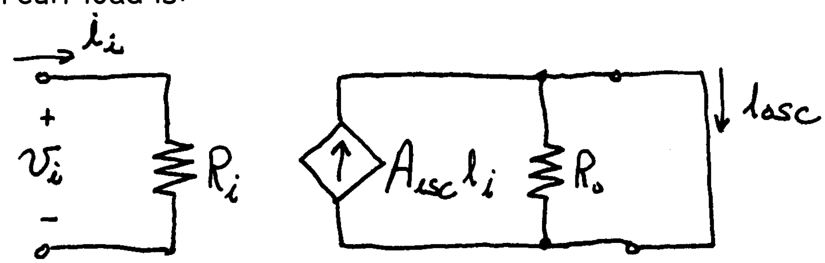
$$\eta = \frac{P_o}{P_s}\times 100\% = 11.11\%$$

E11.7 The input resistance and output resistance are the same for all of the amplifier models. Only the circuit configuration and the gain parameter are different. Thus we have $R_i = 1\ \text{k}\Omega$ and $R_o = 20\ \Omega$ and we need to find the open-circuit voltage gain. The current amplifier with an open-circuit load is:



$$A_{voc} = \frac{v_{ooc}}{v_i} = \frac{A_{isc} i_i R_o}{R_i i_i} = \frac{A_{isc} R_o}{R_i} = \frac{200 \times 20}{1000} = 4$$

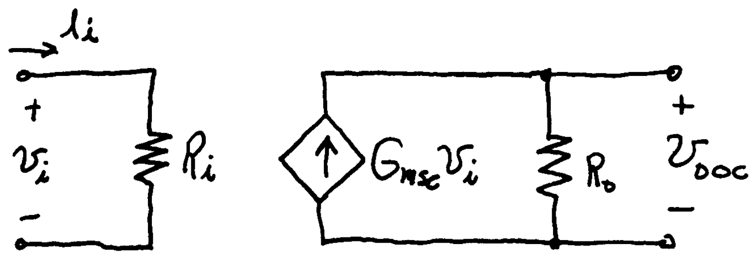
E11.8 For a transconductance-amplifier model, we need to find the short-circuit transconductance gain. The current-amplifier model with a short-circuit load is:



$$G_{msc} = \frac{i_{osc}}{v_i} = \frac{A_{isc} i_i}{R_i i_i} = \frac{A_{isc}}{R_i} = \frac{100}{500} = 0.2\ \mathrm{S}$$

The impedances are the same for all of the amplifier models, so we have $R_i = 500\ \Omega$ and $R_o = 50\ \Omega$.

E11.9 For a transresistance-amplifier model, we need to find the open-circuit transresistance gain. The transconductance-amplifier model with an open-circuit load is:



$$R_{moc} = \frac{v_{ooc}}{i_i} = \frac{G_{msc} v_i R_o}{v_i / R_i} = G_{msc} R_o R_i = 0.05 \times 10 \times 10^6 = 500\ \mathrm{k\Omega}$$

The impedances are the same for all of the amplifier models, so we have $R_i = 1\ \mathrm{M\Omega}$ and $R_o = 10\ \Omega$.

E11.10 The amplifier has $R_i = 1\ \mathrm{k\Omega}$ and $R_o = 1\ \mathrm{k\Omega}$.

(a) We have $R_s < 10\ \Omega$ which is much less than R_i, and we also have $R_L > 100\ \mathrm{k\Omega}$ which is much larger than R_o. Therefore for this source and load, the amplifier is approximately an ideal voltage amplifier.

(b) We have $R_s > 100\ \text{k}\Omega$ which is much greater than R_i, and we also have $R_L < 10\ \Omega$ which is much smaller than R_o. Therefore for this source and load, the amplifier is approximately an ideal current amplifier.

(c) We have $R_s < 10\ \Omega$ which is much less than R_i, and we also have $R_L < 10\ \Omega$ which is much smaller than R_o. Therefore for this source and load, the amplifier is approximately an ideal transconductance amplifier.

(d) We have $R_s > 100\ \text{k}\Omega$ which is much larger than R_i, and we also have $R_L > 100\ \text{k}\Omega$ which is much larger than R_o. Therefore for this source and load, the amplifier is approximately an ideal transresistance amplifier.

(e) Because we have $R_s \cong R_i$, the amplifier does not approximate any type of ideal amplifier.

E11.11 We want the amplifier to respond to the short-circuit current of the source. Therefore, we need to have $R_i << R_s$. Because the amplifier should deliver a voltage to the load that is independent of the load resistance, the output resistance R_o should be very small compared to the smallest load resistance. These facts (R_s very small and R_o very small) indicate that we need a nearly ideal transresistance amplifier.

E11.12 The gain magnitude should be constant for all components of the input signal, and the phase should by proportional to the frequency of each component. The input signal has components with frequencies of 500 Hz, 1000 Hz and 1500 Hz, respectively. The gain is $5\angle 30^\circ$ at a frequency of 1000 Hz. Therefore the gain should be $5\angle 15^\circ$ at 500 Hz, and $5\angle 45^\circ$ at 1500 Hz.

E11.13 We have

$$v_{\text{in}}(t) = V_m \cos(\omega t)$$

$$v_o(t) = 10 v_{\text{in}}(t - 0.01) = 10 V_m \cos[\omega(t - 0.01)] = 10 V_m \cos(\omega t - 0.01\omega)$$

The corresponding phasors are $\mathbf{V}_{\text{in}} = V_m \angle 0$ and $\mathbf{V}_{\text{o}} = 10 V_m \angle -0.01\omega$. Thus the complex gain is

$$A_v = \frac{\mathbf{V}_o}{\mathbf{V}_{\text{in}}} = \frac{10 V_m \angle -0.01\omega}{V_m \angle 0} = 10\angle -0.01\omega$$

E11.14 $B \cong \dfrac{0.35}{t_r} = \dfrac{0.35}{66.7\times10^{-9}} = 5.247\ \text{MHz}$

E11.15 Equation 11.13 states

$$\text{Percentage tilt} \cong 200\pi f_L T$$

Solving for f_L and substituting values, we obtain

$$f_L \cong \frac{\text{percentage tilt}}{200\pi T} = \frac{1}{200\pi\times100\times10^{-6}} = 15.92\ \text{Hz}$$

as the upper limit for the lower half-power frequency.

E11.16 (a) $v_o(t) = 100v_i(t) + v_i^2(t)$

$$= 100\cos(\omega t) + \cos^2(\omega t)$$
$$= 100\cos(\omega t) + 0.5 + 0.5\cos(2\omega t)$$

The desired term has an amplitude of V_1 = 100 and a second-harmonic distortion term with an amplitude of V_2 = 0.5. There are no higher order distortion terms so we have $D_2 = V_2 / V_1 = 0.005$ or 0.5%.

$$D = \sqrt{D_2^2 + D_3^2 + D_4^2 \ldots} = D_2 = 0.5\%$$

(b) $v_o(t) = 100v_i(t) + v_i^2(t)$

$$= 500\cos(\omega t) + 25\cos^2(\omega t)$$
$$= 500\cos(\omega t) + 12.5 + 12.5\cos(2\omega t)$$

The desired term has an amplitude of V_1 = 500 and a second-harmonic distortion term with an amplitude of V_2 = 12.5. There are no higher order distortion terms so we have $D_2 = V_2 / V_1 = 0.025$ or 2.5%.

$$D = \sqrt{D_2^2 + D_3^2 + D_4^2 \ldots} = D_2 = 2.5\%$$

E11.17 With the input terminals tied together and a 1-V signal applied, the differential signal is zero and the common-mode signal is 1 V. The common-mode gain is $A_{cm} = V_o / V_{icm} = 0.1/1 = 0.1$, which is equivalent to -20 dB. Then we have $CMRR = 20\log(|A_d| / |A_{cm}|) = 20\log(500{,}000) = 114.0\ \text{dB}$.

E11.18 (a) $v_{id} = v_{i1} - v_{i2} = 1\ \text{V} \qquad v_{icm} = (v_{i1} + v_{i2})/2 = 0\ \text{V}$

$$v_o = A_1 v_{i1} - A_2 v_{i2} = (A_1 + A_2)/2$$
$$= A_d v_{id} + A_{cm} v_{icm} = A_d$$

Thus $A_d = (A_1 + A_2)/2$.

(b) $v_{id} = v_{i1} - v_{i2} = 0\text{ V} \qquad v_{icm} = (v_{i1} + v_{i2})/2 = 1\text{ V}$

$$v_o = A_1 v_{i1} - A_2 v_{i2} = (A_1 - A_2)$$
$$= A_d v_{id} + A_{cm} v_{icm} = A_{cm}$$

Thus $A_{cm} = A_1 - A_2$.

(c) $A_d = (A_1 + A_2)/2 = (100 + 101)/2 = 100.5$

$$A_{cm} = A_1 - A_2 = 100 - 101 = -1$$
$$\text{CMRR} = 20\log\left(\frac{|A_d|}{|A_{cm}|}\right) = 20\log\left(\frac{|A_1 + A_2|}{2|A_1 - A_2|}\right)$$
$$\text{CMRR} = 20\log\left(\frac{|A_1 + A_2|}{2|A_1 - A_2|}\right) = 20\log\left(\frac{|100 + 101|}{2|100 - 101|}\right) = 40.0\text{ dB.}$$

E11.19 Except for numerical values this Exercise is the same as Example 11.13 in the book. With equal resistances at the input terminals, the bias currents make no contribution to the output voltage. The extreme contributions to the output due to the offset voltage are

$$A_d V_{Voff} = A_d V_{off} \frac{R_{in}}{R_{in} + R_{s1} + R_{s2}}$$
$$= 500 \times (\pm 10 \times 10^{-3}) \frac{100 \times 10^3}{(100 + 50 + 50)10^3} = \pm 2.5\text{ V}$$

The extreme contributions to the output voltage due to the offset current are

$$A_d V_{Ioff} = A_d \frac{I_{off}}{2} \frac{R_{in}(R_{s1} + R_{s2})}{R_{in} + R_{s1} + R_{s2}}$$
$$= 500 \times \frac{\pm 100 \times 10^{-9}}{2} \frac{100 \times 10^3 (50 + 50) \times 10^3}{(100 + 50 + 50)10^3} = \pm 1.25\text{ V}$$

Thus, the extreme output voltages due to all sources are ± 3.75 V.

E11.20 This Exercise is similar to Example 11.13 in the book with R_{s1} = 50 kΩ and R_{s2} = 0. With unequal resistances at the input terminals, the bias currents make a contribution to the output voltage given by

$$V_{oBias} = A_d I_B \frac{R_{s1} R_{in}}{R_{s1} + R_{in}}$$
$$= 500 \times 400 \times 10^{-9} \frac{50 \times 10^3 \times 100 \times 10^3}{50 \times 10^3 + 100 \times 10^3} = +6.667\text{ V}$$

The extreme contributions to the output due to the offset voltage are

$$A_d V_{V\text{off}} = A_d V_{\text{off}} \frac{R_{\text{in}}}{R_{\text{in}} + R_{s1} + R_{s2}}$$

$$= 500 \times (\pm 10 \times 10^{-3}) \frac{100 \times 10^3}{(100 + 50 + 0)10^3} = \pm 3.333 \text{ V}$$

The extreme contributions to the output voltage due to the offset current are

$$A_d V_{I\text{off}} = A_d \frac{I_{\text{off}}}{2} \frac{R_{\text{in}}(R_{s1} + R_{s2})}{R_{\text{in}} + R_{s1} + R_{s2}}$$

$$= 500 \times \frac{\pm 100 \times 10^{-9}}{2} \frac{100 \times 10^3 (50 + 0) \times 10^3}{(100 + 50 + 0)10^3} = \pm 0.8333 \text{ V}$$

Thus, the extreme output voltages due to all sources are a minimum of 2.5 V and a maximum of 10.83 V.

Answers for Selected Problems

P11.4* $A_v = 50$
$A_{vs} = 33.33$
$A_i = 1.25 \times 10^6$
$G = 62.5 \times 10^6$

P11.5* $A_i = 100$
$R_i = 200\ \Omega$

P11.10* $R_i = 666.7\ \Omega$.

P11.15* $R_{in} = 1\ \text{M}\Omega$

P11.20* $R_i = 2\ \text{k}\Omega$
$R_o = 3\ \text{k}\Omega$
$A_{voc} = 3.6 \times 10^6$

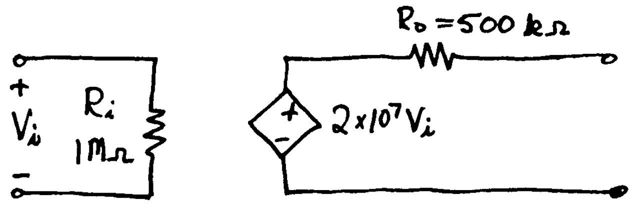
P11.22* Five amplifiers must be cascaded to attain a voltage gain in excess of 1000.

P11.25* $P_s = P_1 + P_2 + P_3 = 40\text{ W}$

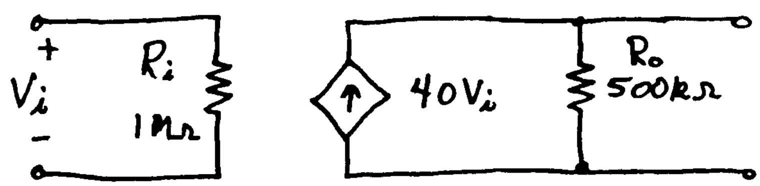
P11.32* $A_i = 2000 \quad A_v = 500 \quad G = 10^6 \quad P_d = 19.87\text{ W} \quad \eta = 17.2\%$

P11.33* $A_{voc} = 100\ \text{V/V} \quad G_{msc} = 0.1\text{ S} \quad A_{isc} = 10\ \text{A/A}$

P11.38* The voltage-amplifier model is:



The transconductance-amplifier model is:



P11.40* $A_{voc} = 100$
$A_{isc} = 500$
$R_{moc} = 100\text{ k}\Omega$

P11.41* $A_{voc} = 20$
$A_{isc} = 100$
$G_{msc} = 0.01\text{ S}$

P11.52* $R_x = -2.23\ \Omega$

P11.55* To sense the open-circuit voltage of a sensor, we need an amplifier with very high input resistance (compared to the Thévenin resistance of the sensor). To avoid loading effects by the variable load resistance, we need an amplifier with very low output resistance (compared to the smallest load resistance). Thus, we need a nearly ideal voltage amplifier with a gain of 1000.

P11.56* The input resistance is that of the ideal transresistance amplifier which is zero. The output resistance of the cascade is the output resistance of the ideal transconductance amplifier which is infinite. An amplifier having zero input resistance and infinite output resistance is an ideal current amplifier. Also, we have $A_{isc} = R_{moc}G_{msc}$.

P11.61* We need a nearly ideal transconductance amplifier.

$R_i = 98\ \text{k}\Omega \qquad R_o = 19.7\ \text{k}\Omega$

P11.67* The complex gain for the 1000-Hz component is

$A_v = 100\angle -20^\circ$

The complex gain for the 2000-Hz component is

$A_v = 75\angle -10^\circ$

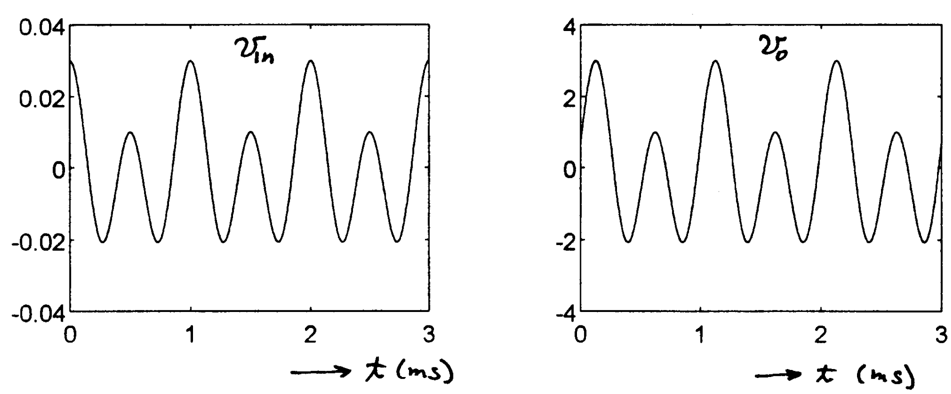
P11.68* The signal to be amplified is the short-circuit current of an electrochemical cell (or battery). This signal is dc and therefore a dc-coupled amplifier is needed.

P11.70* $f_{hp} \cong 0.6436 f_B$

P11.75* The gain at 2000 Hz must be $100\angle -90^\circ$. The output signal is

$$v_o(t) = 1\cos(2000\pi t - 45^\circ) + 2\cos(4000\pi t - 90^\circ)$$

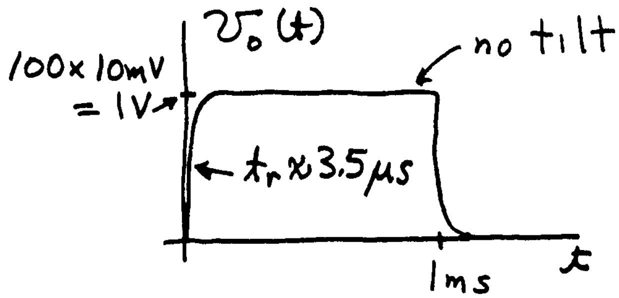
The plots are:



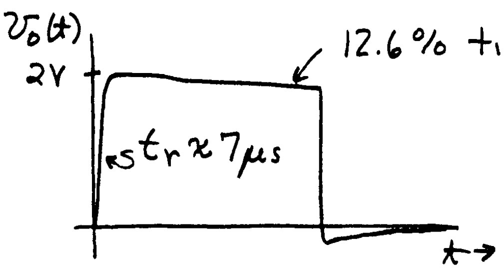
P11.82* $t_r \cong 23.3\ \mu s$

Percentage tilt $\cong 18.8\%$

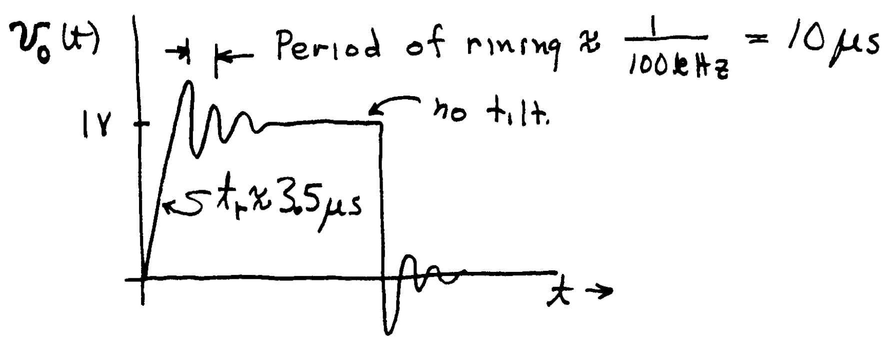
P11.83* (a)



(b)



(c)



P11.86* $D_2 = 0.02$

$D_3 = 0.01$

$D_4 = 0$

$D = 0.02236$

P11.93* $CMRR = 47.96$ dB

P11.98* The extreme values of the output voltage are:

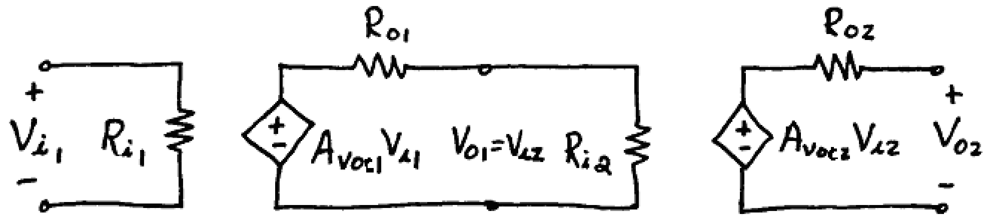
$$v_o = A_d v_{id} = \pm 5 \text{ mV}$$

If the resistors are exactly equal, then the output voltage is zero.

P11.99* The output voltage can range from -3.333 to +3.333 V.

Practice Test

T11.1 The equivalent circuit for the cascaded amplifiers is:



We can write:

$$V_{i2} = A_{voc1}V_{i1} \times \frac{R_{i2}}{R_{i2} + R_{o1}}$$

$$V_{o2} = A_{voc2}V_{i2} = A_{voc2}A_{voc1}V_{i1}\frac{R_{i2}}{R_{i2} + R_{o1}}$$

Thus, the open-circuit voltage gain is:

$$A_{voc} = \frac{V_{o2}}{V_{i1}} = A_{voc2}A_{voc1}\frac{R_{i2}}{R_{i2} + R_{o1}} = 50 \times 50\frac{60}{60 + 40} = 1500$$

The input resistance of the cascade is that of the first stage which is $R_i = 60\ \Omega$. The output resistance of the cascade is the output resistance of the last stage which is $R_o = 40\ \Omega$.

T11.2 Your answer should be similar to Table 11.1.

Table 11.1. Characteristics of Ideal Amplifiers

Amplifier Type	Input Impedance	Output Impedance	Gain Parameter
Voltage	∞	0	A_{voc}
Current	0	∞	A_{isc}
Transconductance	∞	∞	G_{msc}
Transresistance	0	0	R_{moc}

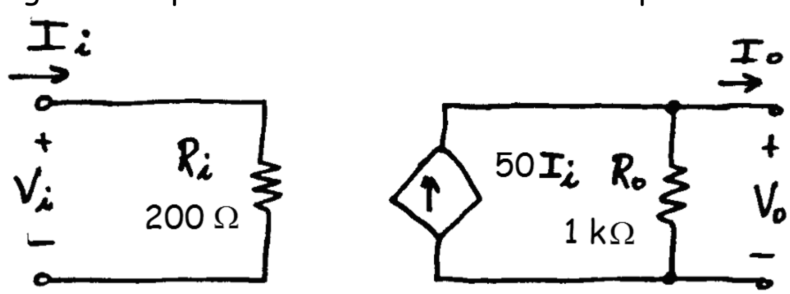
T11.3 **a.** The amplifier should sense the open-circuit source voltage, thus the input impedance should be infinite. The load current should be independent of the variable load, so the output impedance should be infinite. Thus, we need an ideal transconductance amplifier.

b. The amplifier should respond to the short-circuit source current, thus the input impedance should be zero. The load current should be independent of the variable load impedance so the output impedance should be infinite. Therefore, we need an ideal current amplifier.

c. The amplifier should sense the open-circuit source voltage, thus the input impedance should be infinite. The load voltage should be independent of the variable load, so the output impedance should be zero. Thus, we need an ideal voltage amplifier.

d. The amplifier should respond to the short-circuit source current, thus the input impedance should be zero. The load voltage should be independent of the variable load impedance, so the output impedance should be zero. Therefore, we need an ideal transresistance amplifier.

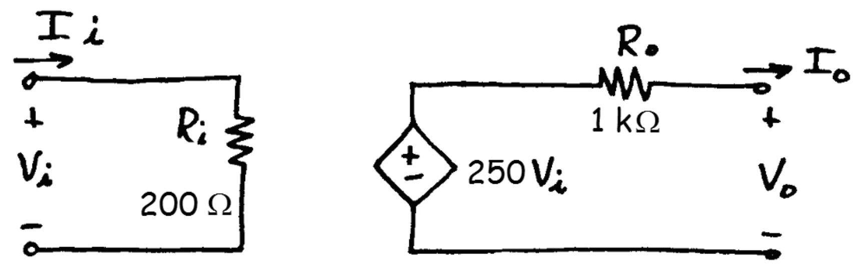
T11.4 We are given the parameters for the current-amplifier model, which is:



The open-circuit voltage gain is:

$$A_{voc} = \frac{V_{ooc}}{V_i} = \frac{50 I_i R_o}{R_i I_i} = 250$$

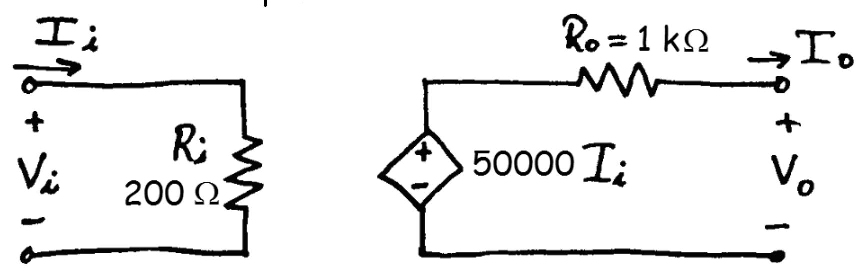
A_{voc} is unitless. (Sometimes we give the units as V/V.) The voltage-amplifier model is:



The transresistance gain is:

$$R_{moc} = \frac{V_{ooc}}{I_i} = \frac{50 I_i R_o}{I_i} = 50\ \text{k}\Omega$$

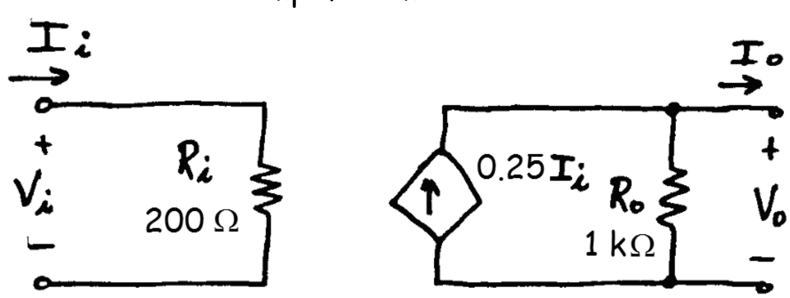
The transresistance-amplifier model is:



The transconductance gain is:

$$G_{msc} = \frac{I_{osc}}{V_i} = \frac{50 I_i}{R_i I_i} = 0.25\ \text{S}$$

The transconductance-amplifier model is:



T11.5 $P_i = I_i^2 R_i = (10^{-3})^2 \times 2 \times 10^3 = 2\ \text{mW}$

$P_o = (V_o)^2 / R_L = (12)^2 / 8 = 18\ \text{W}$

$P_s = V_s I_s = 15 \times 2 = 30\ \text{W}$

$P_d = P_s + P_i - P_o \cong 12\ \text{W}$

$\eta = \frac{P_o}{P_s} \times 100\% = 60\%$

T11.6 To avoid linear waveform distortion, the gain magnitude should be constant and the phase response should be a linear function of frequency over the frequency range from 1 to 10 kHz. Because the gain is 100 and the peak input amplitude is 100 mV, the peak output amplitude should be 10 V. The amplifier must not display clipping or unacceptable nonlinear distortion for output amplitudes of this value.

T11.7 The principal effect of offset current, bias current, and offset voltage of an amplifier is to add a dc component to the signal being amplified.

T11.8 Harmonic distortion can occur when a pure sinewave test signal is applied to the input of an amplifier. The distortion appears in the output as components whose frequencies are integer multiples of the input frequency. Harmonic distortion is caused by a nonlinear relationship between the input voltage and output voltage.

T11.9 Common mode rejection ratio (CMRR) is the ratio of the differential gain to the common mode gain of a differential amplifier. Ideally, the common mode gain is zero, and the amplifier produces an output only for the differential signal. CMRR is important when we have a differential signal of interest in the presence of a large common-mode signal not of interest. For example, in recording an electrocardiogram, two electrodes are connected to the patient; the differential signal is the heart signal of interest to the cardiologist; and the common mode signal is due to the 60-Hz power line.