Montogue

Quiz EL206

Basic Operational Amplifier Circuits

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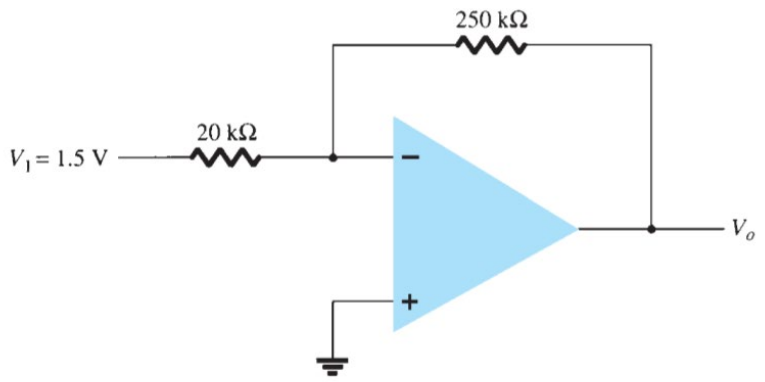
PROBLEMS

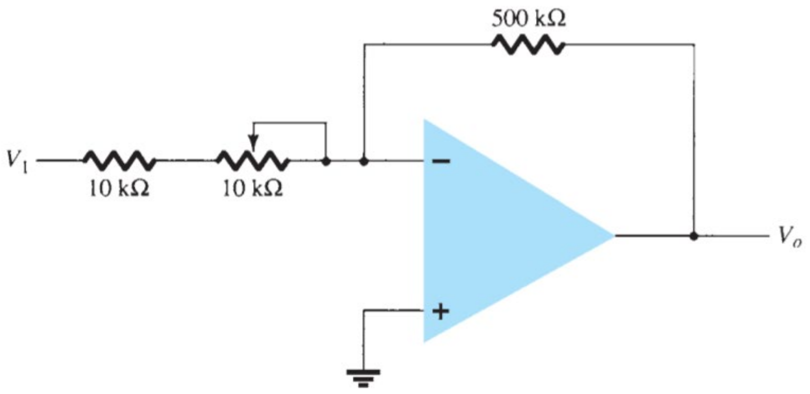
Problem 1 (Boylestad and Nashelsky, 2013, w/ permission)

Find the output voltage in the inverting amplifier circuit illustrated below.



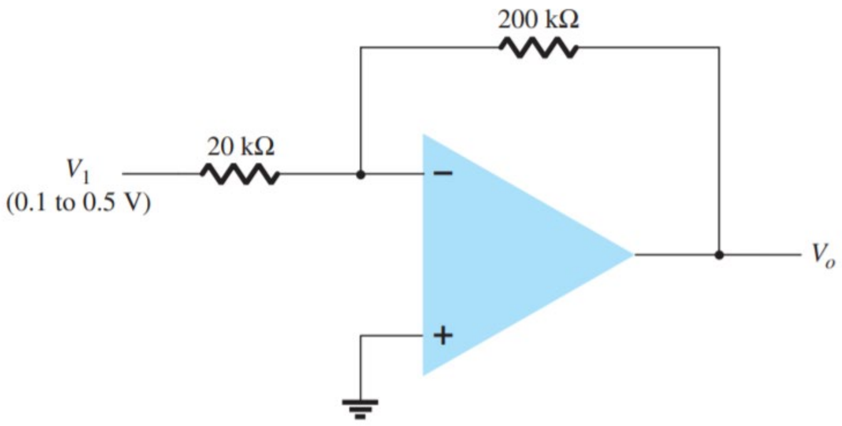
Problem 2 (Boylestad and Nashelsky, 2013, w/ permission)

Find the range of the voltage-gain adjustment of the inverting amplifier circuit illustrated below.



Problem 3 (Boylestad and Nashelsky, 2013, w/ permission)

What is the range of the output voltage in the inverting amplifier circuit illustrated below if the input can vary from 0.1 to 0.5 V?

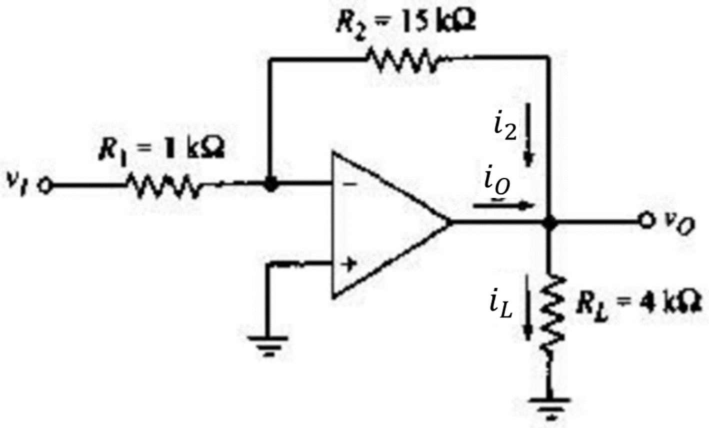


Problem 4 (Neamen, 2000)

The input to the inverting amplifier circuit illustrated below is v_I = 10*sin ωt.* mV.

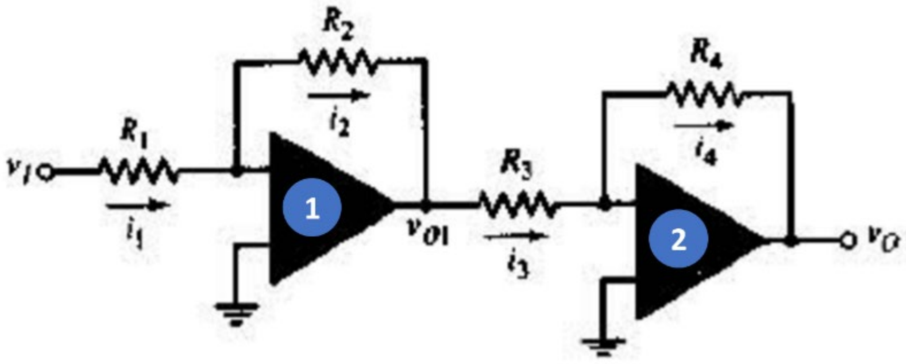
Problem 4.1: What is the output voltage v_O?

Problem 4.2: Determine the currents i_2, i_L, and i_O.



Problem 5 (Neamen, 2000)

Consider two inverting op-amp circuits connected in cascade, as shown below. Let R_1 = 10 kΩ, R_2 = 50 kΩ, R_3 = 25 kΩ, and R_4 = 150 kΩ. If the input voltage is v_I = 0.15 V, calculate v_{OI}, v_O, i_1, i_2, i_3, and i_4.



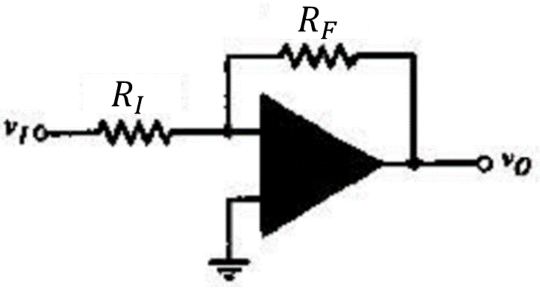
Problem 6 (Neamen, 2000)

The simple inverting amplifier circuit illustrated below has R_I = 10 kΩ, R_F = 50 kΩ, and finite open-loop differential gain A_{od} = 2×10⁵. The input voltage is from an ideal voltage source whose value is v_I = 100 mV.

Problem 6.1: Calculate the closed-loop voltage gain. Use 5 decimal places.

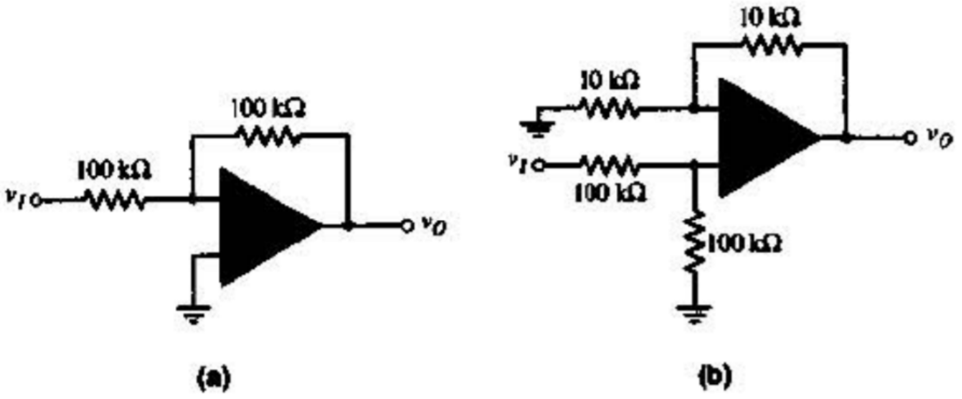
Problem 6.2: Using the closed-loop voltage gain, compute the output voltage.

Problem 6.3: Calculate the error in the output voltage due to the finite open-loop gain.



Problem 7 (Neamen, 2000)

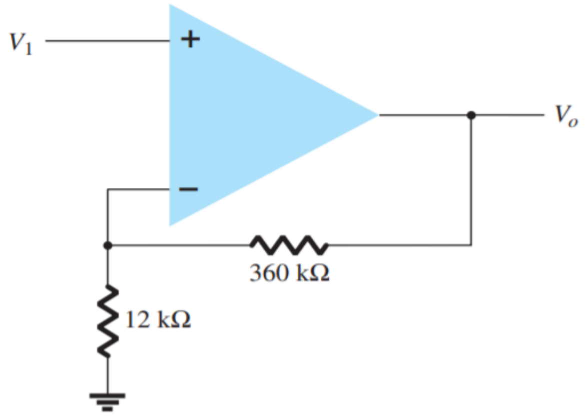
Consider the two op-amp circuits illustrated below. If the open-loop differential gain for each op-amp is $A_{od} = 10^3$, determine the output voltage v_O when v_I = 2 V.



Problem 8 (Boylestad and Nashelsky, 2013, w/ permission)

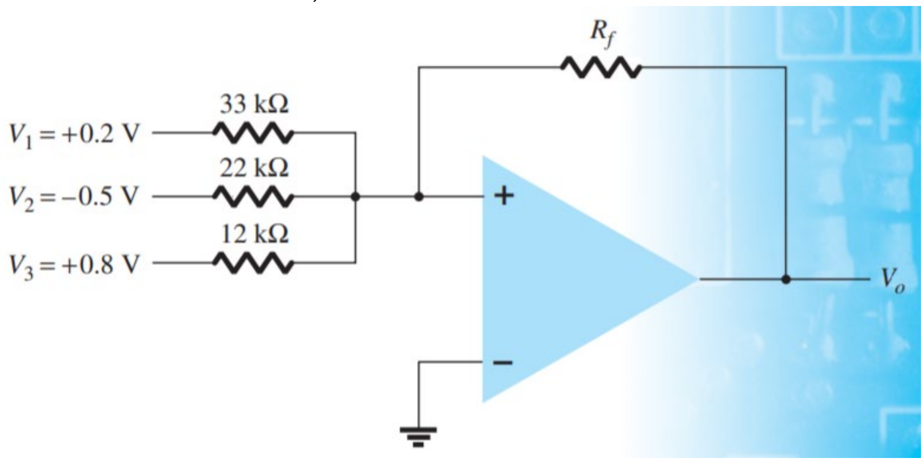
Problem 8.1: What output voltage results in the noninverting amplifier circuit illustrated to the side if the input voltage $V_1 = -0.3$ V?

Problem 8.2: What input voltage must be applied to result in an output of 2.4 V?



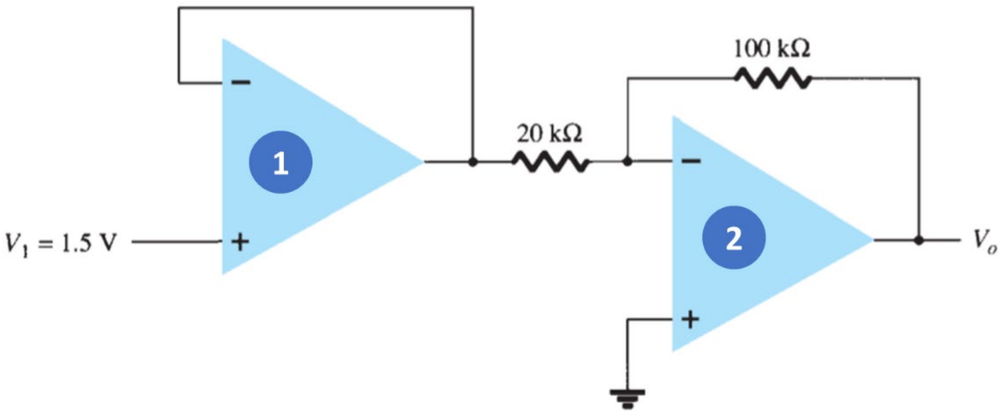
Problem 9 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the output voltage developed by the summing amplifier circuit illustrated below if $R_f = 330$ kΩ.



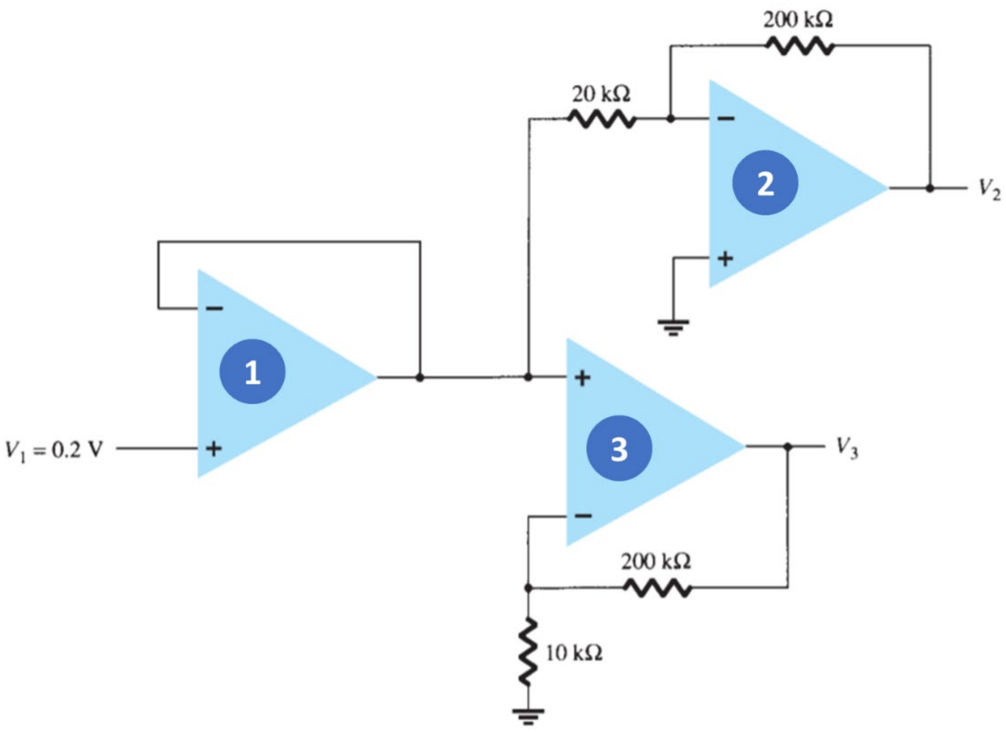
Problem 10 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the output voltage V_o for the two-amplifier circuit illustrated below.



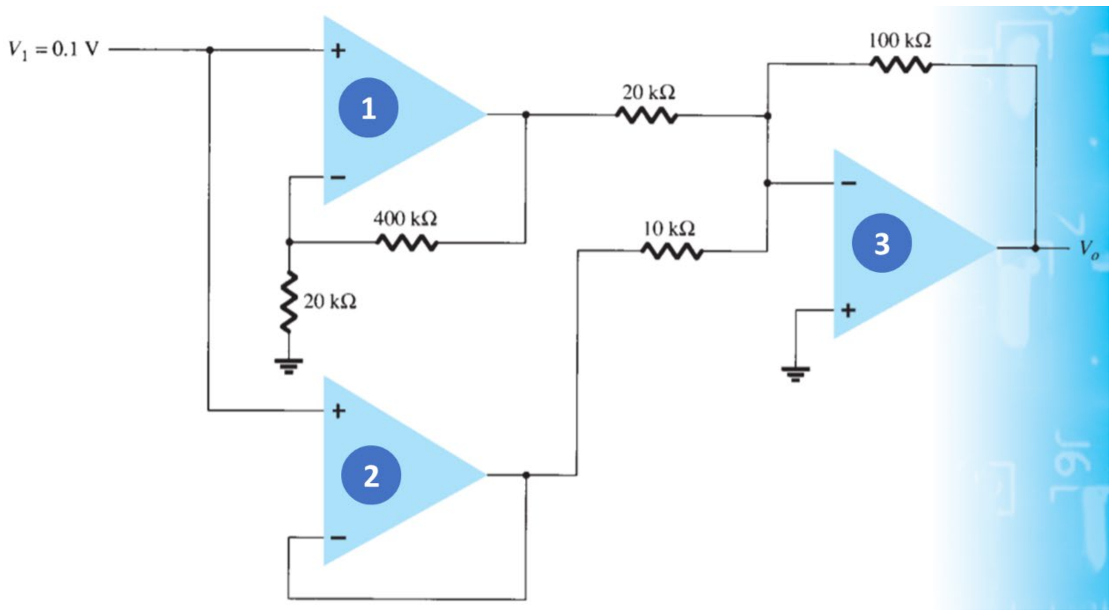
Problem 11 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the output voltages V_2 and V_3 in the circuit illustrated below.



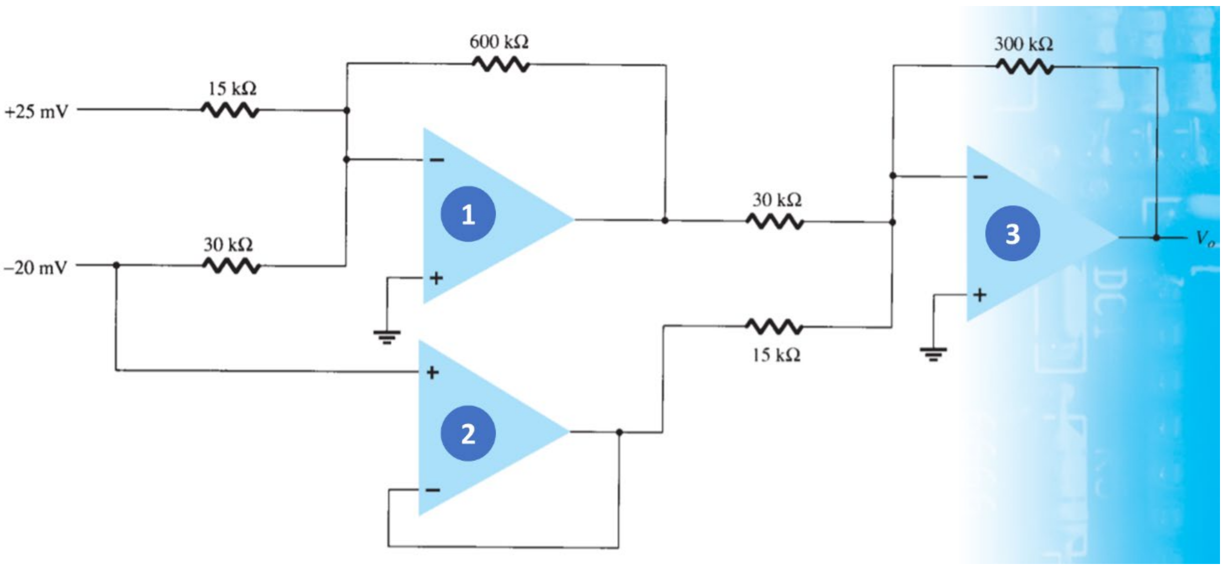
Problem 12 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the output voltage V_o in the circuit illustrated below.



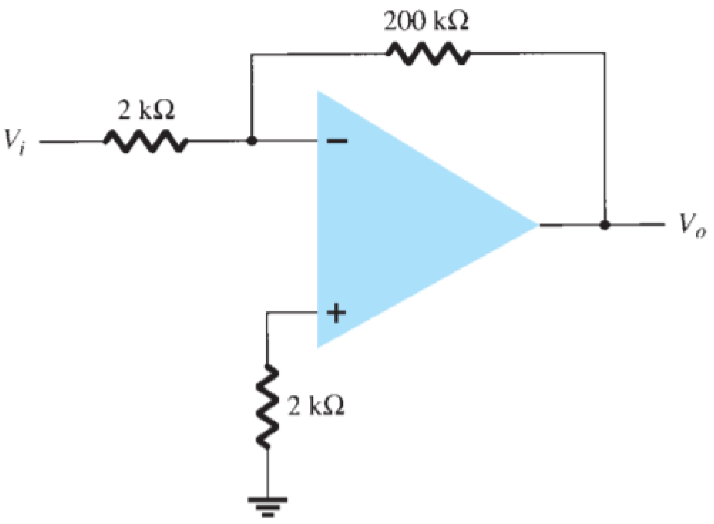
Problem 13 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the output voltage V_o in the circuit illustrated below.



Problem 14 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the total offset voltage for the circuit illustrated below if the op-amp has specified values of input offset voltage V_{IO} = 6 mV and input offset current I_{IO} = 120 nA.



Problem 15 (Boylestad and Nashelsky, 2013, w/ permission)

For an op-amp having a slew rate of SR = 2.4 V/μs, what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.3 V in 10 μs?

Problem 16 (Boylestad and Nashelsky, 2013, w/ permission)

Determine the cutoff frequency f_C of an op-amp having specified values of unity-gain bandwidth B_1 = 800 kHz and voltage differential gain A_{VD} = 150 V/mV.

Problem 17 (Boylestad and Nashelsky, 2013, w/ permission)

For an input of V_1 = 50 mV in the circuit of Problem 14, determine the maximum frequency that may be used. The op-amp slew rate is 0.4 V/μs.

Problem 18 (Boylestad and Nashelsky, 2013, w/ permission)

Table 1 lists the specifications for the μA741 operational amplifier. Using those data, specify the typical offset voltage for the circuit connection introduced in Problem 14.

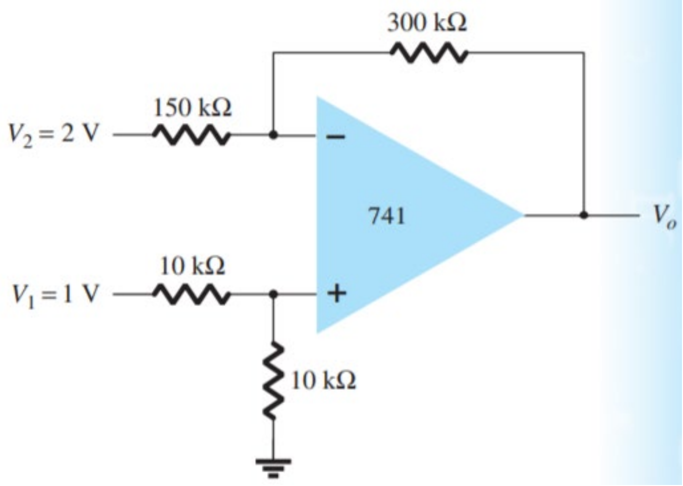
Problem 19 (Boylestad and Nashelsky, 2013, w/ permission)

For the typical characteristics of the 741 op-amp, calculate the following values for the circuit introduced in Problem 14:

1. The closed-loop gain A_{CL}.
2. The input impedance Z_i.
3. The output impedance Z_o.

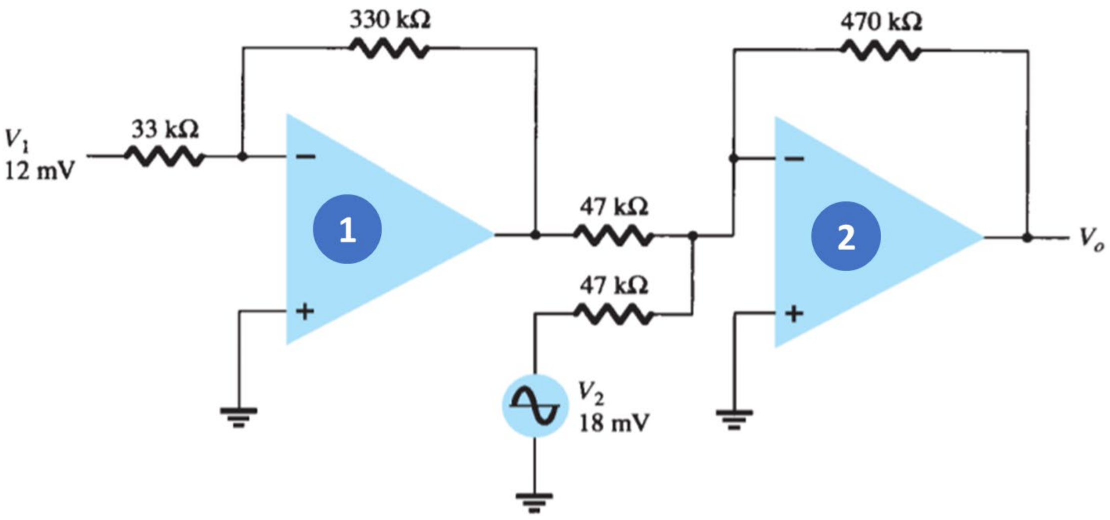
Problem 20 (Boylestad and Nashelsky, 2013, w/ permission)

Determine the output voltage V_o for the circuit illustrated below.



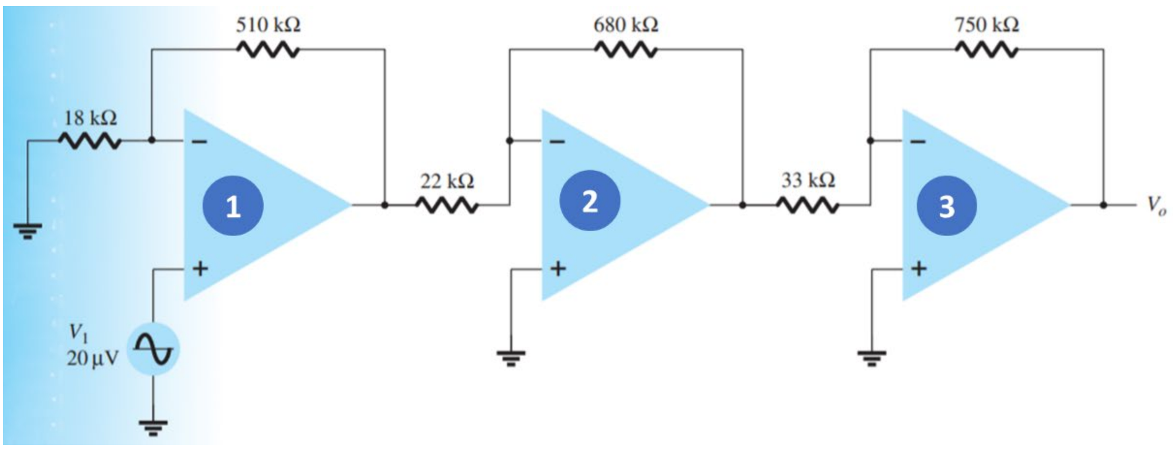
Problem 21 (Boylestad and Nashelsky, 2013, w/ permission)

Determine the output voltage V_o for the circuit illustrated below.



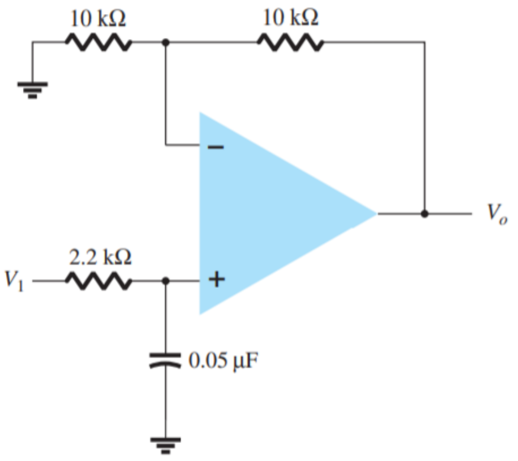
Problem 22 (Boylestad and Nashelsky, 2013, w/ permission)

Determine the output voltage for the multiple-stage gain circuit illustrated below.



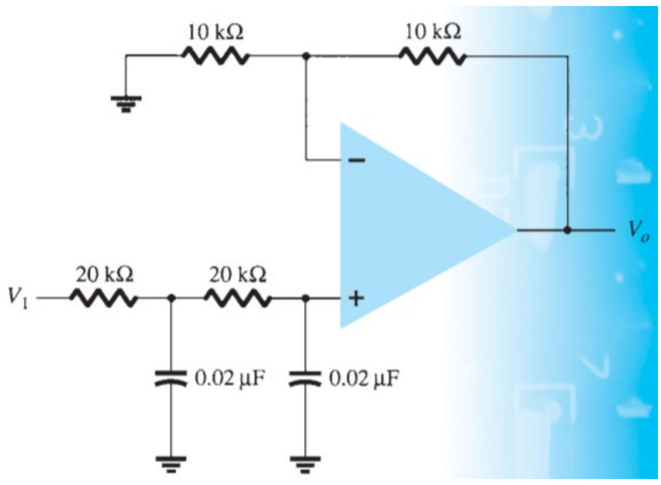
Problem 23 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the cutoff frequency of a first-order low-pass filter in the circuit illustrated below.



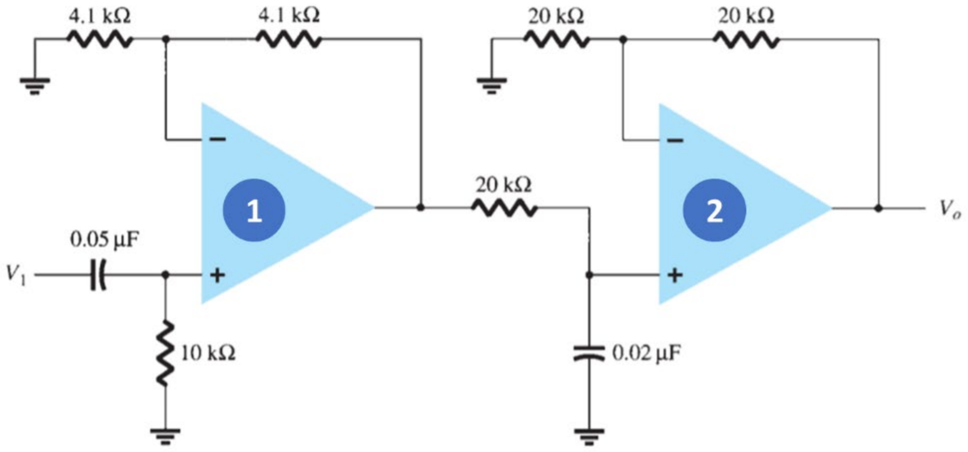
Problem 24 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the cutoff frequency of the high-pass filter circuit in the circuit illustrated below.



Problem 25 (Boylestad and Nashelsky, 2013, w/ permission)

Calculate the lower and upper cutoff frequencies of the bandpass filter circuit illustrated below.



ADDITIONAL INFORMATION

Table 1 Electrical characteristics of the μA741 operational amplifier

μA741 Electrical Characteristics: $V_{CC} = \pm 15$ V, $T_A = 25°C$

Characteristic	Minimum	Typical	Maximum	Unit
V_{IO} Input offset voltage		1	6	mV
I_{IO} Input offset current		20	200	nA
I_{IB} Input bias current		80	500	nA
V_{ICR} Common-mode input voltage range	±12	±13		V
V_{OM} Maximum peak output voltage swing	±12	±14		V
A_{VD} Large-signal differential voltage amplification	20	200		V/mV
r_i Input resistance	0.3	2		MΩ
r_o Output resistance		75		Ω
C_i Input capacitance		1.4		pF
CMRR Common-mode rejection ratio	70	90		dB
I_{CC} Supply current		1.7	2.8	mA
P_D Total power dissipation		50	85	mW

Equations

1 → Voltage gain in an inverting amplifier

$$\frac{V_o}{V_I} = -\frac{R_F}{R_I}$$

where V_o is output voltage, V_I is input voltage, R_F is feedback resistance, and R_I is input resistance.

2 → Closed -loop gain of an inverting amplifier

$$A_{CL} = -\frac{R_F}{R_I} \times \frac{1}{\left[1 + \frac{1}{A_{od}}\left(1 + \frac{R_F}{R_I}\right)\right]}$$

where R_F is feedback resistance, R_I is input resistance, and A_{od} is open-loop differential gain.

3 → Voltage gain in a non-inverting amplifier

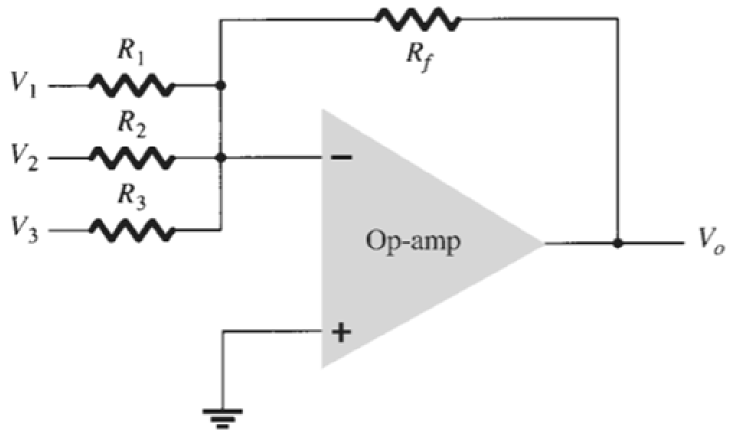
$$\frac{V_o}{V_I} = \left(1 + \frac{R_F}{R_I}\right)$$

where V_o is output voltage, V_I is input voltage, R_F is feedback resistance, and R_I is input resistance.

4 → Output voltage in a summing amplifier

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

where variables are defined in the illustration below.



5 → Offset voltage across an op-amp

$$V_o(\text{offset}) = \left(1 + \frac{R_f}{R_I}\right)V_{IO} + I_{IO}R_f$$

where, in addition to the familiar resistance variables, we have the input offset voltage V_{IO} and the input offset current I_{IO}.

6 → Slew rate

$$SR = \frac{\Delta V_o}{\Delta t}$$

that is, slew rate is defined as the maximum rate of change of output when driven by a large step-input signal.

7 → Maximum signal frequency

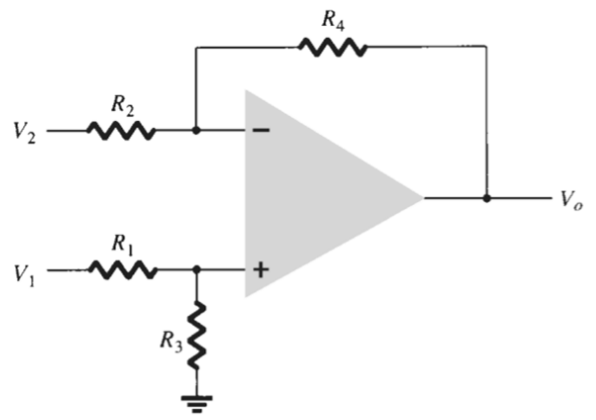
$$f_{\max} = \frac{\text{SR}}{2\pi K}$$

where *SR* is slew ratio and *K* is the amplitude of a sinusoidal signal of general form $v_o = K\sin(2\pi ft)$.

8 → Voltage subtraction – arrangement 1

$$V_o = \frac{R_3}{R_1 + R_3}\left(\frac{R_2 + R_4}{R_2}\right)V_1 - \frac{R_4}{R_2}V_2$$

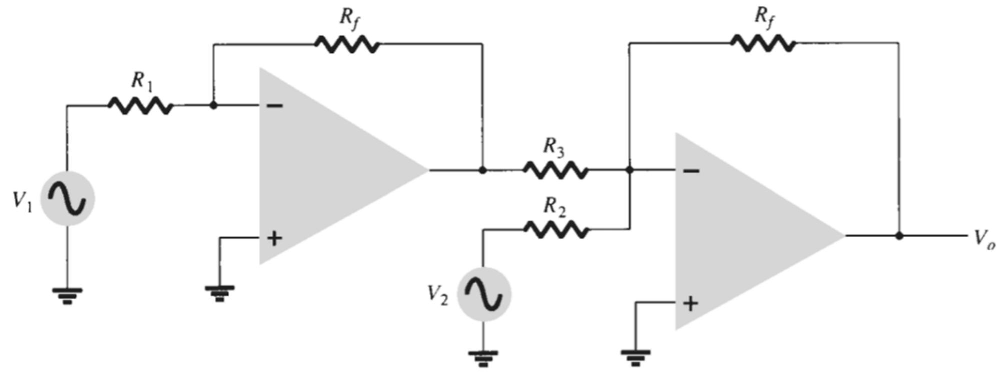
where variables are defined in the illustration below.



9 → Voltage subtraction – arrangement 2

$$V_o = -\left(\frac{R_{f,2}}{R_2} V_2 - \frac{R_{f,2}}{R_3} \frac{R_{f,1}}{R_1} V_1 \right)$$

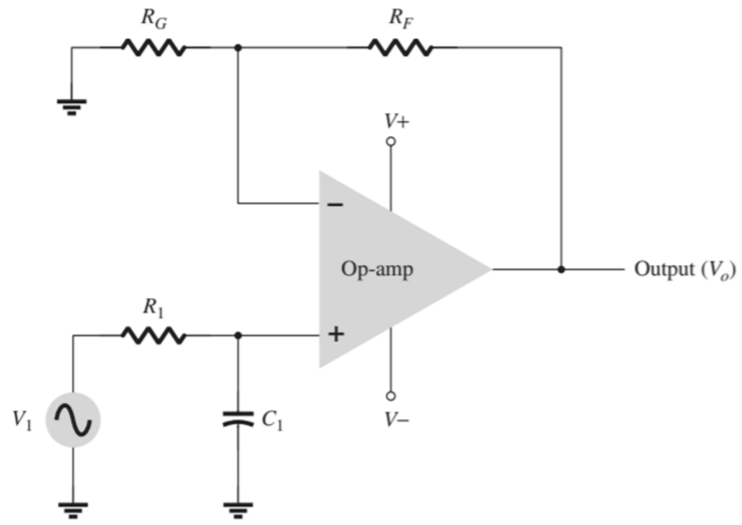
where variables are defined in the illustration below.



10 → Cutoff frequency of a first-order low-pass filter

$$f_{OH} = \frac{1}{2\pi R_1 C_1}$$

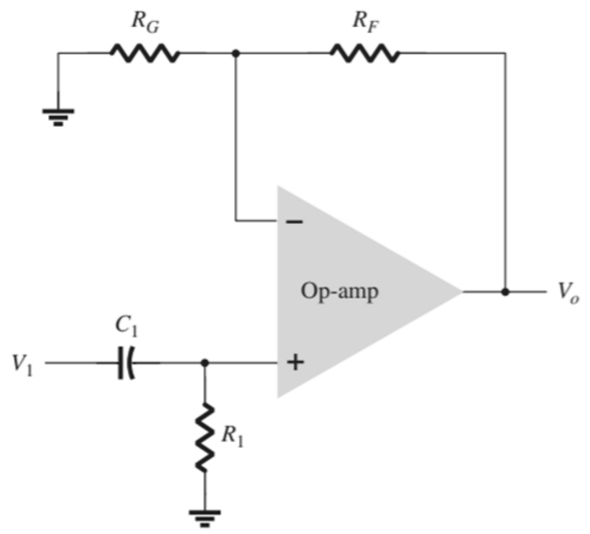
where variables are defined in the illustration below.



11 → Cutoff frequency of a first-order high-pass filter

$$f_{OL} = \frac{1}{2\pi R_1 C_1}$$

where variables are defined in the illustration below.



SOLUTIONS

P.1 Solution

The output voltage is given by equation 1,

$$V_o = -\frac{R_F}{R_I}V_I = -\frac{250}{20}\times 1.5 = \boxed{-18.75\ \text{V}}$$

P.2 Solution

The voltage-gain adjustment varies with input resistance R_I, which in the present case consists of a constant 10-kΩ resistance connected in series to a variable resistance that can yield 10 kΩ at most. In the mildest case, the variable resistance offers 0 Ω and the input resistance becomes R_I = 10 + 0 = 10 kΩ, yielding a voltage-gain adjustment

$$A_v = \frac{V_o}{V_i} = -\frac{R_F}{R_I} = -\frac{500}{10} = -50$$

In the most severe case, the variable resistance is set to 10 kΩ and the input resistance becomes R_I = 10 + 10 = 20 kΩ, leading to a voltage-gain adjustment

$$A_v = \frac{V_o}{V_i} = -\frac{R_F}{R_I} = -\frac{500}{20} = -25$$

Thus, $|A_v| \in [25, 50]$.

P.3 Solution

This system can be modelled similarly to the one in Problem 2, the difference being that the input voltage, not the input resistance, is a variable parameter. V_0 is given by equation 1,

$$V_o = -\frac{R_F}{R_1}V_1 = -\frac{200}{20}V_1 = -10V_1$$

so that, with V_I = 0.1 V,

$$V_1 = -10\times 0.1 = -1\ \text{V}$$

and, with V_1 = 0.5 V,

$$V_1 = -10\times 0.5 = -5\ \text{V}$$

Thus, $|V_1| \in [1, 5]$ V.

P.4 Solution

Problem 4.1: The voltage gain is given by

$$A_v = -\frac{R_2}{R_1} = -\frac{15}{1.0} = -15$$

so that

$$v_O = -15v_I = -15\times 10\sin\omega t = \boxed{-150\sin\omega t\,[\text{mV}]}$$

Problem 4.2: Let i_I denote the current stemming directly from the source node. Current i_2 is identical to i_I and can be determined as

$$i_2 = i_I = \frac{v_I}{R} = \frac{\left(10\times 10^{-3}\right)\times\sin\omega t}{1.0\times 10^3} = \left(10\times 10^{-6}\right)\sin\omega t\ \text{A} = \boxed{10\sin\omega t\,[\mu\text{A}]}$$

The current i_L flowing through load resitance R_L is, in turn,

$$i_L = \frac{v_O}{R_L} = -\frac{\left(150\times 10^{-3}\right)\sin\omega t}{4\times 10^3} = -\left(37.5\times 10^{-6}\right)\sin\omega t\ \text{A} = \boxed{-37.5\sin\omega t\,[\mu\text{A}]}$$

Lastly, i_O follows from Kirchhoff's current law,

$$i_O = i_L - i_2 = -37.5\sin\omega t - 10\sin\omega t = \boxed{-47.5\sin\omega t\,[\mu\text{A}]}$$

P.5 Solution

First, voltage v_{OI} is the output voltage of inverting amplifier 1 and can be determined as

$$v_{OI} = -\frac{R_2}{R_1} v_I = -\frac{50}{10} \times 0.15 = \boxed{-0.75\,\text{V}}$$

Next, voltage v_O is the output voltage of inverting amplifier 2, which is fed with v_{OI} as input, giving

$$v_O = -\frac{R_4}{R_3} v_{OI} = -\frac{150}{25} \times (-0.75) = \boxed{4.5\,\text{V}}$$

Current i_1 can be determined by applying Ohm's law to the first resistor in the cascade,

$$i_1 = \frac{v_I}{R_1} = \frac{0.15}{10 \times 10^3} = 1.5 \times 10^{-5}\ \text{A} = \boxed{15\,\mu\text{A}}$$

Current i_2 has the same intensity and direction as i_1,

$$i_2 = i_1 = \boxed{15\,\mu\text{A}}$$

Current i_3 is calculated by applying Ohm's law to resistor R_3,

$$i_3 = \frac{v_{OI}}{R_3} = -\frac{0.75}{25 \times 10^3} = -3.0 \times 10^{-5}\ \text{A} = \boxed{-30\,\mu\text{A}}$$

The negative sign indicates that the current flows toward amplifier 1, which must sink 30 + 15 = 45 μA. Lastly, current i_4 has the same intensity and direction as i_3,

$$i_4 = i_3 = \boxed{-30\,\mu\text{A}}$$

P.6 ➡ *Solution*

Problem 6.1: The closed-loop voltage gain is given by equation 2,

$$A_{CL} = -\frac{R_F}{R_I} \times \frac{1}{\left[1 + \frac{1}{A_{od}}\left(1 + \frac{R_F}{R_I}\right)\right]} = -\frac{50}{10} \times \frac{1}{\left[1 + \frac{1}{2 \times 10^5} \times \left(1 + \frac{50}{10}\right)\right]} = \boxed{-4.99985}$$

Problem 6.2: The output voltage is

$$v_o = -A_{CL} v_i = -4.99985 \times 100 = \boxed{-499.985\,\text{mV}}$$

Problem 6.3: Ideally, the output voltage is $\bar{v}_o = -500$ mV. The error due to finite open-loop gain is

$$\text{Error} = \frac{500 - 499.985}{500} \times 100\% = \boxed{0.003\%}$$

P.7 ➡ *Solution*

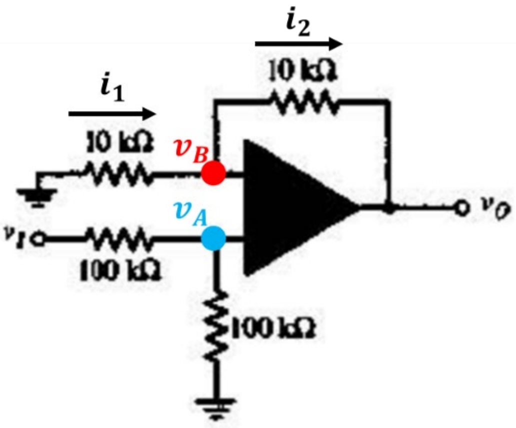
Consider first arrangement (*a*). The closed-loop voltage gain is given by equation 2,

$$A_{CL} = -\frac{R_F}{R_I} \times \frac{1}{\left[1 + \frac{1}{A_{od}}\left(1 + \frac{R_F}{R_I}\right)\right]} = -\frac{100}{100} \times \frac{1}{\left[1 + \frac{1}{10^3} \times \left(1 + \frac{100}{100}\right)\right]} = -0.9980$$

and the output voltage v_o with v_I = 2 V becomes

$$v_O = A_{CL} v_I = -0.998 \times 2 = \boxed{-1.996\,\text{V}}$$

Arrangement (*b*) is a little trickier to investigate. Let the voltage just before the junction connected to the positive terminal of the amplifier be v_A, and the voltage just before the junction connected to the negative terminal of the amplifier be v_B. It can be shown that output voltage v_O is given by



$$v_O = A_{od}(v_A - v_B) \quad \text{(I)}$$

Also, if the current flowing through resistor 1 is to be the same as that flowing through resistor 2, we may write

$$\frac{v_B}{R_1} = \frac{v_O - v_B}{R_2} \rightarrow \frac{v_B}{R_1} = \frac{v_O}{R_2} - \frac{v_B}{R_2}$$

$$\therefore \frac{v_B}{R_1} + \frac{v_B}{R_2} = \frac{v_O}{R_2}$$

$$\therefore v_B\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{v_O}{R_2}$$

$$\therefore v_B = \frac{\frac{v_O}{R_2}}{\left(\frac{1}{R_1} + \frac{1}{R_2}\right)}$$

$$\therefore v_B = \frac{v_O}{\left(1 + \frac{R_2}{R_1}\right)}$$

Substituting in (I),

$$v_O = A_{od}\left(v_A - v_B\right) \rightarrow v_O = A_{od} v_A - A_{od} v_B$$

$$\therefore v_O = A_{od} v_A - \frac{A_{od} v_O}{\left(1 + \frac{R_2}{R_1}\right)}$$

$$\therefore v_O + \frac{A_{od} v_O}{\left(1 + \frac{R_2}{R_1}\right)} = A_{od} v_A$$

$$\therefore v_O\left[1 + \frac{A_{od}}{\left(1 + \frac{R_2}{R_1}\right)}\right] = A_{od} v_A$$

$$\therefore v_O\left[\frac{\left(1 + \frac{R_2}{R_1}\right) + A_{od}}{\left(1 + \frac{R_2}{R_1}\right)}\right] = A_{od} v_A$$

$$\therefore v_O = \frac{A_{od} v_A \left(1 + \frac{R_2}{R_1}\right)}{\left(1 + \frac{R_2}{R_1}\right) + A_{od}}$$

$$\therefore v_O = \frac{\left(1 + \frac{R_2}{R_1}\right) v_A}{1 + \frac{1}{A_{od}}\left(1 + \frac{R_2}{R_1}\right)}$$

Thus, with an input voltage of 2 V and noting that $v_I = v_A/2 = 2$ V, we obtain

$$v_O = \frac{\left(1 + \frac{R_2}{R_1}\right) \times \frac{v_I}{2}}{1 + \frac{1}{A_{od}}\left(1 + \frac{R_2}{R_1}\right)} = \frac{\left(1 + \frac{10}{10}\right) \times \frac{2}{2}}{1 + \frac{1}{10^3}\left(1 + \frac{10}{10}\right)} = \boxed{1.9960\text{ V}}$$

P.8 ➡ *Solution*

Problem 8.1: The output voltage is given by equation 3,

$$V_o = \left(1 + \frac{R_F}{R_I}\right)V_I = \left(1 + \frac{360}{12}\right) \times (-0.3) = \boxed{-9.3\text{ V}}$$

Problem 8.2: Setting V_o = 2.4 V in equation 3 and solving for input voltage, we get

$$V_o = \left(1+\frac{R_F}{R_I}\right)V_I = 2.4 \to V_I = \frac{2.4}{1+\frac{R_F}{R_I}}$$

$$\therefore V_I = \frac{2.4}{\frac{R_I+R_F}{R_I}}$$

$$\therefore V_I = \frac{2.4R_I}{R_I+R_F}$$

$$\therefore V_I = \frac{2.4\times 12}{12+360} = 0.0774\text{ V} = \boxed{77.4\text{ mV}}$$

P.9 ➡ *Solution*

This is a straightforward application of equation 4,

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right) = -330\times\left(\frac{0.2}{33} - \frac{0.5}{22} + \frac{0.8}{12}\right) = \boxed{-16.5\text{ V}}$$

P.10 ➡ *Solution*

Notice that the amplifier closest to the input node has its positive terminal connected to the voltage source and its negative terminal connected to the output; accordingly, this amplifier is functioning as a buffer. Because the gain of a buffer amplifier is unity, we may write

$$A_v = \frac{v_o}{V_I} = 1 \to v_o = V_I = 1.5\text{ V}$$

Since v_0 = 1.5 V serves as input for the inverting amplifier, the final output voltage is calculated to be

$$V_o = -\frac{R_f}{R_I}V_I = -\frac{R_f}{R_I}v_o = -\frac{100}{20}\times 1.5 = \boxed{-7.5\text{ V}}$$

P.11 ➡ *Solution*

Amplifier 1 is a buffer and therefore maintains the same voltage magnitude in its output. Amplifier 2 is fed a voltage of 0.2 V and functions as an inverter with output voltage V_2 such that (equation 1)

$$V_2 = -\frac{R_f}{R_I}V_I = -\frac{200}{20}\times 0.2 = \boxed{-2\text{ V}}$$

Amplifier 3 likewise receives a voltage of 0.2 V as input; by inspection, we see that it functions as a noninverting amp, which means that its output voltage V_3 can be determined with equation 3,

$$V_3 = \left(1+\frac{R_F}{R_I}\right)V_I = \left(1+\frac{200}{10}\right)\times 0.2 = \boxed{+4.2\text{ V}}$$

P.12 ➡ *Solution*

Firstly, amplifier 1 functions as a noninverter and yields a voltage v_1 such that

$$v_1 = \left(1+\frac{R_F}{R_I}\right)V_1 = \left(1+\frac{400}{20}\right)\times 0.1 = 2.1\text{ V}$$

Amplifier 2 is a buffer and outputs the same voltage that it receives, namely v_2 = 0.1 V. Lastly, amplifier 3 functions as a summing amplifier that receives inputs from amps 1 (v_1 = 2.1 V) and 2 (v_2 = 0.1 V), so that (equation 4)

$$V_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2\right) = -\left(\frac{100}{20}\times 2.1 + \frac{100}{10}\times 0.1\right) = \boxed{-11.5\text{ V}}$$

P.13 ➡ *Solution*

Firstly, device 1 functions as an adding amplifier with output voltage v_1 such that (equation 4)

$$v_1 = -\left(\frac{R_f}{R_1}V_{I,1} + \frac{R_f}{R_2}V_{I,2}\right) = -\left[\frac{600}{15}\times\left(25\times10^{-3}\right) + \frac{600}{30}\times\left(-20\times10^{-3}\right)\right] = -0.6\text{ V}$$

Amplifier 2 is a buffer and outputs the same voltage that it receives, namely $v_2 = -20$ mV. The third and last amplifier is an adding amp fed by the output of amplifier 1, $v_1 = -0.6$ V, and the output of amplifier 2, $v_2 = -20$ mV, so that

$$V_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2\right) = -\left[\frac{300}{30}\times(-0.6) + \frac{300}{15}\times(-0.02)\right] = \boxed{+6.4\text{ V}}$$

P.14 ➡ Solution

The total offset voltage consists of two contributions, one from the input offset voltage V_{IO} and another from the input offset current I_{IO}. Adding these two contributions yields the total offset voltage $V_o(offset)$ (equation 5),

$$V_o(\text{offset}) = \left(1 + \frac{R_f}{R_I}\right)V_{IO} + I_{IO}R_f = \left(1 + \frac{200}{2}\right)\times\left(6\times10^{-3}\right) + \left(120\times10^{-9}\right)\times\left(200\times10^3\right) = 0.63\text{ V}$$

$$\therefore \boxed{V_o(\text{offset}) = 630\text{ mV}}$$

P.15 ➡ Solution

Using $V_o = A_{CL}V_i$, we may write

$$\frac{\Delta V_o}{\Delta t} = A_{CL}\frac{\Delta V_i}{\Delta t}$$

The rate of change of amplifier output $\Delta V_o/\Delta t$ can be replaced with the slew rate SR (see equation 6), so that

$$\frac{\Delta V_o}{\Delta t} = A_{CL}\frac{\Delta V_i}{\Delta t} \to \text{SR} = A_{CL}\frac{\Delta V_i}{\Delta t}$$

$$\therefore A_{CL} = \frac{\text{SR}}{\Delta V_i/\Delta t} = \frac{2.4\text{ V/μs}}{0.3\text{ V/10 μs}} = \boxed{80}$$

P.16 ➡ Solution

The unity-gain bandwidth/frequency f_1 is given by the product of voltage differential gain A_{VD} and cutoff frequency f_C; solving for f_C, we obtain

$$f_1 = A_{VD}f_C \to f_C = \frac{f_1}{A_{VD}}$$

$$\therefore f_C = \frac{800\times10^3}{150\times10^3} = \boxed{5.33\text{ Hz}}$$

P.17 ➡ Solution

Referring to the circuit in Problem 14, the closed-loop gain is given by the ratio

$$|A_{CL}| = \frac{R_f}{R_I} = \frac{200}{2} = 100$$

It follows that the amplitude coefficient K of the output signal voltage v_o must be no greater than (equation 7)

$$K = A_{CL}V_i = 100\times\left(50\times10^{-3}\right) = 5\text{ V}$$

With this value of K and a slew rate of 0.4 V/μs, the maximum frequency is calculated to be

$$f_{\max} = \frac{\text{SR}}{2\pi K} = \frac{\left(0.4\times10^6\right)}{2\pi\times5} = 12{,}700\text{ Hz} = \boxed{12.7\text{ kHz}}$$

P.18 ➡ Solution

The offset voltage is given by equation 5; the only device information we need is the input offset voltage V_{IO} and the input offset current I_{IO}, whose typical values can be read as 1 mV and 20 nA, respectively. It follows that

$$V_o(\text{offset}) = \left(1 + \frac{R_f}{R_I}\right)V_{IO} + I_{IO}R_f = \left(1 + \frac{200}{2}\right)\times\left(1.0\times10^{-3}\right) + \left(20\times10^{-9}\right)\times\left(200\times10^3\right) = 0.105\text{ V}$$

$$\therefore \boxed{V_o(\text{offset}) = 105\text{ mV}}$$

P.19 ➡ *Solution*

The closed-loop gain A_{CL} can be estimated with the circuit resistances R_f and R_I only; there is no need to refer to the amp specifications:

$$A_{CL} = -\frac{R_f}{R_I} = -\frac{200}{2} = \boxed{-100}$$

Since the input impedance Z_i of the 741 is taken as zero, input impedance Z_I becomes equal to the input resistance of the circuit; that is,

$$Z_I = R_I = \boxed{2\,\text{k}\Omega}$$

The output impedance is given by

$$Z_o = \frac{r_o}{1+\beta A_{CL}}$$

Here, output resistance r_o is read from Table 1 to equal 75 Ω; the large-signal voltage amplification A_{VD} is read as 200 V/mV = 200×10^3 V/V; and the feedback coefficient β is approximated as the reciprocal of the closed-loop gain calculated just now,

$$\beta \approx \frac{1}{|A_{CL}|} = \frac{1}{100} = 0.01$$

so that

$$Z_o = \frac{75}{1+0.01\times\left(200\times10^3\right)} = \boxed{0.0375\,\Omega}$$

P.20 ➡ *Solution*

The circuit functions as a voltage-subtraction arrangement; the output voltage is given by equation 8,

$$V_o = \frac{R_3}{R_1+R_3}\left(\frac{R_2+R_4}{R_2}\right)V_1 - \frac{R_4}{R_2}V_2 = \frac{10}{10+10}\times\left(\frac{150+300}{150}\right)\times1.0 - \frac{300}{150}\times2.0 = \boxed{-2.5\,\text{V}}$$

P.21 ➡ *Solution*

Much like the one in Problem 20, this is a voltage-subtraction configuration. The output voltage can be shown to be (equation 9)

$$V_o = -\left(\frac{R_{f,2}}{R_2}V_2 - \frac{R_{f,2}}{R_3}\frac{R_{f,1}}{R_1}V_1\right) = -\left(\frac{470}{47}\times18 - \frac{470}{47}\times\frac{330}{33}\times12\right) = 1020\,\text{mV}$$

$$\therefore \boxed{V_o = +1.02\,\text{V}}$$

P.22 ➡ *Solution*

In a multiple-stage gain circuit such as the one in question, the overall gain is the product of the individual stage gains. In this circuit, the first stage is connected to provide noninverting gain A_1 given by equation 1, while amps 2 and 3 provide inverting gains A_2 and A_3 that can be computed with equation 3. Thus,

$$A = A_1A_2A_3$$

where

$$A_1 = \left(1+\frac{R_f}{R_1}\right) = \left(1+\frac{510}{18}\right) = 29.3$$

$$A_2 = -\frac{R_f}{R_2} = -\frac{680}{22} = -30.9$$

and

$$A_3 = -\frac{R_f}{R_2} = -\frac{750}{33} = -22.7$$

The output voltage follows as

$$V_o = A_1A_2A_3V_I = 29.3\times(-30.9)\times(-22.7)\times\left(20\times10^{-6}\right) = 0.411\text{ V}$$

$$\therefore \boxed{V_o = 411\,\text{mV}}$$

P.23 ➡ *Solution*

Simply apply equation 10,

$$f_{OH} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi \times \left(2.2\times 10^3\right)\times\left(0.05\times 10^{-6}\right)} = 1450\,\text{Hz} = \boxed{1.45\,\text{kHz}}$$

P.24 ➡ *Solution*

This is a second-order filter with $R_1 = R_2 = 20$ kΩ and $C_1 = C_2 = 0.02$ μF; its cutoff frequency can be determined from equation 11,

$$f_{OL} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi \times \left(20\times 10^3\right)\times\left(0.02\times 10^{-6}\right)} = \boxed{398\,\text{Hz}}$$

P.25 ➡ *Solution*

This circuit is a bandpass filter. The junctions connected to amp 1 constitute the high-pass section; noting that $R_1 = 10$ kΩ and $C_1 = 0.05$ μF, the cutoff frequency f_{OL} can be determined as

$$f_{OL} = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi \times \left(10\times 10^3\right)\times\left(0.05\times 10^{-6}\right)} = \boxed{318\,\text{Hz}}$$

The junctions connected to amp 2 make up the low-pass section; with $R_2 = 20$ kΩ and $C_2 = 0.02$ μF, cutoff frequency f_{OH} is calculated to be

$$f_{OH} = \frac{1}{2\pi R_2 C_2} = \frac{1}{2\pi \times \left(20\times 10^3\right)\times\left(0.02\times 10^{-6}\right)} = \boxed{398\,\text{Hz}}$$

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