Lec-15

- Operational Amplifier
- Decibel & Bode Plot

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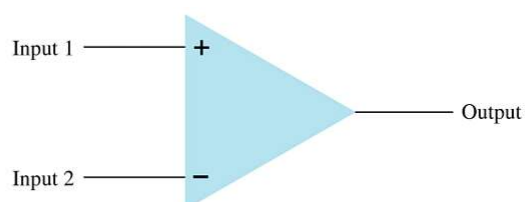
Basic Op-Amp



Operational amplifier or op-amp, is a very high gain differential amplifier with a high input impedance (typically a few meg-Ohms) and low output impedance (less than 100 Ω).

Note the op-amp has two inputs and one output.

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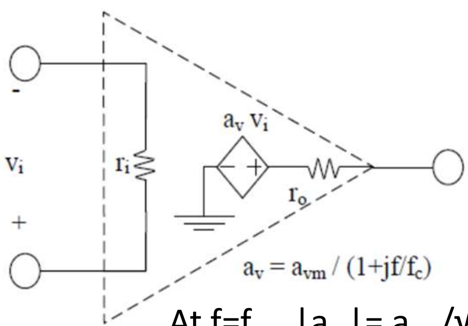
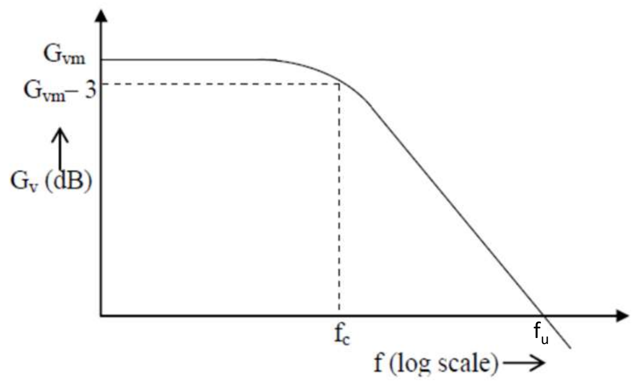
Amplifier and Bode Plot

Amplifier Model (VCVS)



At $f=f_c$, $|a_v| = a_{vm}/\sqrt{2}$

Frequency Response



G_{vm} is maximum overall gain across load with respect to applied signal.

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Bode Plots and Decibel

The voltage transfer function of a two-port network is usually expressed in Bel: (and/or the ratio of output to input

Number of Bels $= \log_{10}\left(\frac{P_o}{P_i}\right)$ or Number of Bels $= 2\log_{10}\left|\frac{V_o}{V_i}\right|$ because $P \propto V^2$

Bel is a large unit and decibel (dB) is usually used:

$$\text{Number of decibels} = 20\log_{10}\left|\frac{V_o}{V_i}\right| \quad \text{or} \quad \left|\frac{V_o}{V_i}\right|_{dB} = 20\log_{10}\left|\frac{V_o}{V_i}\right|$$

using dB definition, 3 dB difference between maximum gain and gain at the cut-off frequency:

$$20\log|H(j\omega_c)| - 20\log|H(j\omega)|_{max} = 20\log\left[\frac{|H(j\omega_c)|}{|H(j\omega)|_{max}}\right] = 20\log\left(\frac{1}{\sqrt{2}}\right) \approx -3 \text{ dB}$$

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Op-Amp Gain

Op-Amps have a very high gain. They can be connected open-loop or closed-loop.

- **Open-loop : gain can exceed 10,000.**

- **Closed-loop configuration reduces the gain.**
- **This feedback is a negative feedback. A negative feedback reduces the gain and improves many characteristics of the op-amp.**

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Basic Block Diagram with Negative Feedback used in Amplifiers

Assume:
- Voltage gain **A** is without feedback and $\mathbf{A_f}$ is with feedback.
- β is known as feedback ratio.

Let:

$$E = V_{in} - \beta V_{out}$$

$$V_{out} = AE = A(V_{in} - \beta Vout)$$

$$A_f = \frac{V_{out}}{V_{in}} = \frac{A}{1+A\beta}$$

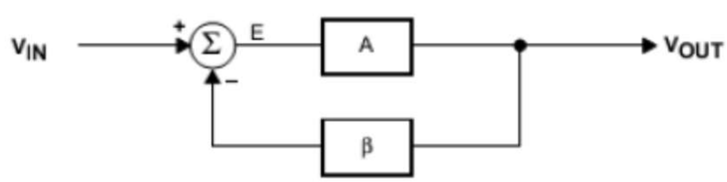

Figure 1 Basic block diagram explaining feedback

With Negative Feedback gain reduced as (1+Aβ)> 1

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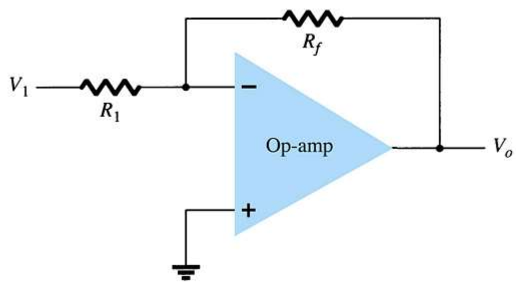
Inverting Op-Amp



- **The signal input is applied to the inverting (–) input**
- **The non-inverting input (+) is grounded**
- **The resistor R_f is the feedback resistor. It is connected from the output to the negative (inverting) input. This is *negative feedback*.**

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Inverting Op-Amp Gain

Gain can be determined from external resistors: R_f and R_1

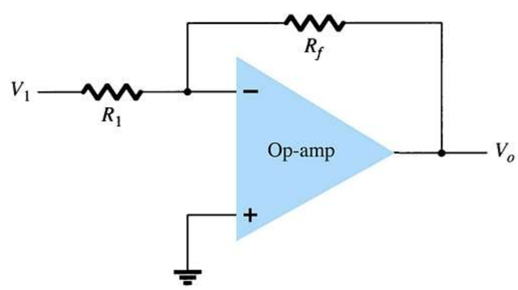
$$A_v = \frac{V_o}{V_i} = -\frac{R_f}{R_1}$$

Unity gain—voltage gain is 1

$$\mathbf{R_f = R_1}$$

$$\mathbf{A_v = \frac{-R_f}{R_1} = -1}$$

The negative sign denotes a 180° phase shift between input and output.



Constant Gain—R_f is a multiple of R_1

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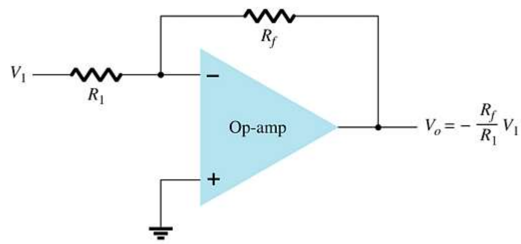
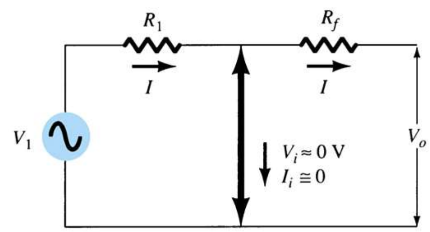
Virtual Ground

An understanding of the concept of virtual ground provides a better understanding of how an op-amp operates.



The *non-inverting* input pin is at ground. *The inverting* input pin is also at 0 V for an AC signal.



The op-amp has such high input impedance that even with a high gain there is no current from inverting input pin, therefore there is no voltage from inverting pin to ground—all of the current is through R_f.

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Ideal OpAmp Rule

1. No current ever flows into either input terminal . (current can flow at the output terminal).
2. there is no voltage difference between the 2 input terminals .

Note: This is valid for negative feedback case only.

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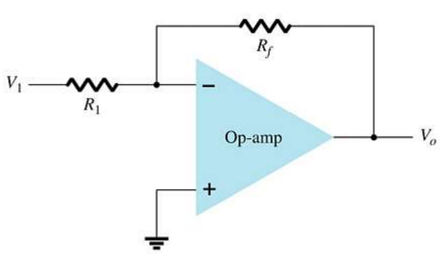
Practical Op-Amp Circuits

Inverting amplifier
Noninverting amplifier
Unity follower
Summing amplifier
Integrator
Differentiator

Inverting/Noninverting Op-Amps

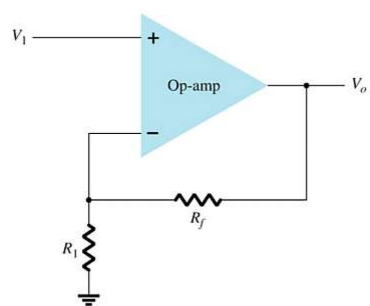
Inverting Amplifier

$$V_o = \frac{-R_f}{R_1} V_1$$



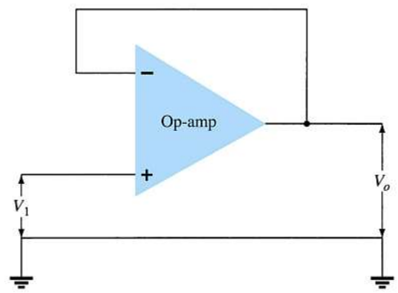
Noninverting Amplifier

$$V_o = (1 + \frac{R_f}{R_1}) V_1$$



Unity Follower

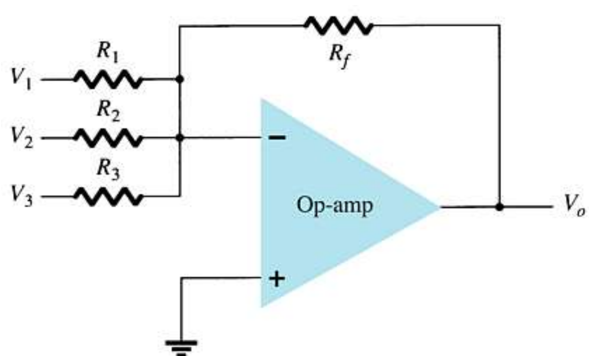
$$V_o = V_1$$



Summing Amplifier

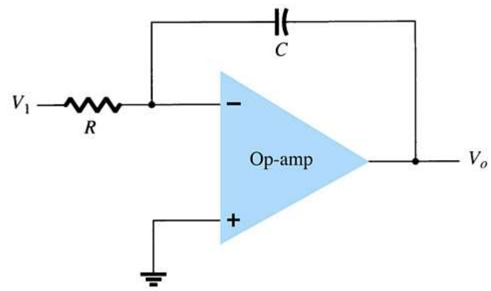
Because the op-amp has a high input impedance, the multiple inputs are treated as separate inputs.

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



Integrator

The output is the integral of the input. Integration is the operation of summing the area under a waveform or curve over a period of time. This circuit is useful in low-pass filter circuits and sensor conditioning circuits.



$$v_o(t) = -\frac{1}{RC}\int v_1(t)dt$$

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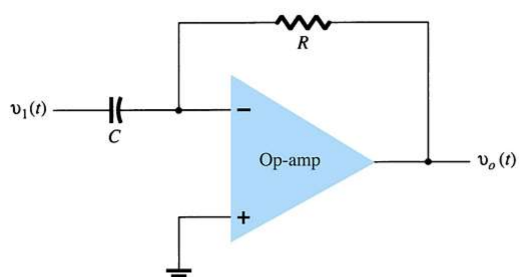
Differentiator

The differentiator takes the derivative of the input. This circuit is useful in high-pass filter circuits.



$$v_o(t) = -RC\frac{dv_1(t)}{dt}$$

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Electrical Characteristics

TABLE 13.2 mA741 Electrical Characteristics: $V_{CC} = \pm 15$ V, $T_A = 25°C$

Characteristic	*MIN*	*TYP*	*MAX*	*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

Note: These ratings are for specific circuit conditions, and they often include minimum, maximum and typical values.

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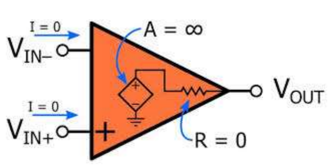
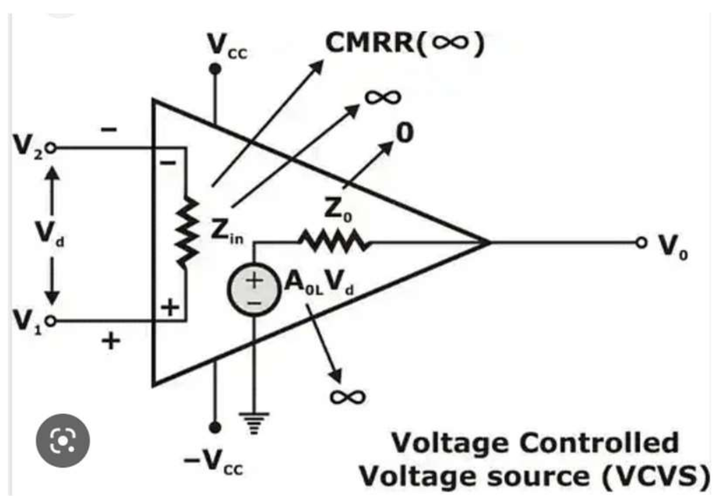
Ideal Op-AMP

Ideal OpAmp Model





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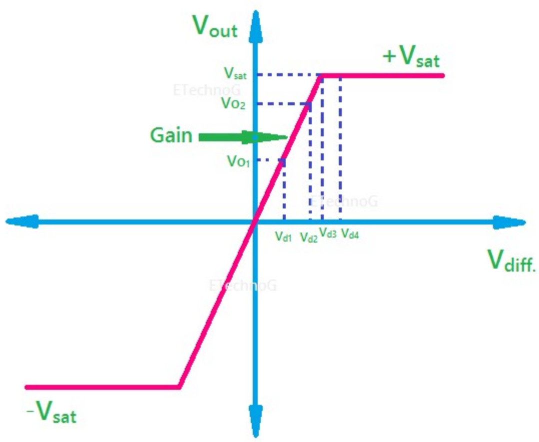
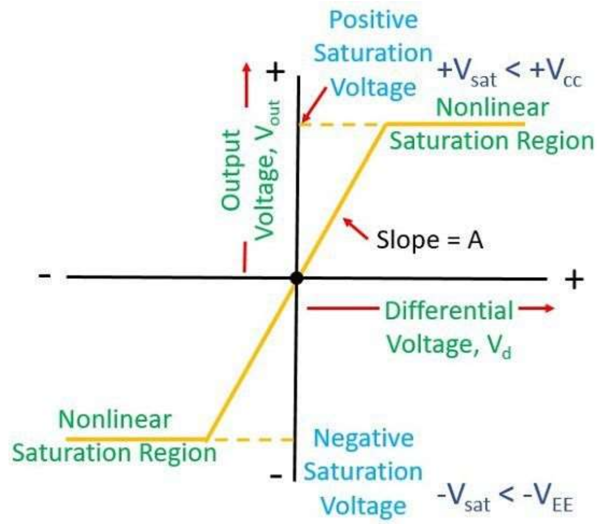
Voltage Gain and Voltage Swing(G_v, G_{vo} and A_v &A_{vo})





Frequency Response: Cut-off Freq./Break Freq./ 3dB cut-off freq./ Half power freq.
Gain x Bandwidth= G.B.P= constant= unity-gain bandwidth product (f_u)

- **Freq. dependency due to internal capacitance or total effective capacitance at output node.**

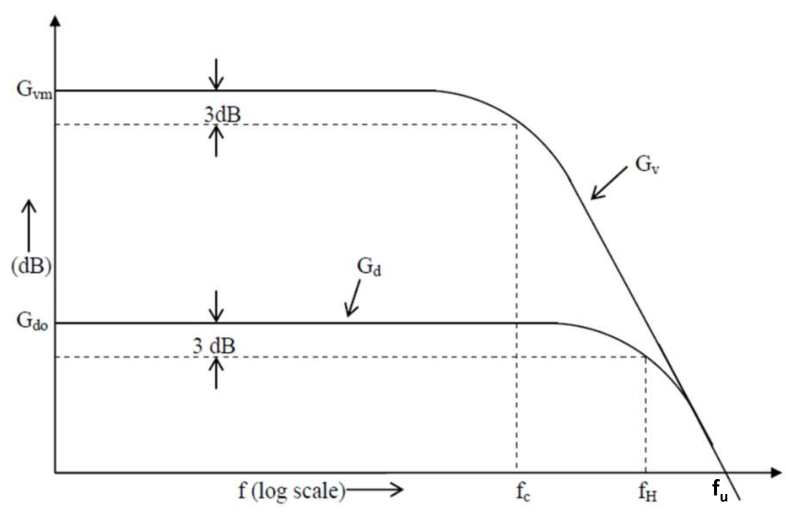
$$f_o = \frac{1}{2\pi R_O C}$$

$$A_{OL}(f) = \frac{A_{OL}}{1 + j\left(\frac{f}{f_o}\right)}$$

f = Operating frequency

f_0 = Break frequency or cutoff frequency

$$|A_{OL}(f)| = \frac{A_{OL}}{\sqrt{1 + \left(\frac{f}{f_o}\right)^2}}$$



(b) Frequency Response

Thanks

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OpAMP Cont.......

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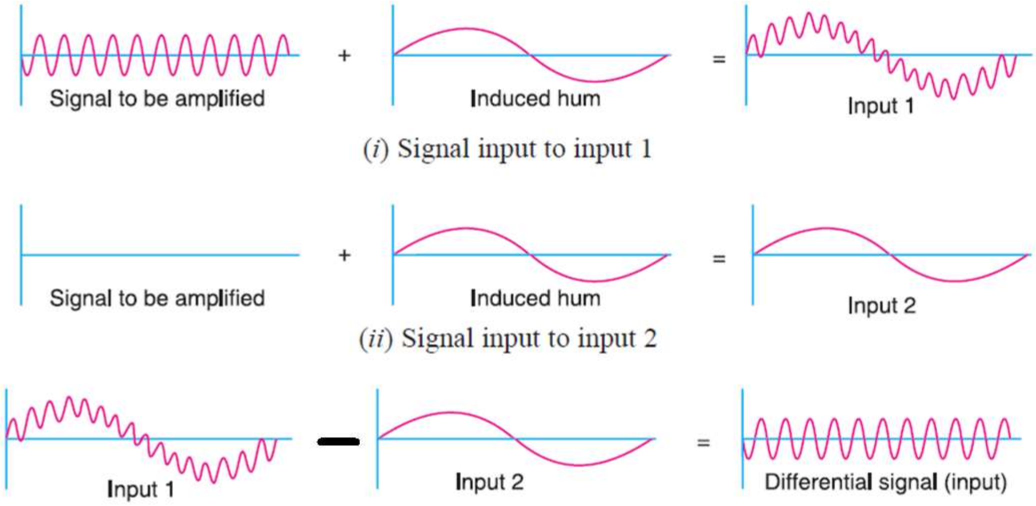
Differential and Common Mode Input



(*i*) Signal input to input 1

(*ii*) Signal input to input 2

(*iii*) Differential input signal

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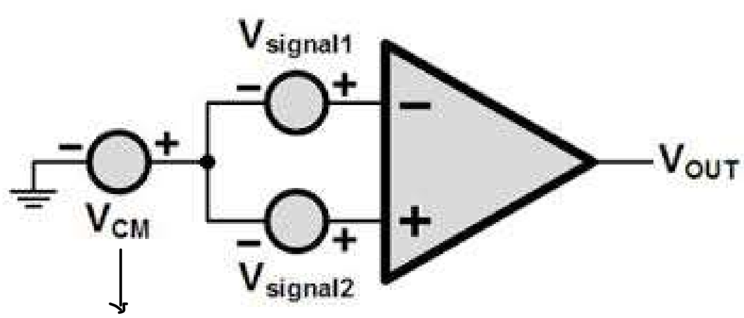
Differential and Common Mode Input



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Common Mode Rejection Ratio

Differential Mode Gain: A_{dm} for differential mode input v_{dm}

Common Mode Gain: A_{cm} for common mode input v_{cm}

In general OpAMP Out put Voltage

$$v_o = A_{dm}.v_{dm} + A_{cm}.v_{cm}$$

CMRR= A_{dm}/A_{cm}

CMRR (in dB) = 20 $\log_{10}(A_{dm}/A_{cm})$

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Example 25.3. *A differential amplifier has an output of 1V with a differential input of 10 mV and an output of 5 mV with a common-mode input of 10 mV. Find the CMRR in dB.*

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Solution. Differential gain, $A_{DM} = 1\text{V}/10\text{ mV} = 100$

Common-mode gain, $A_{CM} = 5\text{ mV}/10\text{ mV} = 0.5$

$\therefore \quad CMRR_{dB} = 20\log_{10}(100/0.5) =$ **46 dB**

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Example 25.4. *A differential amplifier has a voltage gain of 150 and a CMRR of 90 dB. The input signals are 50 mV and 100 mV with 1 mV of noise on each input. Find (i) the output signal (ii) the noise on the output.*

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Solution.

(*i*) Output signal, $v_{out} = A_{DM}(v_1 - v_2) = 150\ (100\ \text{mV} - 50\ \text{mV}) = \mathbf{7.5\ V}$

(*ii*) $CMRR_{dB} = 20 \log_{10} (150/A_{CM})$

or $90 = 20 \log_{10} (150/A_{CM})$

$\therefore\ A_{CM} = 4.7 \times 10^{-3}$

Noise on output $= A_{CM} \times 1\ \text{mV} = 4.7 \times 10^{-3} \times 1\text{mV} = \mathbf{4.7 \times 10^{-6}\ V}$

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Assignment Problems Types and Discussion

1. **Mic and Speaker with Amplifier (VCVS) Model**
2. **OPAMP based circuit analysis using ideal Op-Amp properties.**
3. **Design Problem using cascading multiple stage Op-AMP circuits**

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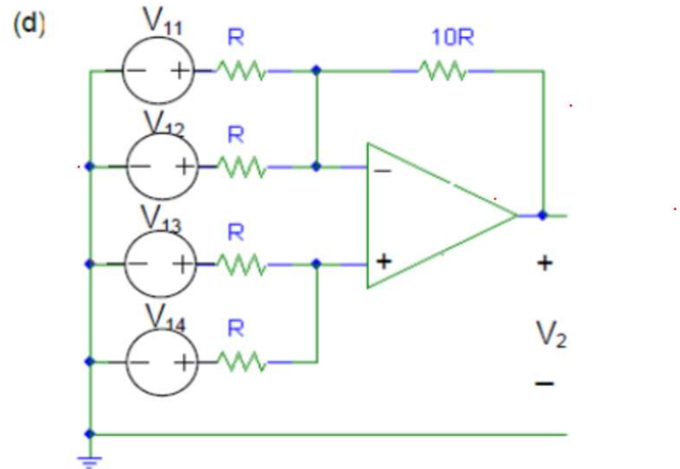
Assignment Problems Discussions:



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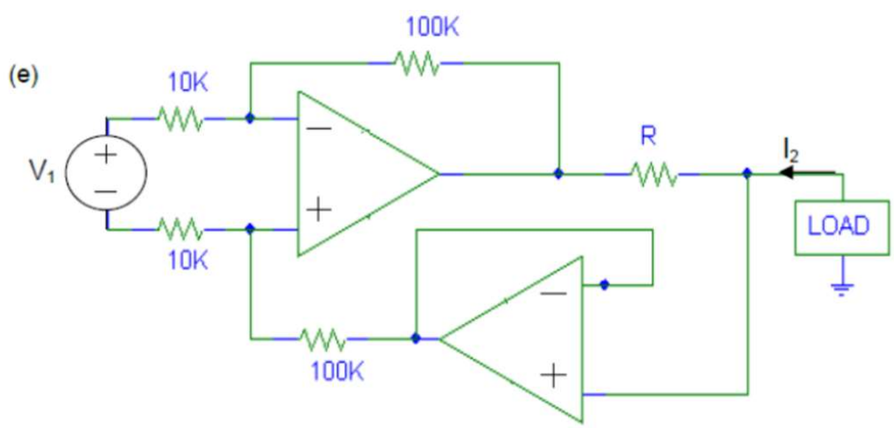

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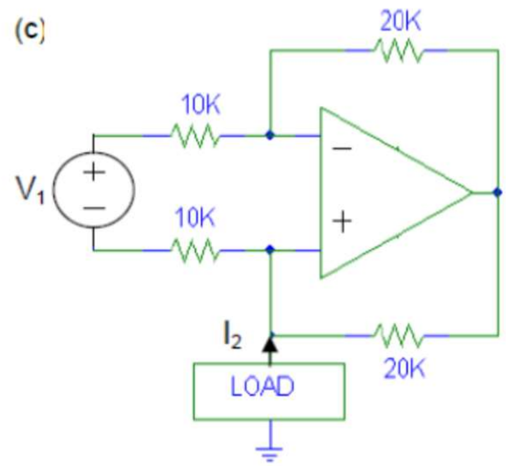

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Thanks

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