DR. GYURCSEK ISTVÁN

Operational Amplifiers

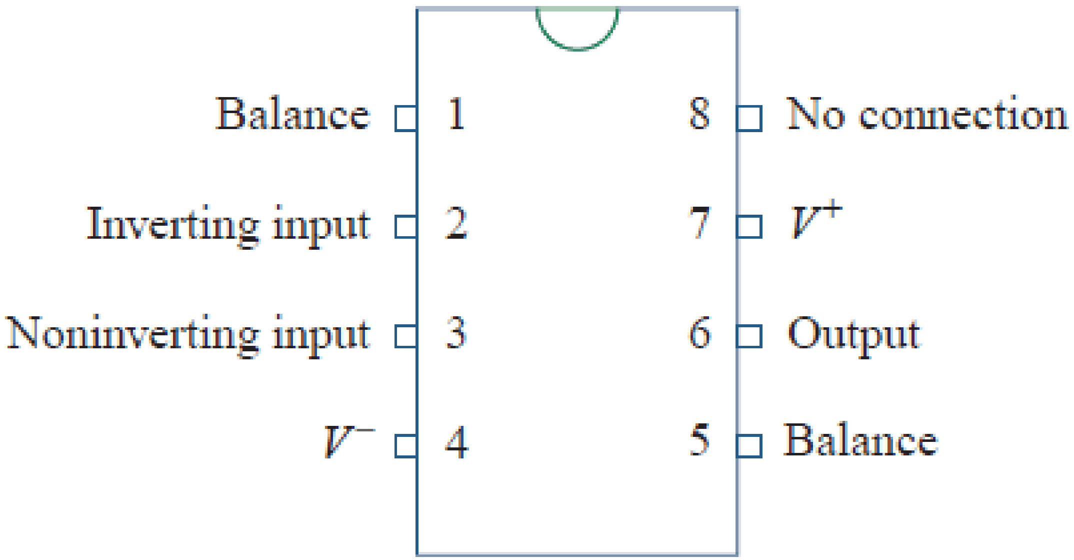
Sources and additional materials (recommended)

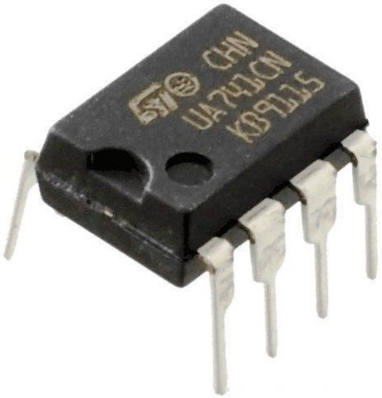
- *Dr. Gyurcsek – Dr. Elmer: Theories in Electric Circuits, GlobeEdit, 2016, ISBN:978-3-330-71341-3*
- *Ch. Alexander, M. Sadiku: Fundamentals of Electric Circuits, 6th Ed., McGraw Hill NY 2016, ISBN: 978-0078028229*
- *Simonyi K.: Villamosságtan. AK Budapest 1983, ISBN:9630534134*
- *Dr. Selmeczi K. – Schnöller A.: Villamosságtan 1. MK Budapest 2002, TK szám: 49203/I*
- *Dr. Selmeczi K. – Schnöller A.: Villamosságtan 2. TK Budapest 2002, ISBN:9631026043*
- *Zombory L.: Elektromágneses terek. MK Budapest 2006, (www.electro.uni-miskolc.hu)*

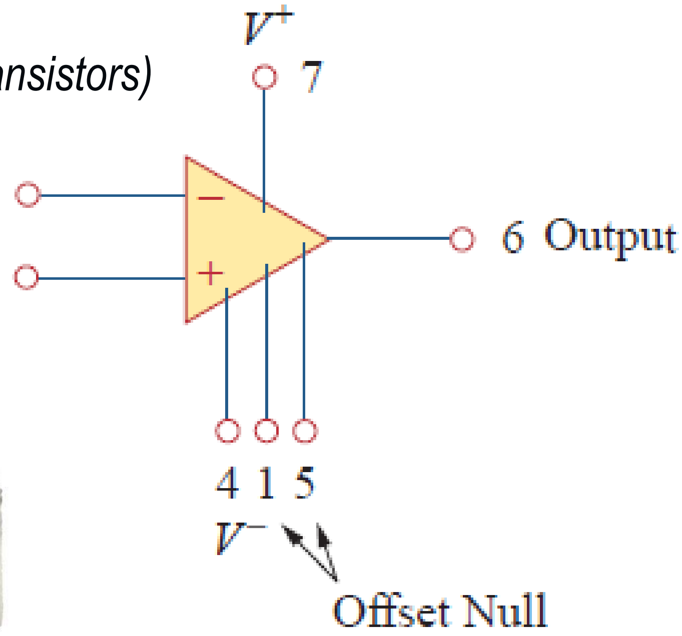
Progress in Content

Operational amplifier (op amp)

- Circuit building block → mathematical ‚operations' *(amplify, sum, integrate, differentiate signals)*
- Voltage controlled voltage source *(very high gain)* → contains R, C, D, T
- *John Ragazzini (1947, National Defense Research Council)* → *vacuum tubes (no transistors)*





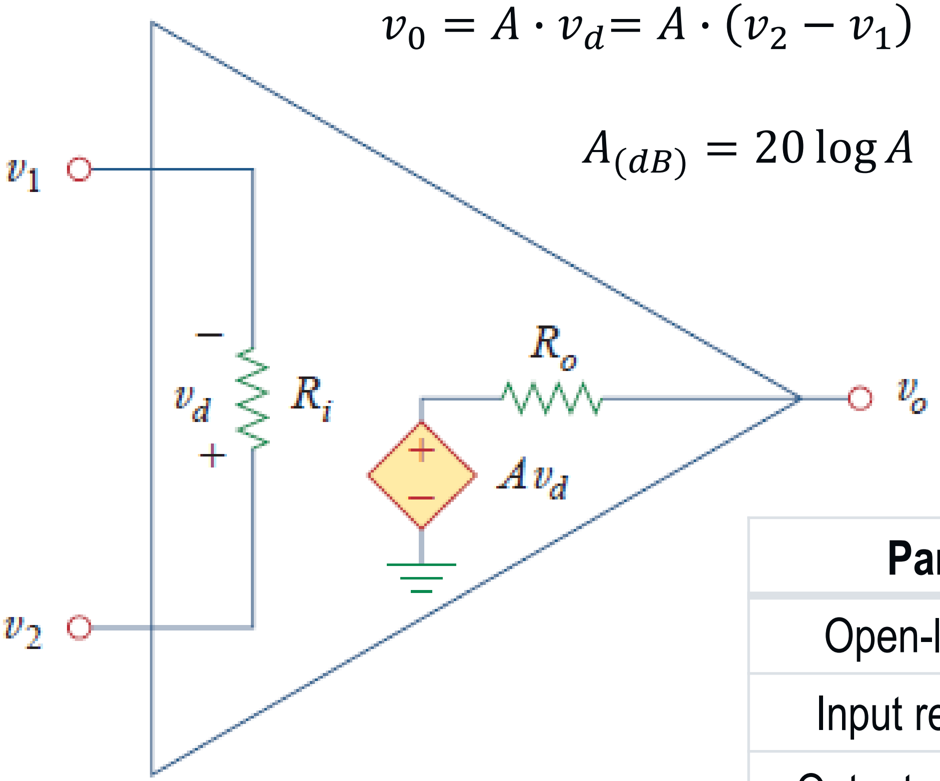


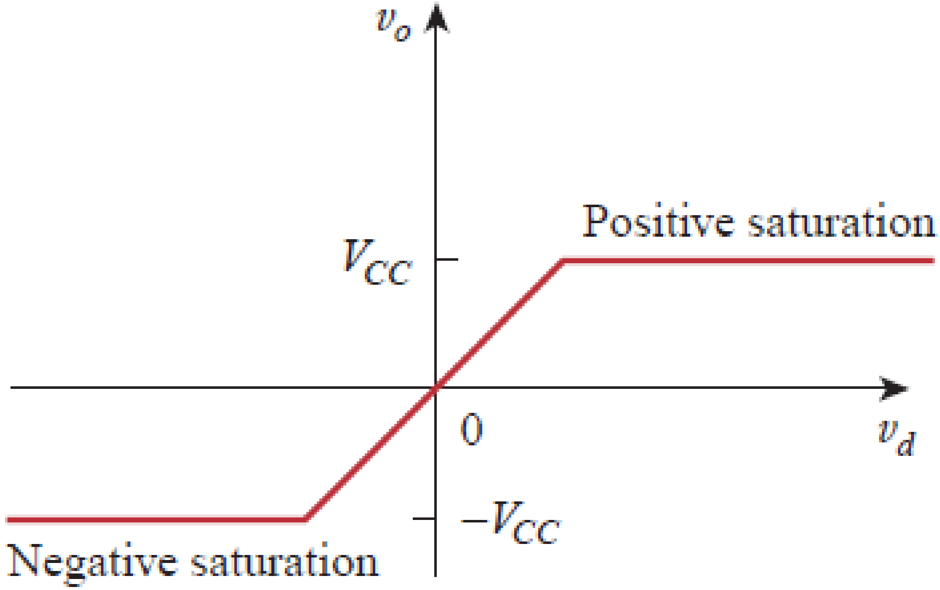
Equivalent Circuit

A → open loop (no feedback) voltage gain

$$v_0 = A \cdot v_d = A \cdot (v_2 - v_1)$$

$$A_{(dB)} = 20 \log A$$





Parameter	Ideal value	Typical range
Open-loop gain, A	∞	10^5-10^8 *(100-160 dB)*
Input resistance, R_i	$\infty\ \Omega$	$10^5 - 10^{13}\ \Omega$
Output resistance, R_o	$0\ \Omega$	$10 - 100\ \Omega$
Supply voltage, V_{CC}		5 – 24 V

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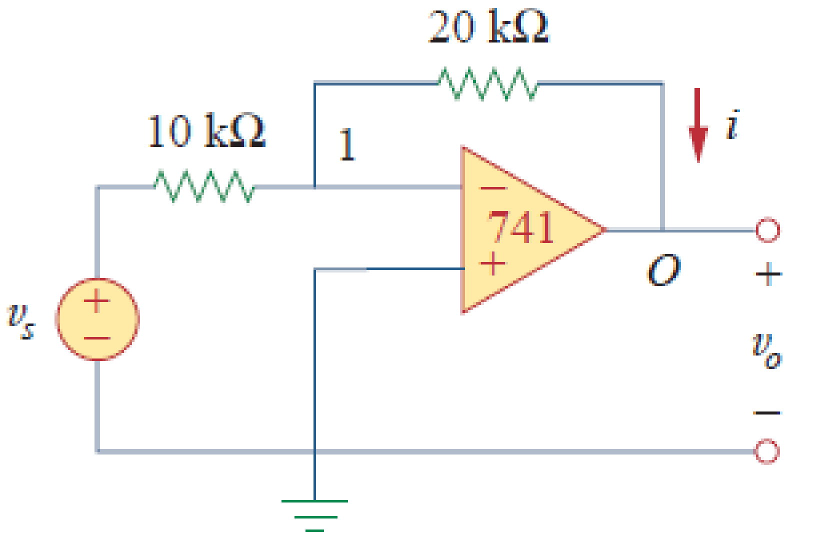
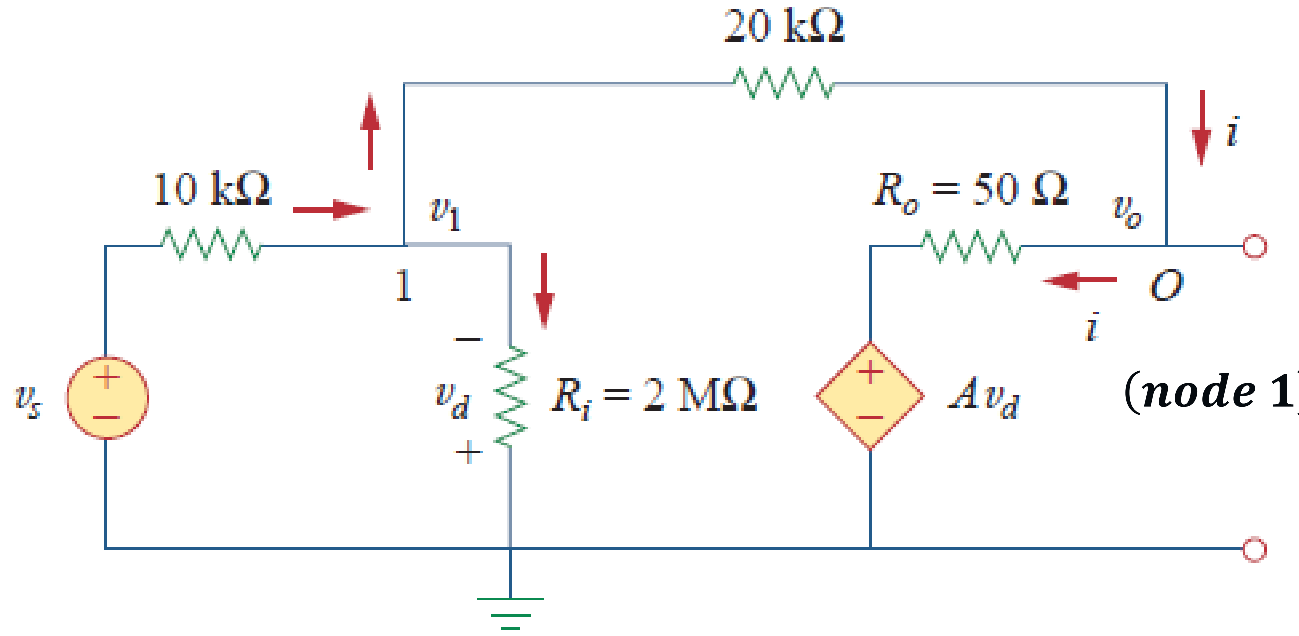
A = 2 10^5, R_i = 2 MΩ, R_o = 50 Ω. Find the closed-loop gain (v_0/v_S) and i when v_s = 2 V.



Solution (equivalent circuit)

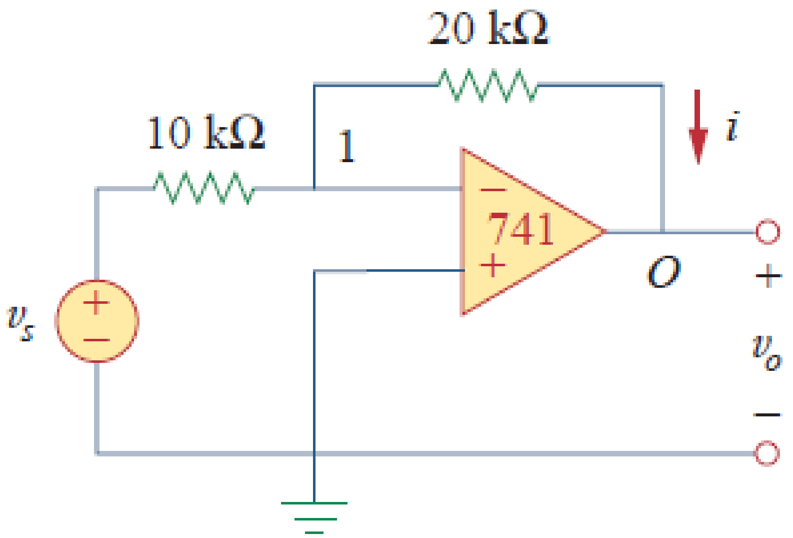


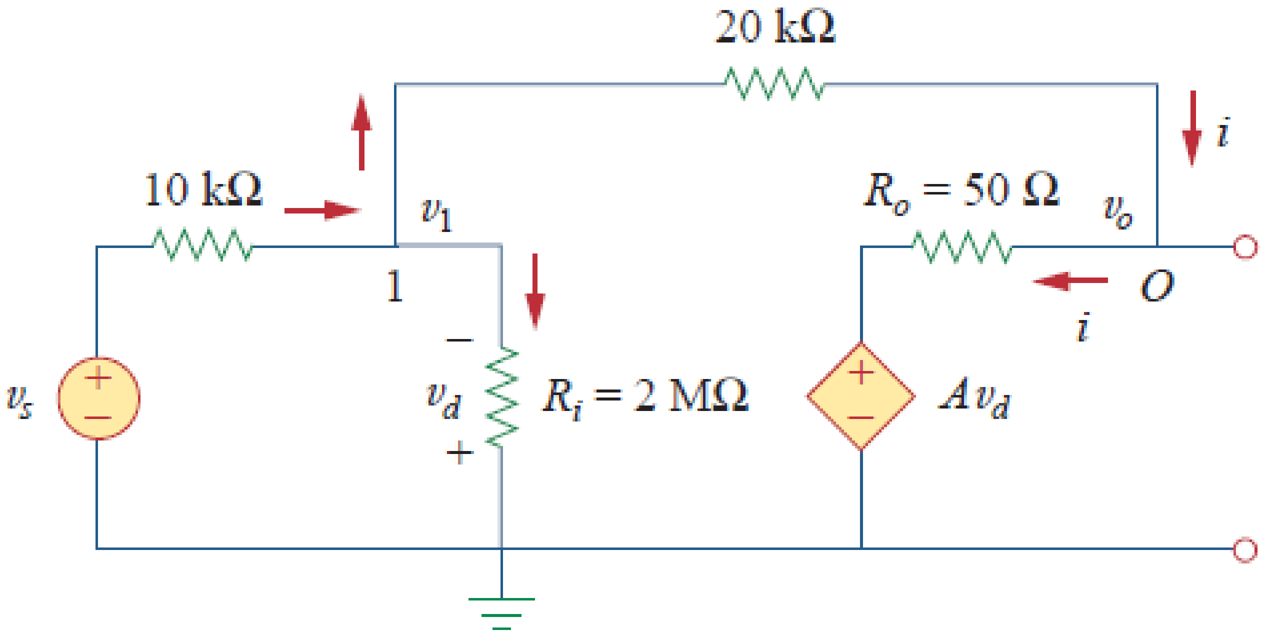
$$(\textbf{node 1}):\ \frac{v_S - v_1}{10\cdot 10^3} = \frac{v_1}{2\cdot 10^6} + \frac{v_1 - v_0}{20\cdot 10^3} \rightarrow (\mathbf{1}):\ v_1 = \frac{2v_S + v_0}{3}$$

$$(\textbf{node } \boldsymbol{O}):\ \frac{v_1 - v_0}{20\cdot 10^3} = \frac{v_0 - Av_d}{50},\ v_d = -v_1$$

$$(\mathbf{2}):\ v_1 - v_0 = 400(v_0 + 200{,}000 v_1)$$

Op Amp Example 1





$$(\mathbf{1}):\ v_1 = \frac{2v_S + v_0}{3}$$

$$v_S = 2 \to v_0 = 3.9999398\,V$$

$$(\mathbf{2}):\ v_1 - v_0 = 400(v_0 + 200{,}000 v_1)$$

$$v_1 = 20.066667\,\mu V$$

$$(\mathbf{1}) \to (\mathbf{2}): 0 \cong 26{,}667{,}067 v_0 + 53{,}333{,}333 v_S \to \frac{v_0}{v_S} = -1.9999$$

$$i = \frac{v_1 - v_0}{20 \cdot 10^3} = 199.99\,\mu A$$

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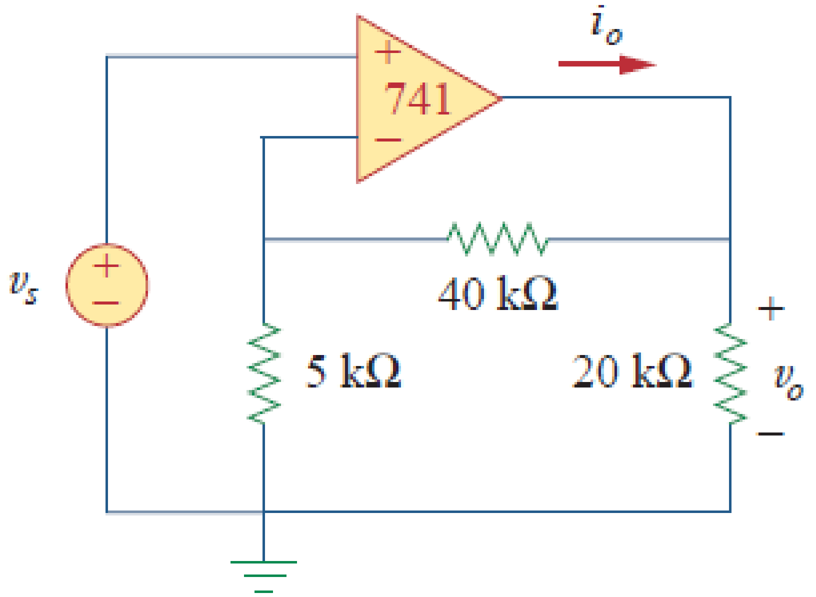
Op Amp Example 2

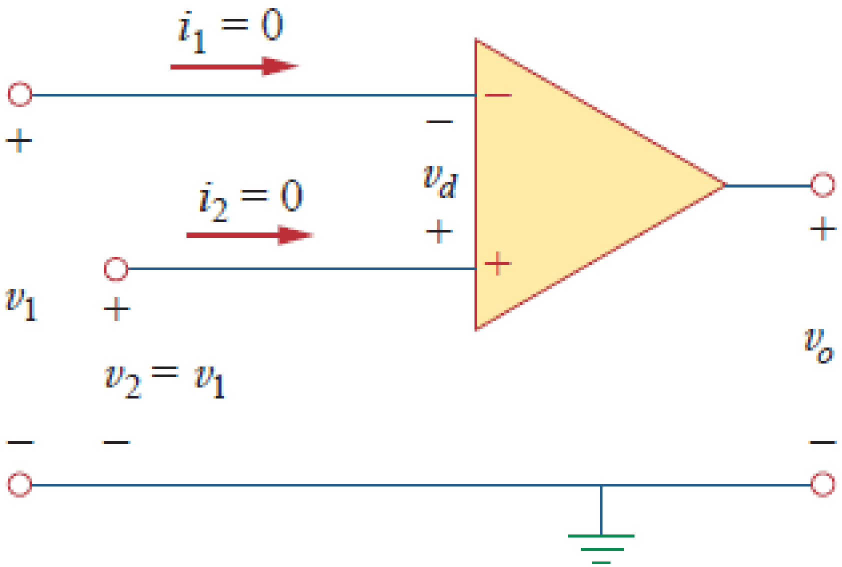
$A = 2\ 10^5$, $R_i = 2$ MΩ, $R_o = 50$ Ω. Calculate the closed-loop gain (v_0 / v_S) and i_0 when $v_s = 1$V.



Solution (9.00041, 0.657 mA.)

Ideal Op Amp

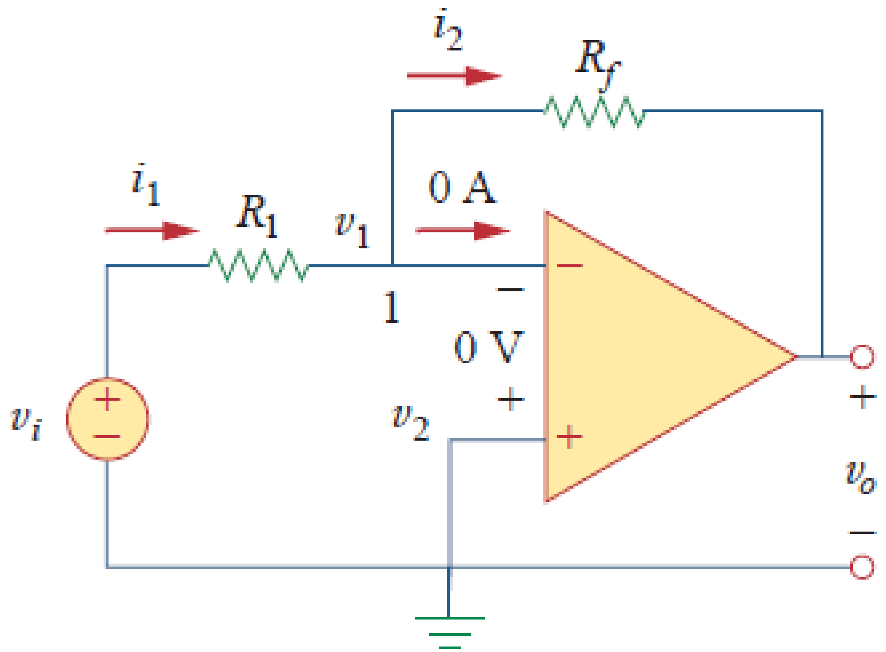
$$\left.\begin{aligned} A &\cong \infty \\ R_i &= \infty \\ R_O &= 0 \end{aligned}\right\} \rightarrow \begin{cases} i_1 = 0 \\ i_2 = 0 \\ v_1 = v_2 \end{cases}$$



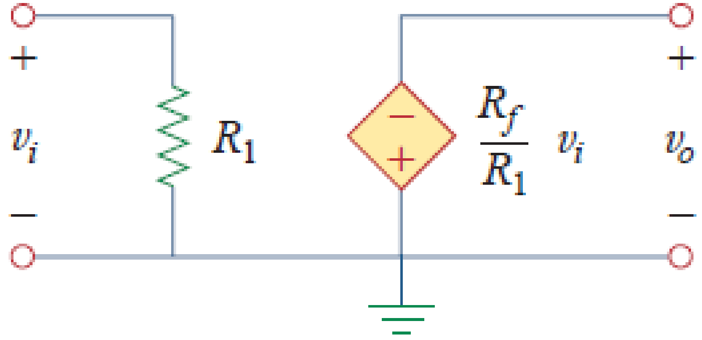
Progress in Content

- ❑ Operation Amplifier
- ❑ **Op Amp Circuits**
- ❑ Applications

Inverting Amplifier *(Inverter)*



Equivalent circuit



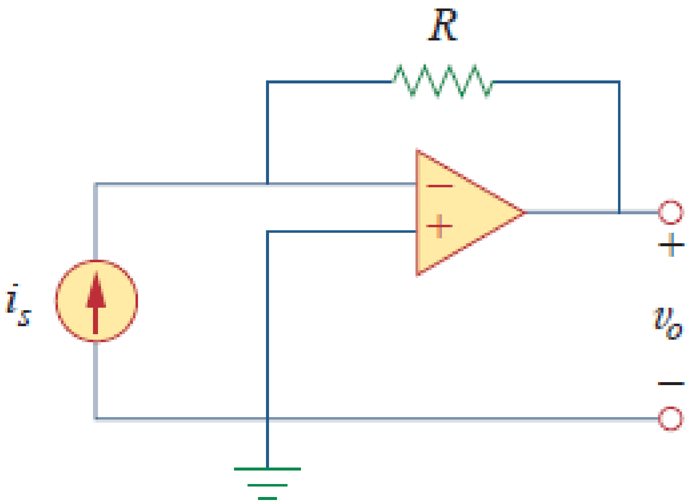
$$i_1 = i_2 \rightarrow \frac{v_i - v_1}{R_1} = \frac{v_1 - v_0}{R_f}$$

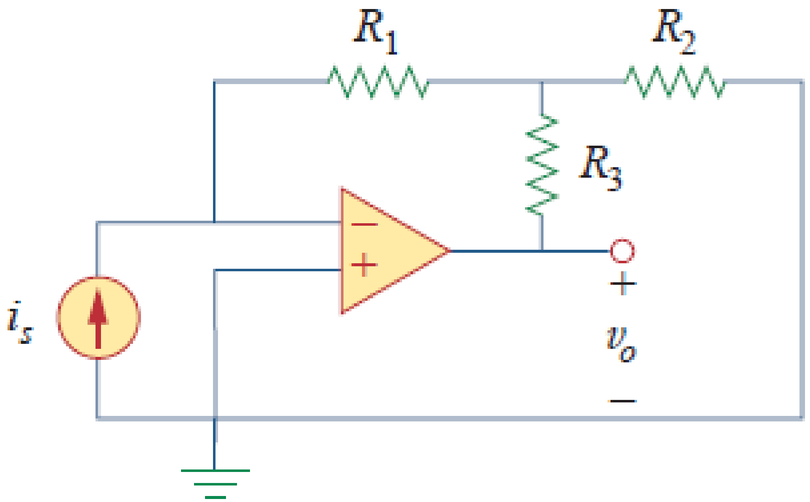
$$v_1 = v_2 = 0 \rightarrow \frac{v_i}{R_1} = -\frac{v_0}{R_f}$$

$$v_0 = -\frac{R_f}{R_1} v_i \leftarrow \mathit{reverses\ the\ polarity}$$

Current-to-Voltage Converters *(Transresistance Amplifiers)*

HW – Show the followings…

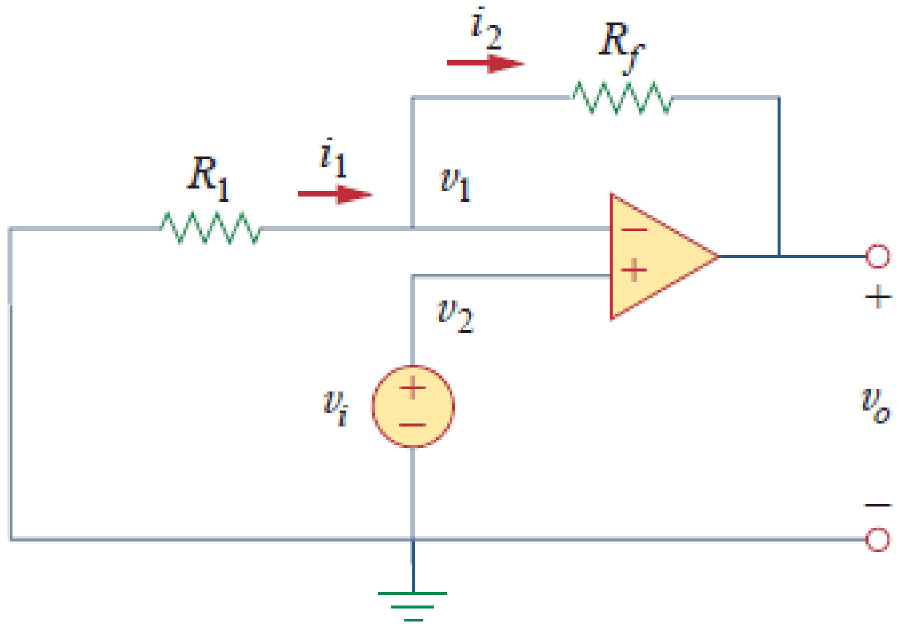




$$\frac{v_0}{i_S} = -R$$

$$\frac{v_0}{i_S} = -R_1\left(1 + \frac{R_3}{R_1} + \frac{R_3}{R_2}\right)$$

Noninverting Amplifier

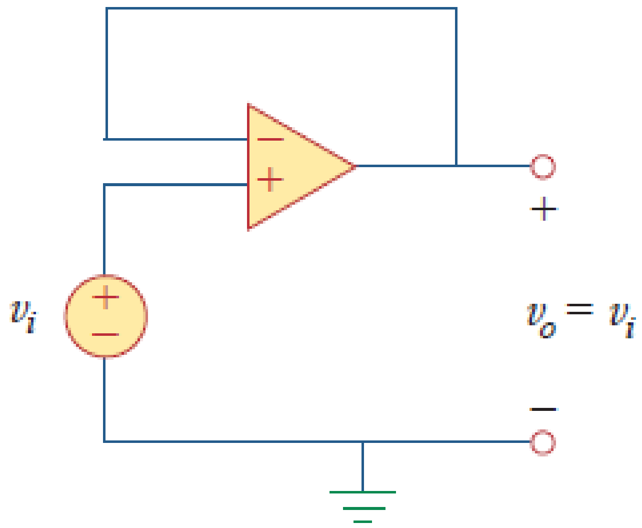


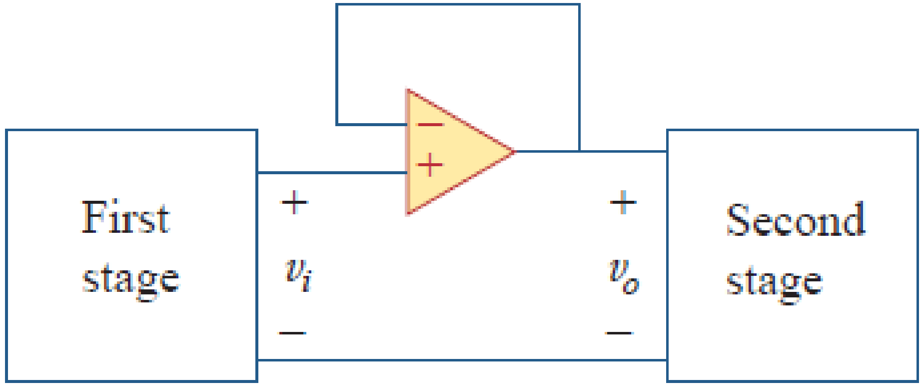
$$i_1 = i_2 \rightarrow \frac{0 - v_1}{R_1} = \frac{v_1 - v_0}{R_f}$$

$$v_1 = v_2 = v_i \rightarrow \frac{-v_i}{R_1} = \frac{v_i - v_0}{R_f}$$

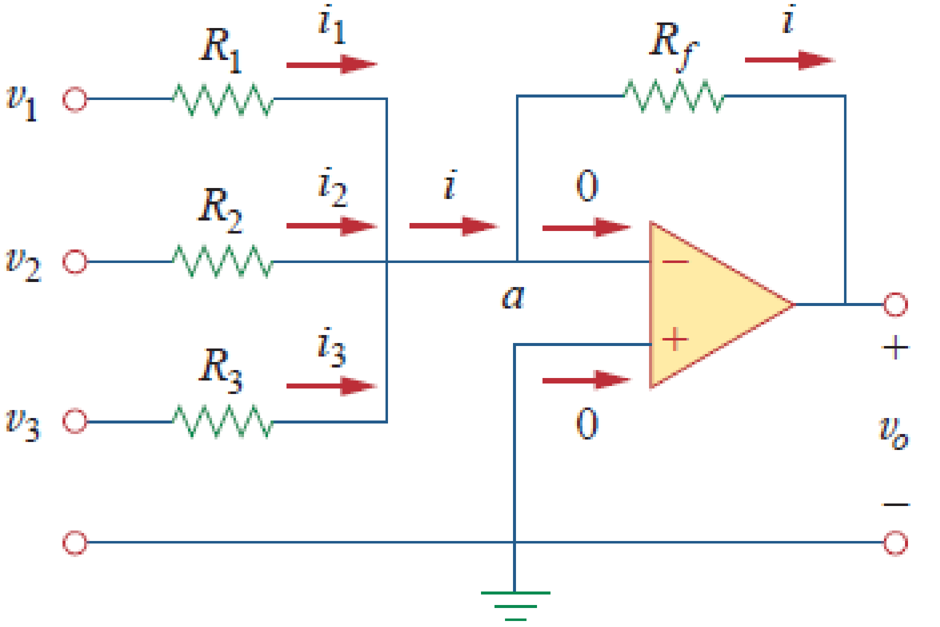
$$v_0 = \left(1 + \frac{R_f}{R_1}\right) v_i \qquad A_v = \frac{v_0}{v_i} = 1 + \frac{R_f}{R_1} > 0$$

Voltage follower – to isolate two cascaded stages





Summing Amplifier *(Weighted Summing)*



$$(\mathbf{1}):\ i = i_1 + i_2 + i_3$$

$$(\mathbf{2}):\ v_a = 0$$

$$(\mathbf{3}):\ i_1 = \frac{v_1 - v_a}{R_1}, \qquad i_2 = \frac{v_2 - v_a}{R_2}, \qquad i_3 = \frac{v_3 - v_a}{R_3}, \qquad i = \frac{v_a - v_o}{R_f}$$

$$(\mathbf{2})(\mathbf{3}) \rightarrow (\mathbf{1}):\ \frac{0 - v_o}{R_f} = \frac{v_1 - 0}{R_1} + \frac{v_2 - 0}{R_2} + \frac{v_3 - 0}{R_3} \rightarrow v_0 = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$

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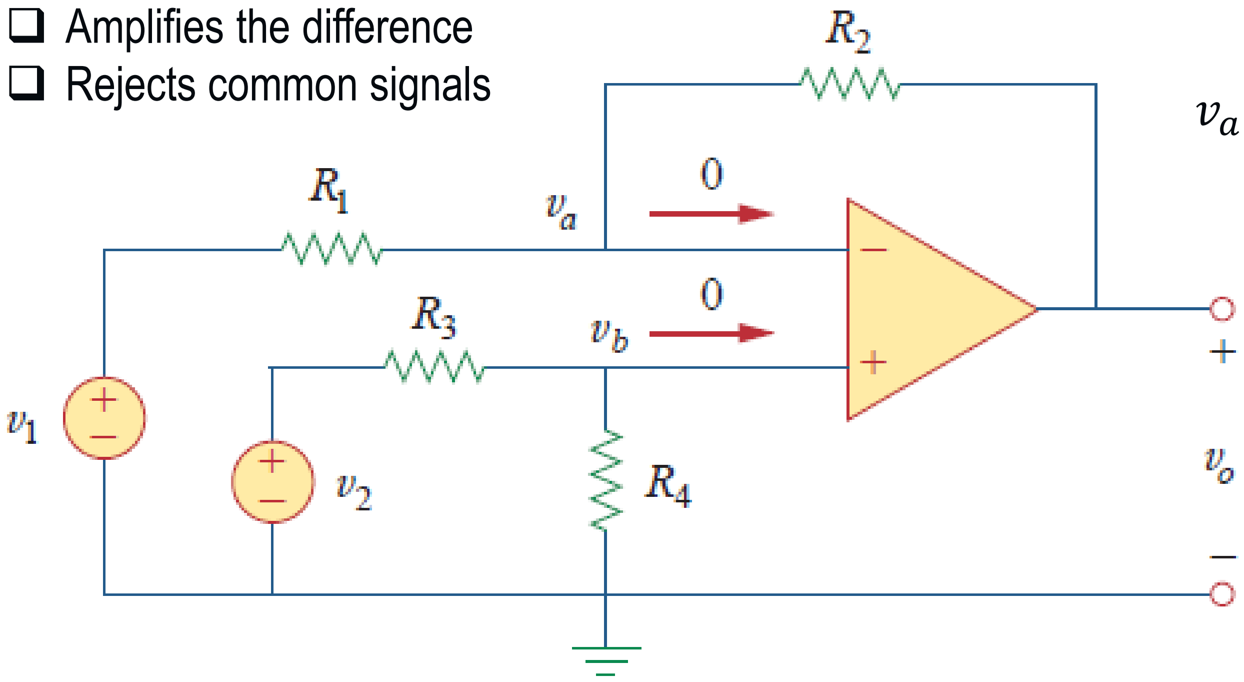
Difference *(or Differential)* Amplifier

- ❑ Amplifies the difference
- ❑ Rejects common signals



$$(\boldsymbol{node\ a}): \frac{v_1 - v_a}{R_1} = \frac{v_a - v_o}{R_2} \rightarrow v_0 = v_a\left(1 + \frac{R_2}{R_1}\right) - v_1\frac{R_2}{R_1}$$

$$(\boldsymbol{node\ b}): \frac{v_2 - v_b}{R_3} = \frac{v_b - 0}{R_4} \rightarrow v_b = v_2\frac{R_4}{R_3 + R_4}$$

$$v_a = v_b\,, (\boldsymbol{b} \rightarrow \boldsymbol{a}): v_0 = v_2\left(1 + \frac{R_2}{R_1}\right)\frac{R_4}{R_3 + R_4} - v_1\frac{R_2}{R_1}$$

$$v_0 = v_2\frac{R_2\left(1 + {R_1}/{R_2}\right)}{R_1\left(1 + {R_3}/{R_4}\right)} - v_1\frac{R_2}{R_1}$$

- ❑ ‚*very high’* Common Mode Rejection (CMR) when

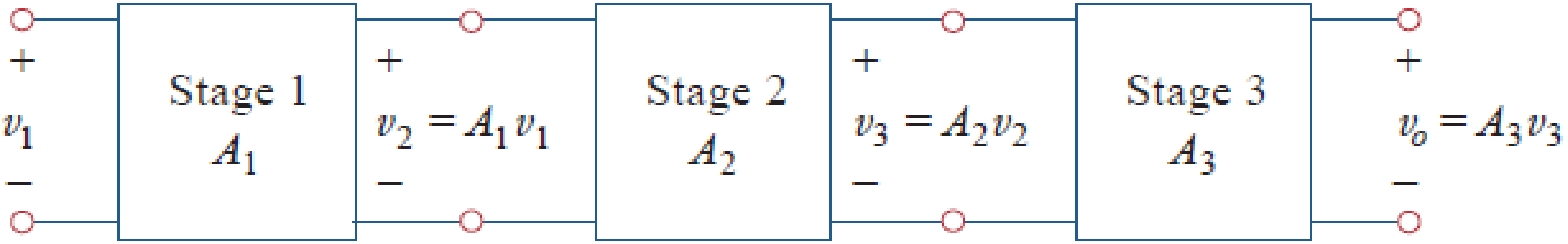
$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \rightarrow v_0 = \frac{R_2}{R_1}(v_2 - v_1)$$

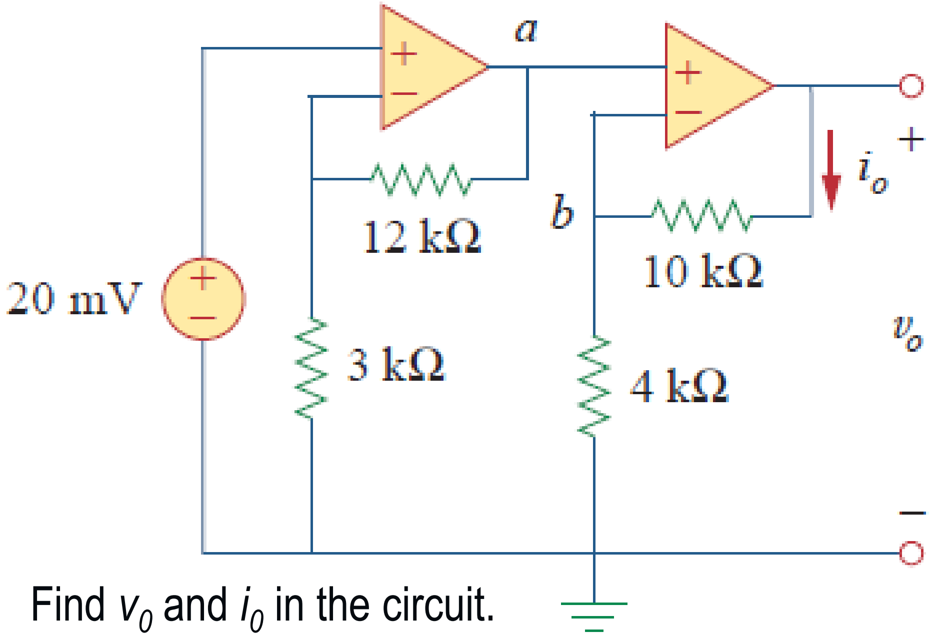
- ❑ ‚Substractor’ when

$$R_1 = R_2\,, R_3 = R_4 \rightarrow v_0 = v_2 - v_1$$

Cascaded Op Amp Circuits

Cascade connection → ‚head-to-tail arrangement' [output of one] → [input of the next].





Find v_0 and i_0 in the circuit.

$$A = A_1 \cdot A_2 \cdot A_3$$

$$v_a = \left(1 + \frac{12}{3}\right) \cdot 20 = 100\ mV$$

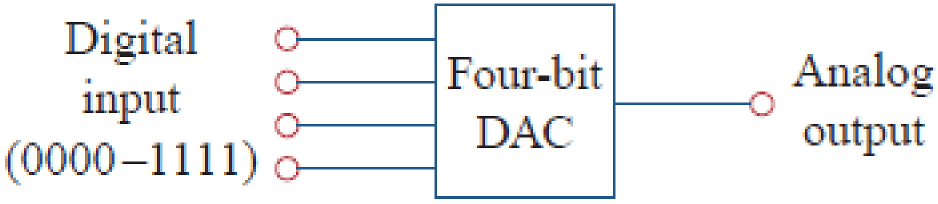
$$v_0 = \left(1 + \frac{10}{4}\right) \cdot v_a = 350\ mV$$

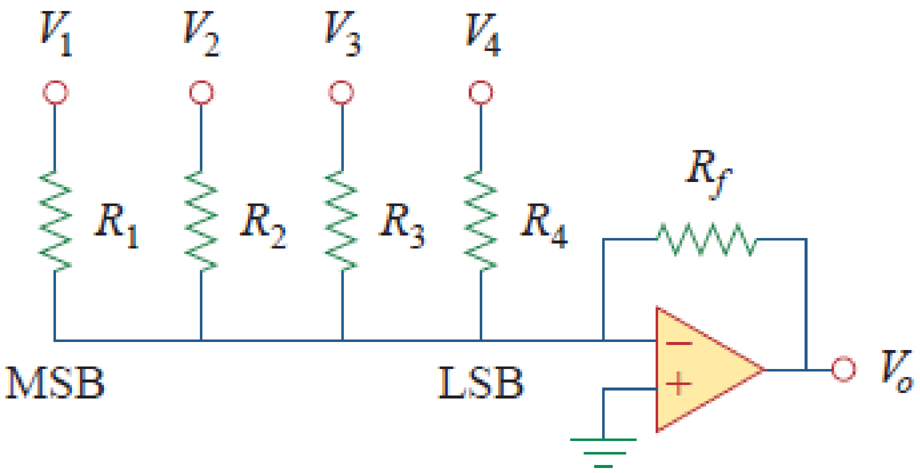
$$v_b = v_a \rightarrow i_0 = \frac{v_0 - v_b}{10k} = \frac{250}{10} = 25\ \mu A$$

Progress in Content

- ❑ Operation Amplifier
- ❑ Op Amp Circuits
- ❑ **Applications**

Applications – DA Converter





Binary weighted ladder

(V_1 - MSB: Most SignificantBit)

(V_4 - LSB: Least SignificantBit)

$$-V_0 = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \frac{R_f}{R_4}V_4$$

Example R_f = 2k, R_1 = 10k, R_2 = 20k, R_3 = 40k, R_4 = 80k

Find analog output(s) for [0000], [0001], [0010], …, [1111]

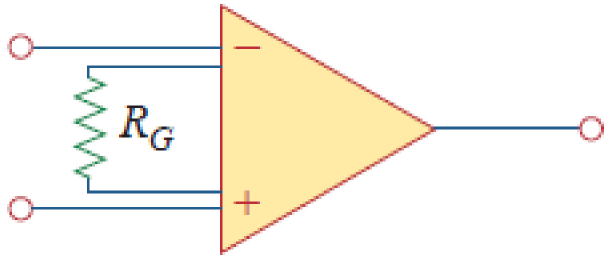
$$-V_0^{(0000)} = \frac{2k}{10k}\cdot 0 + \frac{2k}{20k}\cdot 0 + \frac{2k}{40k}\cdot 0 + \frac{2k}{80k}\cdot 0 = 0\ \mathrm{V}$$

$$-V_0^{(0001)} = \frac{2k}{10k}\cdot 0 + \frac{2k}{20k}\cdot 0 + \frac{2k}{40k}\cdot 0 + \frac{2k}{80k}\cdot (5V) = 125\ mV$$

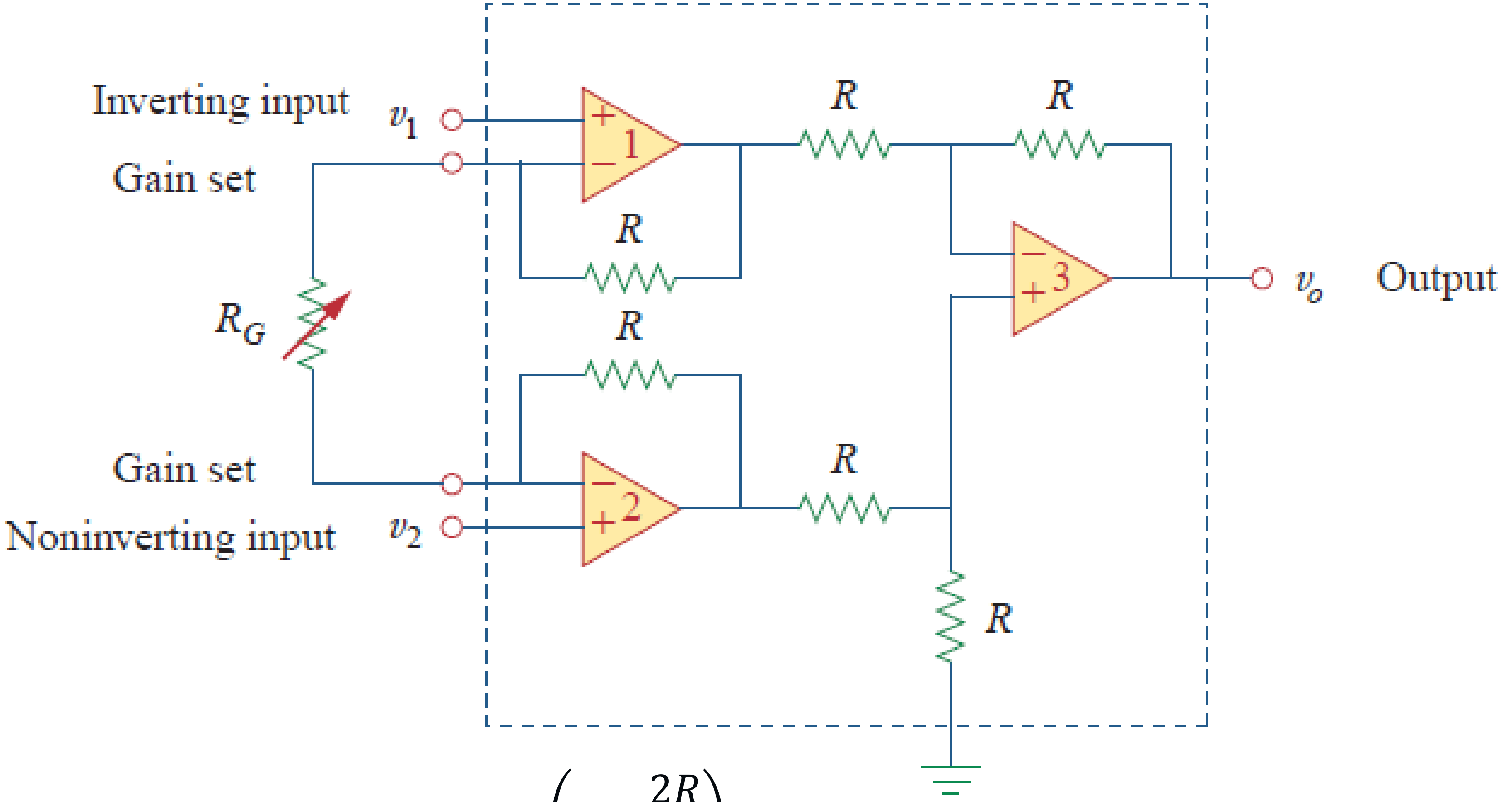
$$-V_0^{(0011)} = \frac{2k}{10k}\cdot 0 + \frac{2k}{20k}\cdot 0 + \frac{2k}{40k}\cdot (5\ V) + \frac{2k}{80k}\cdot (5V) = 375\ mV$$

$$-V_0^{(1111)} = \frac{2k}{10k}\cdot (5\ V) + \frac{2k}{20k}\cdot (5\ V) + \frac{2k}{40k}\cdot (5\ V) + \frac{2k}{80k}\cdot (5V) = 1.875\ V$$

IA – [mérőerősítő]
- ❑ Extension of the difference amplifier
- ❑ Consists of three op amps + resistors
- ❑ External R_G for gain adjustment



Widely used
- ❑ Precision measurement
- ❑ Process control
- ❑ Data acquisition systems.
- ❑ *Isolation amplifiers*
- ❑ *Thermo couple amplifiers*



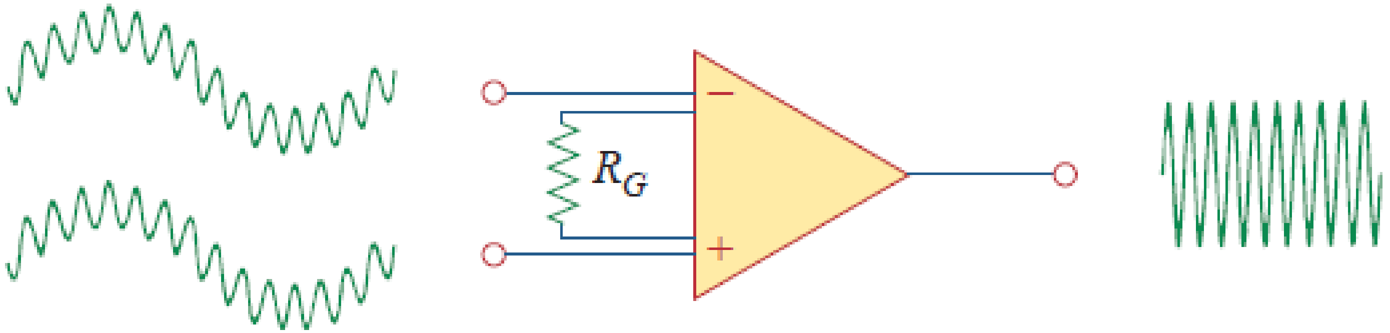
$$v_0 = A_v(v_2 - v_1)\,, \qquad A_v = \left(1 + \frac{2R}{R_G}\right)$$

Applications – Instrumentation Amplifier

Small differential signals riding on larger common-mode signals

$$v_0 = A_v(v_2 - v_1)$$

Amplified differential signal
No common-mode signal



‚*IA*' characteristics

- Gain is adjusted by *one* external resistor R_G.
- Gain independent and very high input impedances
- Very high CMR (common mode rejection)

Single-package units

- LH0036 *(National Semiconductor)*
- Gain …1 - 1,000 by external R_G *(R_G … 100 - 10 k)*

Questions