EE 254

Electronic Instrumentation

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Lecture Note #09

Content (Brief)

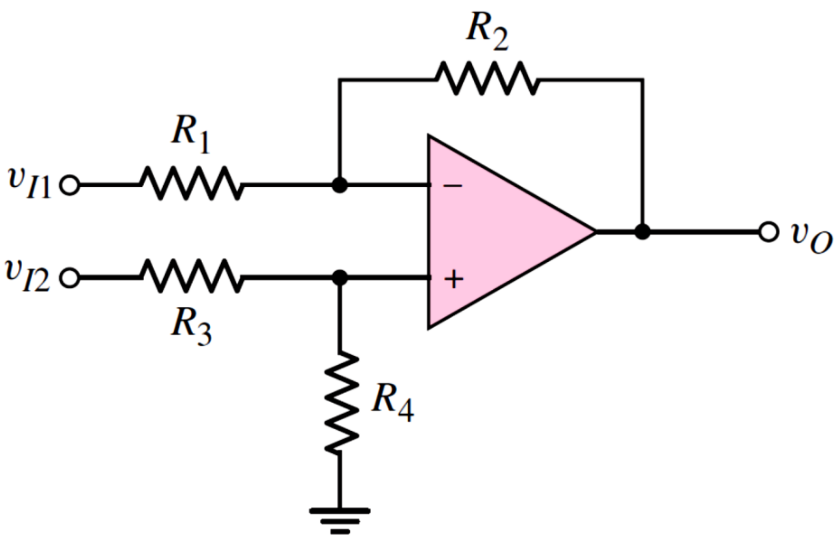
2. Op-Amp Applications

- Linear Applications
  - Inverting amplifiers
  - Noninverting amplifiers
  - Differential amplifiers
  - Summing amplifiers
  - Integrators
  - Differentiators
  - Low/ High pass filters
  - Instrumentational amplifiers

- Nonlinear Applications
  - Precision rectifiers
  - Peak detectors
  - Schmitt-trigger comparator
  - Logarithmic amplifiers

Instrumentation Amplifiers

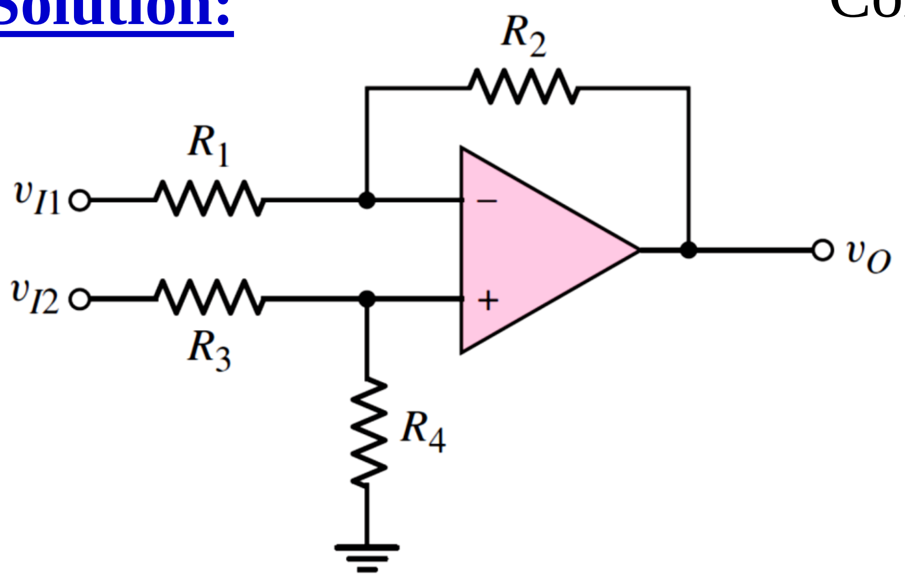
Review: Design a Difference Amplifier



Design the difference amplifier with the configuration shown in Figure such that the differential gain is 30. Standard valued resistors are to be used and the maximum resistor value is to be 500 $k\Omega$.

Review: Design a Difference Amplifier

Solution:



Consider an ideal op-amp available.

The differential gain:

$$\frac{R_2}{R_1} = \frac{R_4}{R_3} = 30$$

We can select standard resistors;

$$R_2 = R_4 = 390k\Omega$$

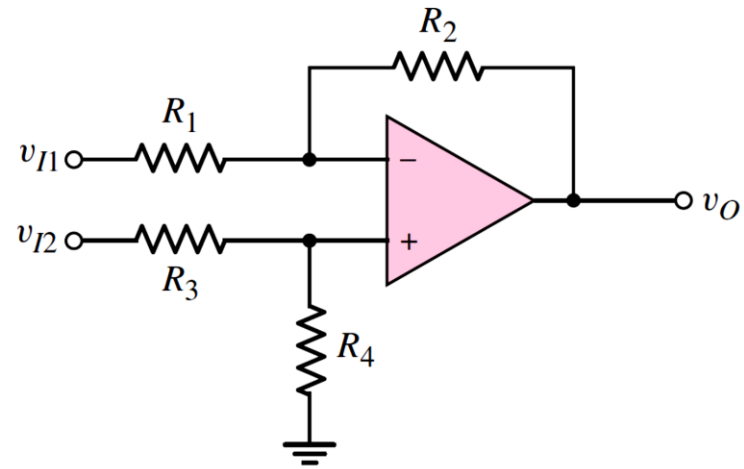
and $$R_1 = R_3 = 13k\Omega$$

These resistor values are obviously less than $500k\Omega$ and will give an input resistance of $R_i = 2R_1 = 2(13) = 26k\Omega.$

Resistor tolerances must be considered as we have done in other designs.

Review: Design a Difference Amplifier

Comment on the Design:



- It cannot achieve both **high gain** and **high input impedance** without using extremely large resistor values.
- This is one of the ***Disadvantage*** of differential amplifier design.
- In the ideal amplifier, the output voltage v_o is **zero** when $v_{I1} = v_{I2}$.

$$v_O = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{\frac{R_4}{R_3}}{1 + \frac{R_4}{R_3}}\right)v_{I2} - \left(\frac{R_2}{R_1}\right)v_{I1} \Rightarrow \frac{R_4}{R_3} = \frac{R_2}{R_1}$$

- When $v_{I1} = v_{I2}$, the input is called **a common-mode input signal**.

Common-Mode Rejection Ratio (CMRR)

- The common-mode input voltage: $v_{cm} = (v_{I1} + v_{I2})/2$

- The common-mode gain: $A_{cm} = \dfrac{v_O}{v_{cm}}$

- Ideally, when a common-mode signal is applied, $v_O = 0$ and $A_{cm} = 0$.

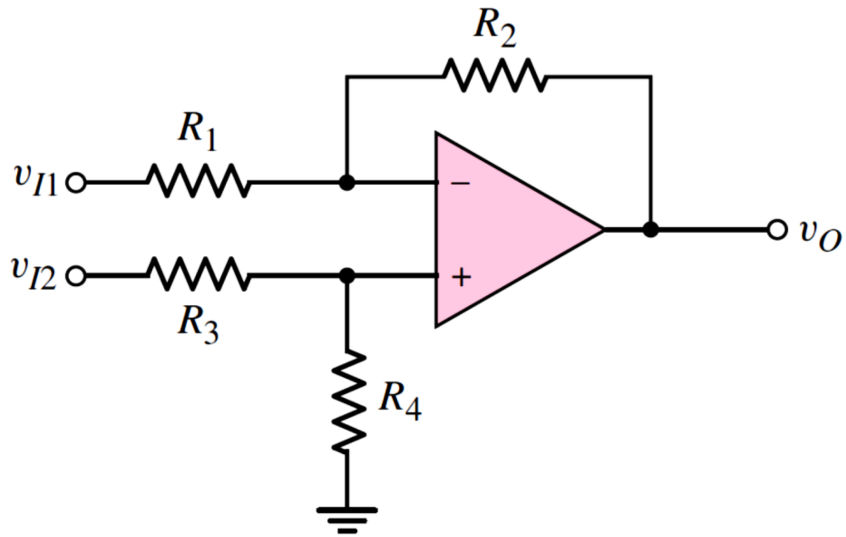
- A nonzero common-mode gain may be generated in actual op-amp circuits.

The common-mode rejection ratio (CMRR)

$$\text{CMRR} = \left| \frac{A_d}{A_{cm}} \right| \qquad \text{CMRR(dB)} = 20 \log_{10} \left| \frac{A_d}{A_{cm}} \right|$$

Example 01 :: CMRR

Calculate the common-mode rejection ratio of a difference amplifier shown below. Let $R_2/R_1 = 10$ and $R_4/R_3 = 11$. Determine CMRR(dB).



Example 01 :: CMRR (Solution)

$$v_O = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{\frac{R_4}{R_3}}{1 + \frac{R_4}{R_3}}\right)v_{I2} - \left(\frac{R_2}{R_1}\right)v_{I1}$$

$$v_O = (1 + 10)\left(\frac{11}{1 + 11}\right)v_{I2} - (10)v_{I1}$$

$$v_O = 10.0833v_{I2} - 10v_{I1}$$

- The differential-mode input voltage: $v_d = v_{I2} - v_{I1}$
- The common-mode input voltage: $v_{cm} = (v_{I1} + v_{I2})/2$

From these: $v_{I1} = v_{cm} - \dfrac{v_d}{2}$ $\qquad$ $v_{I2} = v_{cm} + \dfrac{v_d}{2}$

By substituting: $v_O = (10.0833)\left(v_{cm} + \dfrac{v_d}{2}\right) - (10)\left(v_{cm} - \dfrac{v_d}{2}\right)$

Example 01 :: CMRR (Solution)

$$v_O = (10.0833)\left(v_{cm} + \frac{v_d}{2}\right) - (10)\left(v_{cm} - \frac{v_d}{2}\right)$$

or $$v_O = 10.042 v_d + 0.0833 v_{cm}$$

- The output voltage: $$v_O = A_d v_d + A_{cm} v_{cm}$$

Then; $A_d = 10.042$ and $A_{cm} = 0.0833$

$$\text{CMRR(dB)} = 20 \log_{10}\left(\frac{10.042}{0.0833}\right) = 41.6\,\text{dB}$$

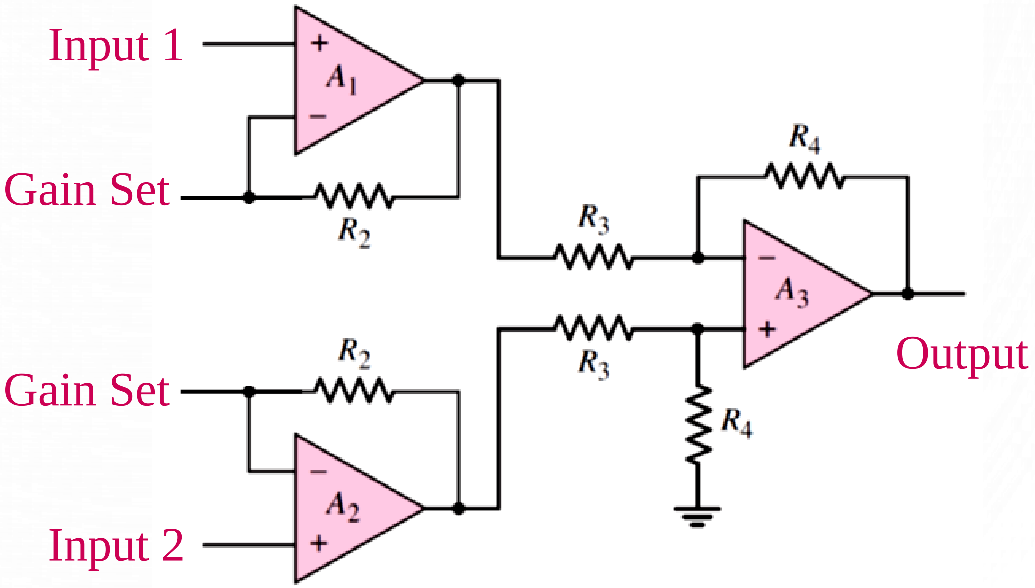
- **For good differential amplifiers, typical CMRR values are in the range of 80 – 100 dB.**

What is the Solution?

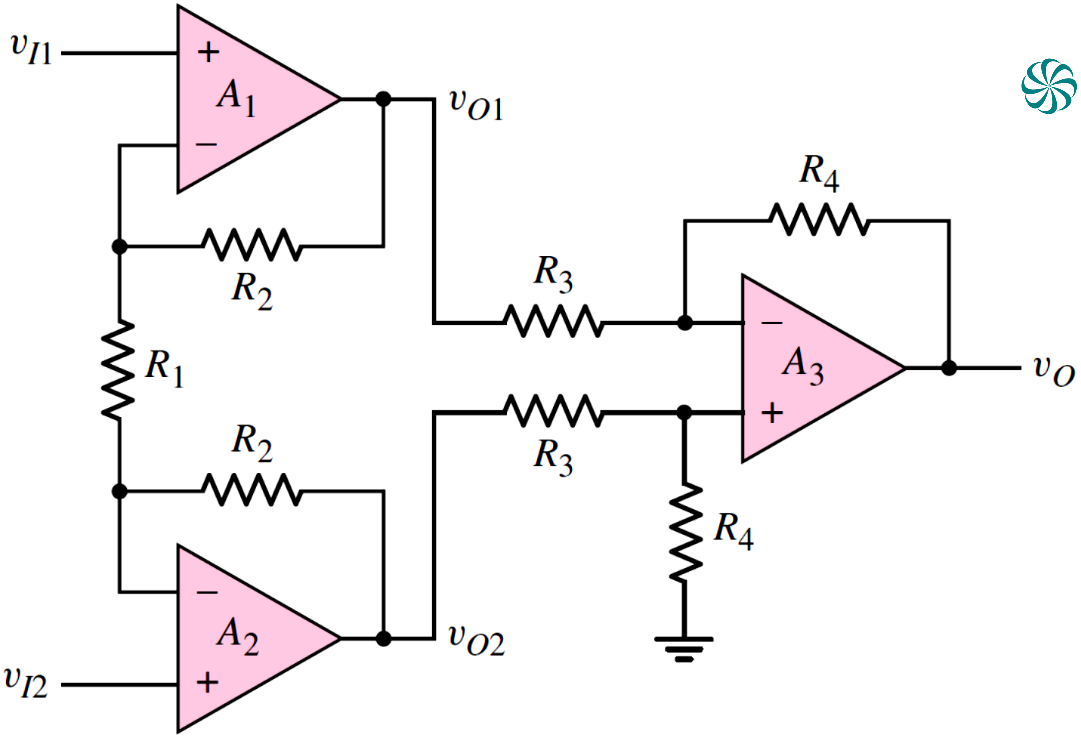
- It is difficult to obtain a **high input impedance** and a **high gain** in a ***difference amplifier*** with reasonable resistor values.
- However, a disadvantage of this design is that the gain of the amplifier cannot easily be changed.
- We would need to change two resistance values and still maintain equal ratios between R_2/R_1 and R_4/R_3.
- Optimally, we would like to be able to change the gain by changing only a single resistance value.

Instrumentation Amplifier

- It is a **differential voltage-gain amplifier** that amplifies the difference between the voltages existing at its two input terminals.
- The main purpose of an instrumentation amplifier is to **amplify small signals**.
- The key characteristics are **high input impedance, high common-mode rejection, low output offset**, and **low output impedance**.
- The voltage gain is usually set with an external resistor.
- High-precision resistors are used



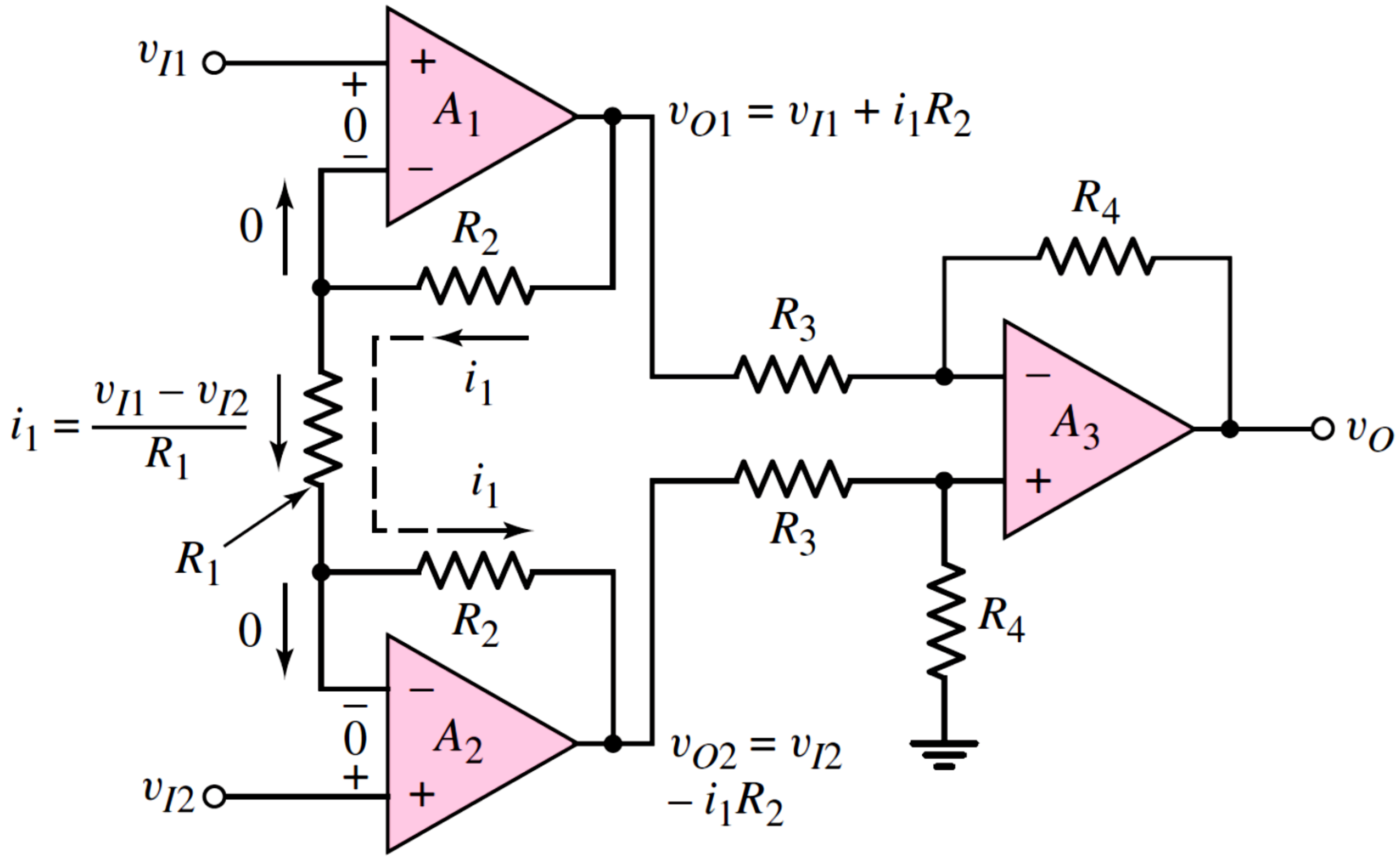
Instrumentation Amplifier



- The gain-setting resistor, R_1 is connected externally
- Change two resistance values and still maintain equal ratios between R_2/R_1 and R_4/R_3.
- The gain is changed by changing only a single resistance value

Instrumentation Amplifier

- The gain is set by R_1 externally connected resistor



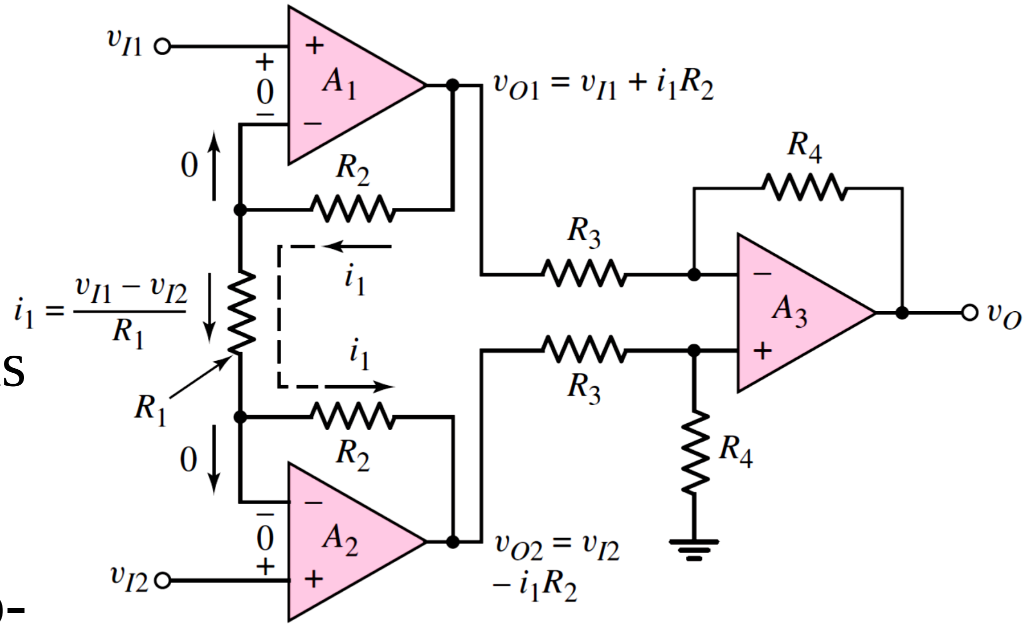
Instrumentation Amplifier

- The current in resistor R_1

$$i_1 = \frac{v_{I1} - v_{I2}}{R_1}$$

- The current in resistor R_2 is also i_1

- The output voltages of op-amps A_1 and A_2



$$v_{O1} = v_{I1} + i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{I1} - \frac{R_2}{R_1} v_{I2}$$

$$v_{O2} = v_{I2} - i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{I2} - \frac{R_2}{R_1} v_{I1}$$

- The output of the difference amplifier

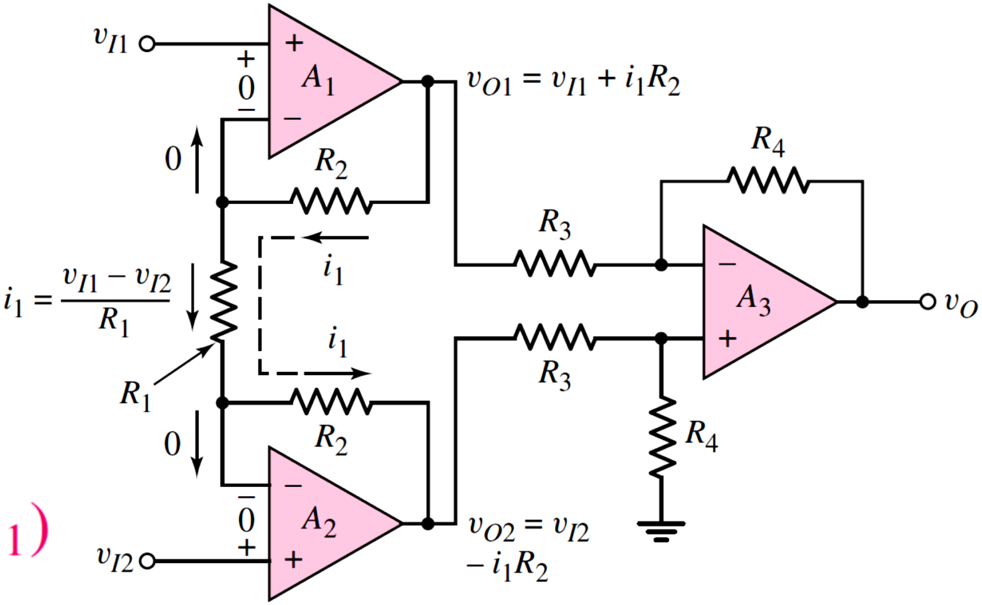
$$v_O = \frac{R_4}{R_3}(v_{O2} - v_{O1})$$

Instrumentation Amplifier

- Solving above equations

$$v_O = \frac{R_4}{R_3}(v_{O2} - v_{O1})$$

$$v_O = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)(v_{I2} - v_{I1})$$

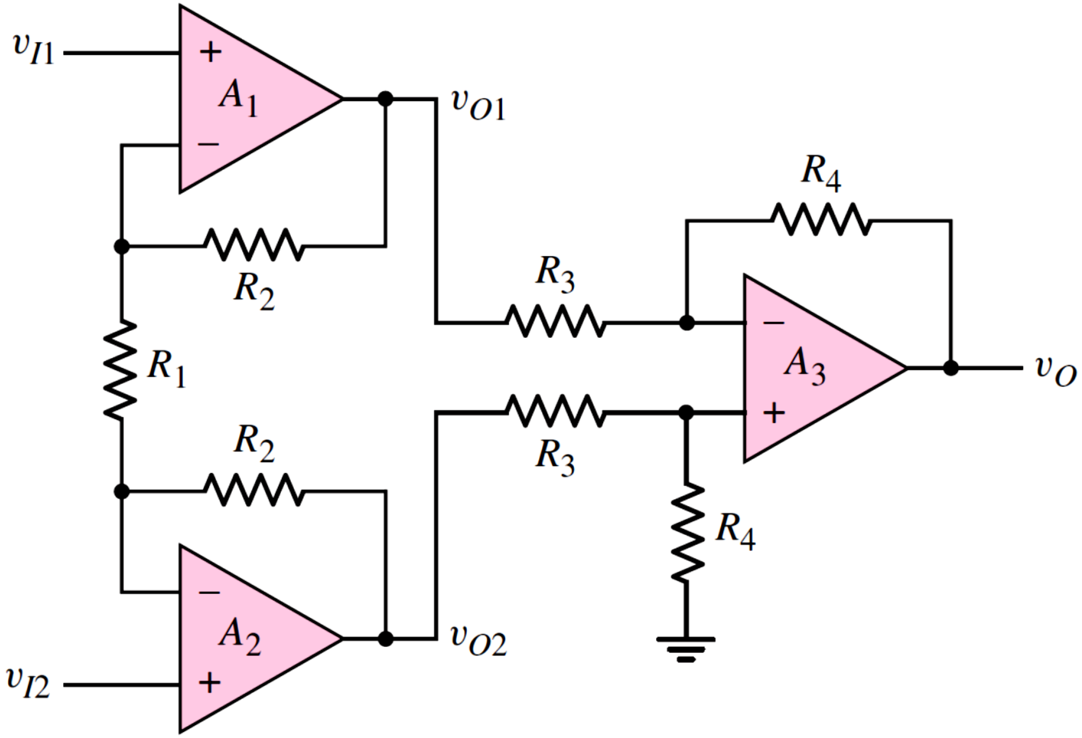


- Since the input signal voltages are applied directly to the noninverting terminals of A_1 and A_2, the input impedance is very large.

- Ideally infinite, which is one desirable characteristic of the instrumentation amplifier.

Ex. 02: Instrumentation Amplifier

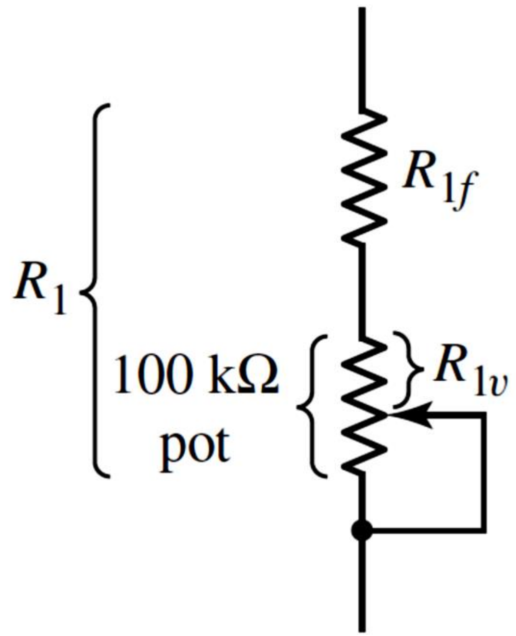
Determine the range required for resistor R_1, to realize a differential gain adjustable from 5 to 500. The instrumentation amplifier circuit is shown in figure below. Assume that $R_4 = 2R_3$, so that the difference amplifier gain is 2.



Ex. 01: Instrumentation Amplifier

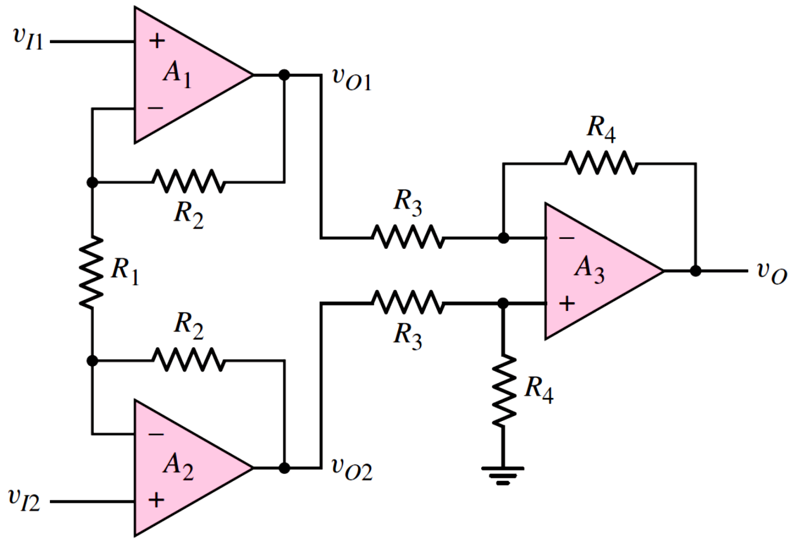
Assumption:

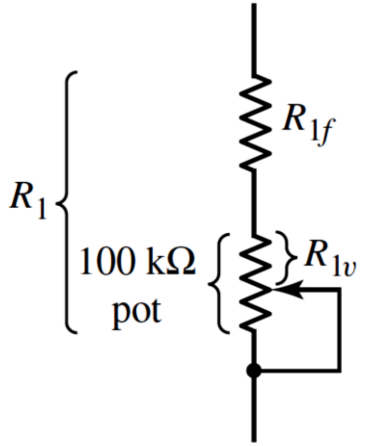
Assume that resistance R_1 is a combination of a fixed resistance R_{1f} and a variable resistance R_{1v}, as shown in the figure. The fixed resistance ensures that the gain is limited to a maximum value, even if the variable resistance is set equal to zero. Assume the variable resistance is a $100\ k\Omega$ potentiometer.



Ex. 02: Instrumentation Amplifier

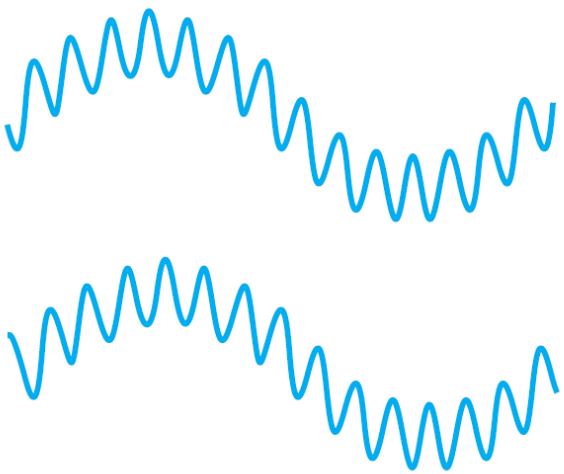
Solution:



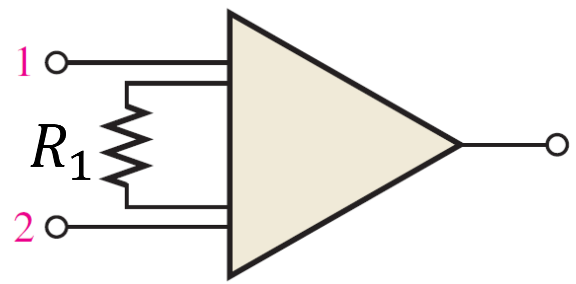


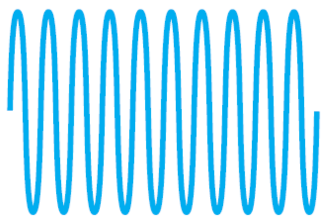
Instrumentation Amplifier - Applications

- Applications include situations where a quantity is sensed by a remote device, such as a temperature- or pressure-sensitive transducer, and the resulting small electrical signal is sent over a long line subject to electrical noise that produces common-mode voltages in the line.



Small differential high-frequency signal riding on a larger low-frequency common-mode signal



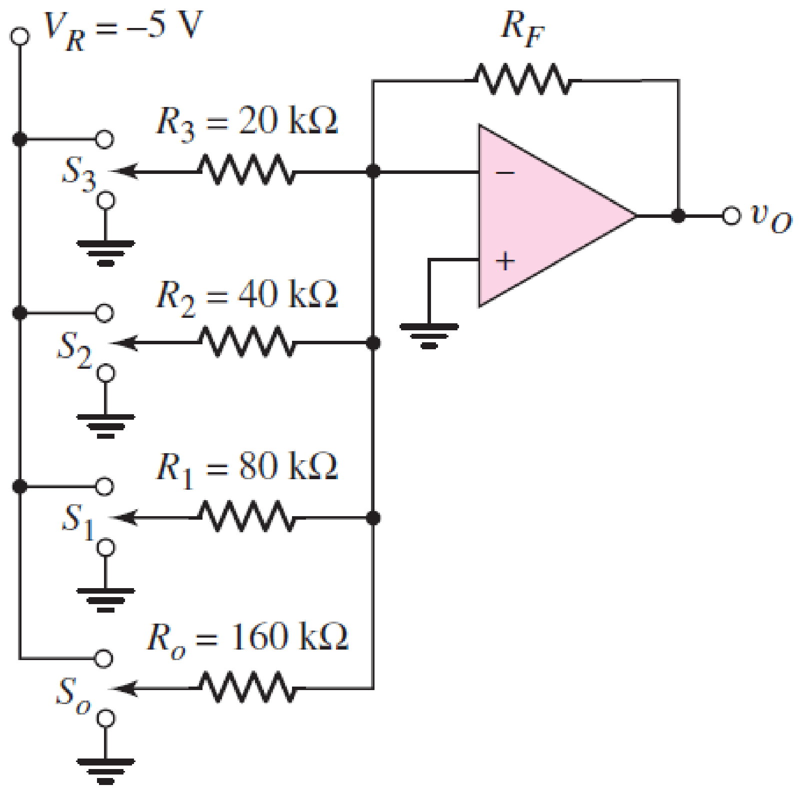


Amplified differential signal.
No common-mode signal.

More Examples

Ex. 03: Digital-to-Analog Converter

A summing amplifier can be used as a digital-to-analog converter (DAC). An example of a 4-bit DAC is shown in the Figure. When switch S_3 is connected to the -5V supply, the most significant bit is $a_3 = 1$; when S3 is connected to ground, the most significant bit is $a_3 = 0$. The same condition applies to the other switches S_2, S_1, and S_0, corresponding to bits a_2, a_1, and a_0, where a_o is the least significant bit.



Ex. 03: Digital-to-Analog Converter

a) Show that the output voltage is given by

$$v_O = \frac{R_F}{10}\left[\frac{a_3}{2} + \frac{a_2}{4} + \frac{a_1}{8} + \frac{a_o}{16}\right] (5)$$

where R_F is in $k\Omega$.

b) Find the value of R_F such that $v_O = 2.5V$ when the digital input is $a_3a_2a_1a_0 = 1000$.

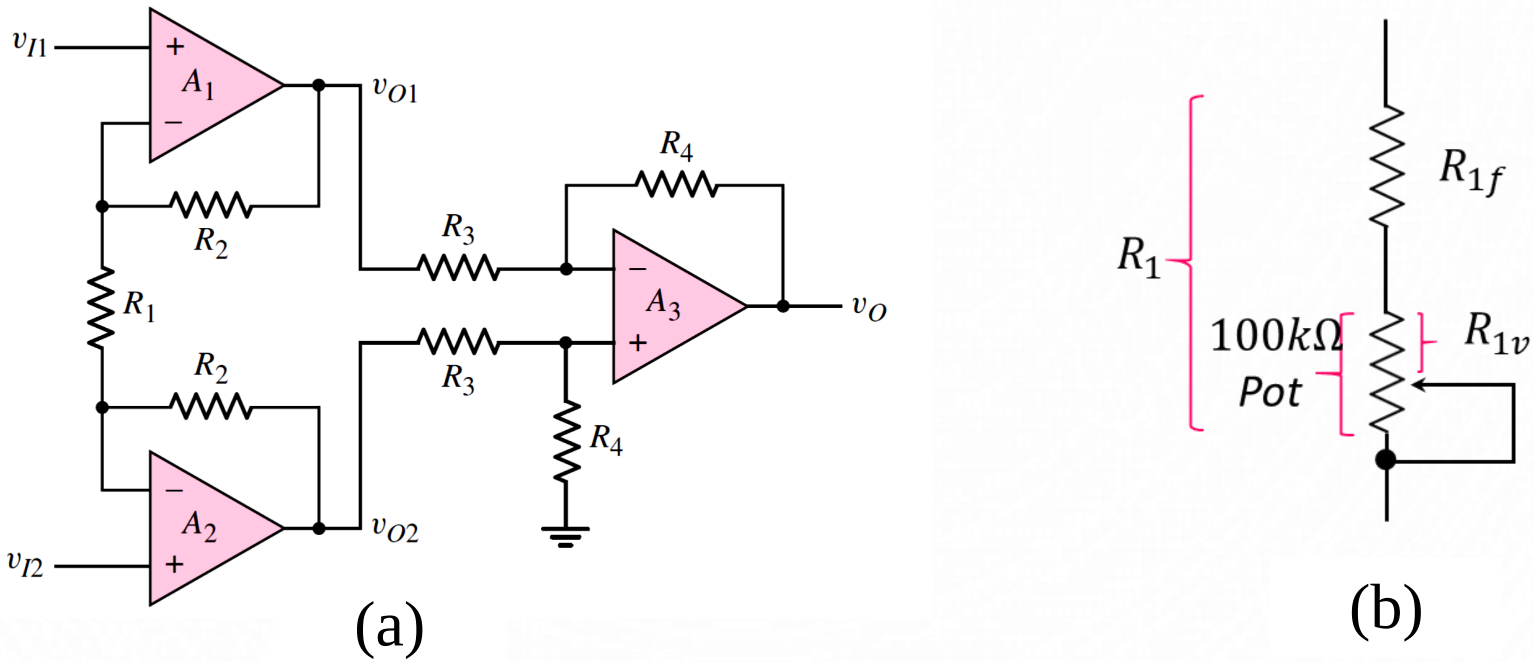
c) Using the results of part (b), find v_o for:

(i) $a_3a_2a_1a_0 = 0001$

(ii) $a_3a_2a_1a_0 = 1111$

Ex. 04: Analyze an Instrumentation Amplifier

The instrumentation amplifier in Figure (a) has an ideal op-amps. The circuit parameters are $R_1 = 10\ k\Omega$, $R_2 = 40\ k\Omega$, $R_3 = 40\ k\Omega$, and $R_4 = 120\ k\Omega$ and input voltages are $v_{I1} = 1.2 + 0.08 \sin \omega t$ and $v_{I2} = 1.2 - 0.08 \sin \omega t$. R_1 is a fixed resistance consists of R_{1f} in series with a potentiometer, as shown in Figure (b). Determine the values of R_{1f} and the potentiometer resistance if the magnitude of the output has a minimum value of $|v_O| = 0.5V$ and a maximum value of $|v_O| = 8V$.



Ex. 05: Design and Instrumentation Amplifier

Design the instrumentation amplifier in the Figure such that the variable differential voltage gain covers the range of 5 to 200. Set the gain of the difference amplifier to 2.5. The maximum current in R_1 is to be limited to $50\mu A$ for an output voltage of $10V$. What value of potentiometer is required?