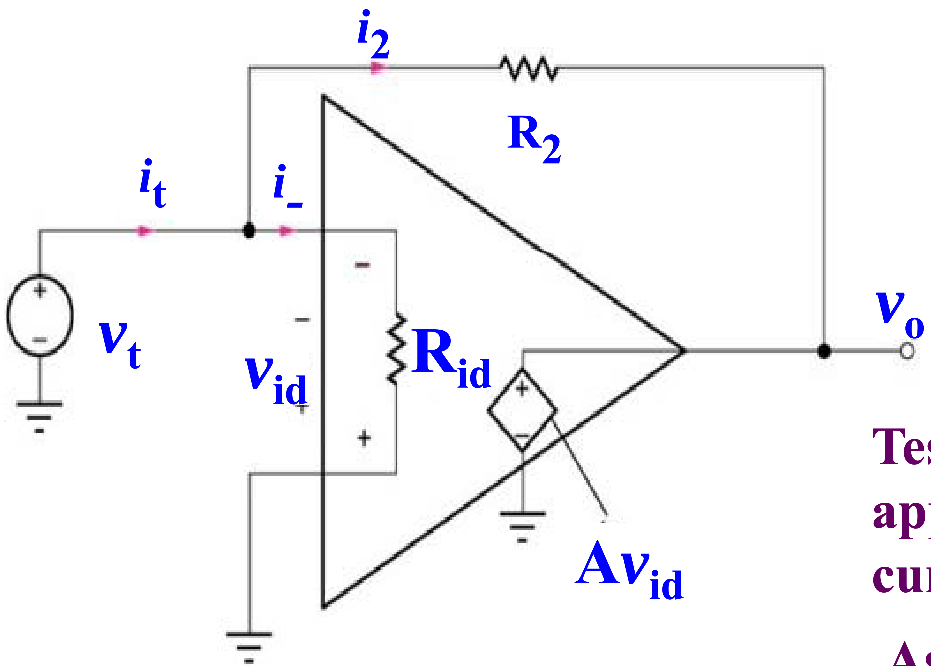
Input resistances for non-ideal OpAmp:

Difficult to derive with non-ideality in both. Hence do it one at a time (Let R_o=0)

Finite Input Resistance: Inverting Amplifier

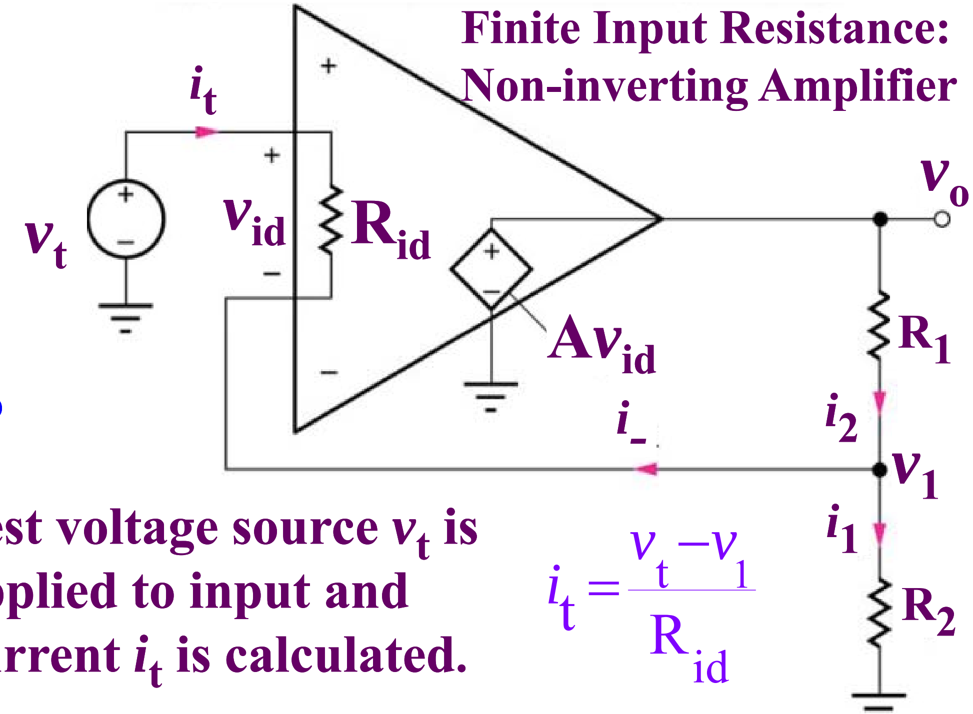


$$i_1 = i_- + i_2 = \frac{v_1}{R_{id}} + \frac{v_1 - v_o}{R_2} = \frac{v_1}{R_{id}} + \frac{v_1 - Av_1}{R_2}$$

$$\therefore G_1 = \frac{i_1}{v_1} = \frac{1}{R_{id}} + \frac{1+A}{R_2}$$ Hence with R_1

$$R_{in} = R_1 + R_{id} \left\| \frac{R_2}{1+A} \right. \cong R_1 + \left(\frac{R_2}{1+A}\right)$$

Finite Input Resistance: Non-inverting Amplifier



Test voltage source v_t is applied to input and current i_t is calculated.

$$i_t = \frac{v_t - v_1}{R_{id}}$$

Assuming $i_- << i_2$ implies $i_1 = i_2$, $v_1 = i_1 R_1 \cong i_2 R_1$

$$v_1 \cong \frac{R_1}{R_1 + R_2} v_o = \beta v_o = \beta(A v_{id}) = A\beta(v_t - v_1)$$

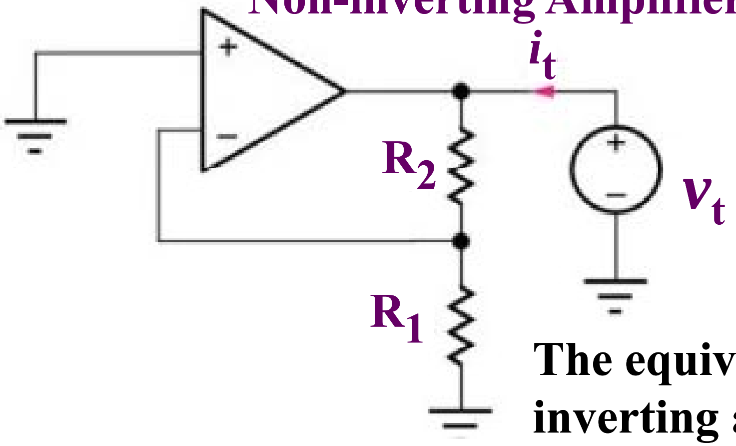
$$v_1 = \frac{A\beta}{1 + A\beta} v_t, \text{ Or } = \frac{v_t - \frac{A\beta}{1+A\beta} v_t}{R_{id}}$$

$$\therefore i_t = \frac{v_t}{(1 + A\beta) R_{id}}, \quad R_{in} = R_{id}\left(1 + \frac{A R_1}{R_1 + R_2}\right)$$

ESc201, Lecture 24: Operational Amplifier

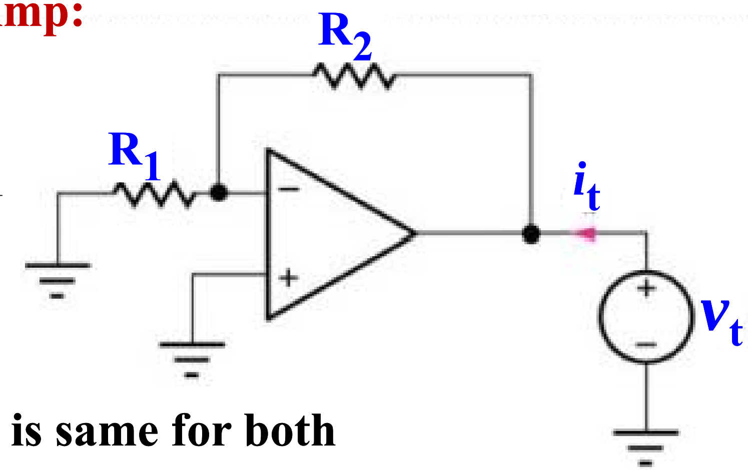
Output resistances for non-ideal OpAmp:

Non-inverting Amplifier

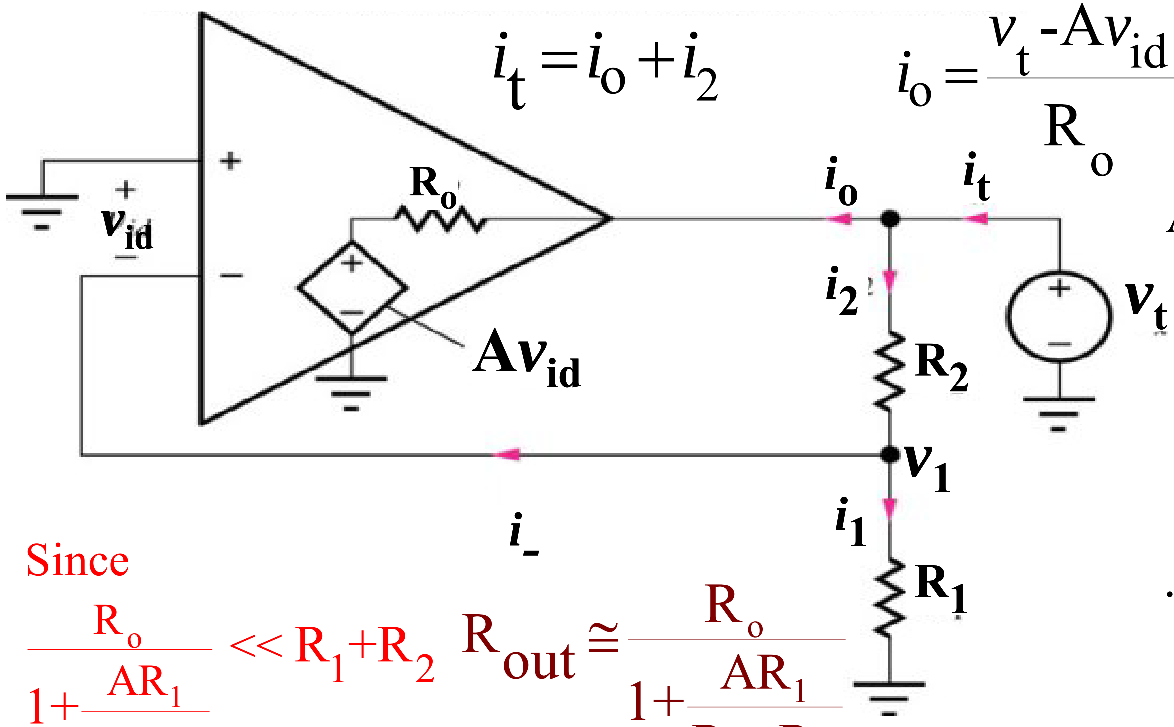


$$R_{out} = \frac{v_t}{i_t}$$

Inverting Amplifier



The equivalent circuit is same for both inverting and non-inverting amplifiers.



$$i_t = i_o + i_2 \qquad i_o = \frac{v_t - Av_{id}}{R_o} \qquad i_2 = \frac{v_t}{R_1 + R_2} \text{ neglecting } i_-$$

Also, $v_{id} = -v_1$ and $v_1 = \frac{R_1}{R_1+R_2} v_t$

$$\therefore \frac{1}{R_{out}} = \frac{i_t}{v_t} = \frac{1 + \frac{AR_1}{R_1+R_2}}{R_o} + \frac{1}{R_1+R_2}$$

$$\therefore R_{out} = \frac{R_o}{1 + \frac{AR_1}{R_1+R_2}} \Big\| \left(R_1 + R_2\right)$$

Since $\frac{R_o}{1+\frac{AR_1}{R_1+R_2}} << R_1 + R_2$ $\quad R_{out} \cong \frac{R_o}{1+\frac{AR_1}{R_1+R_2}}$

For $A \rightarrow \infty$, $R_{out} = 0$

Summary of Non-ideal OpAmp

Inverting Amplifier — **Non-inverting Amplifier**

Open Loop Voltage Gain (A)

$$A_{dv} = \frac{v_o}{v_{in}} = \frac{R_{id}}{R_{id}+R_i} \times \frac{R_L}{R_o+R_L}$$

Same for both

Finite A:

Non-Inverting $v_{id} = v_i - v_1 = v_i - \frac{R_1 v_o}{R_1+R_2}$

$$= v_i - \frac{1}{1+\frac{R_1+R_2}{AR_1}} v_i = \frac{v_i}{1+\frac{AR_1}{R_1+R_2}} \Bigg|_{A\to\infty} \cong 0$$

No longer zero, v_{id} is small for large $AR_1/(R_1+R_2)$.

Voltage Gain (A_v) (negative feedback)

Inverting: $$-\frac{R_2}{R_1}\left(\frac{1}{1+\frac{R_1+R_2}{AR_1}}\right) \cong -\frac{R_2}{R_1}$$

Non-inverting: $$\left(\frac{A}{1+\frac{AR_1}{R_1+R_2}}\right) \cong 1+\frac{R_2}{R_1}$$

Input Resistance (R_{in})

Inverting: $$R_1 + R_{id} \,\Big\|\, \frac{R_2}{1+A} \cong R_1 + \left(\frac{R_2}{1+A}\right)$$

Non-inverting: $$R_{id}\left(1+\frac{AR_1}{R_1+R_2}\right)$$

Output Resistance (R_{out})

$$\frac{R_o}{1+AR_1/(R_1+R_2)} \,\Big\|\, (R_1+R_2) \cong \frac{R_o}{1+AR_1/(R_1+R_2)}$$

Same for both

Instrumentation Amplifier: The signal may get thoroughly corrupted by noise during transmission from a sensor to the signal measuring unit, and it becomes extremely difficult to distinguish the original signal using conventional circuits.

Solution: Have a Differential Amplifier stage with High A_d and High CMRR, preceded by a buffer stage to provide a high R_{in} and impedance matching.

Combines 2 non-inverting OpAmps with a difference OpAmp for high gain and low input resistance.

Requirements of an Instrumentation Amplifier:

Finite, Accurate and Stable Gain: Since the instrumentation amplifiers are required to amplify very low-level signals from the transducer device, **extremely high but finite differential gain** A_{dm} is the basic requirement. The gain also needs to be accurate and the closed-loop gain must be stable.

Easier Gain Adjustment: Apart from a finite and stable gain, variation in the gain factor over a prescribed range of values is also necessary. The gain adjustment must be easier and precise.

High Input Impedance: To avoid the loading of input sources, the input impedance of the instrumentation amplifier must be very high (ideally infinite).

Low Output Impedance: The output impedance of a good instrumentation amplifier must be very low (ideally zero), to avoid loading effect on the immediate next stage.

Perfect impedance matching is required for maximum power transfer from the sensor.

High CMRR: The output from the transducer usually contains common mode signals, when transmitted over long wires. A good instrumentation amplifier must amplify only the differential input, completely rejecting common mode inputs. **Ideally zero common mode gain** A_{cm} **to suppress noise**. Thus, CMRR must $\to \infty$.

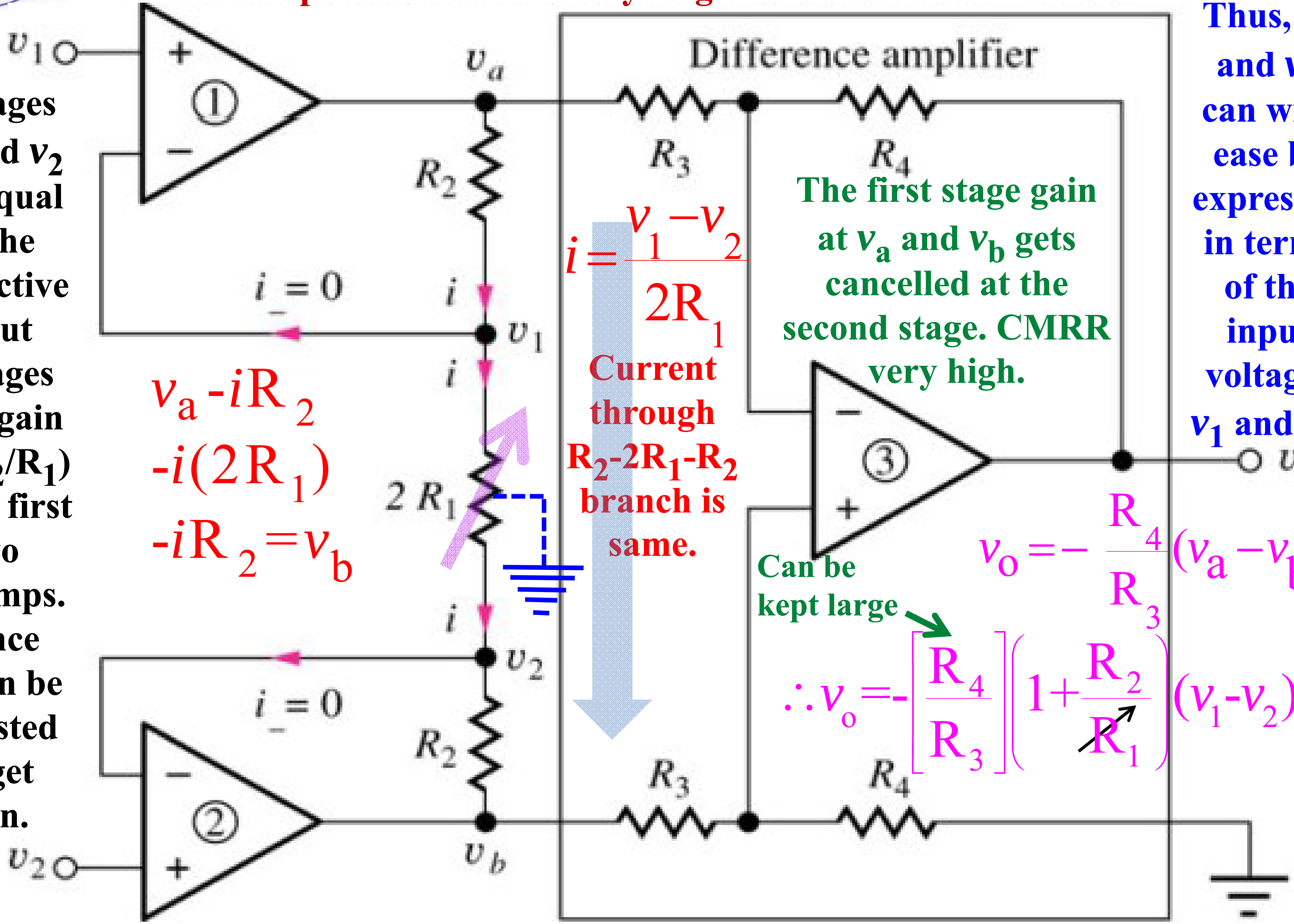
High Slew Rate: The slew rate of the instrumentation amplifier must be as high as possible to provide maximum undistorted output voltage swing.

ESc201, Lecture 23: Operational Amplifier

Instrumentation Amplifier:

Buffer stage: OpAmps (1) and (2) draw little or no input current. Hence the input Resistance is very large.

Voltages v_1 and v_2 are equal to the respective input voltages with gain $(1+R_2/R_1)$ at the first two OpAmps. Hence R_1 can be adjusted to get gain.



$$i = \frac{v_1 - v_2}{2R_1}$$

Current through R_2-$2R_1$-R_2 branch is same.

$$v_a - iR_2 - i(2R_1) - iR_2 = v_b$$

The first stage gain at v_a and v_b gets cancelled at the second stage. CMRR very high.

$$v_o = -\frac{R_4}{R_3}(v_a - v_b)$$

$$\therefore v_o = -\left[\frac{R_4}{R_3}\right]\left(1 + \frac{R_2}{R_1}\right)(v_1 - v_2)$$

Thus, v_a and v_b can with ease be expressed in terms of the input voltages v_1 and v_2.

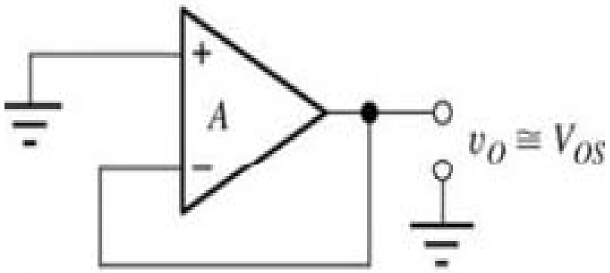
ESc201, Lecture 24: Operational Amplifier (LIMITATIONS) Input Offset Voltage.

(MOS input OpAmps have high R_i but also higher V_{OS} than BJT input)

With inputs being zero, the amplifier output rests at some dc voltage level instead of zero. The equivalent dc input offset voltage is: $V_{OS}=V_o/A$ (1-10 mV).

The amplifier is connected as voltage-follower to give output voltage equal to offset voltage.

To include effect of offset voltage, $v_o = A\left(v_{id} + \frac{v_{ic}}{CMRR} + V_{OS}\right)$



If v_{id} =0,

$$v_o = A\left(\frac{v_{ic}}{CMRR} + V_{OS}\right) = A(v_{OS}) \qquad \therefore CMRR = \frac{v_{ic}}{v_{OS}}\ \mu V/V$$

Limitations : Bandwidth (Unity Gain Cut-off) f_T:

OpAmps are compensated for stability to suppress unwanted oscillations, which introduces a pole in the frequency response characteristic, typically ~ 5-10Hz.

After that, the gain rolls off at -20dB/decade. The frequency at which the magnitude of this gain becomes unity (i.e., 0 dB) is known as the unity gain cut-off frequency (f_T). Where :

$$A_{v\,op.\,loop} \times f_{op.\,loop} = Af_{op.\,loop} = f_T = A_{v\,feedback} \times f_{3dB}$$

For a closed-loop feedback amplifier:

$$A_V(s) = \frac{A_o/\{1+A_oR_1/(R_1+R_1)\}}{1+s/\{[1+A_oR_1/(R_1+R_1)]\omega_{3dB}\}} = \frac{A_v(0)}{1+s/\omega_H}$$

$$\omega_H = [1+A_oR_1/(R_1+R_1)]\omega_{3dB} = \frac{\omega_T}{A_v(0)}$$