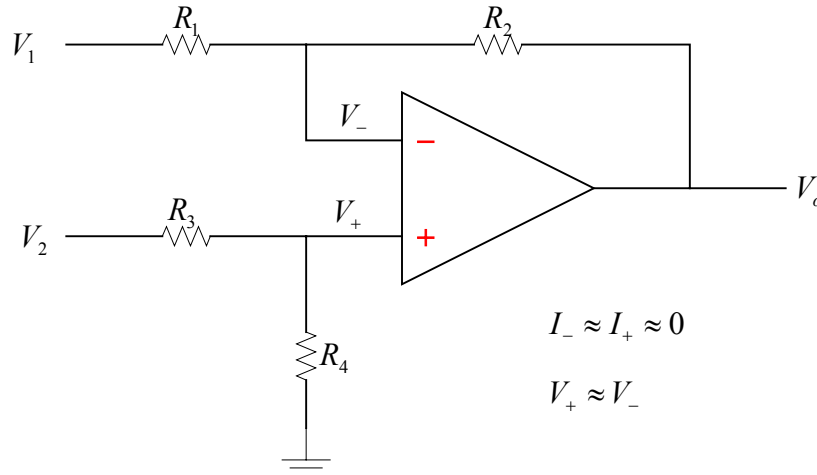


Op-Amp : Operational Amplifier

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1. Basic Op-Amp



Op-Amp has very high input impedance, ie $I_- \approx I_+ \approx 0$, so

$$\frac{V_1 - V_-}{R_1} = \frac{V_- - V_o}{R_2} \Rightarrow V_- = \frac{G_1 V_1 + G_2 V_o}{G_1 + G_2}, \quad G_i = \frac{1}{R_i} \quad (1)$$

and

$$\frac{V_2 - V_+}{R_3} = \frac{V_+}{R_4} \Rightarrow V_+ = \frac{G_3 V_2}{G_3 + G_4} \quad (2)$$

Very input impedance also gives

$$V_- = V_+ \quad (3)$$

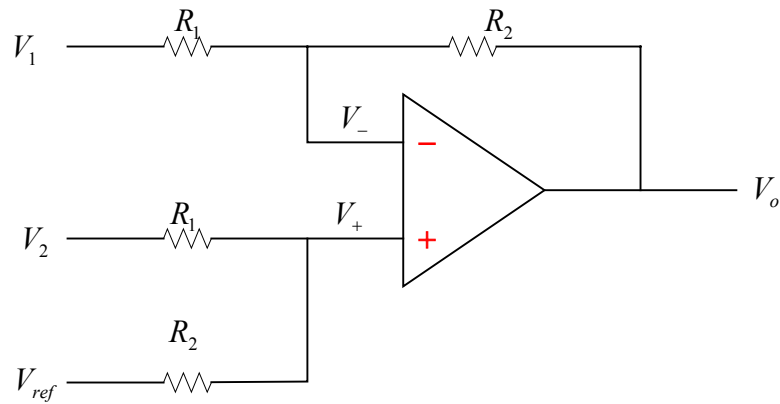
thus, equating Eq(1) & (2) gives

$$\frac{G_1 V_1 + G_2 V_o}{G_1 + G_2} = \frac{G_3 V_2}{G_3 + G_4} \quad (4)$$

Therefore

$$V_o = V_2 \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1} \right) - V_1 \left(\frac{R_2}{R_1} \right) \quad (5)$$

2. Op-Amp with Vref



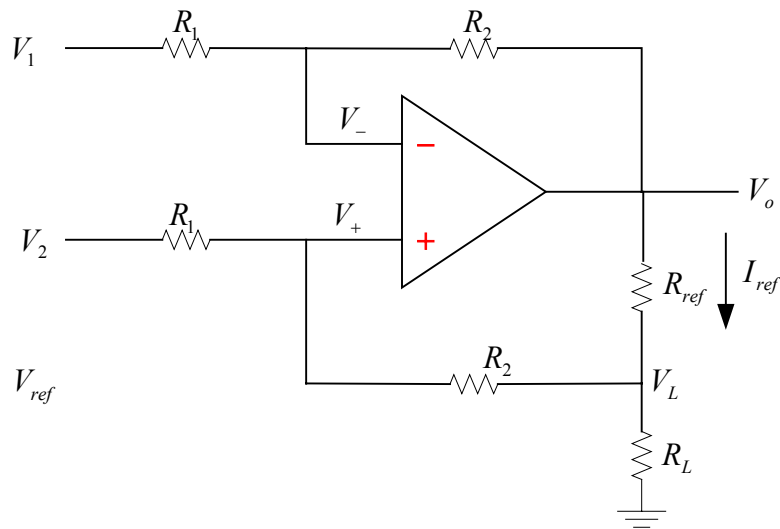
By superposition principle for linear devices, we have

$$V_o = V_2 \frac{R_2}{R_1 + R_2} \left(1 + \frac{R_2}{R_1} \right) + V_{ref} \frac{R_1}{R_1 + R_2} \left(1 + \frac{R_2}{R_1} \right) - V_1 \left(\frac{R_2}{R_1} \right) = V_2 \left(\frac{R_2}{R_1} \right) + V_{ref} - V_1 \left(\frac{R_2}{R_1} \right)$$

or

$$V_o - V_{ref} = (V_2 - V_1) \left(\frac{R_2}{R_1} \right) \quad (6)$$

3. Op-Amp with Iref



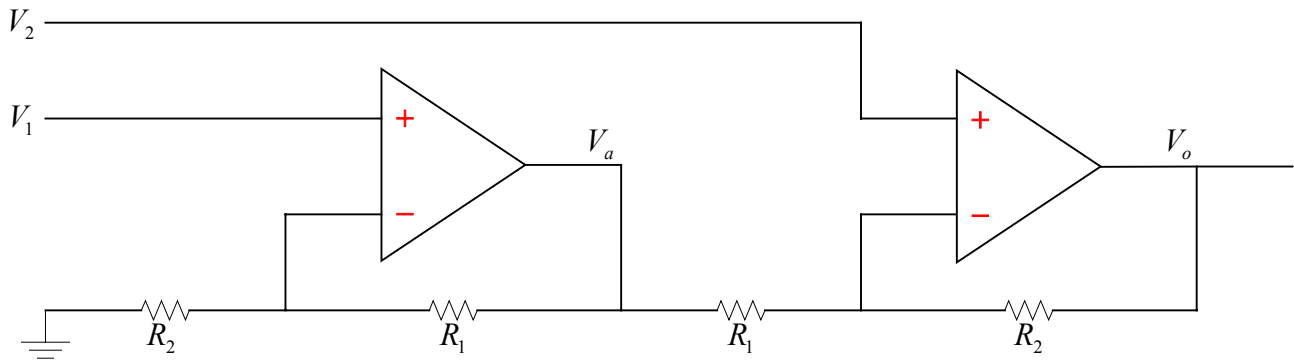
By Eq(6), we have

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

or

$$I_{ref} R_{ref} = (V_2 - V_1) \left(\frac{R_2}{R_1} \right) \quad (7)$$

4. Two Op-Amp



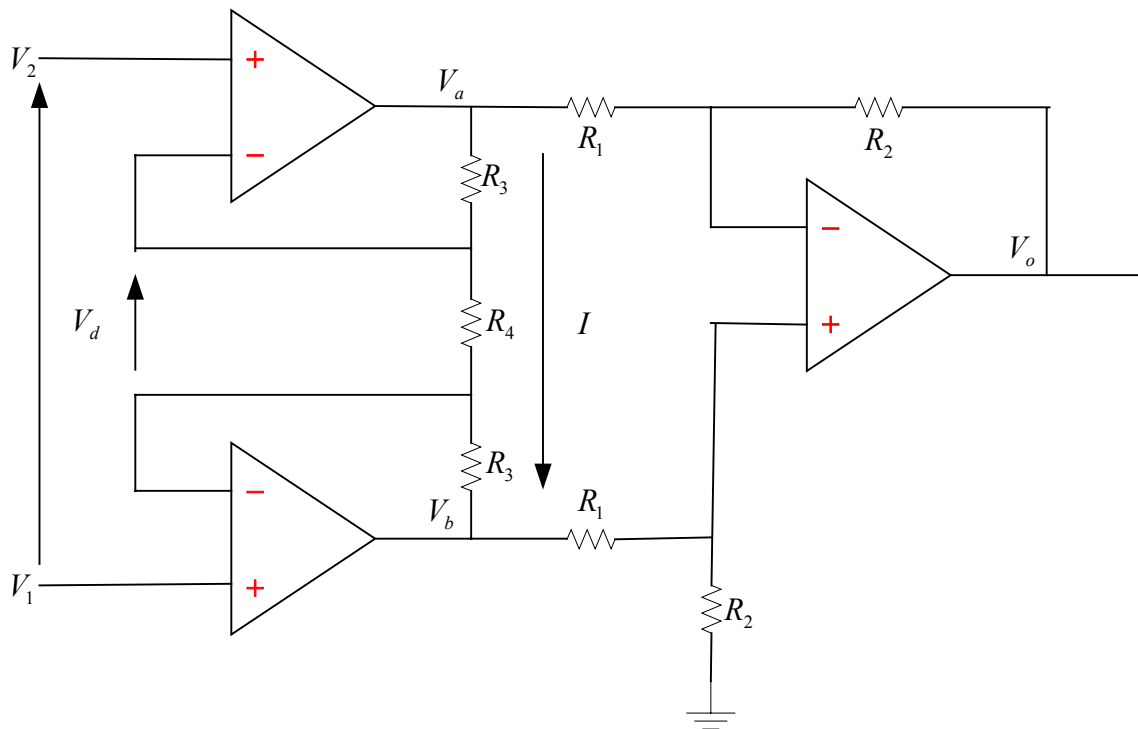
We have

$$V_o = V_2 \left(1 + \frac{R_2}{R_1} \right) - V_a \left(\frac{R_2}{R_1} \right) = V_2 \left(1 + \frac{R_2}{R_1} \right) - V_1 \left(1 + \frac{R_1}{R_2} \right) \left(\frac{R_2}{R_1} \right) = V_2 \left(1 + \frac{R_2}{R_1} \right) - V_1 \left(1 + \frac{R_2}{R_1} \right)$$

or

$$V_o = (V_2 - V_1) \left(1 + \frac{R_2}{R_1} \right) \quad (8)$$

5. Three Op-Amp



We have

$$V_o = V_b \frac{R_2}{R_1 + R_2} \left(1 + \frac{R_2}{R_1} \right) - V_a \left(\frac{R_2}{R_1} \right) = (V_b - V_a) \left(\frac{R_2}{R_1} \right) = -I(2R_3 + R_4) \left(\frac{R_2}{R_1} \right) = -\frac{V_d}{R_4} (2R_3 + R_4) \left(\frac{R_2}{R_1} \right)$$

or

$$V_o = -(V_2 - V_1) \left(\frac{R_2}{R_1} \right) \left(1 + 2 \frac{R_3}{R_4} \right) \quad (9)$$

