Operational Amplifiers (Op Amps)

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Introduction

- Op Amp is short for operational amplifier.
- An operational amplifier is modeled as a voltage controlled voltage source.
- An operational amplifier has a very high input impedance and a very high gain.

Use of Op Amps

- Op amps can be configured in many different ways using resistors and other components.
- Most configurations use feedback.

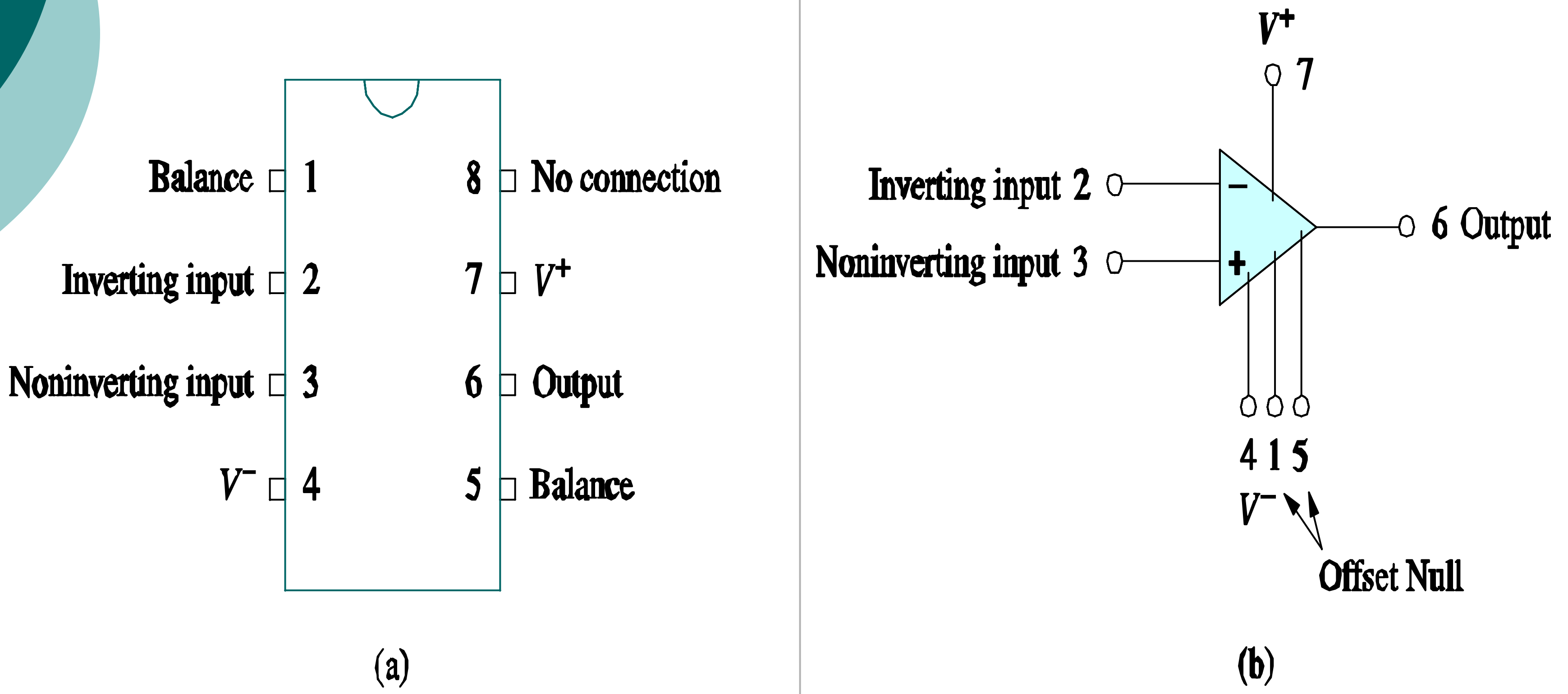
Applications of Op Amps

- Amplifiers provide gains in voltage or current.
- Op amps can convert current to voltage.
- Op amps can provide a buffer between two circuits.
- Op amps can be used to implement integrators and differentiators.

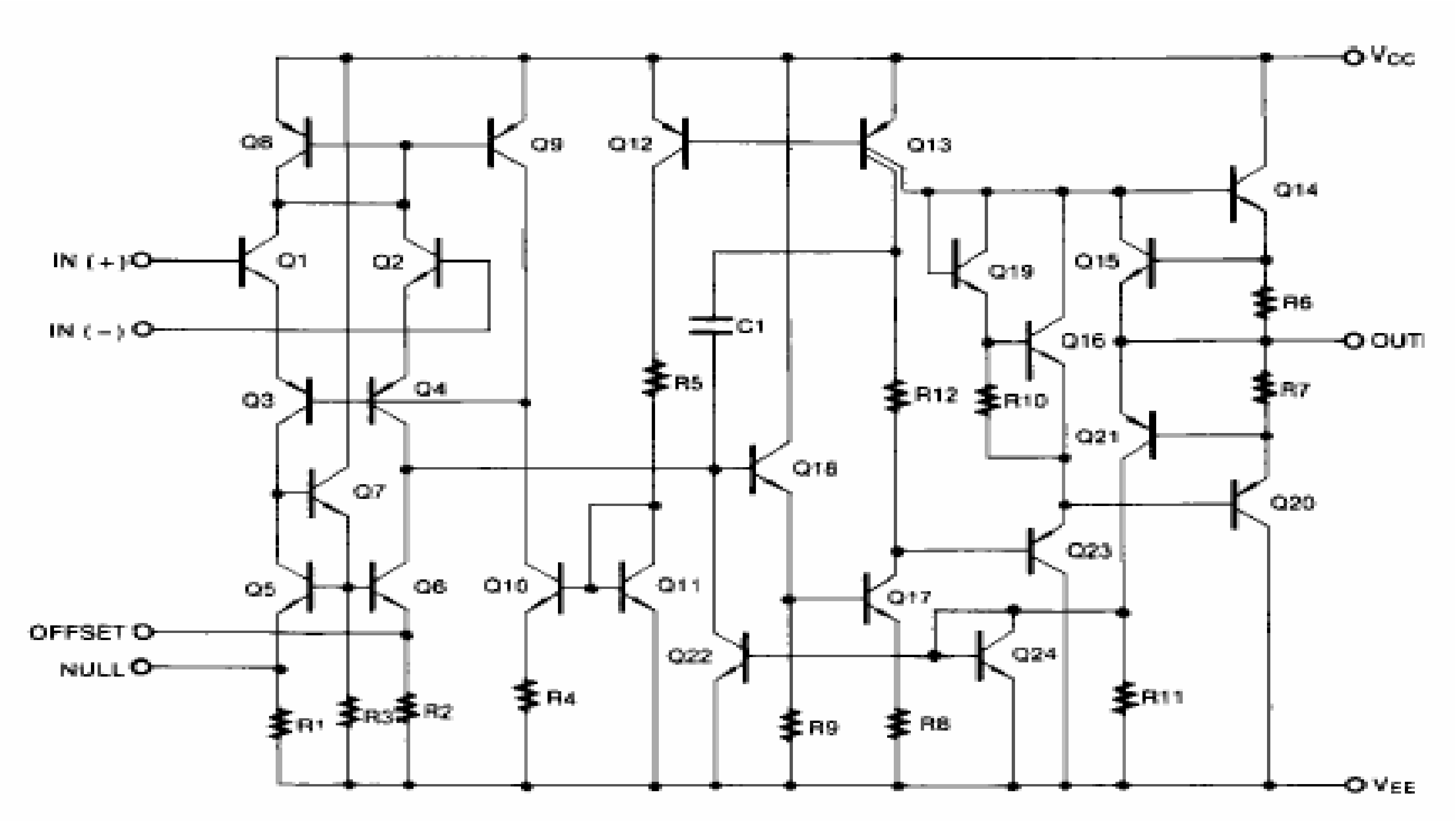
More Applications

- Lowpass and bandpass filters.

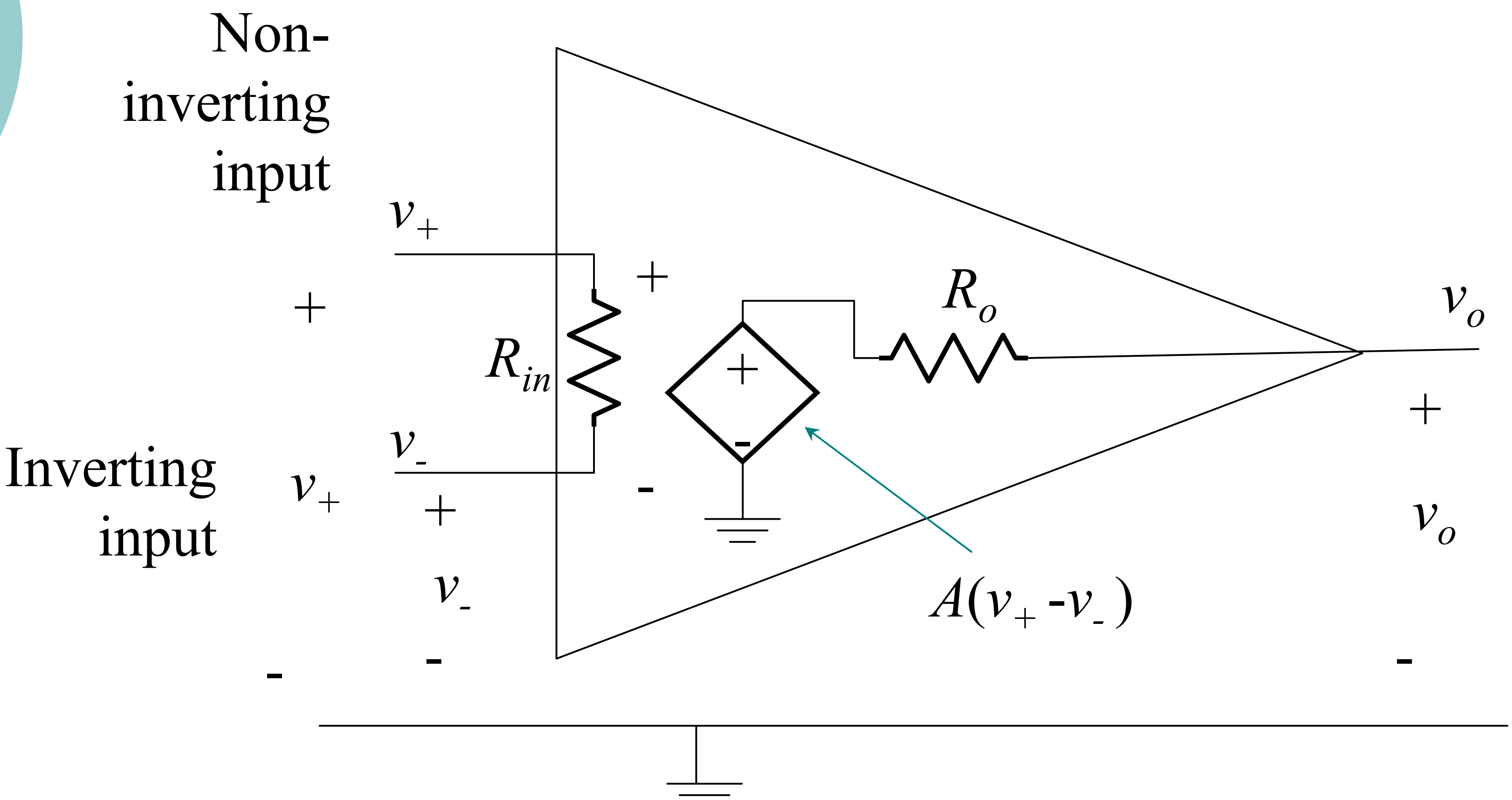
The Op Amp Symbol



Schematic diagram of op amp



The Op Amp Model

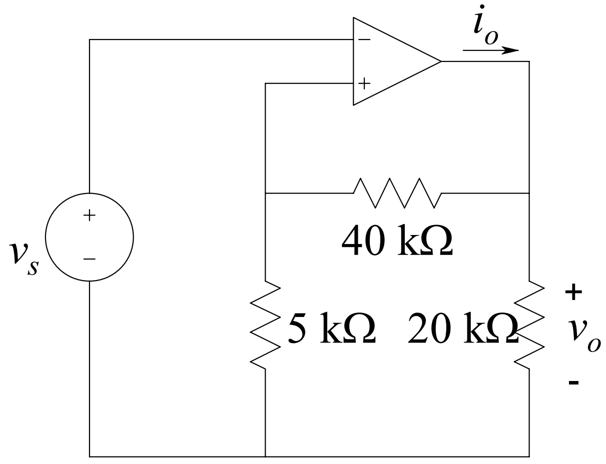


Typical Op Amp

Parameter	Typical Range	Ideal Values
Open-loop gain, A	10^5 to 10^8	∞
Input resistance, R_{in}	10^6 to 10^{13}	∞
Output resistance, R_o	10 to 100	0 Ω
Supply voltage, v_{cc}	5 to 24	

Example

- A 741 op amp has an open-loop voltage gain of 2 x 10^5, input resistance of 2 MΩ, and output resistance of 50 Ω.The op amp is used in the circuit shown below. Find the closed- loop gain v_0/v_s. Find i_0 when $v_s = 1$ V.



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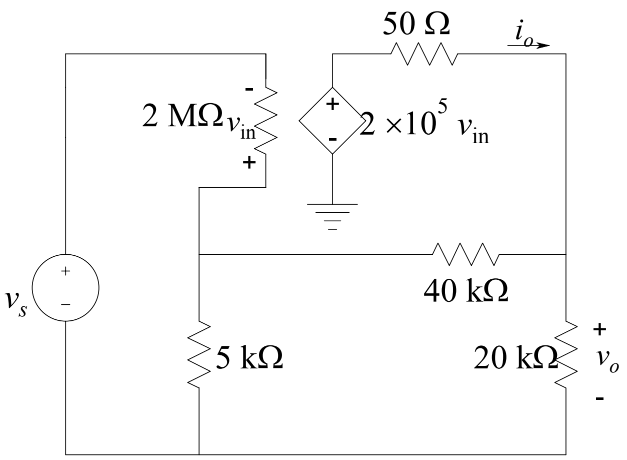
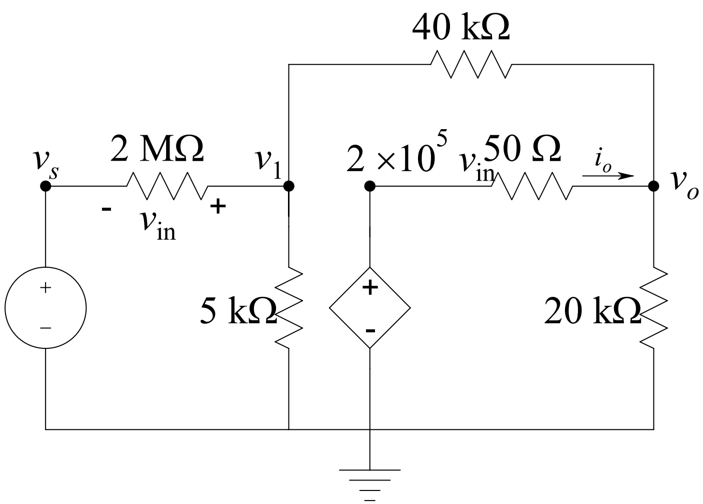


Equivalent circuit

Example cont.

- Redrawn for clarity



KCL at v_1

$$\frac{v_1 - v_s}{2\times10^6} + \frac{v_1}{5\times10^3} + \frac{v_1 - v_0}{40\times10^3} = 0$$

KCL at v_0

$$\frac{v_0}{20\times10^3} + \frac{v_0 - v_1}{40\times10^3} + \frac{v_0 - 2\times10^5(v_1 - v_s)}{50} = 0$$

$$v_0 = 9.0004 v_s$$

$$i_0 = 0.675 \text{ mA}$$

“Ideal” Op Amp

- The input resistance is infinite, $R_{in}=\infty$
- The gain is infinite, $A = \infty$
- Zero output resistance, $R_o= 0$
- The op amp is in a negative feedback configuration.

Consequences of the Ideal

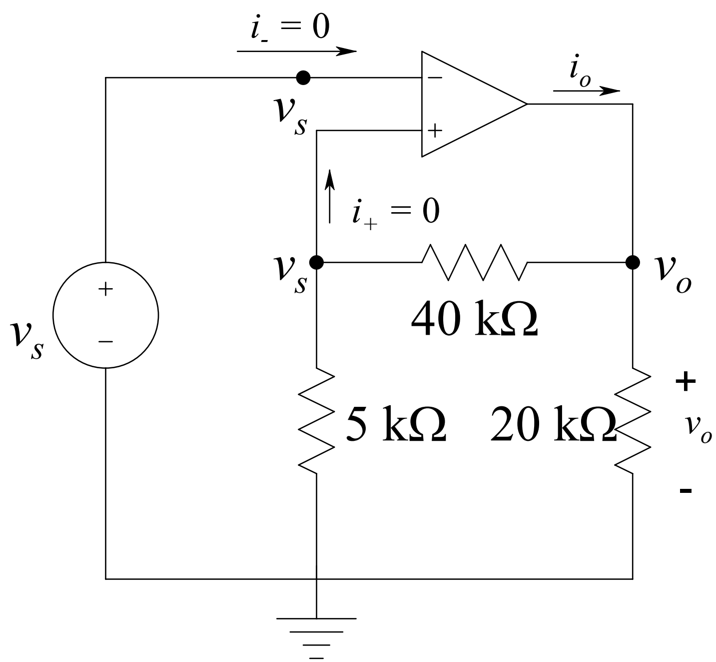
- Infinite input resistance means the current into the inverting input is zero:

$$i_- = 0 = i_+$$

- Infinite gain means the difference between v_+ and v_- is zero:

$$v_+ - v_- = 0$$

Example



KCL at noninverting terminal:

$$\frac{v_s - v_0}{40} + \frac{v_s}{5} = 0$$

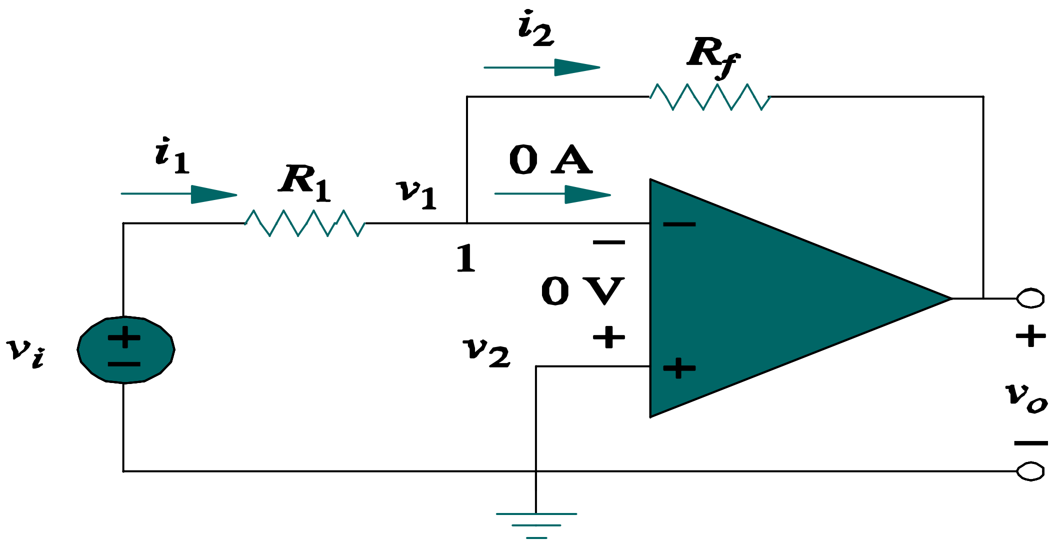
$$9v_s = v_0$$

KCL at v_0:

$$i_0 = \left(\frac{v_0}{20k} + \frac{v_0 - v_s}{40k} \right)$$

If v_s = 1 V then $i_0 = 0.65\ \mathrm{mA}$

Inverting Amplifier



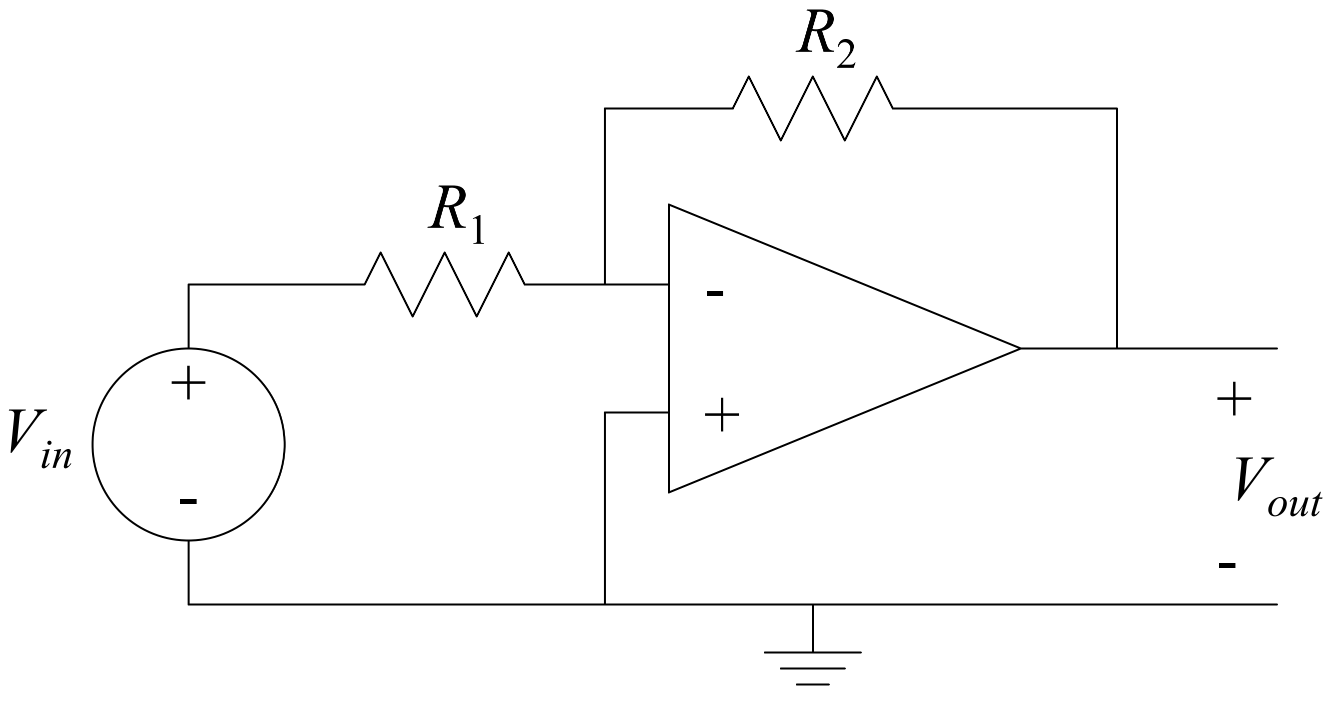
Since the noninverting terminal is grounded

$$v_1 = v_2 = 0$$

KCL at v_1: $i_1 = i_2 \Rightarrow \frac{v_i - 0}{R_1} = \frac{0 - v_0}{R_f}$

$$v_0 = -\frac{R_f}{R_1} v_i$$

Where is the Feedback?



Review

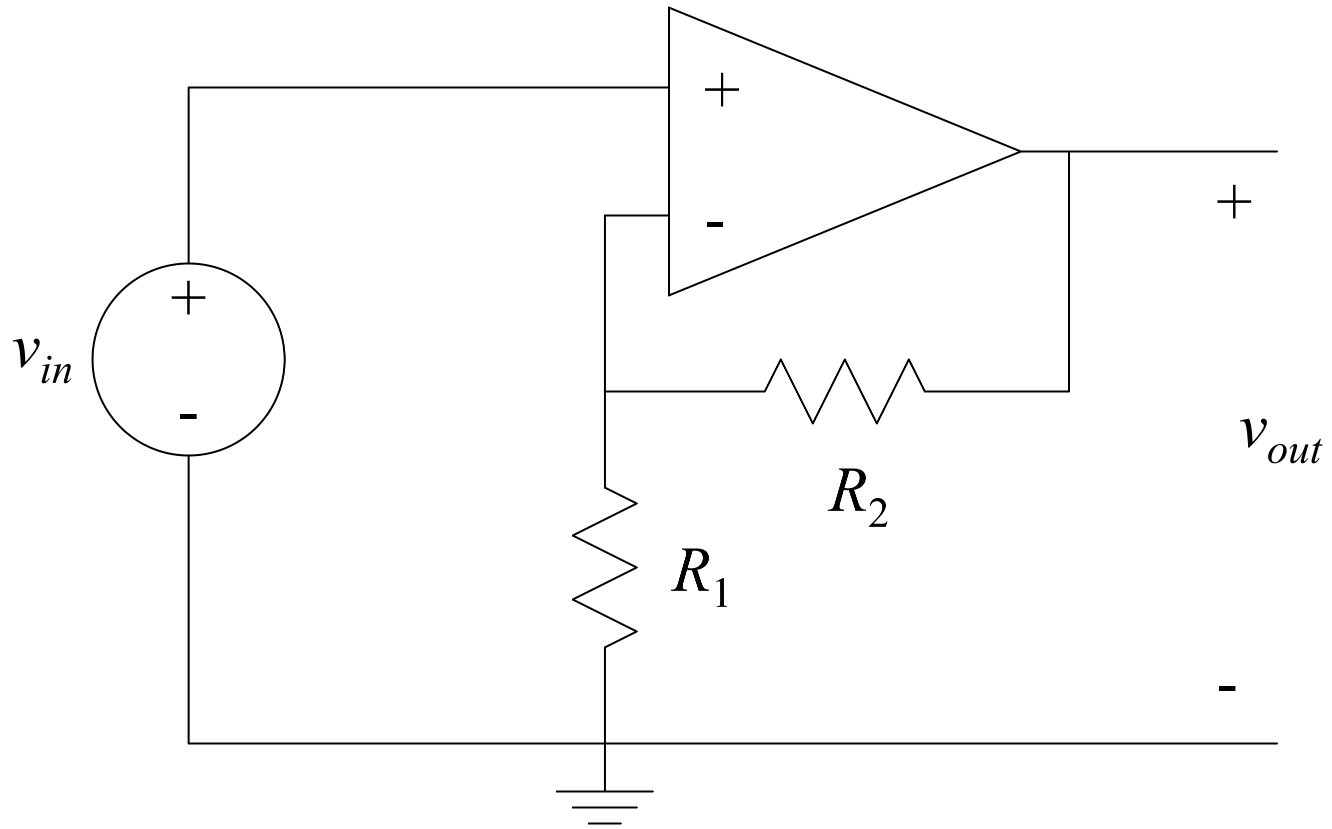
- To solve an op amp circuit, we usually apply KCL at one or both of the inputs.
- We then invoke the consequences of the ideal model.

$$i_- = 0 = i_+$$

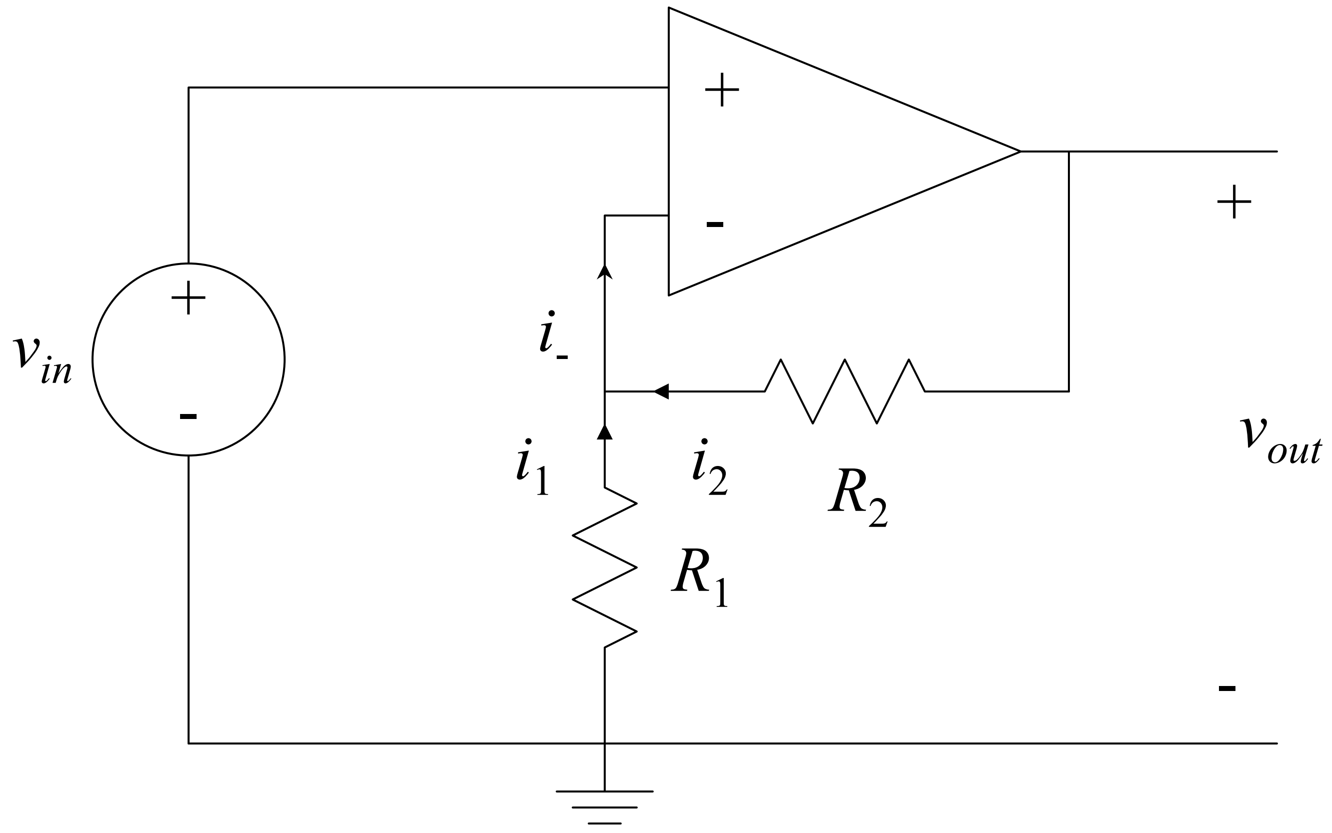
$$v_+ - v_- = 0$$

- We solve for the op amp output voltage.

The Non-Inverting Amplifier



KCL at the Inverting Input



KCL

$$i_{-} = 0$$

$$i_1 = \frac{-v_{-}}{R_1} = \frac{-v_{in}}{R_1}$$ Since $v_{-} = v_{+} = v_{in}$

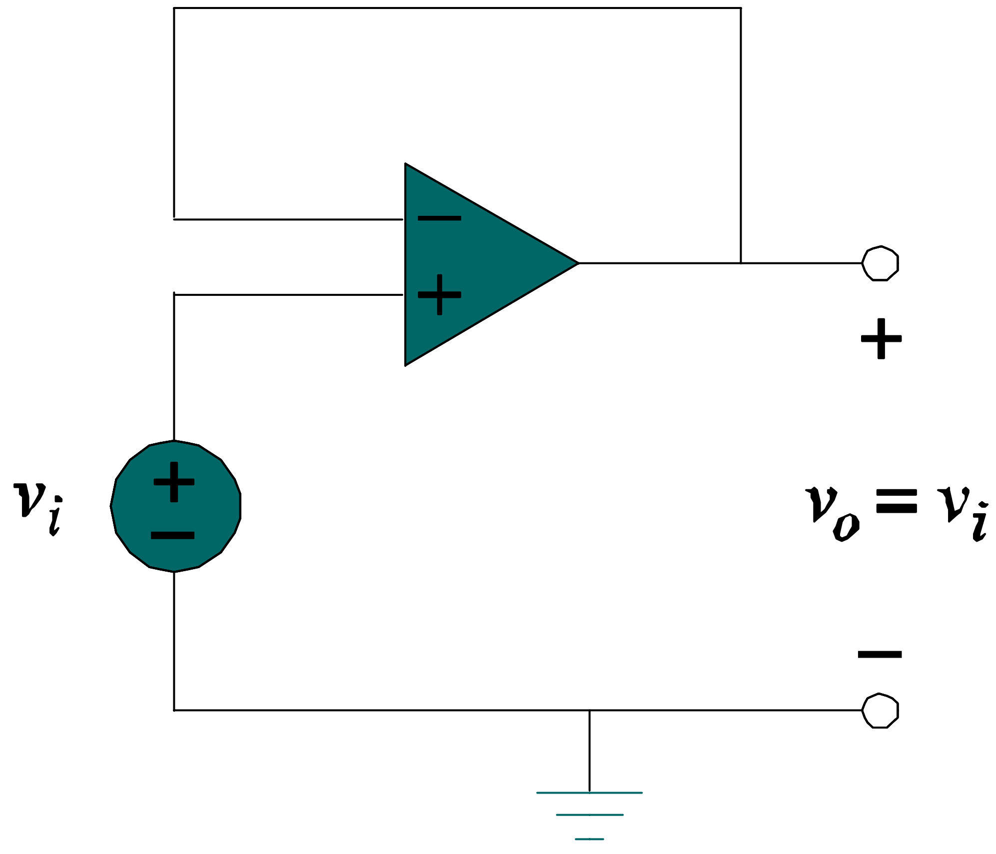
$$i_2 = \frac{v_{out} - v_{-}}{R_2} = \frac{v_{out} - v_{in}}{R_2}$$

Solve for V_{out}

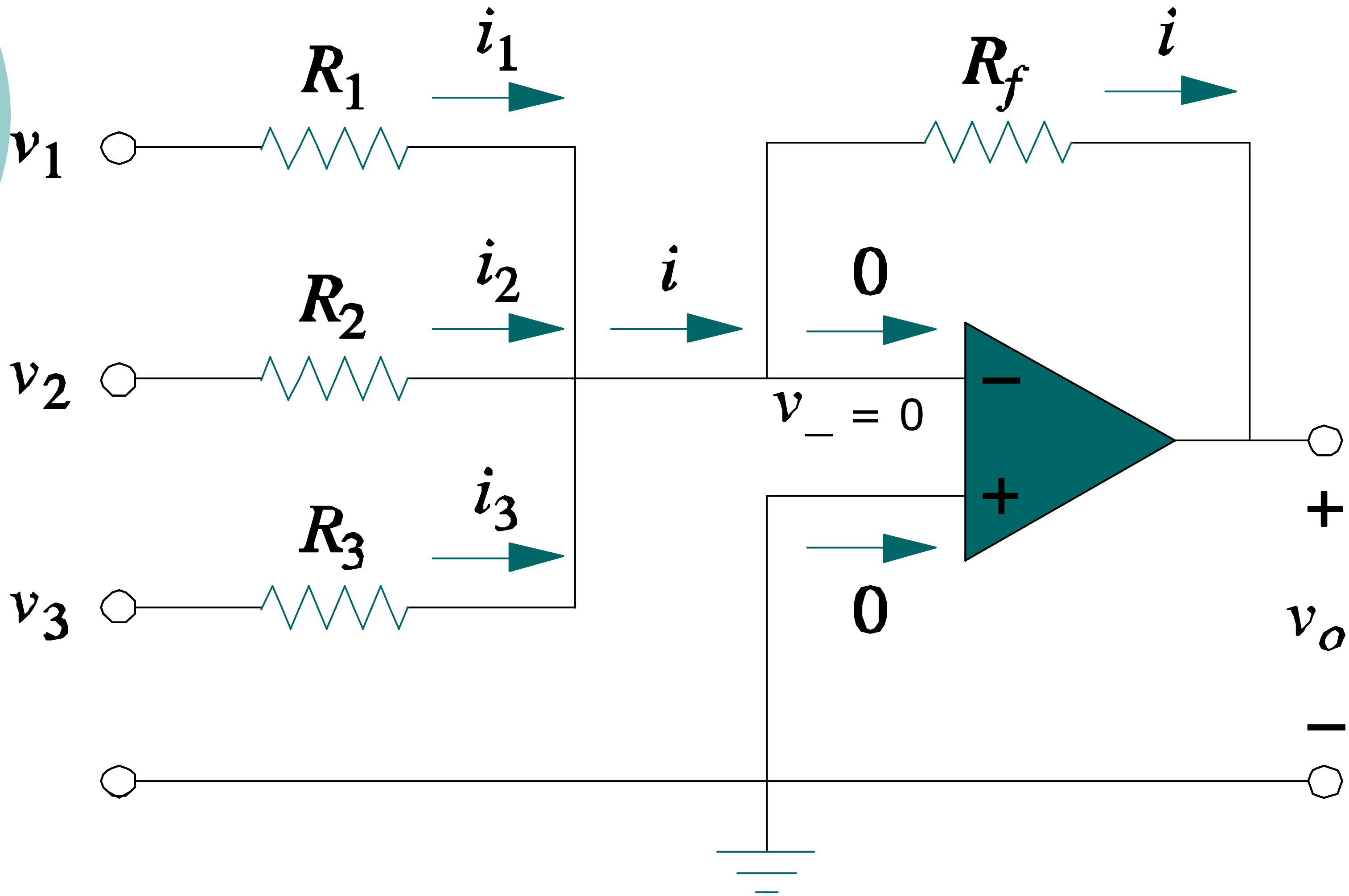
$$\frac{-v_{in}}{R_1} + \frac{v_{out} - v_{in}}{R_2} = 0$$

$$v_{out} = v_{in}\left(1 + \frac{R_2}{R_1}\right)$$

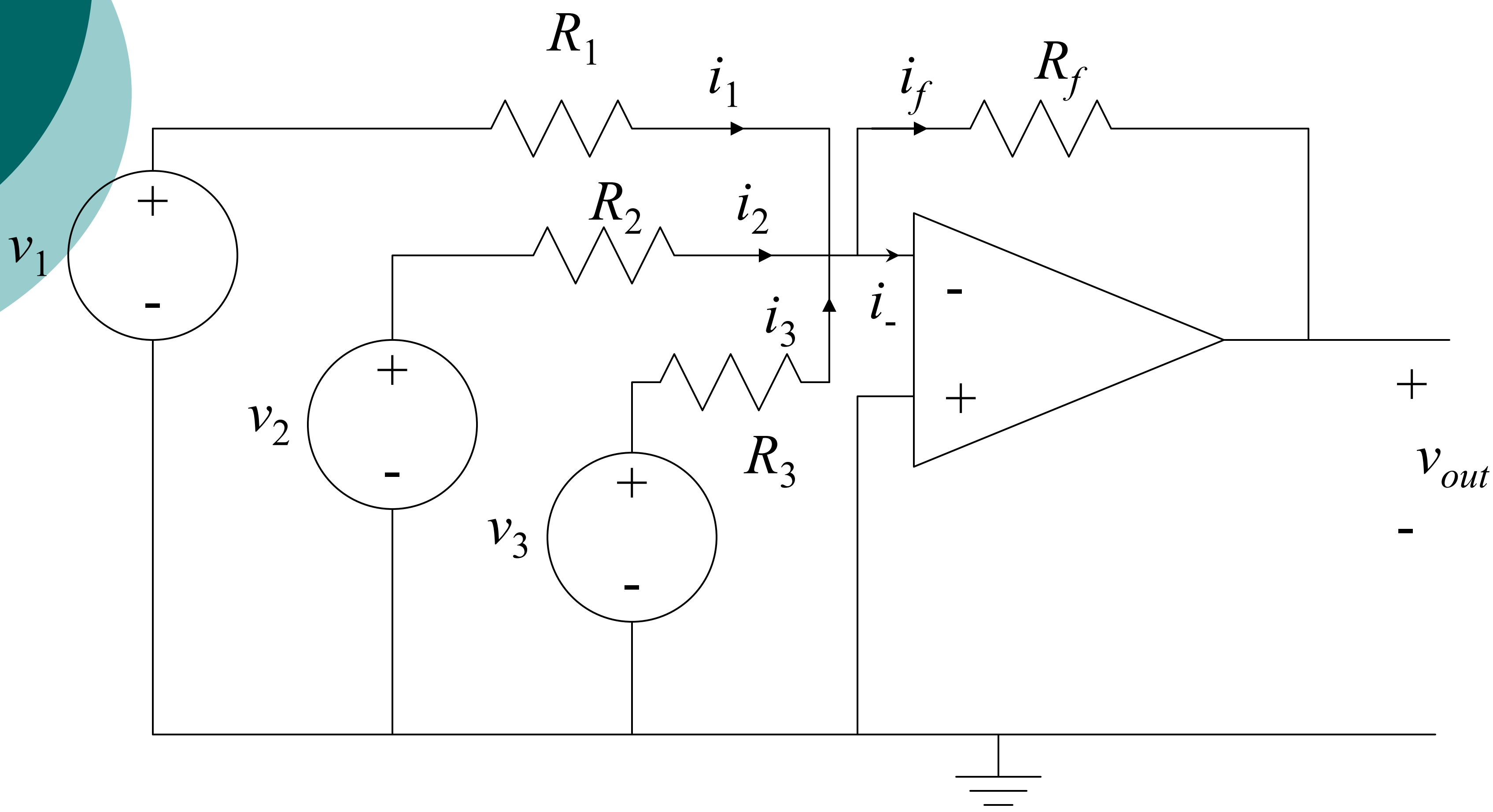
The Voltage Follower



Inverting Summer



KCL at the Inverting Input



KCL

$$i_1 = \frac{v_1 - v_-}{R_1} = \frac{v_1}{R_1} \quad \text{since} \;\; v_- = 0$$

$$i_2 = \frac{v_2 - v_-}{R_2} = \frac{v_2}{R_2}$$

$$i_3 = \frac{v_3 - v_-}{R_3} = \frac{v_3}{R_3}$$

KCL

$$i_- = 0$$

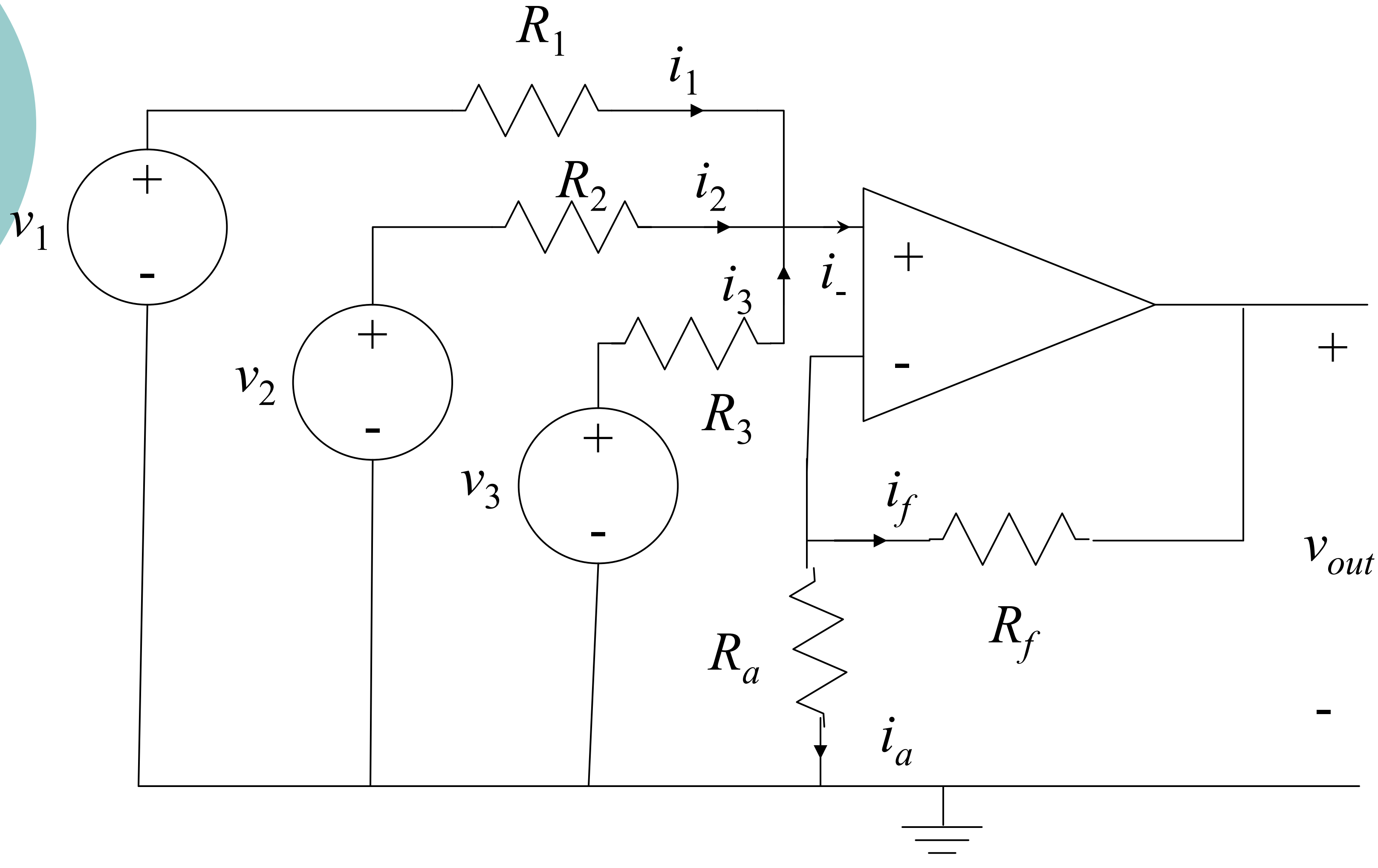
$$i_f = \frac{v_{out} - v_-}{R_f} = \frac{v_{out}}{R_f}$$

Solve for V_{out}

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} + \frac{v_{out}}{R_f} = 0$$

$$v_{out} = -\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2 - \frac{R_f}{R_3} v_3$$

Noninverting Summer



KCL at noninverting input:

$$i_1 + i_2 + i_3 = 0$$

$$i_1 = \frac{v_1 - v_+}{R_1}$$

$$i_2 = \frac{v_2 - v_+}{R_2}$$

$$i_3 = \frac{v_3 - v_+}{R_3}$$

KCL at inverting input:

$$i_f + i_a = 0$$

$$i_f = \frac{v_- - v_{out}}{R_f}$$

$$i_a = \frac{v_-}{R_a}$$

$$v_- = \frac{R_a}{R_a + R_f} v_{out}$$

$$v_- = v_+$$

$$i_1 + i_2 + i_3 = 0$$

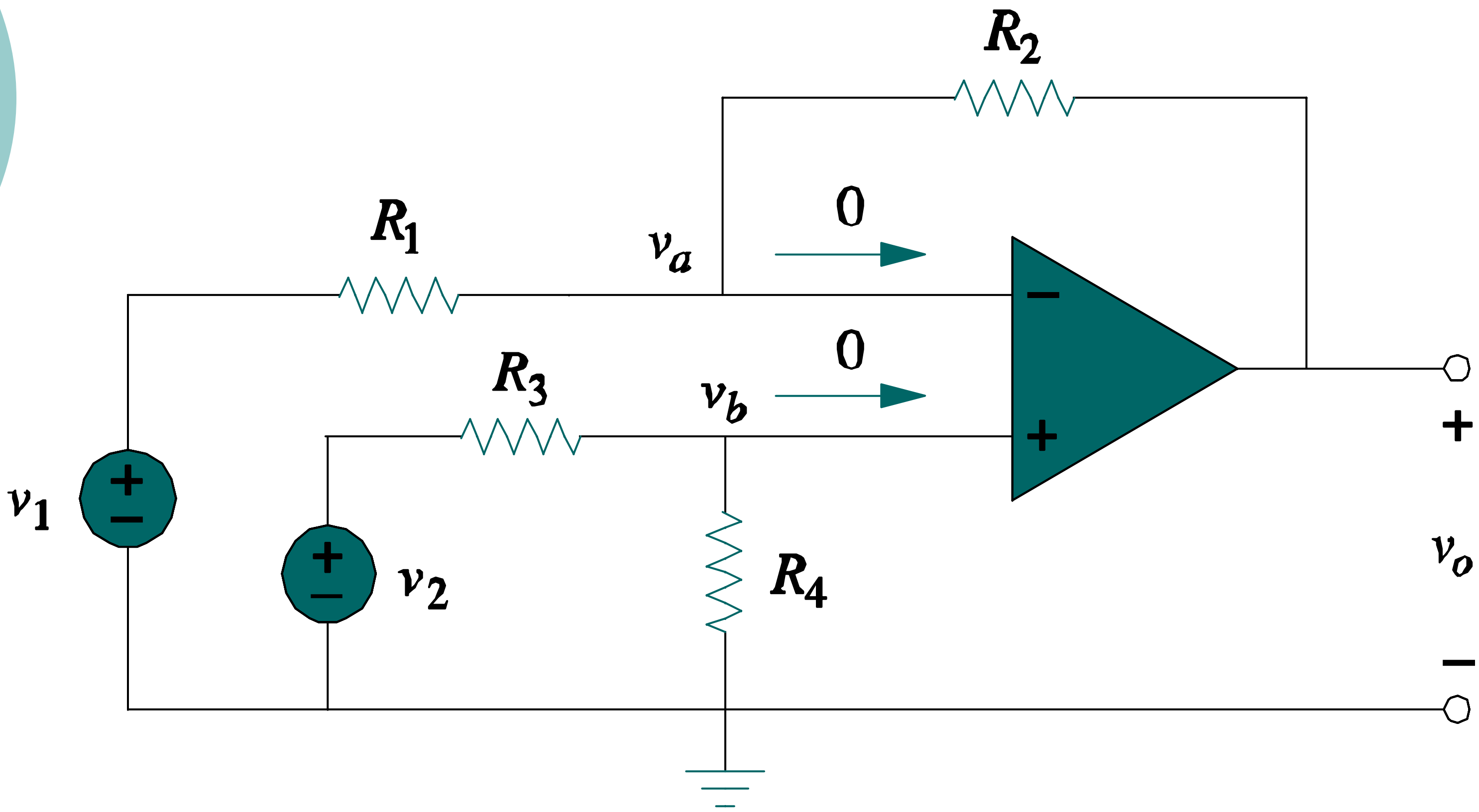
$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) v_+$$

$$\frac{1}{R_T} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} = \frac{1}{R_T} \frac{R_a}{R_a + R_f} v_{out}$$

$$v_{out} = \left(1 + \frac{R_f}{R_a}\right)\left(\frac{R_T}{R_1} v_1 + \frac{R_T}{R_2} v_2 + \frac{R_T}{R_3} v_3\right)$$

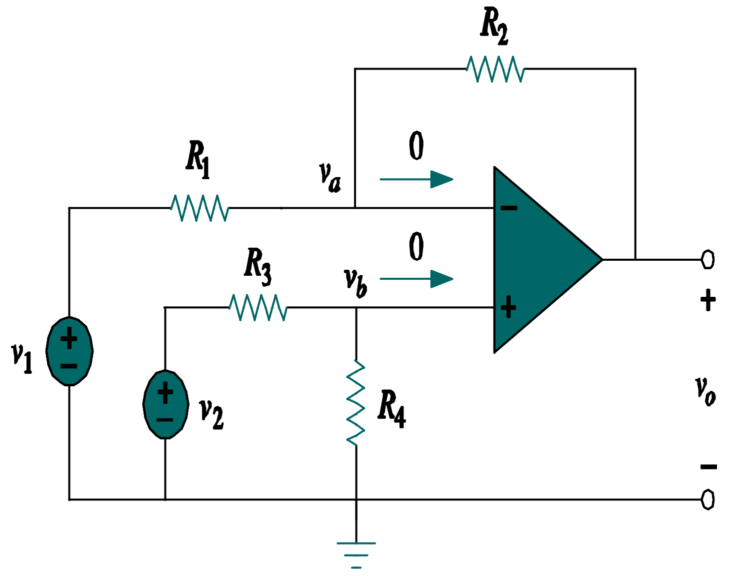
The difference amplifier

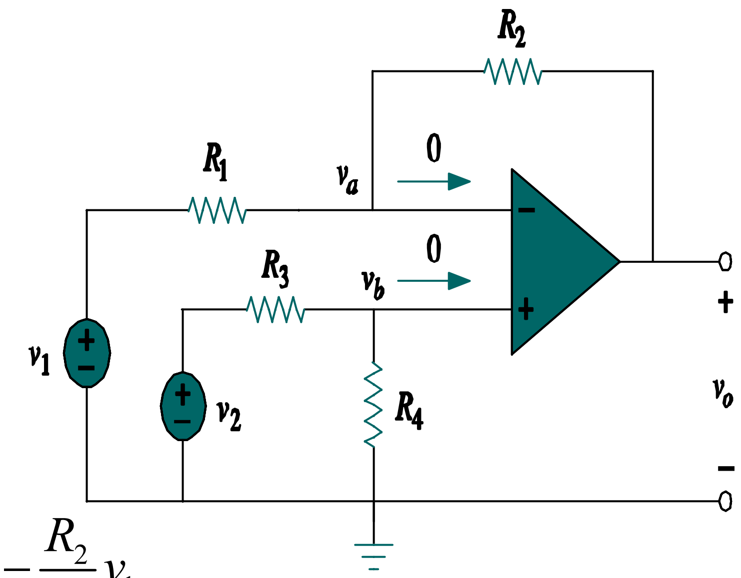


KCL at node v_b :

$$\frac{v_b - v_2}{R_3} = \frac{v_b}{R_4}$$

$$v_b = \frac{R_4}{R_3 + R_4} v_2 = v_a$$





KCL at v_a

$$\frac{v_a - v_1}{R_1} + \frac{v_a - v_o}{R_2} = 0$$

$$\frac{1}{R_2} v_o = \left(\frac{1}{R_1} + \frac{1}{R_2} \right) v_a - \frac{1}{R_1} v_1$$

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

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

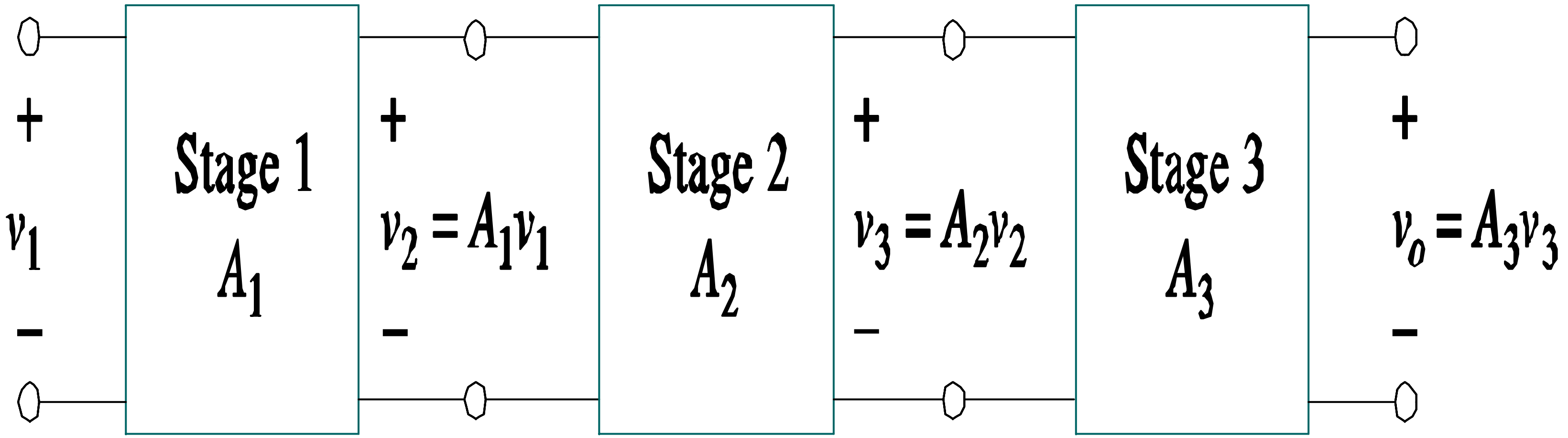
- Since a difference must reject a signal common to the two inputs, the amplifier must have the property that $v_0 = 0$ when $v_1 = v_2$. This implies that

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

When $R_1 = R_2$ and $R_3 = R_4$ it acts like a subtractor

$$\boxed{v_o = v_2 - v_1}$$

Interconnecting of Op Amps



Example

Find the voltage transfer equation of the following circuit