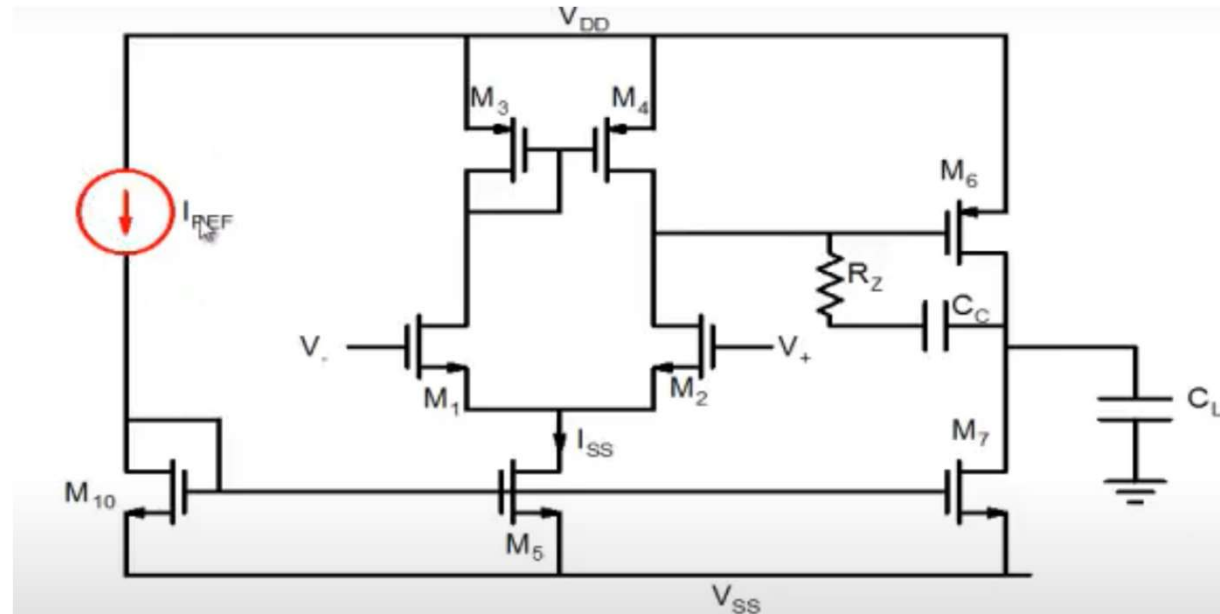
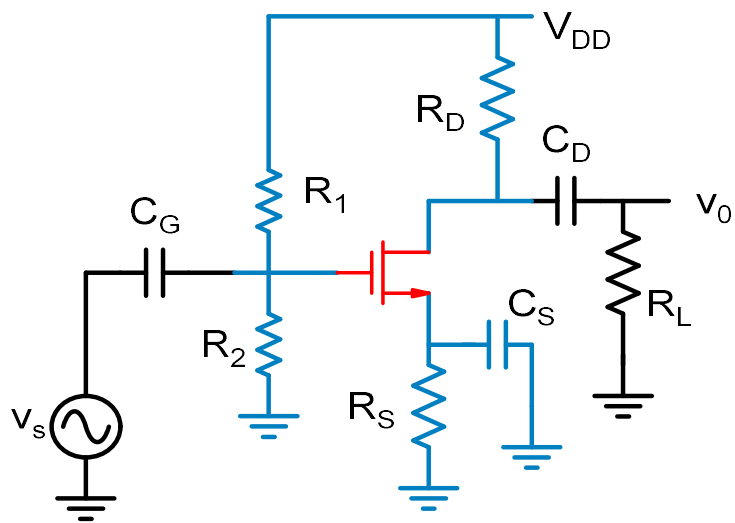


ESC201T : Introduction to Electronics

Lecture 29: Operational Amplifier

B. Mazhari
Dept. of EE, IIT Kanpur

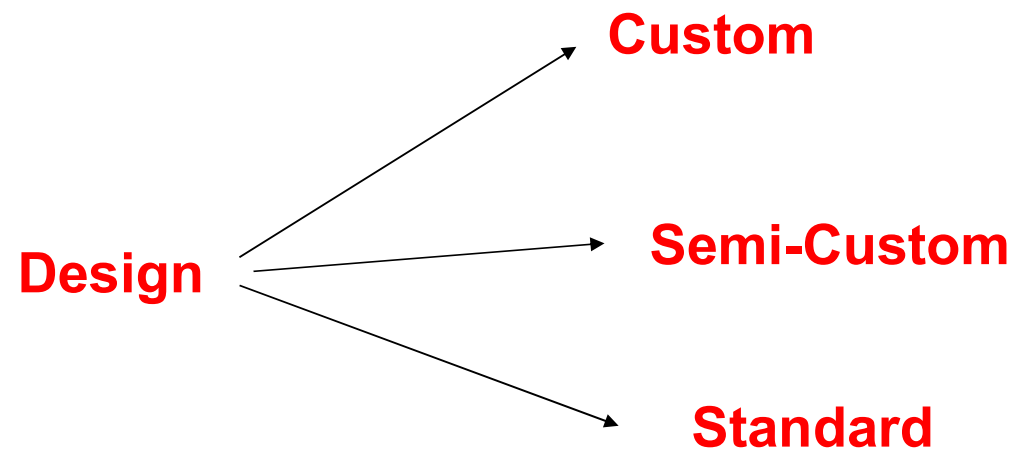
Amplifier Design requires specialized knowledge



It is not possible for every user to design his/her own amplifier !

Why can't we have experts design and implement amplifiers and make it available to everybody else !

Although this is done, it does not satisfy all the users due to diverse requirements

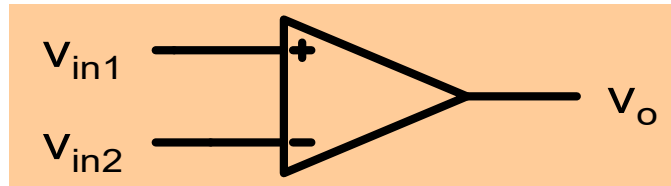


Semi-custom: partially completed design which is customized by the user

Opamp is a good illustration of the advantages of semi-custom approach

Difference Amplifier

-An amplifier that is sensitive to difference in input voltages and insensitive to what is common.



$$v_{id} = v_{in1} - v_{in2}$$

$$v_{ic} = \frac{v_{in1} + v_{in2}}{2}$$

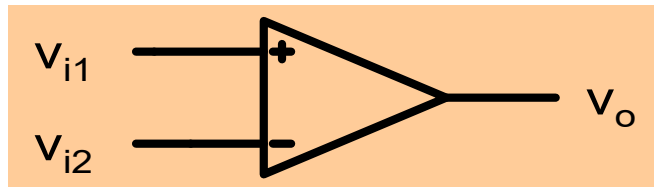
$$v_o = A_d v_{id} + A_{cm} v_{ic}$$

A_d : Differential mode gain

A_{cm} : Common mode gain

$$A_d \gg A_{cm}$$

$$\text{Common Mode Rejection Ratio: } CMRR = \frac{A_d}{A_{cm}}$$



$$A_d = 100; \quad A_{cm} = 0.01$$

$$v_{i1} = 1V + 5mV \times \sin(\omega t); \quad v_{i2} = 1V - 5mV \times \sin(\omega t)$$

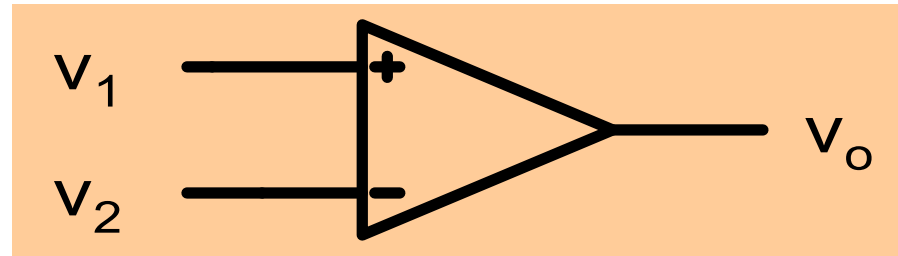
$$v_{id} = v_{in1} - v_{in2} = 10mV \times \sin(\omega t)$$

$$v_{ic} = \frac{v_{in1} + v_{in2}}{2} = 1V$$

$$\begin{aligned} v_o &= A_d v_{id} + A_{cm} v_{ic} \\ &= 1V \times \sin(\omega t) + 10mV \end{aligned}$$

Whatever is common is rejected and whatever is different is amplified !

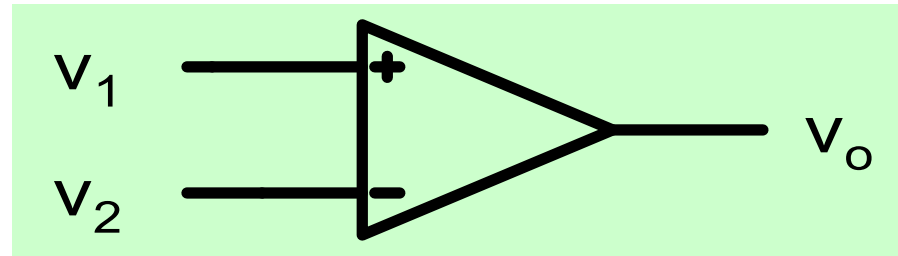
Operational Amplifier



A **special** kind of difference amplifier

1. Very High Differential-mode voltage gain
2. Very High Common mode Rejection ratio
3. Very High Input Resistance
4. Very Low output Resistance
5.

Ideal Operational Amplifier



1. Infinite Differential-mode voltage gain
2. Infinite Common mode Rejection ratio
3. Infinite Input Resistance
4. Zero output Resistance
5.

Example: LM 741

LM741

Operational Amplifier

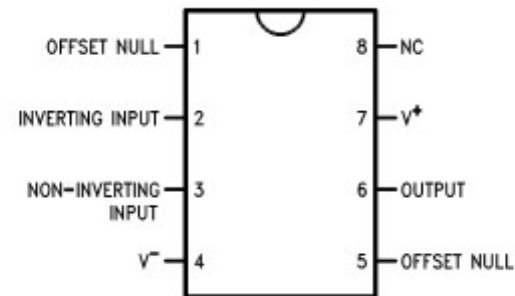
General Description

The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0°C to +70°C temperature range, instead of -55°C to +125°C.

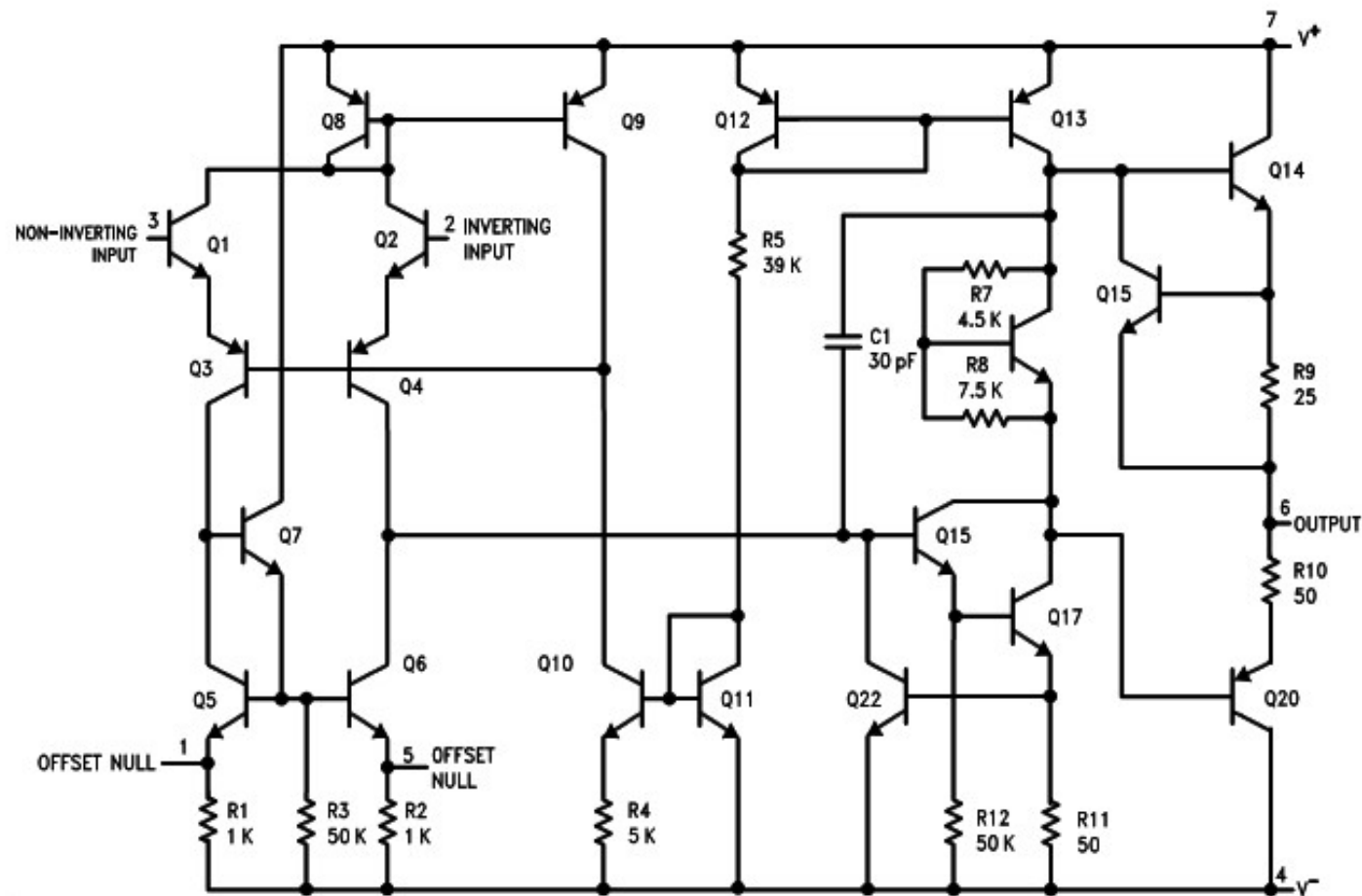
Dual-In-Line or S.O. Package



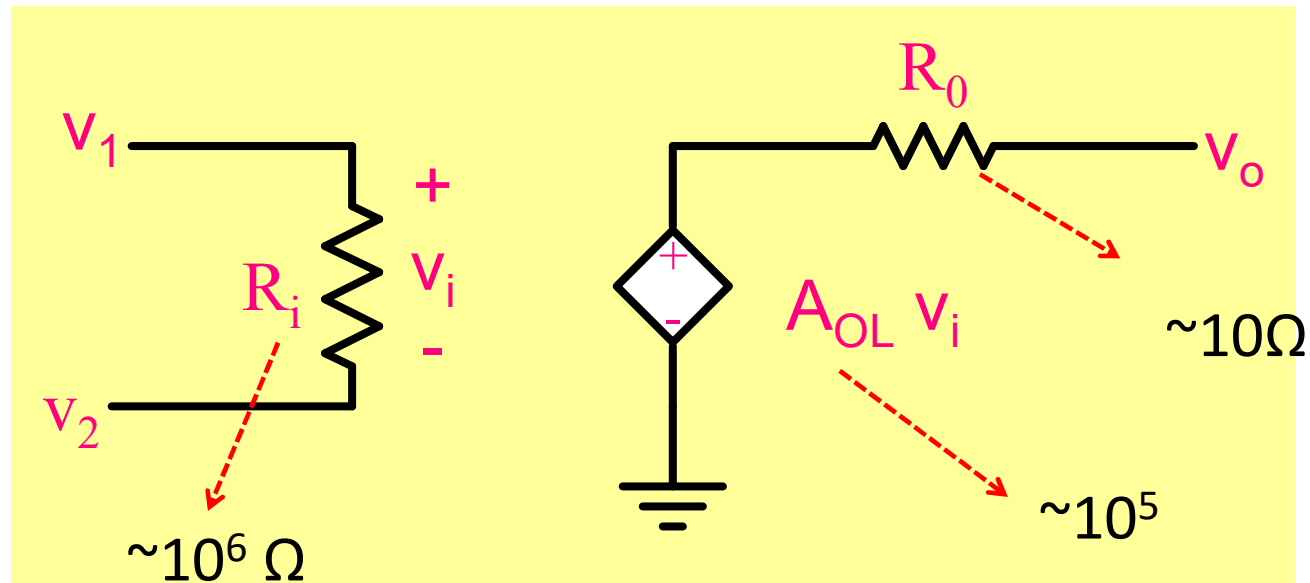
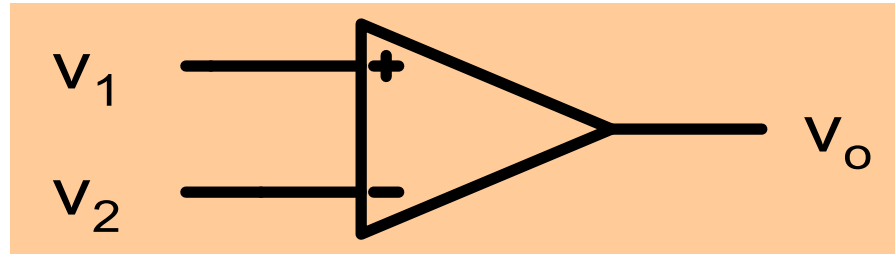
| Parameter | Conditions | LM741A | | | LM741 | | | LM741C | | | Units |
|-----------------------------|--|----------|-----|-----|-------|-----|-----|--------|-----|-----|------------------|
| | | Min | Typ | Max | Min | Typ | Max | Min | Typ | Max | |
| Input Resistance | $T_A = 25^\circ\text{C}$, $V_S = \pm 20\text{V}$ | 1.0 | 6.0 | | 0.3 | 2.0 | | 0.3 | 2.0 | | $\text{M}\Omega$ |
| | $T_{\text{AMIN}} \leq T_A \leq T_{\text{AMAX}}$, $V_S = \pm 20\text{V}$ | 0.5 | | | | | | | | | $\text{M}\Omega$ |
| Large Signal Voltage Gain | $T_A = 25^\circ\text{C}$, $R_L \geq 2\text{ k}\Omega$ $V_S = \pm 20\text{V}$, $V_O = \pm 15\text{V}$ $V_S = \pm 15\text{V}$, $V_O = \pm 10\text{V}$ | 50 | | | 50 | 200 | | 20 | 200 | | V/mV V/mV |
| Common-Mode Rejection Ratio | $T_{\text{AMIN}} \leq T_A \leq T_{\text{AMAX}}$ $R_S \leq 10\text{ k}\Omega$, $V_{\text{CM}} = \pm 12\text{V}$ $R_S \leq 50\Omega$, $V_{\text{CM}} = \pm 12\text{V}$ | 70 80 | | | 70 | 90 | | 70 | 90 | | dB dB |

Inside the opamp, there is a complicated circuit containing several transistors and resistors.

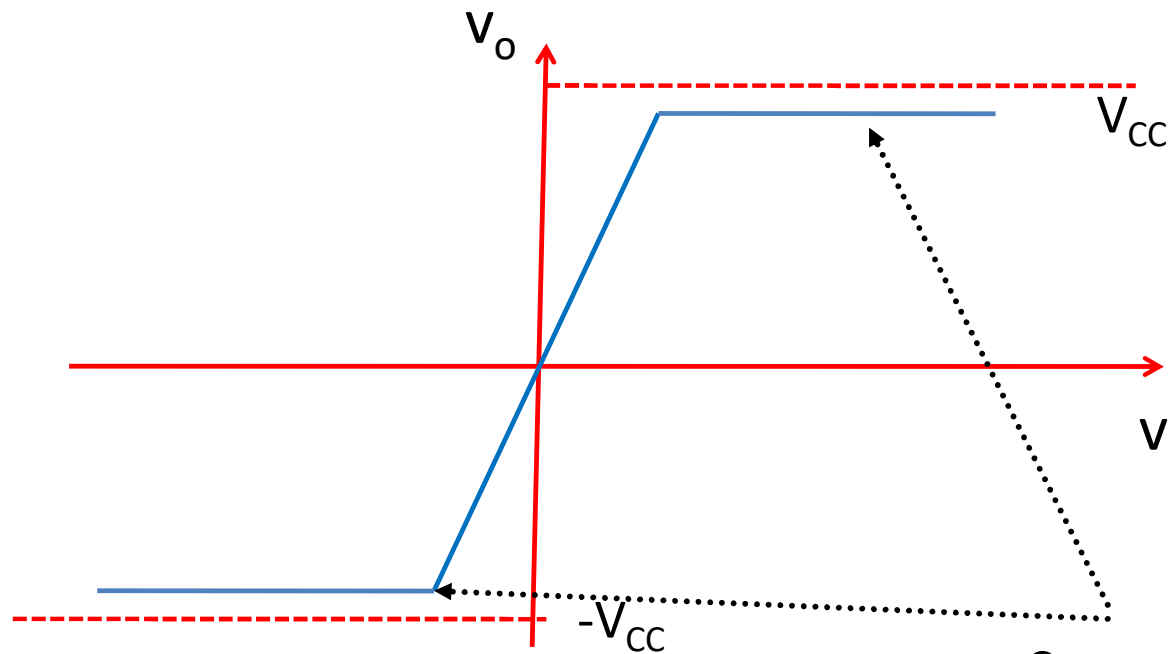
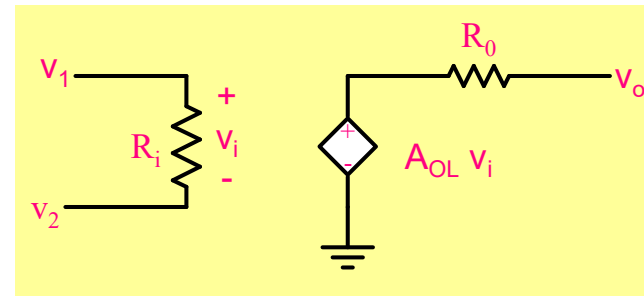
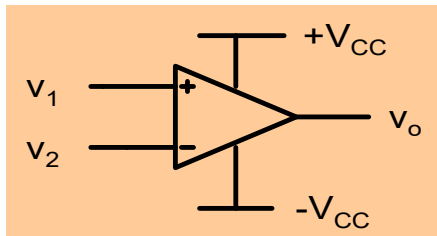
Schematic Diagram



Simple equivalent circuit model of an opamp

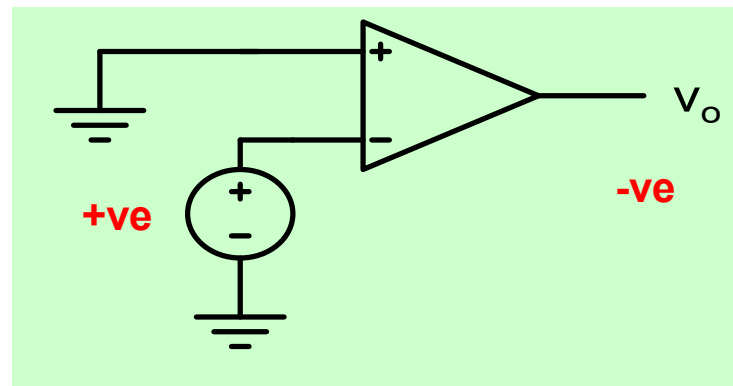
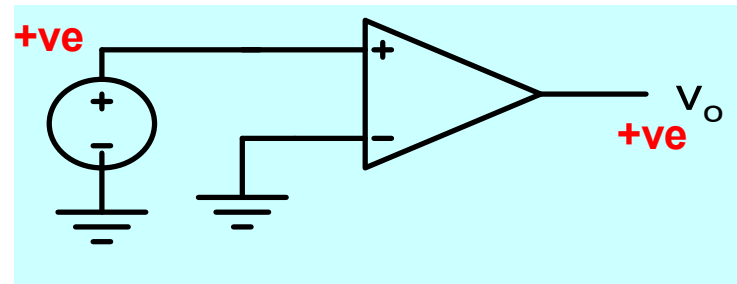
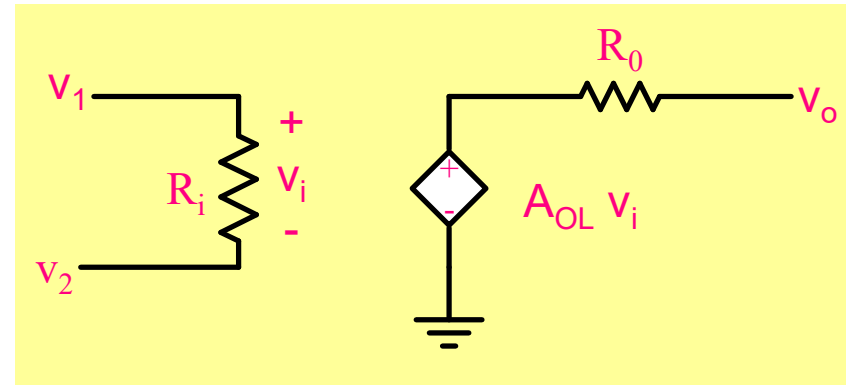
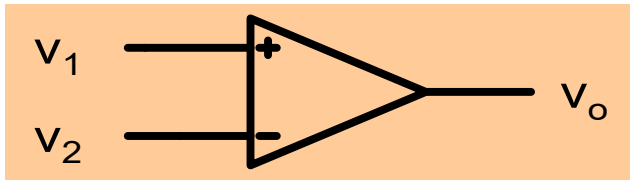


This assumes very high CMRR

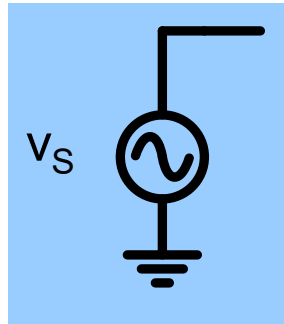


$$v_o = A_{OL} \times v_i$$

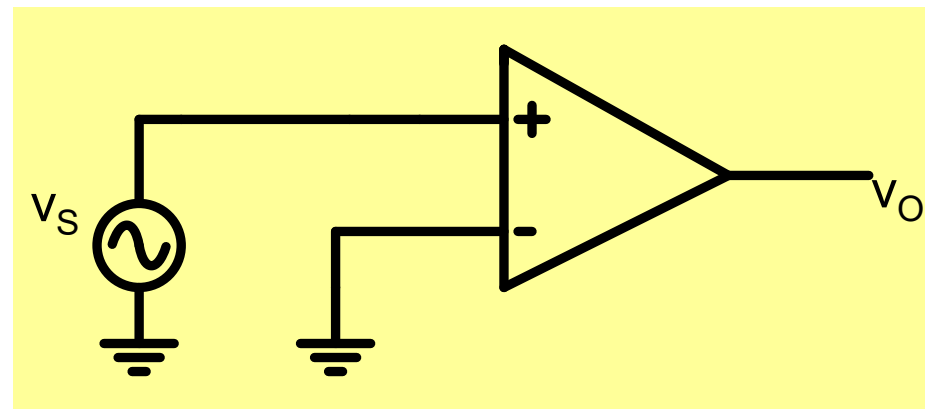
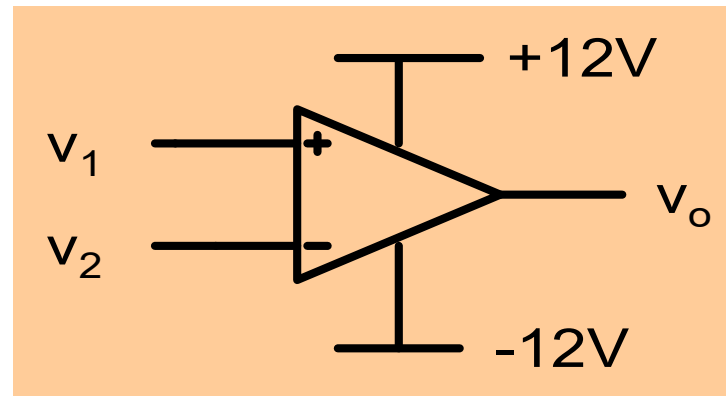
Opamp is said to be saturated

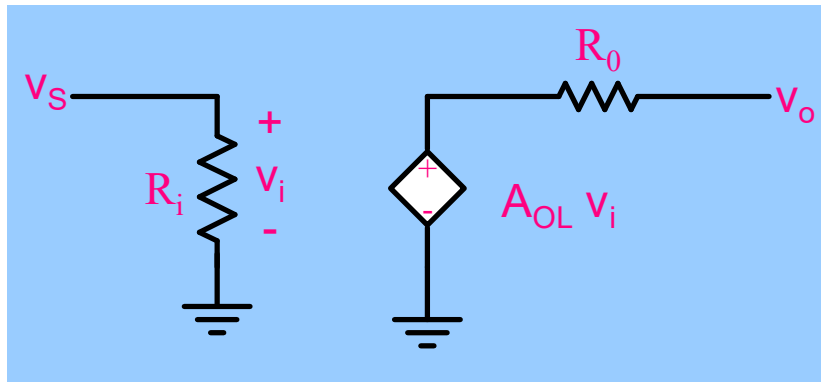
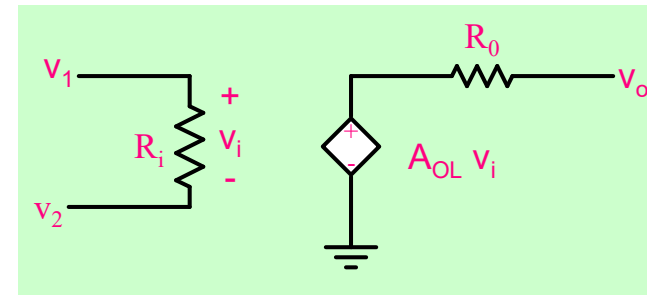
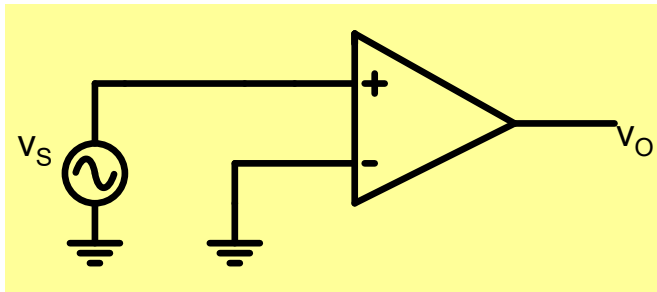


How do we amplify this signal?



$$v_S = 1mV \sin(\omega t)$$

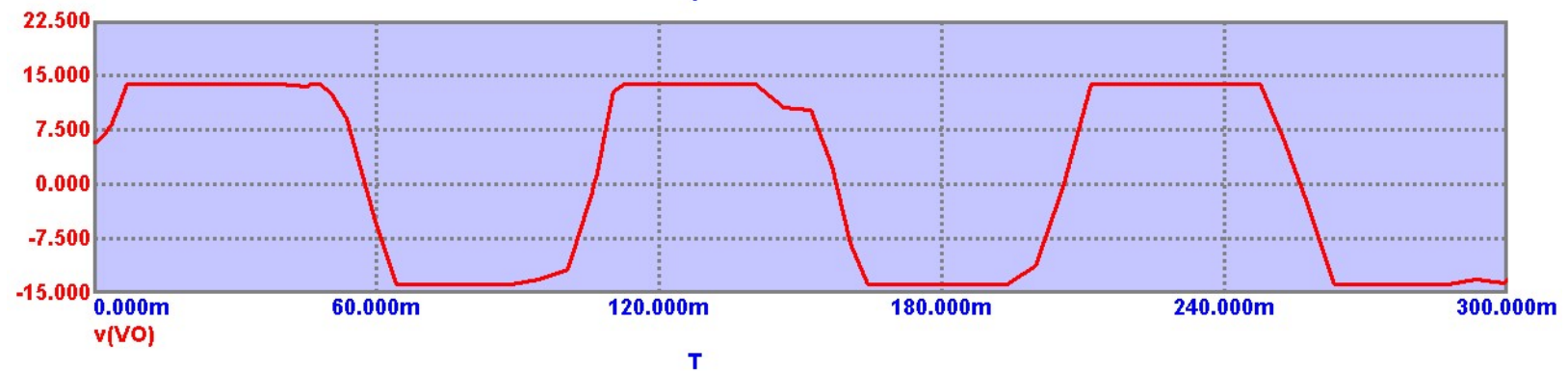
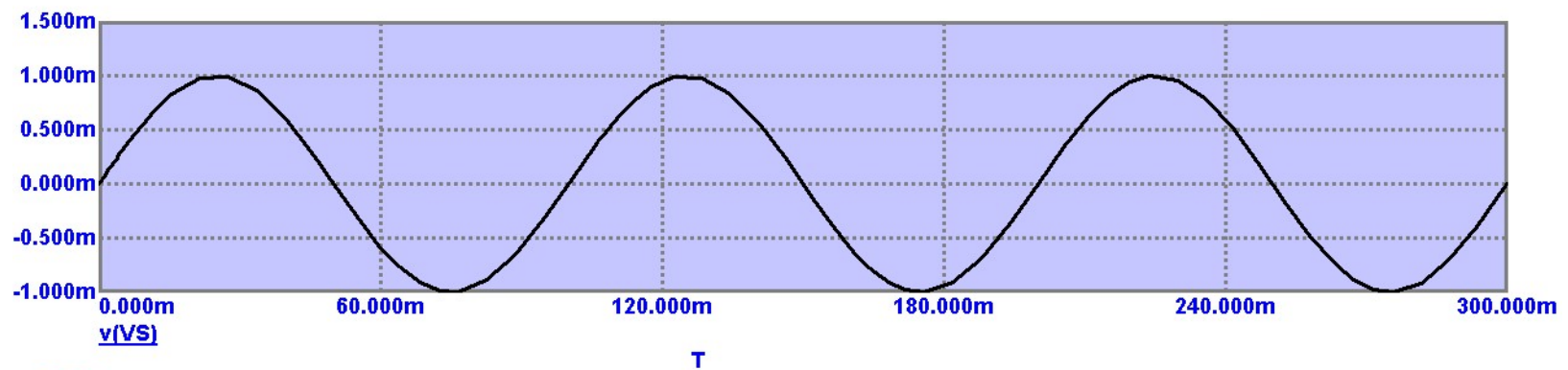
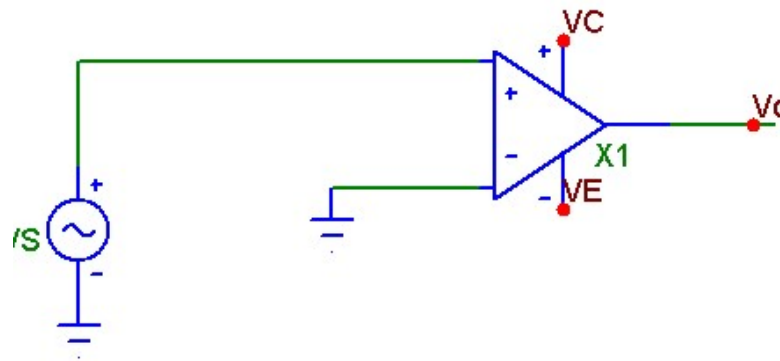




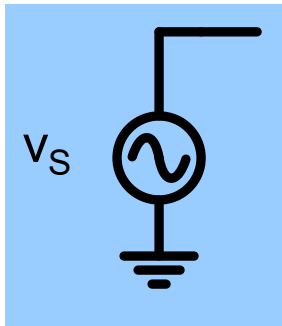
$$v_o = A_{ol} \times v_S = 10^2 \sin(\omega t)$$

But opamp voltage is limited to $\pm 12V$

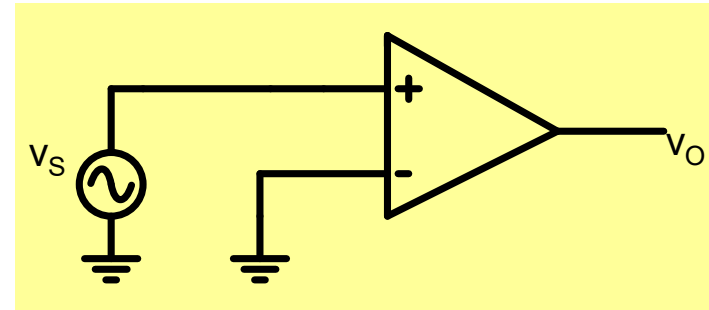
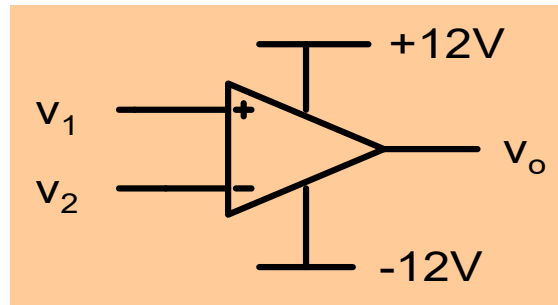
Simulation Results



How do we amplify this signal then ?

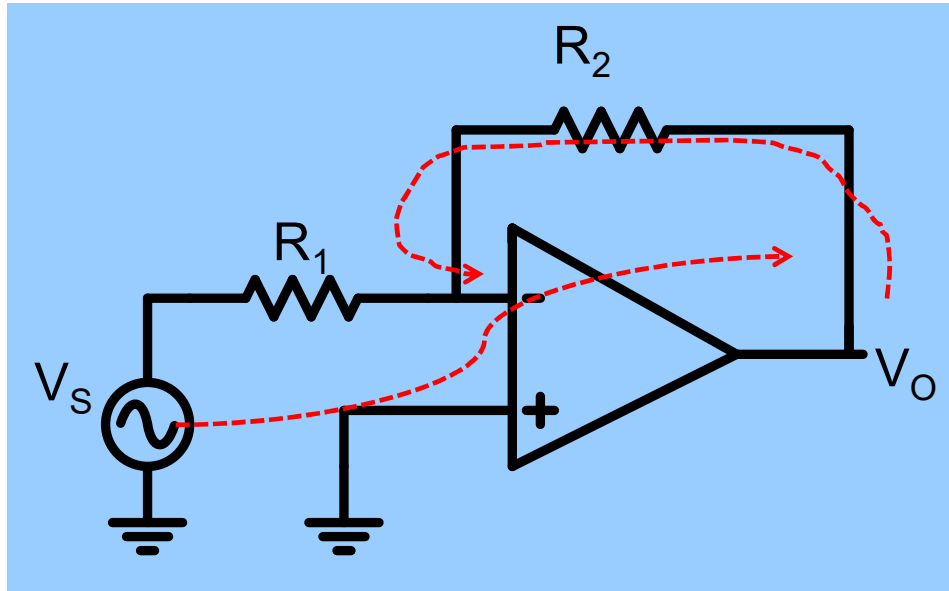


$$v_S = 1mV \sin(\omega t)$$



1. Attenuate the signal to 0.1mV and then amplify ?
2.

A Better Solution

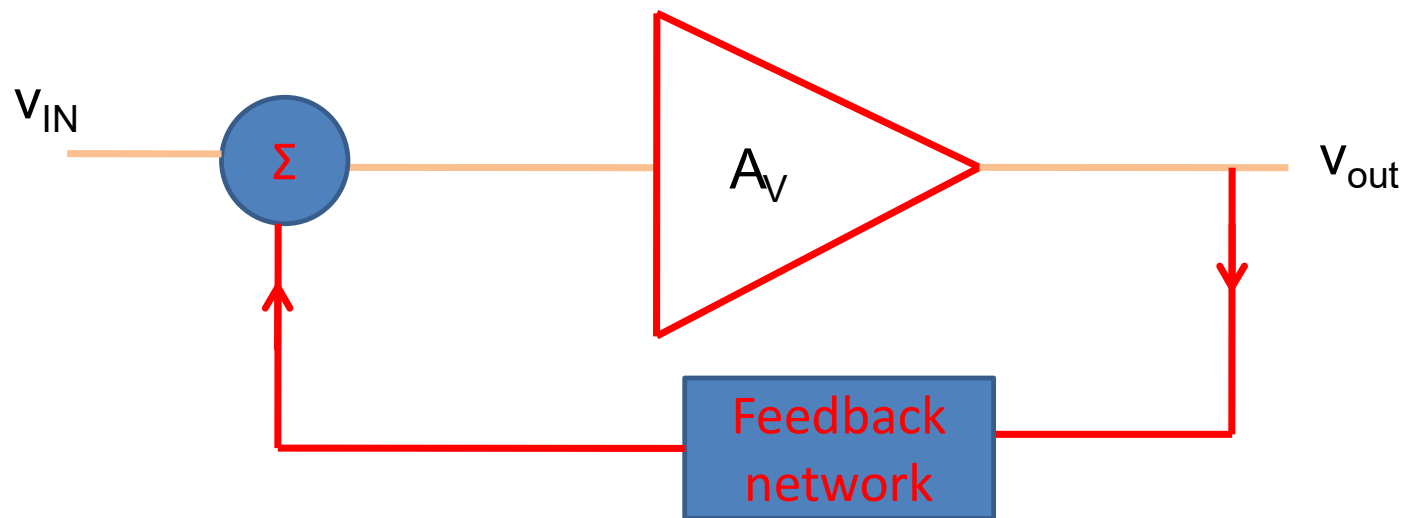
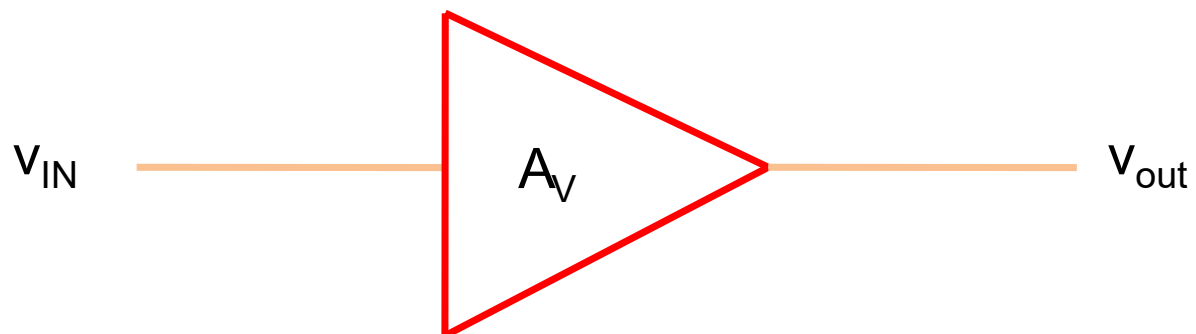


$$\frac{v_o}{v_S} = -\frac{R_2}{R_1}$$

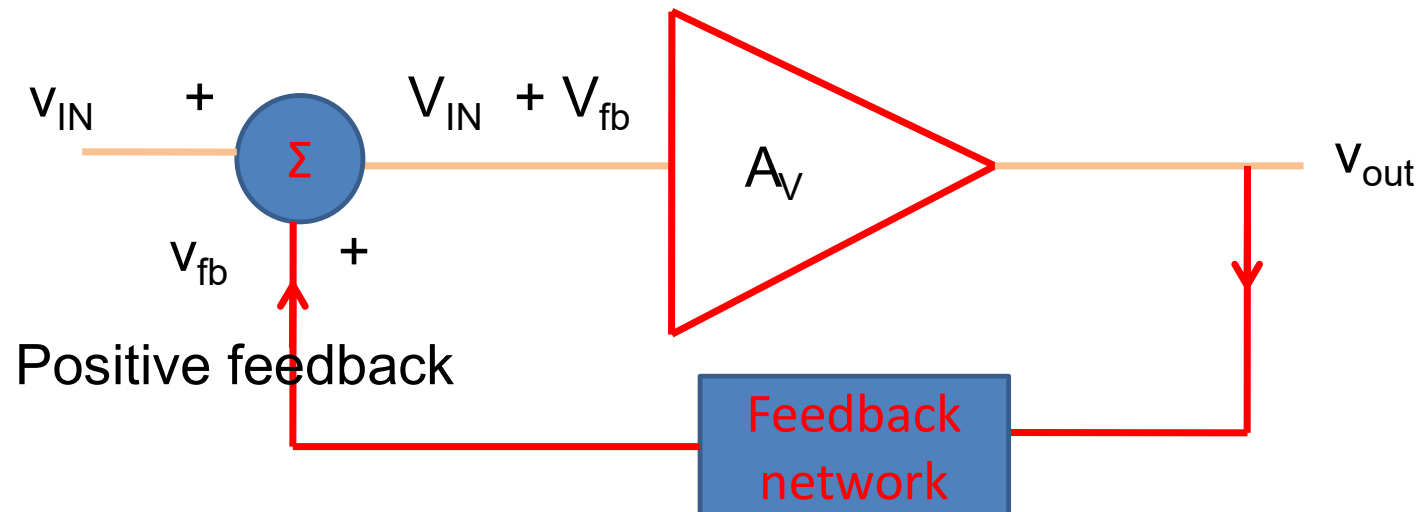
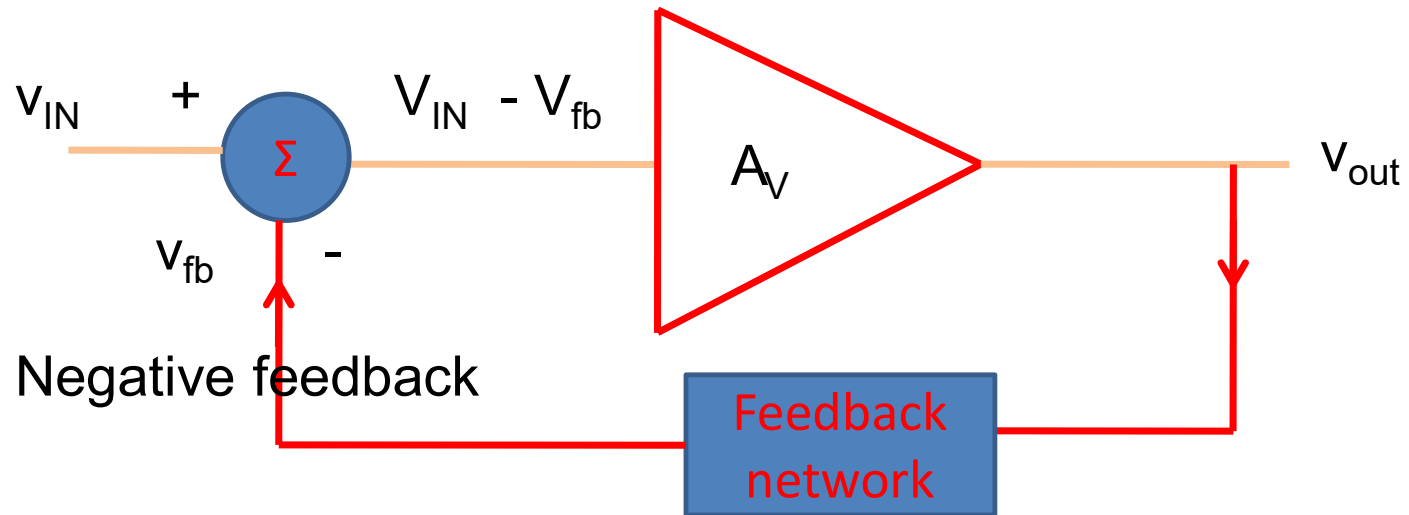
Amplifier has feedback

If the feedback signal helps the input voltage we have positive feedback, otherwise negative.

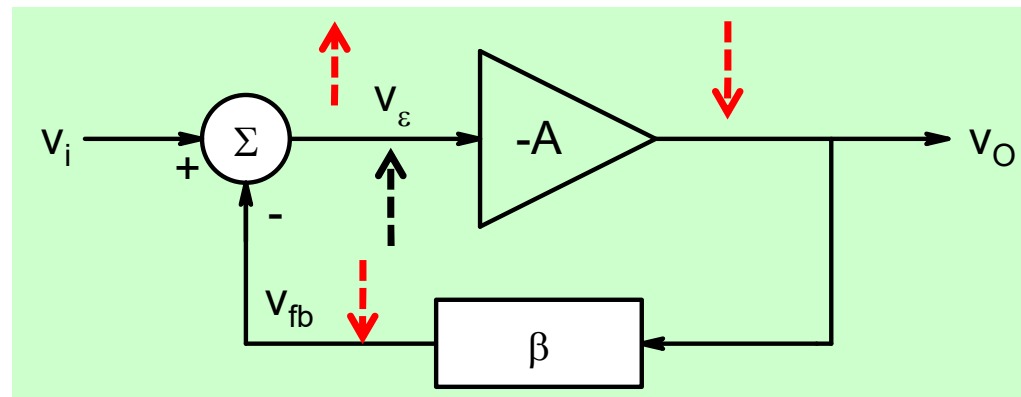
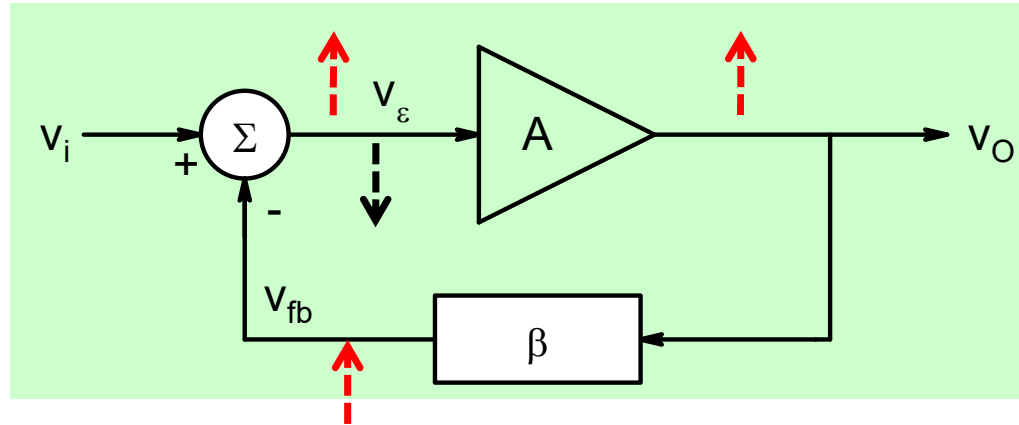
Feedback



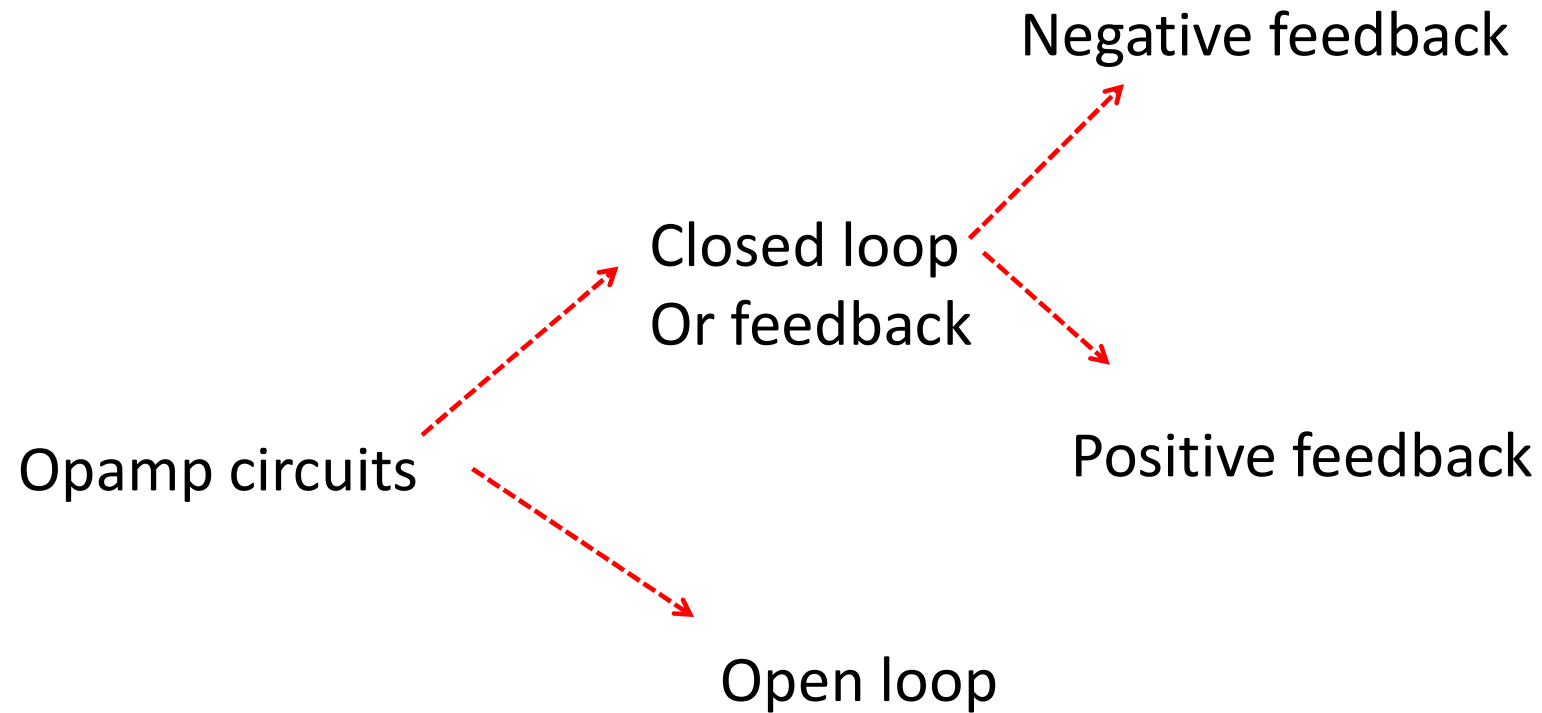
Negative and Positive feedback



Negative and positive feedback

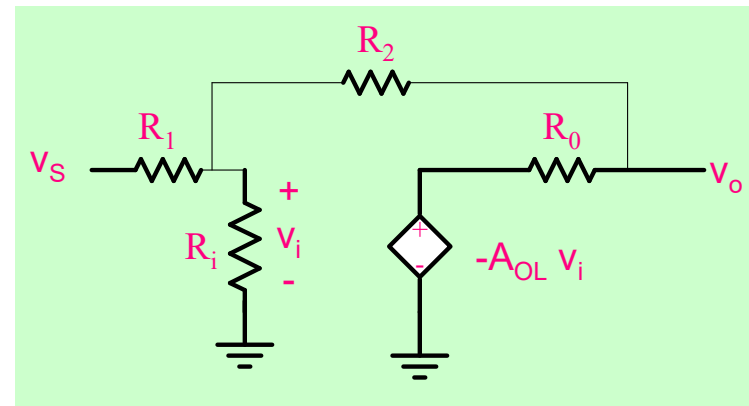
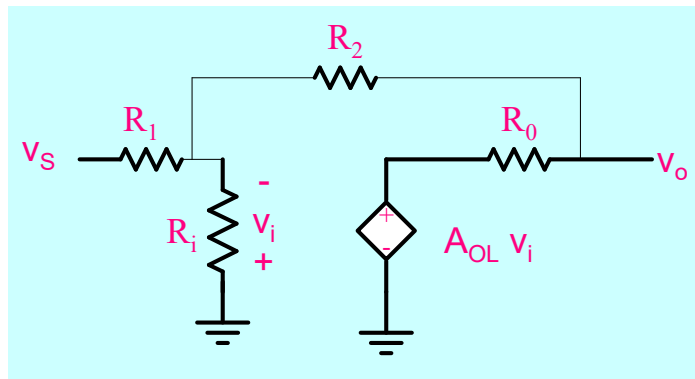
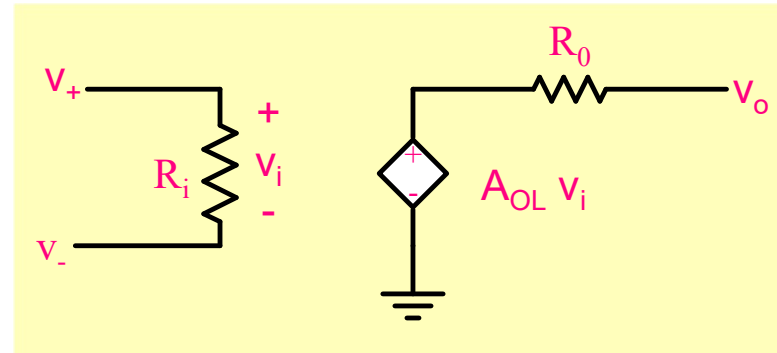
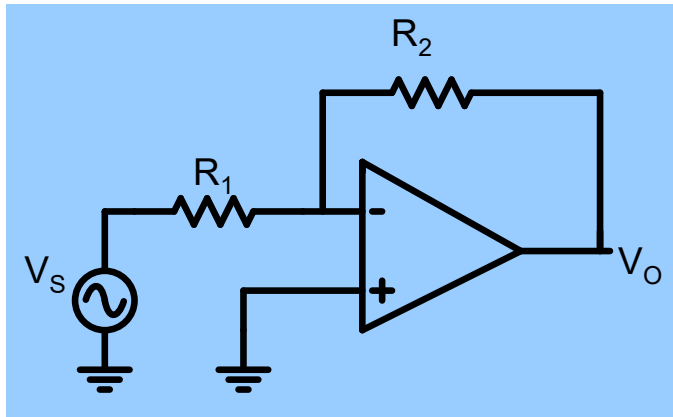


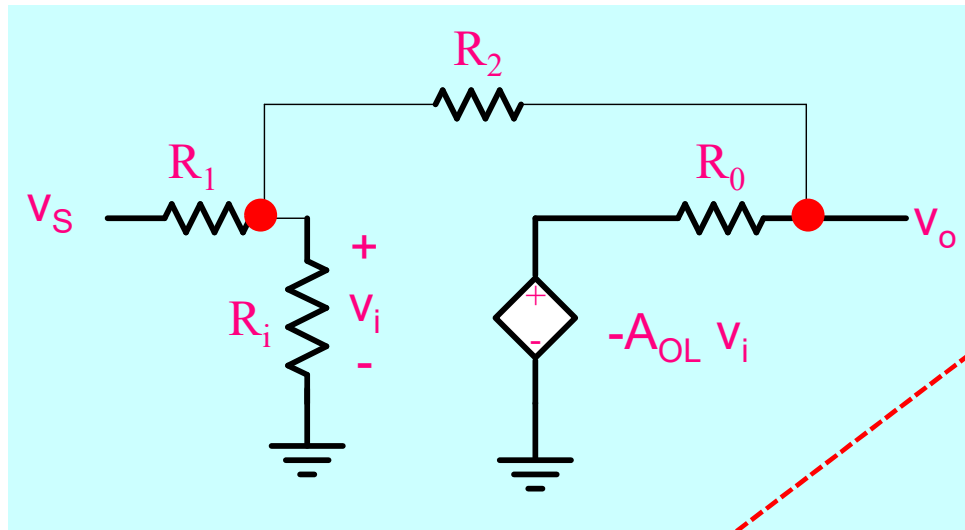
Opamp circuits classification



Most Opamp Circuits employ negative feedback

Inverting amplifier





Nodal Analysis

$$\frac{v_S - v_i}{R_1} = \frac{v_i}{R_i} + \frac{v_i - v_o}{R_2} \quad (1)$$

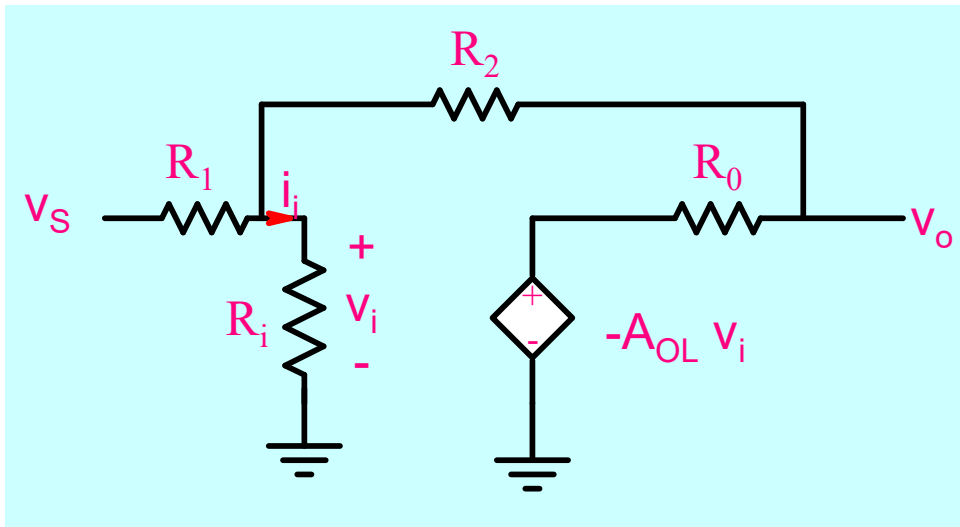
$$\frac{-A_{OL}v_i - v_o}{R_o} = \frac{v_o - v_i}{R_2} \quad (2)$$

$$\frac{v_S}{R_1} = -\frac{v_o}{R_2} + v_i \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_i} \right) \quad (3)$$

$$\text{As } A_{OL} \rightarrow \infty \quad v_i \rightarrow 0$$

$$v_i = v_o \frac{\frac{1}{R_o} + \frac{1}{R_2}}{\frac{-A_{OL}}{R_o} + \frac{1}{R_2}} \quad (4)$$

This is called the **Virtual Ground** property

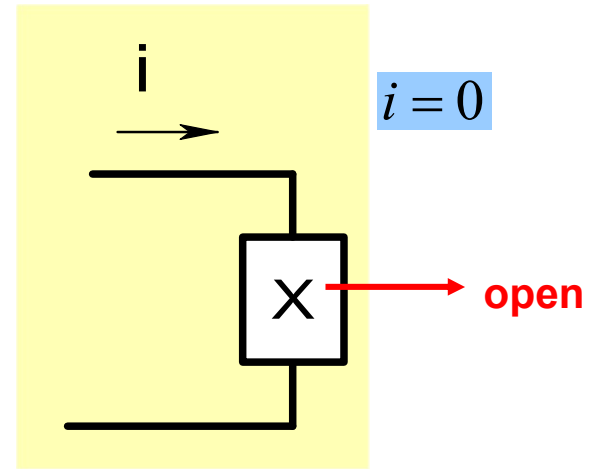
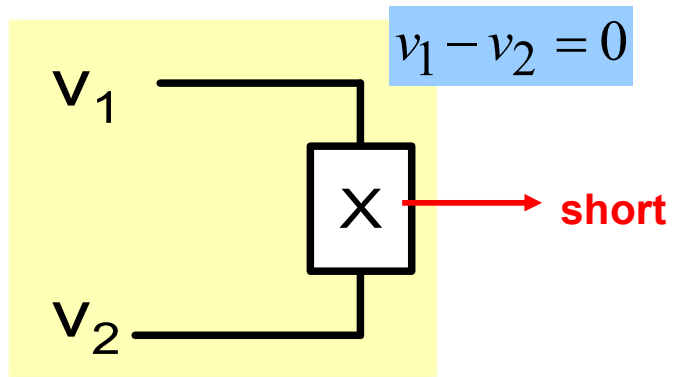


$$\text{As } A_{OL} \rightarrow \infty \quad v_i \rightarrow 0$$

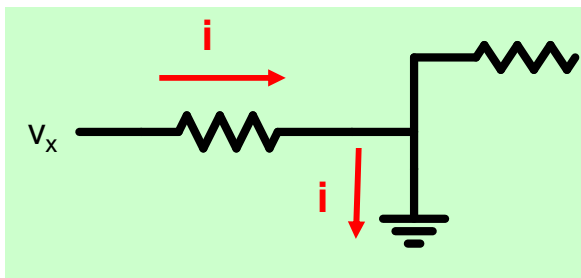
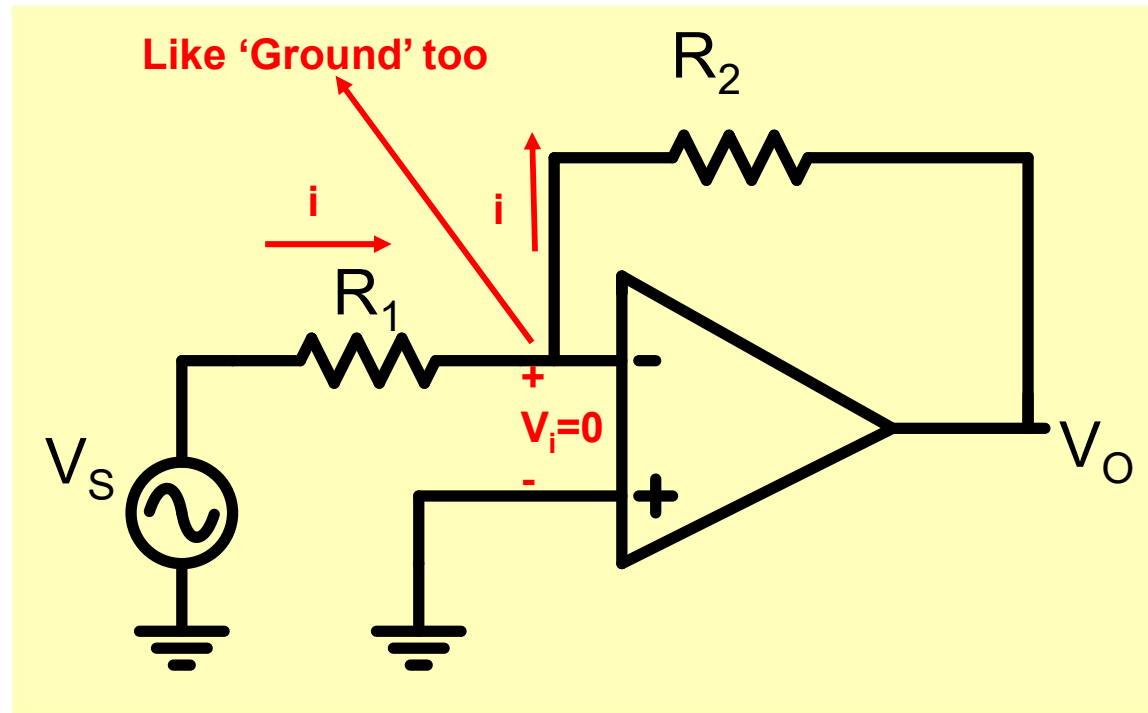
This implies that :

$$i_i \rightarrow 0$$

No current flows in or out of either inverting or non-inverting terminals of an ideal opamp

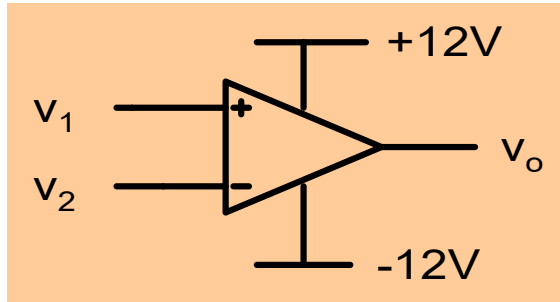


Can something be both a short as well as open circuit ?



Hence the name Virtual ground

Virtual Ground Property



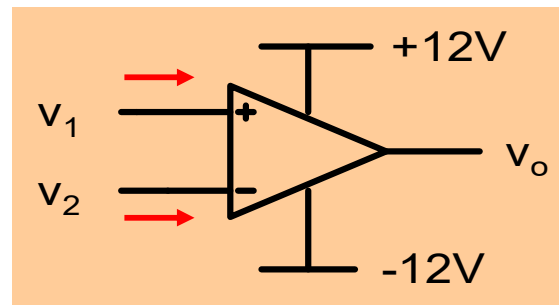
$$v_1 \cong v_2$$

In an opamp with **negative feedback**, the voltage of the inverting terminal is equal to the voltage of the non-inverting terminal if the **gain of the opamp is sufficiently high**

This property **does not** hold under certain conditions such as

- ☐ open loop,
- ☐ positive feedback
- ☐ or if the opamp is saturated.

Two important property for analyzing ideal opamp circuits under negative feedback



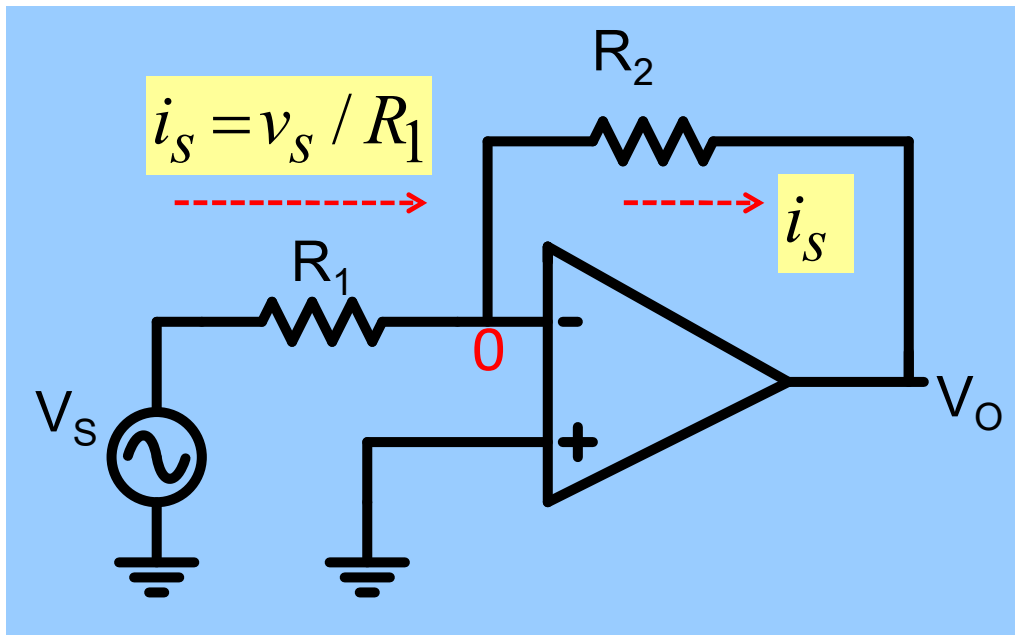
$$1. \quad v_1 = v_2$$

$$2. \quad i_1 = i_2 = 0$$

At the input side opamp appears to be like a short and an open circuit simultaneously !

Inverting amplifier

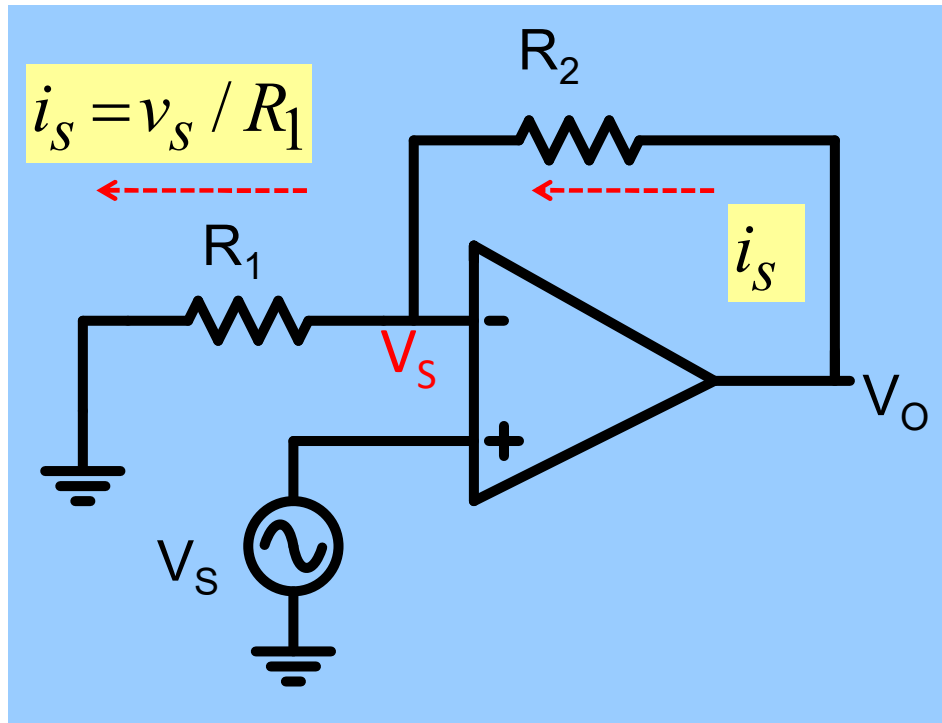
Re-analyze inverting amplifier with these properties



$$\frac{0 - v_o}{R_2} = i_s = \frac{v_s}{R_1}$$

$$\frac{v_o}{v_S} = -\frac{R_2}{R_1}$$

Non-Inverting Amplifier



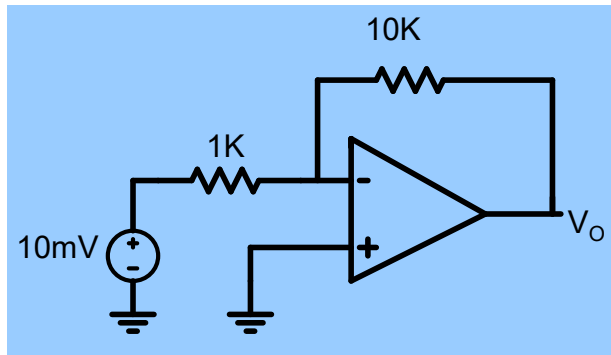
$$1. \quad v_1 = v_2$$

$$2. \quad i_1 = i_2 = 0$$

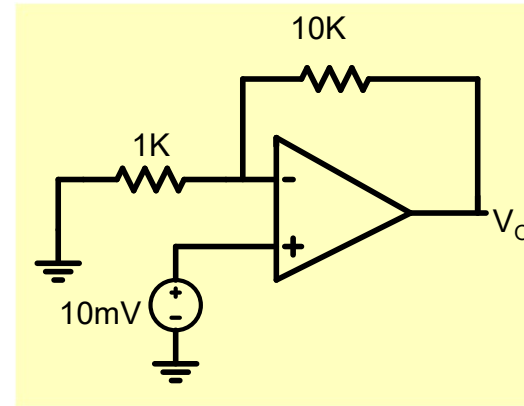
$$\frac{v_O - v_S}{R_2} = i_S = \frac{v_S}{R_1}$$

$$\frac{v_O}{v_S} = 1 + \frac{R_2}{R_1}$$

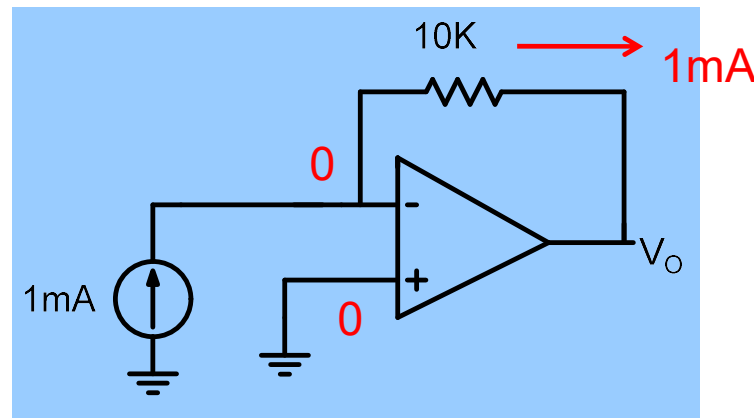
Examples



$$\frac{v_o}{v_S} = -\frac{R_2}{R_1} \Rightarrow v_o = -100mV$$



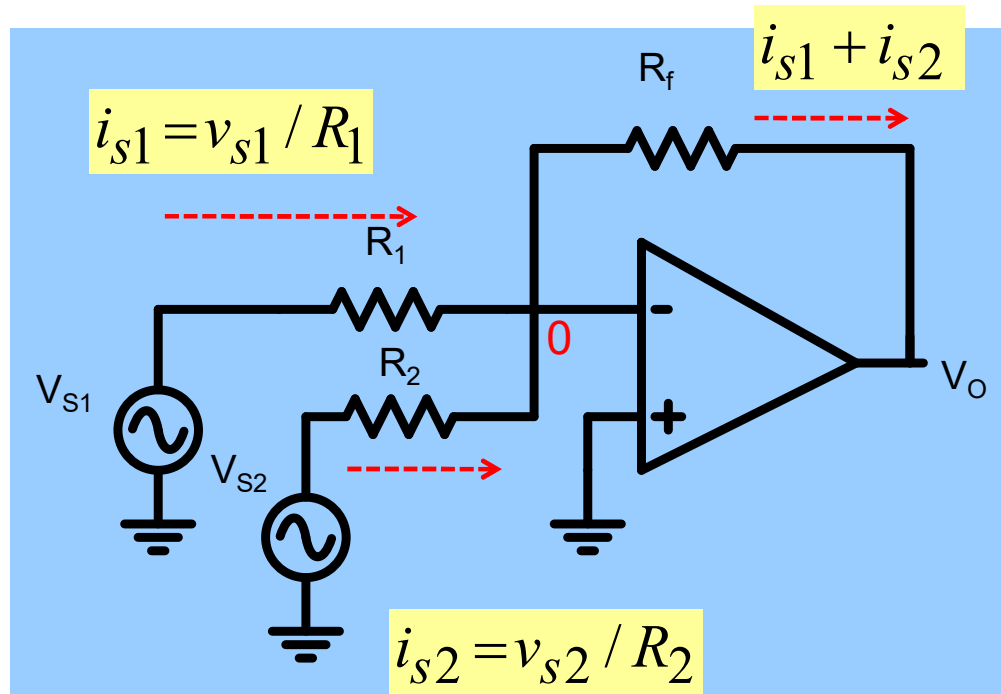
$$\frac{v_o}{v_S} = 1 + \frac{R_2}{R_1} \Rightarrow v_o = 110mV$$



$$\frac{0 - v_o}{10K} = 1mA$$

$$v_o = -10V$$

Adder

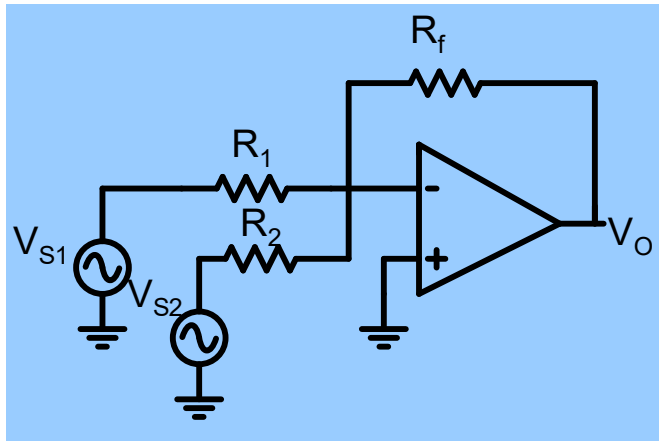


$$\frac{0 - v_o}{R_f} = i_{s1} + i_{s2} = \frac{v_{s1}}{R_1} + \frac{v_{s2}}{R_2}$$

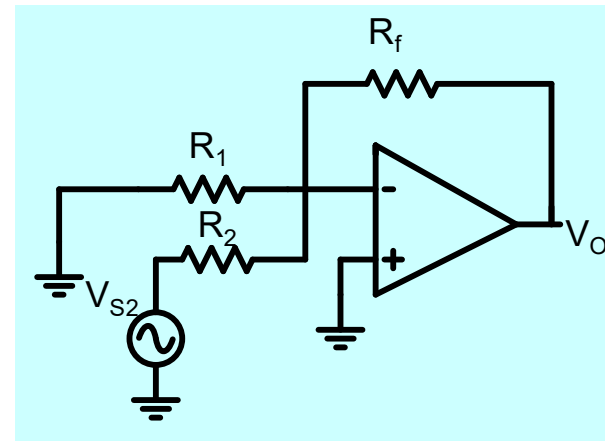
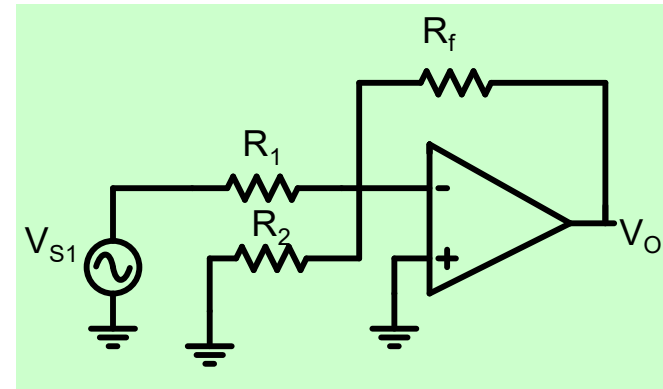
$$v_o = -\left(\frac{R_f}{R_1} v_{s1} + \frac{R_f}{R_2} v_{s2}\right)$$

$$\text{For } R_1 = R_2 = R \quad v_o = -\frac{R_f}{R} (v_{s1} + v_{s2})$$

Alternative Analysis



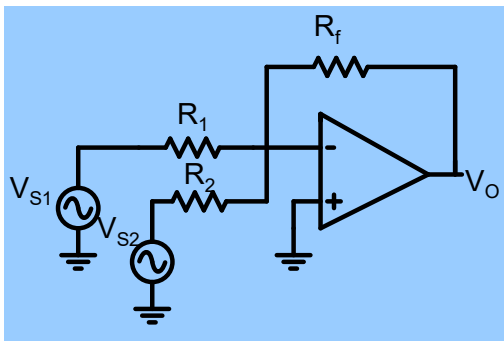
$$v_o = -\left(\frac{R_f}{R_1}\right)v_{s1} + -\left(\frac{R_f}{R_2}\right)v_{s2}$$



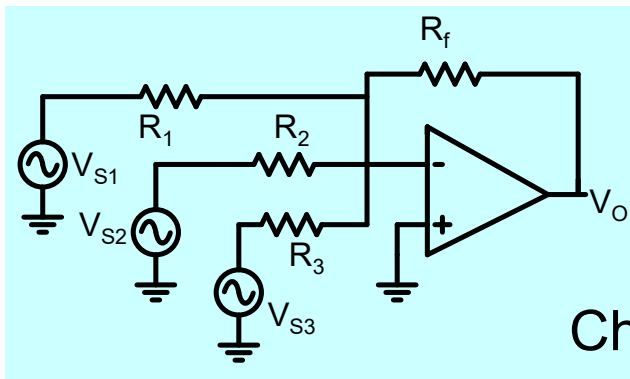
Design Example

Design a circuit that would generate the following output given three input voltages v_{s1} , v_{s2} and v_{s3} .

$$v_o = -10v_{s1} - 4v_{s2} - 5v_{s3}$$



$$v_o = -\frac{R_f}{R_1}v_{s1} - \frac{R_f}{R_2}v_{s2}$$



$$v_o = -\frac{R_f}{R_1}v_{s1} - \frac{R_f}{R_2}v_{s2} - \frac{R_f}{R_3}v_{s3}$$

Choose :

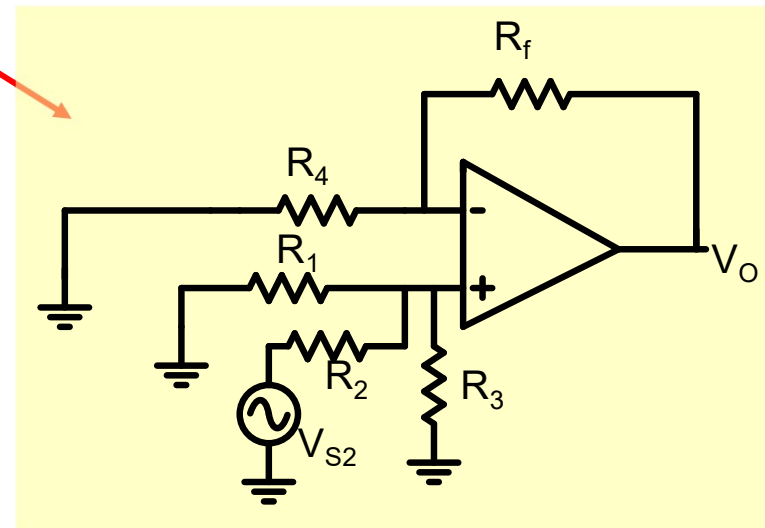
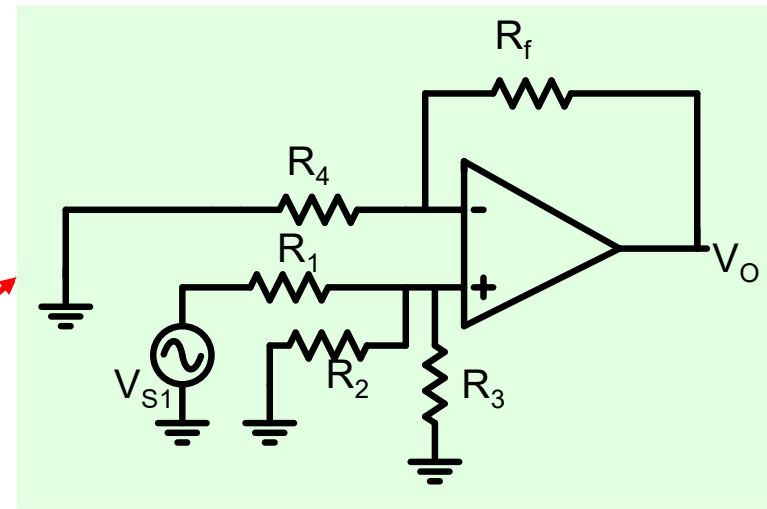
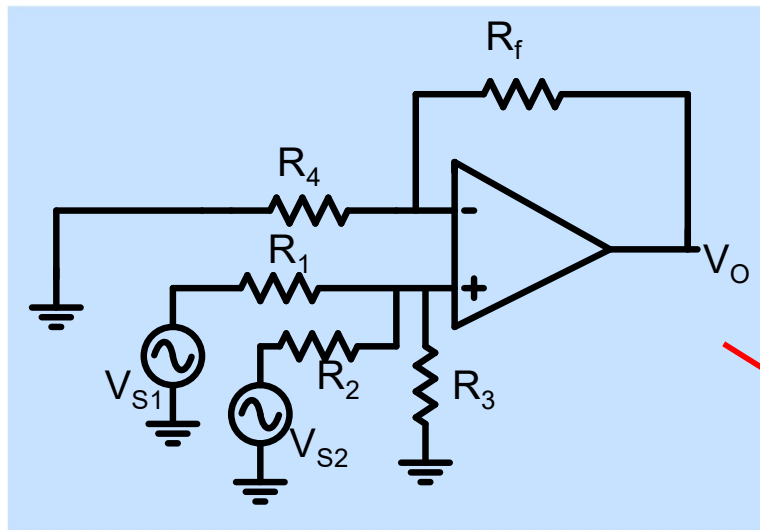
$$R_f = 10K$$

$$\Rightarrow R_1 = 1K$$

$$\Rightarrow R_2 = 2.5K$$

$$\Rightarrow R_3 = 2K$$

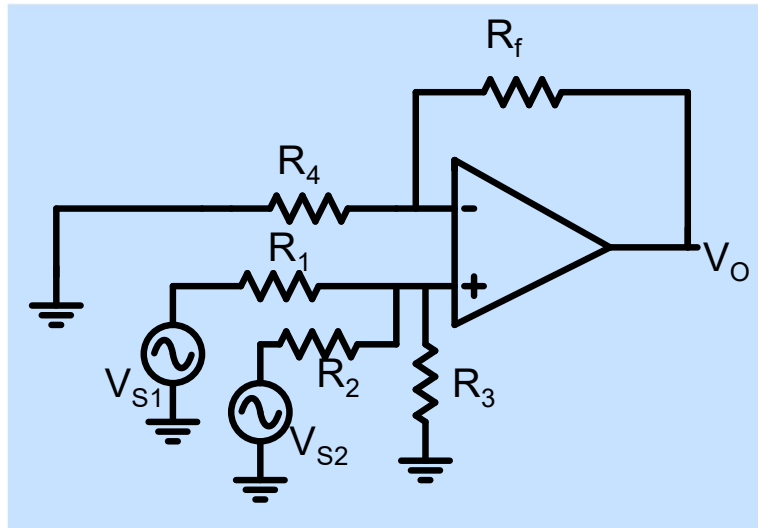
Adder



$$v_o = v_{s1} \frac{R_2 \parallel R_3}{R_2 \parallel R_3 + R_1} \times \left(1 + \frac{R_f}{R_4}\right)$$

$$+ v_{s2} \frac{R_1 \parallel R_3}{R_1 \parallel R_3 + R_2} \times \left(1 + \frac{R_f}{R_4}\right)$$

Adder



$$v_o = v_{s1} \frac{R_2 \parallel R_3}{R_2 \parallel R_3 + R_1} \times \left(1 + \frac{R_f}{R_4}\right)$$

$$+ v_{s2} \frac{R_1 \parallel R_3}{R_1 \parallel R_3 + R_2} \times \left(1 + \frac{R_f}{R_4}\right)$$

High entropy expression !

$$R_P = R_1 \parallel R_2 \parallel R_3$$

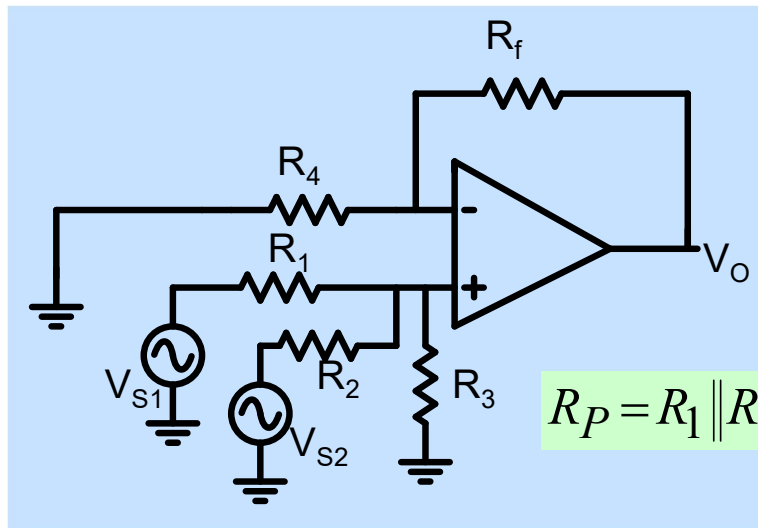
$$v_o = \left(\frac{R_P}{R_1} v_{s1} + \frac{R_P}{R_2} v_{s2} \right) \times \left(1 + \frac{R_f}{R_4}\right)$$

Low entropy expression !

Design Example

Design a circuit that would generate the following output given three input voltages v_{s1} , v_{s2} and v_{s3} .

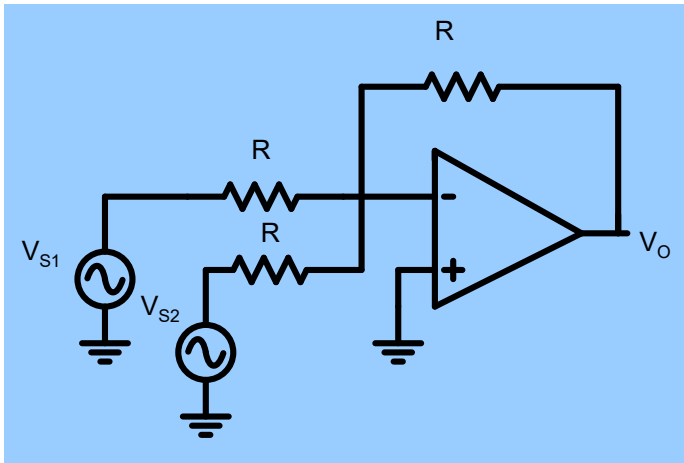
$$v_o = 10v_{s1} + 4v_{s2}$$



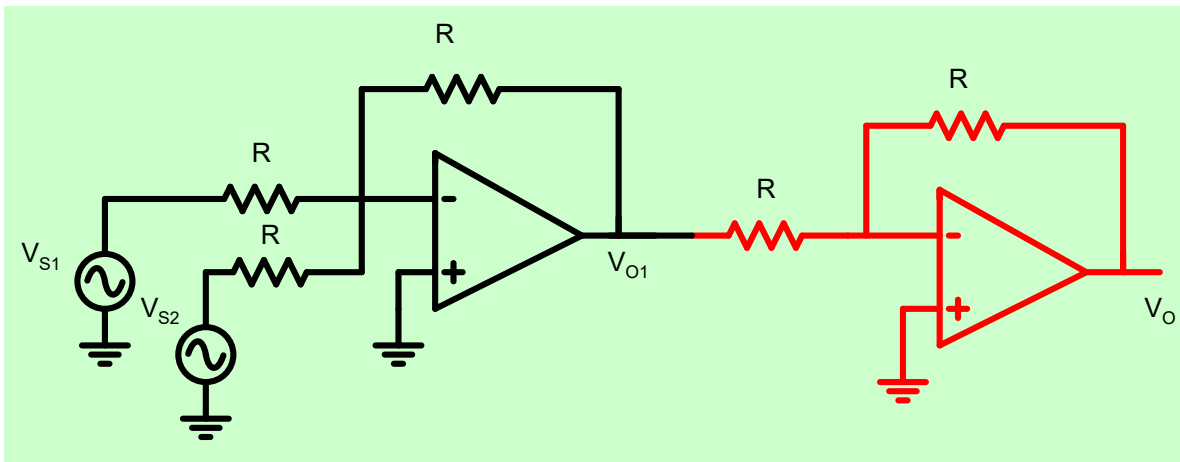
$$v_o = \left(\frac{R_p}{R_1} v_{s1} + \frac{R_p}{R_2} v_{s2} \right) \times \left(1 + \frac{R_f}{R_4} \right)$$

$$R_p = R_1 \parallel R_2 \parallel R_3$$

Homework problem !



$$v_o = -(v_{s1} + v_{s2})$$



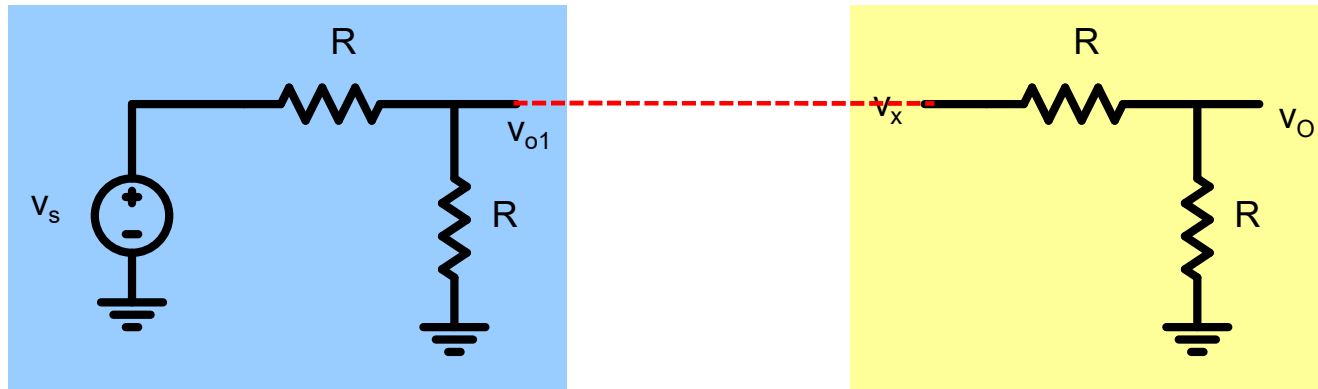
$$v_{o1} = -(v_{s1} + v_{s2})$$

$$v_o = -v_{o1}$$

$$v_o = (v_{s1} + v_{s2})$$

Have we made some assumption here ?

Example



$$\frac{v_{o1}}{v_s} = 0.5$$

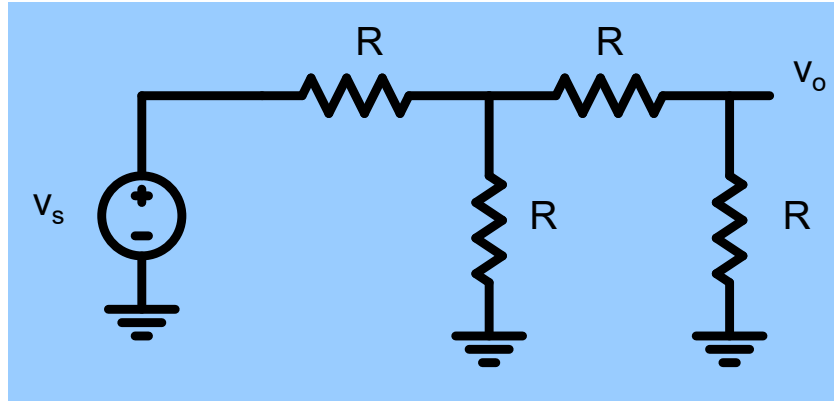
$$\frac{v_o}{v_x} = 0.5$$

$$v_{o1} = v_x$$

$$\frac{v_o}{v_x} = \frac{v_o}{v_{o1}} = 0.5$$

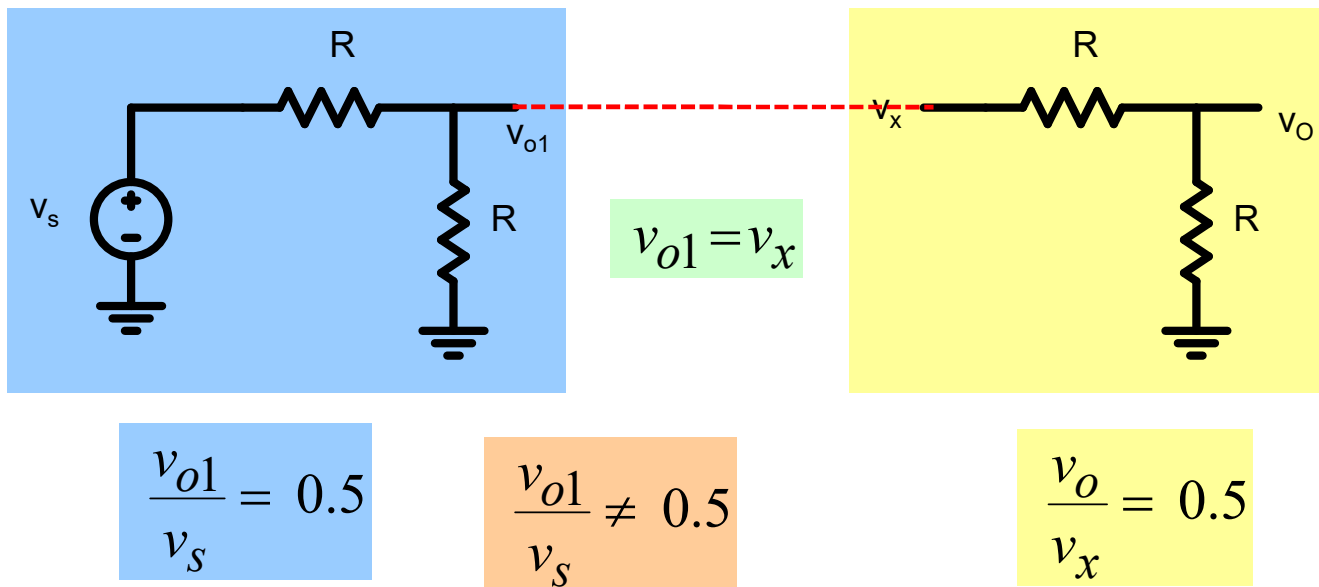
$$\frac{v_o}{v_s} = \frac{v_o}{v_{o1}} \times \frac{v_{o1}}{v_s} = 0.5 \times 0.5 = 0.25$$

BUT



$$\frac{v_o}{v_s} = 0.2$$

Where is the error ?



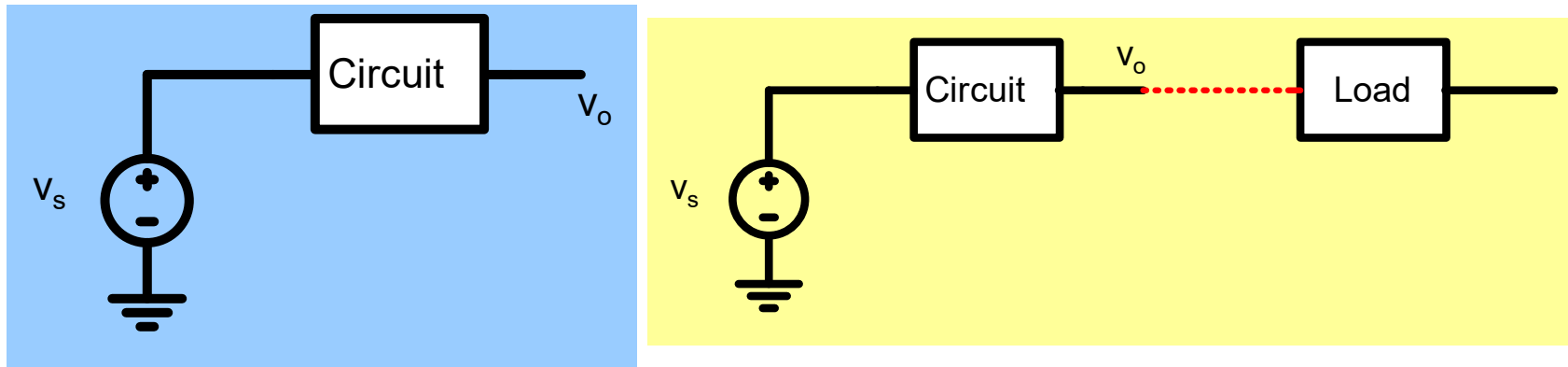
$$\frac{v_{o1}}{v_s} = 0.5$$

$$\frac{v_{o1}}{v_s} \neq 0.5$$

$$\frac{v_o}{v_x} = 0.5$$

Circuit-1 gets 'loaded' by circuit-2 and its output vs. input characteristics get modified.

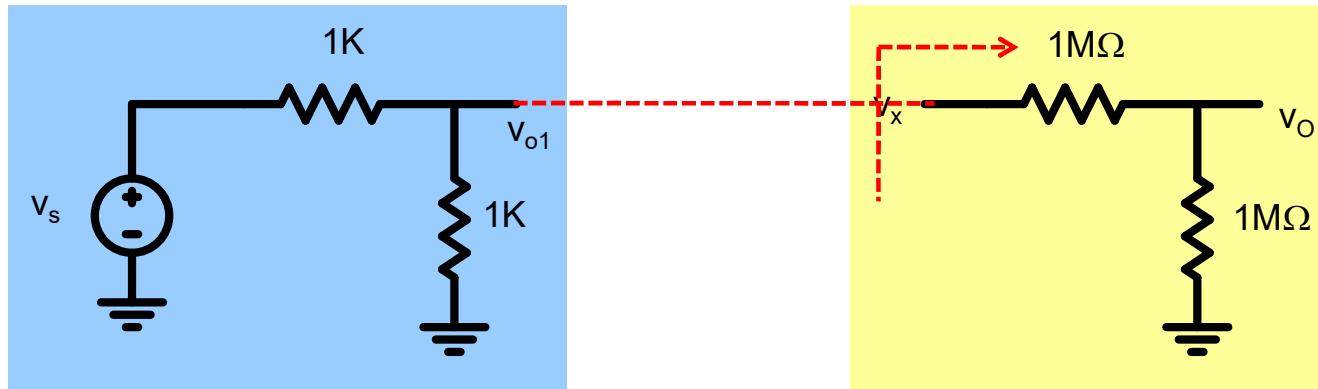
Loading Effect



V_o in general gets altered when we connect a load to it

Under what conditions is change in V_o small upon connection of a load ?

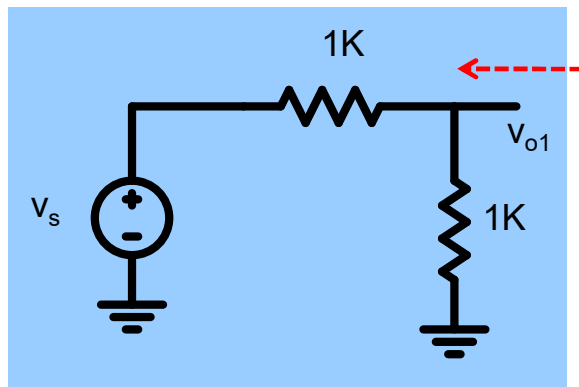
Example



$$\frac{v_{o1}}{v_s} = 0.5$$

$$\frac{v_{o1}}{v_s} \cong 0.5$$

We can describe this effect in terms of output resistance



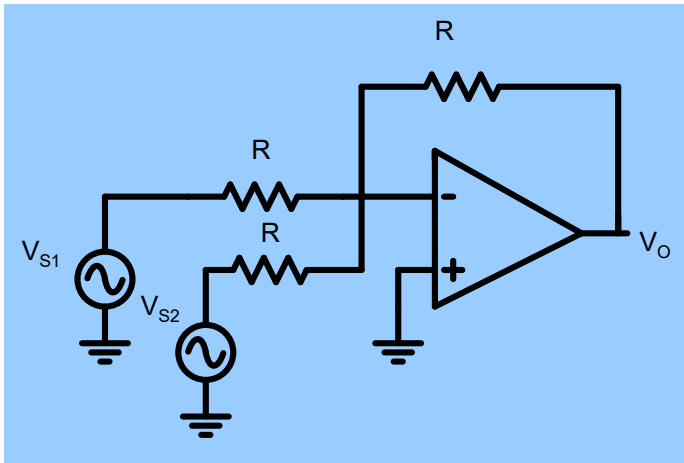
$$R_o = 0.5K$$

$$R_L = 2M\Omega$$

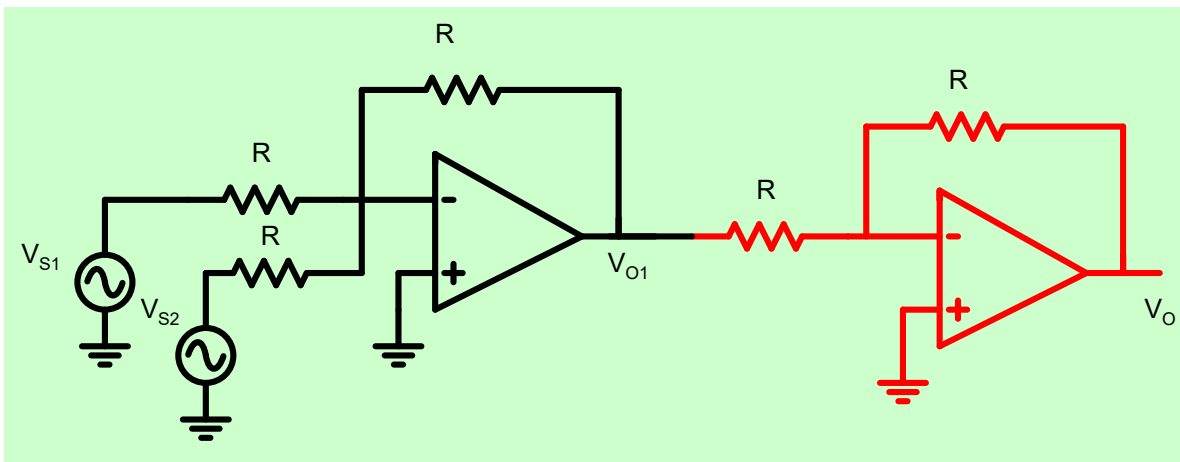
Loading Effect

Whenever output resistance of a circuit is much smaller than the load resistance, the loading effect is minimal.

$$R_o \ll R_L$$



$$v_o = -(v_{s1} + v_{s2})$$



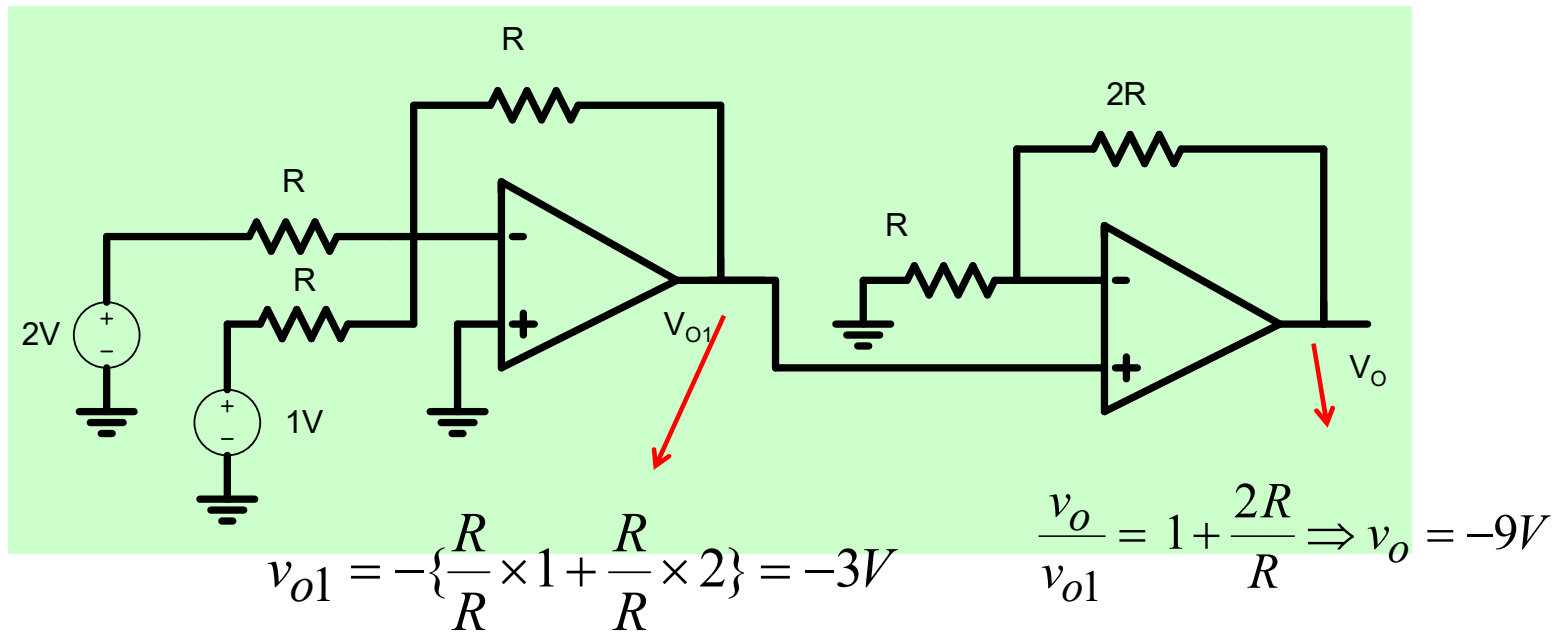
$$v_{o1} = -(v_{s1} + v_{s2})$$

$$v_o = -v_{o1}$$

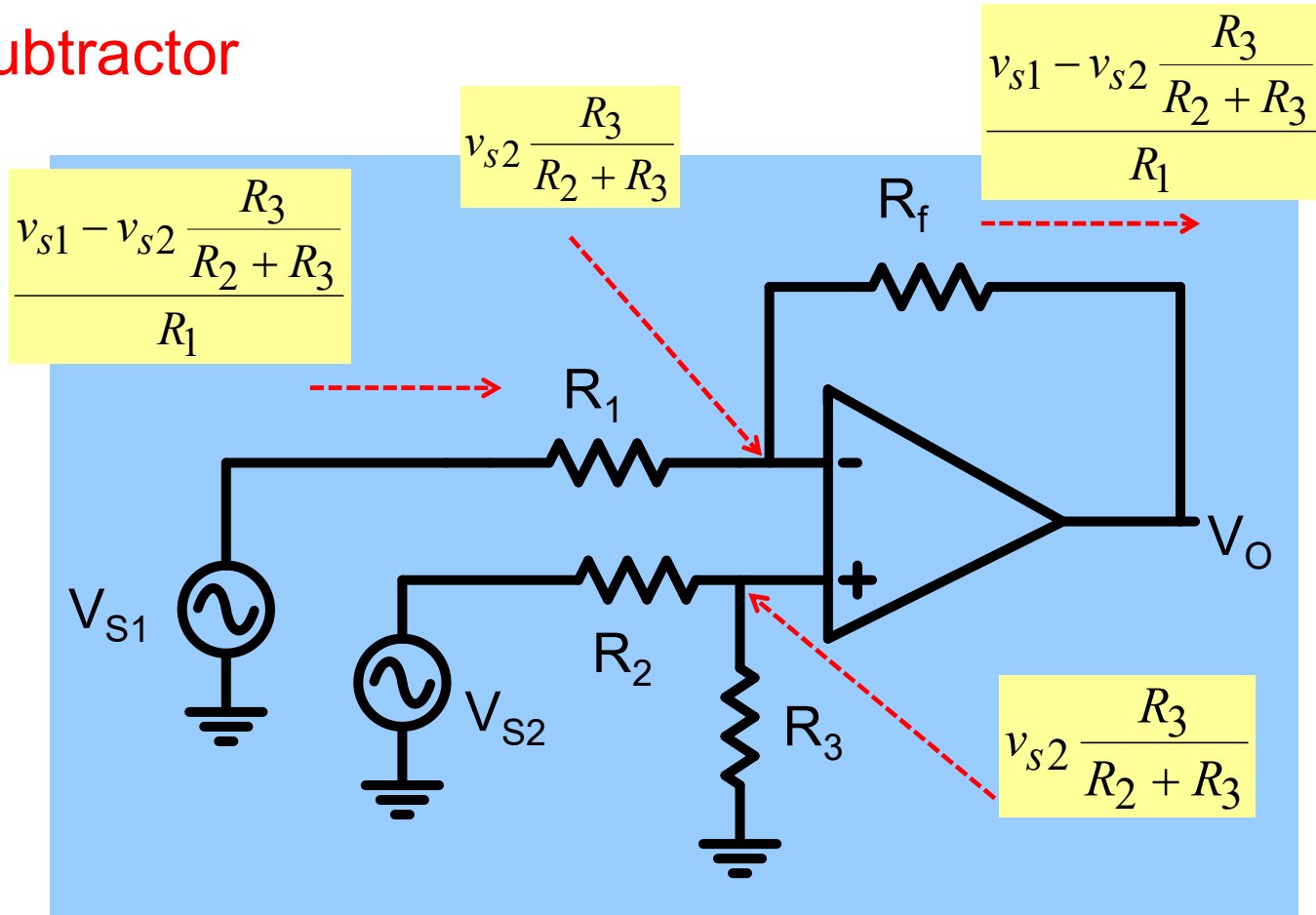
$$v_o = (v_{s1} + v_{s2})$$

The assumption made here is that there is no loading which is reasonable because opamps have very low resistance

Example

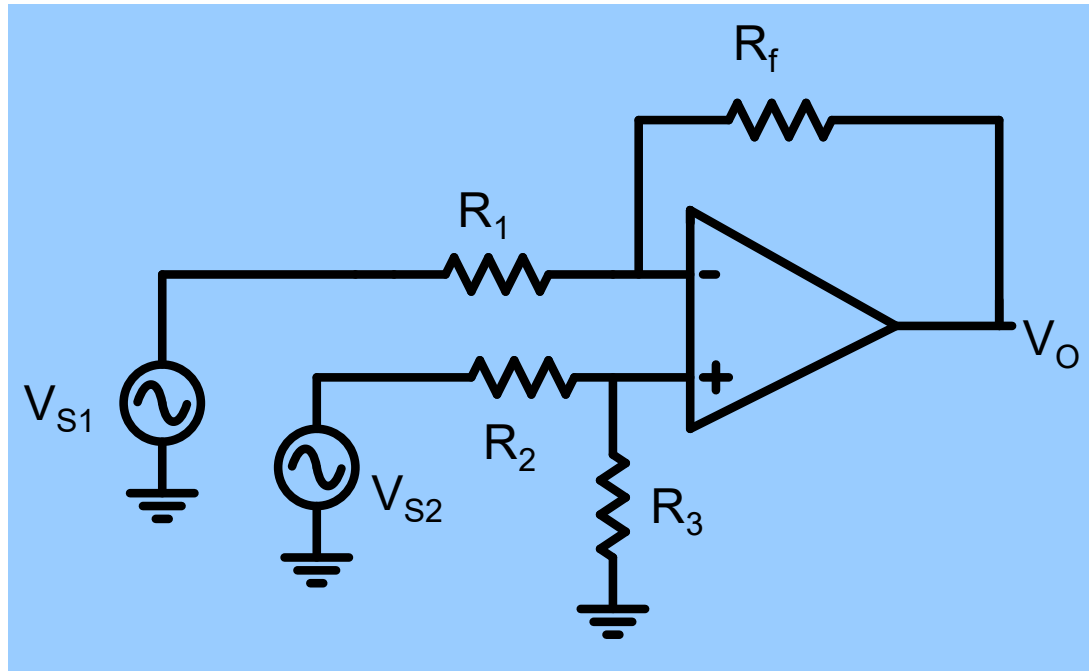


Subtractor



$$\frac{v_{s2} \frac{R_3}{R_2 + R_3} - v_o}{R_f} = \frac{v_{s1} - v_{s2} \frac{R_3}{R_2 + R_3}}{R_1}$$

$$v_o = v_{s2} \frac{\frac{R_3}{R_2}}{(1 + \frac{R_3}{R_2})} (1 + \frac{R_f}{R_1}) - (\frac{R_f}{R_1}) v_{s1}$$

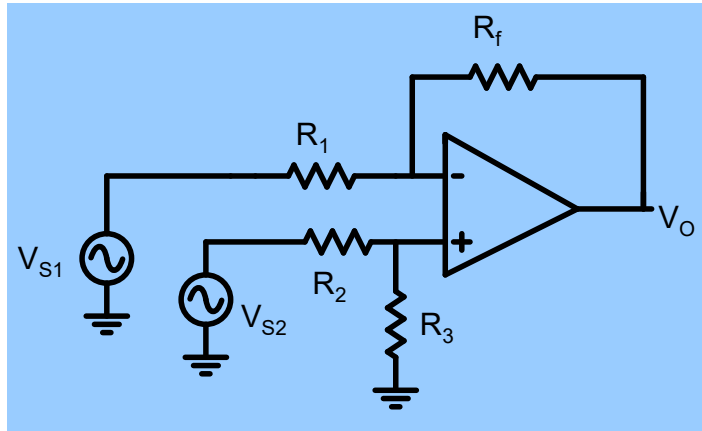


$$v_o = v_{s2} \frac{\frac{R_3}{R_2}}{(1 + \frac{R_3}{R_2})} (1 + \frac{R_f}{R_1}) - (\frac{R_f}{R_1}) v_{s1}$$

Choose $\frac{R_3}{R_2} = \frac{R_f}{R_1}$

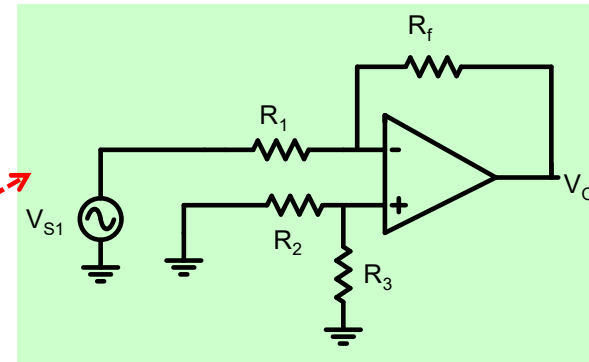
$$v_o = \frac{R_f}{R_1} (v_{s2} - v_{s1})$$

Subtractor: Alternative Analysis

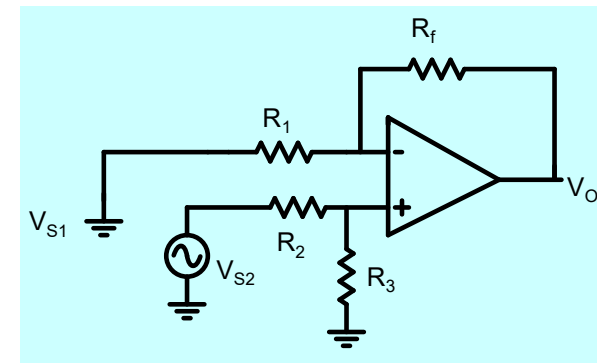


Use superposition theorem

$$v_o = -\left(\frac{R_f}{R_1}\right)v_{s1} + v_{s2} \frac{R_3}{(R_3 + R_2)} \times \left(1 + \frac{R_f}{R_1}\right)$$



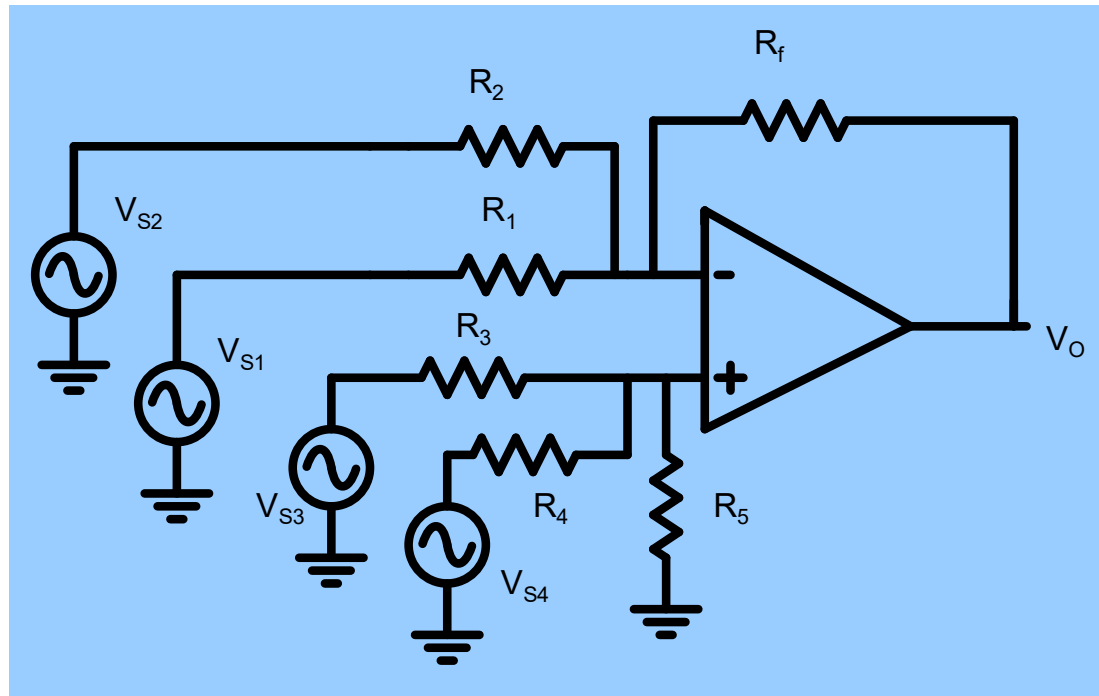
Inverting amplifier



Non-inverting amplifier

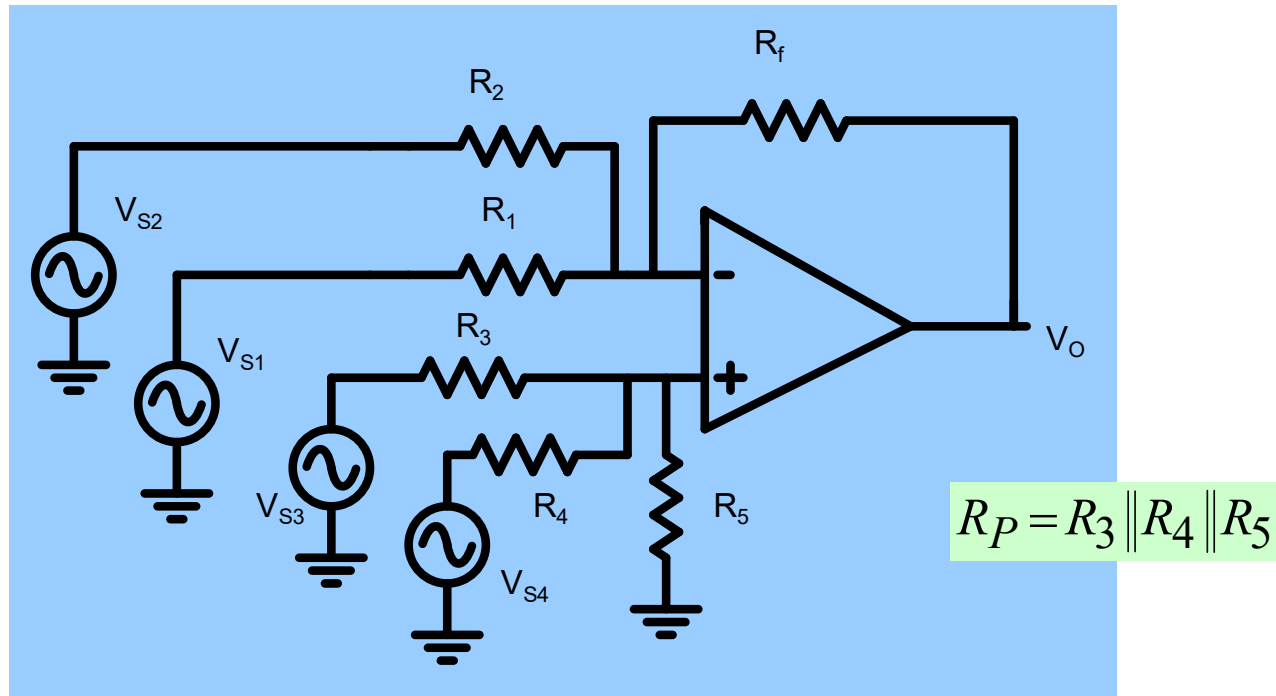
Analysis is made simpler by **Re-Using** results derived earlier

Adder/Subtractor



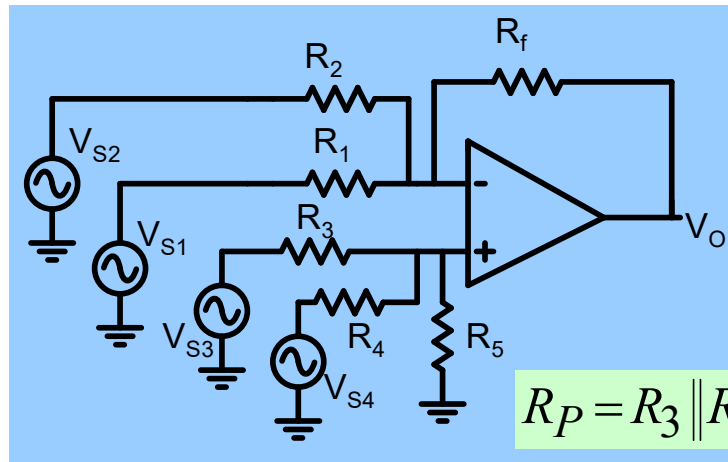
$$v_o = -\left(\frac{R_f}{R_1}\right)v_{s1} + -\left(\frac{R_f}{R_2}\right)v_{s2} + v_{s3} \frac{R_5 \parallel R_4}{R_5 \parallel R_4 + R_3} \times \left(1 + \frac{R_f}{R_1 \parallel R_2}\right) + v_{s4} \frac{R_5 \parallel R_3}{R_5 \parallel R_3 + R_4} \times \left(1 + \frac{R_f}{R_1 \parallel R_2}\right)$$

Adder/Subtractor



$$v_o = -\left(\frac{R_f}{R_1}\right)v_{s1} + -\left(\frac{R_f}{R_2}\right)v_{s2} + v_{s3} \frac{R_P}{R_3} \times \left(1 + \frac{R_f}{R_1 \parallel R_2}\right) + v_{s4} \frac{R_P}{R_4} \times \left(1 + \frac{R_f}{R_1 \parallel R_2}\right)$$

Example



$$v_o = -10v_{s1} - 4v_{s2} + 5v_{s3} + 2v_{s4}$$

$$R_P = R_3 \parallel R_4 \parallel R_5$$

$$v_o = -\left(\frac{R_f}{R_1}\right)v_{s1} - \left(\frac{R_f}{R_2}\right)v_{s2} + \left(1 + \frac{R_f}{R_1 \parallel R_2}\right) \times \frac{R_P}{R_3}v_{s3} + \left(1 + \frac{R_f}{R_1 \parallel R_2}\right) \times \frac{R_P}{R_4}v_{s4}$$

Choose :

$$R_f = 10K$$

$$\Rightarrow R_1 = 1K$$

$$\Rightarrow R_2 = 2.5K$$

$$\Rightarrow \frac{R_P}{R_3} = 0.33$$

$$\Rightarrow \frac{R_P}{R_4} = 0.133$$

$$\Rightarrow \frac{R_4}{R_3} = 2.5$$

Choose :

$$R_3 = 1K$$

$$\Rightarrow R_4 = 2.5K$$

$$\Rightarrow R_P = 0.33K$$

$$\Rightarrow R_5 = 0.625K$$