

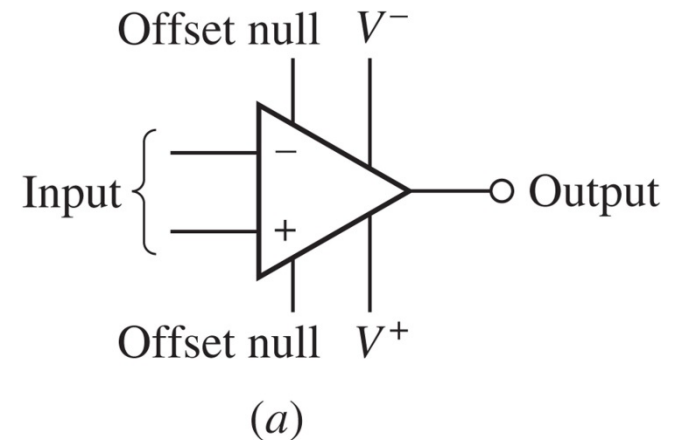
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# Chapter 6

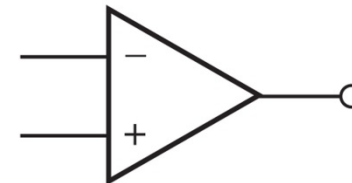
## The Operational Amplifier

- 6.1 Background
- 6.2 The Ideal Op Amp: A Cordial Introduction
- 6.3 Cascades Stages
- 6.4 Circuits for Voltage and Current Sources
- 6.5 Practical Considerations
- 6.6 Comparators and the Instrumentation Amplifier

**Operational Amplifier (Op amp):** Originally constructed for mathematical operations such as addition, subtraction, multiplication, division, differentiation, and integration. Voltage controlled voltage source (VCVS)



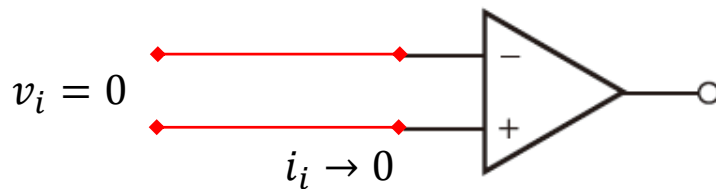
inverting input  
noninverting input



• Ideal Op Amp Rules

1. No current ever flows into their input terminal
2. There is no voltage difference between the two input terminal

} **Contradiction!!!!!!**



femtoampere input current and a small voltage difference between two input terminals in real Op Amp.

Virtual ground

• Inverting Amplifier

$$-v_{in} + R_1 i + R_f i + v_{out} = 0$$

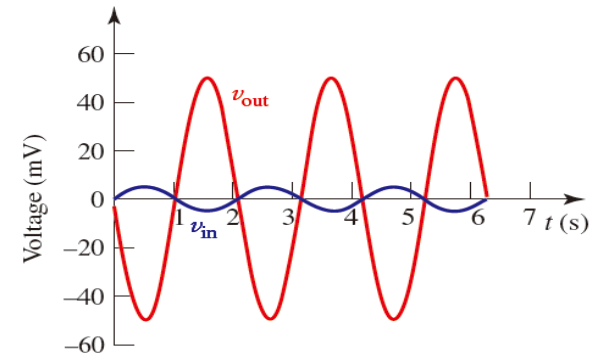
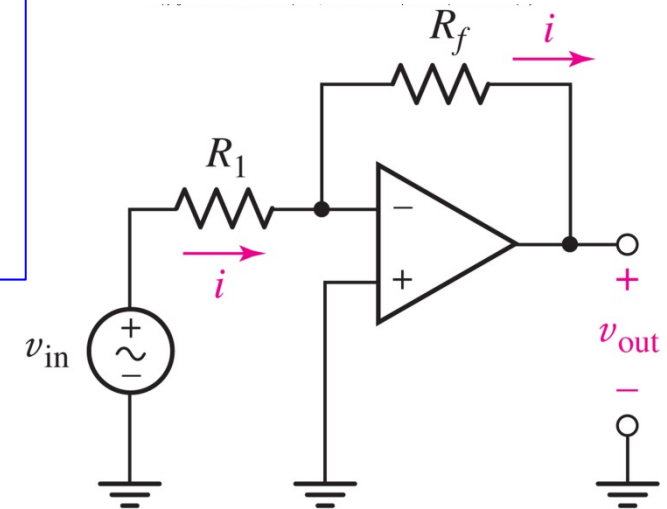
$$-v_{in} + R_1 i + 0(= v_i) = 0 \rightarrow i = \frac{v_{in}}{R_1}$$

$$v_{out} = v_{in} - (R_1 + R_f) i$$

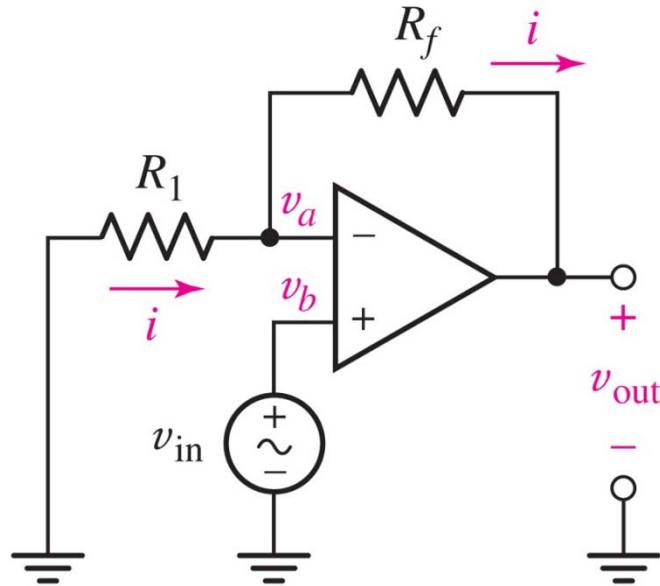
$$= v_{in} - (R_1 + R_f) \frac{v_{in}}{R_1}$$

$$\Rightarrow \frac{v_{out}}{v_{in}} = 1 - \frac{R_1 + R_f}{R_1} = -\frac{R_f}{R_1} \Rightarrow v_{out} = -\frac{R_f}{R_1} v_{in}$$

$R_f > R_1$ : amplify  
 $R_f < R_1$ : attenuate



Example 6.1 Sketch the output waveform (Noninverting Amplifier)



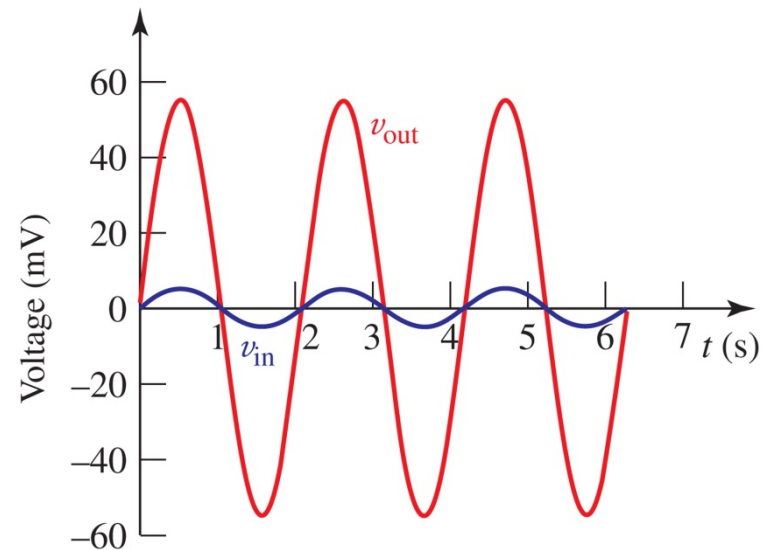
node  $b$  :  $v_b = v_{in} \rightarrow v_a = v_b = v_{in}$  virtual ground

$$\text{node } a : \frac{v_a}{R_1} + \frac{v_a - v_{out}}{R_f} = 0$$

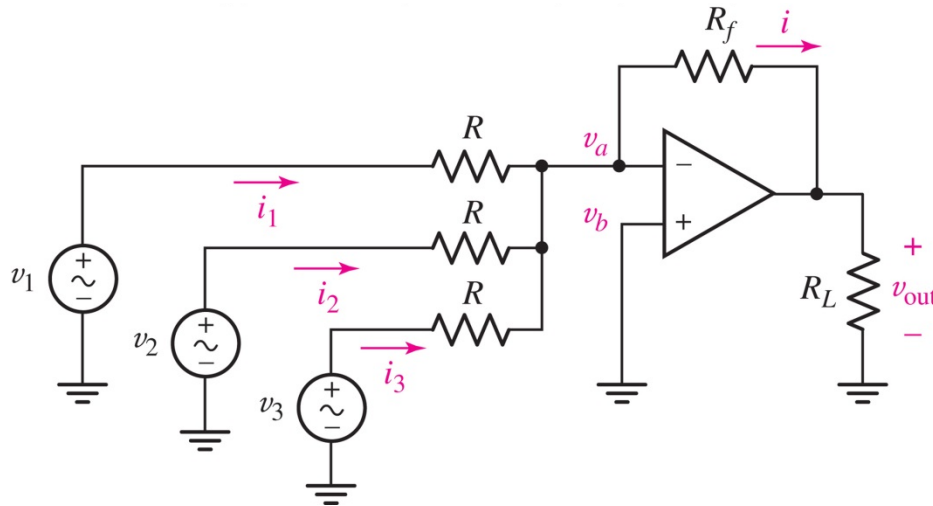
$$\rightarrow \frac{v_{in}}{R_1} + \frac{v_{in} - v_{out}}{R_f} = 0 \Rightarrow v_{out} = \left(1 + \frac{R_f}{R_1}\right) v_{in}$$

$$v_{in} = 5 \sin 3t \text{ mV}, R_1 = 4.7 \text{ k}\Omega, R_f = 47 \text{ k}\Omega$$

$$\Rightarrow v_{out} = \left(1 + \frac{R_f}{R_1}\right) v_{in} = 11v_{in} = 55 \sin 3t \text{ mV}$$



Example 6.2 Obtain the expression for  $v_{out}$  (Summing Amplifier)

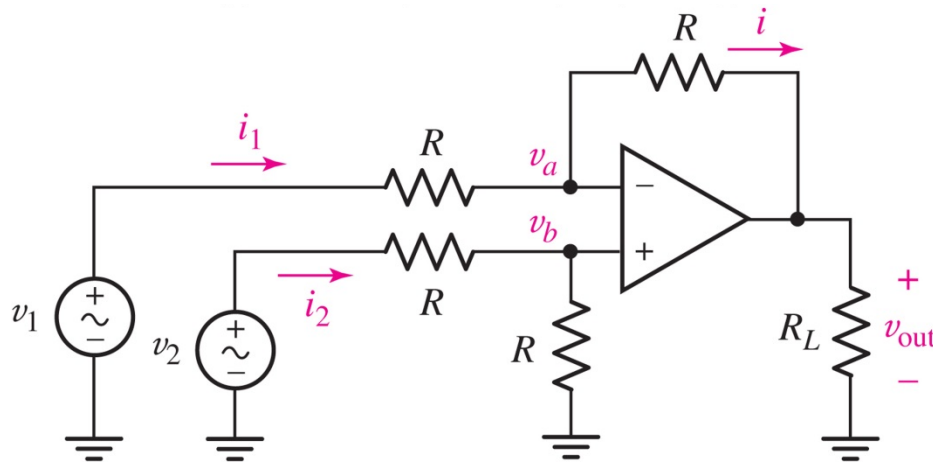


$$i_1 + i_2 + i_3 = i$$

$$\frac{v_1 - v_a}{R} + \frac{v_2 - v_a}{R} + \frac{v_3 - v_a}{R} = \frac{v_a - v_{out}}{R_f}$$

$$v_a = 0 \rightarrow v_{out} = -\frac{R_f}{R}(v_1 + v_2 + v_3)$$

Practice 6.2 Derive the expression for  $v_{out}$  (Difference Amplifier)



$$\text{node } a : \frac{v_1 - v_a}{R} = \frac{v_a - v_{out}}{R} \rightarrow v_{out} = 2v_a - v_1$$

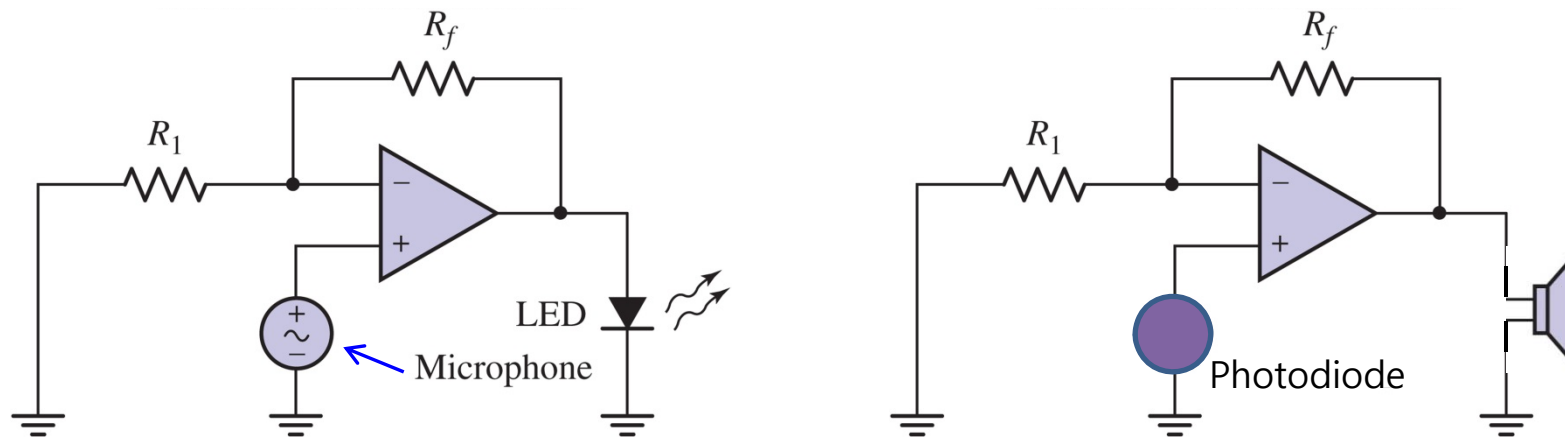
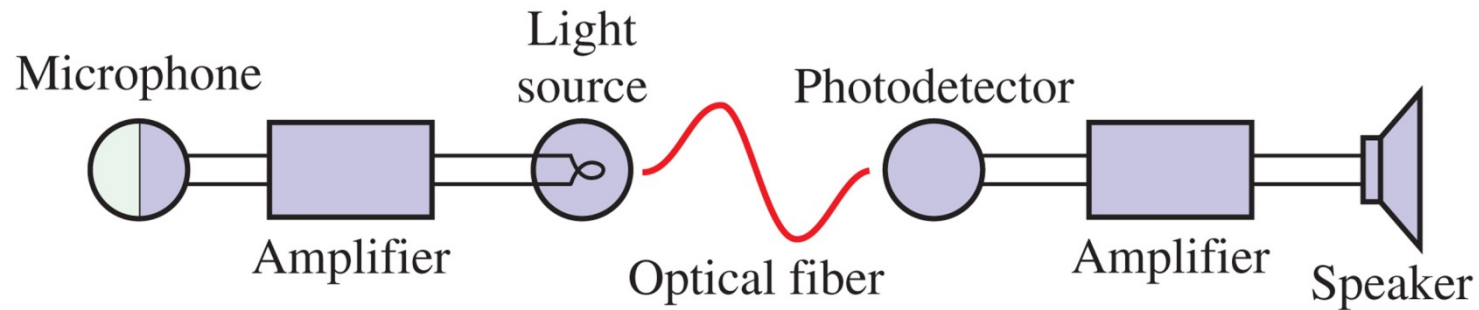
$$\text{node } b : \frac{v_2 - v_b}{R} = \frac{v_b}{R} \rightarrow v_b = \frac{1}{2}v_2$$

$$v_a = v_b$$

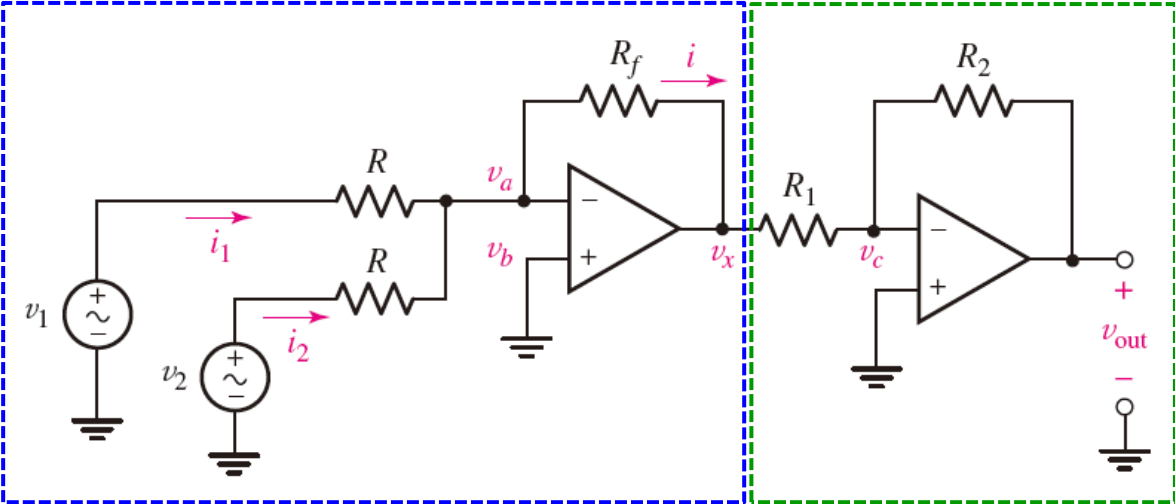
$$\Rightarrow v_{out} = 2v_a - v_1 = 2v_b - v_1$$

$$= 2\left(\frac{1}{2}v_2\right) - v_1 = v_2 - v_1$$

A Fiber Optic Intercom : to avoid wire corrosion and short circuit and weight issues



Cascaded stages : Multiple Op amp. stages connected in series



**inverting summation amp.**

**inverting amp.**

$$R_2 = R_1, R_f = R$$

$$\Rightarrow v_{out} = v_1 + v_2$$

$$v_x = -\frac{R_f}{R}(v_1 + v_2)$$

$$v_{out} = -\frac{R_2}{R_1}v_x$$

$$= -\frac{R_2}{R_1}\left(-\frac{R_f}{R}\right)(v_1 + v_2)$$

$$\therefore v_{out} = \frac{R_2R_f}{R_1R}(v_1 + v_2)$$

**Example 6.3** Op Amp cascaded stages for a multiple-tank gas propellant system  
 - Design a circuit measuring the total remaining fuel.

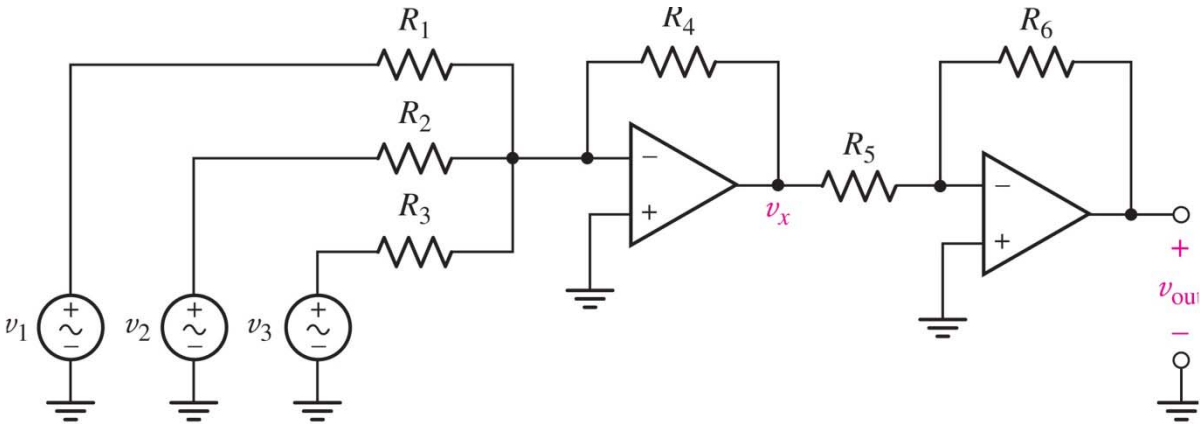
**TABLE 6.2** Technical Data for Tank Pressure Monitoring System

Tank 1 Capacity	10,000 psia
Tank 2 Capacity	10,000 psia
Tank 3 Capacity	2000 psia
Sensor Pressure Range	0 to 12,500 psia
Sensor Voltage Output	0 to 5 Vdc

gas (0~12,500) → voltage (0~5)

$$\frac{10,000}{12,500} 5 = 4 V \text{ for tank 1, 2}$$

$$\frac{2,000}{12,500} 5 = 0.8 V \text{ for tank 3}$$



$$v_x = - \left( \frac{R_4}{R_1} v_1 + \frac{R_4}{R_2} v_2 + \frac{R_4}{R_3} v_3 \right)$$

set  $R_1 = R_2 = R_3 = R_4 = 1k\Omega$

$$\Rightarrow v_x = -(v_1 + v_2 + v_3)$$

$$v_x = -(4 + 4 + 0.8) = -8.8 V$$

$$v_{out} = -\frac{R_6}{R_5} v_x$$

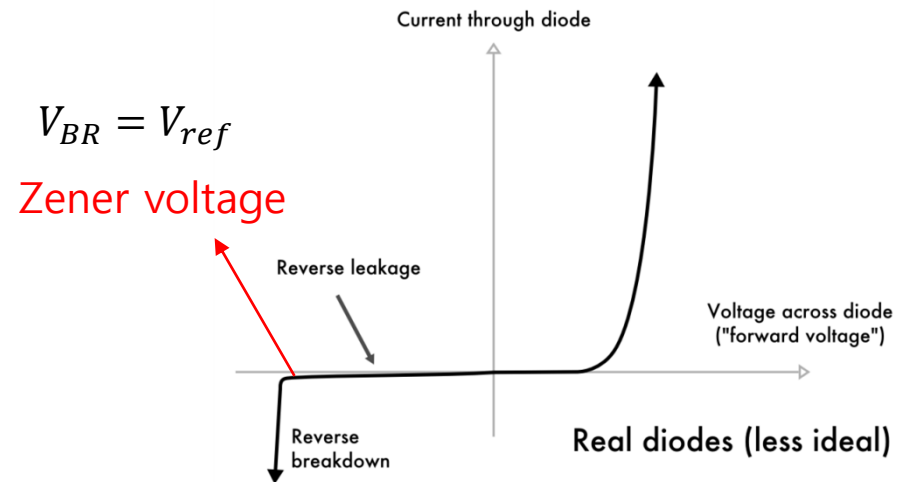
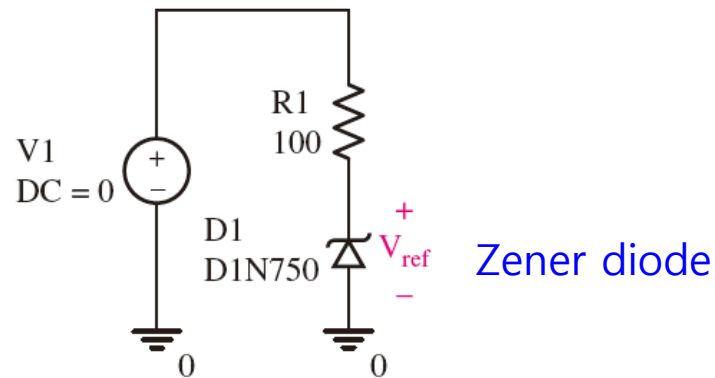
set  $R_6 = 1 k\Omega,$   
 $R_5 = 8.8 k\Omega$

$$\Rightarrow v_{out|full} = -\frac{1}{8.8} (-8.8) = 1 V$$

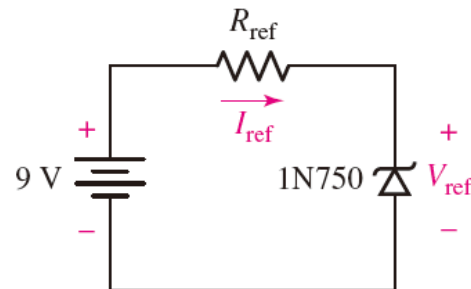
$v_{out} = 1$  if tanks are full



- Reliable Voltage Source



**Example 6.4** Design a circuit using 1N750 Zener diode that provides a ref. voltage of 4.7V



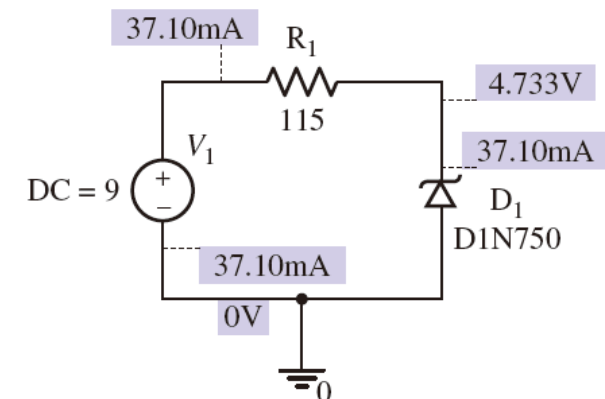
Zener voltage :  $V_{ref} = 4.7 \text{ V}$

Maximum current = 75 mA

$$R_{ref} = \frac{9 - V_{ref}}{I_{ref}} = \frac{4.3}{I_{ref}}$$

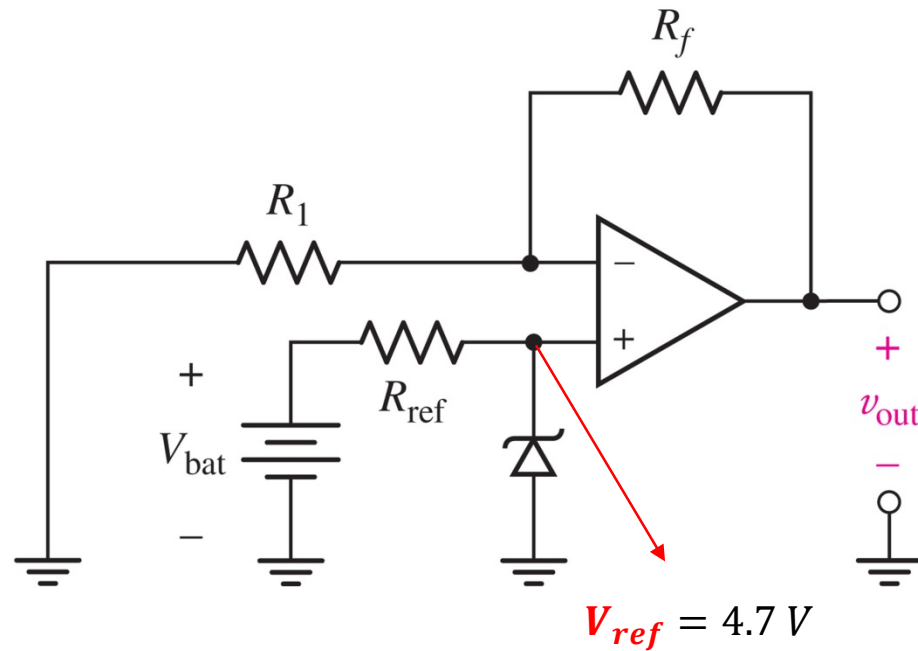
Set  $I_{ref} = 0.5 \times 75 \times 10^{-3} = 0.0375 \text{ A}$

$$\Rightarrow R_{ref} = \frac{4.3}{0.0375} = 115 \Omega$$



Actual simulation result

**Practice 6.4** Design a circuit to provide a ref. voltage of 6V using a 1N750 Zener diode and a noninverting amplifier.



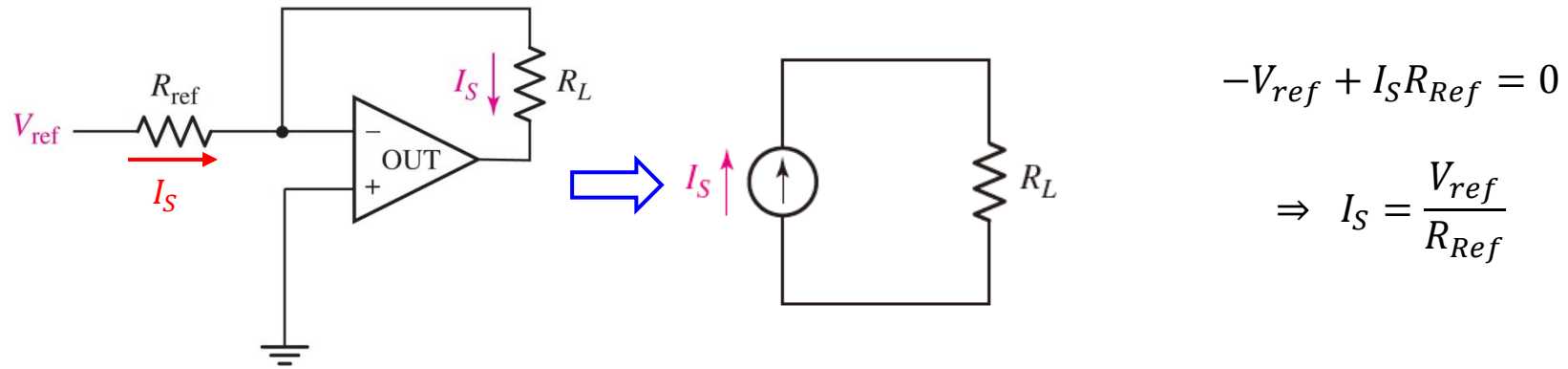
To provide 6 V output voltage

$$v_{out} = \left(1 + \frac{R_f}{R_1}\right) V_{ref}$$

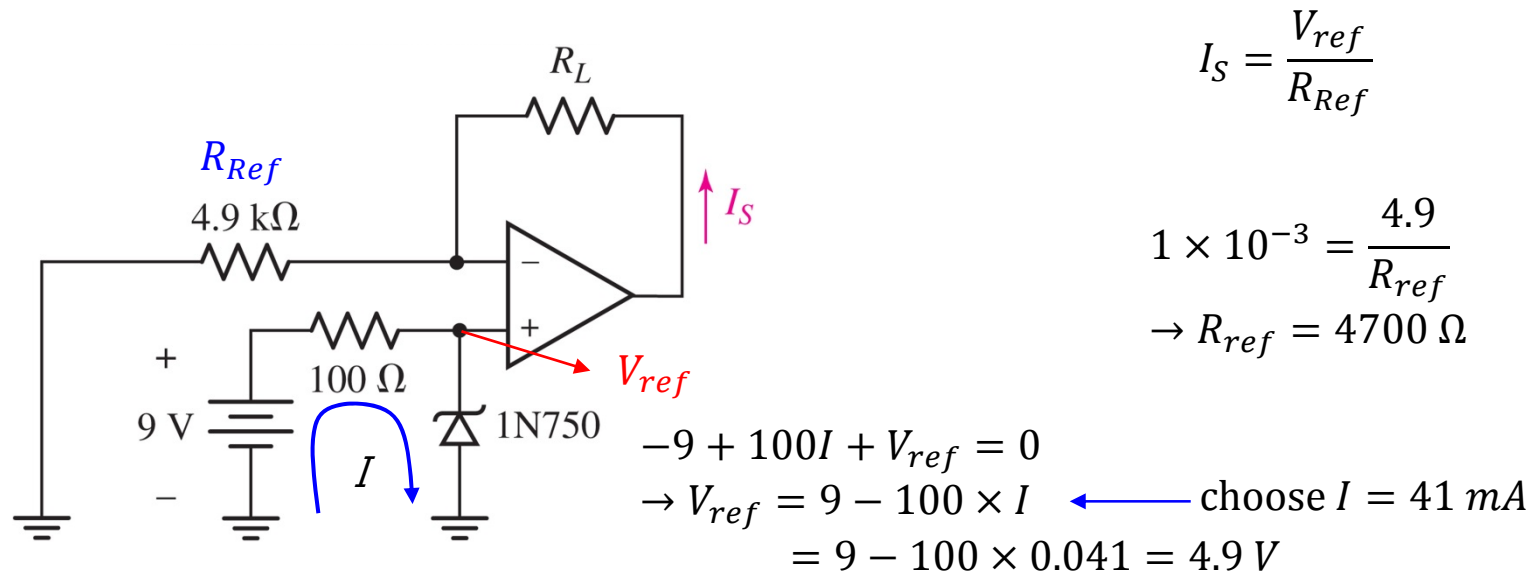
Choose  $R_1 = 1000\ \Omega$ ,  $R_f = 268\ \Omega$

$$v_{out} = \left(1 + \frac{268}{1000}\right) 4.7 = 5.96 \approx 6\text{ V}$$

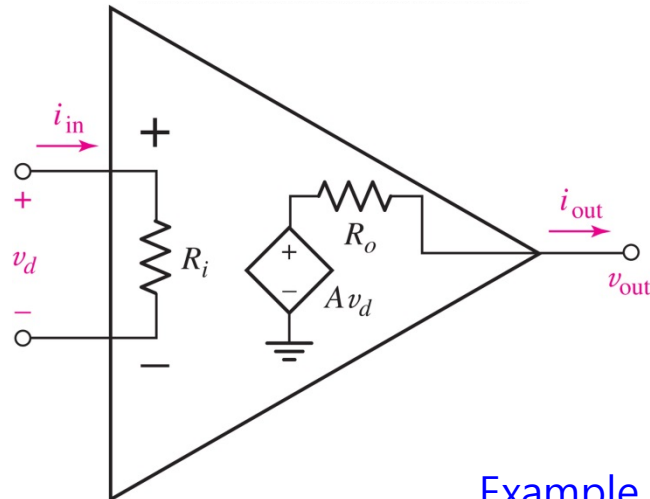
- Reliable Current Source



Example 6.5 Design 1mA current source



- A More Detailed Op Amp Model



Ideal case

$$R_i = \infty \rightarrow i_{in} = 0$$

$$v_d = 0$$

$$R_o = 0$$

$$A = \infty$$

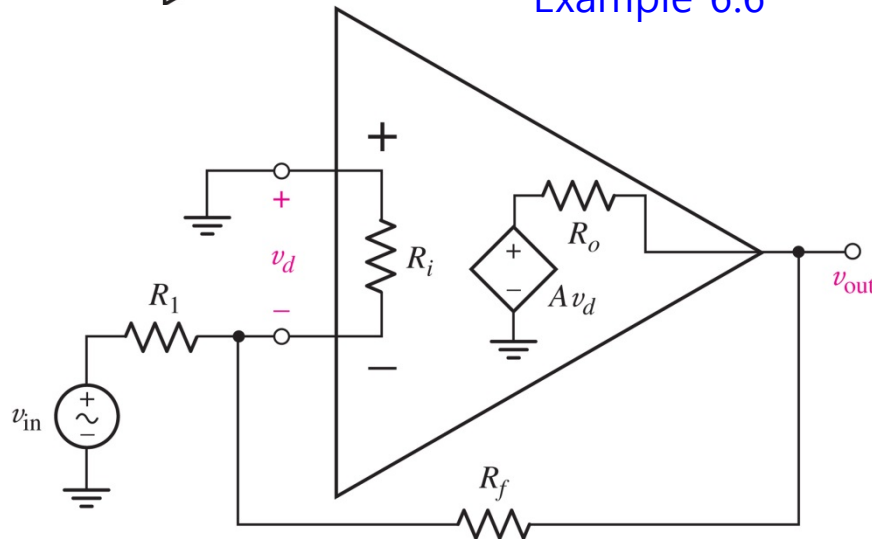
Actual parameters of  $\mu A741$ 

$$R_i = 10 \text{ M}\Omega$$

$$R_o = 75 \Omega$$

$$A = 2 \times 10^5$$

Example 6.6



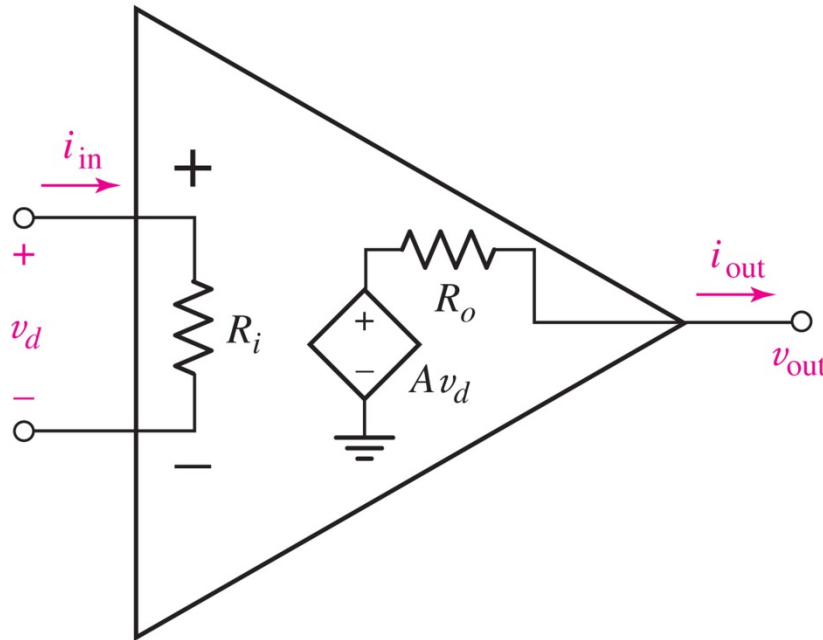
$$\frac{-v_d - v_{out}}{R_f} = \frac{v_{out} - Av_d}{R_o}$$

$$\frac{v_{in} - (-v_d)}{R_1} = \frac{-v_d}{R_i} + \frac{-v_d - v_{out}}{R_f}$$

$$v_{out} = \left[ \frac{R_o + R_f}{R_o - AR_f} \left( \frac{1}{R_1} + \frac{1}{R_f} + \frac{1}{R_i} \right) - \frac{1}{R_f} \right]^{-1} \frac{v_{in}}{R_1}$$

$$v_{out} = -\frac{R_f}{R_1} v_{in} \quad \text{for } A \rightarrow \infty, R_o \rightarrow 0, R_i \rightarrow \infty$$

- Derivation of the Ideal Op Amp Rules



$$-Av_d + i_{out}R_o + v_{out} = 0$$

$$\rightarrow v_{out} = Av_d - i_{out}R_o$$

$$v_{out} = Av_d \text{ for open output}$$

$v_d$  : differential input voltage

In real situation

$$v_{out} : 5 \sim 24 \text{ V}$$

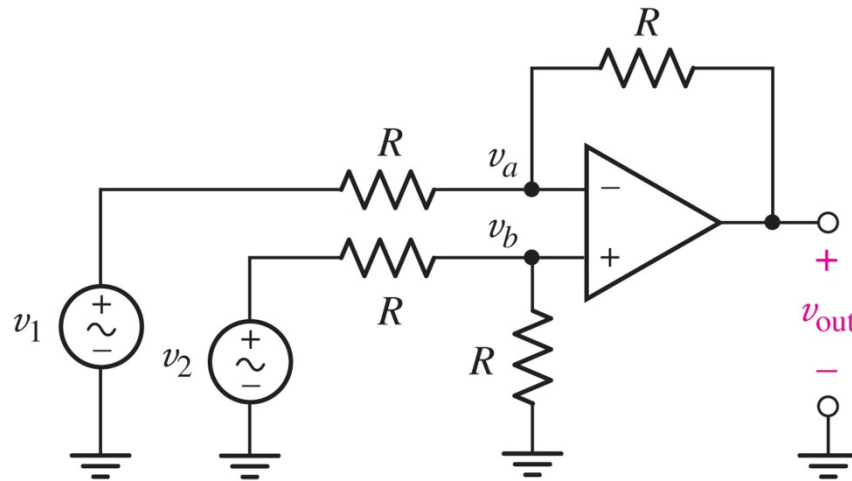
$$A = 2 \times 10^5 \text{ (at } \mu\text{A741 op amp)}$$

$$\rightarrow v_d = \frac{24}{2 \times 10^5} = 120 \mu\text{V (at maximum)}$$

$$24 \text{ V} \gg 120 \mu\text{V} \rightarrow \text{assume } 0 \text{ V}$$

$$\begin{aligned} i_{in} &= \frac{v_d}{R_i} = \frac{120 \mu\text{V}}{2 \text{ M}\Omega} = \frac{120 \times 10^{-6}}{2 \times 10^6} \\ &= 60 \times 10^{-12} \text{ A} \rightarrow \text{assume } 0 \text{ A} \end{aligned}$$

- Common-Mode Rejection Ratio



$$\text{node } b : \frac{v_2 - v_b}{R} = \frac{v_b}{R} \rightarrow v_b = \frac{v_2}{2} = v_a$$

$$\text{node } a : \frac{v_1 - v_a}{R} = \frac{v_a - v_{out}}{R}$$

$$\rightarrow v_{out} = 2v_a - v_1 = v_2 - v_1$$

$$\text{Ex) } v_1 = 2 + 3 \sin 3t \text{ V}, v_2 = 2 \text{ V}$$

$$\rightarrow v_{out} = -3 \sin 3t \text{ V}$$

common component is **not amplified**

$$v_1 = v_2 = v_{CM} \rightarrow v_{out} = v_{oCM}$$

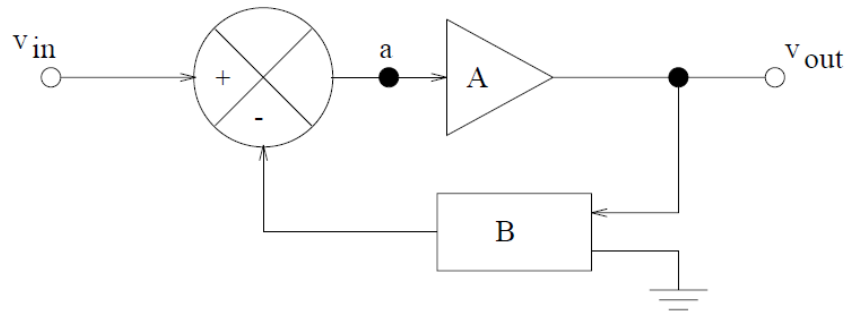
$$\Rightarrow A_{CM} = \left| \frac{v_{oCM}}{v_{CM}} \right|$$

$$\Rightarrow CMMR = \left| \frac{A}{A_{CM}} \right|$$

$$\Rightarrow CMMR_{dB} = 20 \log_{10} \left| \frac{A}{A_{CM}} \right|$$

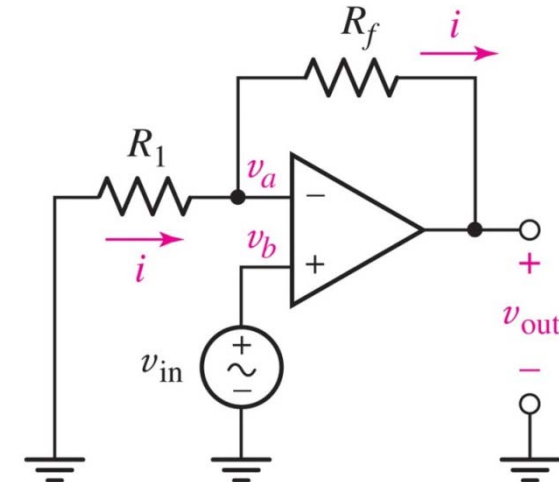
- Negative Feedback

The process of subtracting a small portion of the output from the input



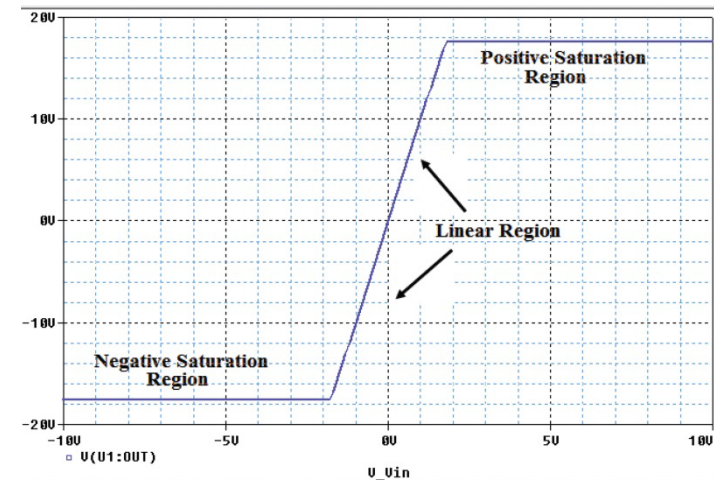
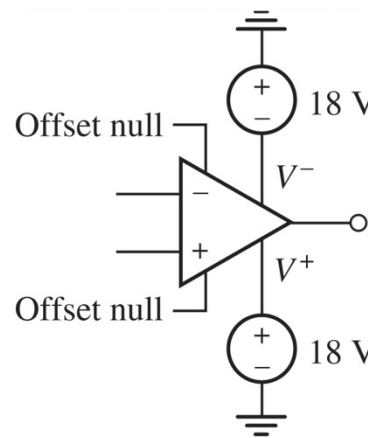
$$v_a = v_{in} - Bv_{out}$$

$$v_{out} = Av_a \Rightarrow v_{out} = \frac{A}{1 + AB} v_{in}$$

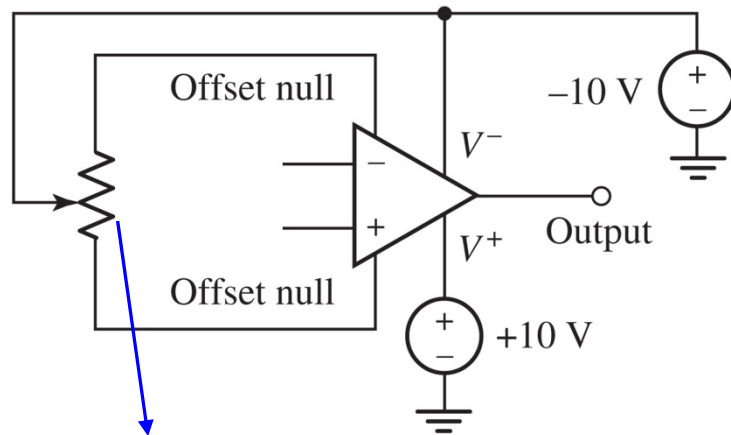


- Saturation Output is no longer proportional to the input

The maximum output voltage is slightly less than the supply voltage by as much as a volt or so



- Input Offset Voltage



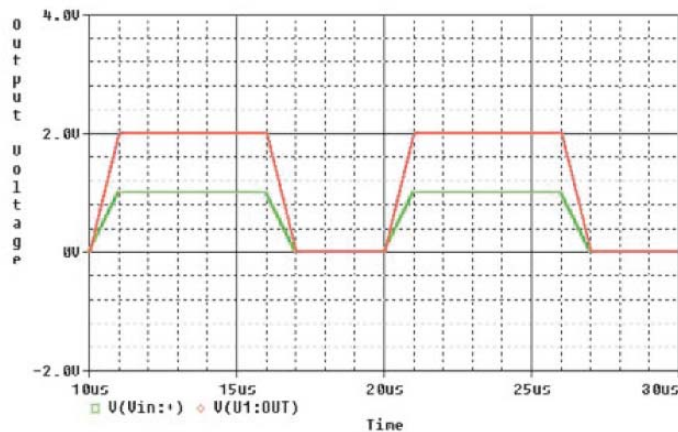
real op amps have a nonzero output even when the two input terminals are shorted together

**input offset voltage:**

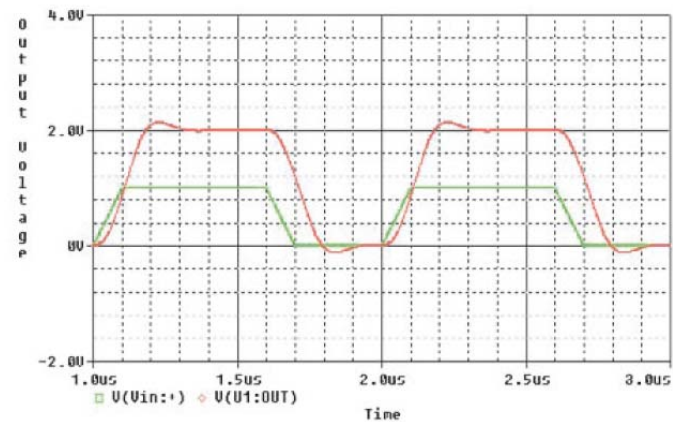
the input voltage required to reduce the output to zero

two control pins connected to variable resistor

- Slew Rate the rate at which the output voltage can respond to changes in the input; it is most often expressed in  $V/\mu s$



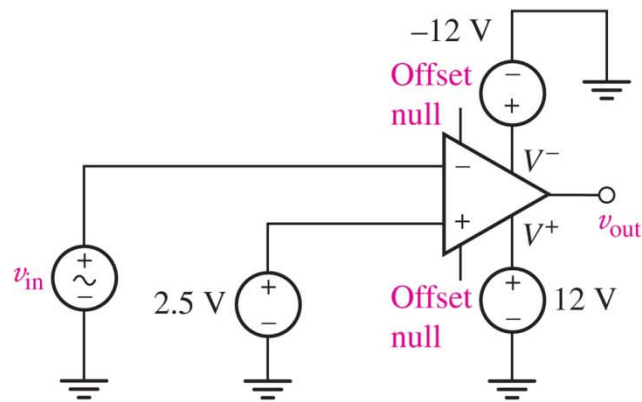
rise and fall times  $1 \mu s$ , pulse width  $5 \mu s$



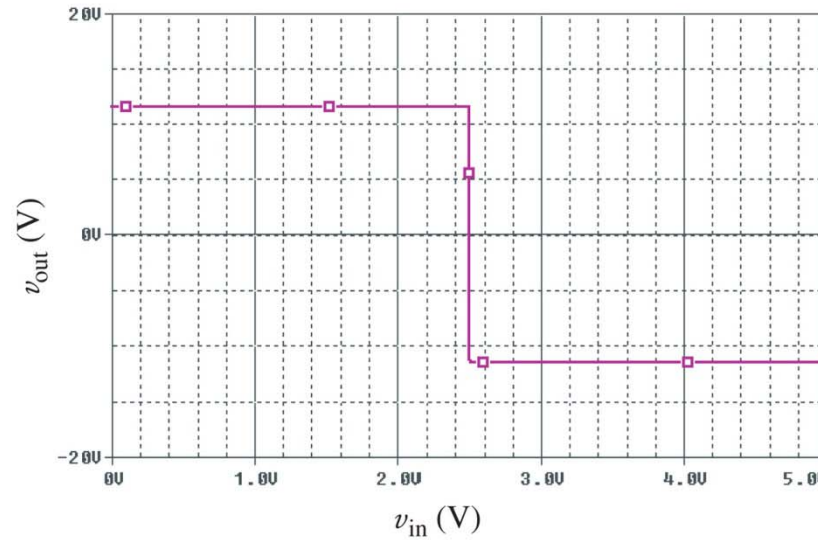
rise and fall times  $100 \text{ ns}$ , pulse width  $500 \text{ ns}$



- Comparator

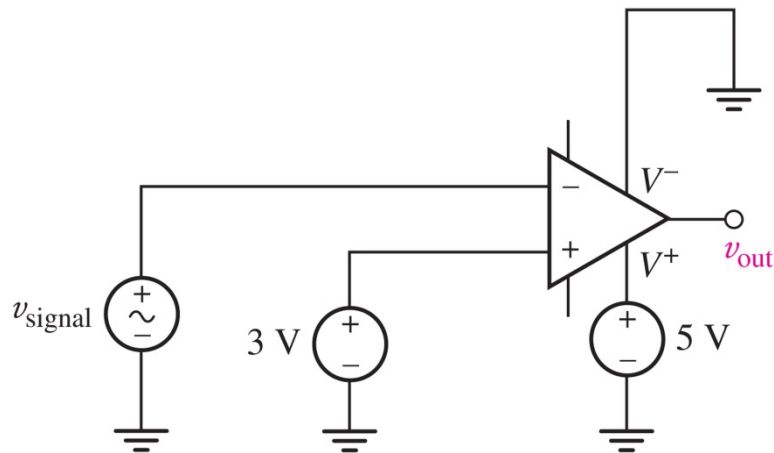


$$v_{out} = A(2.5 - v_{in})$$



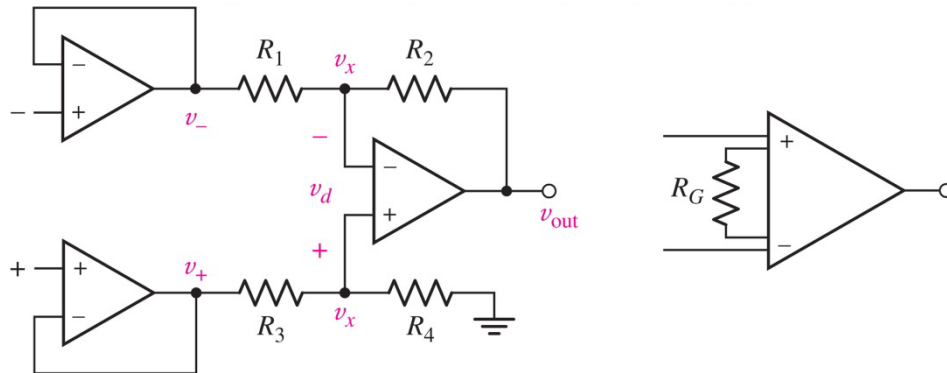
- Op Amp is working at saturation mode.

**Example 6.8** Design a circuit that provides a "login 1.5V output if input is over 3V.



- Instrumentation Amplifier

- Instrumentation amplifier is a kind of differential amplifier with additional input buffer stages.
- The addition of input buffer stages makes it easy to match (impedance matching) the amplifier with the preceding stage.
- Instrumentation are commonly used in industrial test and measurement application.
- The instrumentation amplifier also has some useful features like low offset voltage, high CMRR (Common mode rejection ratio), high input resistance, high gain etc



$$\frac{v_- - v_x}{R_1} = \frac{v_x - v_{out}}{R_2}$$

$$\frac{v_+ - v_x}{R_3} = \frac{v_x}{R_4} \rightarrow v_x = \frac{v_+}{1 + R_3/R_4}$$

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

$$\frac{R_4}{R_3} = \frac{R_2}{R_1} = K \Rightarrow v_{out} = K \left( \frac{1 + K}{1 + K} \right) v_+ - K v_- = K(v_+ - v_-) = K v_d$$

Homework : 6장 Exercises 4의 배수 문제 (56번 문제까지)

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