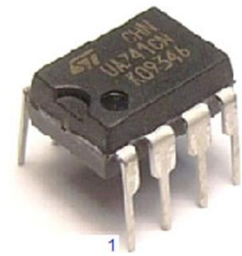

ENEE2360 Analog Electronics

T9:
Operational Amplifiers

Instructor : Nasser Ismail

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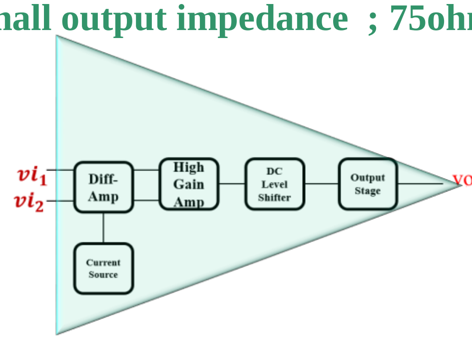
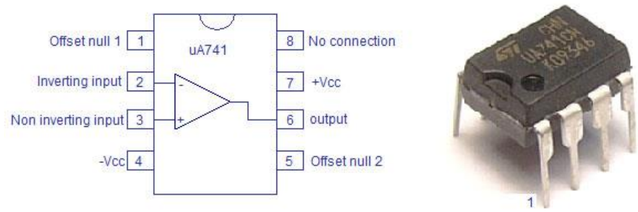
The Operational Amplifier

Designed to do mathematical operations such as addition , subtraction ….

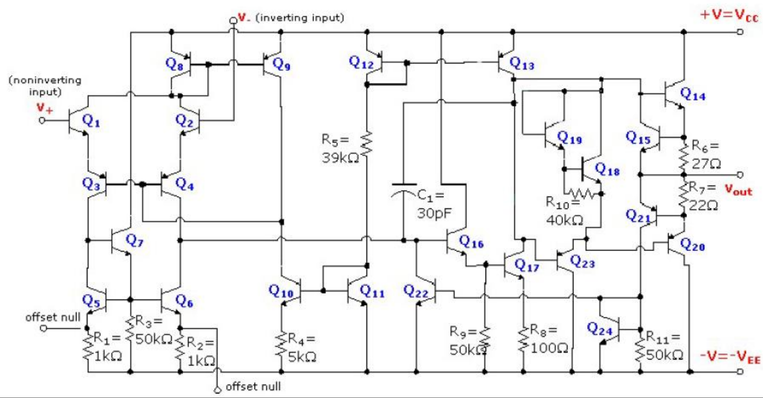
Very high voltage gain ; 200,000
Very High input impedance ; 10M ohm
Very small output impedance ; 75ohm



Operational Amplifiers



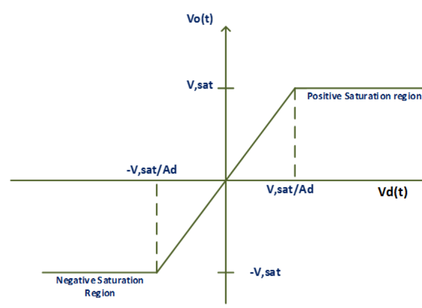
uA741 opamp Pinout and External appearance



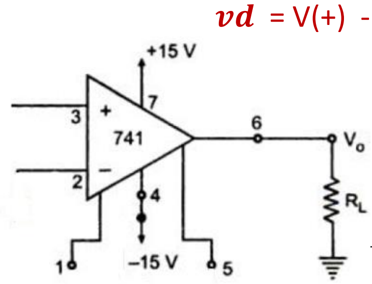
Operational Amplifier

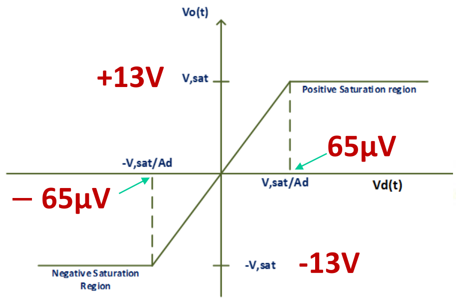
Transfer characteristic Curve:

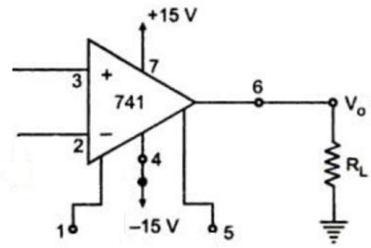
$$V_O = \begin{cases} +V_{sat} & vd > \frac{V_{sat}}{A_d} \\ A_d\, vd & \frac{V_{sat}}{A_d} > vd > -\frac{V_{sat}}{A_d} \\ -V_{sat} & vd < -\frac{V_{sat}}{A_d} \end{cases}$$



vd = V(+) - V(-)







Let $\pm V_{cc} = \pm$ 15V ; $Ad = 200,000$

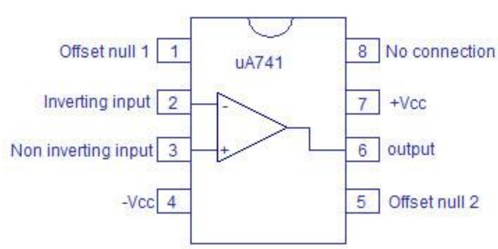
$\therefore \pm V_{sat}$=±13V

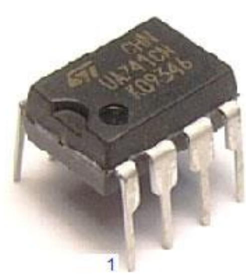
$\therefore$ If Vd $>$ 65µV ; V_O =+13V

$\therefore$ If Vd $<$ − 65µV ; V_O = −13V

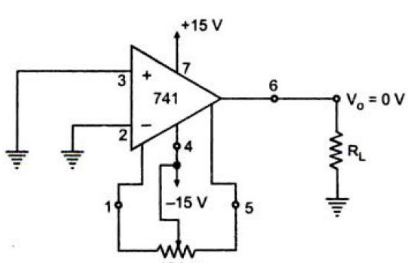
Operational Amplifier

Pin Diagram for 741 :

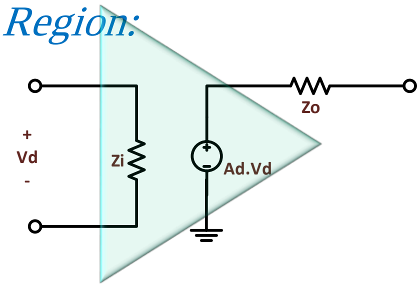




uA741 opamp Pinout and External appearance

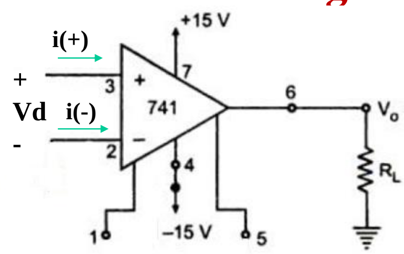


Op-amp Model in the Linear Region:



If the Op-Amp is IDEAL and in the Linear Region

Two Assumptions



1) $Vd \cong 0$ ⇨ V(+) = V(-)

2) i(+) = i(-) = 0

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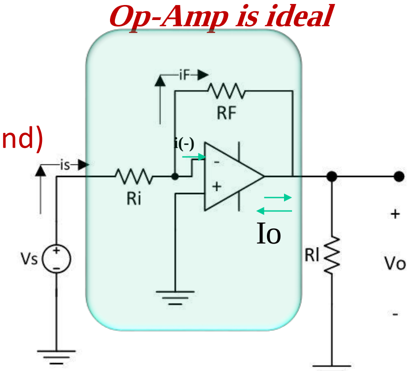
Op-amp Linear Applications:

1. Inverting Amplifier

Op-Amp is ideal



a) Since V(+) = 0 ; ∴ V(-) = 0

(Virtual ground)

And $i_s = \frac{v_s}{R_i}$

b) Since i(-) = 0 ; ∴ $i_F = i_S$

c) $V_O = -R_F i_F$

$V_O = -R_F i_S$

$V_O = -\frac{R_F}{R_i} V_S$ $\therefore A_v = -\frac{R_F}{R_i}$

$+V_{sat} > V_O > -V_{sat}$

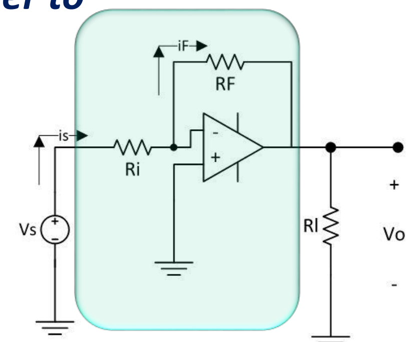
Io < Io,max

The voltage gain does not depend on RL

Op-Amp Linear Applications:

1. Inverting Amplifier

Design an inverting amplifier to provide A_v = -200



Solution :

$$A_v = -\frac{R_F}{R_i} = -200$$

$$\therefore \frac{R_F}{R_i} = 200$$

Let $R_i = 20K$

$$\therefore R_F = 4000K$$

$$Zi = R_i$$

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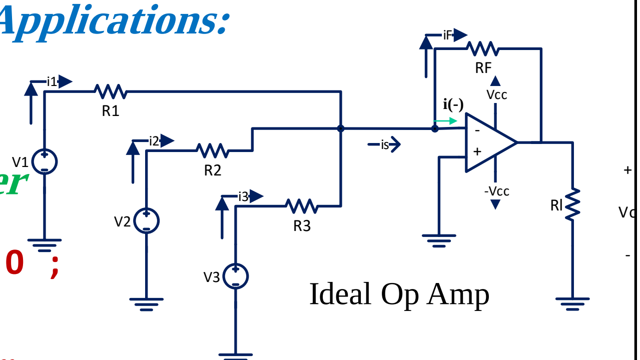
Op-amp Linear Applications:

2. Inverting Adder



1- Since V(+) = 0 ;

$\therefore$ V(-) = 0

$i_1 = \frac{v_1}{R_1}$; $i_2 = \frac{v_2}{R_2}$;

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

$i_s = i_1 + i_2 + i_3$

2- Since i(-) =0 ; $\therefore i_F = i_S$

3- $V_O = -R_F i_F$

$$V_O = -\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2 + \frac{R_F}{R_3}V_3\right)$$

If $R_1 = R_2 = R_3 = R_F = R$

$$V_O = -(V_1 + V_2 + V_3)$$

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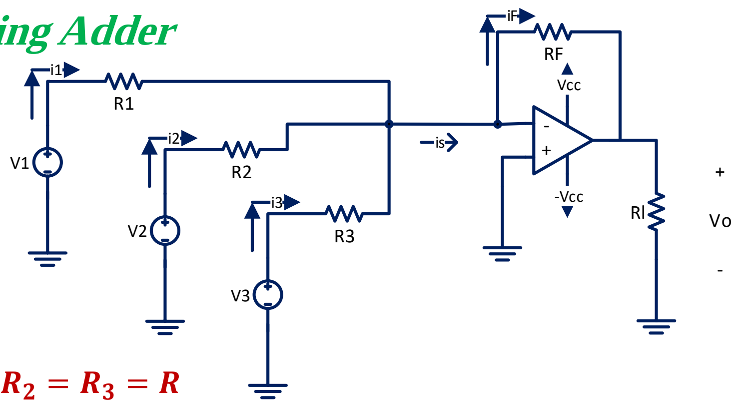
Op-amp Linear Applications:

2. Inverting Adder



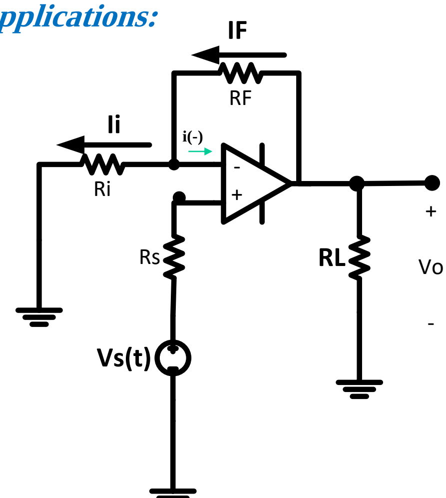
If $R_1 = R_2 = R_3 = R$

And $R_F = \frac{R}{n} = \frac{R}{3}$ ⟹ **Averager**

$\therefore \; V_O = -\left(\frac{V_1+V_2+V_3}{3}\right)$

Op-amp Linear Applications:

3. Non Inverting Amplifier



1- Since $V(+) = V_s$

$\therefore \; V(-) = V_s$

$\therefore \; i_i = \frac{V_s}{R_i}$

2- Since $i(-) = 0$;

$\therefore \quad i_F = i_i$

3 - $V_O = R_F i_F + R_i i_i$

⟹ $V_O = \left(1 + \frac{R_F}{R_i}\right) V_+$

Zi = ∞

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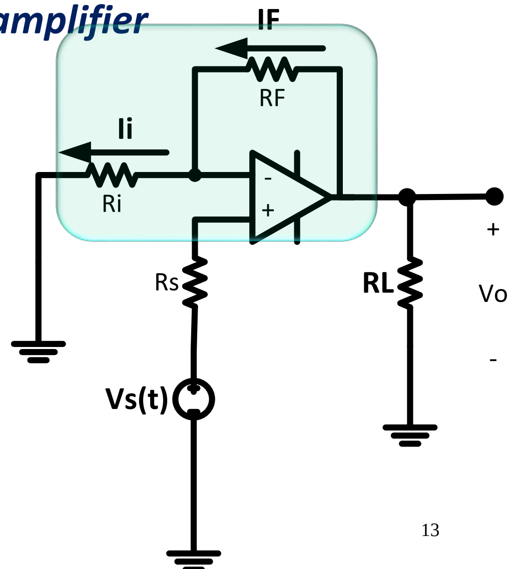
Op-amp Linear Applications:

Non Inverting Amplifier

Design a non inverting amplifier to provide $A_v = 100$



Solution :

$A_v = 1 + \frac{R_F}{R_i} = 100$

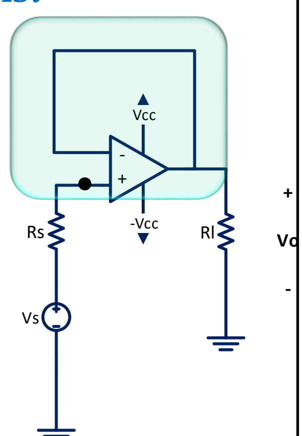
$\therefore \frac{R_F}{R_i} = 99$

Let $R_i = 10K$

$\therefore R_F = 990K$

Op-amp Linear Applications:

4. Buffer , Unity Gain



1- Since V(+) = V_s ; $\therefore$ V(-) = V_s

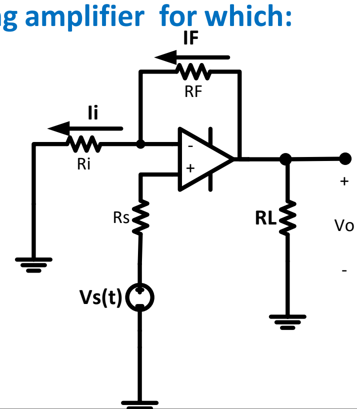
2- V_O = V(-) = V_s

Buffer is a special Case of

non inverting amplifier for which:

$R_i = \infty$

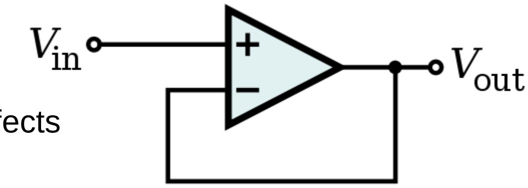
$R_F = 0$

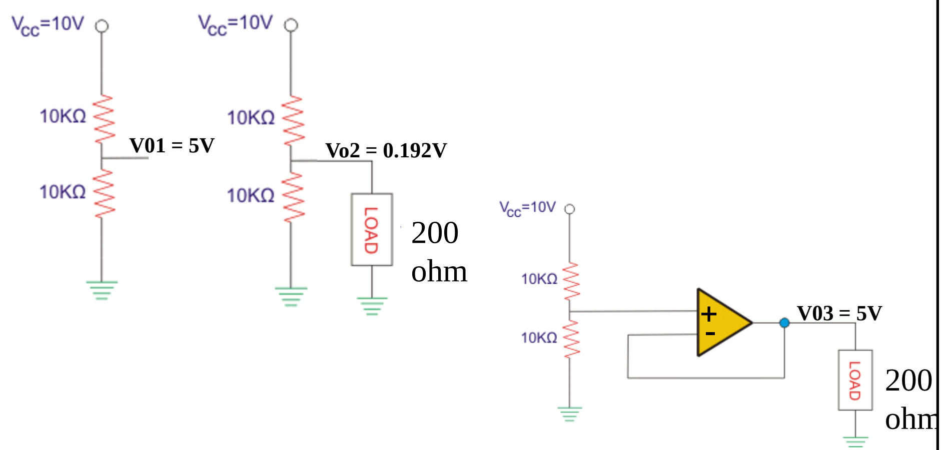


Op-Amp Buffer

Vout = Vin

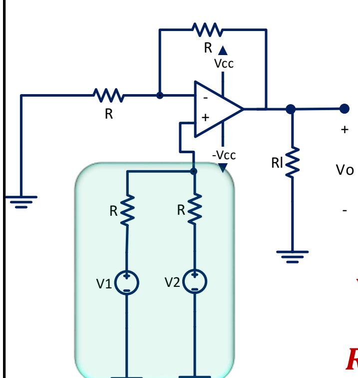
Isolates loading effects





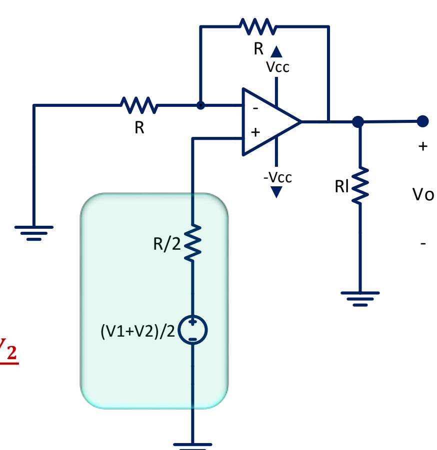
Op-amp Linear Applications:

5. Non-inverting Adder



$$V_{TH} = \frac{V_1+V_2}{2}$$

$$R_{TH} = \frac{R}{2}$$



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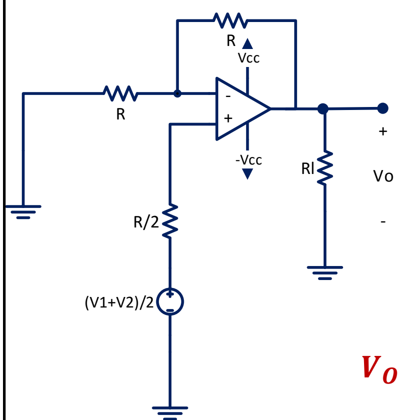

$$V_O = (1+\frac{R}{R})(\frac{V_1+V_2}{2}) = V_1 + V_2$$

If we have n signal :

let $R_F = $ (n-1)R

$$V_O = V_1 + V_2 + \ldots\ldots\ldots\ldots\ldots + V_N$$

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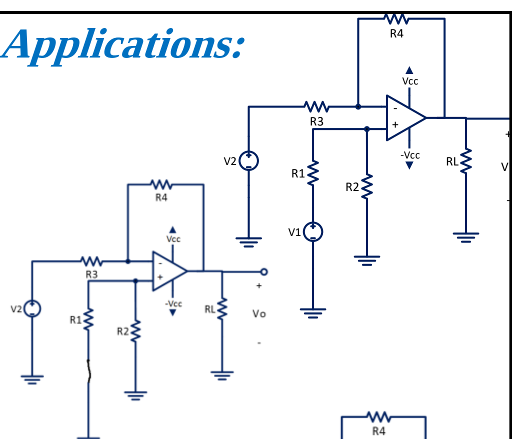
Op-amp Linear Applications:

6. Voltage Subtraction

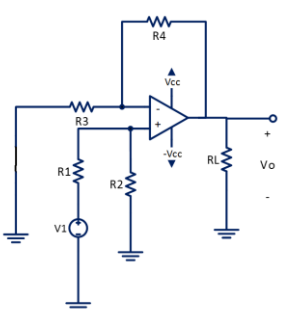
Using superposition



a) Let $V_1 = 0$ (Inverting amplifier)

$$\therefore V_{o1} = -\frac{R_4}{R_3} V_2$$

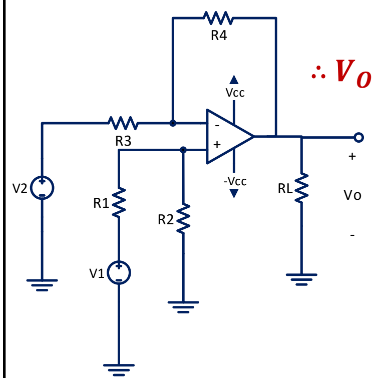
b) Let $V_2 = 0$ (non inverting amplifier)



$$\therefore V_{o2} = (1 + \frac{R_4}{R_3})(\frac{R_2}{R_1+R_2}) V_1$$

c) Total Vo=Vo1+Vo2

$$\therefore V_O = (1 + \frac{R_4}{R_3})(\frac{R_2}{R_1+R_2}) V_1 - \frac{R_4}{R_3} V_2$$



$$\therefore V_O = \left(1+\frac{R_4}{R_3}\right)\left(\frac{R_2}{R_1+R_2}\right)V_1 - \frac{R_4}{R_3}V_2$$

$$V_O = aV_1 - bV_2$$

If $R_1 = R_3 = R$
and $R_2 = R_4 = mR$

$$V_O = m(V_1 - V_2)$$

Basic Difference Amplifier

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Op-amp Linear Applications:

Basic Difference Amplifier

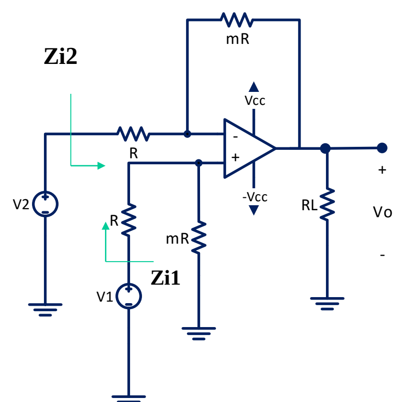
$V_O = m(V_1 - V_2)$

$Z_{i1} = R + mR$

$Z_{i2} = R$

*It has low input impedance

*To Change the gain, we must change two resistors.



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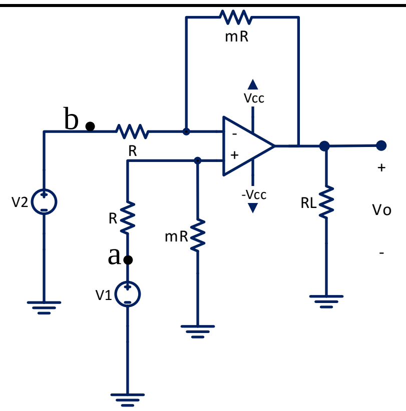
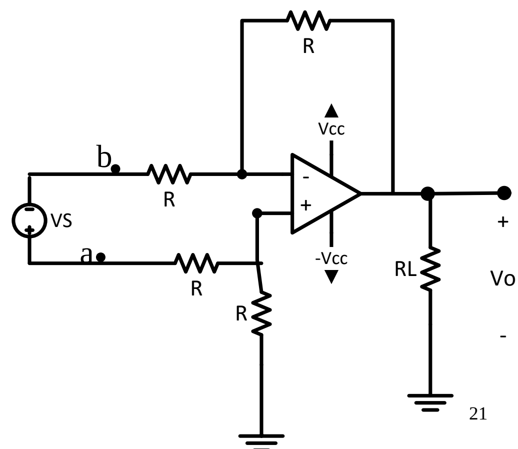


$V_O = m(V_1 - V_2)$

$V_O = m\ V_{ab}$



$V_{ab} = V_1 - V_2$

for m = 1

$V_{ab} = V_s$

$\therefore$ **Vo = Vs**

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Instrumentation Amplifier:

$I = \frac{V_1 - V_2}{aR}$

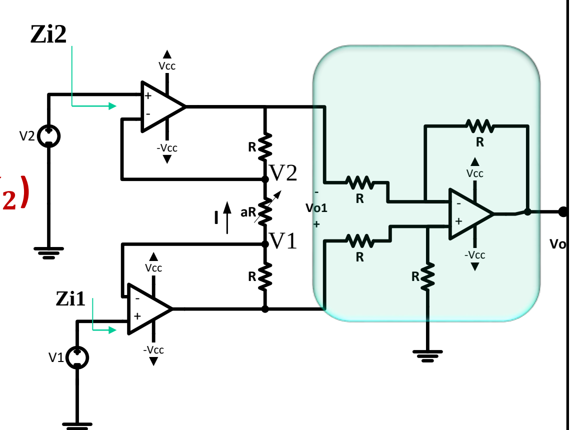
$V_{o1} = (R + aR + R)I$

$V_{o1} = (1 + \frac{2}{a})\ (V_1 - V_2)$

$V_o = V_{o1} = (1 + \frac{2}{a})\ (V_1 - V_2)$

$Z_{i1} = \infty$

$Z_{i2} = \infty$



To change the gain → change a

a << 1

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Measuring small resistance change

$E_1 = \frac{R_1}{R1+R1}$ E = $\frac{E}{2}$

$E_2 = \frac{R}{R+R+\Delta R}$ E = $\frac{R}{2R+\Delta R}$ E

$V_o = (1+\frac{2}{a})\,(E_1 - E_2)$.

$E_1 - E_2 = \frac{E}{2}\left(\frac{\Delta R}{2R+\Delta R}\right)$

ΔR is very small

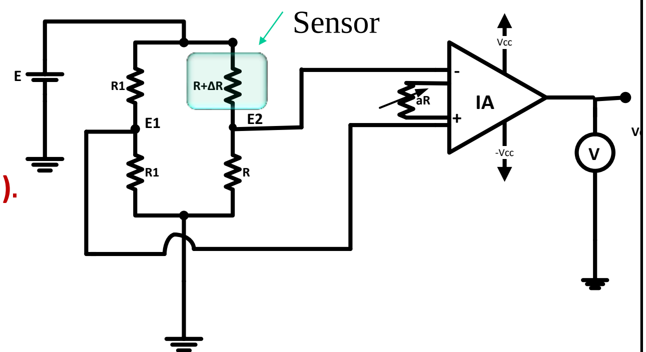
$E_1 - E_2 = \frac{E}{2}\frac{\Delta R}{2R}$

$V_o = (1+\frac{2}{a})\,(E_1 - E_2)$.

Let $(1+\frac{2}{a}) = 400$

$V_o = (400)(\frac{\Delta R}{4R})E$

$V_o = 100\ E\,(\frac{\Delta R}{R})$



Measuring small resistance change

$V_o = 100\ E\,(\frac{\Delta R}{R})$

If R = 10K

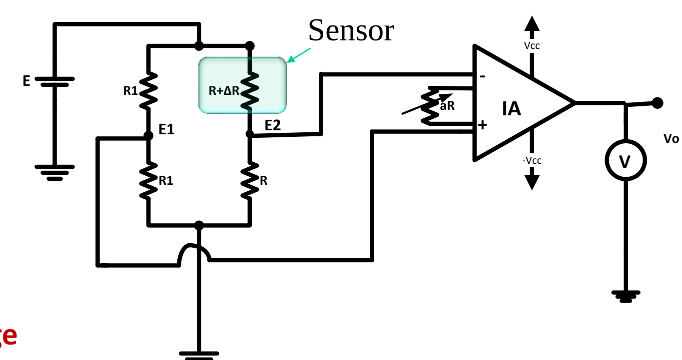
ΔR = 0.1K

E = 1V

$\frac{\Delta R}{R}$ = 1% change

$V_o = 1V$

∴ 1V per 1% change in resistance



If Vo = 2V → ΔR = 0.2K

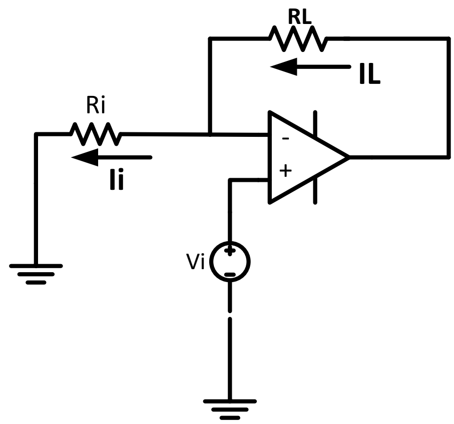
If Vo = 0.1V → ΔR = 0.01K

If Vo = 0.01V → ΔR = 0.001K

If Vo = 1mV → ΔR = 0.0001K

Voltage to current Converter

a) Floating load



Since V(+) = Vi

∴ V(-) = Vi

$$I_i = \frac{V_i}{R_i}$$

$$I_L = I_i = \frac{V_i}{R_i}$$

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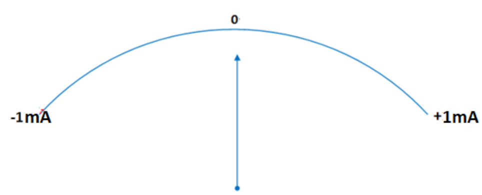
High-Resistance DC Voltmeter



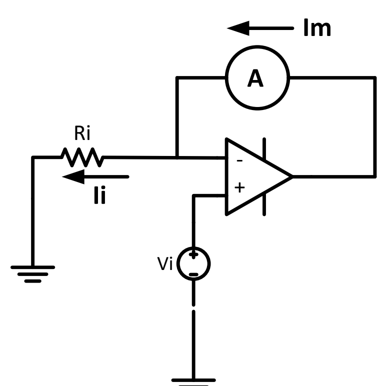
$$I_m = I_i = \frac{V_i}{R_i}$$

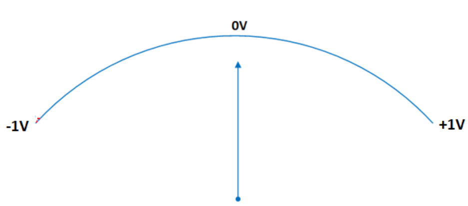
If V_i =+1 → I_m = +1mA

R_i = 1k

If V_i =-1 v → I_m = -1mA

R_i = 1k





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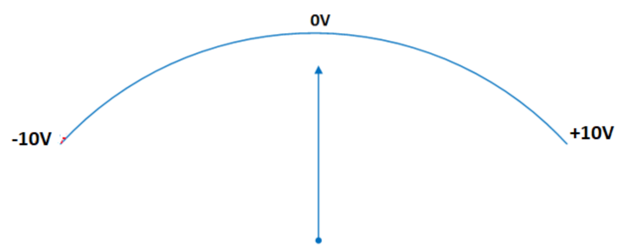
If V_i =+10 v → I_m = +1mA

R_i = 10k

If V_i =-10 v → I_m = -1mA

R_i = 10k



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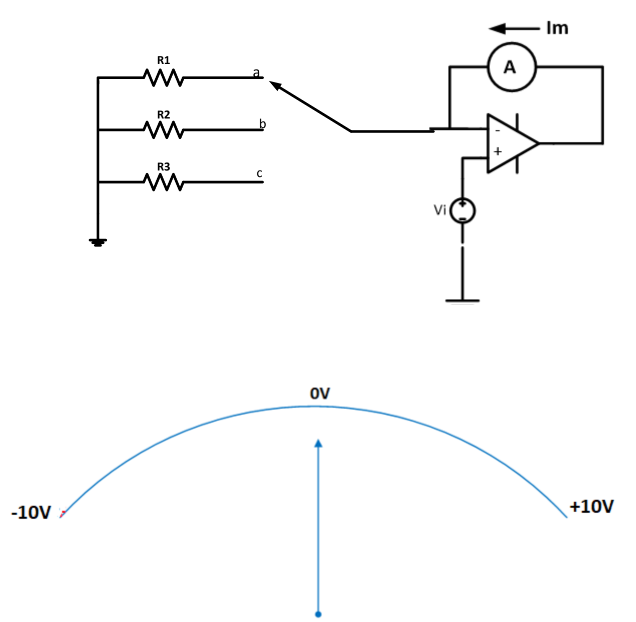

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Voltage to current Converter

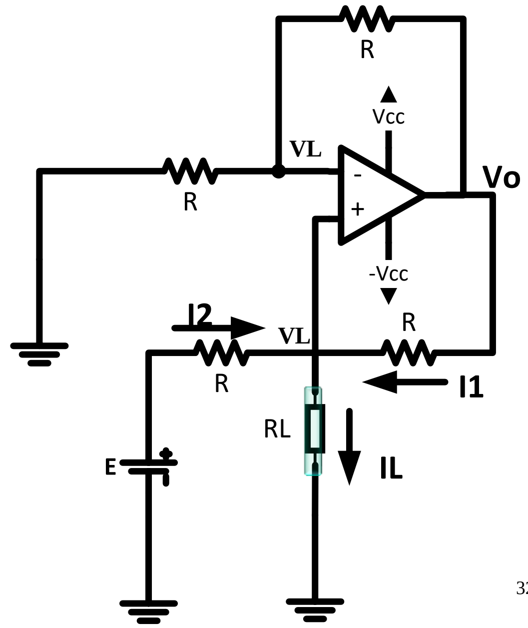
b) Grounded load

$V_L = V(-) = \frac{1}{2} V_o$

$I_L = I_1 + I_2$

$I_L = \frac{V_o - V_L}{R} + \frac{E - V_L}{R}$

$\therefore I_L = \frac{E}{R}$



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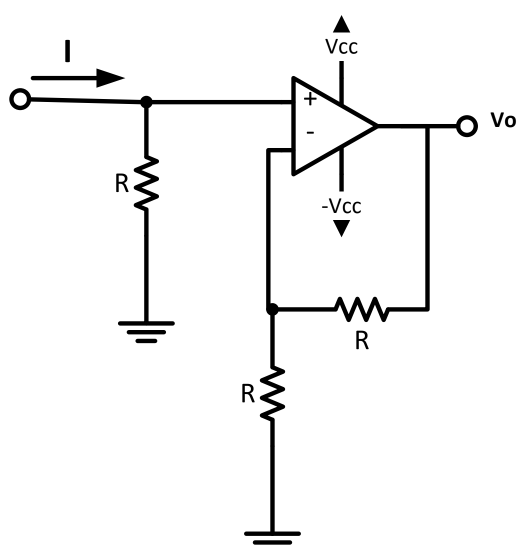
Current to Voltage Converter

$V(+) = R\,I$

$V_o = (1 + \frac{R}{R})\ V(+)$

$V_o = (1 + \frac{R}{R})\ R\,I$

$V_o = K\,I$



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Integrator

- So far, the input and feedback components have been resistors. If the feedback component used is a capacitor,, the resulting connection is called an *integrator.*
- Recall that virtual ground means that we can consider the voltage at the junction of R and X_c to be ground (since $V_+ = 0$ V) but that no current goes into ground at that point.

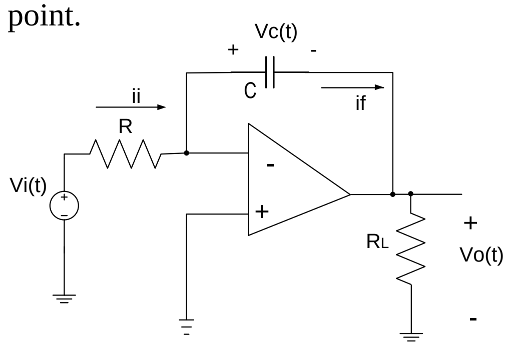
$$i_{i(t)} = i_{f(t)} = \frac{V_{i(t)}}{R}$$

$$Vc(t) = \frac{1}{C}\int_0^t i_f(t)dt$$

$$V_{o(t)} = -Vc(t)$$

$$V_{o(t)} = -\frac{1}{C}\int_0^t \frac{V_i(t)}{R_i}dt$$

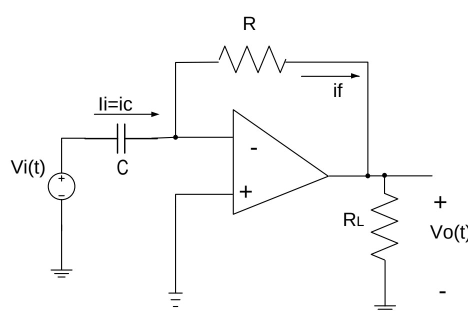
$$= -\frac{1}{RC}\int_0^t V_i(t)dt$$



Differentiator

A differentiator ,while not as useful as the circuit forms covered above, the differentiator does provide a useful operation, the resulting relation for the circuit being

$$\mathrm{i}_{\mathrm{i}(t)} = i_{f(t)} = i_{C(t)} = C\frac{dV_i(t)}{dt}$$

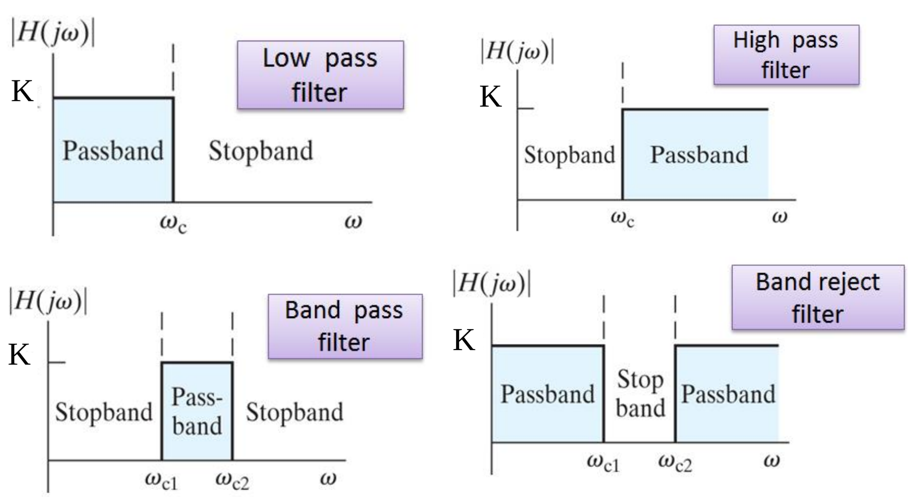


Filters are circuits pass signals of certain frequencies and block or attenuate signals of other frequencies

Active filters

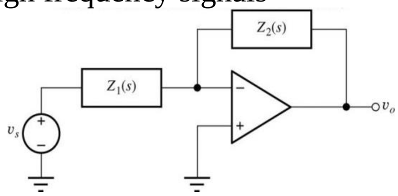
- Based on circuits with op amps, which are active devices, since they require an external power supply (± V_{CC}).
- Eliminate all of the disadvantages of passive filters:
  - Can create a pass band gain > 1;
  - Can add loads without changing the filter characteristics;
  - All four types of filters can be created using op amps, resistors, and capacitors – no inductors;
  - Can cascade simple (first- and second-order) filters to create higher order filters that are more nearly ideal.

Ideal Active Filter Classification



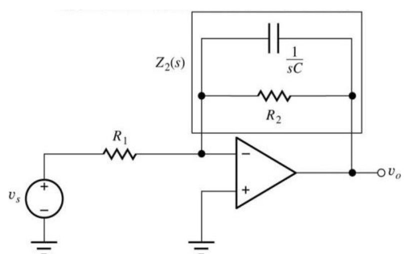
The Active Low-pass Filter

Low pass filters are used to pass low-frequency signals and attenuate high frequency signals



$$A_{v(jw)} = \frac{\tilde{v}_o(j\omega)}{\tilde{v}_s(j\omega)} = -\frac{Z_2(j\omega)}{Z_1(j\omega)}$$

$$Z_2(j\omega) = \frac{R_2 \frac{1}{j\omega C}}{R_2 + \frac{1}{j\omega C}} = \frac{R_2}{j\omega C R_2 + 1} \qquad Z_1(j\omega) = R_1$$



$$A_{v(jw)} = -\frac{R_2}{R_1}\frac{1}{(1 + j\omega C R_2)}$$

$$= \frac{-K}{\left(1 + \frac{j\omega}{\omega_c}\right)}$$

$$K = \frac{R_2}{R_1}$$

& cut-off frequency: $\omega_c = 2\pi f_c = \frac{1}{R_2 C} \quad \therefore f_c = \frac{1}{2\pi R_2 C}$

Frequency Response (Bode Plot)

Magnitude Plot (Magnitude in decibels vs log of frequency)

$\log(AB) = \log A + \log B$

$\log(\frac{N}{D}) = \log N - \log D$

$$A_{dB} = 20\log|H(j\omega)|$$

$$|H(j\omega)| = |A_v(j\omega)|$$

$$|A_v(j\omega)| = \frac{K}{\sqrt{1 + \left(\frac{\omega}{\omega_c}\right)^2}}$$

at $\omega = 0.1\omega_c$

$$20\log\frac{1}{\sqrt{1 + \left(\frac{0.1\omega_c}{\omega_c}\right)^2}}$$

$$= 20\log\frac{1}{\sqrt{1 + 0.01}}$$

$$\cong 20\log 1 = 0dB$$

at $\omega = \omega_c$

$$20\log\frac{1}{\left|\sqrt{1 + \left(\frac{\omega_c}{\omega_c}\right)^2}\right|}$$

$$= 20\log\frac{1}{|\sqrt{1+1}|}$$

$$= 20\log|0.707| = -3dB$$

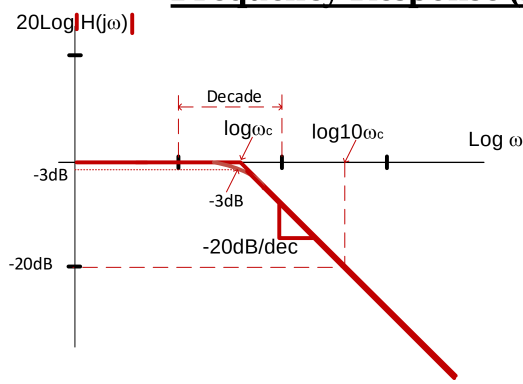
at $\omega = 10\omega_c$

$$20\log\frac{1}{\left|\sqrt{1 + \left(\frac{10\omega_c}{\omega_c}\right)^2}\right|}$$

$$= 20\log\frac{1}{|\sqrt{1+100}|}$$

$$= 20\log|0.1| = -20dB$$

Frequency Response (Bode Plot)



Summary

at $\omega = 0.1\omega_c$

$= 20\log 1 = 0dB$

at $\omega = \omega_c$

$= 20\log 0.707 = -3dB$

at $\omega = 10\omega_c$

$= 20\log 0.1 = -20dB$

at $\omega = 100\omega_c$

$= 20\log 0.01 = -40dB$

- At frequencies below ω_c, the amplifier is an inverting amplifier with gain set by the ratio of resistors R_2 and R_1.
- At frequencies above ω_c, the amplifier response "rolls off" at -20dB/decade.
- Notice that cutoff frequency and gain can be independently set.

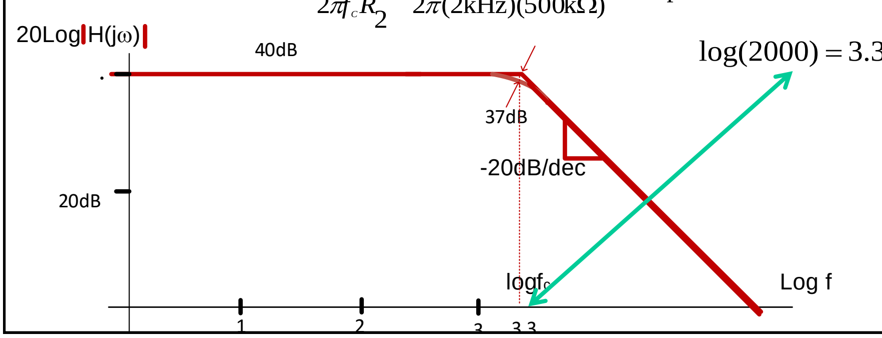
Active Low-pass Filter: Example

- **Problem**: Design an active low-pass filter
- **Given Data**: A_v= 40 dB, R_{in}= 5 kΩ, f_c = 2 kHz
- **Assumptions:** Ideal op amp, specified gain represents the desired low-frequency gain.
- **Analysis**: $|A_v| = 10^{40dB/20dB} = 100$

Input resistance is controlled by R_1 and voltage gain is set by R_2 / R_1.
The cutoff frequency is then set by C.

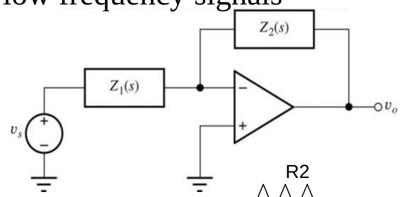
$$R_1 = R_{in} = 5k\Omega \quad \text{and} \quad |A_v| = \frac{R_2}{R_1} \Rightarrow R_2 = 100R_1 = 500k\Omega$$

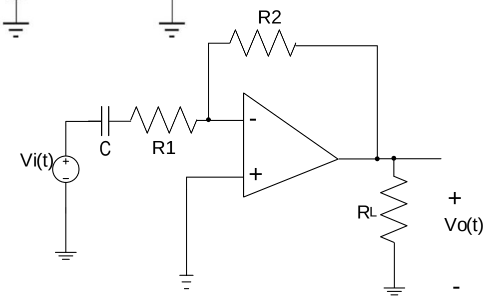
$$C = \frac{1}{2\pi f_c R_2} = \frac{1}{2\pi(2kHz)(500k\Omega)} = 159pF$$



The Active High-pass Filter

High pass filters are used to pass high-frequency signals and attenuate low frequency signals





$$A_{v(jw)} = \frac{\tilde{v}_o(j\omega)}{\tilde{v}_s(j\omega)} = -\frac{Z_2(j\omega)}{Z_1(j\omega)}$$

$$Z_1(j\omega) = R_1 + \frac{1}{j\omega C} \qquad Z_2(j\omega) = R_2$$

$$A_{v(jw)} = -\frac{R_2}{(R_1 + \frac{1}{j\omega C})}$$

$$A_{v(jw)} = -\frac{R_2/R_1}{(1 + \frac{1}{j\omega R_1 C})} = \frac{-K}{\left(1 + \frac{\omega_c}{j\omega}\right)}$$

$$K = \frac{R_2}{R_1} \text{ high frequency gain}$$

$$\omega_c = 2\pi f_c = \frac{1}{R_1 C} \quad \therefore f_c = \frac{1}{2\pi R_1 C}$$

Frequency Response (Bode Plot)

Magnitude Plot
(Magnitude in decibels vs log of frequency)

$A_{dB} = 20\log|H(j\omega)|$

$|H(j\omega)| = |A_v(j\omega)|$

$$= \frac{K}{\sqrt{1 + \left(\frac{\omega_c}{\omega}\right)^2}}$$

at $\omega = 0.1\omega_c$

$$20\log\frac{1}{\sqrt{1 + \left(\frac{\omega_c}{0.1\omega_c}\right)^2}} = 20\log\frac{1}{\sqrt{1 + 100}}$$

$\cong 20\log 0.1 = -20dB$

at $\omega = \omega_c$

$$20\log\frac{1}{\left|\sqrt{1 + \left(\frac{\omega_c}{\omega_c}\right)^2}\right|}$$

$$= 20\log\frac{1}{|\sqrt{1+1}|}$$

$= 20\log|0.707| = -3dB$

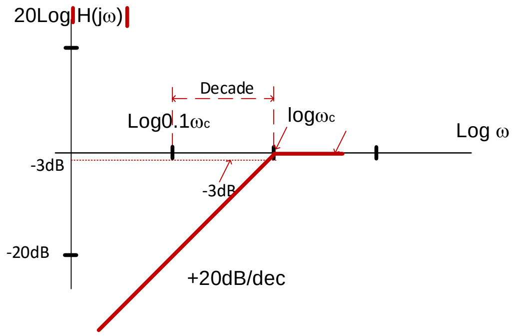
at $\omega = 0.01\omega_c$

$$20\log\frac{1}{\left|\sqrt{1 + \left(\frac{\omega_c}{0.01\omega_c}\right)^2}\right|}$$

$$= 20\log\frac{1}{|\sqrt{1 + 10000}|}$$

$= 20\log 0.01 = -40dB$

Frequency Response (Bode Plot)



Summary

at $\omega = 0.1\omega_c$

$= 20\log 0.1 = -20dB$

at $\omega = \omega_c$

$= 20\log 0.707 = -3dB$

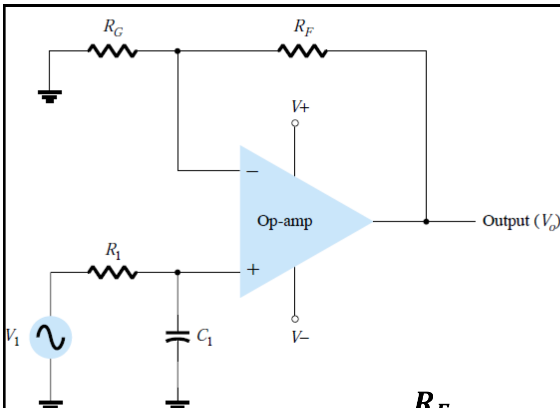
at $\omega = 0.01\omega_c$

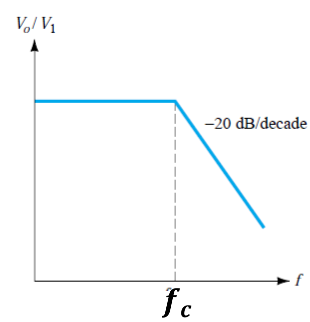
$= 20\log 0.01 = -40dB$

at $\omega = 0$

$= 20\log 1 = 0dB$

- At frequencies above ω_c, the amplifier is an inverting amplifier with gain set by the ratio of resistors R_2 and R_1.
- At frequencies below ω_c, the amplifier response "rolls off" at -20dB/decade.
- Notice that cutoff frequency and gain

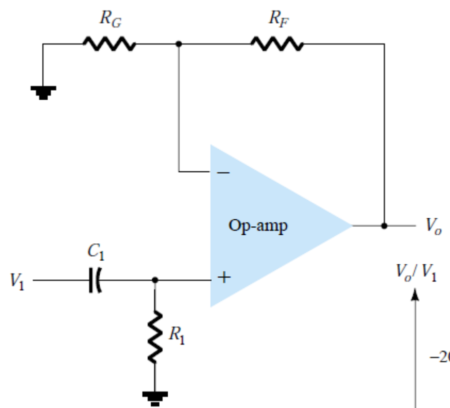




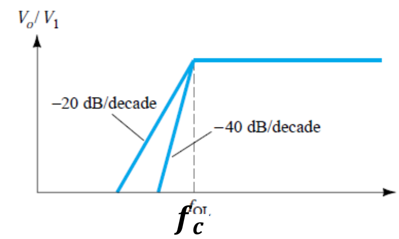
$$A_v = 1 + \frac{R_F}{R_G}$$

$$f_c = \frac{1}{2\pi R_1 C1}$$

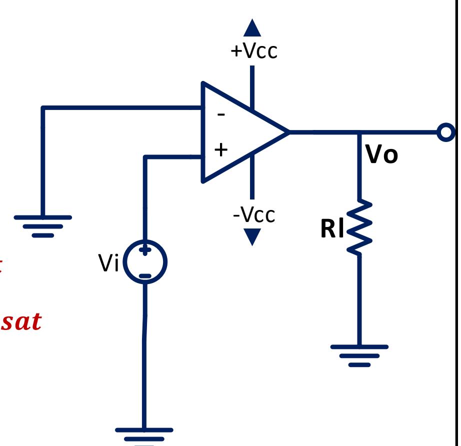
High-Pass Active Filter



$$f_c = \frac{1}{2\pi R_1 C1}$$



Comparator : Zero –Level detector



Exact analysis:

When $vd > 65\mu V$; $V_O = +V_{sat}$

When $vd < -65\mu V$; $V_O = -V_{sat}$

Approximate analysis

When $vd > 0V$; $V_O = +V_{sat}$

When $vd < 0V$; $V_O = -V_{sat}$

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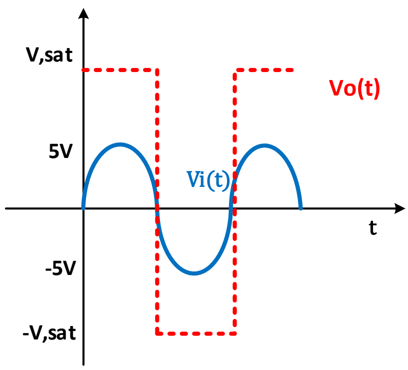
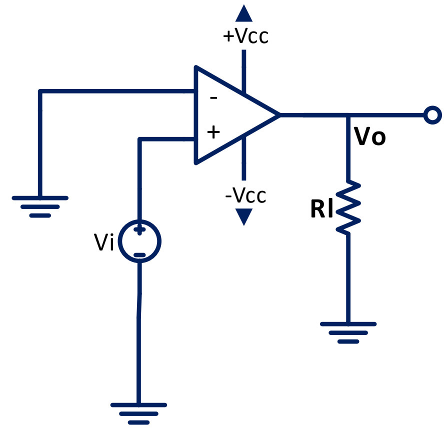
Comparator : Zero –Level detector

V_i (t) = $5 sin\, \omega t$ v

$\pm$ V_{sat} = ± 13 v





When $vd > 0$V ; V_O= + V_{sat}

When $vd < 0$V ; V_O= - V_{sat}

∴ When $V_i > 0$V ; V_O = + V_{sat}

∴ When $V_i < 0$V ; V_O = - V_{sat}

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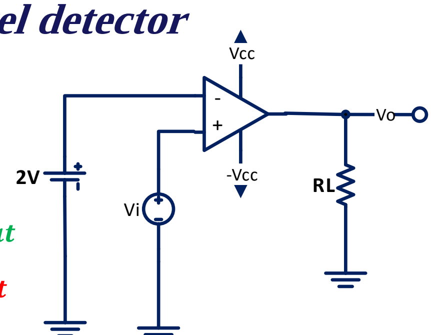
Non Zero –Level detector

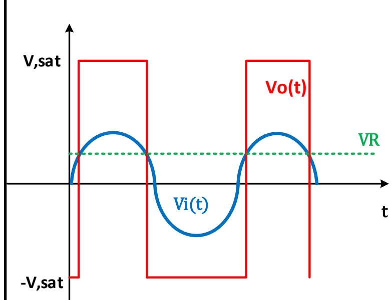


V_i (t) = $5 sin\, \omega t$ v

$\pm$ V_{sat} = ± 13 v

When $V_i > 2$V ; V_O = + V_{sat}

When $V_i < 2$V ; V_O = - V_{sat}



When $vd > 0$V ; V_O= + V_{sat}

When $vd < 0$V ; V_O= - V_{sat}

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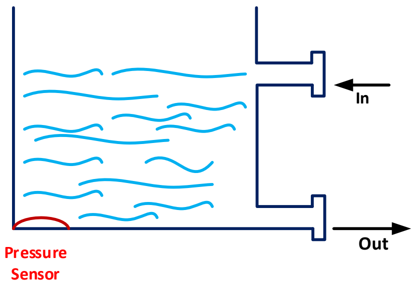
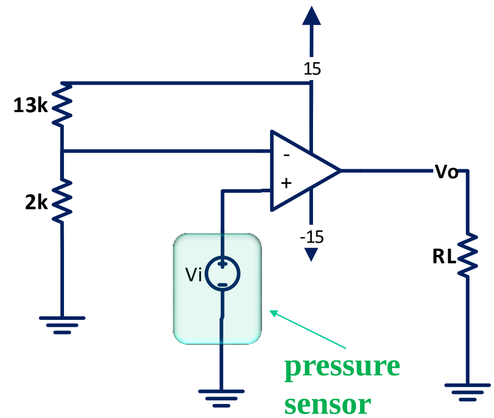
Practical Non Zero –Level detector

Application





The pressure sensor generates a voltage proportional to the water level in the tank

V(-) = 2V

When water level reaches the maximum allowable lever

➡ Vi = 2V

When V_i >2V ; V_O=+ V_{sat}

When V_i <2V ; V_O= - V_{sat}

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Voltage–Level detector with LEDs:

When V_i >2V ; V_O = + V_{sat}

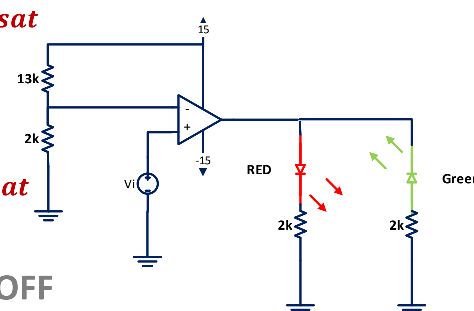
∴ Red LED is ON

∴ green LED is OFF

When V_i < 2V ; V_O = - V_{sat}

∴ green LED is ON

∴ Red LED is OFF



When V_i = 2V ; V_O = 0

∴ green LED and the Red LED are OFF

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Over Temperature sensing Circuit

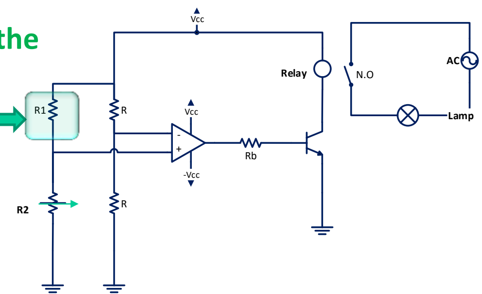
R1 ↑ as T ↓

R1 = Resistance of the thermistor.

R2 is set equal to the resistance of the thermistor at the critical temp.

R = 100k

This is the thermistor



1)At Normal temperature ($T < T_C$)

$R_1 > R_2$

$V(+) = \frac{R_2}{R_1 + R_2} V_{CC} < \frac{1}{2} V_{CC}$

$V(-) = \frac{1}{2} V_{CC}$

∴ $V(-) > V(+)$, ∴ $V_{op} = -V_{sat}$

∴ transistor is cut off ; $I_C = 0$

∴ Relay is denergized

∴ switch is open

∴ Lamp is OFF

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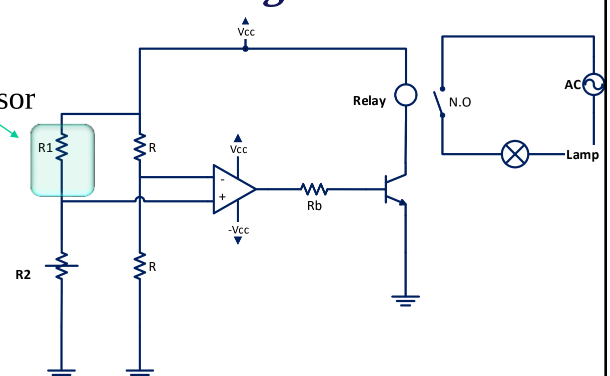
Over Temperature sensing Circuit

Sensor



2)When $T = T_C$

$R_1 = R_2$

$V(+) = V(-) = \frac{1}{2} V_{cc}$

∴ $V_{op} = 0$

∴ transistor is in cut off ;

$I_C = 0$

∴ Relay is denergized

∴ switch is open

∴ Lamp is OFF

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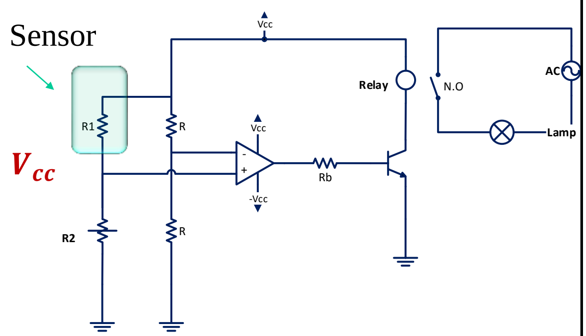
Over Temperature sensing Circuit

3- When $T > T_C$

$R_1 < R_2$



$V(+) = \frac{R_2}{R_1 + R_2} V_{cc} > \frac{1}{2} V_{cc}$

$V(-) = \frac{1}{2} V_{cc}$

$\therefore$ V(+) > V(-)

$\therefore$ transistor is conducting

$\therefore$ V_{op} = + Vsat

$\therefore$ Relay is energized

$\therefore$ Lamp is on

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Schmitt Trigger Comparator

1.Assume $V_O = +V_{sat}$

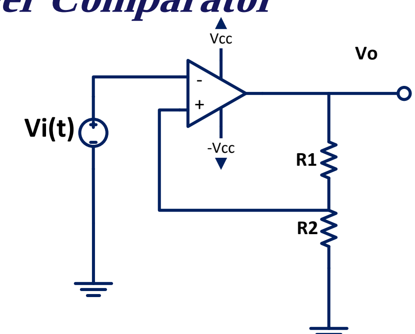
V(-) = Vi

$V(+) = \frac{R_2}{R_1+R_2}(+V_{sat}) = V_{UT}$

$vd > 0$

$\frac{R_2}{R_1 + R_2}(+V_{sat}) - V_i > 0$

$\therefore V_i < \frac{R_2}{R_1 + R_2}(+V_{sat})$



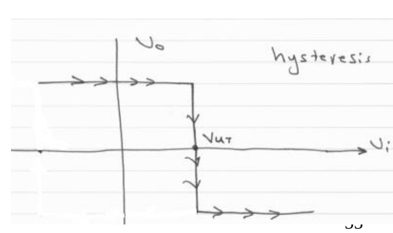
Inverting Schmitt trigger comparator

$\therefore$ as long as $V_i < \frac{R_2}{R_1 + R_2}(+V_{sat})$

$V_O = +V_{sat}$

But when $V_i > \frac{R_2}{R_1 + R_2}(+V_{sat})$

V_O switch to $(-V_{sat})$



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Schmitt Trigger Comparator

2. Assume $V_O = -V_{sat}$

V(-) = Vi

$V(+) = \frac{R_2}{R_1+R_2}(-V_{sat}) = V_{LT}$

$vd < 0$

$\frac{R_2}{R_1+R_2}(-V_{sat}) - V_i < 0$

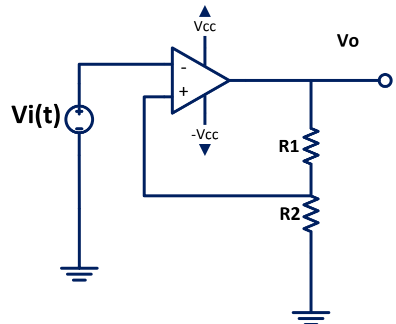
$\therefore V_i > \frac{R_2}{R_1+R_2}(-V_{sat})$

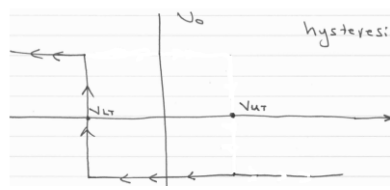
$\therefore$ as long as $V_i > \frac{R_2}{R_1+R_2}(-V_{sat})$

$V_O = -V_{sat}$

But when $V_i < \frac{R_2}{R_1+R_2}(-V_{sat})$

V_O switch to $(+V_{sat})$





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Schmitt Trigger Comparator

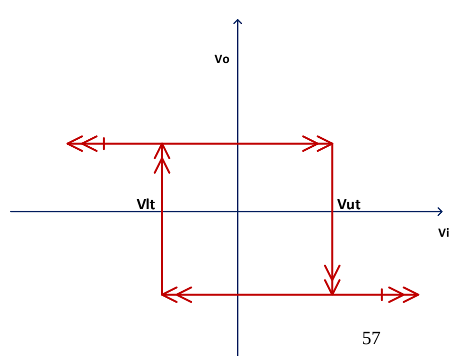
Hysteresis voltage $\equiv V_H = V_{UT} - V_{LT}$

$V_{UT} \equiv$ *Upper Threshold voltage*

$V_{UT} = \frac{R_2}{R_1+R_2}(+V_{sat})$

$V_{LT} \equiv$ *Lower Threshold voltage*

$V_{LT} = \frac{R_2}{R_1+R_2}(-V_{sat})$



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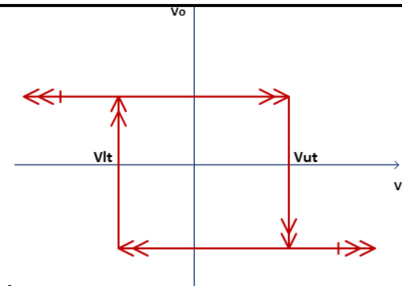
Schmitt Trigger Comparator



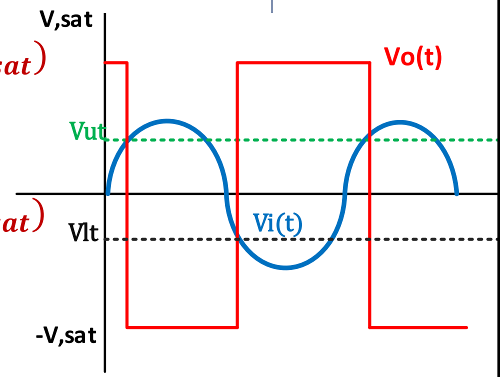
Signal Wave form

when $V_i < \frac{R_2}{R_1 + R_2}(-V_{sat})$

V_O **switch to** $(+V_{sat})$

when $V_i > \frac{R_2}{R_1 + R_2}(+V_{sat})$

V_O **switch to** $(-V_{sat})$



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Room Thermostat

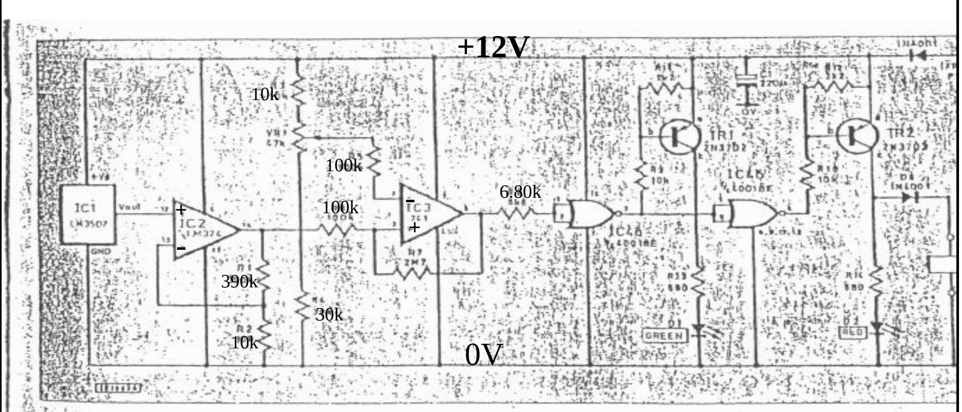
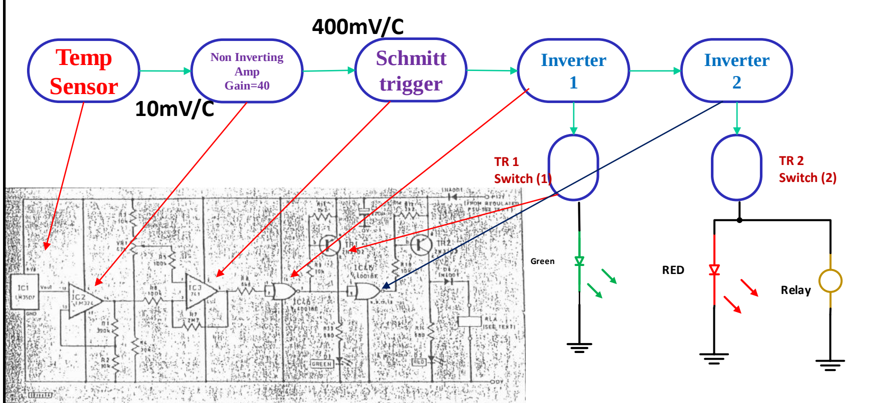


Fig. 2. Complete circuit diagram for the Room Thermostat. The connections to the "relay" are for the low voltag only.

IC1 = LM35DZ			
IC2 = LM324	R1 = 390K	R5 = 100K	R9 = 10K
IC3 = MA741	R2 = 10K	R6 = 100K	R10 = 10K
IC4 = 4001B	R3 = 10K	R7 = 2.7MΩ	R11 = 2.2K
TR1 = 2N3702	VR1 = 47K	R8 = 6.8K	R12 = 2.2K
TR2 = 2N3702	R4 = 30K		R13 = 0.68K

Schmitt Trigger Comparator

Room Thermostat



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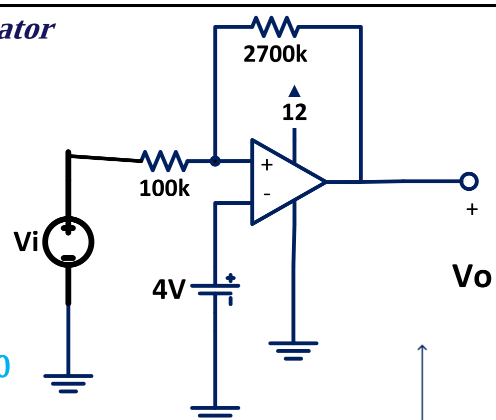
Schmitt Trigger Comparator

Room Thermostat



$V_i = 400mV/C$

1.Let $V_O = +V_{sat} = +10$

$vd > 0$

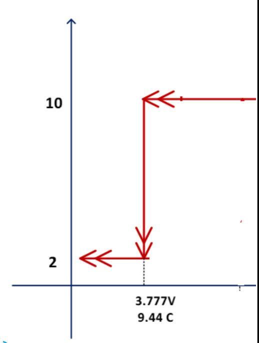
V(-) = 4v

$$V(+) = \frac{100K}{100K+2700K}(+V_{sat}) + \frac{2700K}{2700K+100K} V_i$$

For $vd > 0$; $V_i > 3.777V$

$\therefore$ As long as $V_i > 3.777V$; $V_O = +V_{sat}$

But when $V_i < 3.777V$; V_O switch to $(-V_{sat})$



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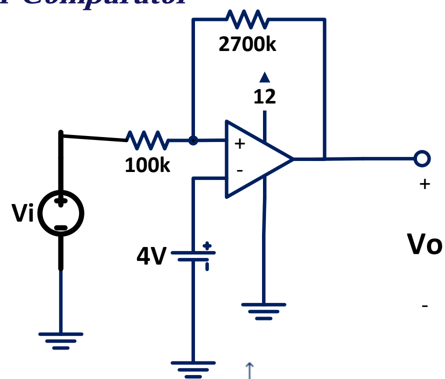
Schmitt Trigger Comparator



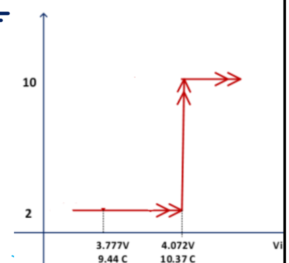
2. Let $V_O = -V_{sat} = +2$

$vd < 0$

$V(-) = 4V$

$$V(+) = \frac{100K}{100K+2700K}(-V_{sat}) + \frac{2700K}{2700K+100K} V_i$$

For $vd<0$; $V_i <$ 4.072V



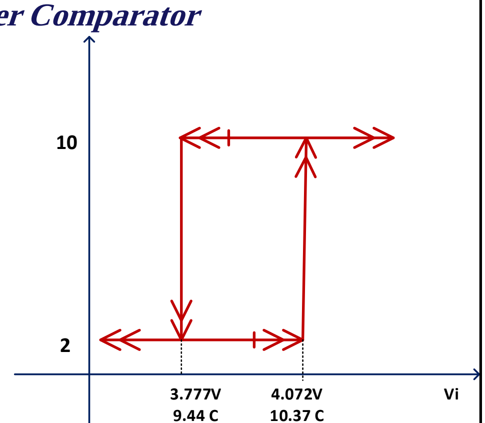
∴ As long as $V_i <$ 4.072V; $V_O = -V_{sat}$

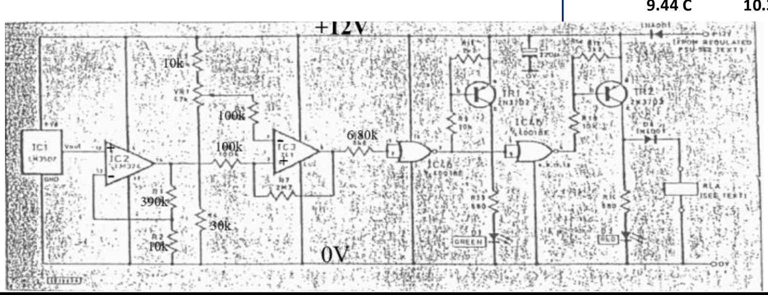
But when $V_i >$ 4.072V; V_O switch to $(+V_{sat})$

Schmitt Trigger Comparator

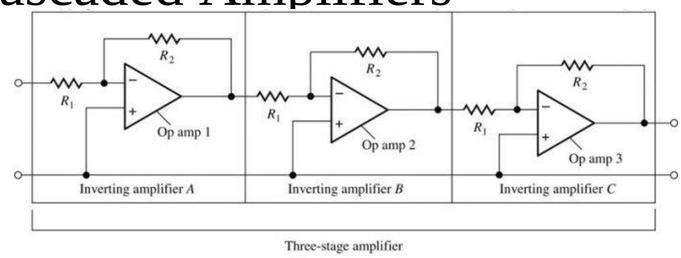
1)When T > 10.37 C , Vo = +Vsat
Transistor (2) is Off , Relay is denergized and Heater is Off.

2)Then T < 9.44 C , Vo = -Vsat
Transistor (2) is On , Relay is energized
and Heater is on .

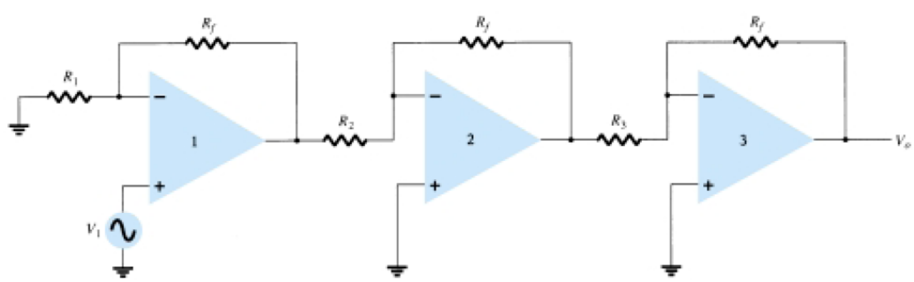




Cascaded Amplifiers



- Connecting several amplifiers in cascade (output of one stage connected to the input of the next) can meet design specifications not met by a single amplifier.
- Each Amplifer stage is built using an op amp with parameters A, R_{id}, R_o, called open loop parameters, that describe the op amp with no external elements.
- A_v, R_{in}, R_{out} are closed loop parameters that can be used to describe each closed-loop op amp stage with its feedback network, as well as the overall composite (cascaded) amplifier.
- The gain of each stage can be calculated separately, then the total gain is found by multiplying the resulting gains



$$A = A_1 A_2 A_3$$

where $A_1 = 1 + R_f/R_1$, $A_2 = -R_f/R_2$, and $A_3 = -R_f/R_3$.