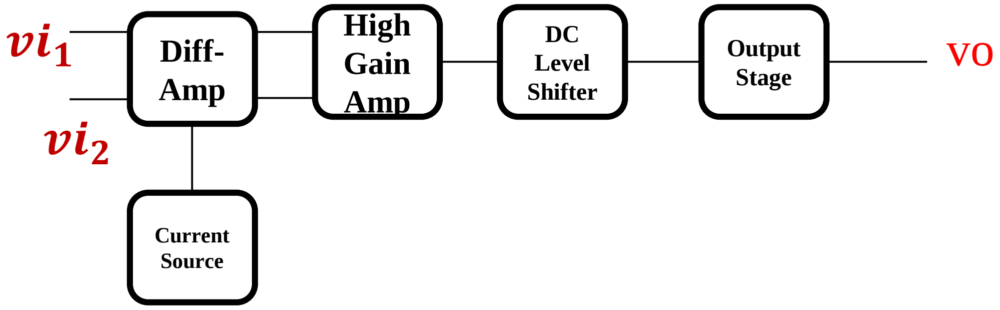
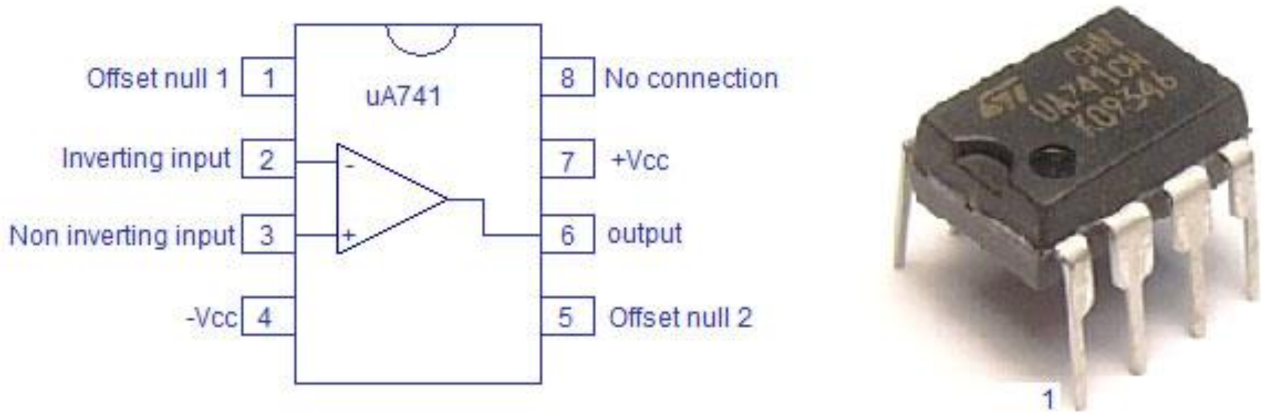
Operational Amplifiers

The Operational Amplifier

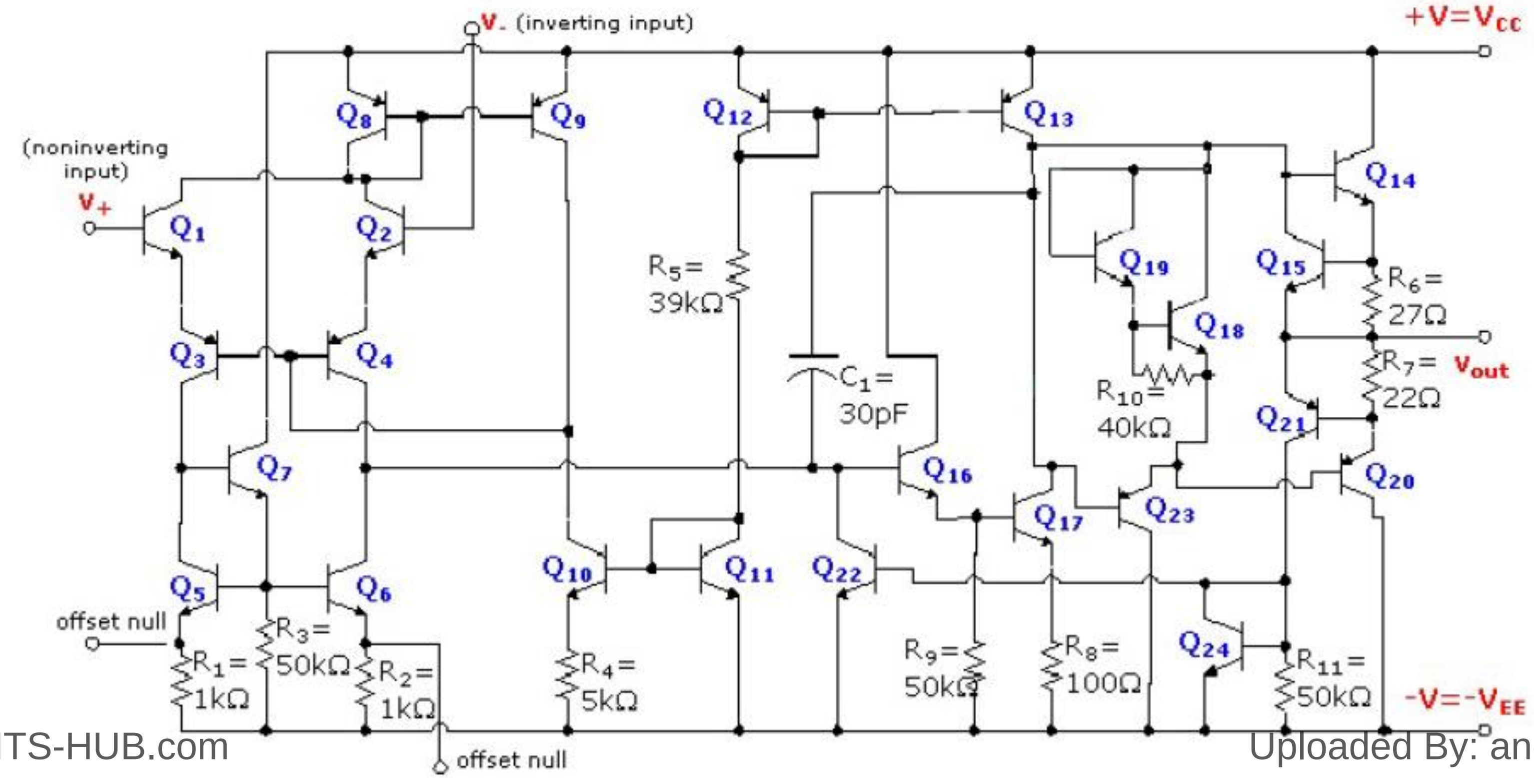
Very high voltage gain ; 200,000
Very High input impedance ; 10M ohm
Very small output impedance ; 75ohm
Designed to do mathematical operations such as addition , subtraction ….



Operational Amplifiers



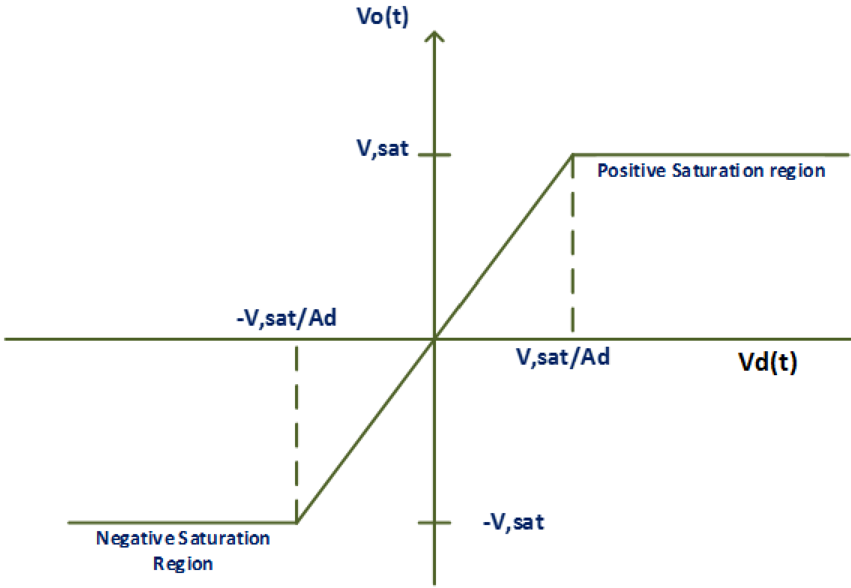
uA741 opamp Pinout and External appearance



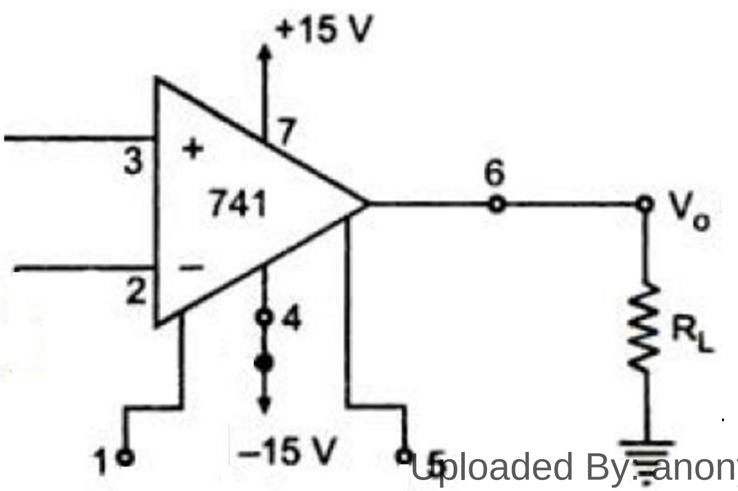
Operational Amplifier

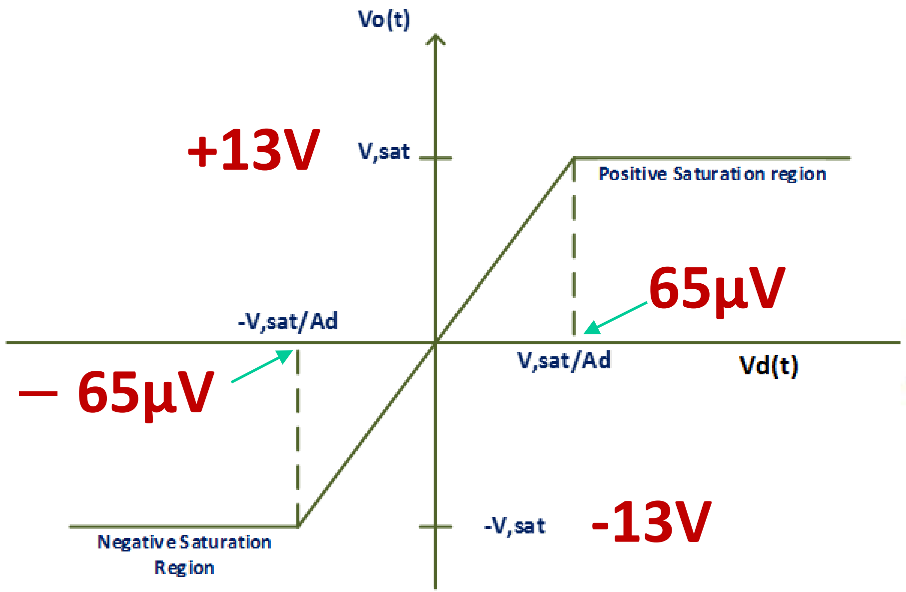
Transfer characteristic Curve:

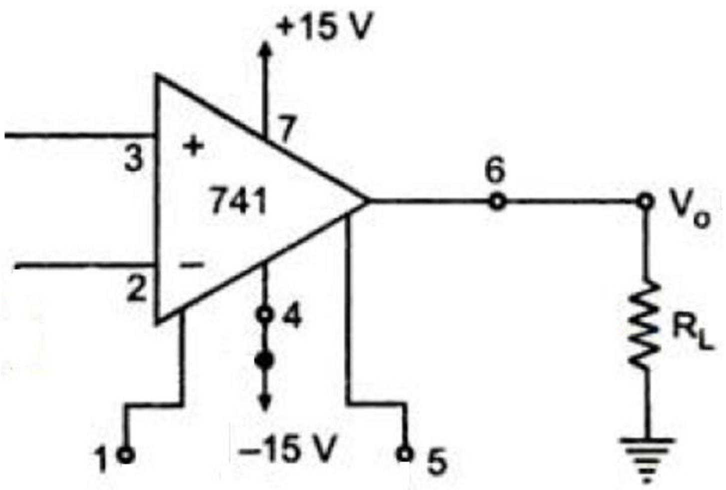
$$V_O = \begin{cases} +V_{sat} & vd > \frac{V_{sat}}{Ad} \\ Advd & \frac{V_{sat}}{Ad} > vd > -\frac{V_{sat}}{Ad} \\ -V_{sat} & vd < -\frac{V_{sat}}{Ad} \end{cases}$$



vd = V(+) - V(-)







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

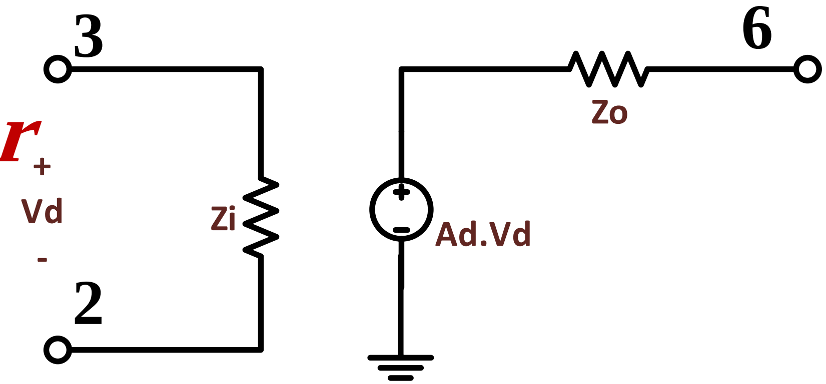
$\therefore \pm V_{sat}$=$\pm$13V

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

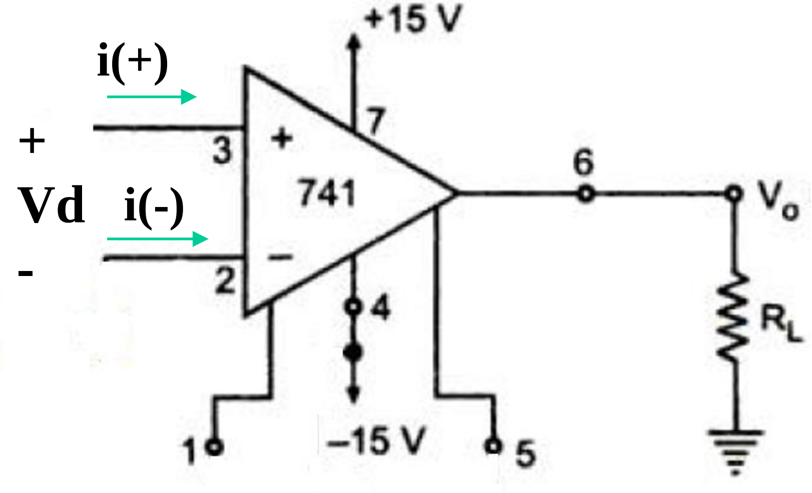
$\therefore$ If Vd $<$ − 65μV ; V_O = −13V

Op-amp Model in the Linear Region:

If the Op-Amp is in the Linear Region:



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



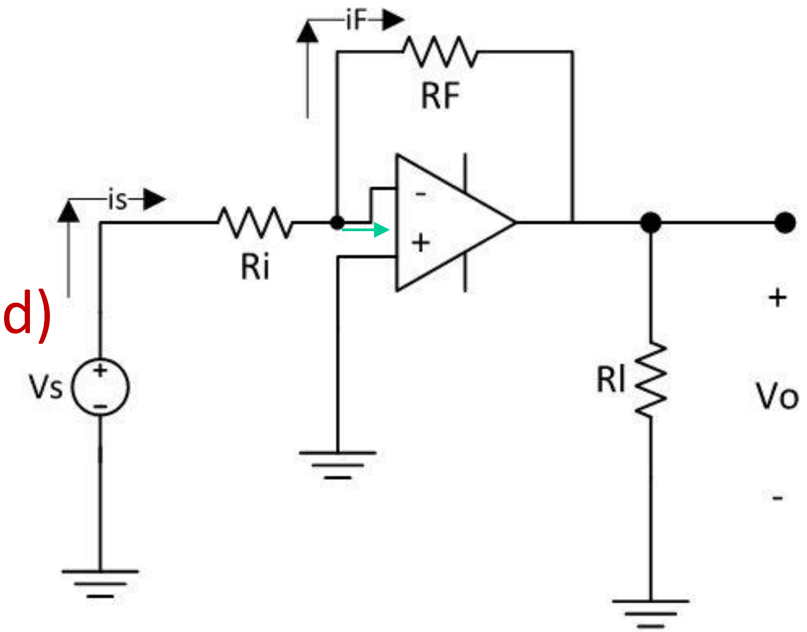
1) $V_d \cong 0$ ➡ $V(+) = V(-)$

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

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 ; ∴ $i_F = i_S$

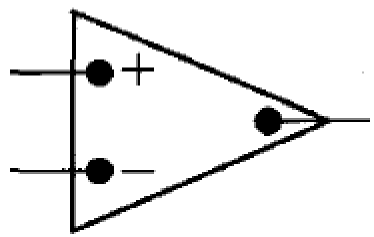
c) $V_O = -R_F i_F$

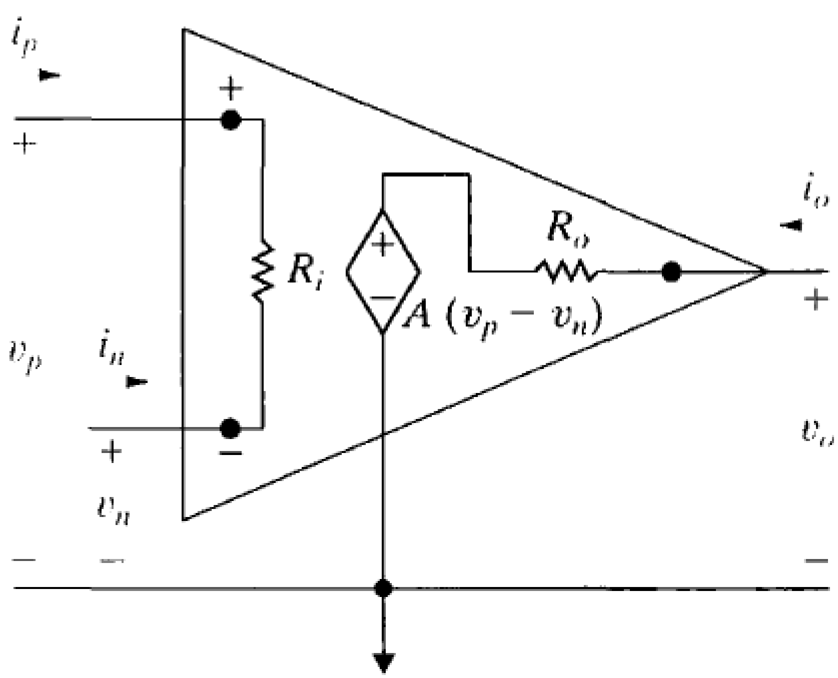
$V_O = -R_F i_S$

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

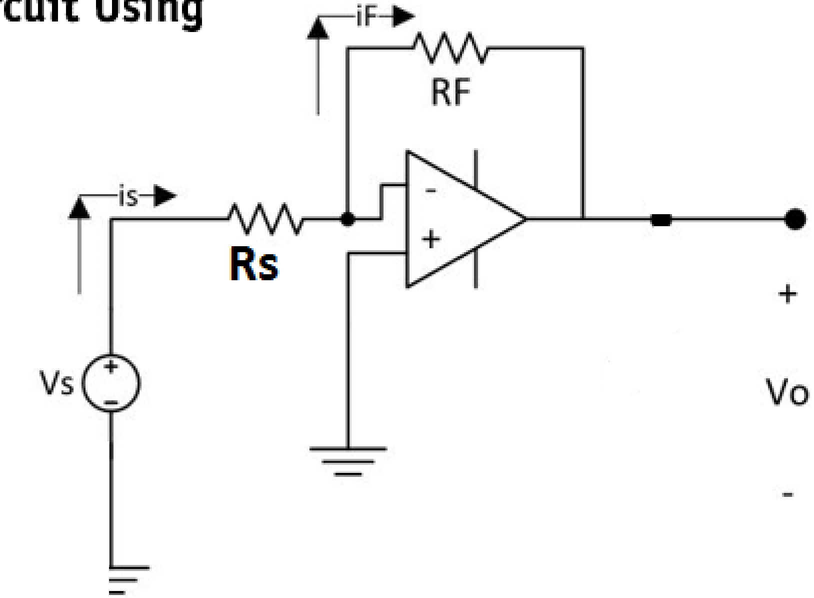
$$\therefore A_{CL} = -\frac{R_F}{R_i}$$

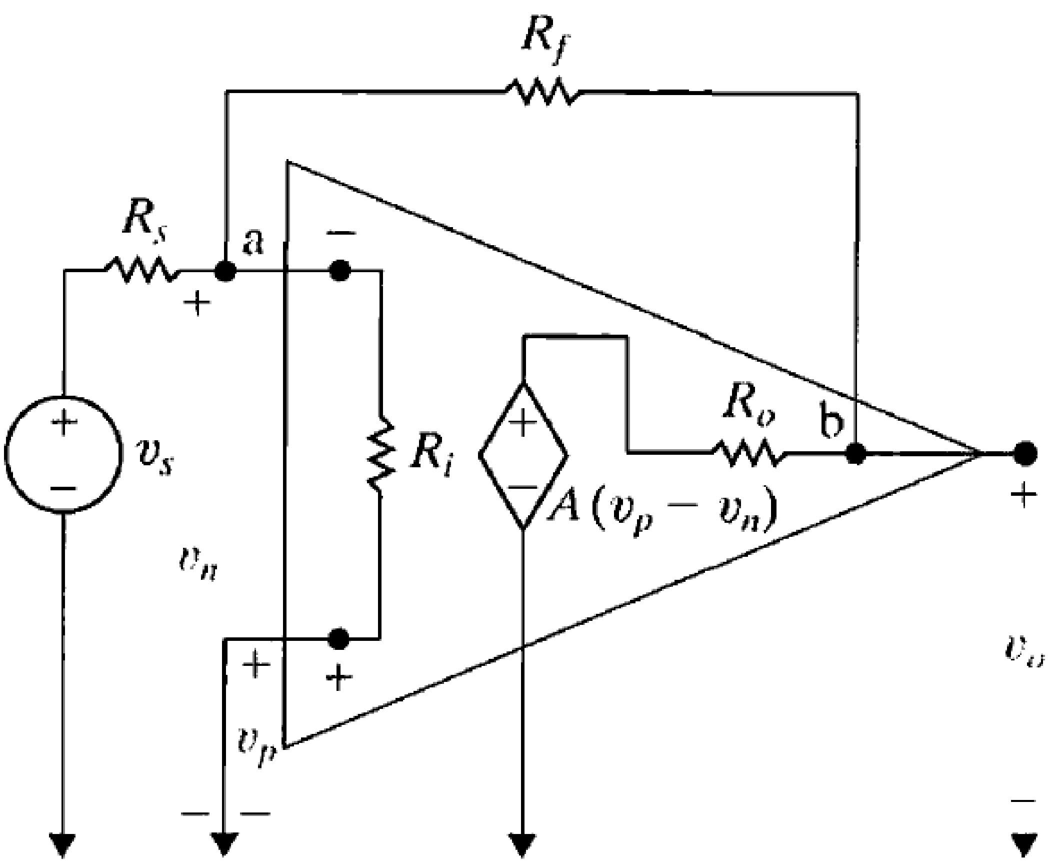
Analysis of an Inverting-Amplifier Circuit Using the More Realistic Op Amp Model



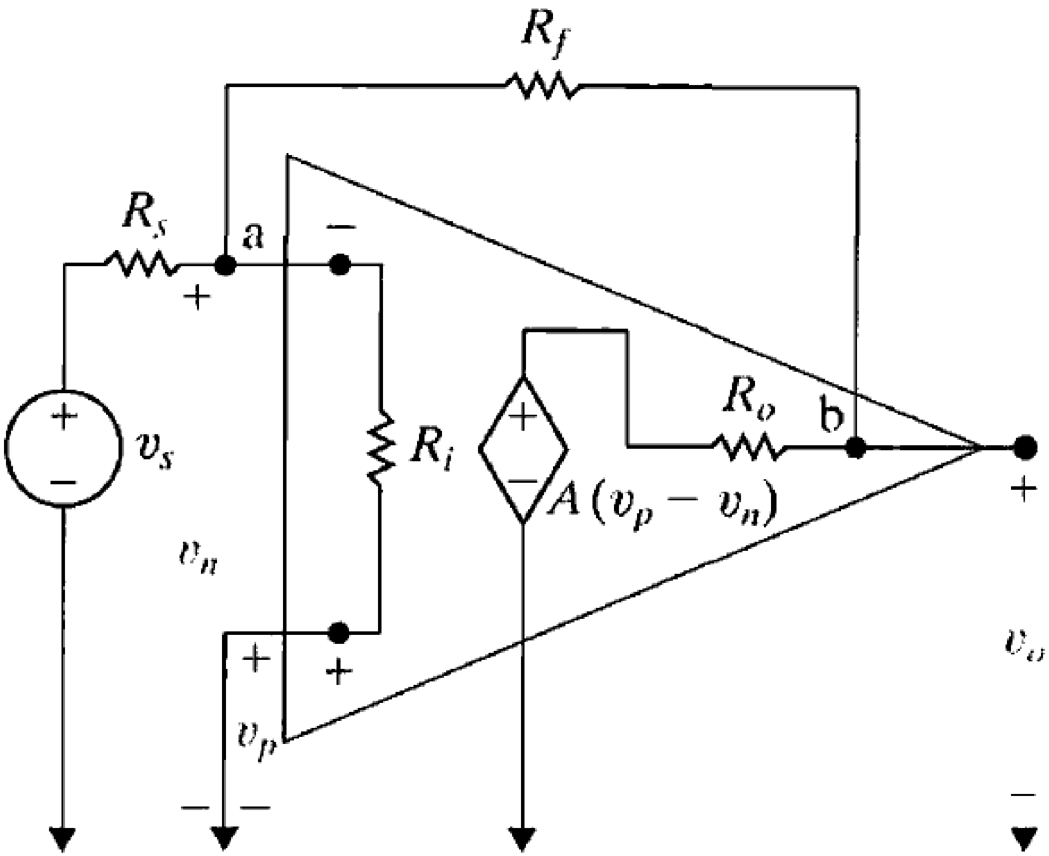


Analysis of an Inverting-Amplifier Circuit Using the More Realistic Op Amp Model





Analysis of an Inverting-Amplifier Circuit Using the More Realistic Op Amp Model



$$\text{node a:} \quad \frac{v_n - v_s}{R_s} + \frac{v_n}{R_i} + \frac{v_n - v_o}{R_f} = 0.$$

$$\text{node b:} \quad \frac{v_o - v_n}{R_f} + \frac{v_o - A(-v_n)}{R_o} = 0.$$

$$\left(\frac{1}{R_s} + \frac{1}{R_i} + \frac{1}{R_f}\right)v_n - \frac{1}{R_f}v_o = \frac{1}{R_s}v_s$$

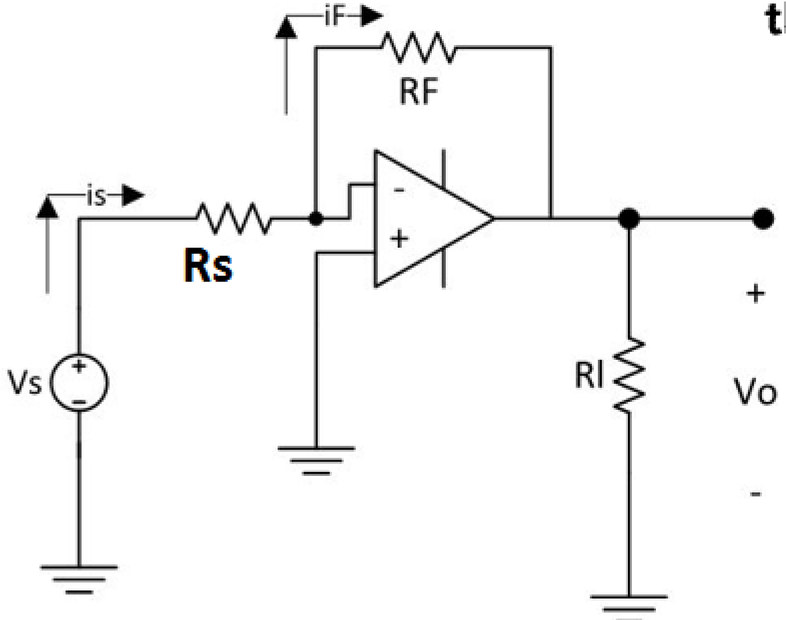
$$\left(\frac{A}{R_o} - \frac{1}{R_f}\right)v_n + \left(\frac{1}{R_f} + \frac{1}{R_o}\right)v_o = 0.$$

$$v_o = \frac{-A + (R_o/R_f)}{\frac{R_s}{R_f}\left(1 + A + \frac{R_o}{R_i}\right) + \left(\frac{R_s}{R_i} + 1\right) + \frac{R_o}{R_f}}v_s$$

$R_o \rightarrow 0$, $R_i \rightarrow \infty$, and $A \rightarrow \infty$

$$v_o = \frac{-R_f}{R_s}v_s$$

Analysis of an Inverting-Amplifier Circuit Using the More Realistic Op Amp Model



$$v_o = \frac{-A + (R_o/R_f)}{\frac{R_s}{R_f}\left(1 + A + \frac{R_o}{R_i} + \frac{R_o}{R_L}\right) + \left(1 + \frac{R_o}{R_L}\right)\left(1 + \frac{R_s}{R_i}\right) + \frac{R_o}{R_f}} v_s$$

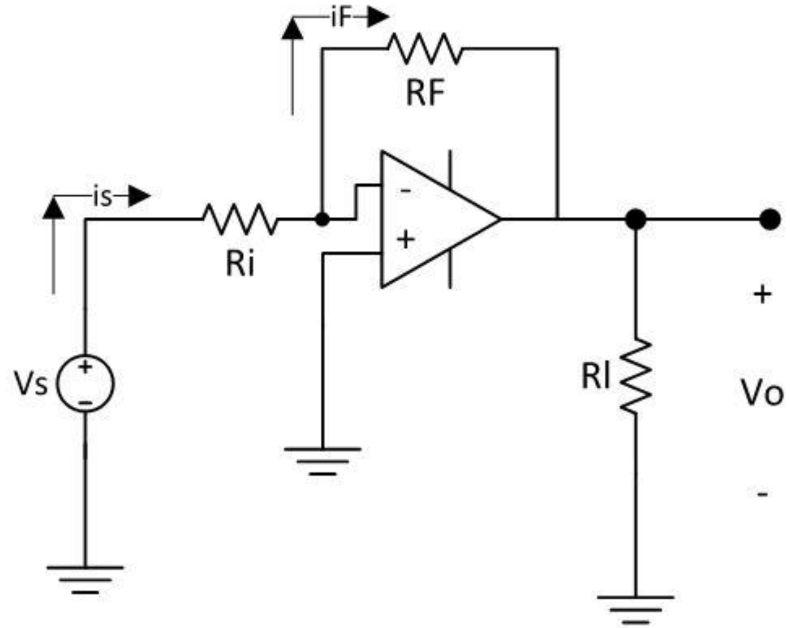
$R_o \longrightarrow 0$, $R_i \longrightarrow \infty$, and $A \longrightarrow \infty$

$$v_o = \frac{-R_f}{R_s} v_s$$

Op-Amp Linear Applications:

1. Inverting Amplifier

Design an inverting amplifier to provide A_{CL}= -200



Solution :

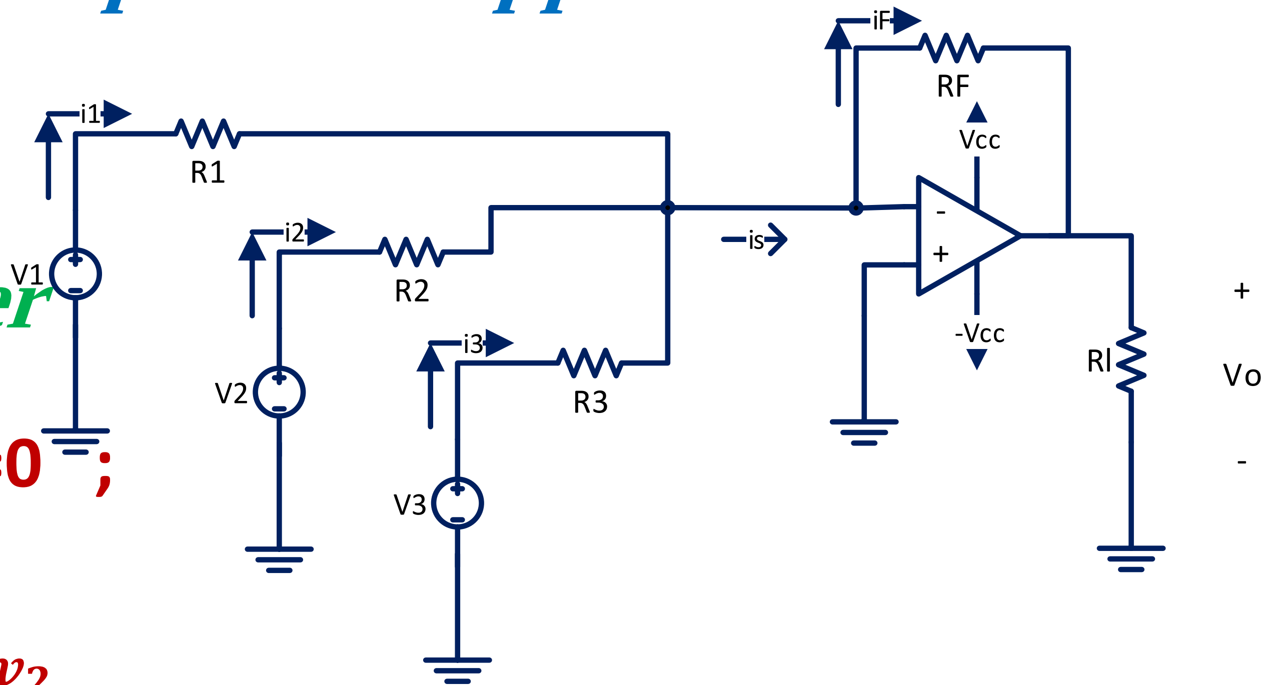
$$A_{CL} = -\frac{R_F}{R_i} = -200$$

Let $\boldsymbol{R_i}$ **= 20K**

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

$\therefore \boldsymbol{R_F}$ **= 4000K**

Op-amp Linear Applications:



2. Inverting Adder

1- Since V(+) =0 ;

∴ V(-)=0

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

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

$$i_s = i_1 + i_2 + i_3$$

2- Since i(-) =0 ; ∴ $i_F = i_S$

3- $V_O = -R_F i_F$

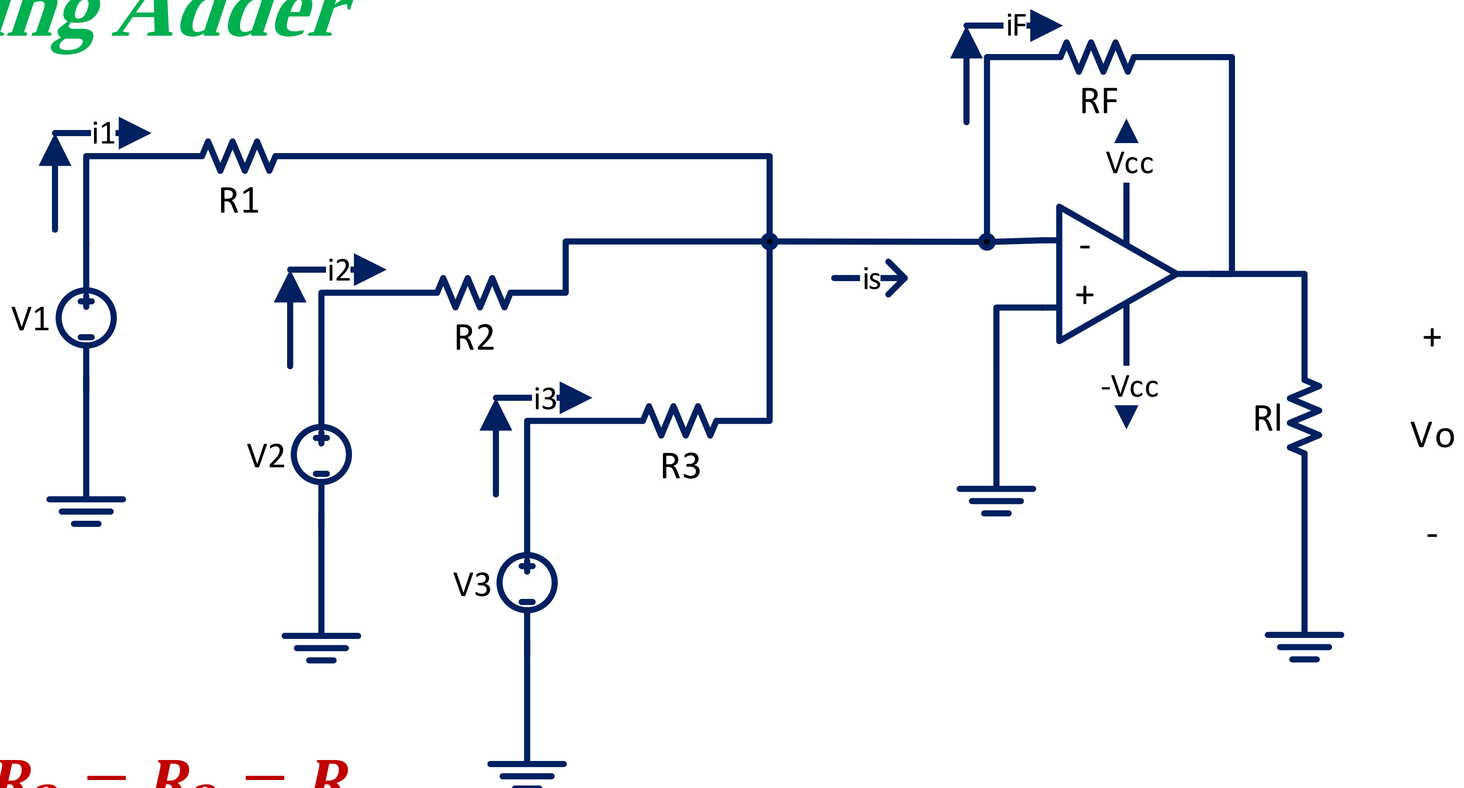
$$V_O = -\left(\frac{R_F}{R_1}V_1 + \frac{R_F}{R_2}V_2 + \frac{R_F}{R_3}V_3\right)$$

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

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

Op-amp Linear Applications:

2. Inverting Adder



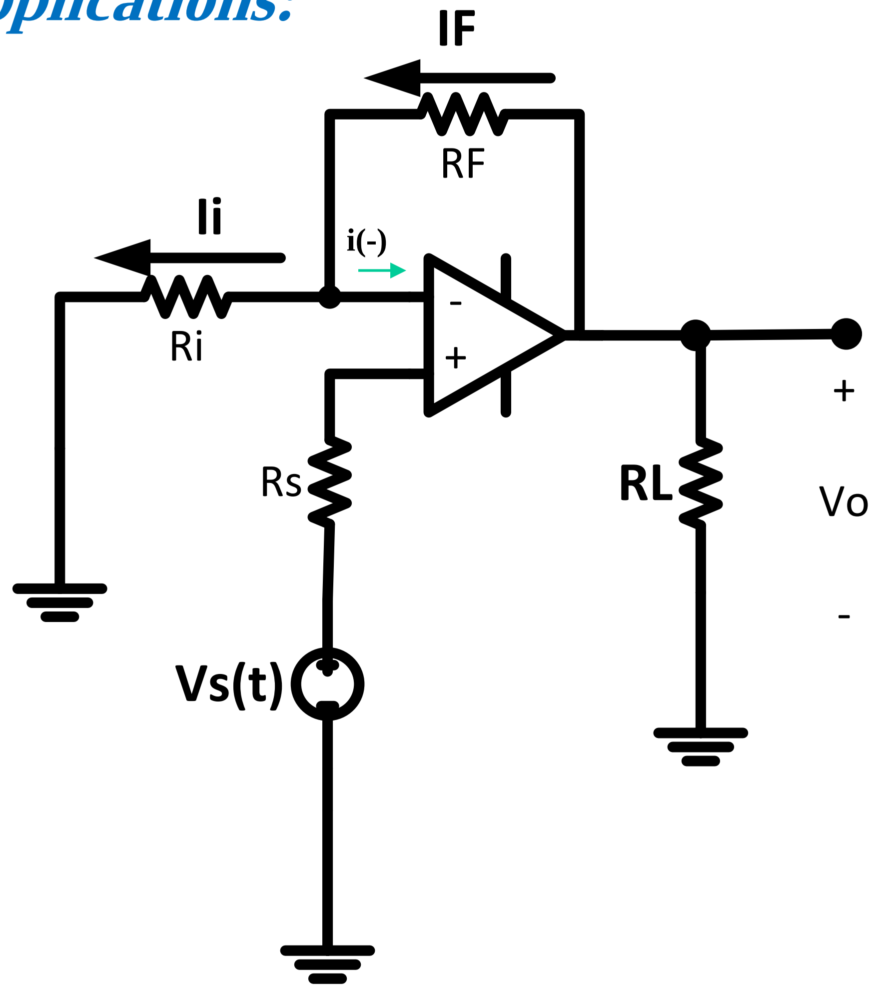
$$If \quad R_1 = R_2 = R_3 = R$$

$$And \quad R_F = \frac{R}{n} = \frac{R}{3}$$

→ **average**

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

3. Non Inverting Amplifier



1- Since V(+) = V_s

∴ V(-) = V_s

∴ $i_i = \frac{V_s}{R_i}$

2- Since i(-) = 0 ;

∴ $i_F = i_i$

3 - $V_O = R_F i_F + R_i i_i$

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

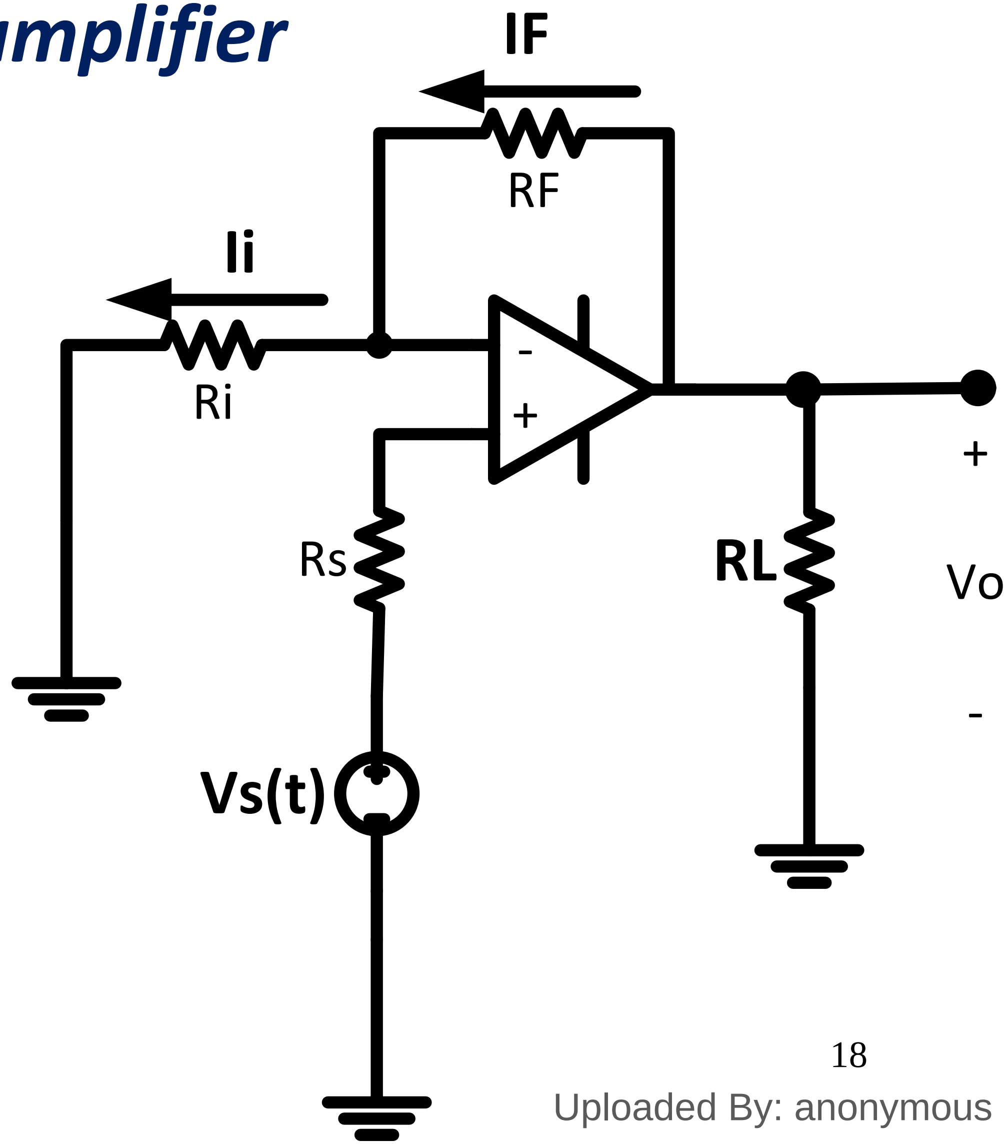
Op-amp Linear Applications:

Non Inverting Amplifier

Design a non inverting amplifier to provide A_{CL}= 100

Solution :

A_{CL} $=1+\frac{R_F}{R_i}$ =100

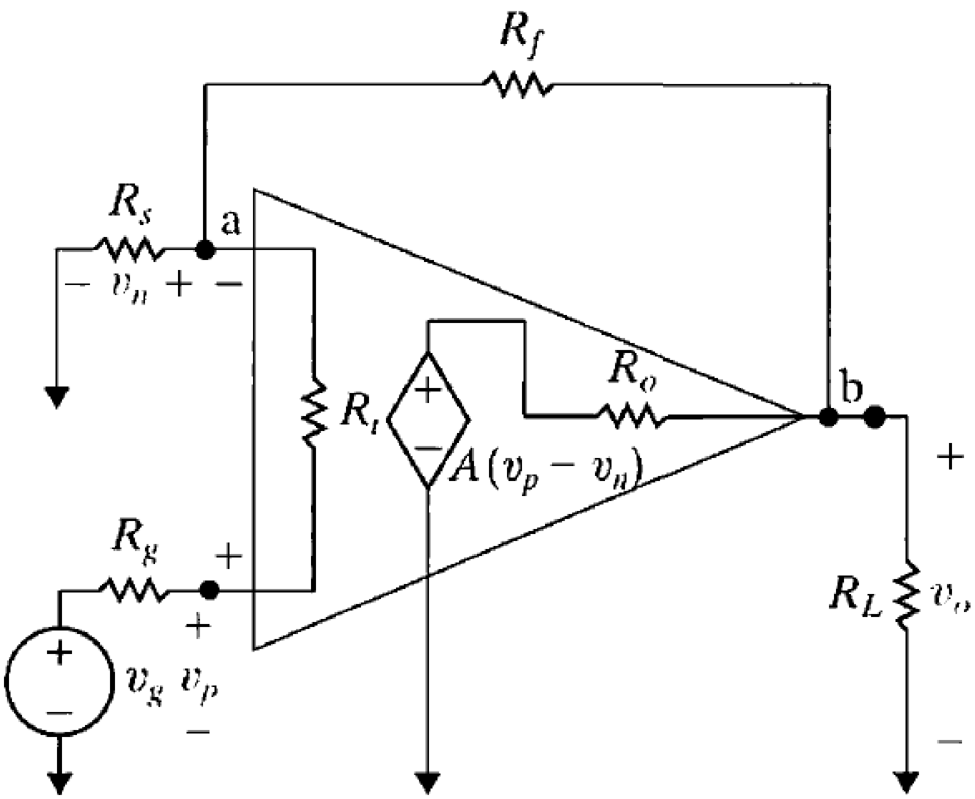


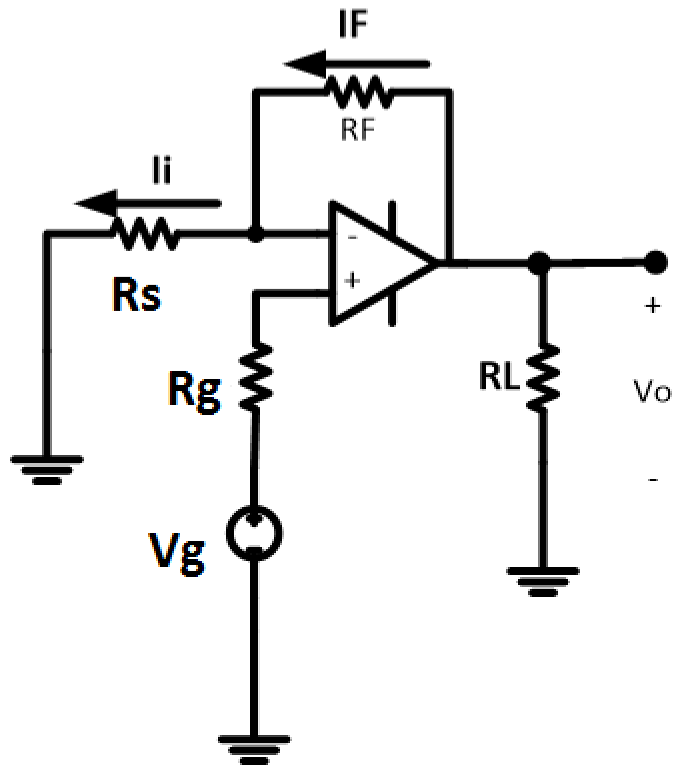
$\therefore \frac{R_F}{R_i}$ **= 99**

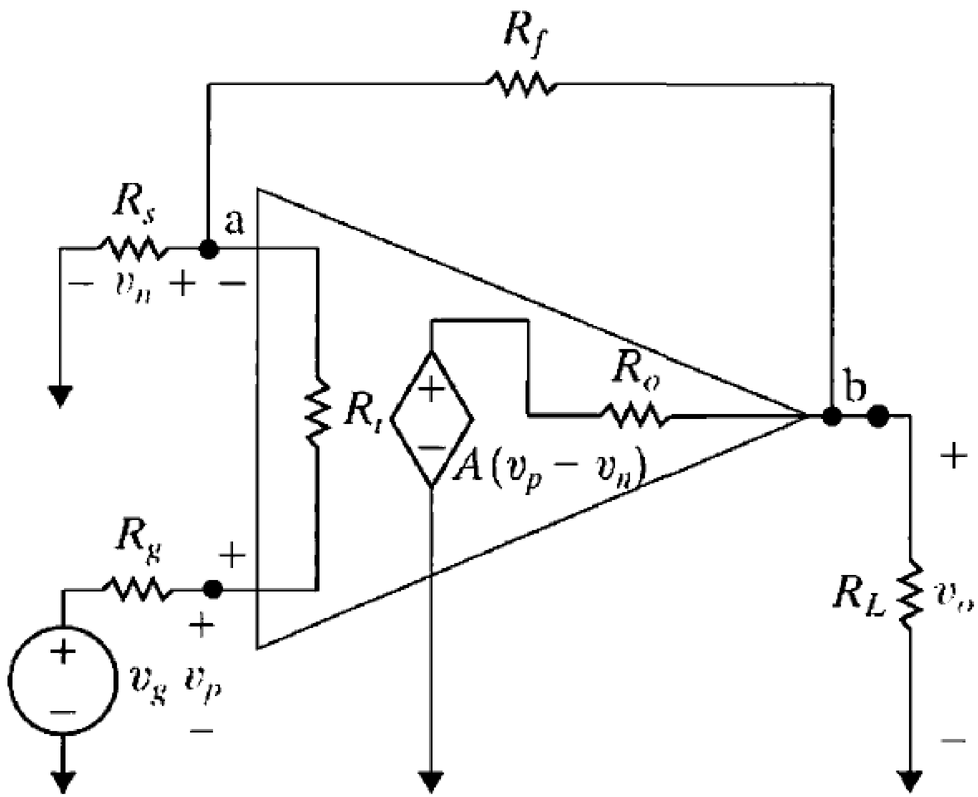
Let R_i =10K

$\therefore R_F$ = 990K

Analysis of a Noninverting-Amplifier Circuit Using the More Realistic Op Amp Model







$$\frac{v_p - v_g}{R_g} = \frac{v_n - v_g}{R_i + R_g}$$

At node a

$$\frac{v_n}{R_s} + \frac{v_n - v_g}{R_g + R_i} + \frac{v_n - v_o}{R_f} = 0$$

at node b

$$\frac{v_o - v_n}{R_f} + \frac{v_o}{R_L} + \frac{v_o - A(v_p - v_n)}{R_o} = 0$$

$$v_o = \frac{[(R_f + R_s) + (R_s R_o / A R_i)] v_g}{R_s + \frac{R_o}{A}(1 + K_r) + \frac{R_f R_s + (R_f + R_s)(R_i + R_g)}{A R_i}}$$

where

$$K_r = \frac{R_s + R_g}{R_i} + \frac{R_f + R_s}{R_L} + \frac{R_f R_s + R_f R_g + R_g R_s}{R_i R_L}$$

$R_o \rightarrow 0$, $R_i \rightarrow \infty$, and $A \rightarrow \infty$

$$v_o = \frac{R_s + R_f}{R_s} v_g$$

Op-amp Linear Applications:

4. Buffer , Unity Gain

1- Since V(+) = V_s ; ∴ V(-)=V_s

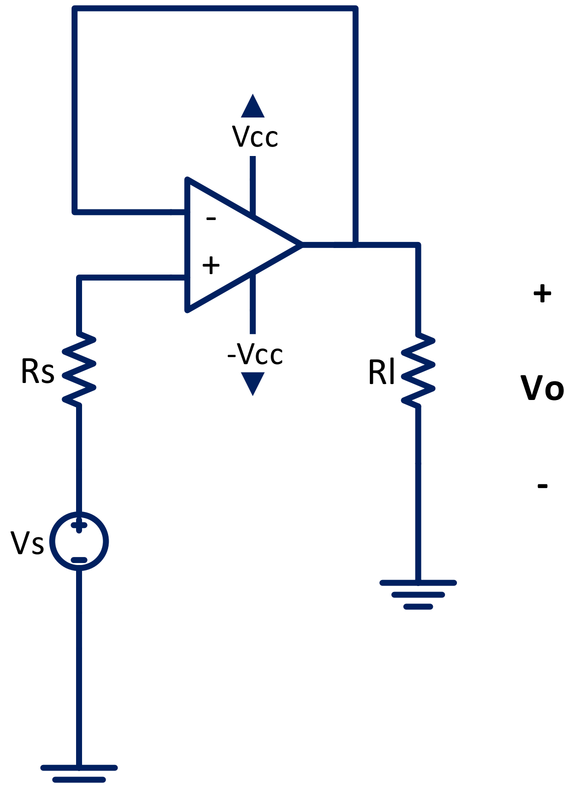
2- $V_O =$ V(-) = V_s

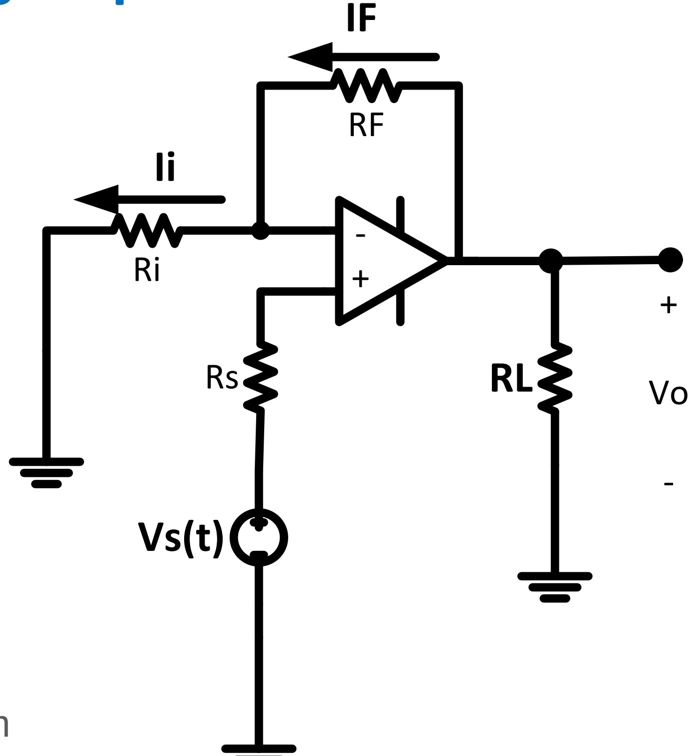
Buffer is a special Case of

non inverting amplifier for which:

$R_i = \infty$

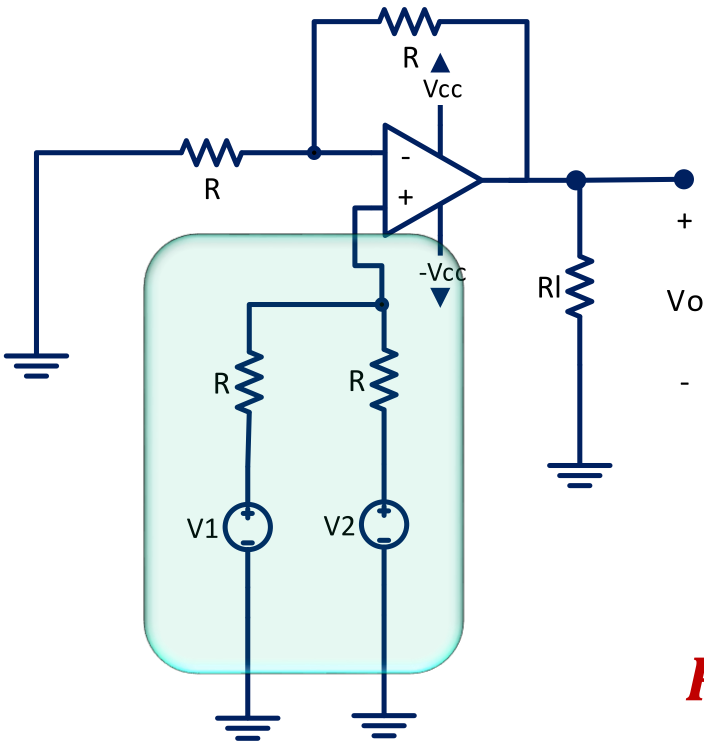
$R_F = 0$





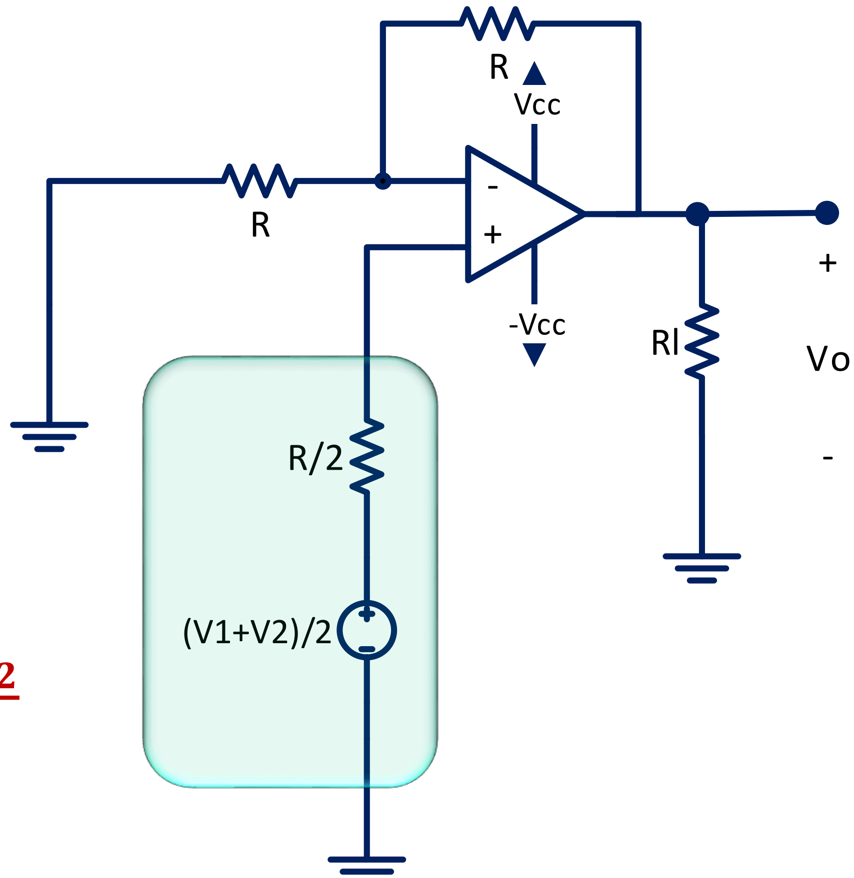
Op-amp Linear Applications:

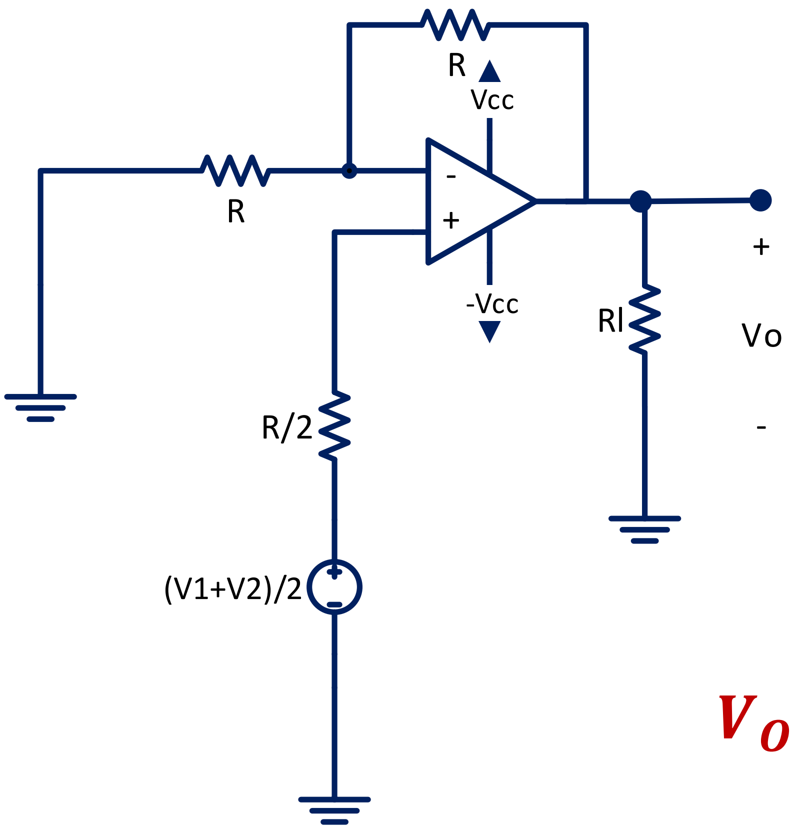
5. Non-inverting Adder



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

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





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

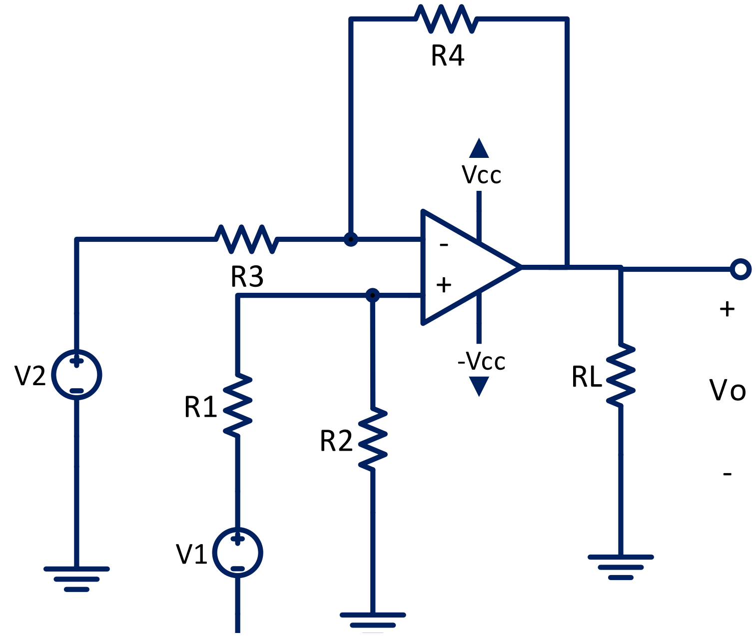
If we have n signal :

let $R_F = (n\text{-}1)R$

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

Op-amp Linear Applications:

6. Voltage Subtraction



Using superposition

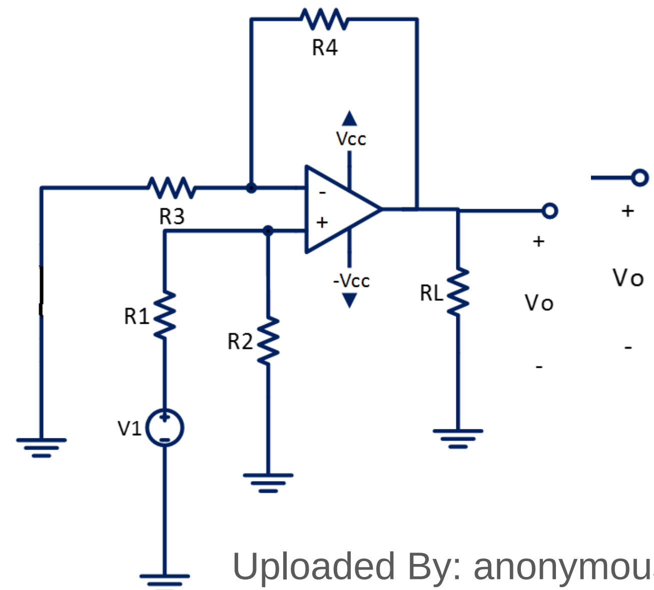
a) Let $V_1 = 0$

$\therefore V_{o1} = -\frac{R_4}{R_3} V_2$ **(Inverting amplifier)**

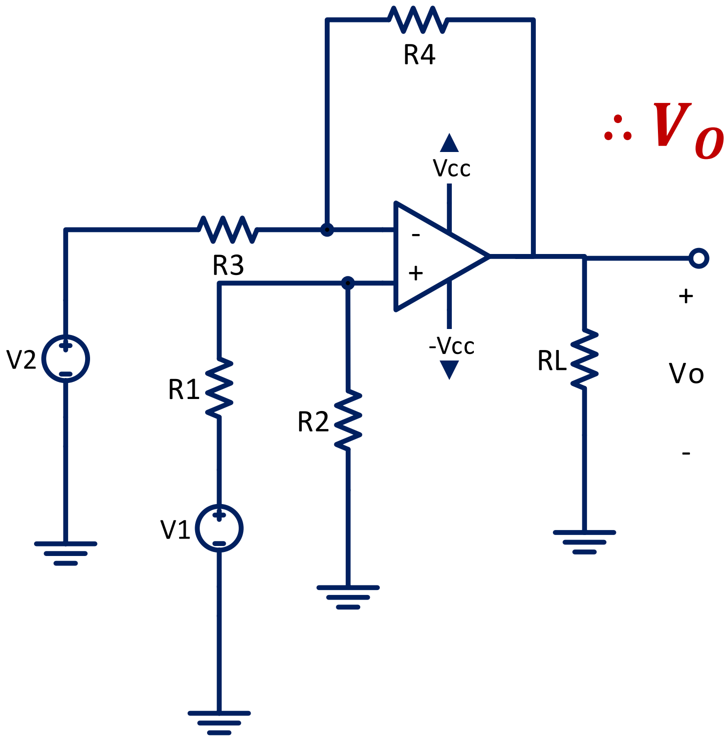
b) Let $V_2 = 0$

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

(non inverting amplifier)



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



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

$$V_O = aV_1 - bV_2$$

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

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

Basic Difference Amplifier

Op-amp Linear Applications:

Basic Difference Amplifier

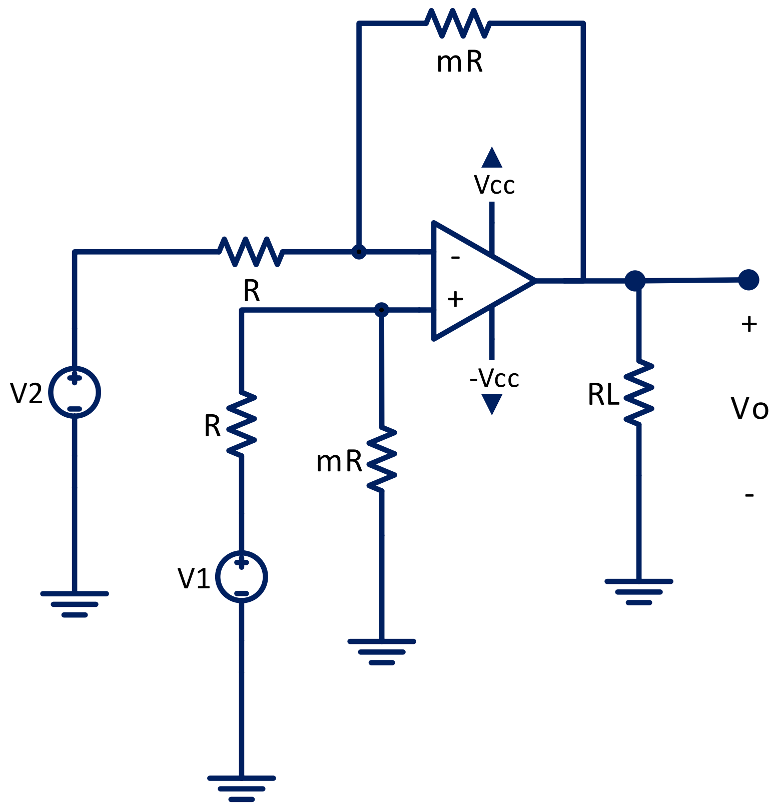
$V_O = m(V_1 - V_2)$

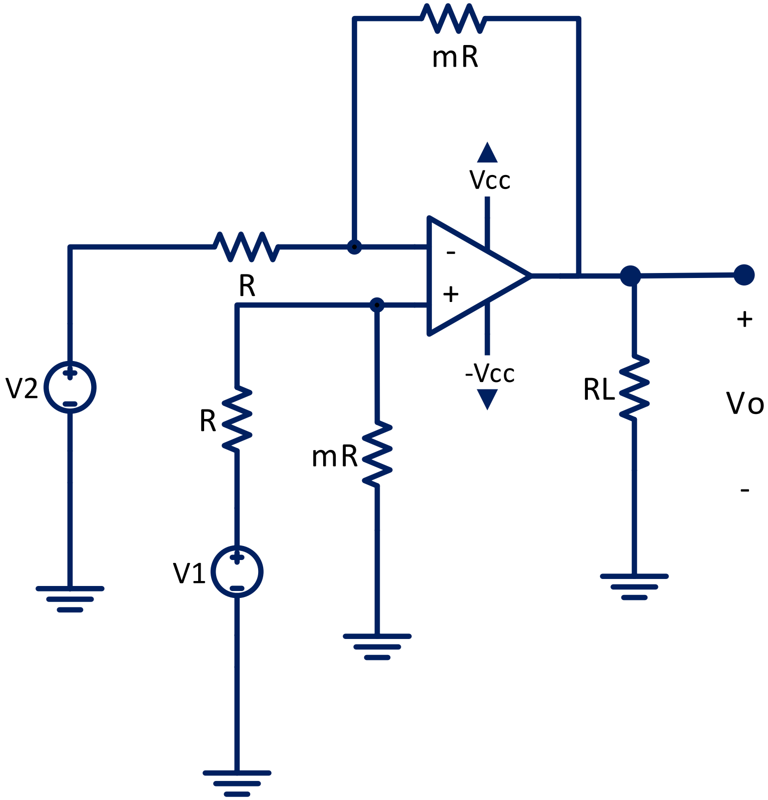
$Z_{i1} = R + mR$

$Z_{i2} = R$

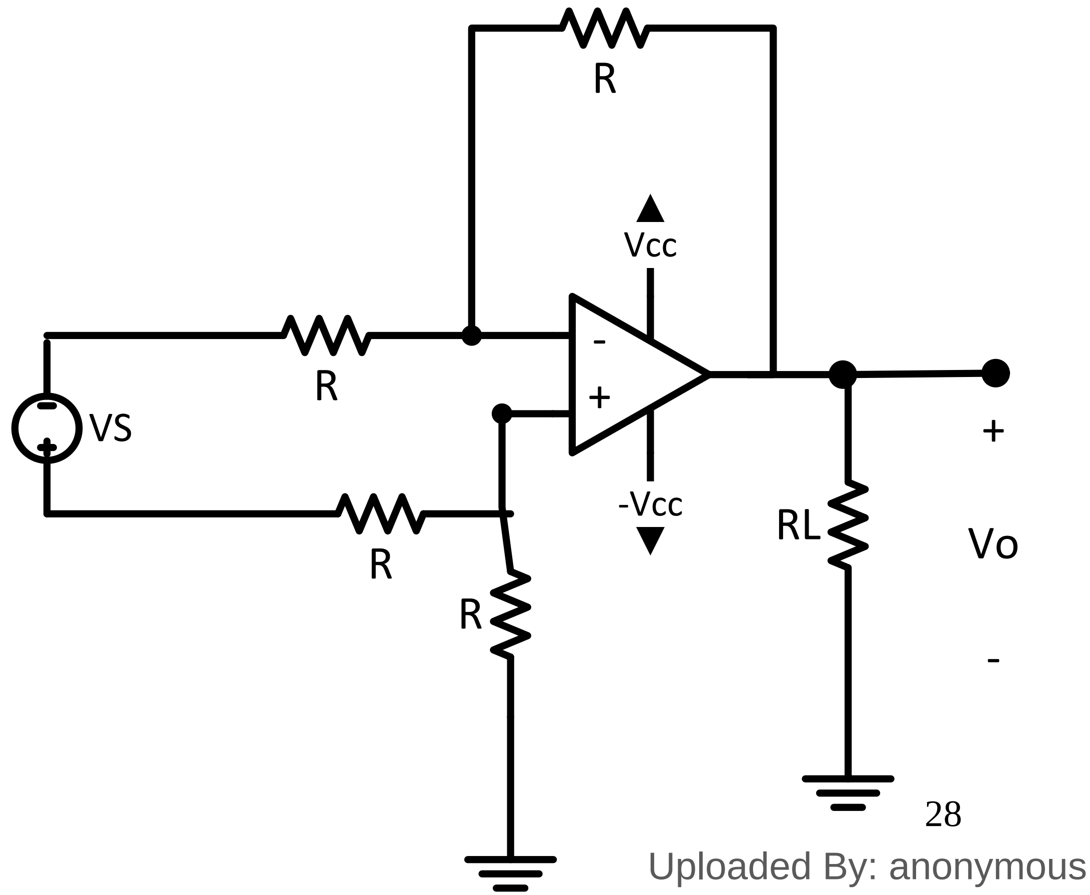
*It has low input impedance

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





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



prove that Vo = Vs

m = 1

Instrumentation Amplifier:

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

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

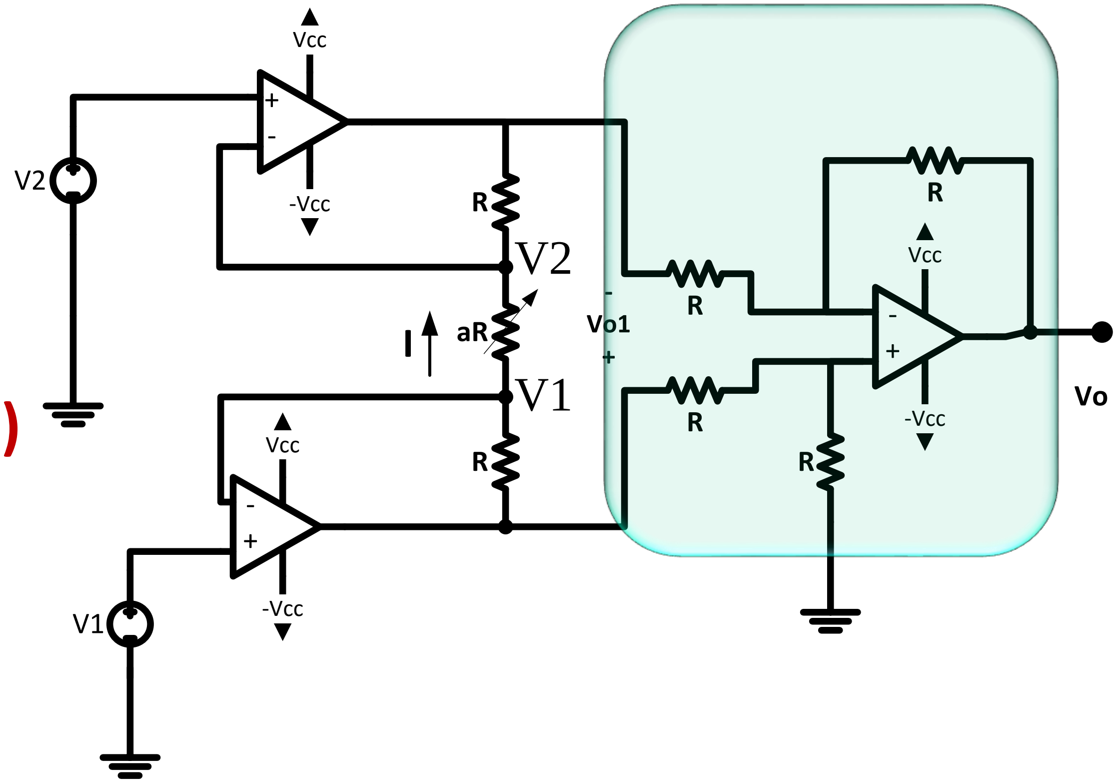
V_{o1} = (1+ $\frac{2}{a}$) $(V_1 - V_2)$

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

$Z_{i1} = \infty$

$Z_{i2} = \infty$

To change the gain $\rightarrow$ change a



a << 1

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

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

ΔR is very small

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

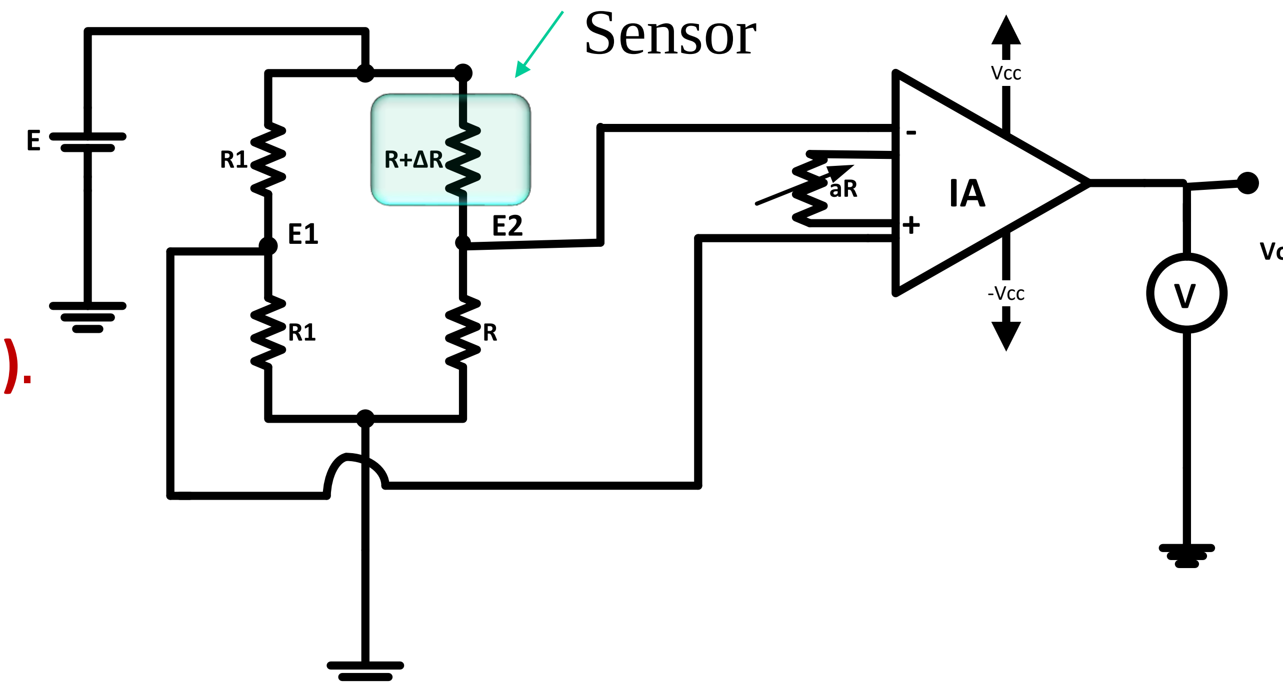
$V_o = (1+\frac{2}{a})\,(E_1 - E_2).$

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

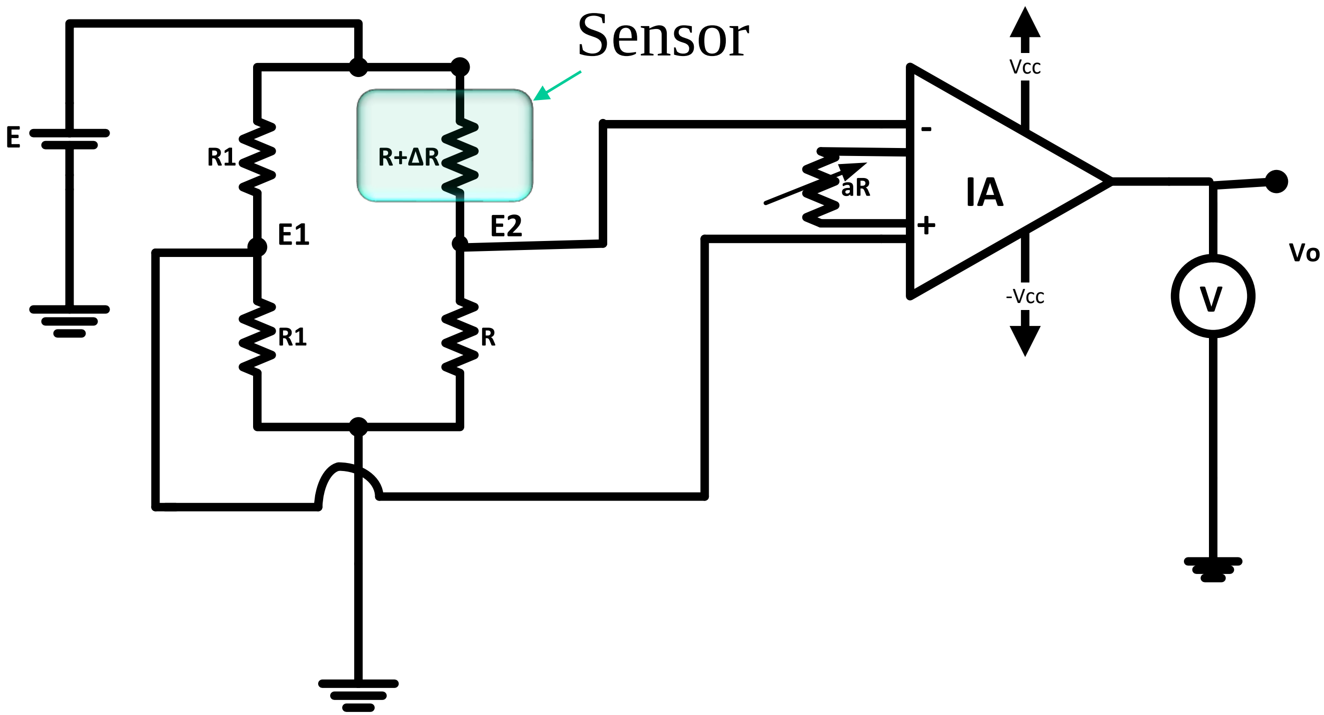
V_o = (400)($\frac{\Delta R}{4R}$)E

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

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



Measuring small resistance change



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

If R = 10K

ΔR = 0.1K

E = 1V

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

V_o = 1V

∴ 1V per 1% change in resistance

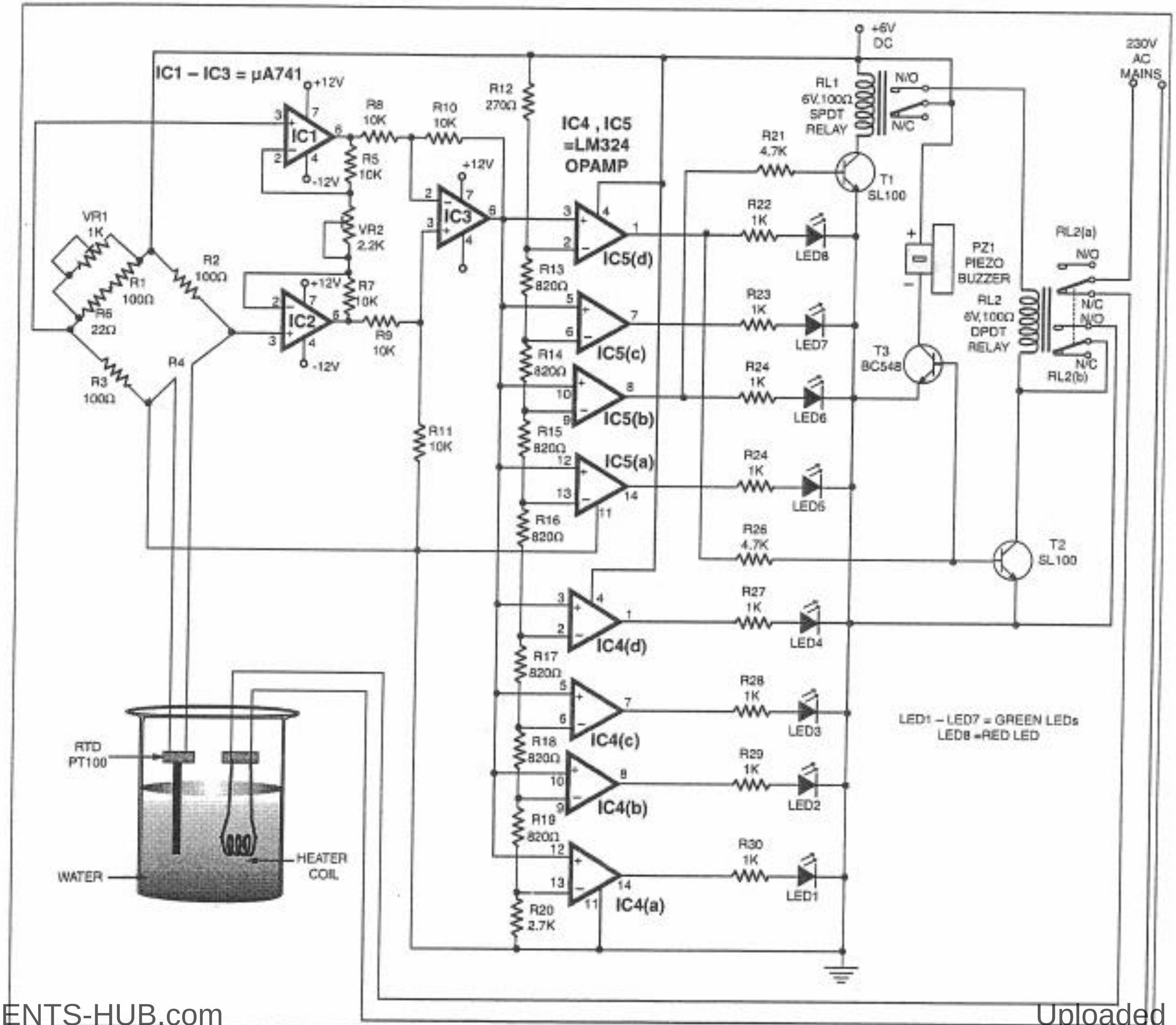
If Vo = 2V ⟹ ΔR = 0.2K

If Vo = 0.1V ⟹ ΔR = 0.01K

If Vo = 0.01V ⟹ ΔR = 0.001K

If Vo = 1mV ⟹ ΔR = 0.0001K

ENEE3304 Project#1 :Water Temperature Controller

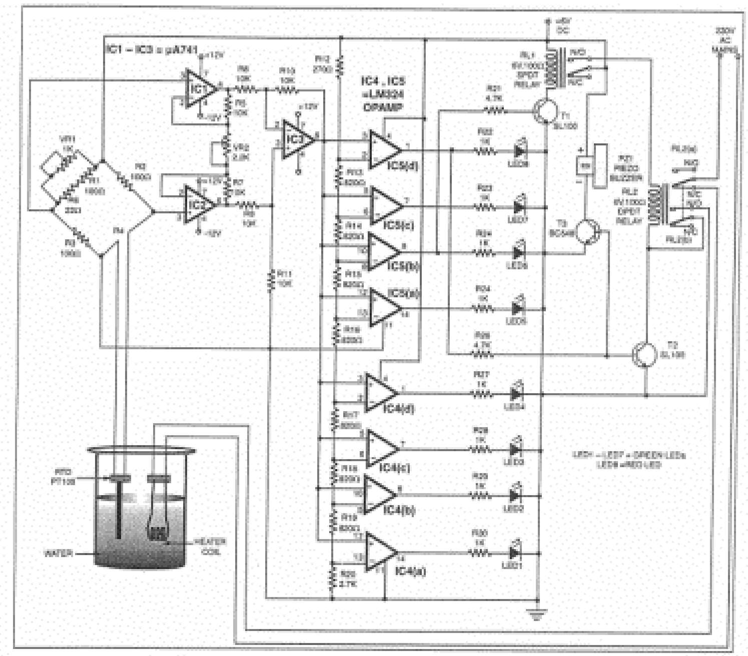


°C	Ohms	°C	Ohms	°C	Ohms	°C	Ohms
–11	95.69	51	119.78	114	143.80	177	167.35
		52	120.16	115	144.17	178	167.72
–10	96.09	53	120.55	116	144.55	179	168.09
–9	96.48	54	120.93	117	144.93		
–8	96.87	55	121.32	118	145.31	180	168.46
–7	97.26	56	121.70	119	145.68	181	168.83
–6	97.65	57	122.09			182	169.20
–5	98.04	58	122.47	120	146.06	183	169.57
–4	98.44	59	122.86	121	146.44	184	169.94
–3	98.83			122	146.81	185	170.31
–2	99.22	60	123.24	123	147.19	186	170.68
–1	99.61	61	123.62	124	147.57	187	171.05
		62	124.01	125	147.94	188	171.42
0	100.00	63	124.39	126	148.32	189	171.79
1	100.39	64	124.77	127	148.70		
2	100.78	65	125.16	128	149.07	190	172.16
3	101.17	66	125.54	129	149.45	191	172.53
4	101.56	67	125.92			192	172.90
5	101.95	68	126.31	130	149.82	193	173.26
6	102.34	69	126.69	131	150.20	194	173.63
7	102.73			132	150.57	195	174.00
8	103.12	70	127.07	133	150.95	196	174.37
9	103.51	71	127.45	134	151.33	197	174.74
		72	127.84	135	151.70	198	175.10
10	103.90	73	128.22	136	152.08	199	175.47
11	104.29	74	128.60	137	152.45		
12	104.68	75	128.98	138	152.83	200	175.84
13	105.07	76	129.37	139	153.20	201	176.21
14	105.46	77	129.75			202	176.57
15	105.85	78	130.13	140	153.58	203	176.94
16	106.24	79	130.51	141	153.95	204	177.31
17	106.63			142	154.32	205	177.68
18	107.02	80	130.89	143	154.70	206	178.04
19	107.40	81	131.27	144	155.07	207	178.41
		82	131.66	145	155.45	208	178.78
20	107.79	83	132.04	146	155.82	209	179.14
21	108.18	84	132.42	147	156.19		
22	108.57	85	132.80	148	156.57	210	179.51
23	108.96	86	133.18	149	156.94	211	179.88
24	109.35	87	133.56			212	180.24
25	109.73	88	133.94	150	157.31	213	180.61
26	110.12	89	134.32	151	157.69	214	180.97
27	110.51			152	158.06	215	181.34
28	110.90	90	134.70	153	158.43	216	181.71
29	111.28	91	135.08	154	158.81	217	182.07
		92	135.46	155	159.18	218	182.44
30	111.67	93	135.84	156	159.55	219	182.80
31	112.06	94	136.22	157	159.93		
32	112.45	95	136.60	158	160.30	220	183.17
33	112.83	96	136.98	159	160.67	221	183.53
34	113.22	97	137.36			222	183.90
35	113.61	98	137.74	160	161.04	223	184.26
36	113.99	99	138.12	161	161.42	224	184.63
37	114.38			162	161.79	225	184.99
38	114.77	100	138.50	163	162.16	226	185.36
39	115.15	101	138.88	164	162.53	227	185.72
		102	139.26	165	162.90	228	186.09
40	115.54	103	139.64	166	163.27	229	186.45
41	115.93	104	140.02	167	163.65		
42	[illegible]	105	140.39	168	164.02	230	[illegible]
43	116.70	106	140.77	169	164.39	231	187.18

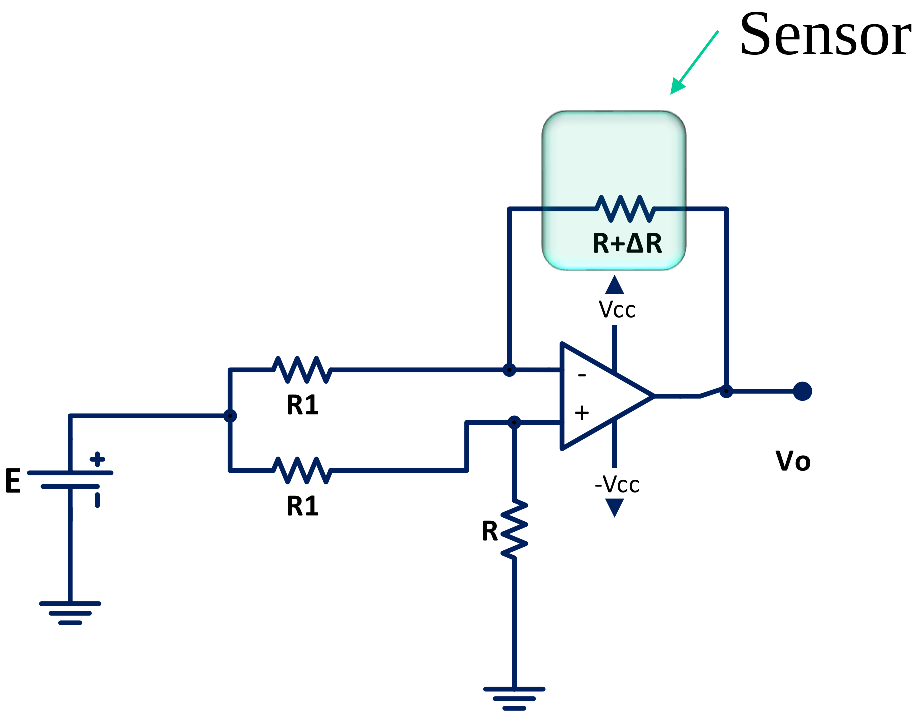
To detect the temperature of water, commonly used resistance-temperature detector (RTD) PT100 is used. It is connected to one of the arms of a Wheatstone bridge as shown in the figure RTD PT100 has a resistance of 100 ohms

Before using this circuit, the following adjustments have to be made. First, immerse the RTD in ice water (0oC) and adjust preset VR1 such that the bridge becomes balanced and the output of IC3 becomes 0V. Next, immerse the RTD in boiling water and slightly adjust preset VR2 such that the output of IC3 becomes 6V.

Water Temperature Controller



Basic Bridge Amplifier

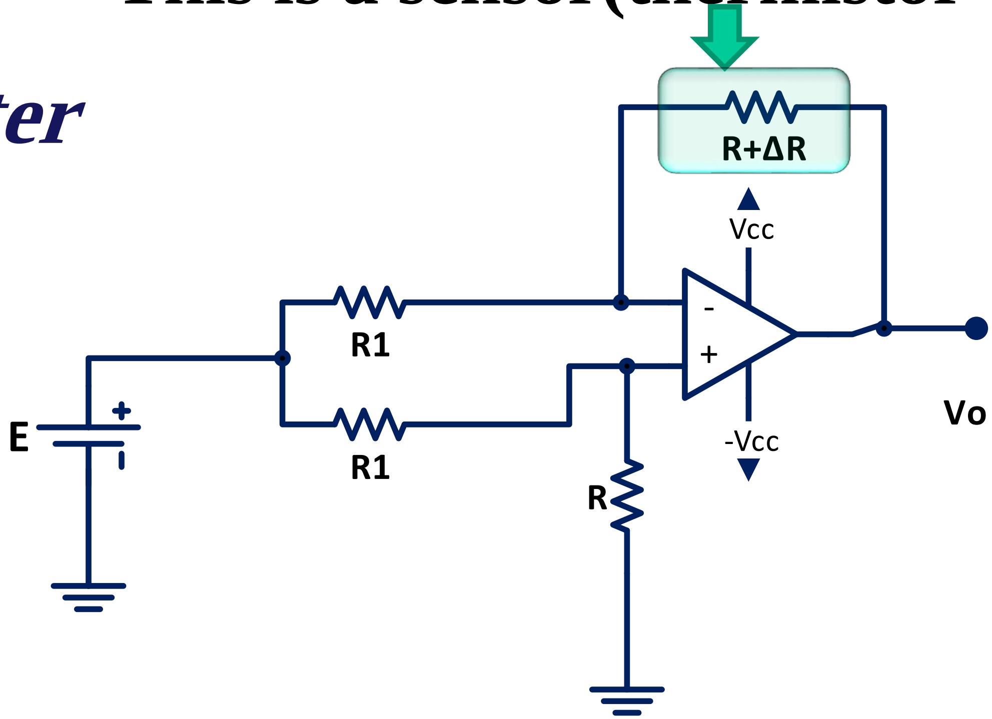


Prove that

$$V_o = -\,E\left(\frac{\Delta R}{R_1+R}\right)$$

This is a sensor(thermistor)

Electronic Thermometer



$$V_o = -\,E\left(\frac{\Delta R}{R_1+R}\right)$$

E = -15v

R_1 = 10K

R = 5K

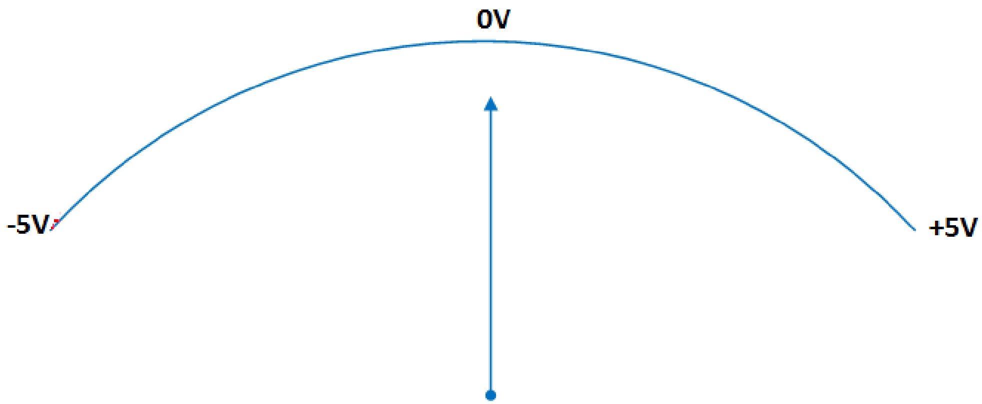
$$V_o = \Delta R$$

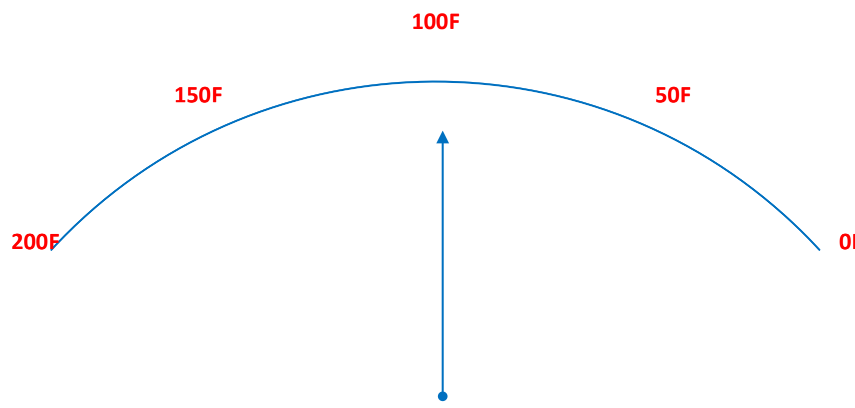
Place the circuit in the reference tempareture (T=100F) and measure the total resistance of the thermistor(R=5k)

Electronic Thermometer

Temp	RT	ΔR	Vo
0	10k	5k	5V
50	7.5k	2.5k	2.5V
100	5k	0k	0V
150	2.5k	-2.5k	-2.5V
200	0k	-5k	-5V

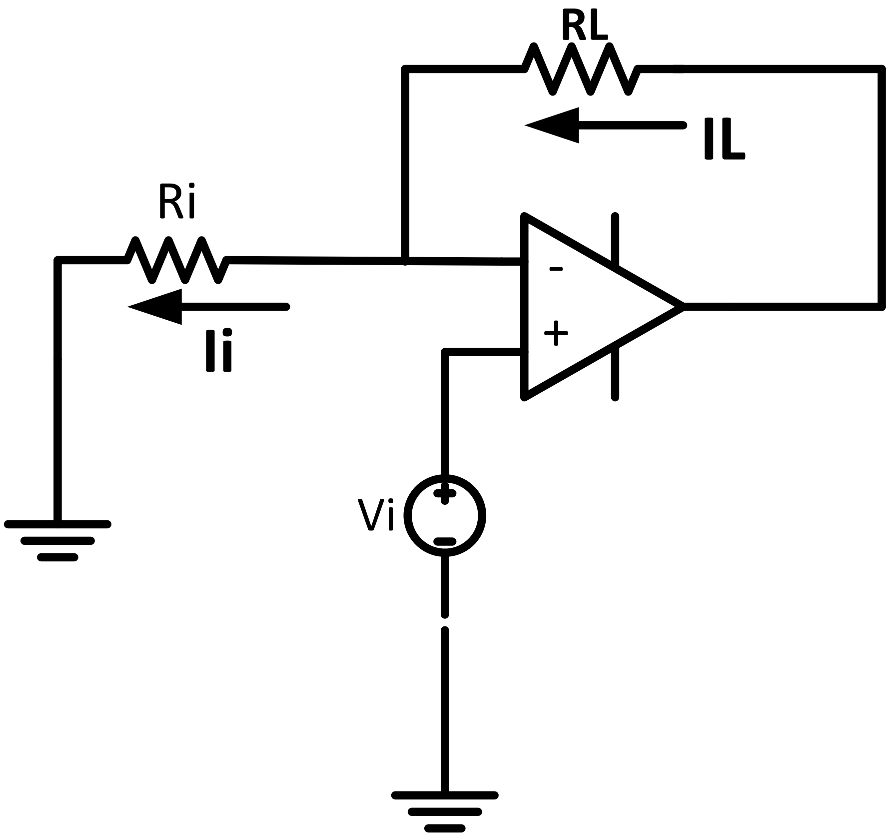
Voltmeter





Voltage to current Converter

a) Floating load



Since V(+) = Vi

∴ V(-) = Vi

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

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

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

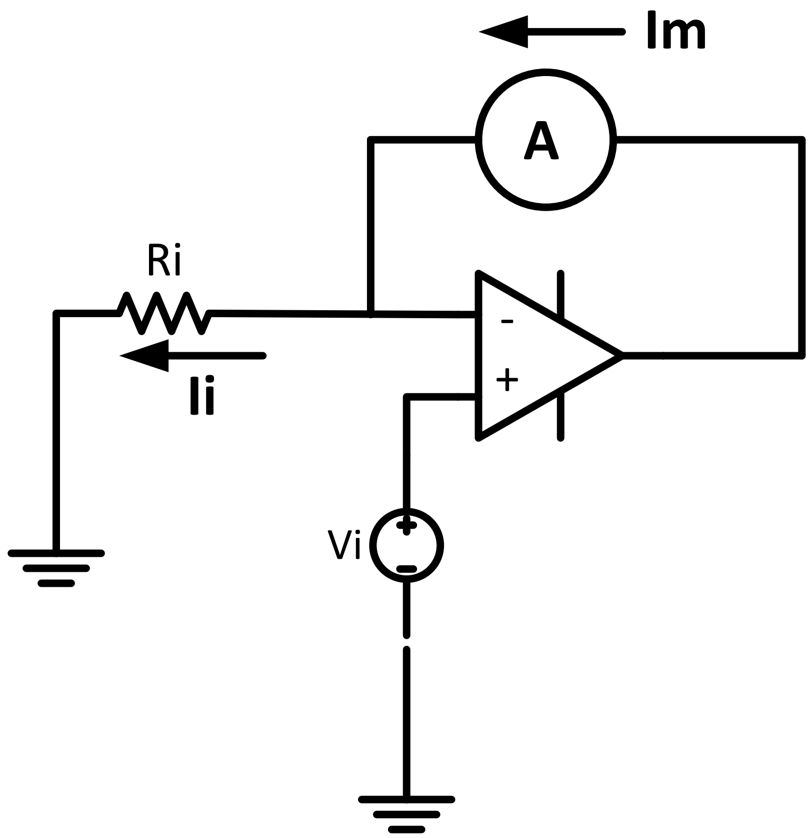
$R_i =$ 1k

If V_i =+10 v → $I_m =$ +1mA

$R_i =$ 10k

If V_i =-10 v → $I_m =$ -1mA

$R_i =$ 10k



Voltage to current Converter

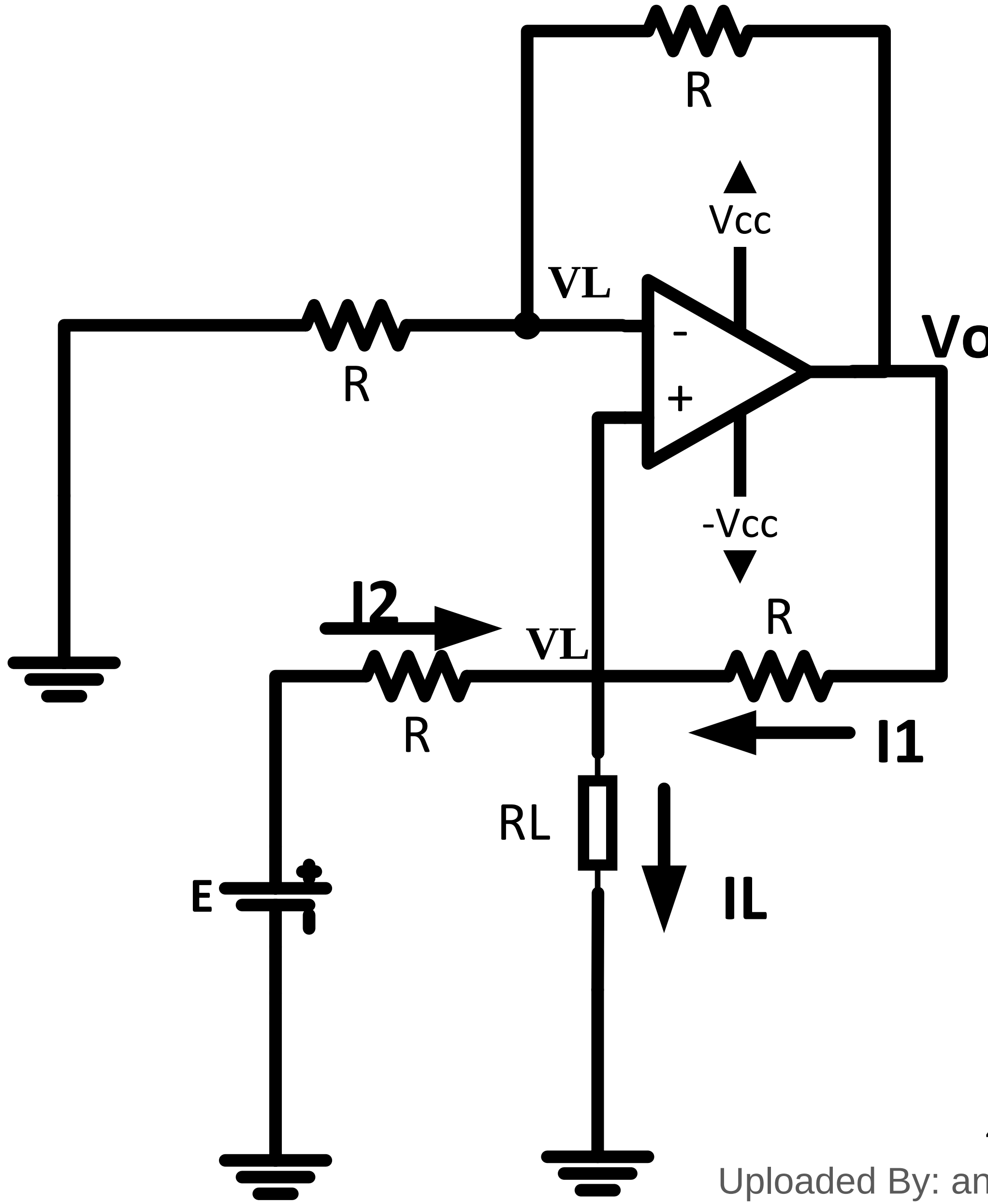
b) Grounded load

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

$$I_L = I_1 + I_2$$

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

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



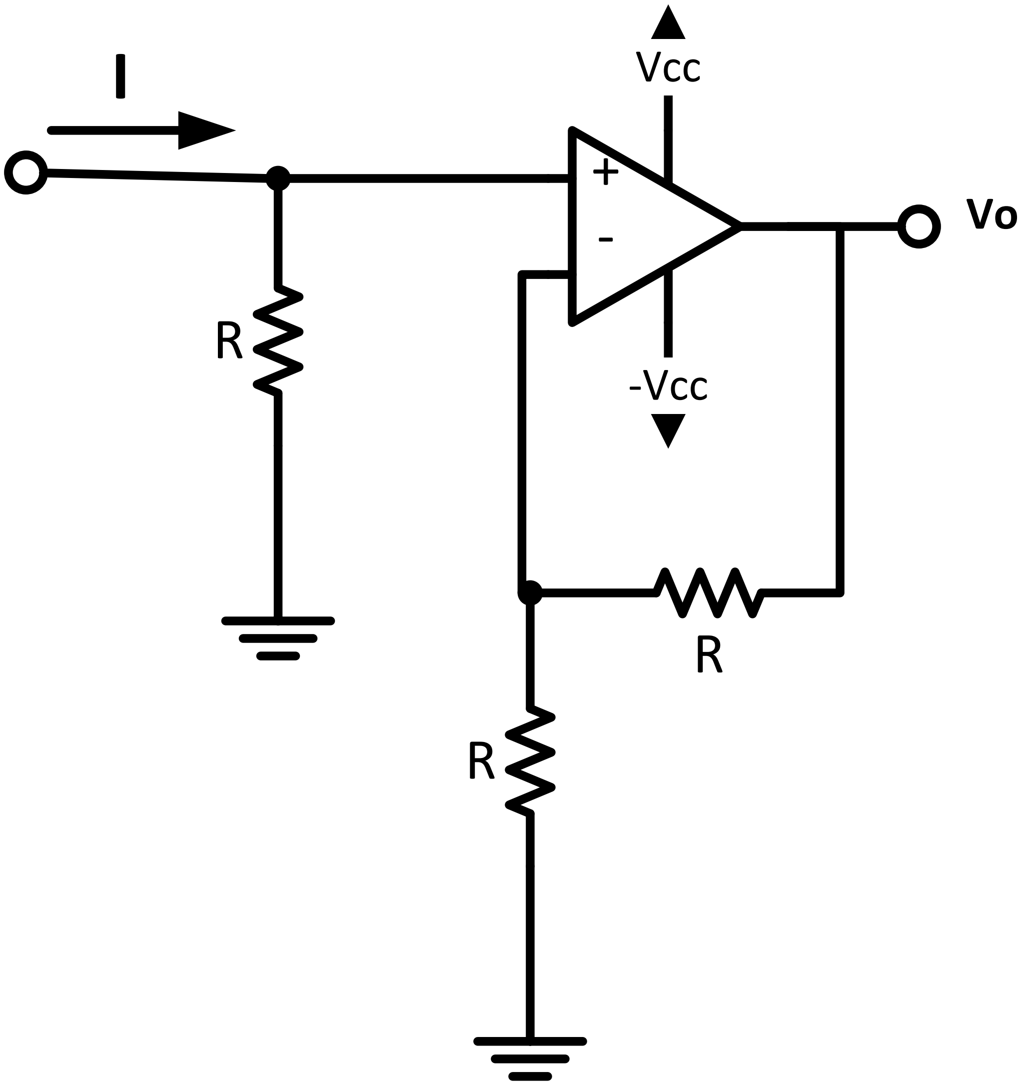
Current to Voltage Converter

$V(+) = R\,I$

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

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

$V_o = K\,I$



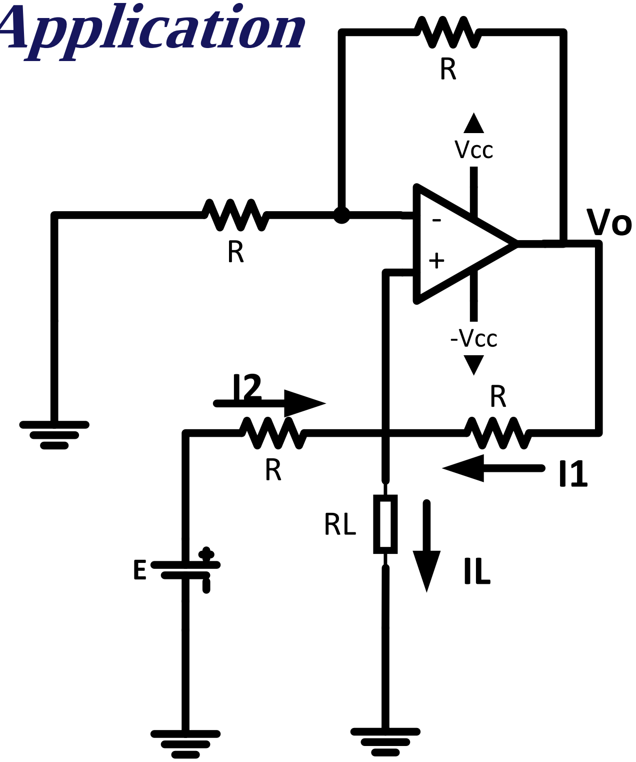
Current to Voltage Converter Application

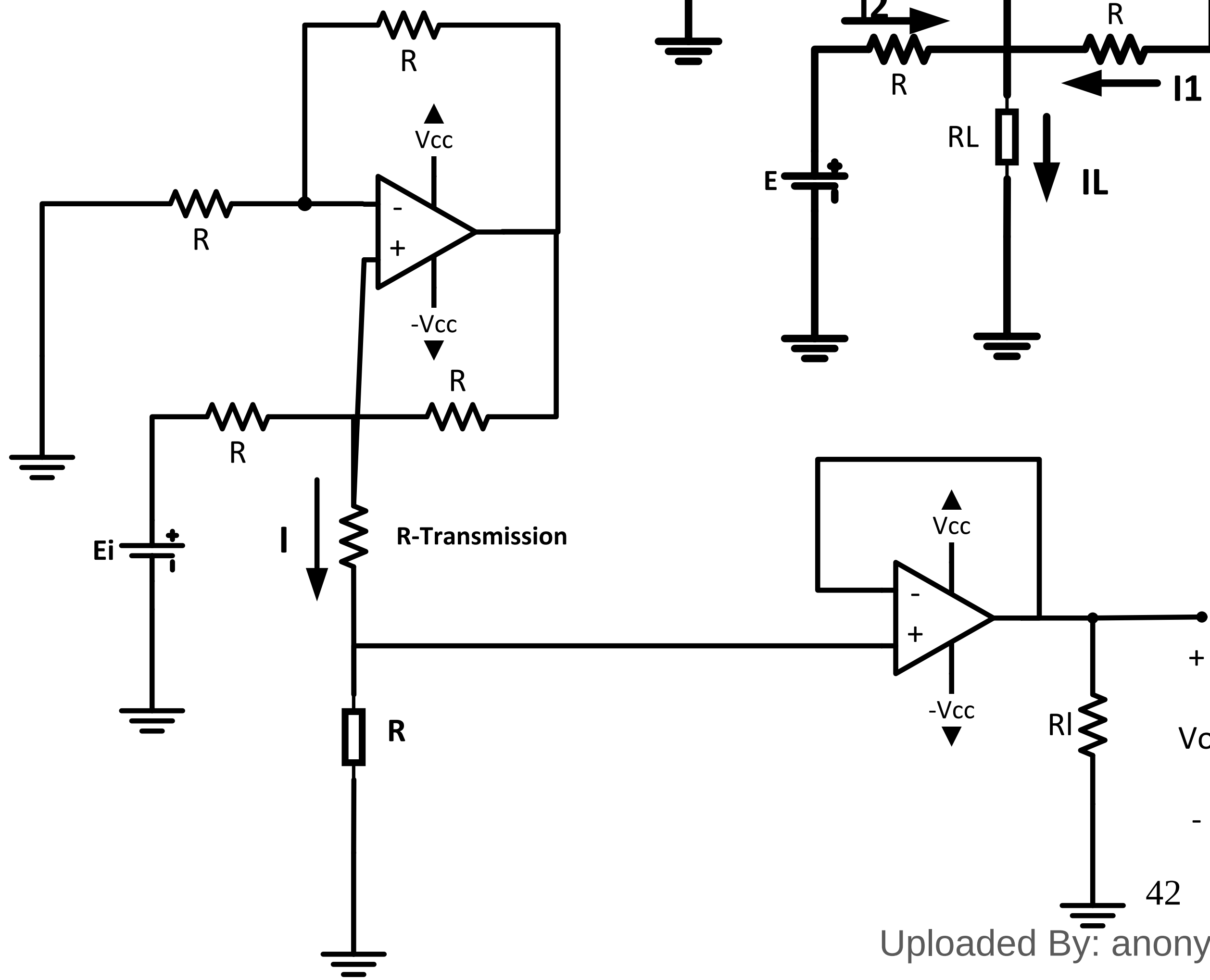
$$I = \frac{E_i}{R}$$

$$V(+) = R\,I = Ei$$

$$V_o = V(+)$$

$$\therefore V_o = E_i$$





Constant High Current Source

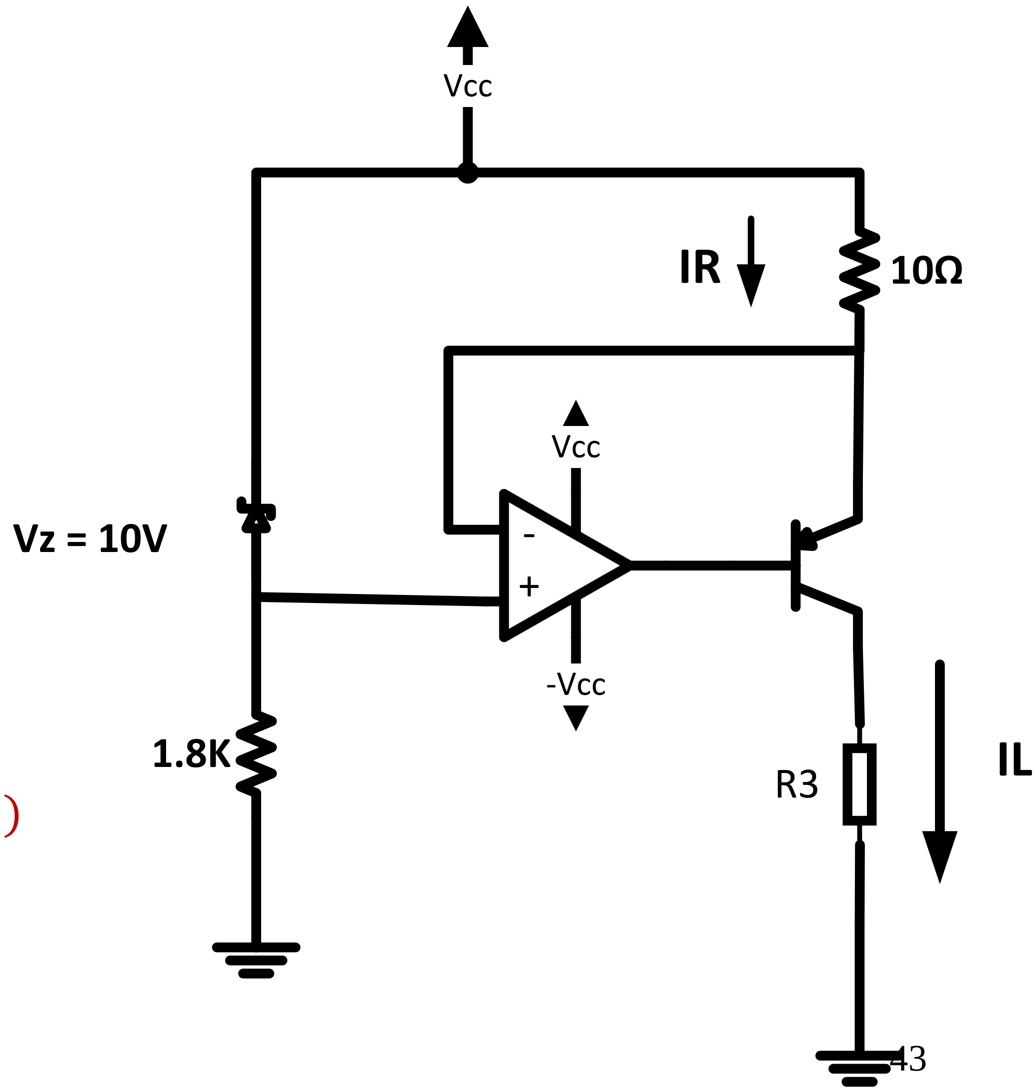
$I_R = \frac{V_Z}{R}$ = 1A

$I_R = I_E$

$I_E \approx I_L$

and since β = 100

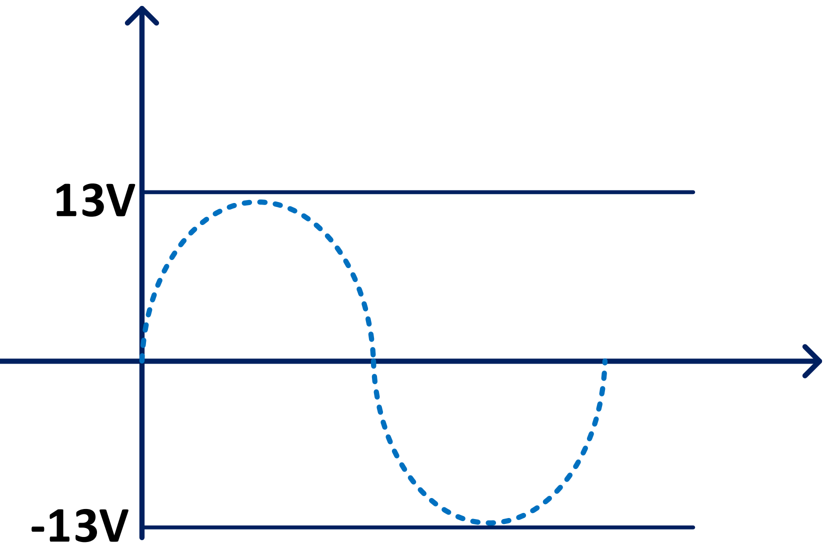
$I_B = \frac{1\,A}{B}$ = 10mA $< I_{O(max)}$

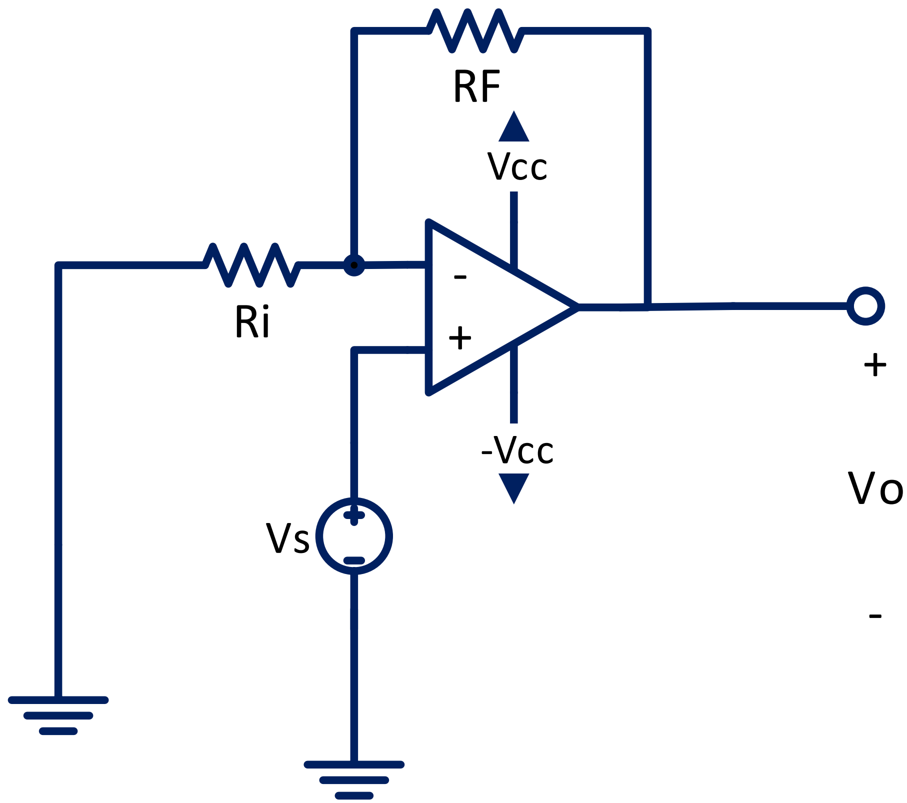


Single Supply Op-amp

If $\pm V_{CC} = \pm 15v$

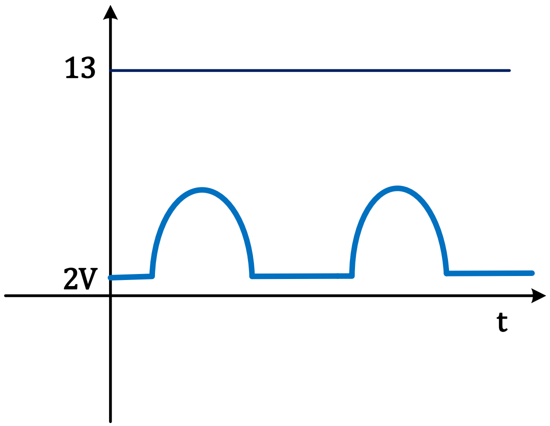
V,sat = ±13v



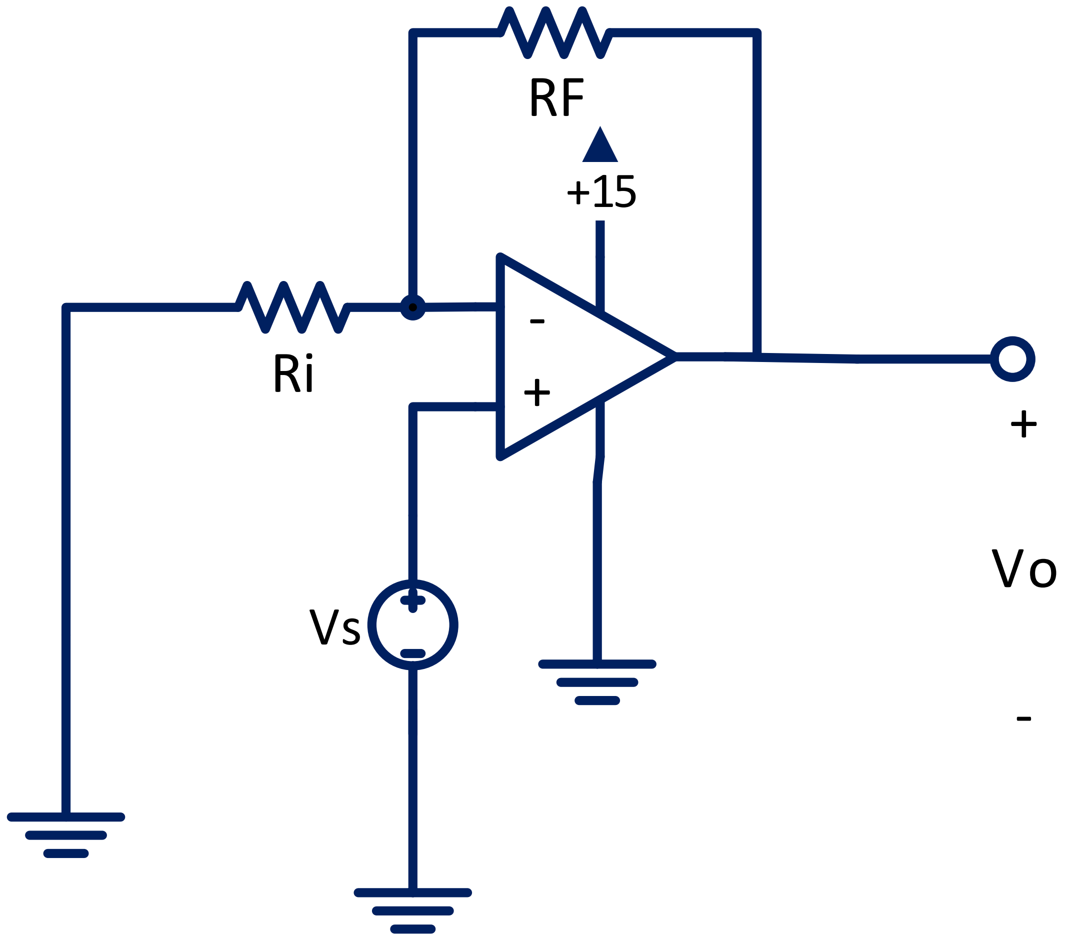


The Maximum possible swing = 26V peak to peak

Single Supply Op-amp

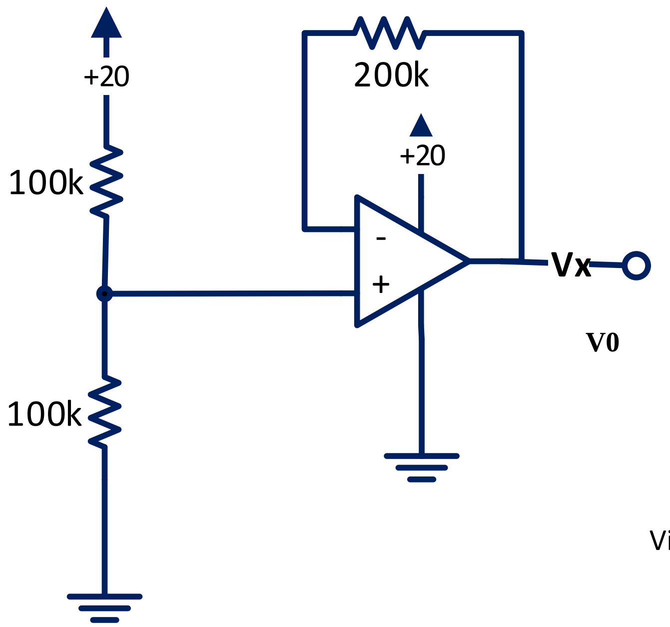


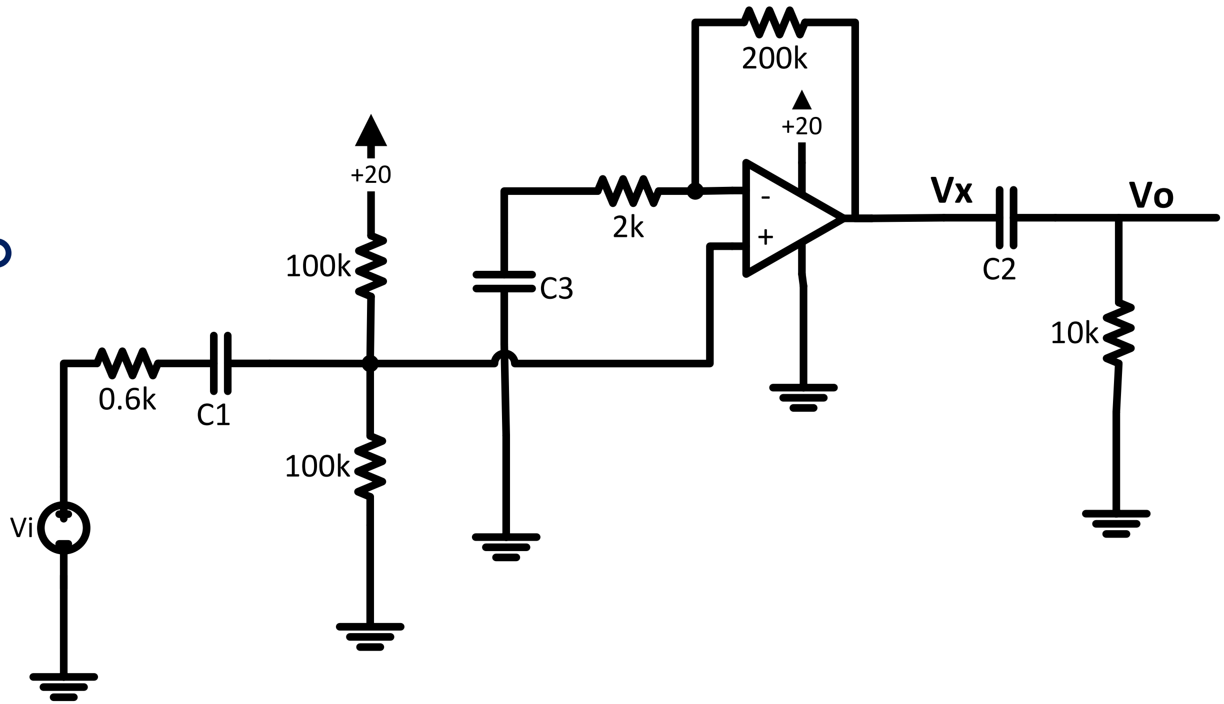
Distortion



Single Supply Op-amp

DC Equivalent ckt:



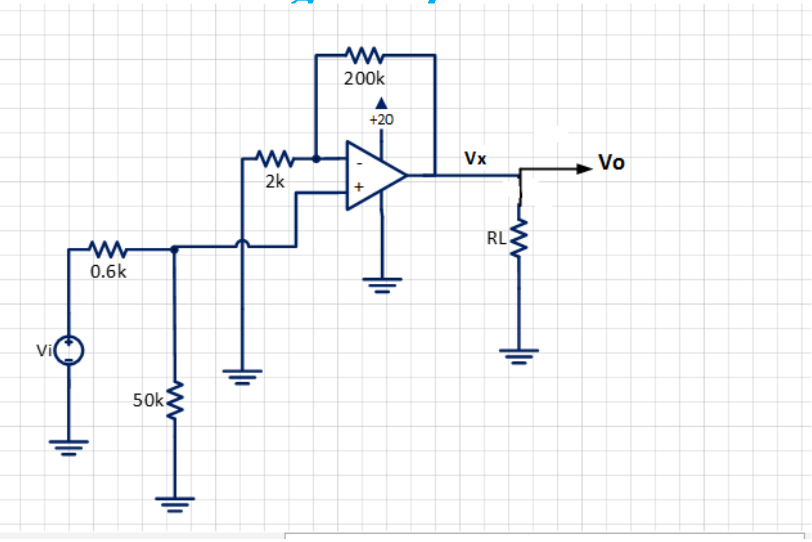


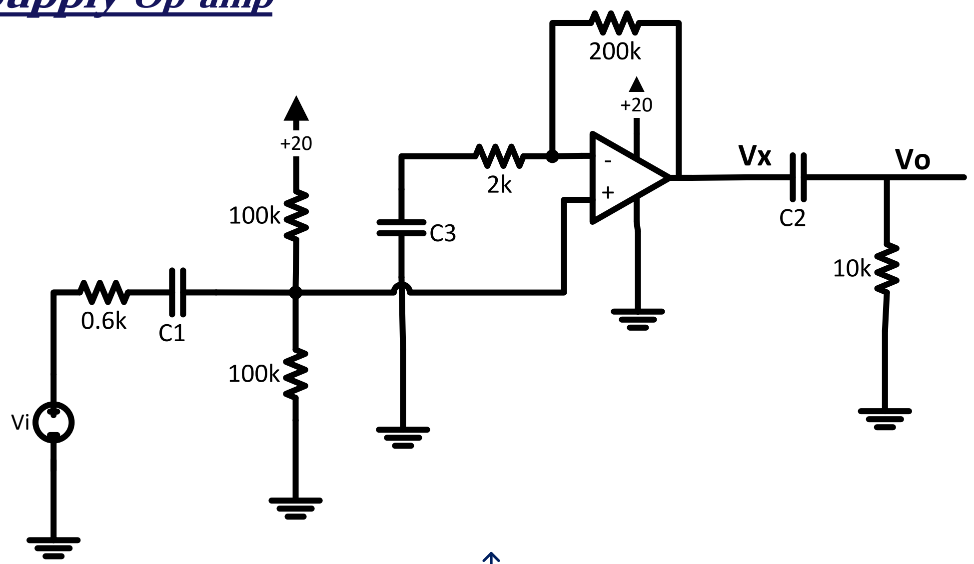
V_X = V(+) =10v

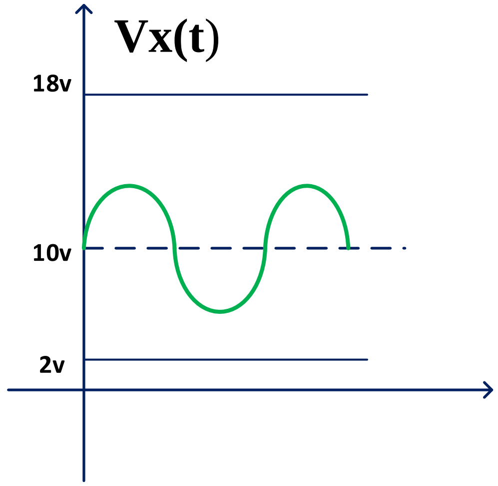
V_o = 0

Single Supply Op-amp

AC small signal equivalent ckt:





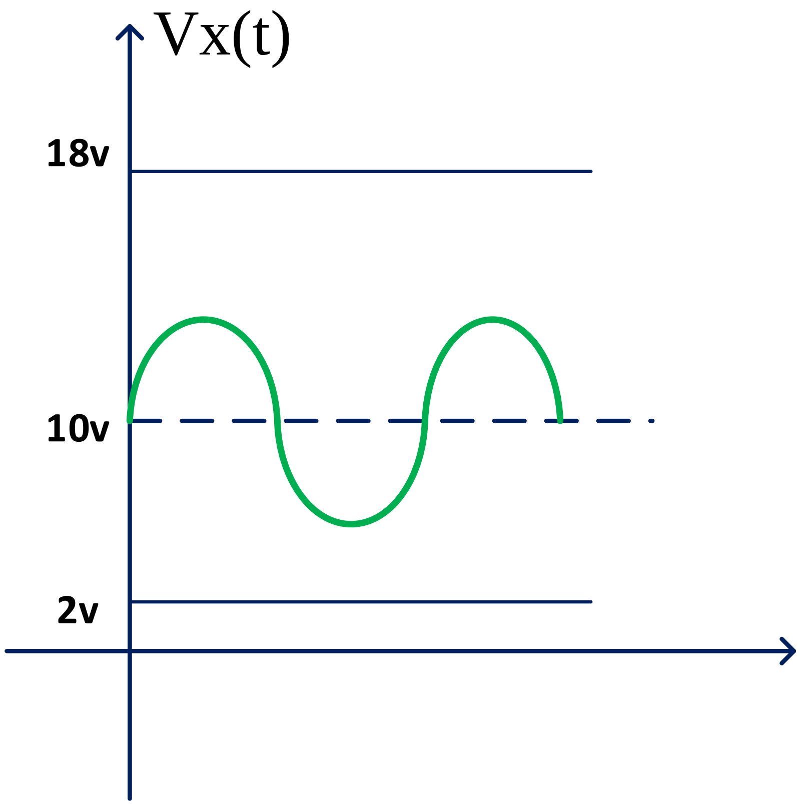


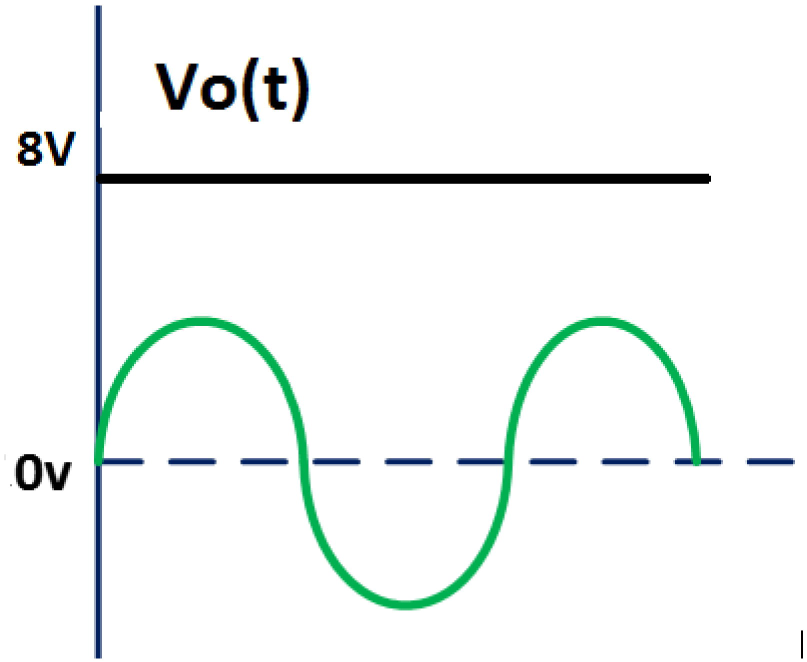
$$V\,(+) = \frac{50K}{50K+0.6K} V_i \approx V_i$$

$$V_X = V_O = \left(1+\frac{200K}{2K}\right)(V\,(+))$$

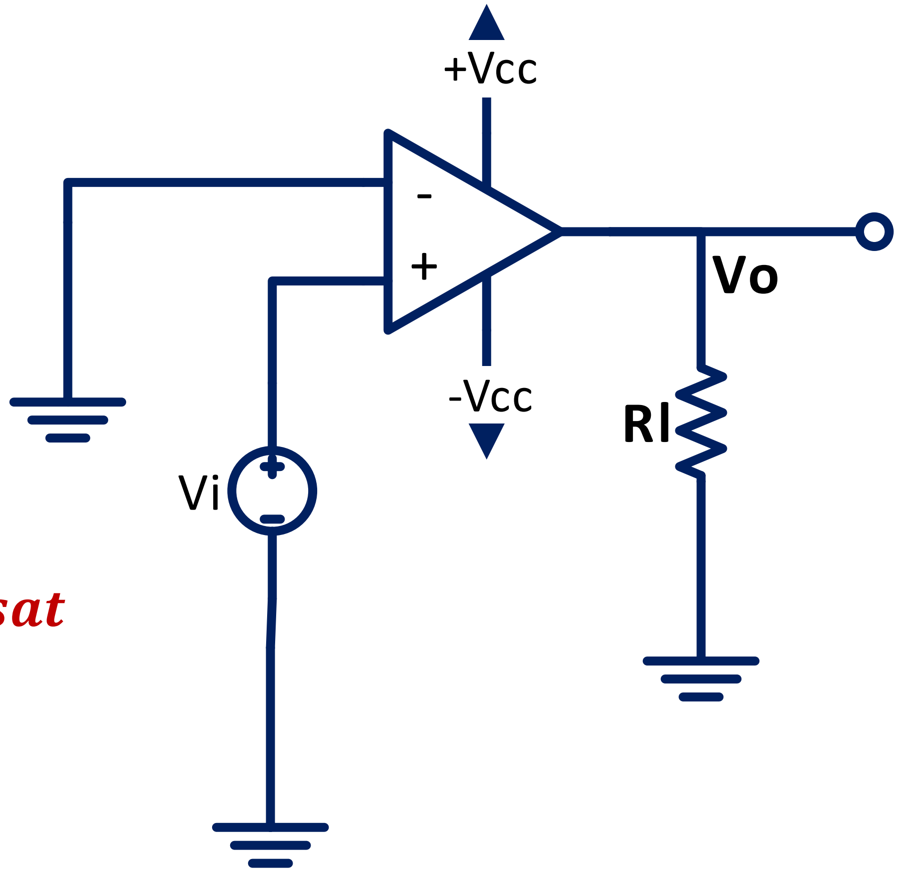
$$V_X = V_O \cong 101\, V_i$$

The Maximum possible swing = 16V peak to peak


Vx(t)
18v
10v
2v


Vo(t)
8V
0v

Comparator : Zero –Level detector



Exact analysis:

When vd $>$65µV ; V_O=+ V_{sat}

When vd $< -$65µV ; V_O= - V_{sat}

Approximate analysis

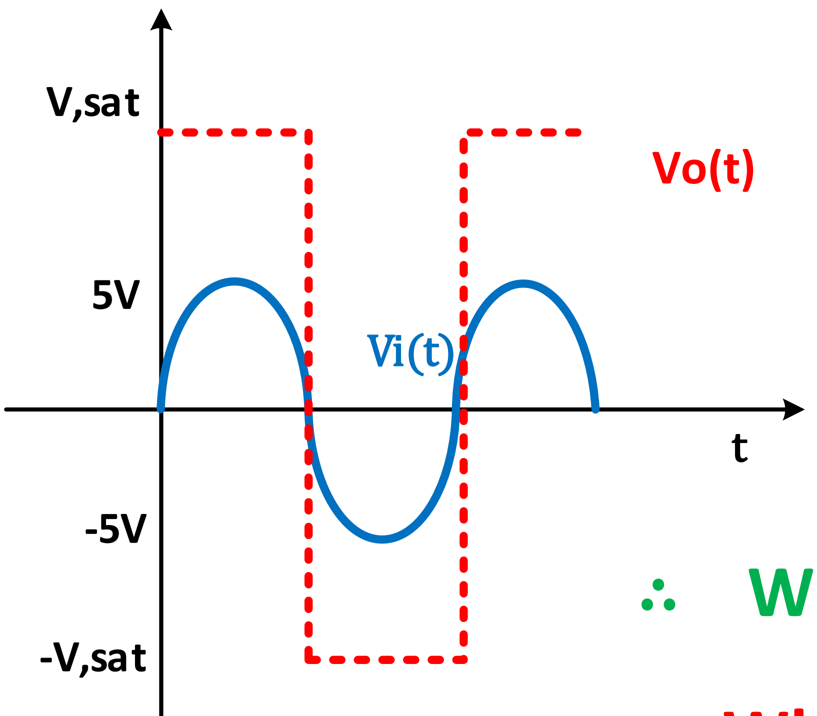
When vd $>$ 0V ; V_O = + V_{sat}

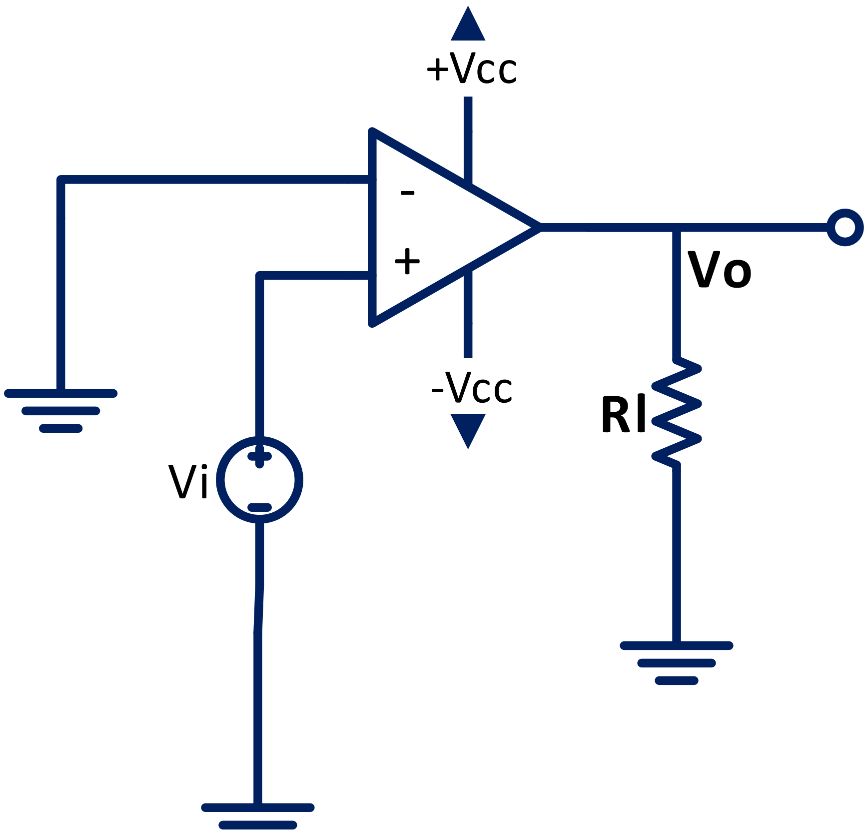
When vd $<$ 0V ; V_O = - V_{sat}

Comparator : Zero –Level detector

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

$\pm \ V_{sat}$ = ± 13 v





∴ When $V_i > 0V$; $V_O = +V_{sat}$

∴ When $V_i < 0V$; $V_O = -V_{sat}$

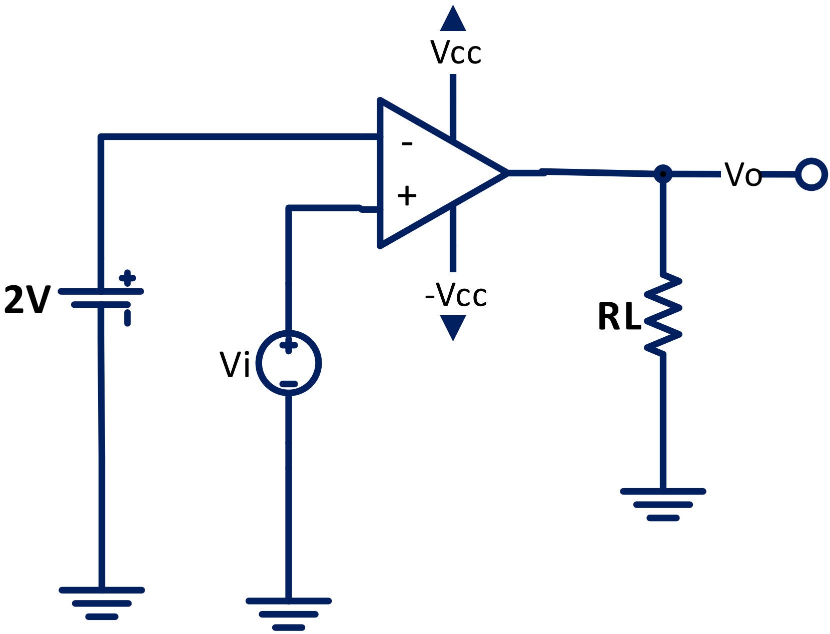
Non Zero –Level detector

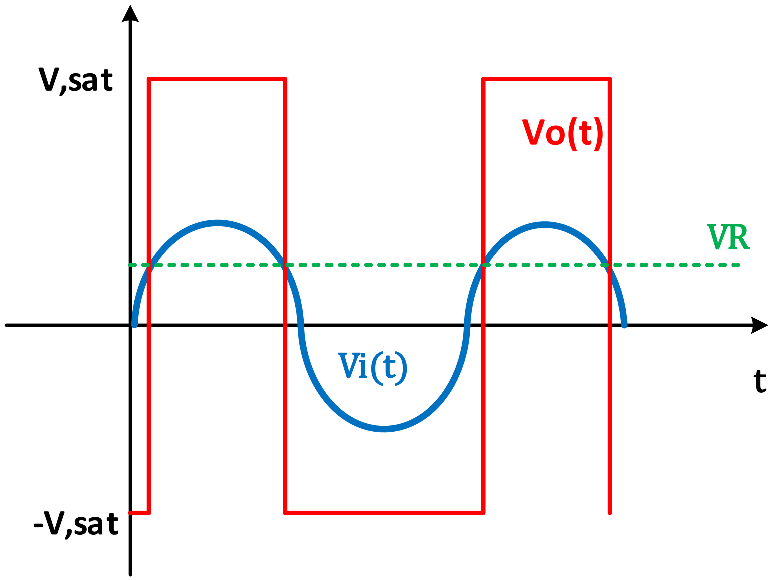
V_i (t) = 5$sin\,\omega t$ v

$\pm$ V_{sat} = $\pm$13 v

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

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



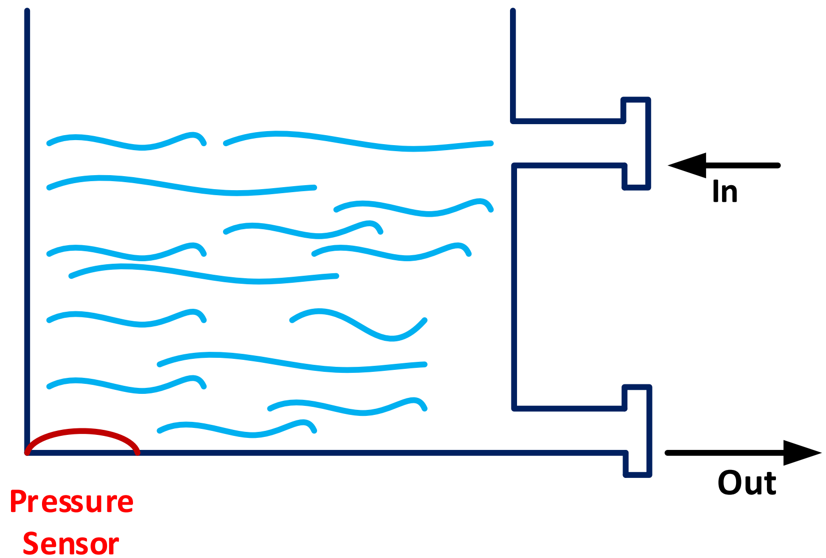


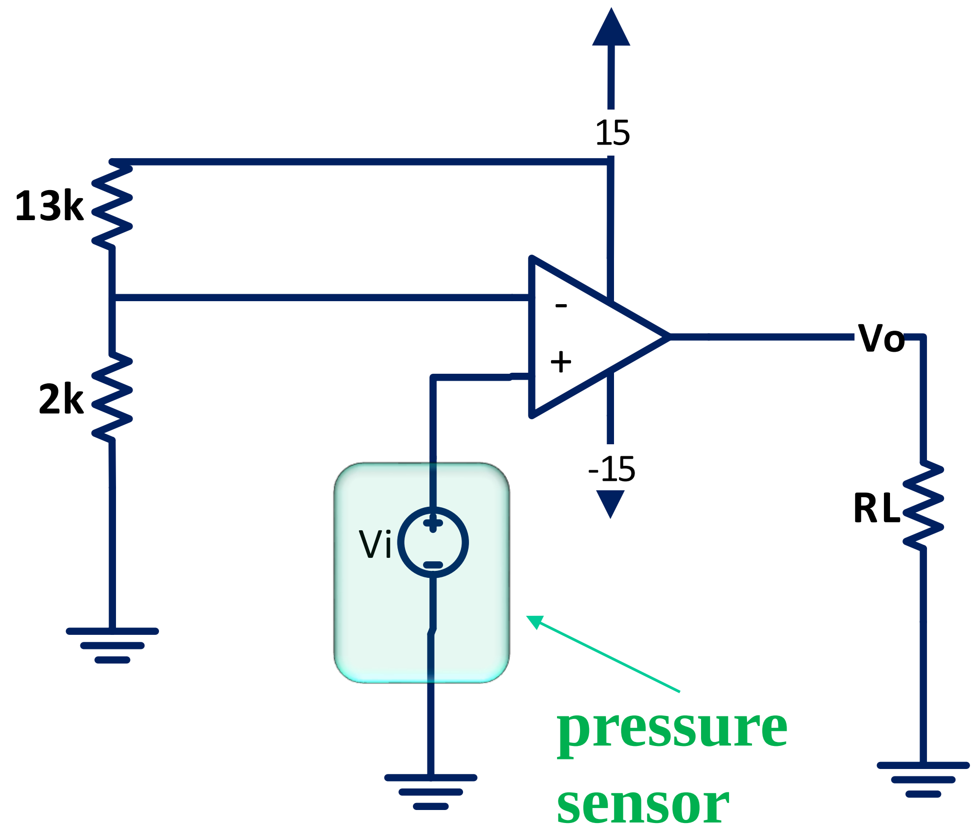
When vd > 0V ; V_O= + V_{sat}

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

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}

Voltage–Level detector with LEDs:

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

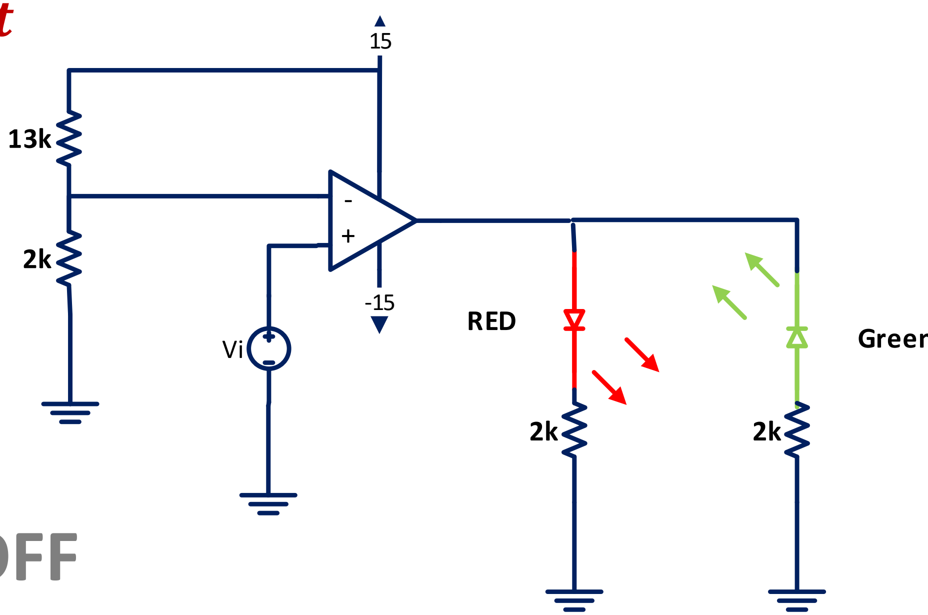
∴ Red LED is ON

∴ 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

Over Temperature sensing Circuit

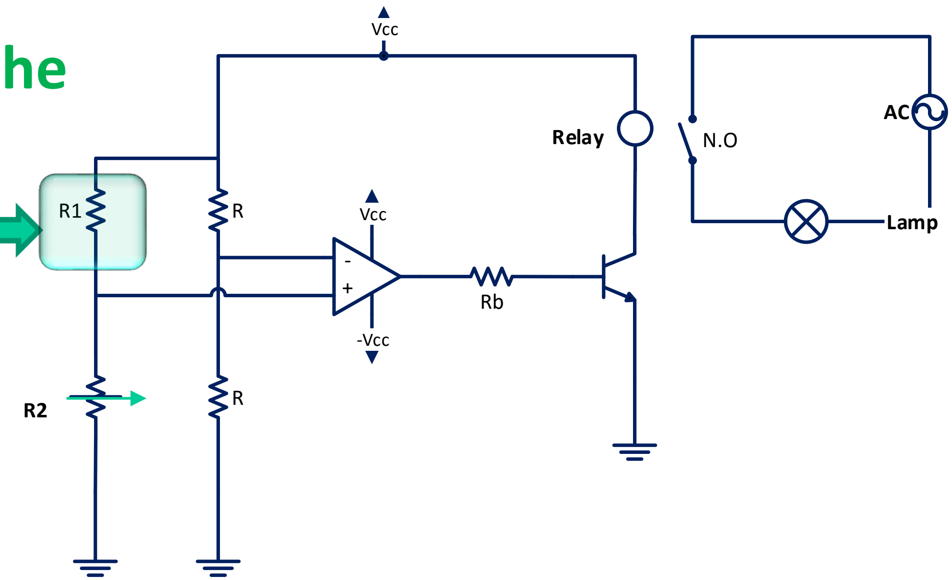
R1 ↑ as T ↓

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

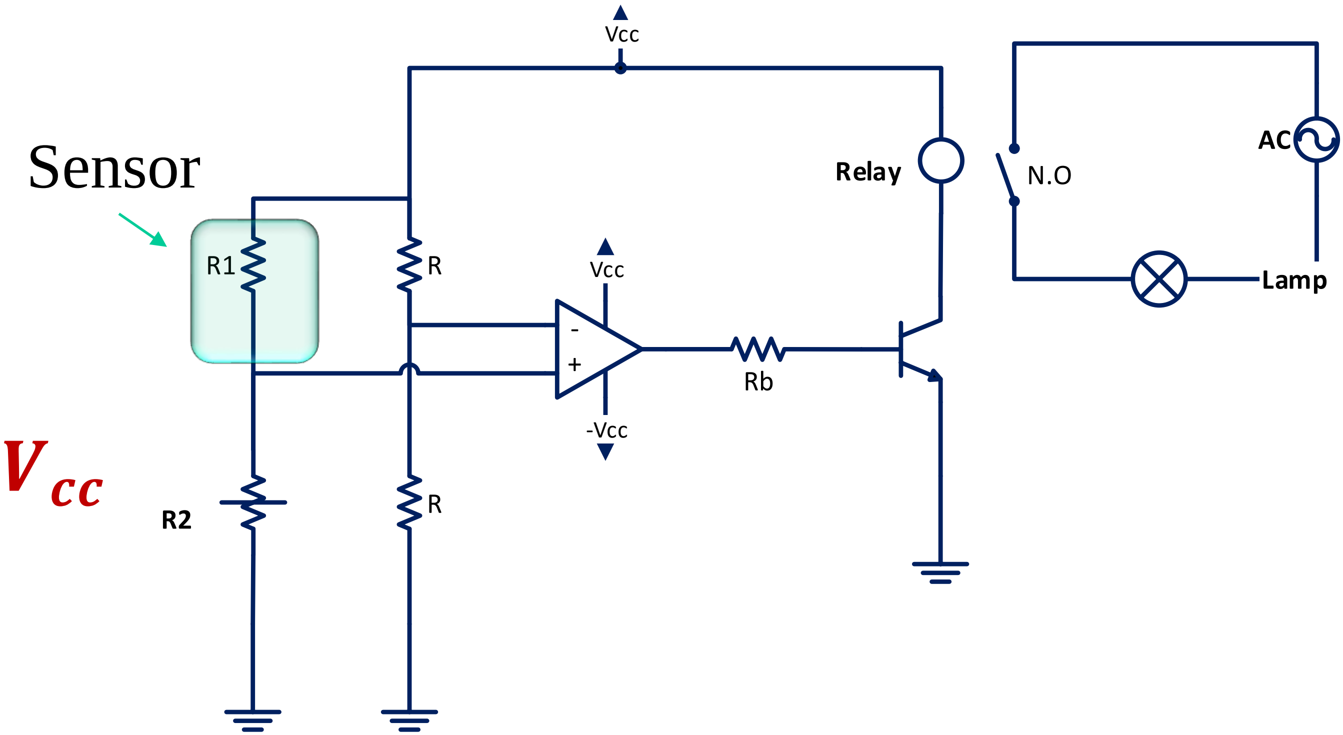
∴ Lamp is OFF

Over Temperature sensing Circuit

2)When $T = T_C$

$R_1 = R_2$

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



$\therefore V_{op} = 0$

∴ transistor is in cut OFF ;

$I_C = 0$

∴ Relay is denergized

∴ switch is open

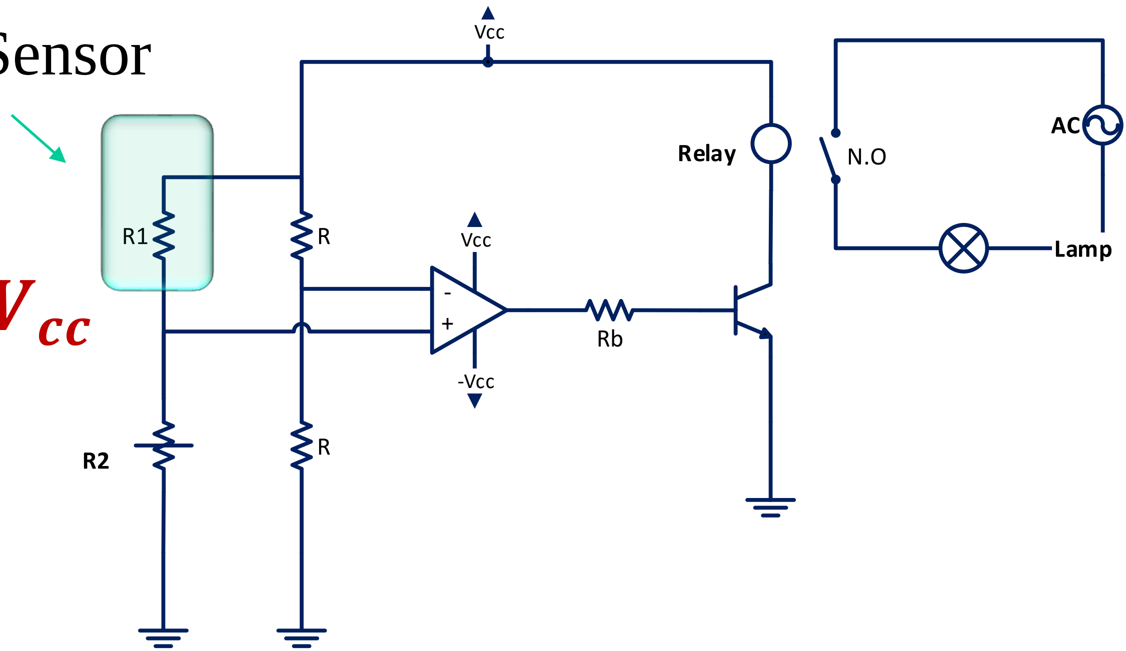
∴ Lamp is OFF

Over Temperature sensing Circuit

3- When $T > T_C$

$R_1 < R_2$

Sensor



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

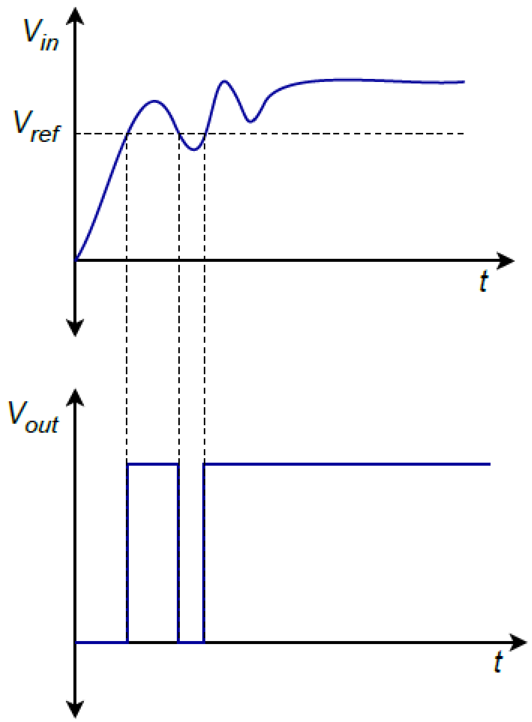
$$V(-) = \frac{1}{2} V_{cc}$$

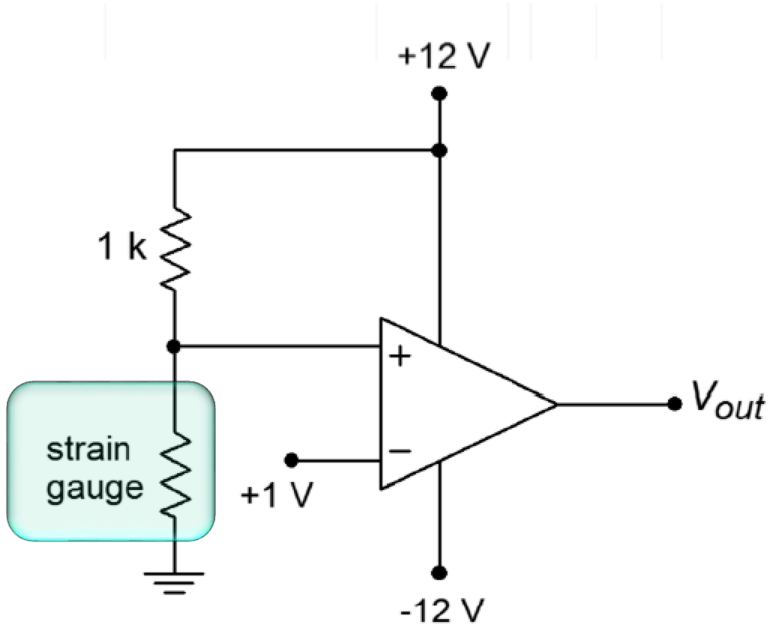
$\therefore V_{op} = + Vsat$

∴ transistor is conducting

∴ Relay is energized

∴ Lamp is on





The signal Vi is noisy

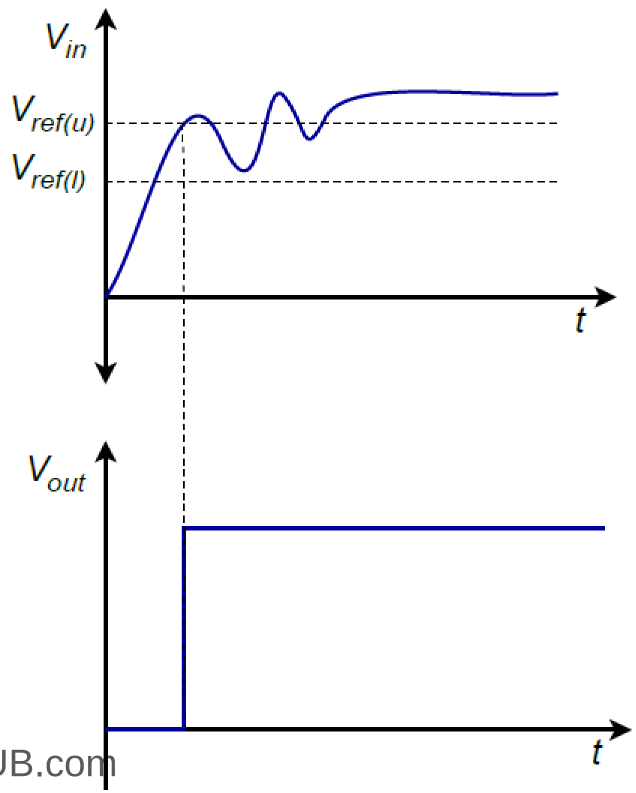
The noise will produce a false turn off spike

The solution is ***Schmitt Trigger Comparator***

We must have two references

When Vi > Vref(U) ➡ Vo switch to **+ Vsat**

When Vi < Vref(L) ➡ Vo switch to **- Vsat** **(This case should not happen in this application)**



Schmitt Trigger Comparator

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

$V(-) = V_i$

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

$vd > 0$

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

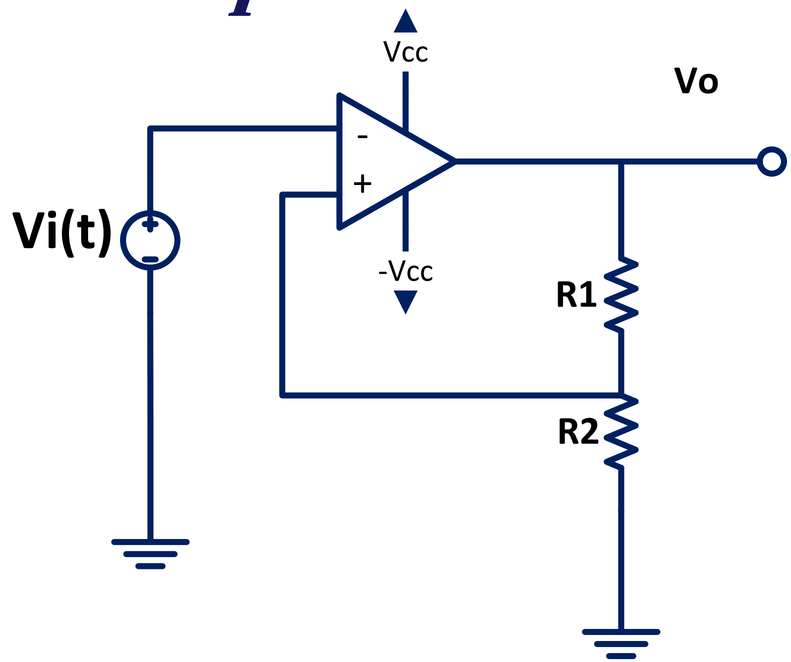
$\therefore V_i < \frac{R_2}{R_1+R_2}(+V_{sat})$

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

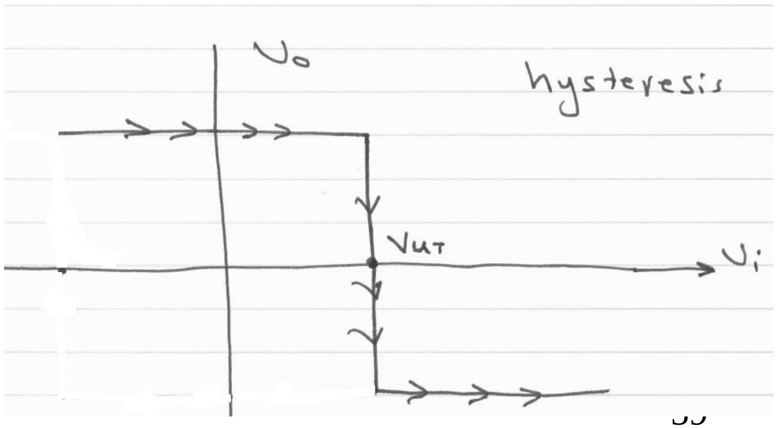
$V_O = +V_{sat}$

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

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



Inverting Schmitt trigger comparator



Schmitt Trigger Comparator

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

$V(-) = V_i$

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

$v_d < 0$

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

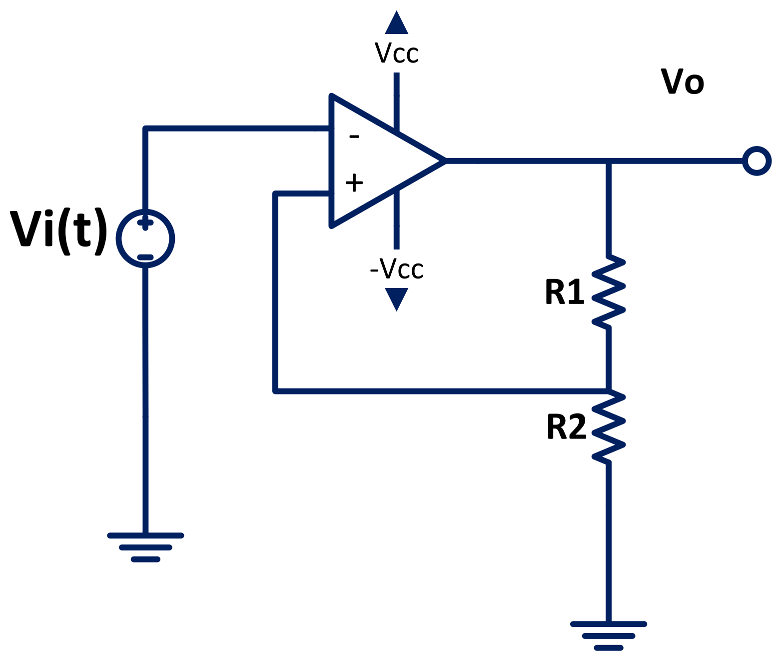
$\therefore V_i > \frac{R_2}{R_1+R_2}(-V_{sat})$

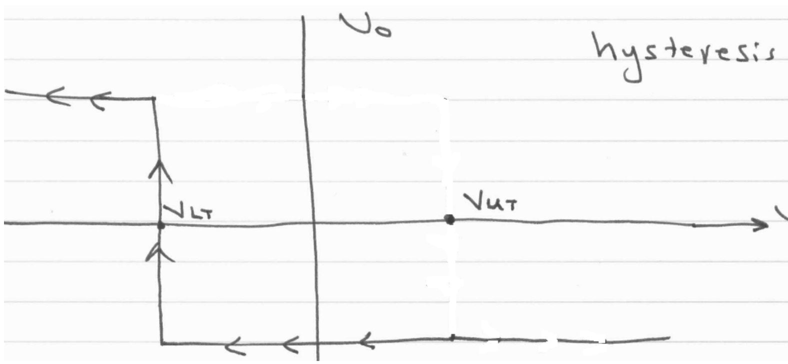
$\therefore$ as long as $V_i > \frac{R_2}{R_1+R_2}(-V_{sat})$

$V_O = -V_{sat}$

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

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





Schmitt Trigger Comparator

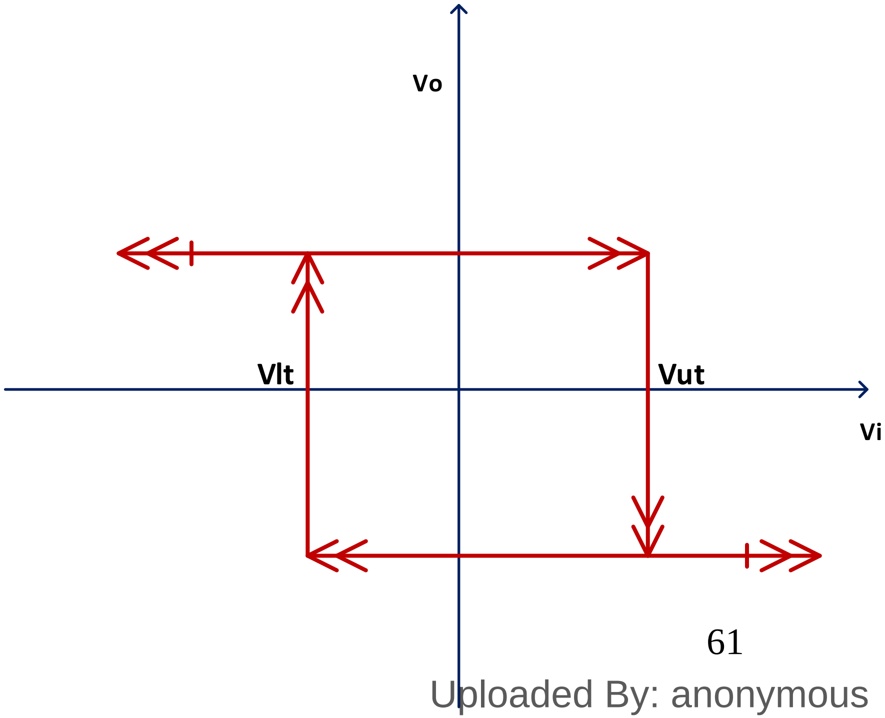
Hysteresis voltage $\equiv V_H = V_{UT} - V_{LT}$

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

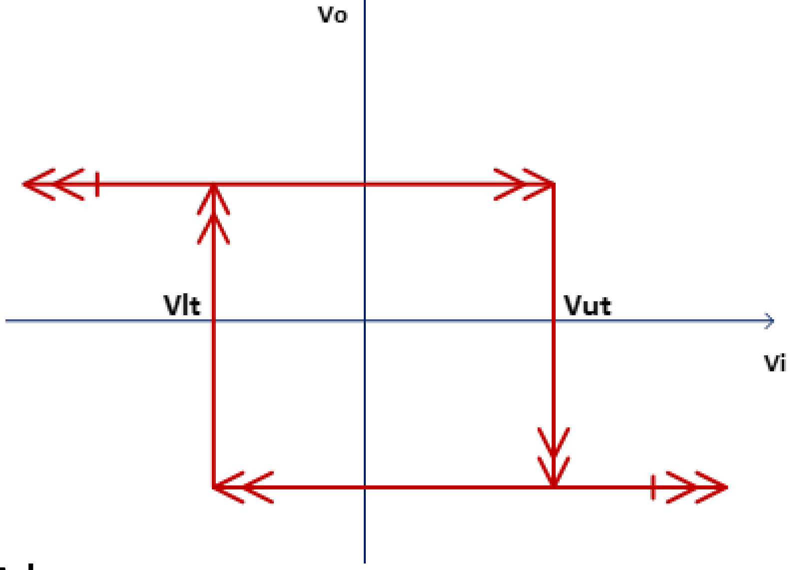
$$V_{UT} = \frac{R_2}{R_1+R_2}(+V_{sat})$$

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

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



Schmitt Trigger Comparator



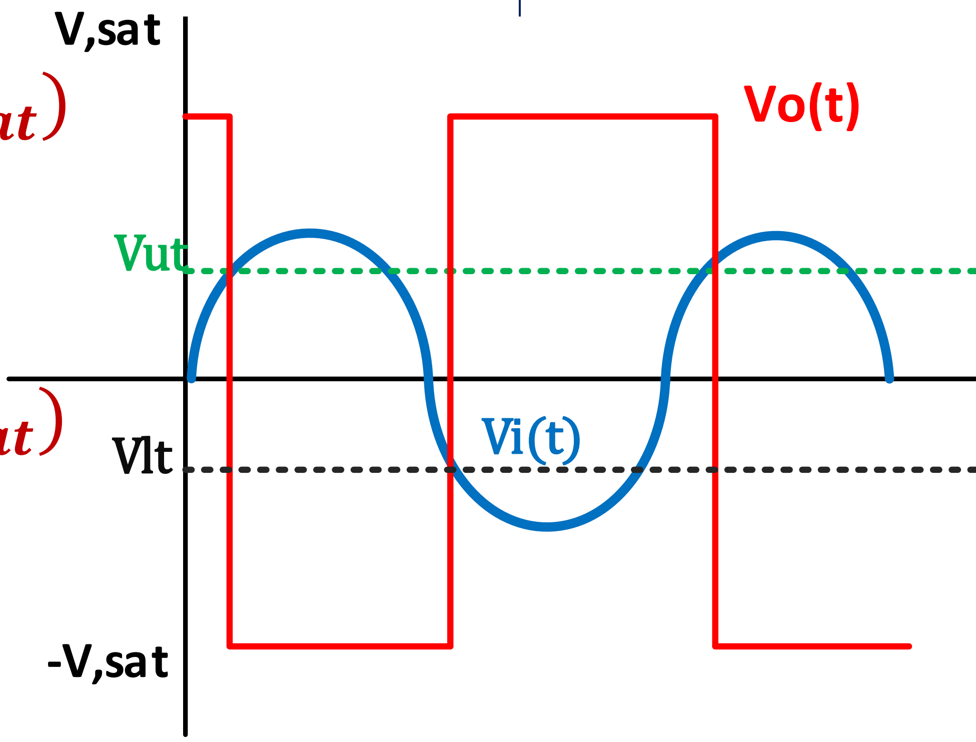
Signal Wave form

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 $(-V_{sat})$



Room Thermostat

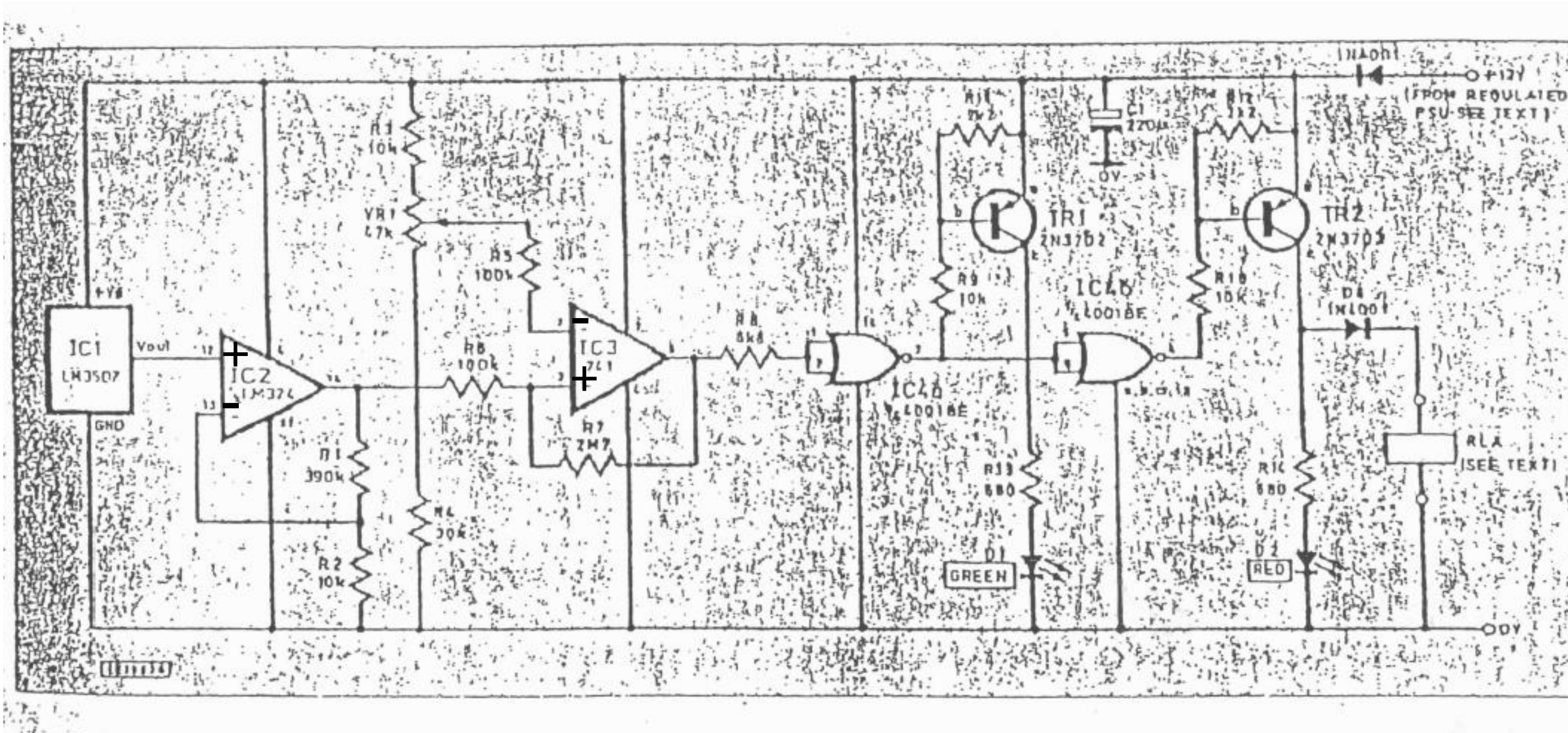


Fig. 2. Complete circuit diagram for the Room Thermostat. The connections to the "relay" are for the low voltage switchin
only.

Room Thermostat

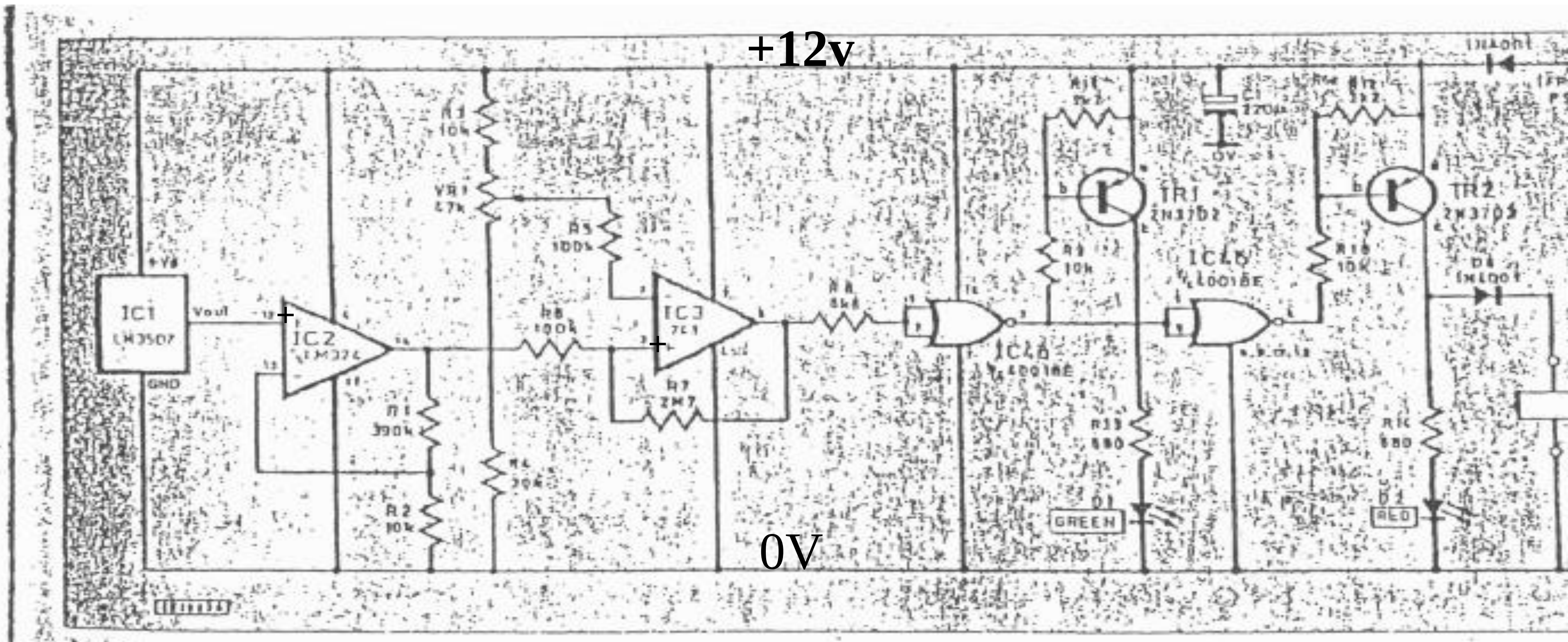


Fig. 2. Complete circuit diagram for the Room Thermostat. The connections to the "relay" are for the low voltag
only.

IC1 = LM35DZ
IC2 = LM324
IC3 = MA741
IC4 = 4001B
TR1 = 2N3702
TR2 = 2N3702

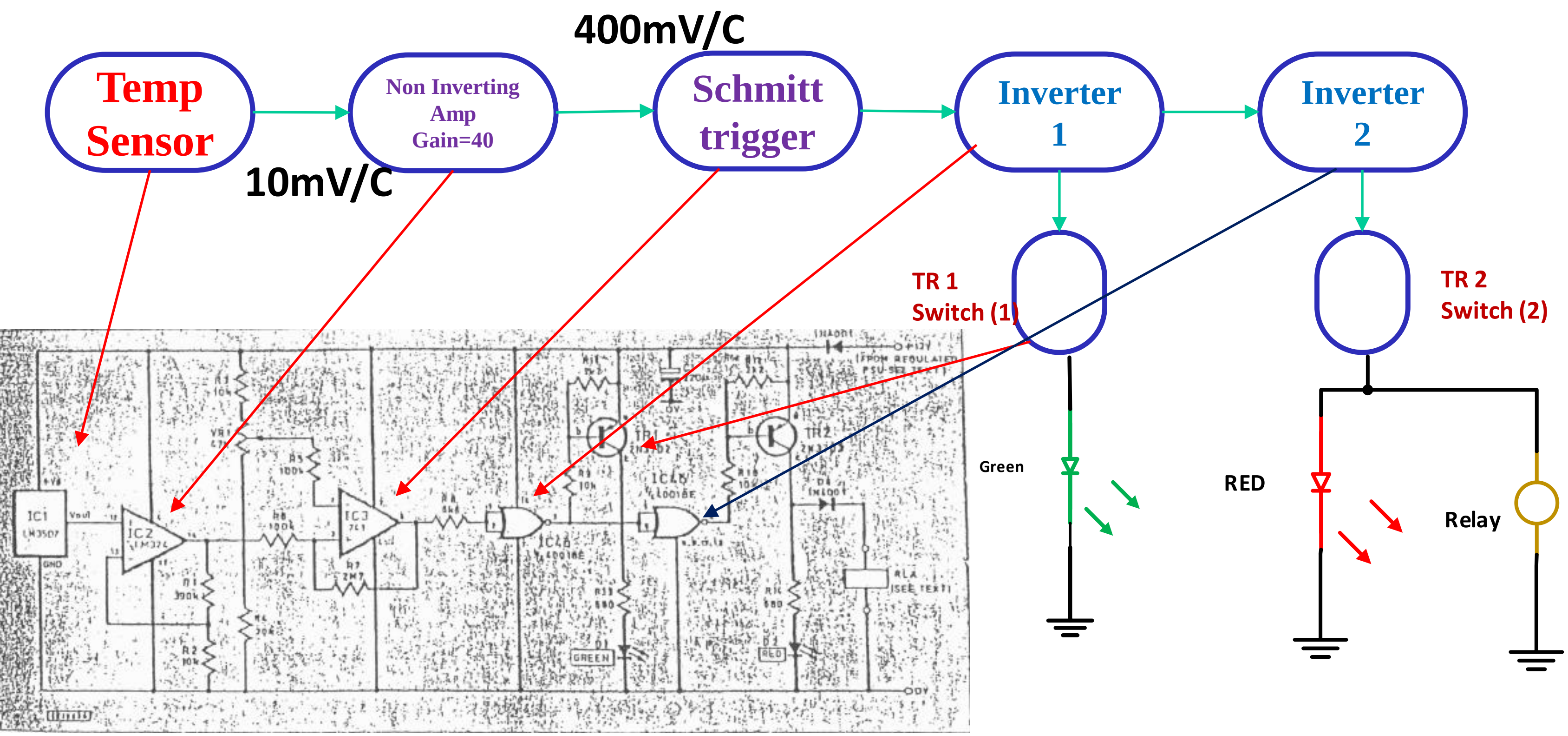
R_1 = 390K
R_2 = 10K
R_3 = 10k
VR1 = 47K
R_4 = 30K

R_5 = 100K
R_6 = 100K
R_7 = 2.7MΩ
R_8 = 6.8K

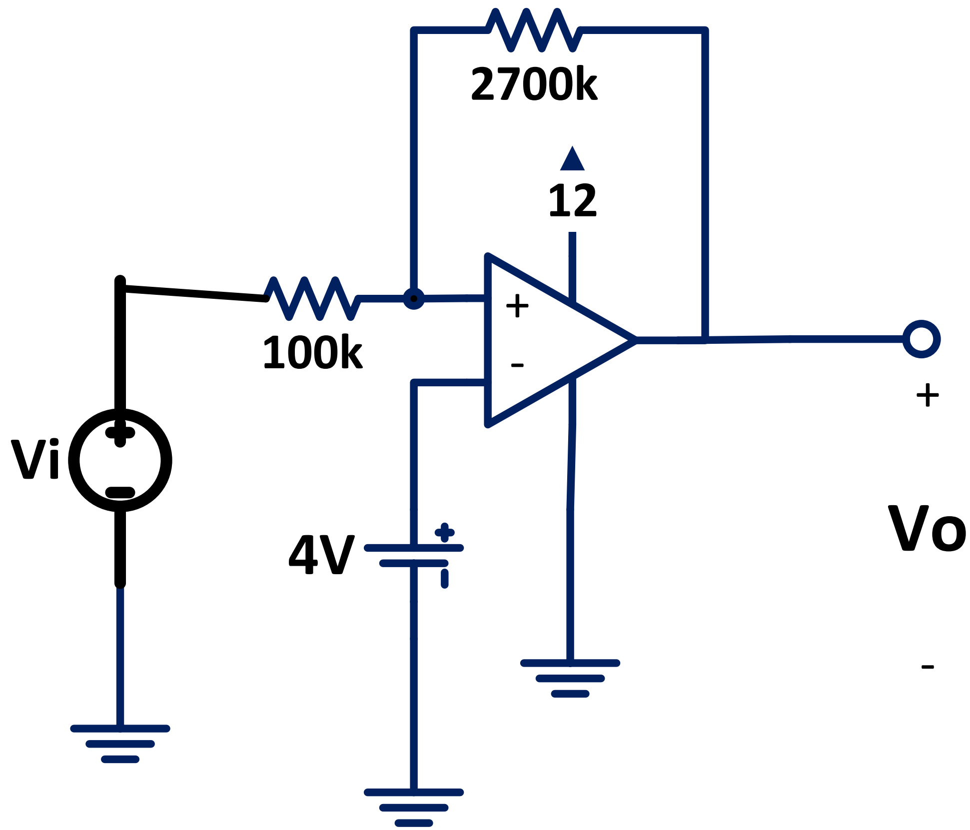
R_9 = 10K
R_{10} = 10K
R_{11} = 2.2K
R_{12} = 2.2K
R_{13} = 0.68K

Schmitt Trigger Comparator

Room Thermostat



Room Thermostat



$V_i = 400\text{mV/C}$

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

$vd > 0$

V(-) = 4v

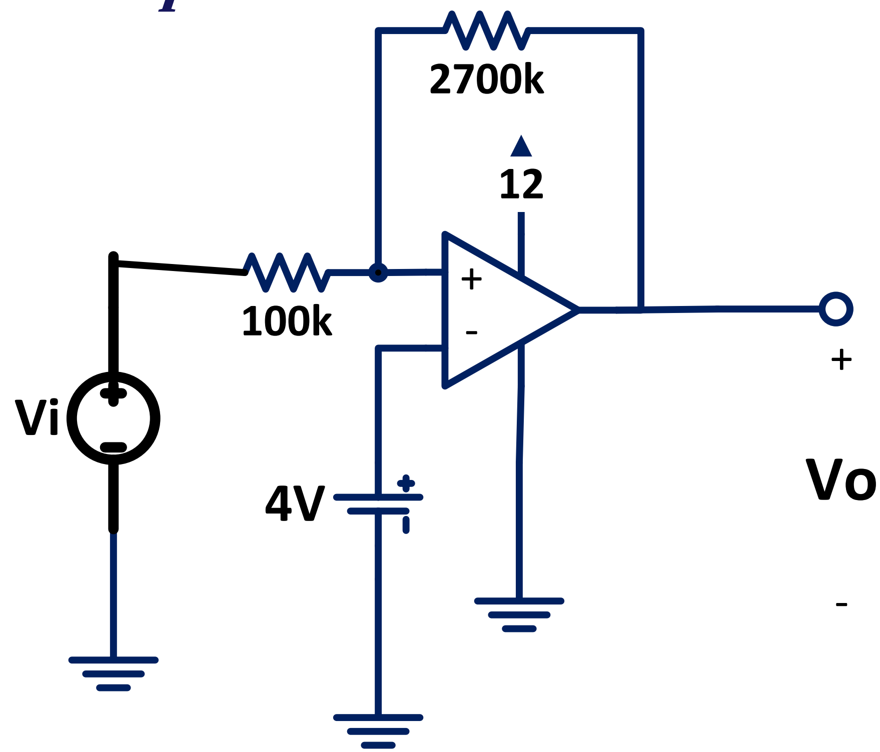
$$V(+) = \frac{100K}{100K+2700K}(+V_{sat}) + \frac{2700K}{2700K+100K} V_i$$

For $vd > 0$; $V_i > 3.777\text{V}$

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

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

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

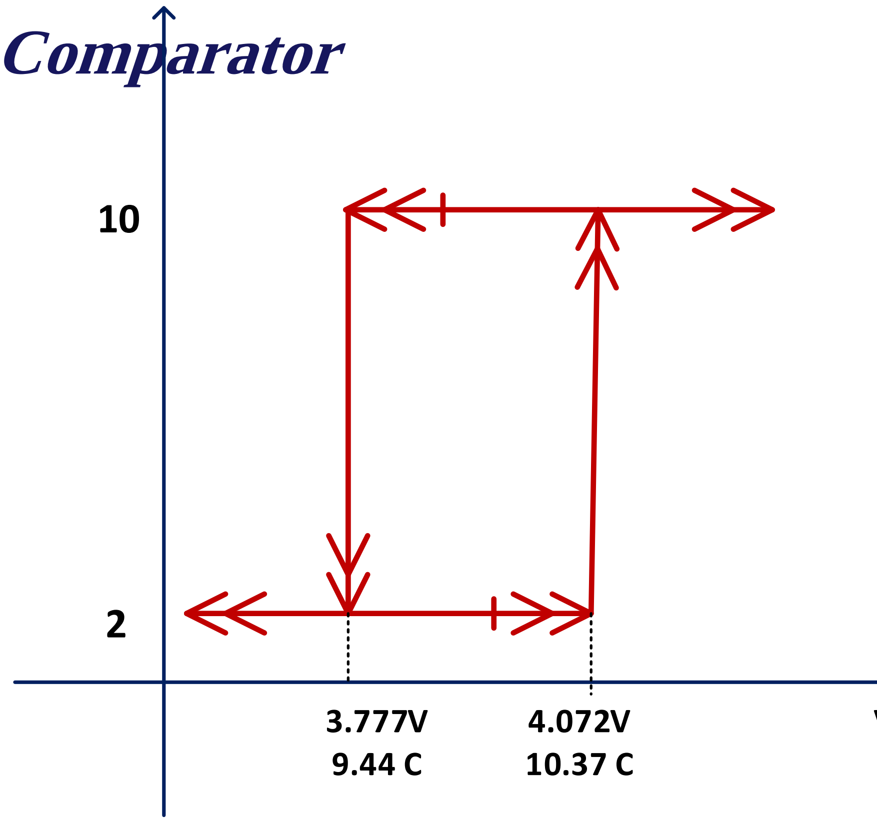
∴ As long as $V_i <$ 4.072V; $V_O = -V_{sat}$

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.

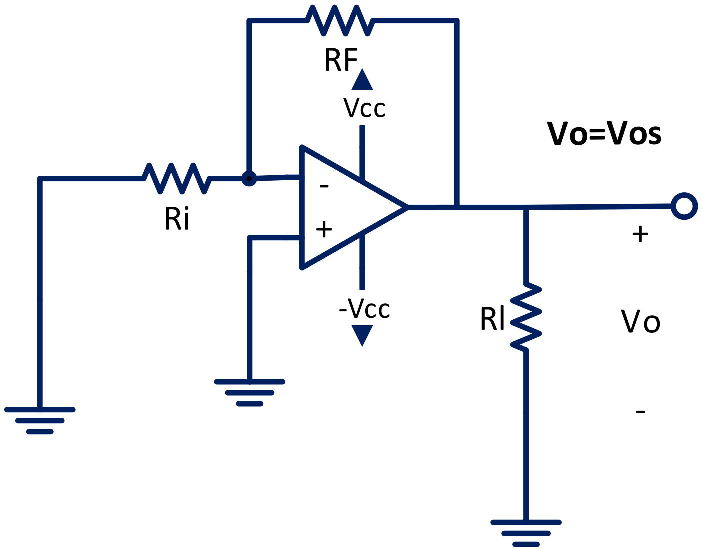
2)Then T < 9.44 C , Vo = -Vsat
Transistor (2) is On , Relay is energized
and Heater is on .

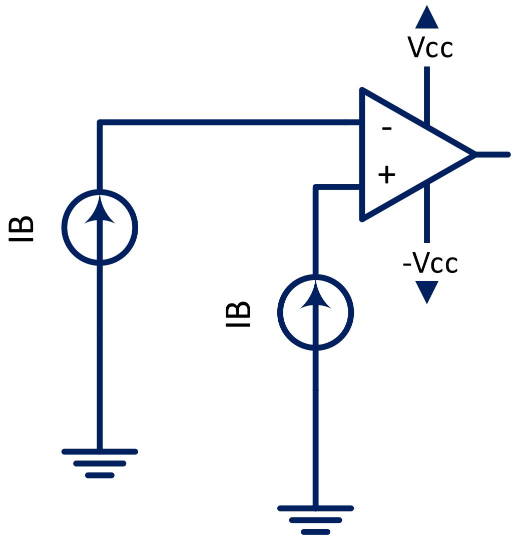


Output offset Voltage

Inverting Amplifier

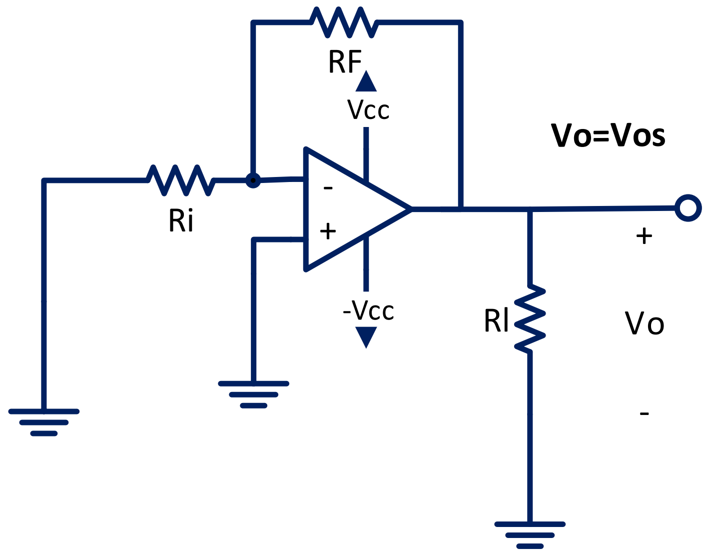
Let Vi = 0





V_{OS} ≡ the output voltage when V_i= 0

Output offset Voltage

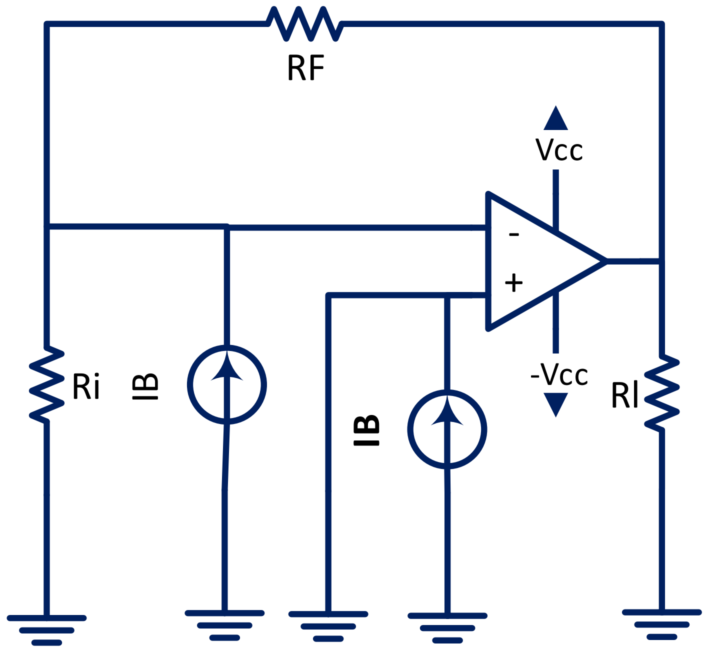


Current source in parallel with short

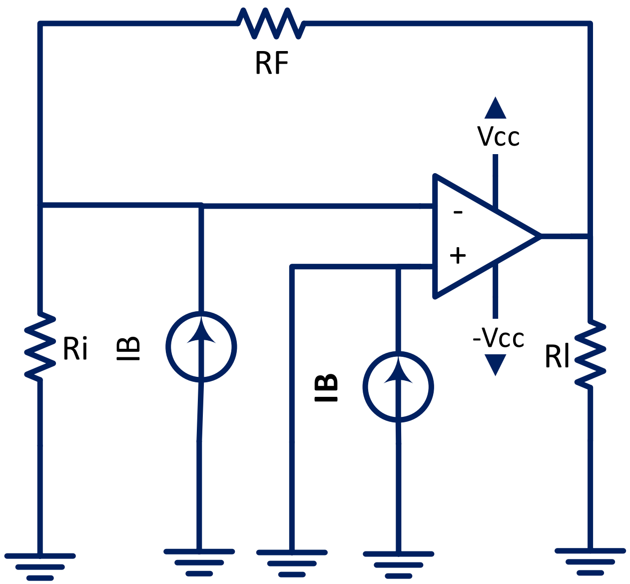
short

Current source in parallel with a resistor

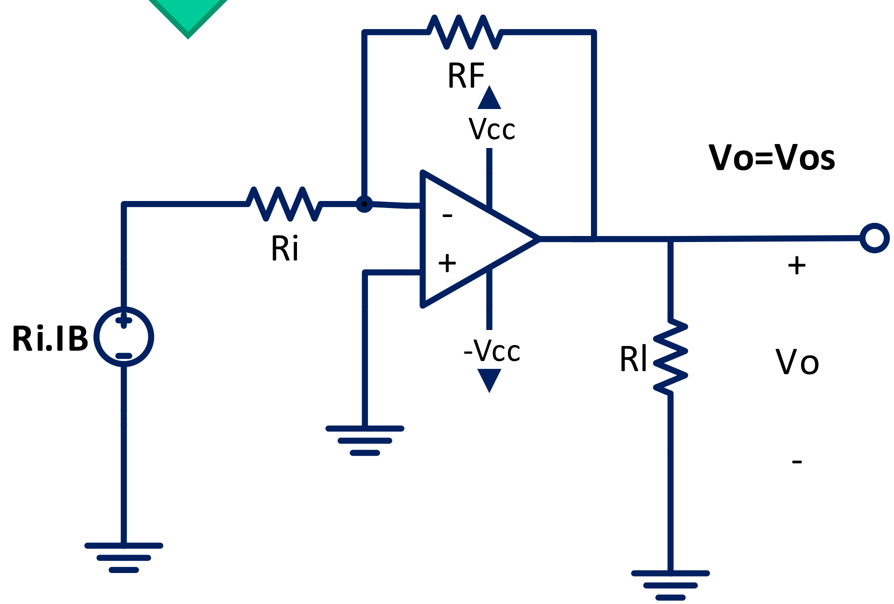
Voltage source in series with the same resistor



Output offset Voltage



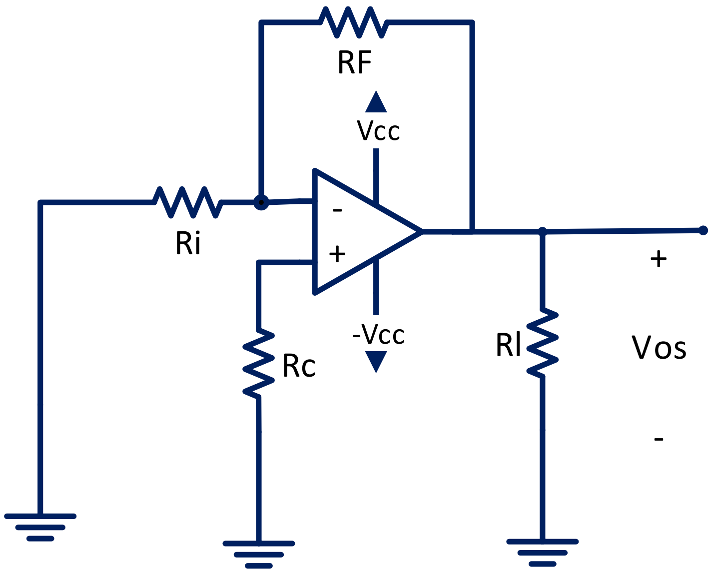
Using source transformation

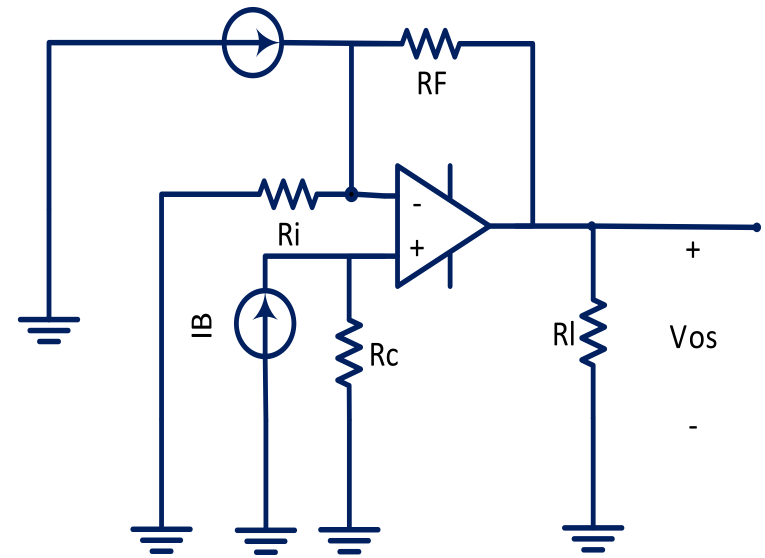


$$V_O = V_{OS} = -\frac{R_f}{R_I} R_i I_B$$

$$V_{OS} = -R_f \; I_B$$

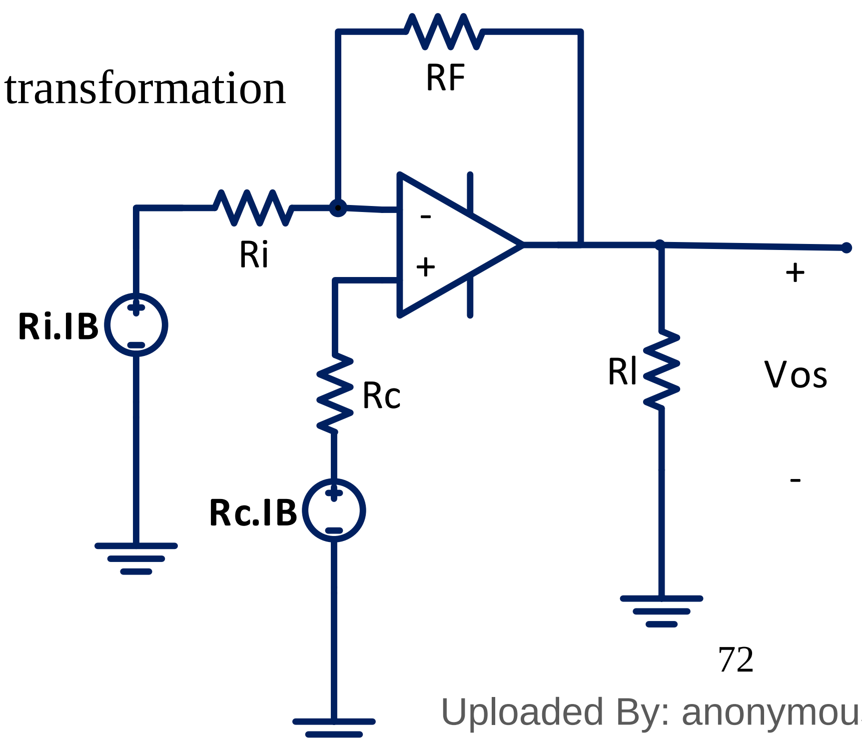
Output offset Voltage





Rc is a compensation resistor

Using source transformation



Output offset Voltage

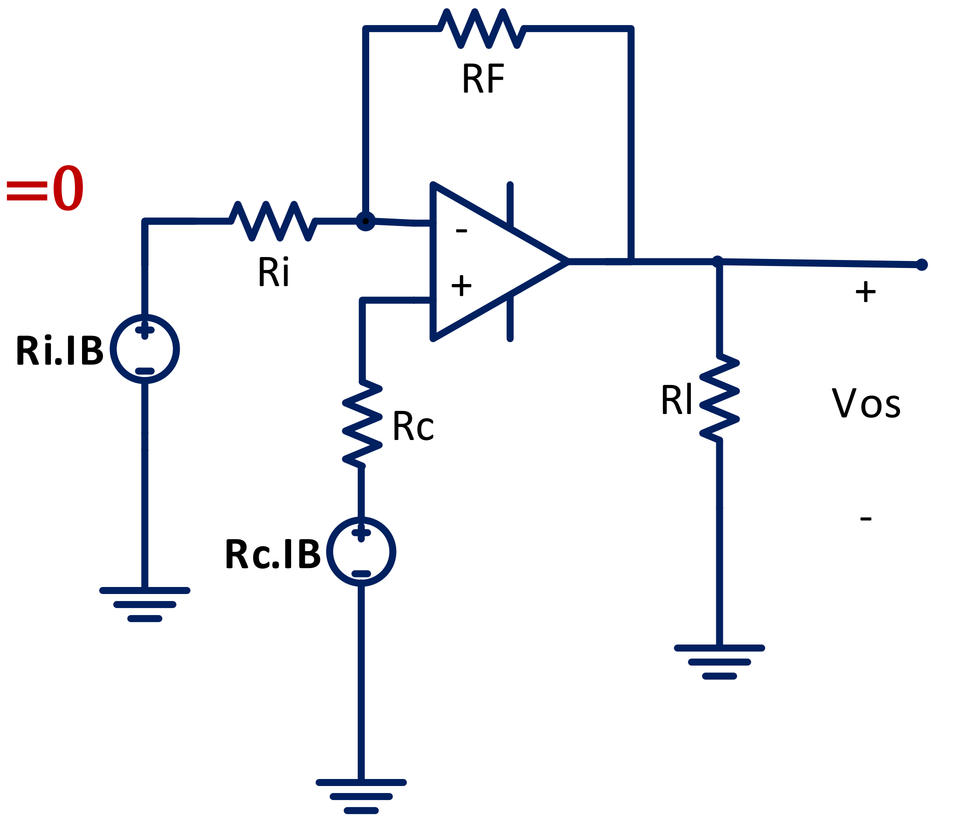
Using Superposition

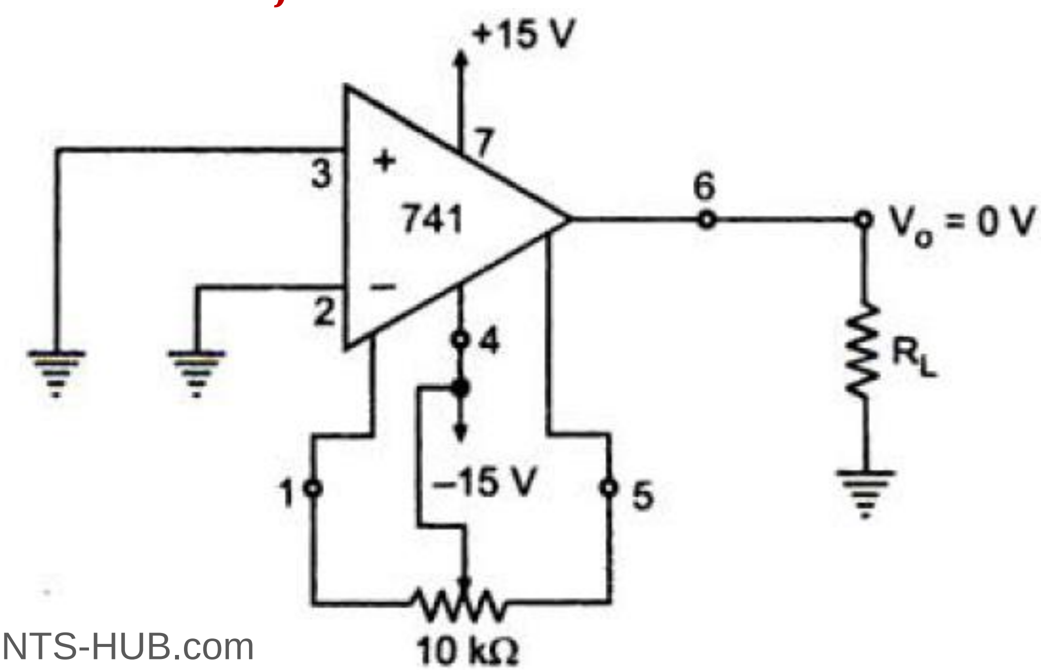
$$V_{OS} = \left(1+\frac{R_f}{R_I}\right) R_C\ I_B - \frac{R_f}{R_I}\ R_i\ I_B = 0$$

For V_O to be zero:

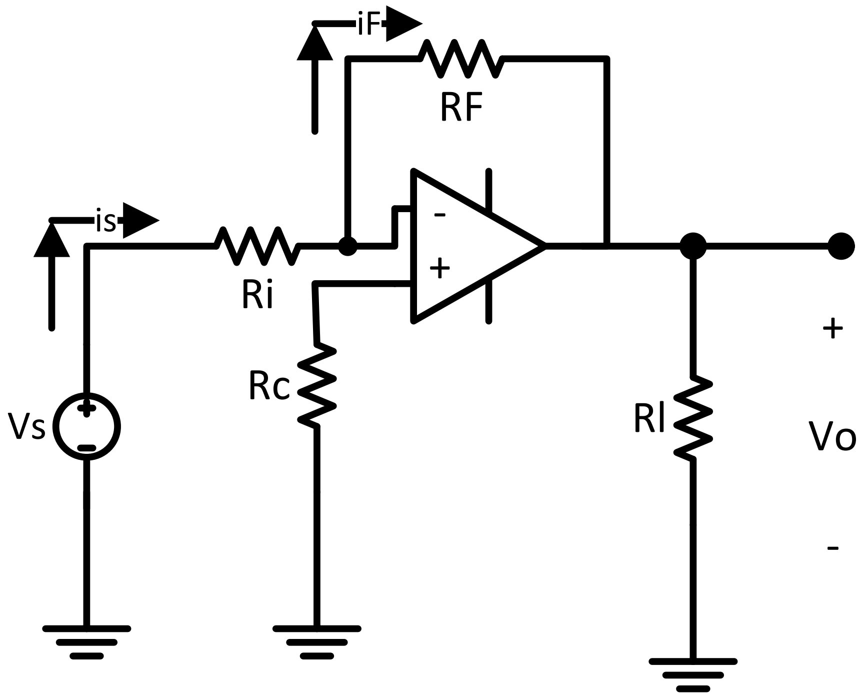
$$\left(1+\frac{R_f}{R_I}\right) R_C - R_f = 0$$

$$\therefore R_C = R_i \parallel R_f$$





Inverting Amplifier



$$V_O = -\frac{R_f}{R_I} V_s$$