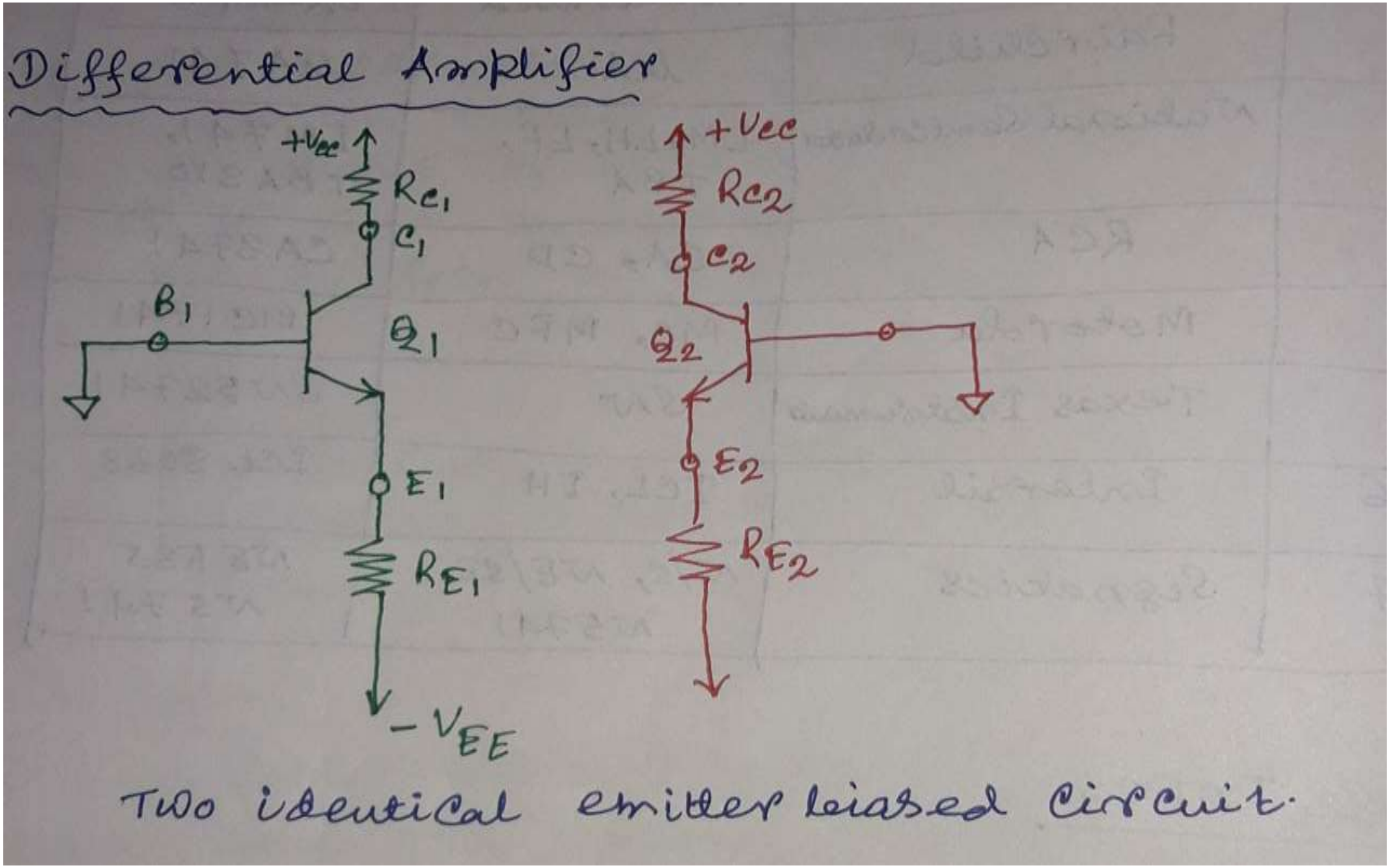
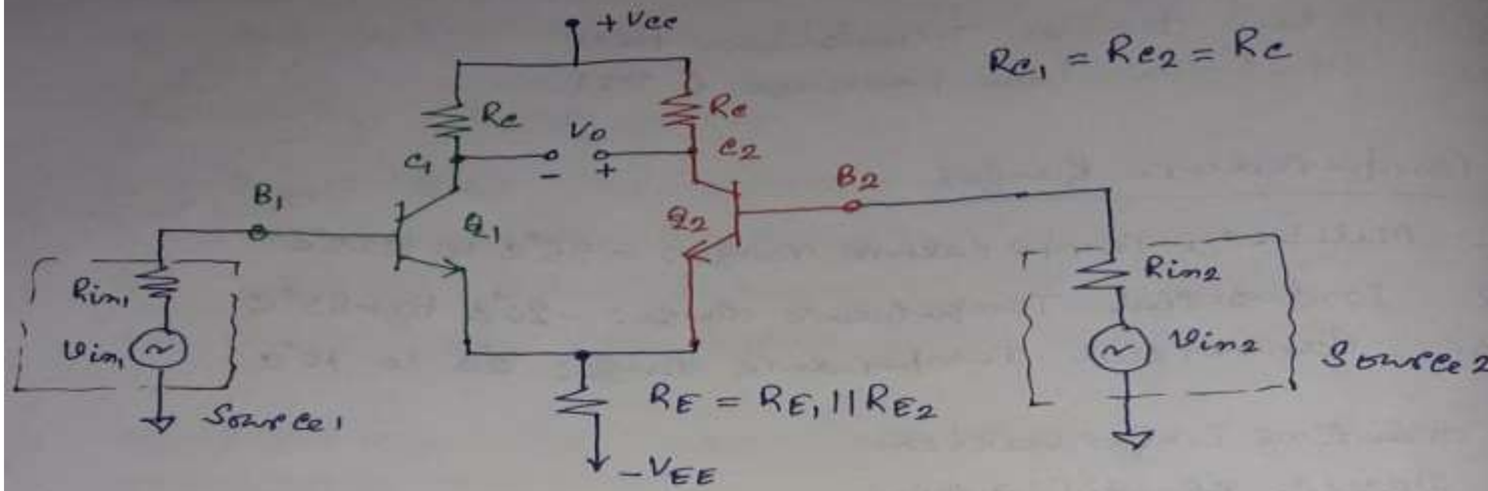
Operational Amplifier

OP AMP



Differential Amplifier
+Vcc
R_{C_1}
C_1
B_1
Q_1
E_1
R_{E_1}
$-V_{EE}$
+Vcc
R_{C_2}
C_2
Q_2
E_2
R_{E_2}
Two identical emitter biased circuit.

OP AMP



Differential Amplifier

or

Difference Amplifier

OP AMP

Four Differential Amplifier Configurations

<1> Dual-input, balanced-output differential amplifier

<2> Dual-input, unbalanced-output differential ~~differential~~ amplifier

<3> Single-input, balanced output differential amplifier

<4> Single-input unbalanced output differential amplifier.

Balanced O/P : O/P between two collectors

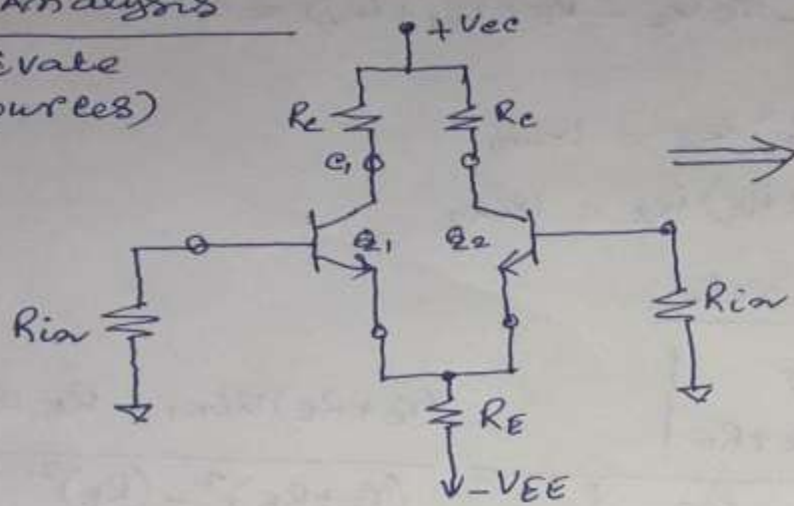
Unbalanced O/P : O/P between one of the collector and ground.

OP AMP

Dual Input, Balanced Output Differential Amplifier

DC Analysis

Deactivate AC Sources)



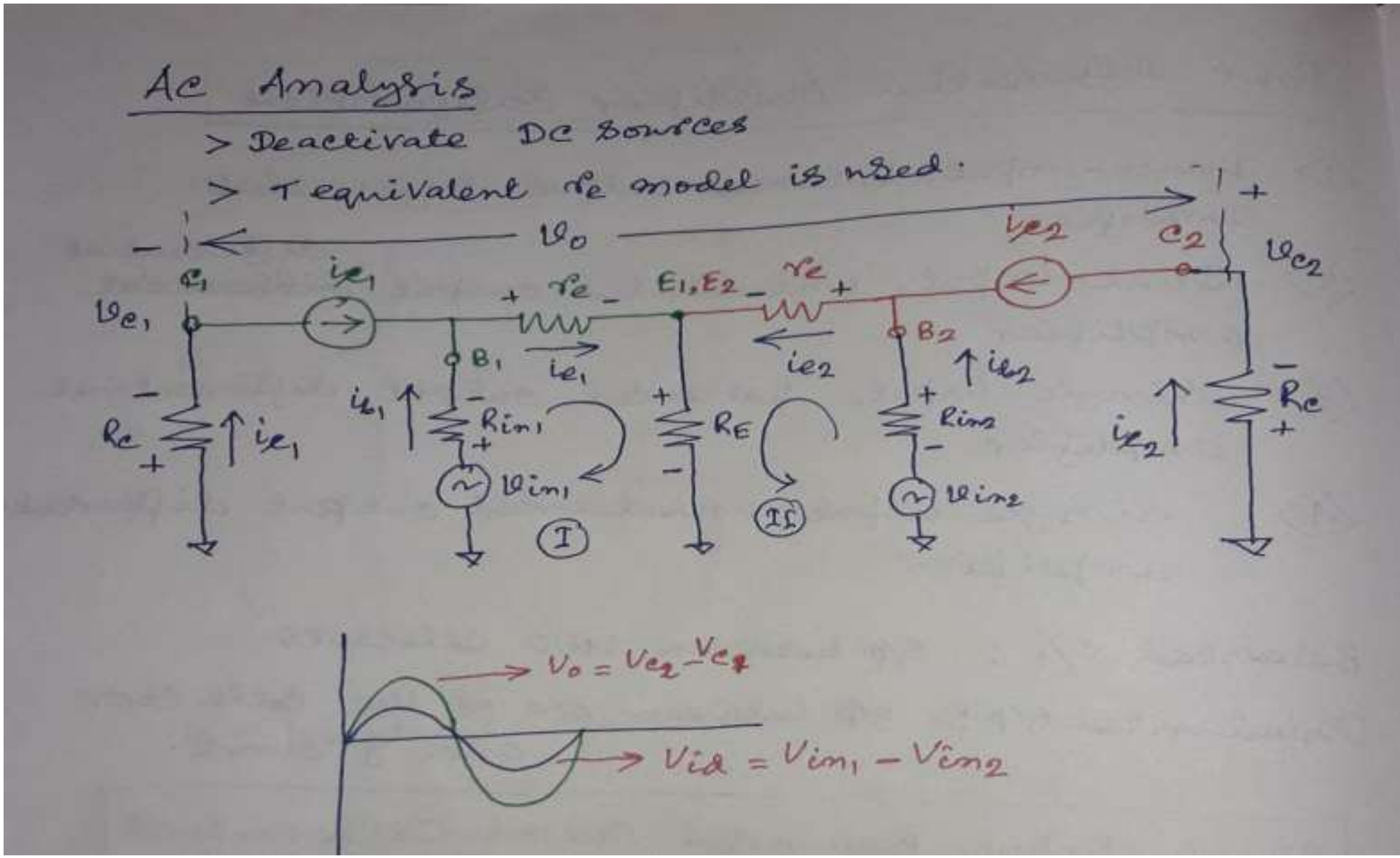
$\Longrightarrow$ Placement of Q point

$\downarrow$

middle of load line.

$$|+V_{cc}| = |-V_{EE}|$$

OP AMP


Ac Analysis
> Deactivate DC sources
> T equivalent re model is used.
vo
C1
C2
vc1
vc2
ie1
ie2
re
E1, E2
B1
B2
ib1
ib2
Rc
RE
Rin1
Rin2
vin1
vin2
I
II
Vo = Vc2 - Vc1
Vid = Vin1 - Vin2

OP AMP

Small

$$v_{in_1} - (R_{in_1} i_{b_1}) - r_e i_{e_1} - R_E (i_{e_1} + i_{e_2}) = 0$$

$$v_{in_2} - (R_{in_2} i_{b_2}) - r_e i_{e_2} - R_E (i_{e_1} + i_{e_2}) = 0$$

Small

$$(r_e + R_E) i_{e_1} + (R_E) i_{e_2} = v_{in_1}$$

$$(R_E) i_{e_1} + (r_e + R_E) i_{e_2} = v_{in_2}$$

Using Cramer's rule

$$i_{e_1} = \frac{\begin{vmatrix} v_{in_1} & R_E \\ v_{in_2} & r_e + R_E \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}} = \frac{(r_e + R_E) v_{in_1} - R_E v_{in_2}}{(r_e + R_E)^2 - (R_E)^2}$$

OP AMP

$$i_{e_2} = \frac{\begin{vmatrix} r_e + R_E & v_{in_1} \\ R_E & v_{in_2} \end{vmatrix}}{\begin{vmatrix} r_e + R_E & R_E \\ R_E & r_e + R_E \end{vmatrix}} \qquad (r_e+R_E)^2 - (R_E)^2$$

$$= \frac{(r_e+R_E)\, v_{in_2} - (R_E)\, v_{in_1}}{(r_e+R_E)^2 - (R_E)^2}$$

$$v_o = v_{c_2} - v_{c_1}$$

$$= -R_c i_{c_2} - (-R_c i_{c_1})$$

$$= R_c i_{e_1} - R_c i_{c_2}$$

$$= R_c (i_{e_1} - i_{e_2}) \qquad \text{since } i_c \simeq i_e$$

OP AMP

$$v_o = R_c \left[\frac{(r_e+R_E)\, v_{in_1} - (R_E)\, v_{in_2}}{(r_e+R_E)^2 - (R_E)^2} - \frac{(r_e+R_E)\, v_{in_2} - (R_E)\, v_{in_1}}{(r_e+R_E)^2 - (R_E)^2} \right]$$

$$= R_c \, \frac{(r_e+R_E)(v_{in_1} - v_{in_2}) + (R_E)(v_{in_1} - v_{in_2})}{(r_e+R_E)^2 - (R_E)^2}$$

$$= R_c \, \frac{(r_e + 2R_E)(v_{in_1} - v_{in_2})}{r_e (r_e + 2R_E)}$$

$$\therefore \boxed{v_o = \frac{R_c}{r_e} (v_{in_1} - v_{in_2})}$$

A_d = Differential Gain $= \dfrac{v_o}{v_{id}} = \dfrac{R_c}{r_e}$

OP AMP

Differential input resistance.

$$R_{i_1} = \left.\frac{v_{in_1}}{i_{b_1}}\right|_{v_{in_2}=0} = \left|\frac{v_{in_1}}{i_{e_1}/\beta_{ac}}\right|_{v_{in_2}=0}$$

$$= \frac{\beta_{ac}\, v_{in_1}}{\dfrac{(r_e+R_E)\,v_{in_1} - (R_E)(0)}{(r_e+R_E)^2 - R_E^2}}$$

$$= \frac{\beta_{ac}\cdot r_e\,(r_e+2R_E)}{(r_e+R_E)}$$

$r_e + 2R_E \simeq 2R_E$, $\quad r_e + R_E \simeq R_E$

$$\boxed{R_{i_1} = 2\,\beta_{ac}\, r_e}$$

OP AMP

$$R_{i2} = \left.\frac{v_{in2}}{i_{b2}}\right|_{v_{in1}=0} = \left|\frac{v_{in2}}{i_{e2}/\beta_{ac}}\right|_{v_{in1}=0}$$

$$= \frac{\beta_{ac}\, v_{in2}}{\dfrac{(r_e+R_E)\, v_{in2} - (R_E)(0)}{(r_e+R_E)^2 - (R_E)^2}}$$

$$= \frac{\beta_{ac}\, r_e\,(r_e + 2R_E)}{(r_e+R_E)}$$

$$\boxed{R_{i2} = 2\beta_{ac}\, r_e.}$$

OP AMP

Output Resistance

$R_{o1} = R_{o2} = R_c$.

Inverting & noninverting terminal.

$$v_o = \frac{R_c}{r_e}(v_{in1} - v_{in2})$$

if $v_{in1} = v_{in}$, $v_{in2} = 0$

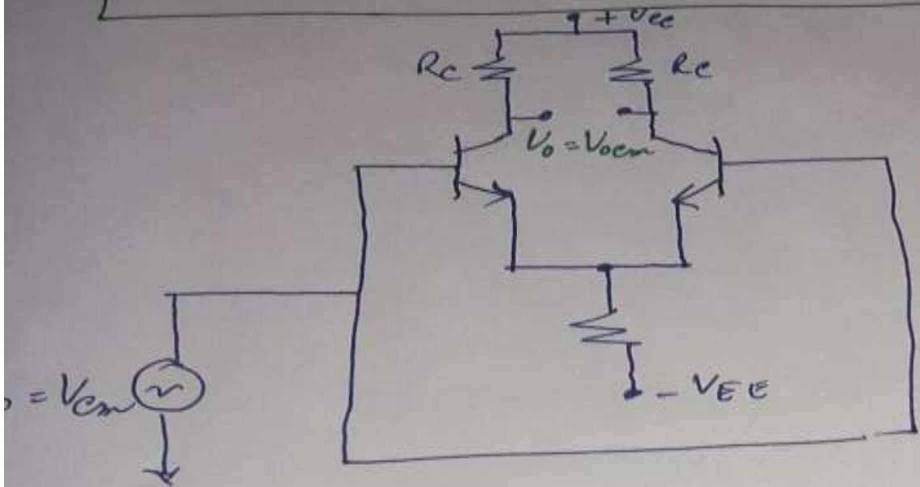
$\therefore v_o = \frac{R_c}{r_e} v_{in}$ (noninverting terminal)

if $v_{in1} = 0$, $v_{in2} = v_{in}$

$v_o = -\frac{R_c}{r_e} v_{in}$ (inverting terminal)

OP AMP

Common Mode Rejection Ratio (CMRR)



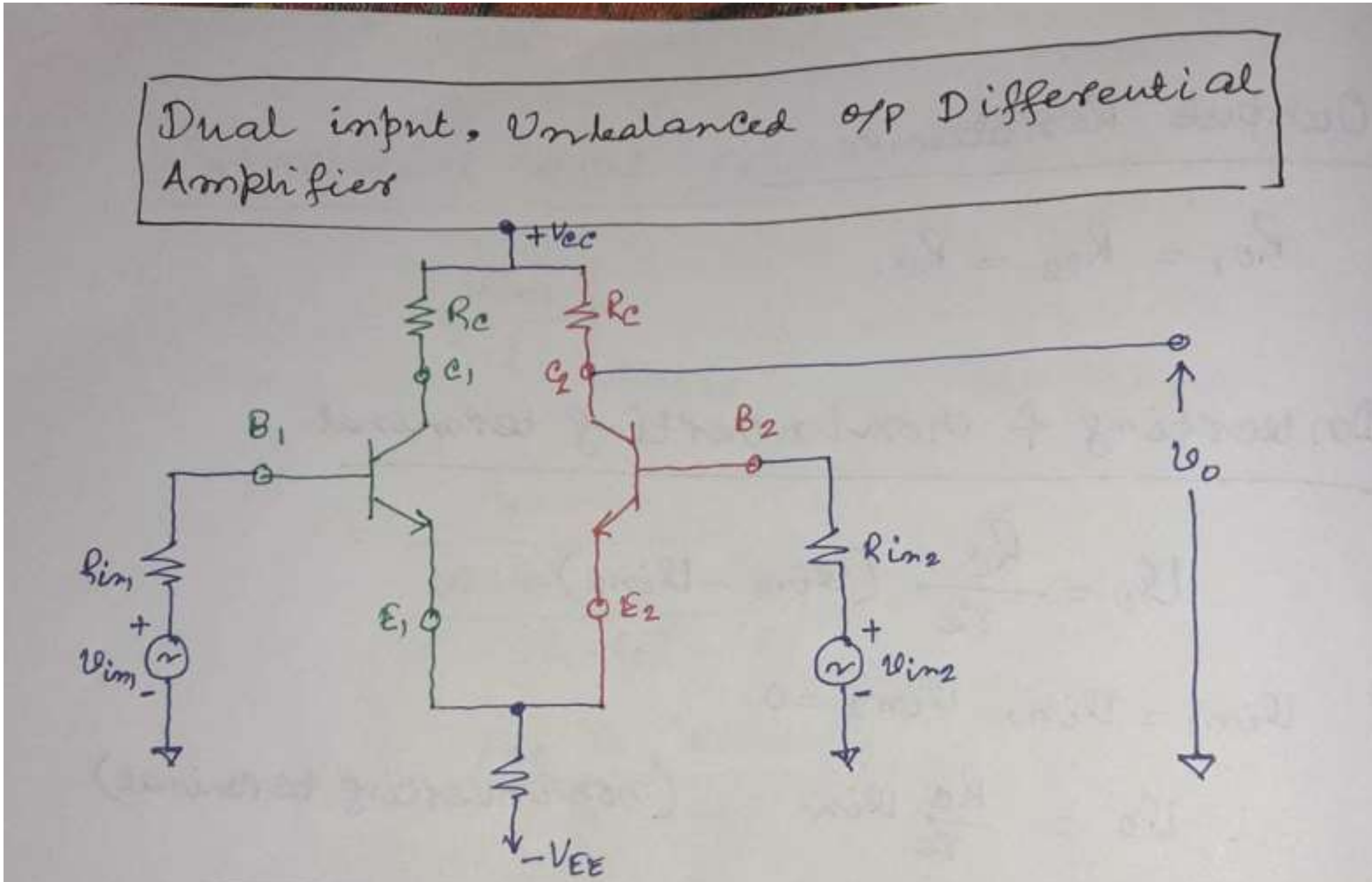
$$A_{cm} = \frac{v_{ocm}}{v_{cm}}$$

$$CMRR = \frac{A_d}{A_{cm}}$$

Ideally, $v_{ocm} = 0$, i.e $A_{cm} = 0$

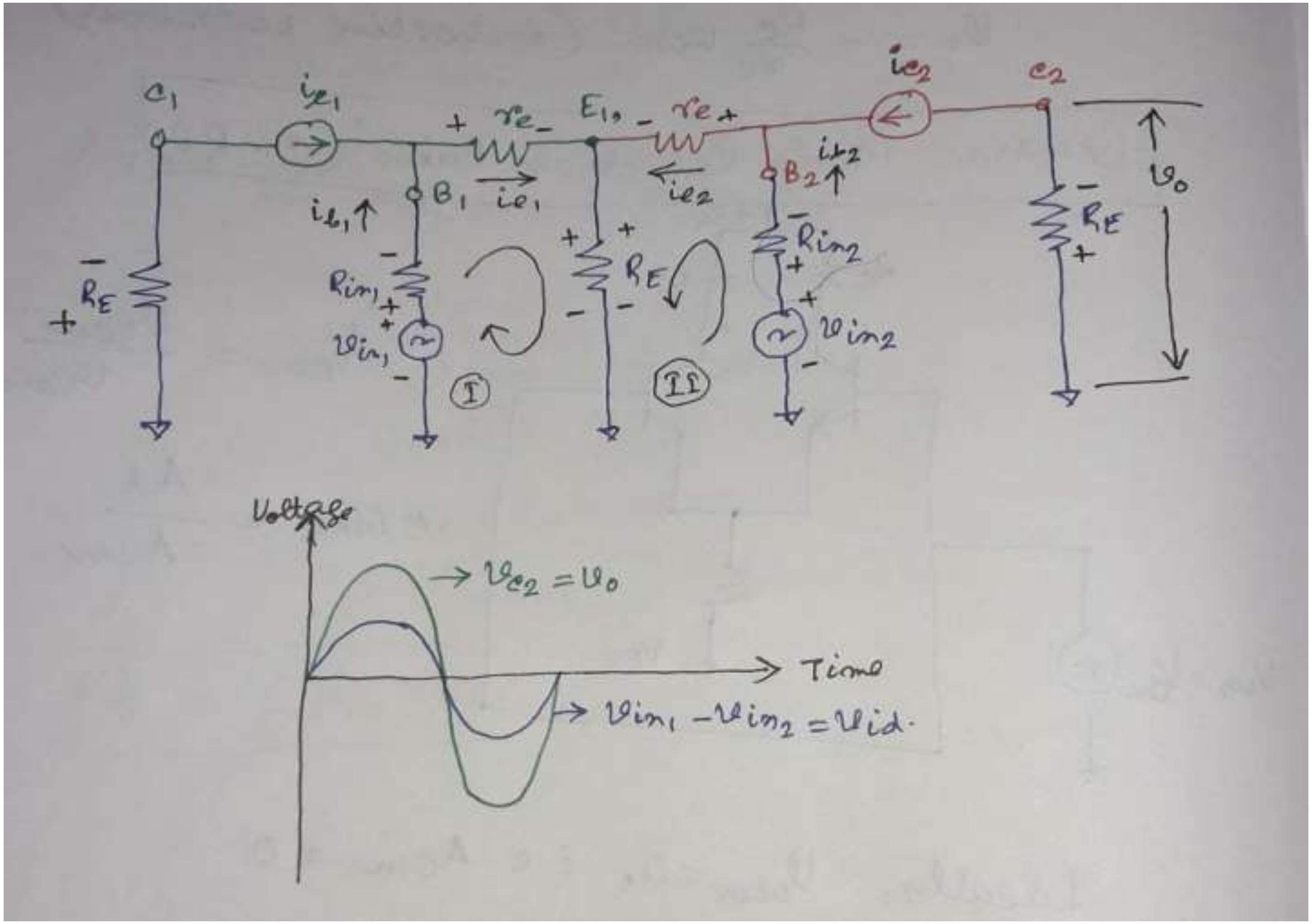
Thus $CMRR = \infty$

OP AMP



Dual input, Unbalanced o/p Differential Amplifier
+Vcc
Rc
Rc
C1
C2
B1
B2
Rin1
Rin2
E1
E2
vin1
vin2
vo
-VEE

OP AMP



C1
ie1
re
E1
re
ie2
e2
B1
ie1
ib1
ie2
ib2
B2
RE
Rin1
vin1
I
RE
II
Rin2
vin2
RE
vo
Voltage
→ ve2 = vo
Time
→ vin1 − vin2 = vid.

OP AMP

The output Voltage is

$$v_o = v_{c2} = -R_c i_{c2} = -R_c i_{e2} \quad \text{since } i_c = i_e$$

$$= -R_c \cdot \frac{(r_e + R_E)v_{in2} - (R_E)v_{in1}}{(r_e + R_E)^2 - (R_E)^2}$$

$$= R_c \cdot \frac{(R_E)v_{in1} - (r_e + R_E)v_{in2}}{r_e(r_e + 2R_E)}$$

Generally,

$R_E >> r_e$. Hence, $r_e + R_E \simeq R_E$ & $r_e + 2R_E \simeq 2R_E$

$$v_o = R_c \cdot \frac{(R_E)v_{in1} - (R_E)v_{in2}}{r_e(2R_E)}$$

$$= \frac{R_c \cdot R_E(v_{in1} - v_{in2})}{2 r_e R_E}$$

$$= \frac{R_c}{2r_e}(v_{in1} - v_{in2})$$

$$\boxed{A_d = \frac{v_o}{v_{id}} = \frac{R_c}{2r_e}.}$$ Voltage Gain.

OP AMP

Differential input resistance

$$R_{i_1} = R_{i_2} = 2\beta_{ac} r_e$$

Output resistance

$$R_o = R_c$$

OP AMP

Single input Balanced o/p Differential Amplifier

$$v_o = \frac{R_c}{r_e} v_{in_1}$$

$$A_d = \frac{v_o}{v_{in}} = \frac{R_c}{r_e}$$ Voltage Gain

Differential input resistance

$$R_i = 2\beta_{ac} r_e$$

Output resistance

$$R_{o_1} = R_{o_2} = R_c$$

OP AMP

Single input Unbalanced O/P Differential Amplifier

$$v_o = \frac{R_C}{2r_e} v_{in}$$

$$A_d = \frac{v_o}{v_{in}} = \frac{R_C}{2r_e} \quad \text{Voltage Gain}$$

Differential input resistance

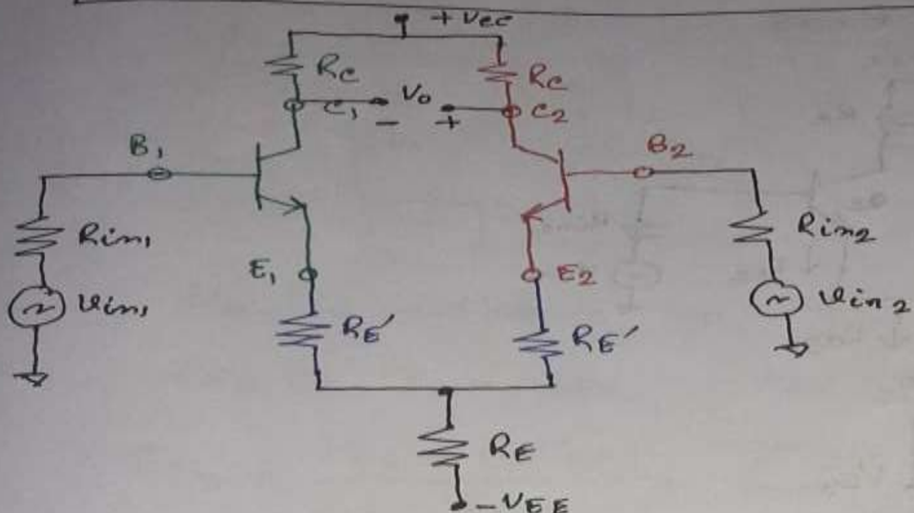
$$R_i = 2\beta_{ac} r_e.$$

Output Resistance

$$R_o = R_C.$$

OP AMP

Differential Amplifier with Swamping Resistance



By using external resistance R_E', the dependence on r_e' can be reduced

Generally, $R_E' >> r_e$

$$A_d = \frac{v_o}{v_{id}} = \frac{R_C}{r_e + R_E'} \approx \frac{R_C}{R_E'}$$

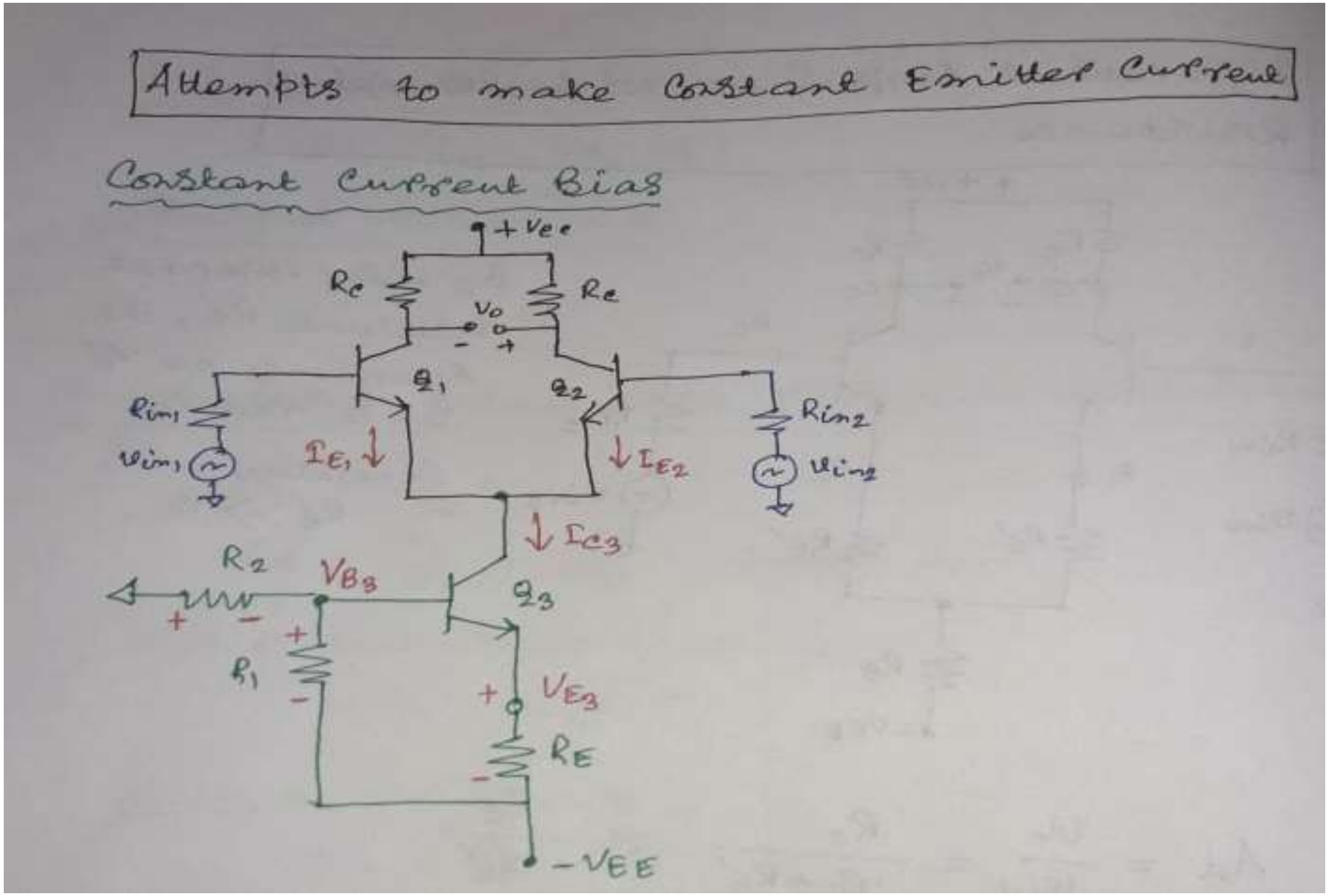
$$R_{i1} = R_{i2} = 2\beta_{ac}(r_e + R_E') \approx 2\beta_{ac} R_E'$$

$$R_{o1} = R_{o2} = R_C.$$

OP AMP

To get desired performance of the differential amplifier it is very important to keep emitter current I_E constant.

OP AMP



Attempts to make Constant Emitter Current
Constant Current Bias
+Vcc
Rc
Rc
Vo
Q1
Q2
Rin1
Rin2
vin1
vin2
IE1
IE2
IC3
R2
VB3
Q3
R1
VE3
RE
-VEE

OP AMP

$$V_{B3} = -\frac{R_2 V_{EE}}{R_1 + R_2}$$

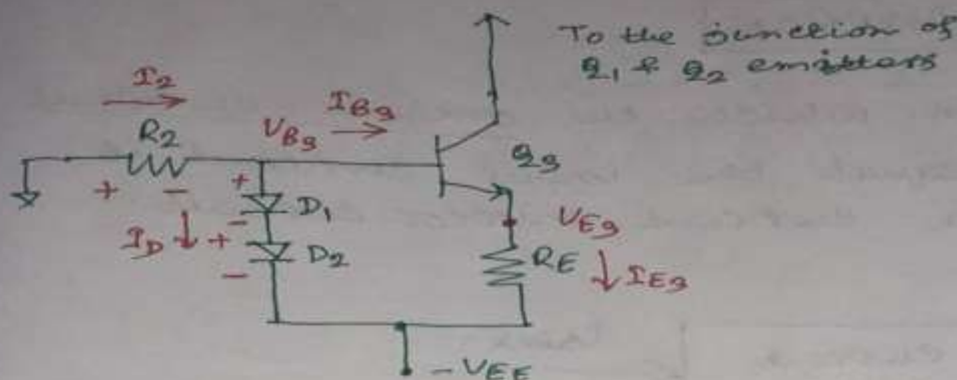
$$V_{E3} = V_{B3} - V_{BE3} = -\frac{R_2 V_{EE}}{R_1 + R_2} - V_{BE3}$$

$$I_{E3} \simeq I_{C3} = \frac{V_{E3} - (-V_{EE})}{R_E}.$$

$$I_{C3} = \frac{V_{EE} - [R_2 V_{EE}/(R_1+R_2)] - V_{BE3}}{R_E}$$

$$\boxed{I_{E1} = I_{E2} = \frac{I_{C3}}{2} = \frac{V_{EE} - [R_2 V_{EE}/(R_1+R_2)] - V_{BE3}}{2 R_E}}$$

OP AMP



$$V_{B3} = -V_{EE} + 2V_D$$

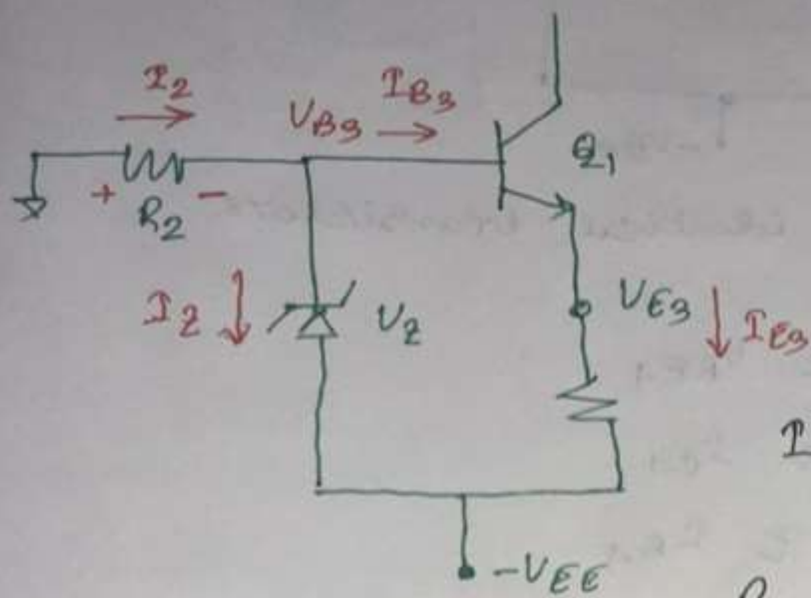
$$V_{E3} = V_{B3} - V_{BE3} = -V_{EE} + 2V_D - V_{BE3}$$

$$I_{E3} = \frac{V_{E3} - (-V_{EE})}{R_E} = \frac{2V_D - V_{BE3}}{R_E}$$

if $V_D = V_{BE3}$

$$\boxed{I_{E3} = \frac{V_D}{R_E}}$$

OP AMP



$$V_{B3} = -V_{EE} + V_Z$$

$$V_{E3} = -V_{EE} + V_Z - V_{BE3}$$

$$I_{E3} = \frac{V_{E3} - (-V_{EE})}{R_E}$$

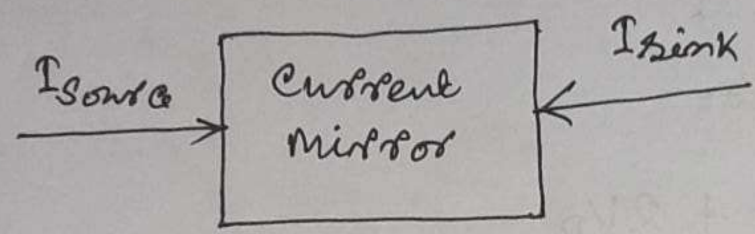
$$I_{E3} = \frac{V_Z - V_{BE3}}{R_E}$$

$$R_2 = \frac{V_{EE} - V_Z}{I_2}$$

OP AMP

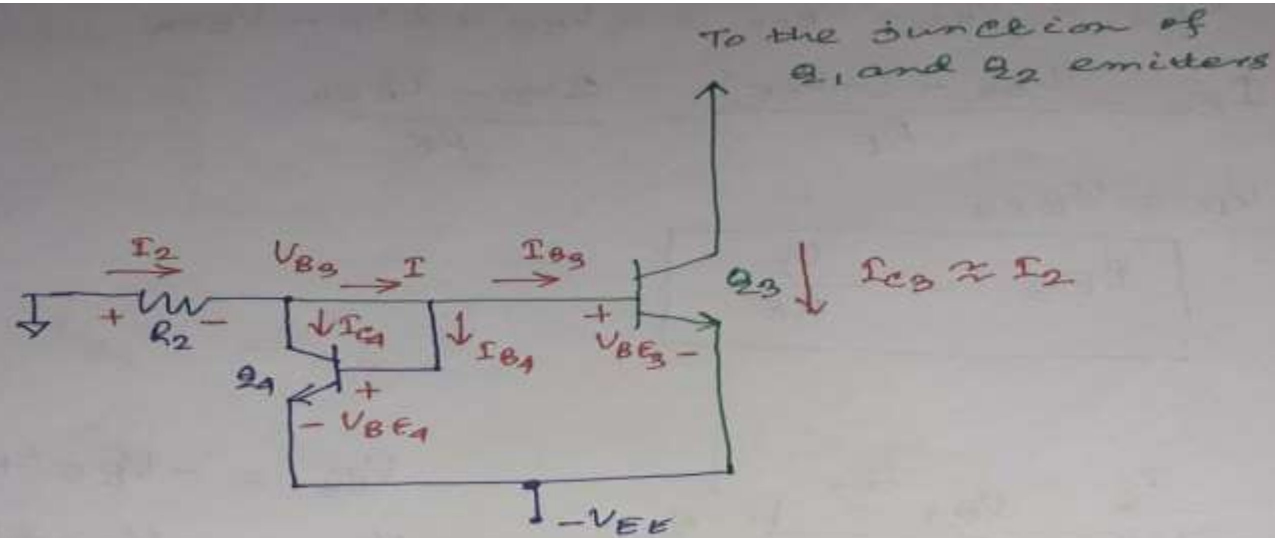
CURRENT MIRROR

The circuit in which the output current is forced to equal the input current is said to be a current mirror circuit.



$I_{source} = I_{sink}$.

OP AMP



Q_3 & Q_4 are identical transistors.

$$V_{BE3} \simeq V_{BE4}$$

$$I_{C3} \simeq I_{C4}$$

$$I_{B3} \simeq I_{B4}$$

OP AMP

$$I_2 = I_{C4} + I$$
$$= I_{C4} + 2I_{B4} = I_{C3} + 2I_{B3}$$
$$= I_{C3} + 2\left(\frac{I_{C3}}{\beta_{dc}}\right)$$
$$= I_{C3}\left(1 + \frac{2}{\beta_{dc}}\right)$$

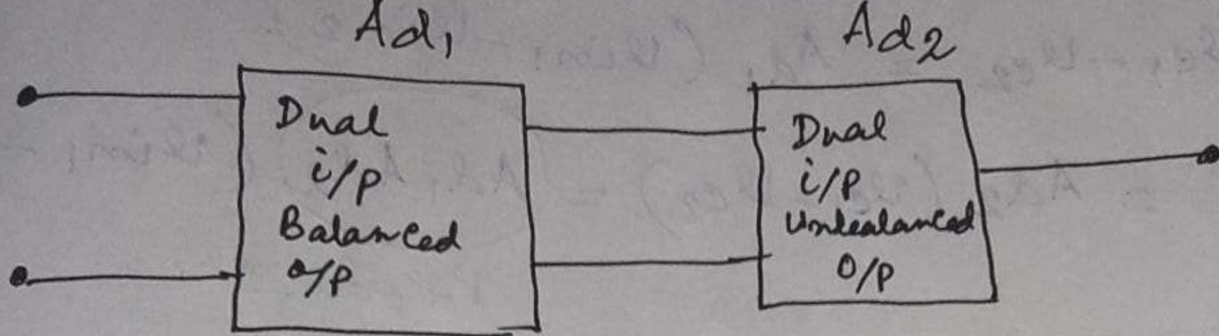
$$\therefore \boxed{I_2 \simeq I_{C3}.}$$

$$-R_2I_2 - V_{BE3} + V_{EE} = 0.$$

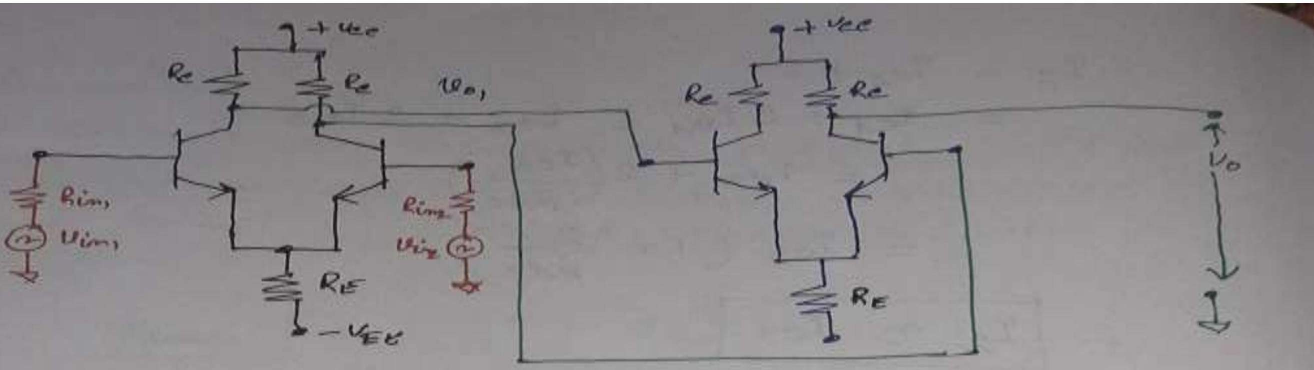
$$\therefore \boxed{I_2 = \frac{V_{EE} - V_{BE3}}{R_2}}$$

OP AMP

CASCADED DIFFERENTIAL AMPLIFIER STAGES.



OP AMP



$$v_{o1} = A_{d1}(v_{in1} - v_{in2})$$

$$\cancel{v_o = A_{d2}(v_{c2})}$$

$$v_{c1} = A_{d1}\, v_{in1}$$
$$v_{c2} = A_{d1}\, v_{in2}$$

$$v_{c1} - v_{c2} = A_{d1}(v_{in1} - v_{in2}).$$

$$\therefore \quad v_o = A_{d2}(v_{c1} - v_{c2}) = A_{d1} A_{d2} (v_{in1} - v_{in2})$$

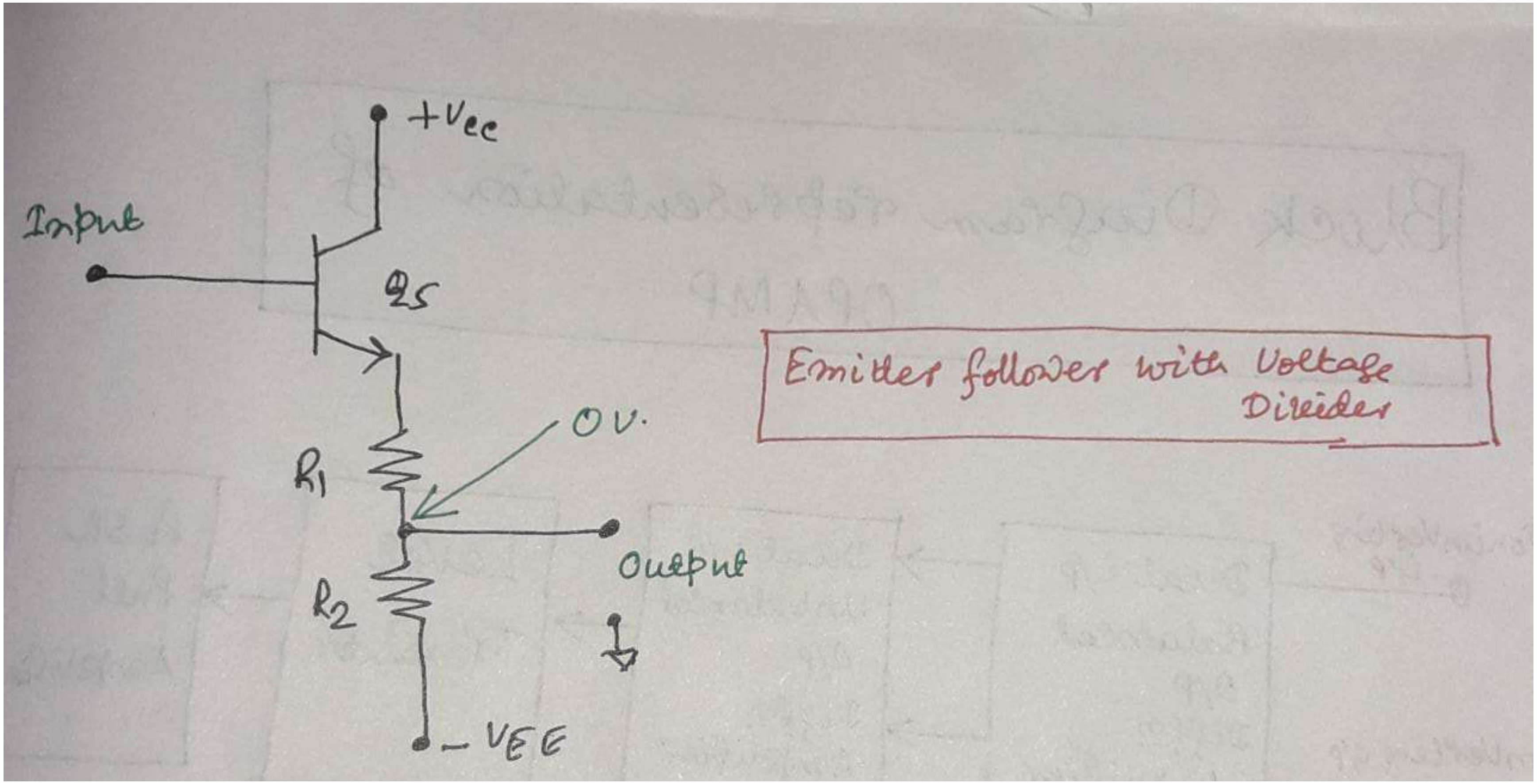
Product.

OP AMP

Level Translator

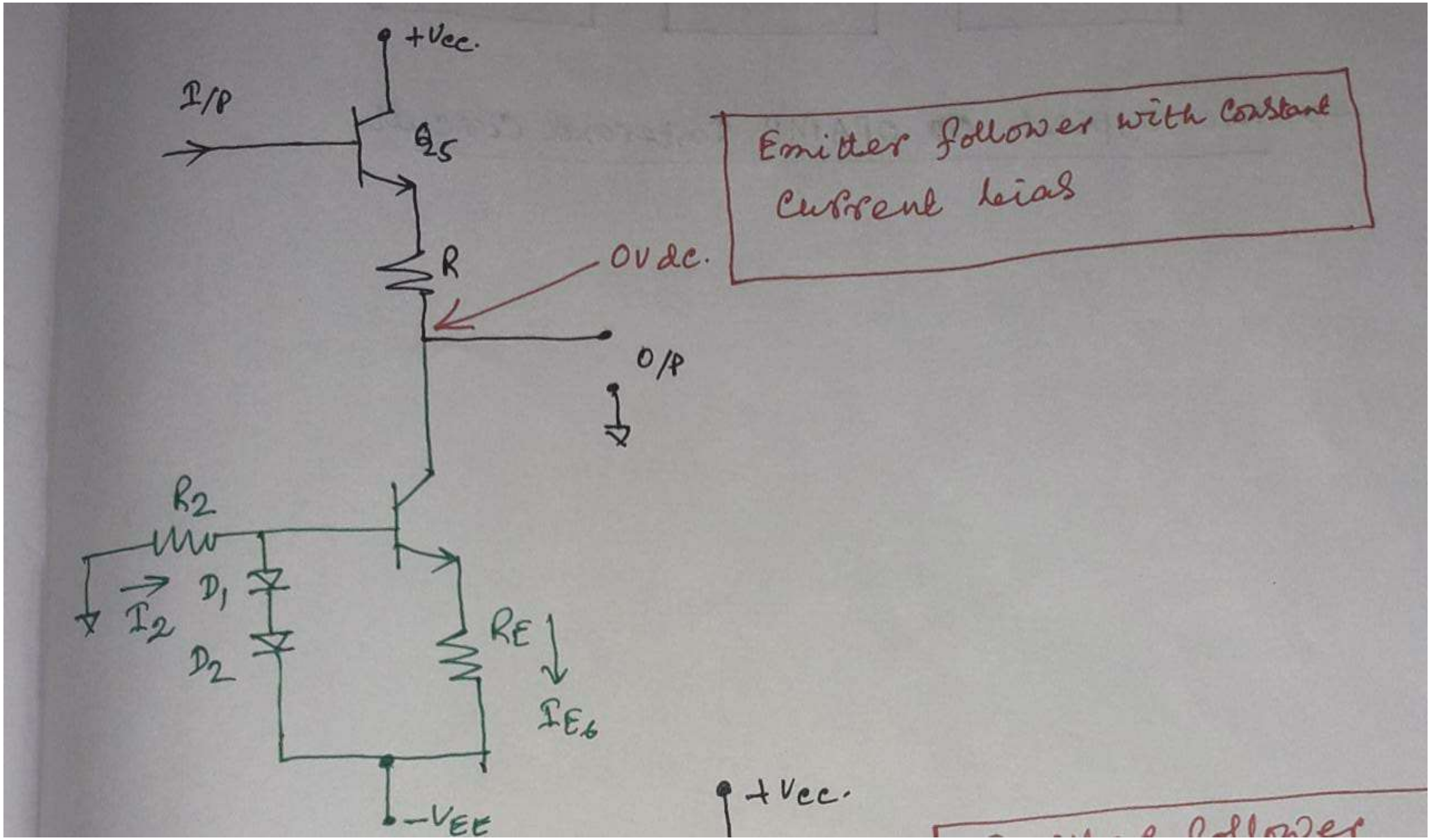
Because of the direct coupling dc level ~~at the~~ ~~emitter~~ of the O/P rises up. Increase in dc level ~~at the emitter~~ tends to shift the operating point, which may cause distortion. So with the help of Level translator attempts are made to fix this problem.

OP AMP



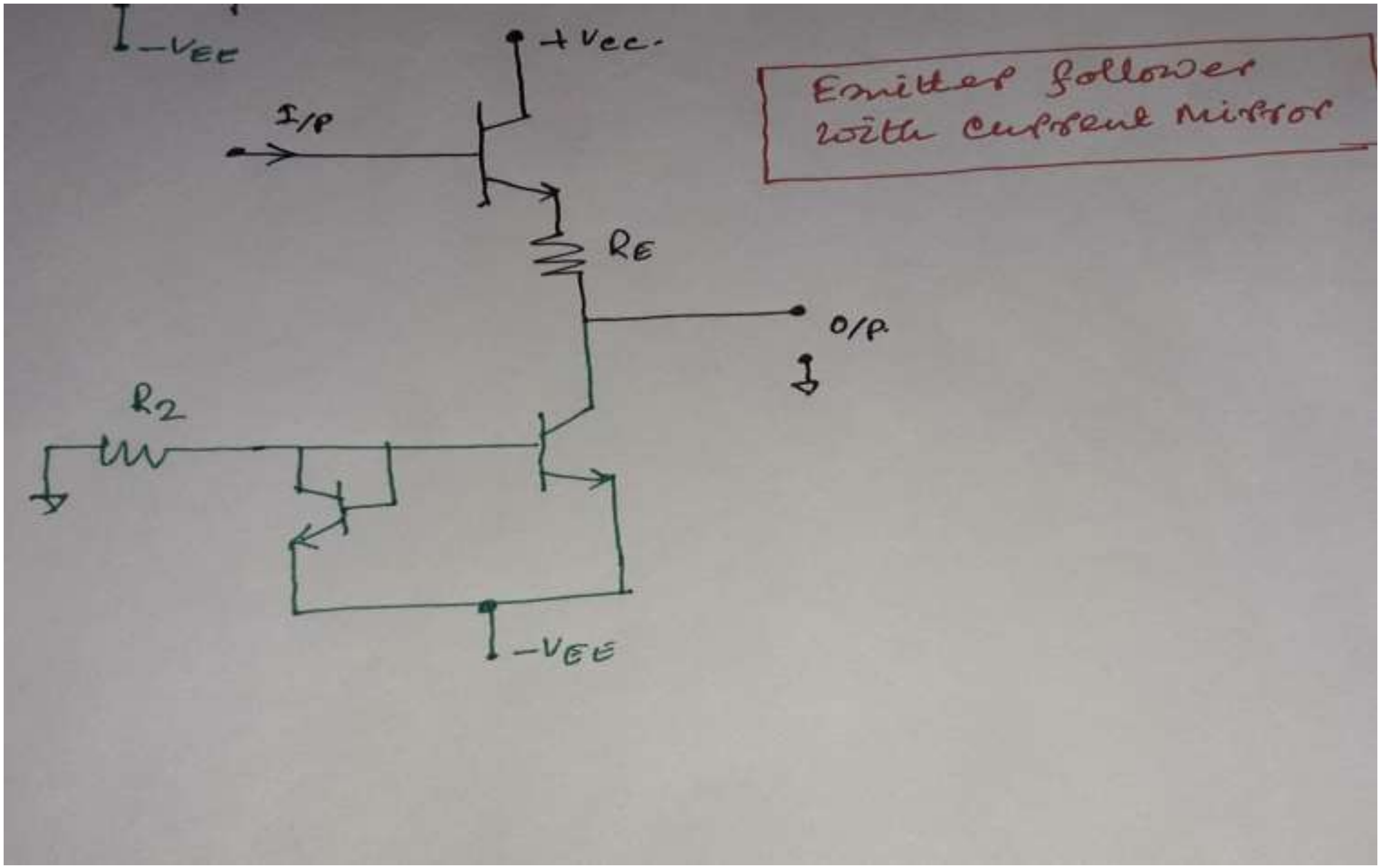
+Vcc
Input
Q5
O V.
R1
R2
Output
-VEE
Emitter follower with Voltage Divider

OP AMP

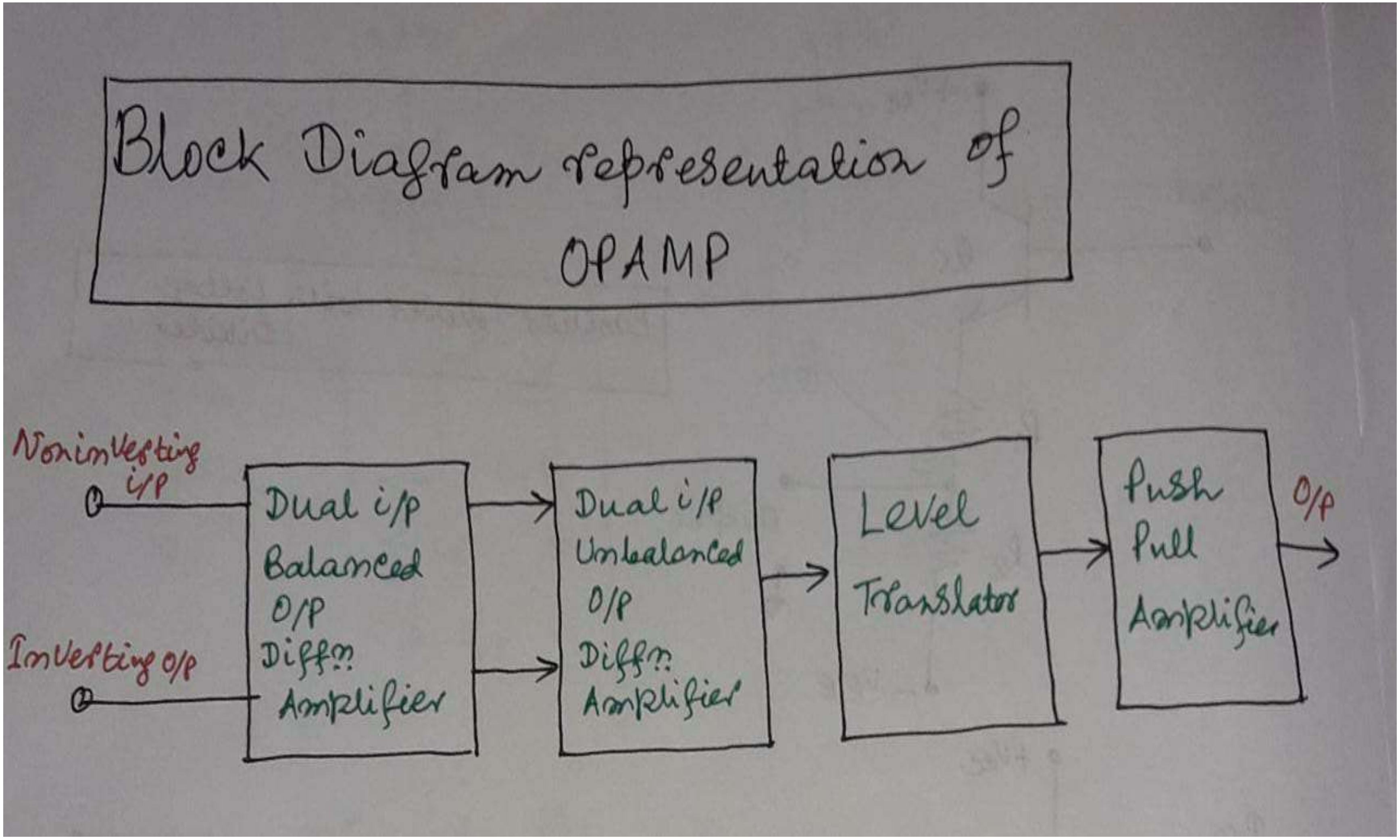


+Vcc
I/P
Q5
R
0V dc.
O/P
Emitter follower with Constant
Current bias
R2
D1
D2
I2
RE
IE6
-VEE
+Vcc

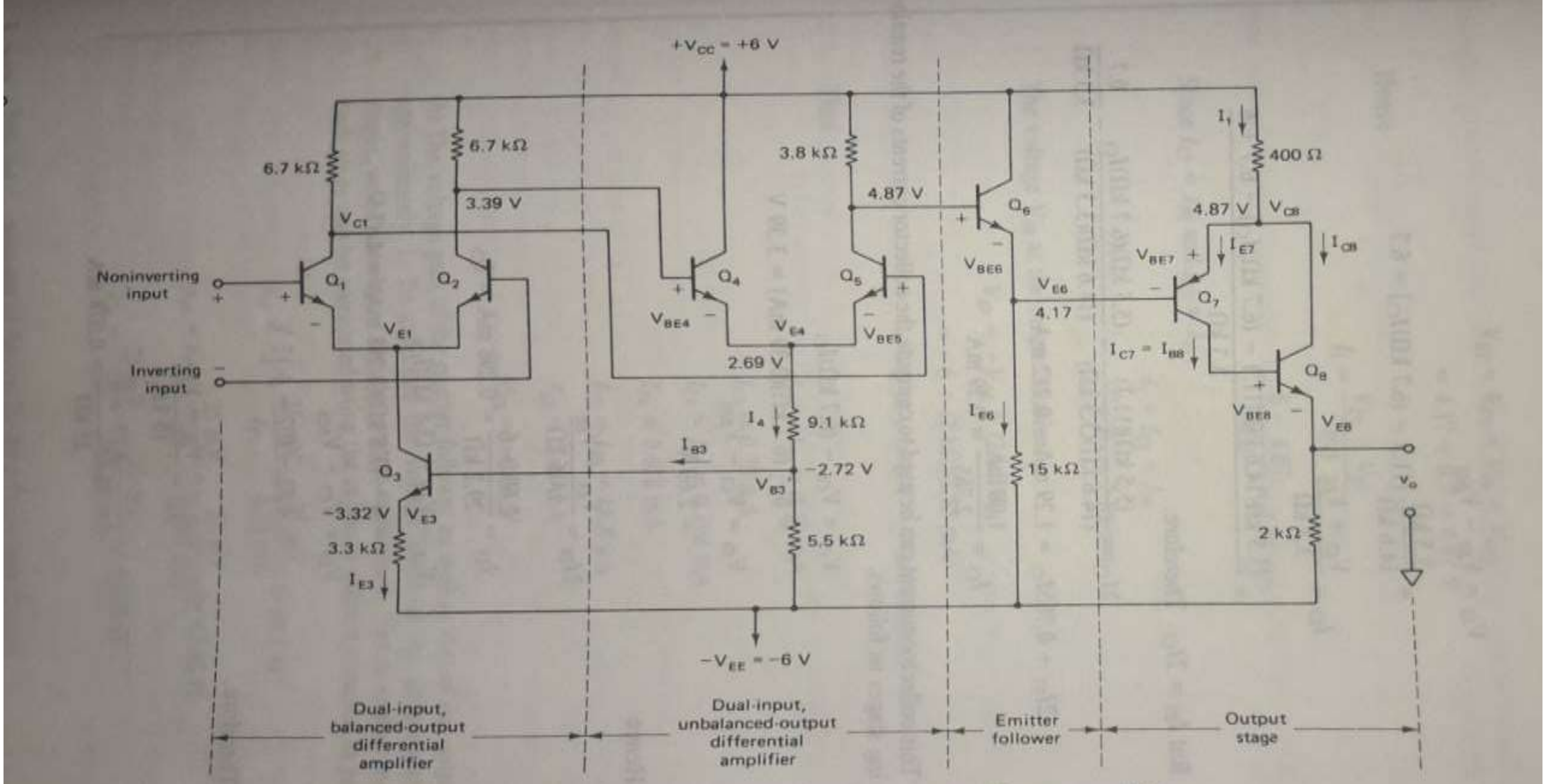
OP AMP



OP AMP

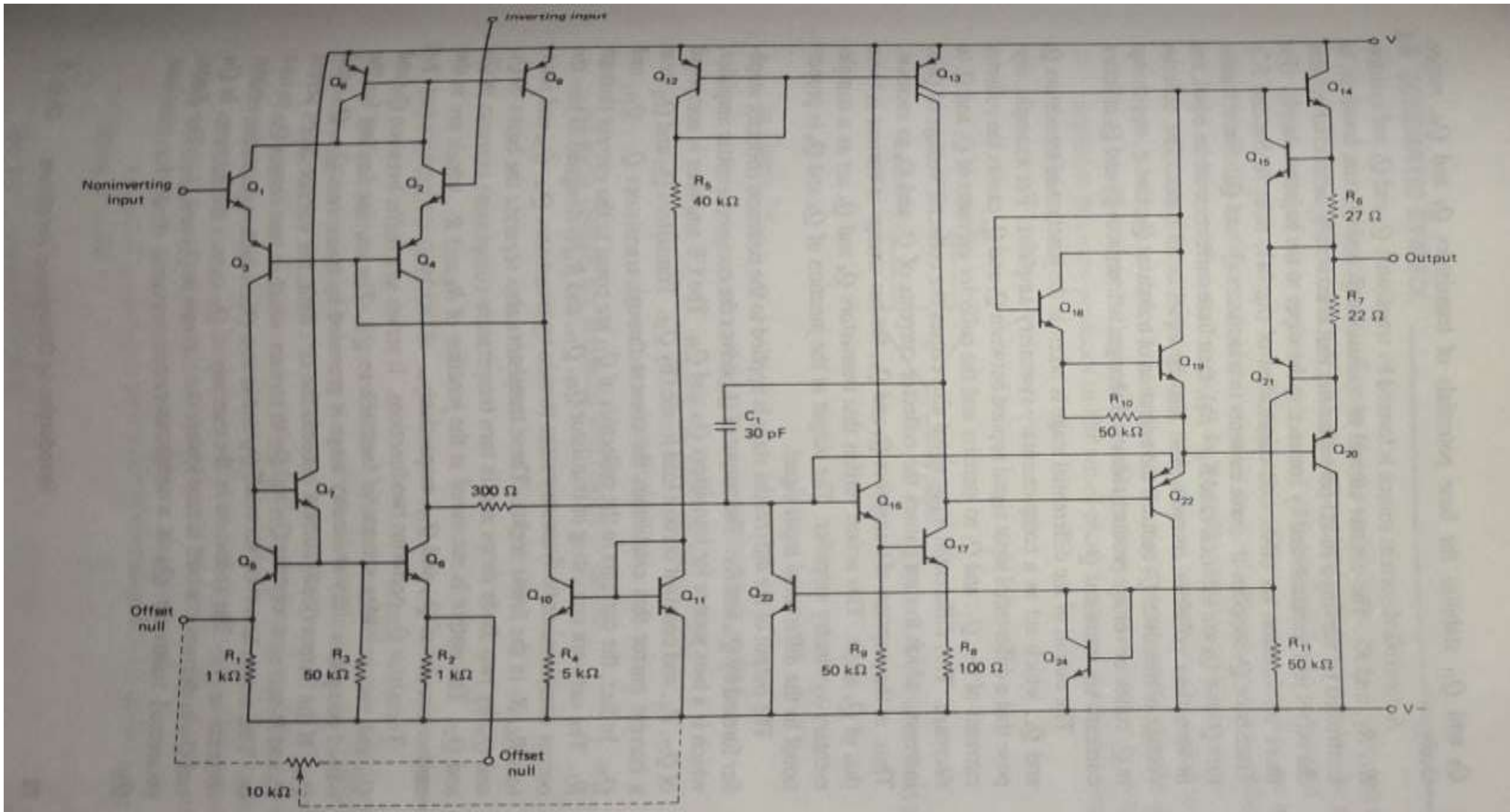

Block Diagram representation of OPAMP
Noninverting i/p
Inverting o/p
Dual i/p Balanced O/P Diffn Amplifier
Dual i/p Unbalanced O/P Diffn Amplifier
Level Translator
Push Pull Amplifier
O/p

OP AMP



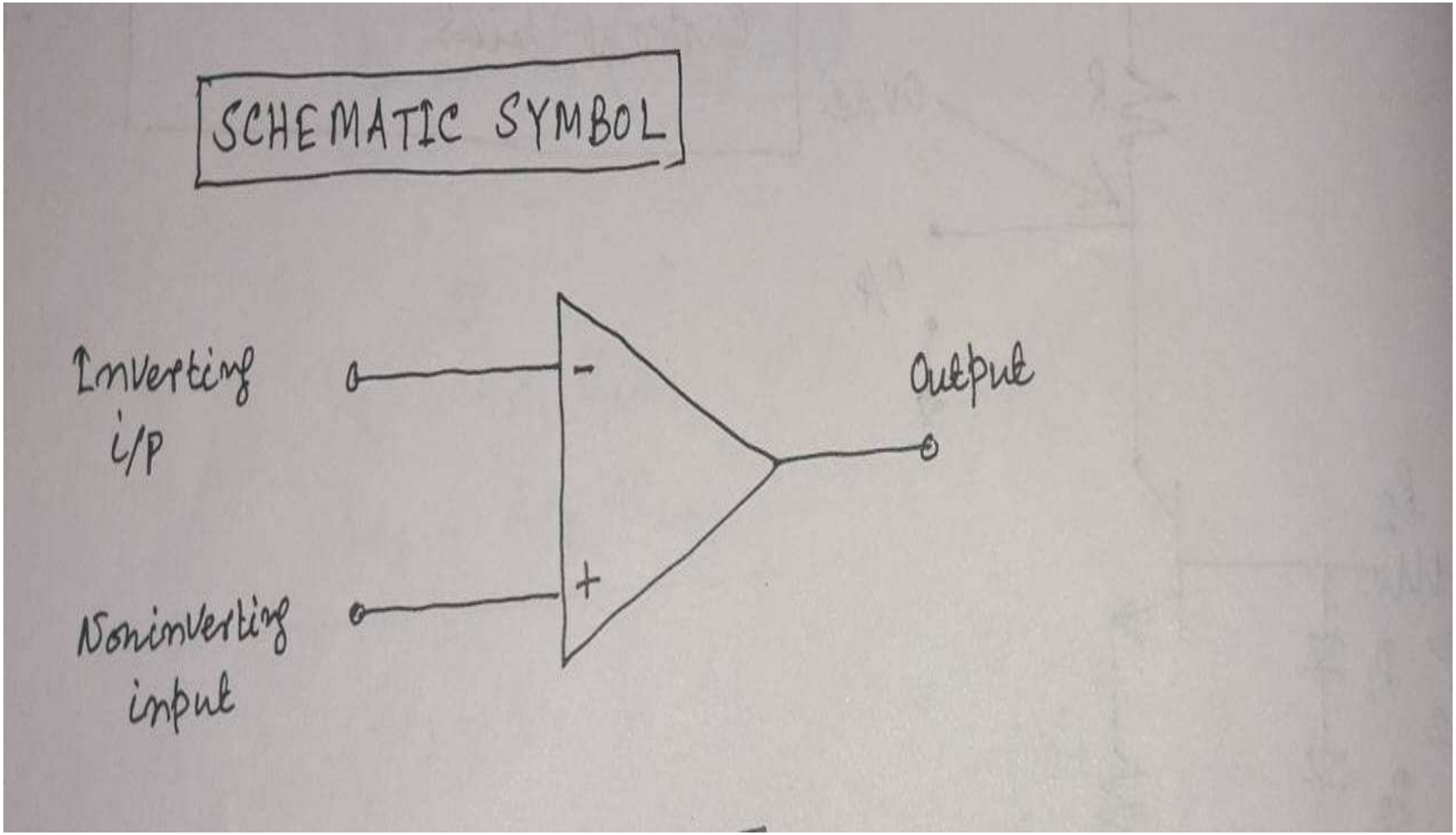
Equivalent circuit of the MC1435 op-amp. (Courtesy of Motorola Semiconductor, Inc.)

OP AMP



Equivalent circuit of the 741 op-amp. (Courtesy of Fairchild Semiconductor Corporation.)

OP AMP



OP AMP

THE IDEAL OPAMP

Characteristics

<1> Infinite Voltage Gain

<2> Infinite Input Impedance

<3> Zero Output Impedance

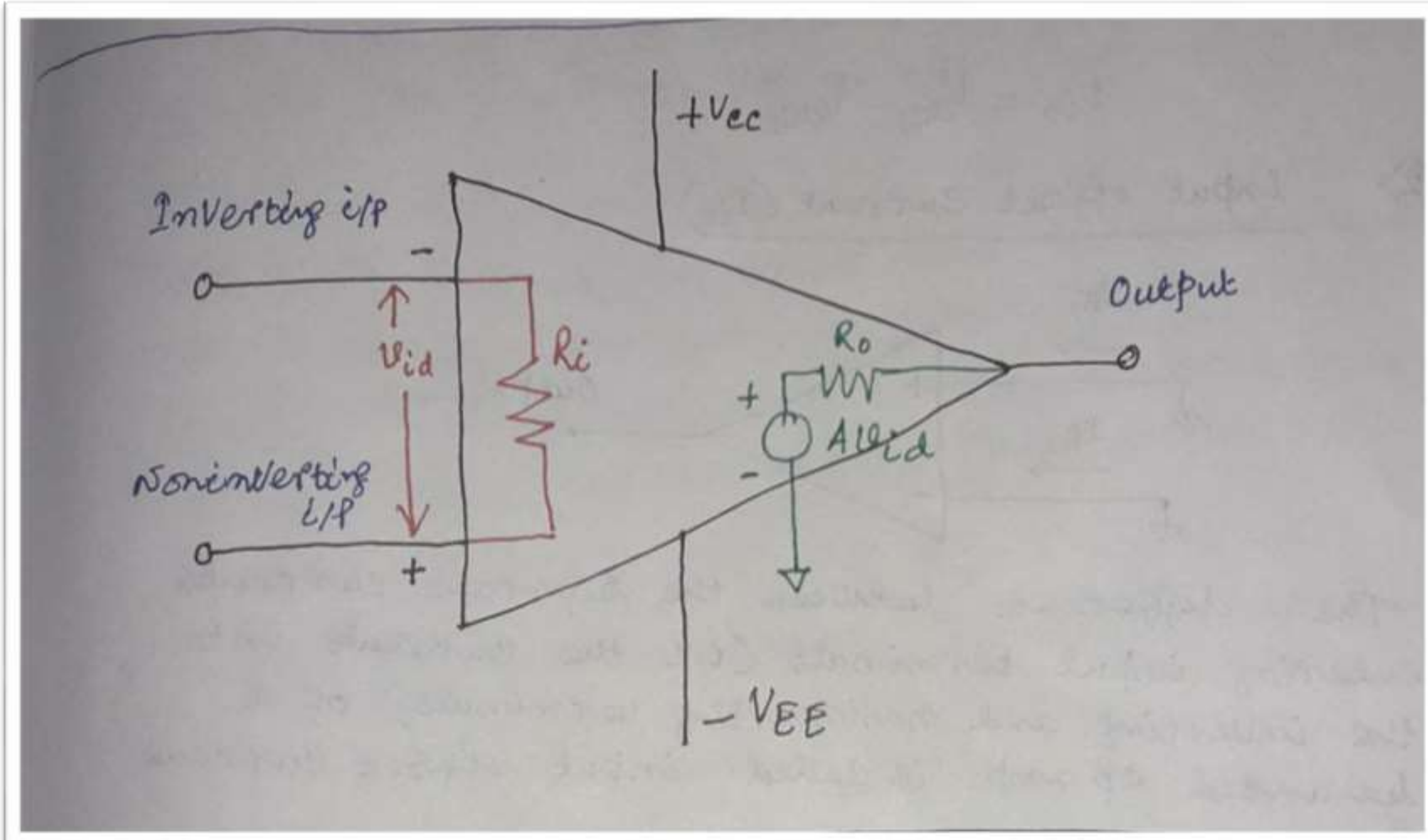
<4> Zero output Voltage when input Voltage is zero.

<5> Infinite Bandwidth.

<6> Infinite Common Mode Rejection Ratio.

<7> Infinite Slew rate.

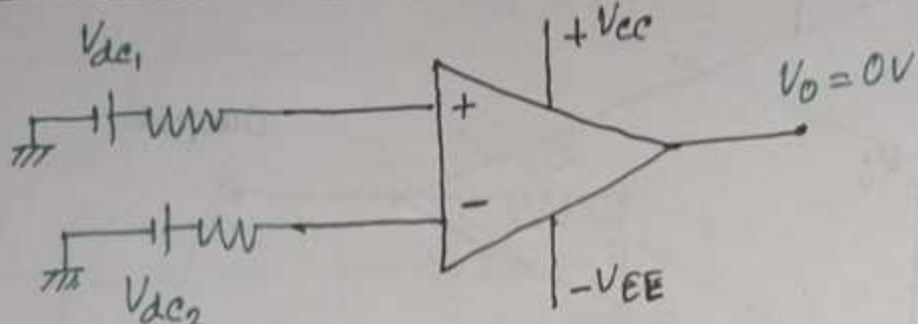
OP AMP



OP AMP

Parameters of Operational Amplifier

(1) Input offset Voltage (V_{io})

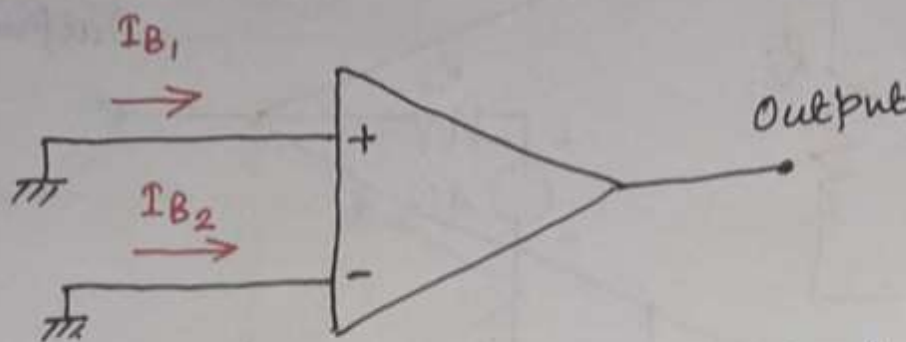


Input offset Voltage is the voltage that must be applied between two input terminals to balance the op-amp i.e to null (making zero) the output.

$$V_{io} = V_{dc_1} - V_{dc_2}$$

OP AMP

⟨2⟩ Input offset current (I_{io})



The difference between the separate currents into entering input terminals (i.e the currents into the inverting and noninverting terminals) of a balanced op amp is called input offset current I_{io}.

$$I_{io} = |I_{B_1} - I_{B_2}| \text{ when } V_o = 0$$

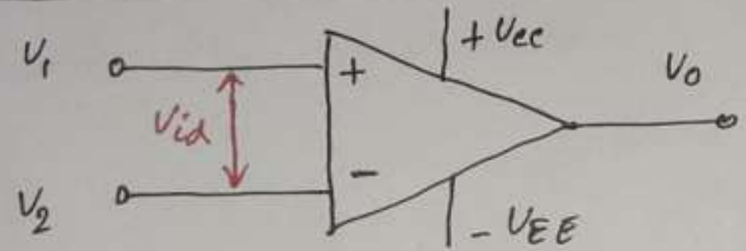
OP AMP

⟨3⟩ Input Bias Current (I_B)

Input bias current I_B is one half of the sum of the separate currents entering the two input terminals of a balanced opamp.

$$I_B = \frac{I_{B1} + I_{B2}}{2} \quad \text{when } V_o = 0.$$

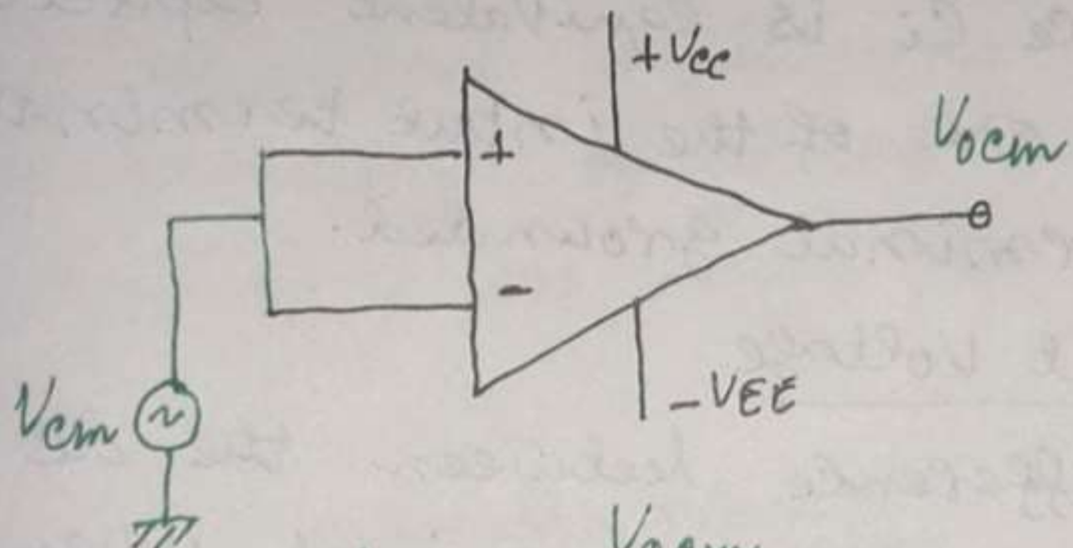
⟨4⟩ Differential Gain (A_d)



$$A_d = \frac{V_o}{V_{id}}.$$

OP AMP

⟨5⟩ Common Mode Voltage Gain. (Acm)



$$A_{cm} = \frac{V_{ocm}}{V_{cm}}$$

OP AMP

(6) Common Mode Rejection Ratio (CMRR)

It is the ratio of the differential voltage gain (A_d) to the common mode voltage gain (A_{cm})

$$CMRR = \left| \frac{A_d}{A_{cm}} \right|$$

Generally A_{cm} is very small and A_d nearly equal to 'A' (large signal gain) is very large.

Hence CMRR is very large. Therefore CMRR is often expressed in decibel (dB) units.

CMRR ↑ , A_{cm} ↓ .... This offers effective rejection of common mode signals like noise etc.

OP AMP

⟨7⟩ **Input offset Current Drift.**

$$= \frac{\Delta I_{io}}{\Delta T}$$

⟨8⟩ **Input offset Voltage Drift.**

$$= \frac{\Delta V_{io}}{\Delta T}$$

(9) **Differential Input Resistance (R_i)**

It is defined as the equivalent resistance that can be measured at one of the input terminals with other terminal grounded.

Value of R_i is generally very large. This prevent loading of OP Amp.

OP AMP

⟨10⟩ Input Capacitance (ci)

Input capacitance Ci is equivalent capacitance measured at one of the input terminals with other terminal grounded.

⟨11⟩ Output offset Voltage

It is the difference between the dc voltage present at the output terminal when two input terminals are grounded. V_{oo} denotes Output offset Voltage.

OP AMP

⟨12⟩ **Slew Rate (SR)**

It is defined as the maximum rate of change of Output Voltage with respect to time.

It can also be defined as the time rate of change of Output Voltage of closed loop amplifier under large-signal condition.

$$SR = \left.\frac{dv_o}{dt}\right|_{max.} \quad \cdots (V/\mu s)$$

SR gives us the information about how fast the output of OPAMP can change with the change in input.

If requirement of Output Signal is greater than slew rate, distortion occurs. Thus, in ac applications slew rate is very important parameter.

OP AMP

<13> Supply Voltage Rejection Ratio (SVRR)

It is defined as the ratio of change in V_{io} to the variation in supply voltage. It is also termed as PSRR, expressed in $\mu V/Volt$ or decibel.

OP AMP

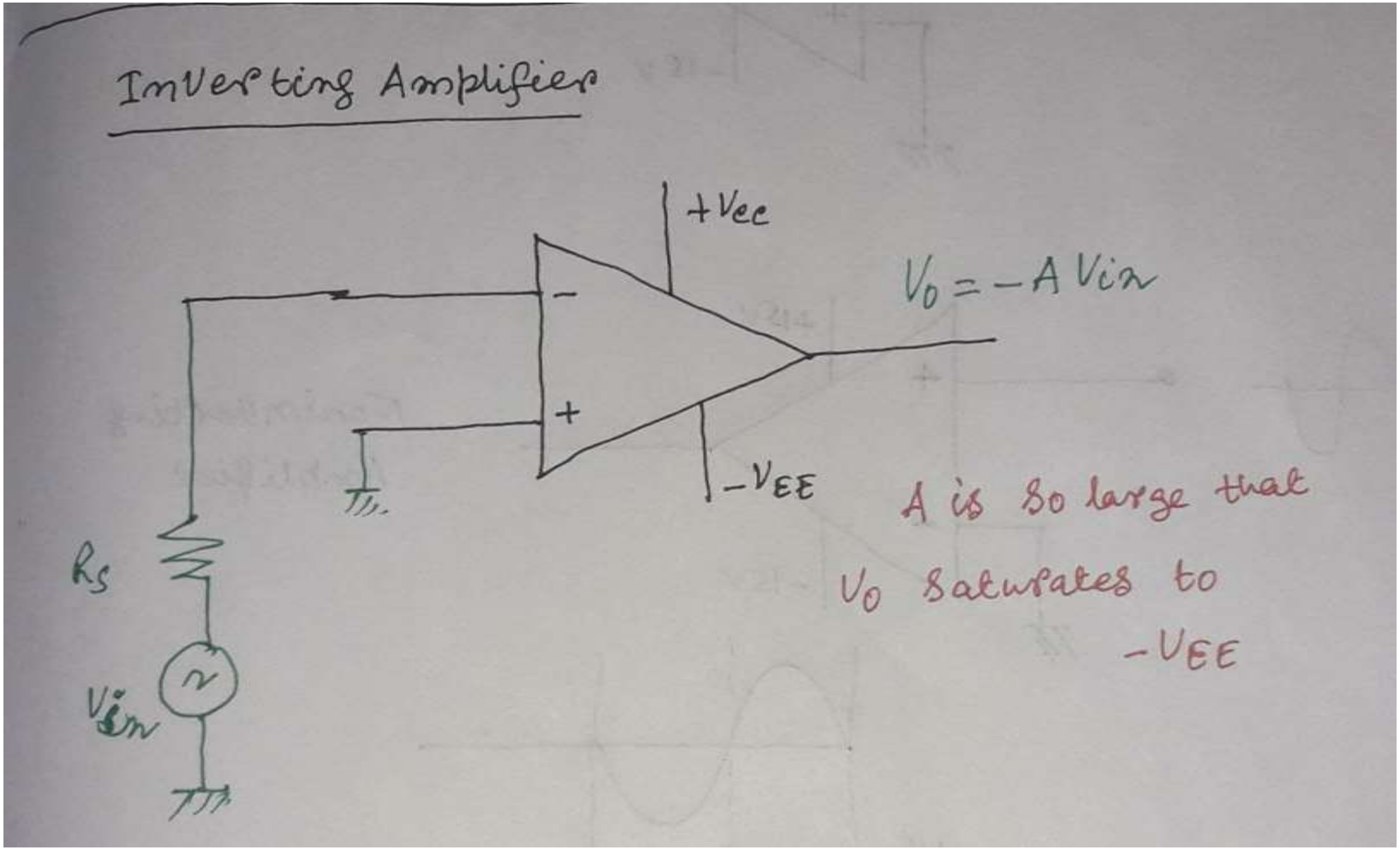
⟨14⟩ Output Resistance (R_o)

It is equivalent resistance measured between output terminal of OP Amp and ground. Generally R_o is less so as to avoid loading effect.

⟨15⟩ Gain - Bandwidth Product.

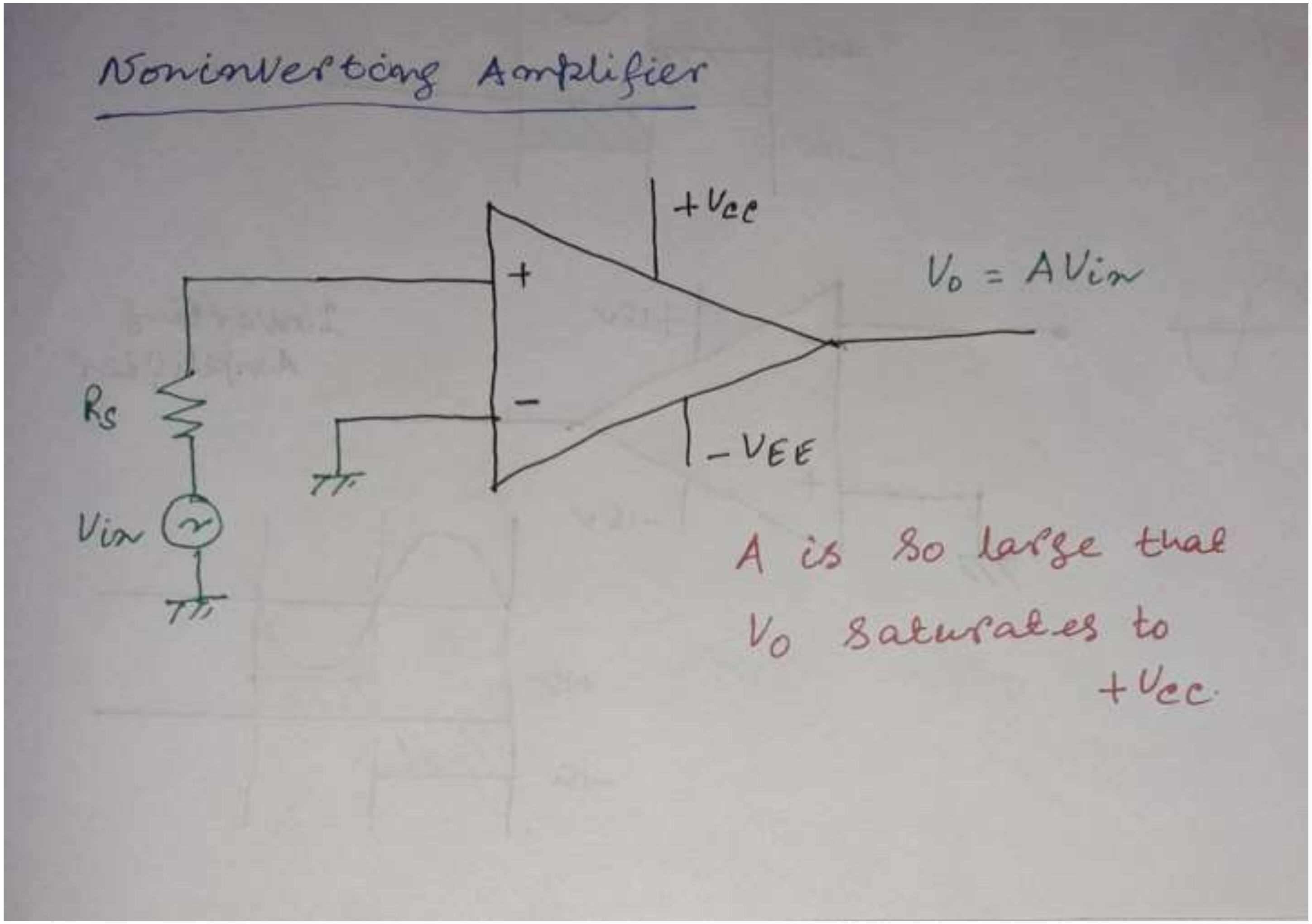
Gain-bandwidth product is the bandwidth of the op-amp when the voltage gain is 1.

OP AMP



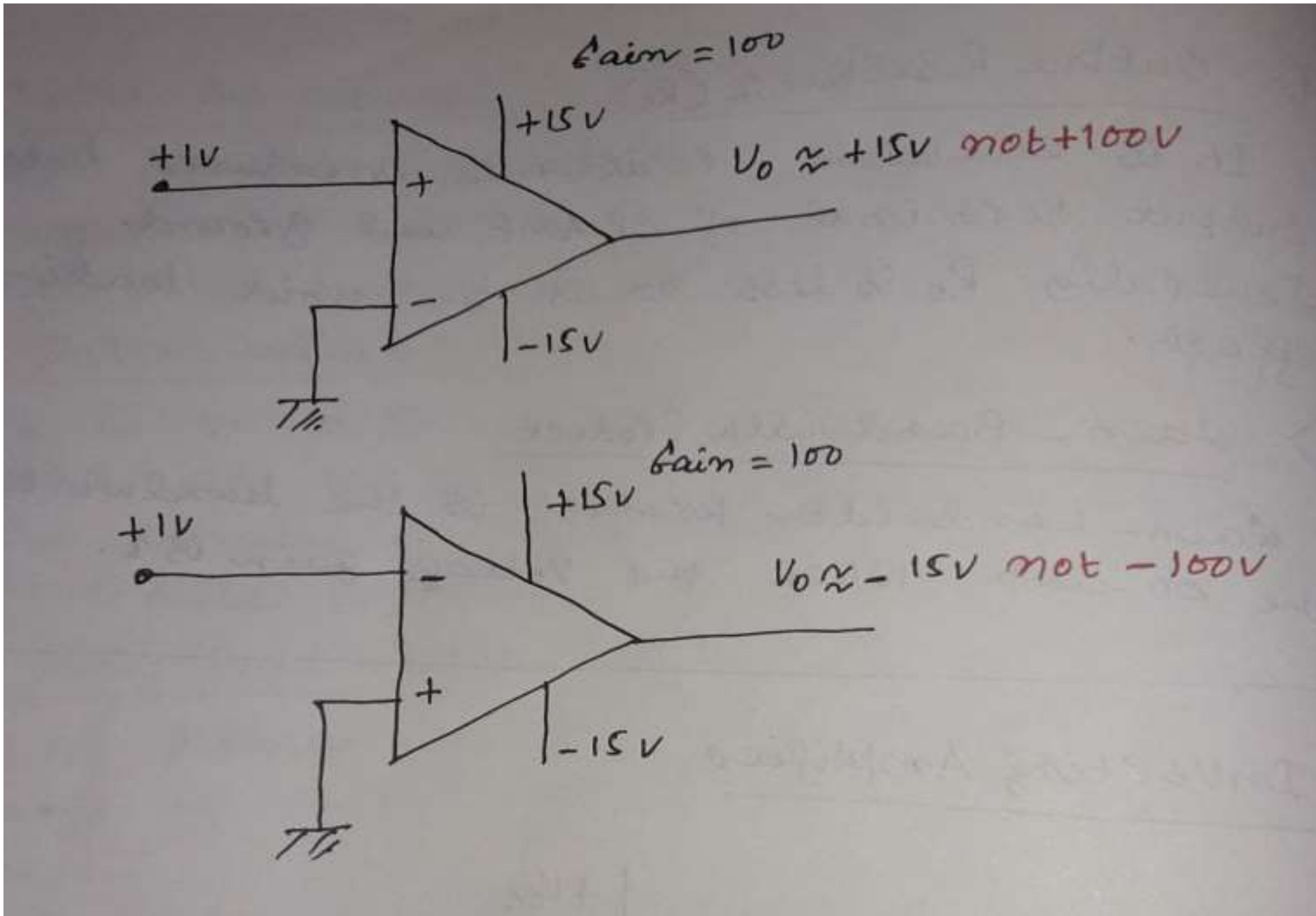
Inverting Amplifier
+Vcc
$V_0 = -A V_{in}$
-VEE
A is so large that
V_0 saturates to
-VEE
Rs
Vin

OP AMP

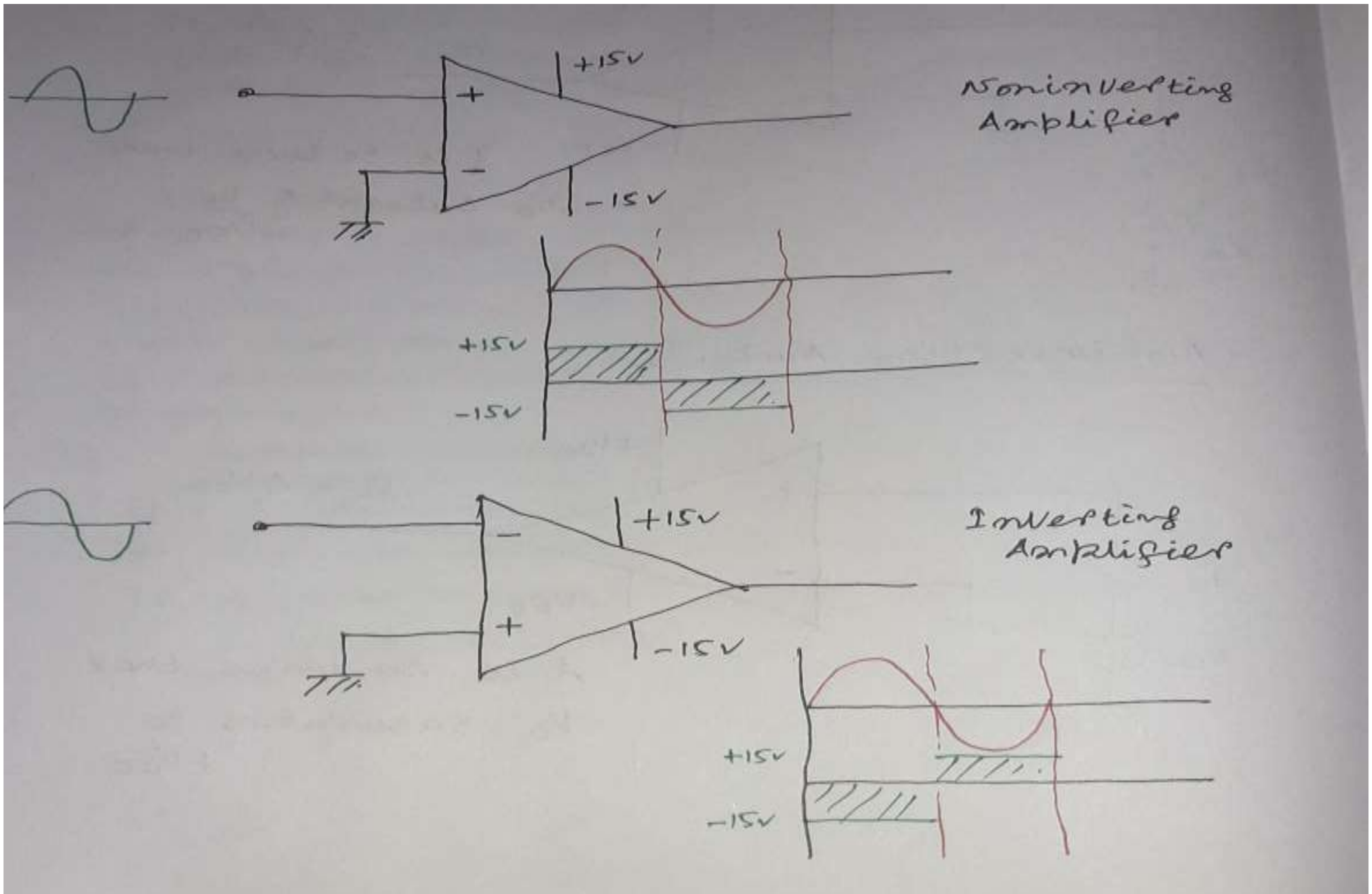


Noninverting Amplifier
+Vcc
+
−
−VEE
Vo = AVin
Rs
Vin
A is so large that
Vo saturates to
+Vcc.

OP AMP


Gain = 100
+15V
+1V
+
−
−15V
Vo ≈ +15V not+100V
Gain = 100
+15V
+1V
−
+
−15V
Vo ≈ − 15V not −100V

OP AMP


+15v
Noninverting
Amplifier
-15v
+15v
-15v
+15v
Inverting
Amplifier
-15v
+15v
-15v

OP AMP

- Here Amplification is not happening.
- This is open loop application of OPAMP.
- This is also called nonlinear applications of OPAMP.

OP AMP

Limitation of open loop Configuration

1. In open-loop, configuration even for small voltage also op-amp gets saturated.
2. open loop configuration can amplify micro volt signals with very low frequency. But such signals are very susceptible to noise.
3. open loop voltage gain is not constant. It changes with change in temperature and power supply. It is not suitable for linear applications.
4. Bandwidth (Band of frequencies for which the gain remains constant) of most open loop opamps is negligibly small almost zero. Hence this configuration is not suitable for ac applications.

To overcome these drawbacks closed loop configuration is used.

OP AMP

Concept of Feedback and Types of Feedback

In closed-loop configurations, there is a loop existing between output and input. The part of output is fed back to the input through a network. (may be resistance, resistance and capacitance etc.) This is called feedback.

Feedback Types
(Based on the polarity of signal fed back to the input)

- **Negative Feedback**
  (Signal feedback is of opposite polarity or out of phase by 180° with input signal)
- **Positive Feedback**
  (Signal feedback is of same polarity or in phase with input)

Difference between Negative and Positive Feedback

OP AMP

Negative Feedback	Positive Feedback.
1. Signal fedback is of opposite polarity or Out of phase by 180° with input.	1. Signal fedback is of same polarity or in phase with input.
2. It is degenerative feedback i.e output reduces.	2. It is regenerative feedback i.e output increases
3. It is used in amplifiers.	3. It is used in oscillators
4. It has self correcting ability against any change in output caused by changes in environmental conditions. It oppose the input.	4. It feeds signal of same polarity and hence aids input signal.
5. It stabilizes the gain, increases bandwidth etc. but reduces the gain.	5. It continuously increases the gain of the amplifier.

OP AMP

Feedback Amplifier (Closed-loop amplifier)

Feedback Amplifiers using op-amp have two parts:

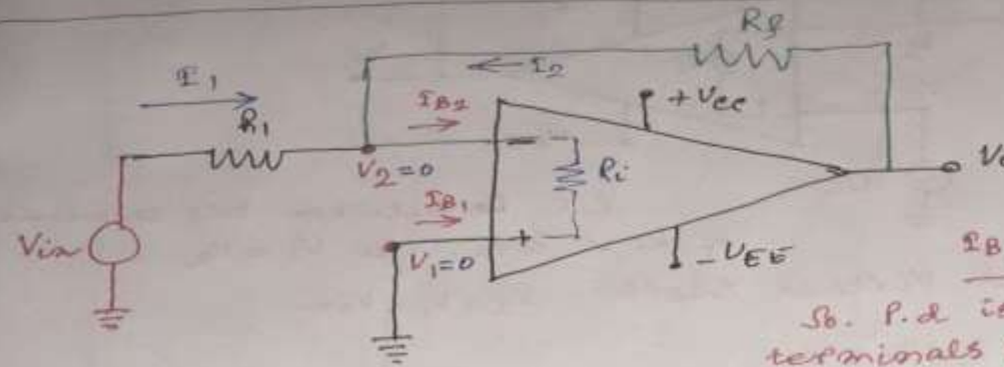
1. op-amp.
2. Feedback Circuit.

Feedback Topologies.

1. Voltage Series Feedback.
2. Voltage Shunt Feedback
3. Current Series Feedback
4. Current Shunt Feedback.

OP AMP

Inverting Amplifier with feedback



$I_{B1} = I_{B2} \approx 0$

So. P.d is zero in two terminals of R_i

So $V_1 = V_2$, since V_2 is grounded. so V_1 is also having zero potential. This is called Virtual ground.

$$I_1 + I_2 = 0$$

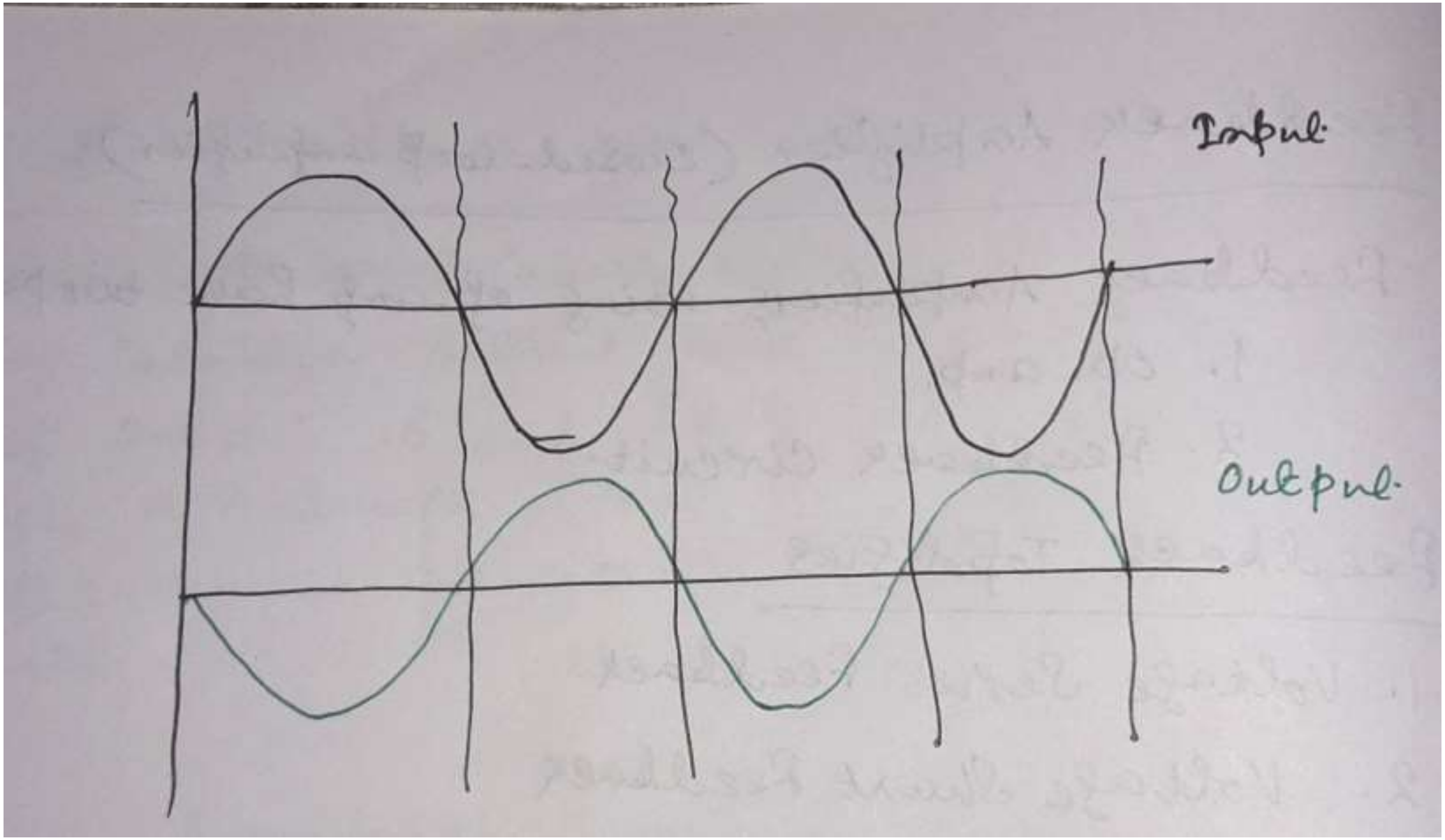
$$\therefore \frac{V_{in}}{R_1} + \frac{V_o}{R_f} = 0.$$

$$\therefore \boxed{V_o = -\frac{R_f}{R_1} V_{in}}$$

$$\text{Gain} = -\frac{R_f}{R_1}$$

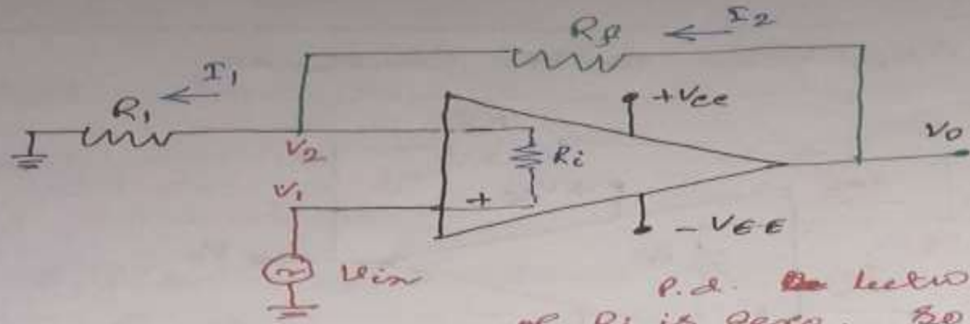
Gain is controllable.

OP AMP



OP AMP

Closed Loop Non-inverting Configuration



P.d. between two terminals of R_i is zero. So $V_1 = V_2$ is called virtual short. $V_2 = V_1 = V_{in}$

$$-I_1 + I_2 = 0.$$

$$\therefore \; -\left(\frac{V_{in}}{R_1}\right) + \frac{V_o - V_{in}}{R_f} = 0.$$

$$\therefore \; \frac{V_o}{R_f} = V_{in}\left(\frac{1}{R_f} + \frac{1}{R_1}\right)$$

$$\therefore \; \frac{V_o}{V_{in}} = R_f\left(\frac{1}{R_f} + \frac{1}{R_1}\right)$$

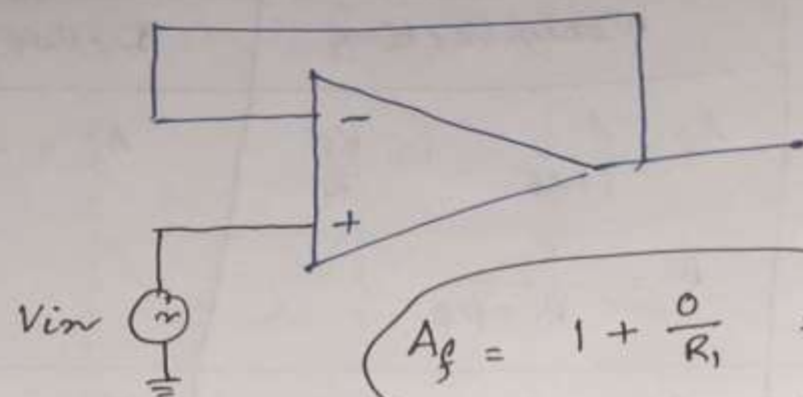
$$\therefore \; \boxed{V_o = \left(1 + \frac{R_f}{R_1}\right) V_{in}}$$

$$\text{Gain} = 1 + \frac{R_f}{R_1}$$

Gain is Controllable.

OP AMP

<u>Voltage Follower</u> (Buffer)



$$A_f = 1 + \frac{0}{R_1} = 1$$

$V_o = V_{in}$

If in case inverting amplifier

$R_f = R_1$, $\boxed{V_o = -V_{in}}$ Inverter.

OP AMP

Differential Amplifier

> It is a circuit that amplifies the difference between two input signals.

Differential Amplifiers are used in Instrumentation systems because:

1. They are better able to reject common mode signals such as noise as compared to inverting and non inverting amplifiers. Thus it can be useful for milivolt signal amplification that is required in instrumentation.

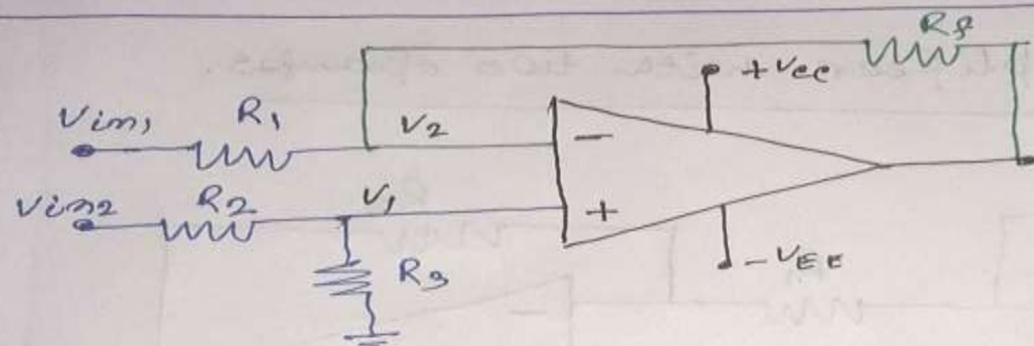
2. They also present balanced input impedance.

OP AMP

Differential Amplifier

- Diff^n amplifier with one op amp
- Diff^n amplifier with two op amp
- Diff^n amplifier with three op amp

Differential Amplifier with single op-amp.



1. with $V_{in1} = 0$ it acts as noninverting amplifier.
2. with $V_{in2} = 0$ it acts as inverting amplifier.

OP AMP

Use superposition theorem.

Say, $V_{in2} = 0$, $\quad V_{o1} = -\dfrac{R_f}{R_1} V_{in1}$

when $V_{in1} = 0$, $\quad V_{o2} = \left(1 + \dfrac{R_f}{R_1}\right) V_1$

$$V_1 = \frac{R_3}{R_2 + R_3} \cdot V_{in2}$$

$$\therefore \quad V_{o2} = \left(1 + \frac{R_f}{R_1}\right) \frac{R_3}{R_2 + R_3} \cdot V_{in2}$$

if $R_1 = R_2$ & $R_f = R_3$

$$V_{o2} = \frac{R_f}{R_1} V_{in2}$$

OP AMP

$$V_0 = V_{01} + V_{02}$$

$$= -\frac{R_f}{R_1} V_{in1} + \frac{R_f}{R_1} V_{in2}$$

Gain.

$$\boxed{V_0 = -\frac{R_f}{R_1}\left(V_{in1} - V_{in2}\right) = -\frac{R_f}{R_1} V_{id}}$$

OP AMP

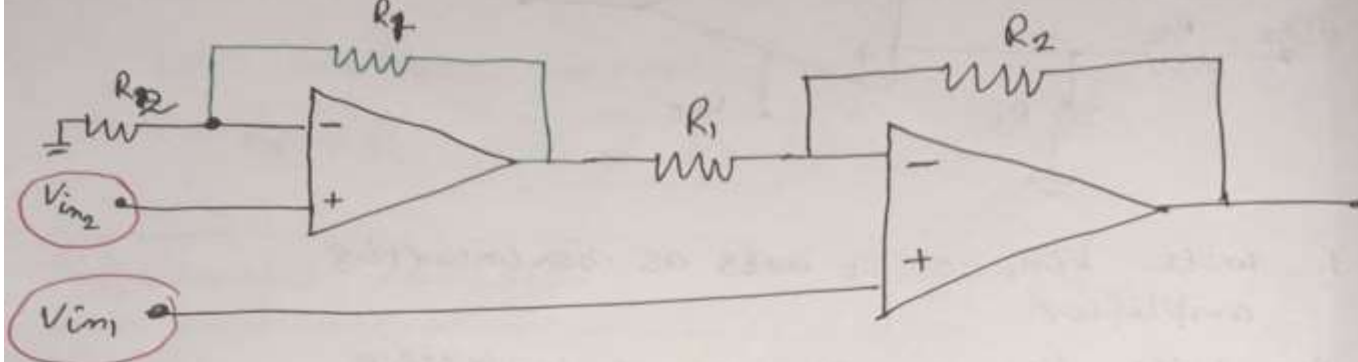
$$V_o = V_{o1} + V_{o2}$$

$$= -\frac{R_f}{R_1} V_{in1} + \frac{R_f}{R_1} V_{in2}$$

Gain

$$\boxed{V_o = -\frac{R_f}{R_1}\left(V_{in1} - V_{in2}\right) = -\frac{R_f}{R_1} V_{id}}$$

Differential Amplifier with two opamps.



OP AMP

Differential Amplifier with two OPAMP

$$V_{o1} = V_{in2}\left(1+\frac{R_1}{R_2}\right)$$

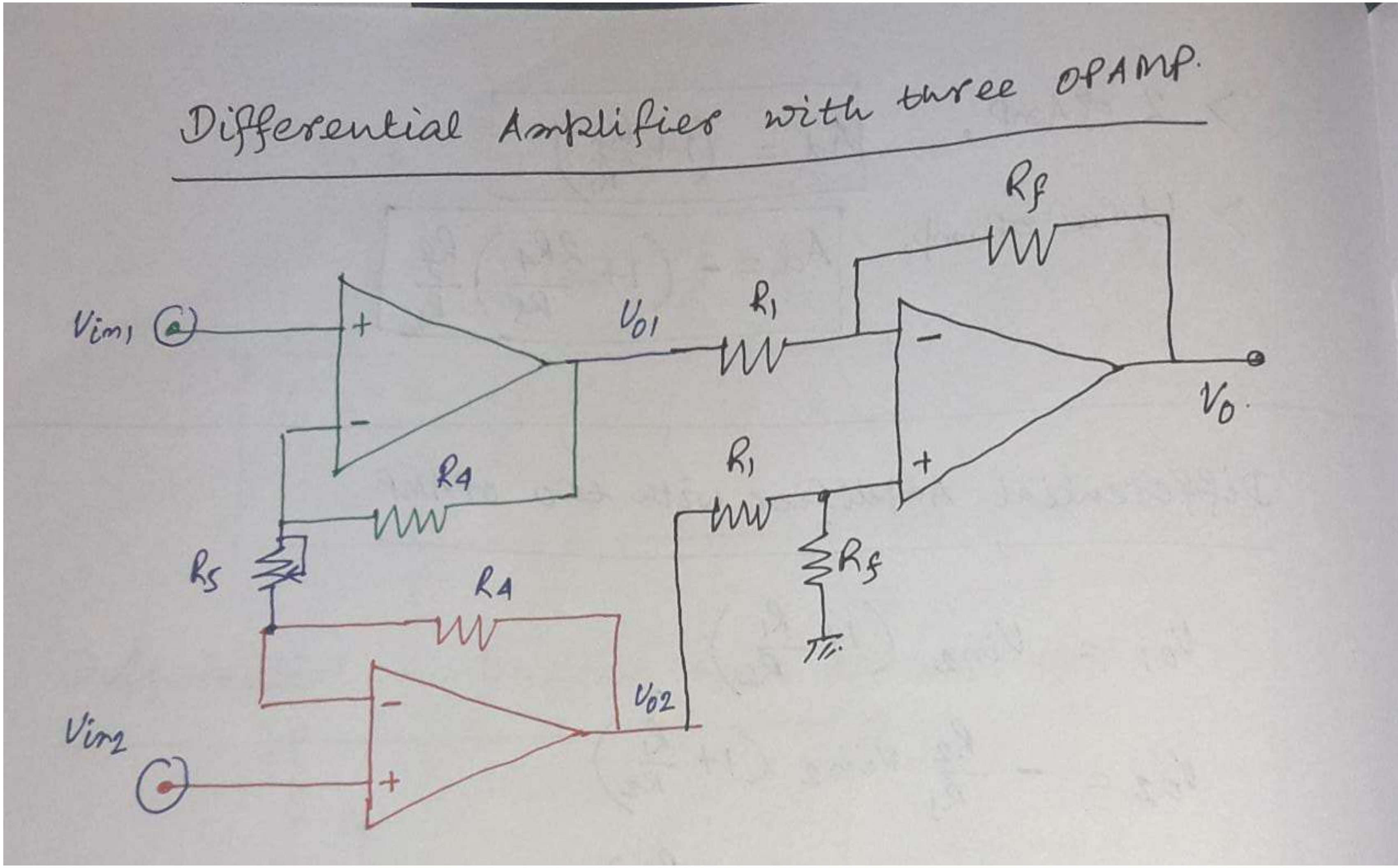
$$V_{o2} = -\frac{R_2}{R_1} V_{in2}\left(1+\frac{R_1}{R_2}\right)$$

$$= -V_{in2}\left(1+\frac{R_2}{R_1}\right)$$

$$V_{o3} = \left(1+\frac{R_2}{R_1}\right)V_{in1}$$

$$V_o = V_{o2}+V_{o3} = \left(1+\frac{R_2}{R_1}\right)(V_{in1}-V_{in2}).$$

OP AMP



Differential Amplifier with three OPAMP.
Rf
Vin1
Vo1
R1
Vo
R1
R4
Rs
Rf
R4
Vo2
Vin2

OP AMP

$$V_{01}' = V_{in1}\left(1+\frac{R_4}{R_5}\right) \quad \ldots\ldots \quad V_{in2}=0$$

$$V_{01}'' = -\frac{R_4}{R_5}V_{in2}$$

$$V_{01} = \frac{R_4+R_5}{R_5}V_{in1} - \frac{R_4}{R_5}V_{in2}$$

$$= \frac{(R_4+R_5)V_{in1} - R_4 V_{in2}}{R_5}$$

$$= \frac{R_4}{R_5}(V_{in1}-V_{in2}) + V_{in1}$$

Similarly

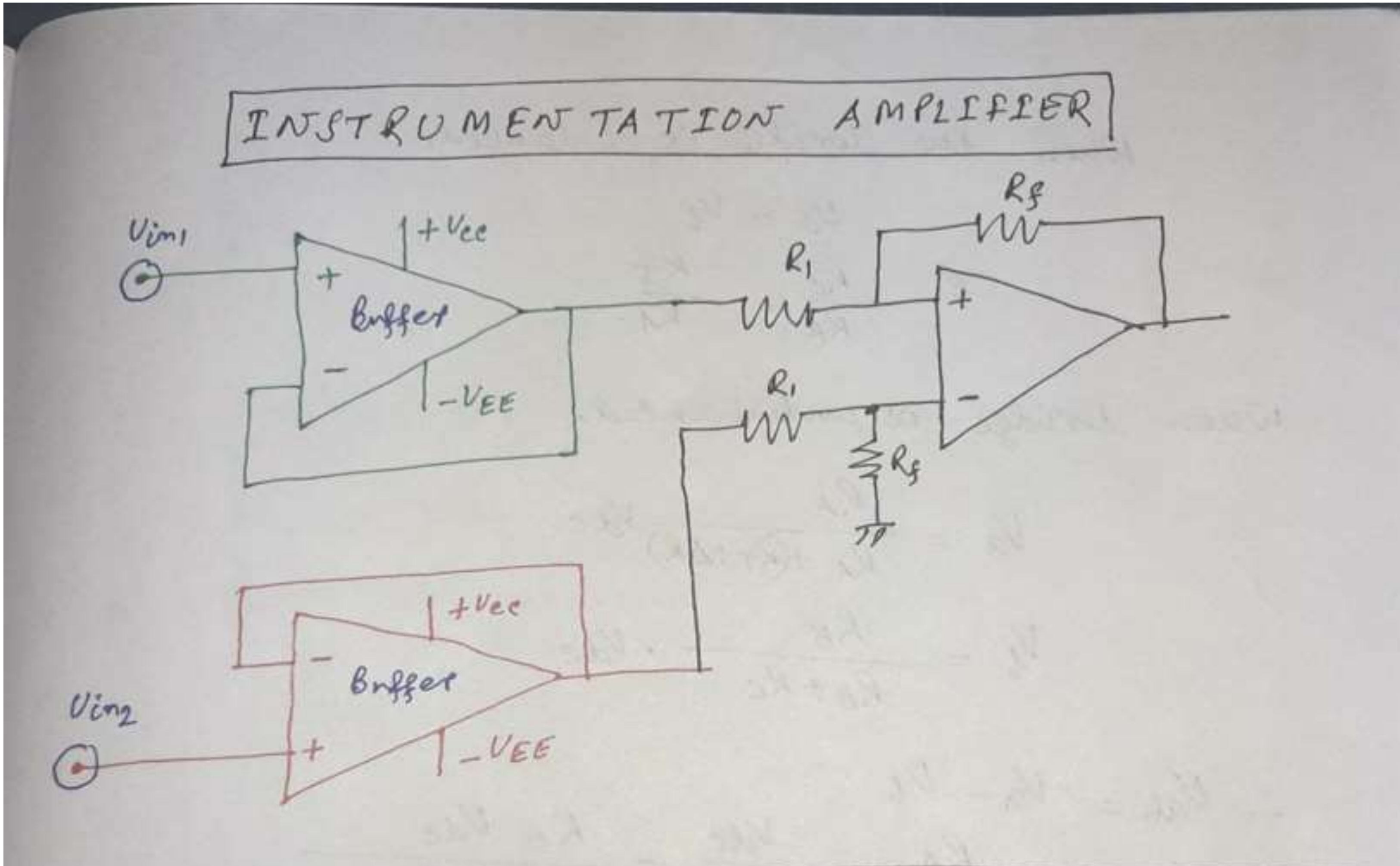
$$V_{02} = \frac{R_4}{R_5}(V_{in2}-V_{in1}) + V_{in2}$$

$$V_0 = \frac{R_f}{R_1}(V_{02}-V_{01})$$

$$= \frac{R_f}{R_1}\left[\frac{R_4}{R_5}(V_{in2}-V_{in1}) + V_{in2} - \frac{R_4}{R_5}(V_{in1}-V_{in2}) - V_{in1}\right]$$

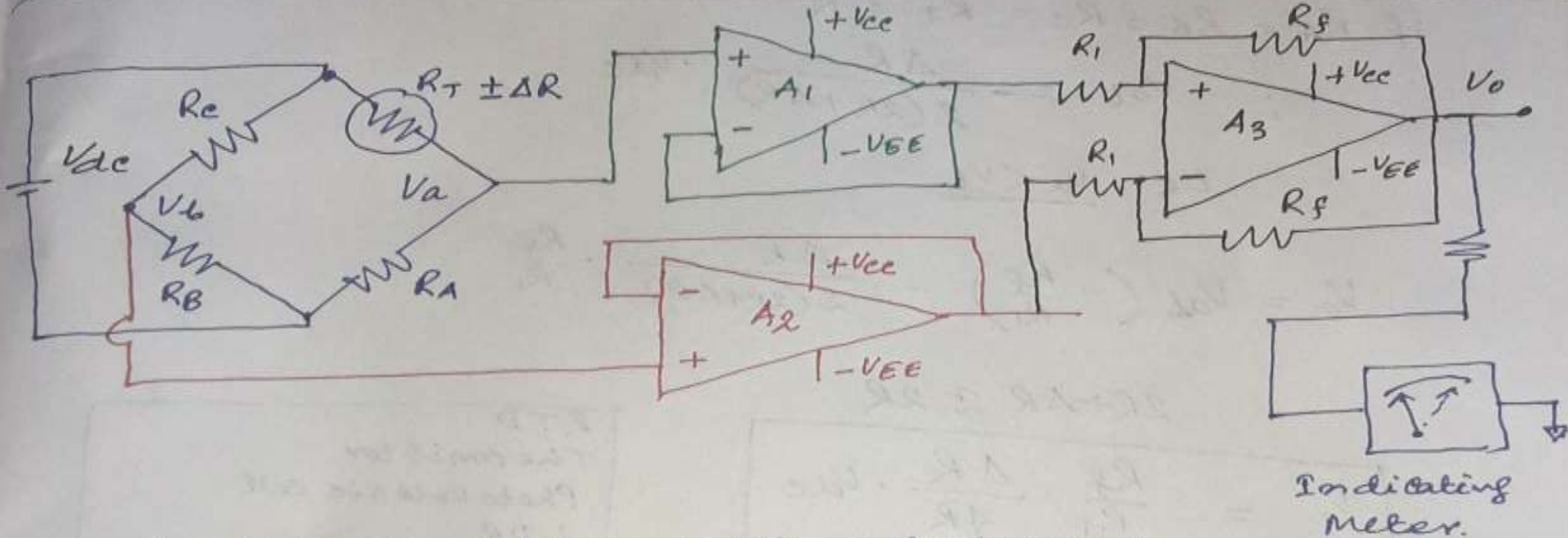
$$\boxed{V_0 = -\left(\frac{R_f}{R_1}\right)\left(1+\frac{2R_4}{R_5}\right)(V_{in1}-V_{in2})}$$

OP AMP


INSTRUMENTATION AMPLIFIER
Vin1
+Vcc
Buffer
-VEE
R1
R1
Rf
Rf
+Vcc
Buffer
Vin2
-VEE

OP AMP

Instrumentation Amplifier with Transducer Bridge.



> Resistive Transducer whose resistance changes as a function of some physical energy.

OP AMP

When the bridge is balanced.

$$V_a = V_b.$$

$$\frac{R_C}{R_B} = \frac{R_T}{R_A}.$$

When bridge is unbalanced.

$$V_a = \frac{R_A}{R_A + (R_T + \Delta R)} V_{dc}.$$

$$V_b = \frac{R_B}{R_B + R_C} \cdot V_{dc}.$$

$$\therefore V_{ab} = V_a - V_b.$$

$$= \frac{R_A \quad V_{dc}}{R_A + R_T + \Delta R} - \frac{R_B V_{dc}}{R_B + R_C}.$$

if $R_A = R_B = R_C = R_T = R$

$$\therefore V_{ab} = -\frac{\Delta R}{2(2R + \Delta R)} \cdot V_{dc}.$$

i.e $\underline{V_a < V_b}$

OP AMP

$$V_0 = V_{ab}\left(-\frac{R_f}{R_1}\right) = \frac{\Delta R}{2(2R+\Delta R)} \cdot \frac{R_f}{R_1}$$

$$2R+\Delta R \simeq 2R$$

$$\boxed{V_0 = \frac{R_f}{R_1} \cdot \frac{\Delta R}{4R} \cdot V_{dc}}$$

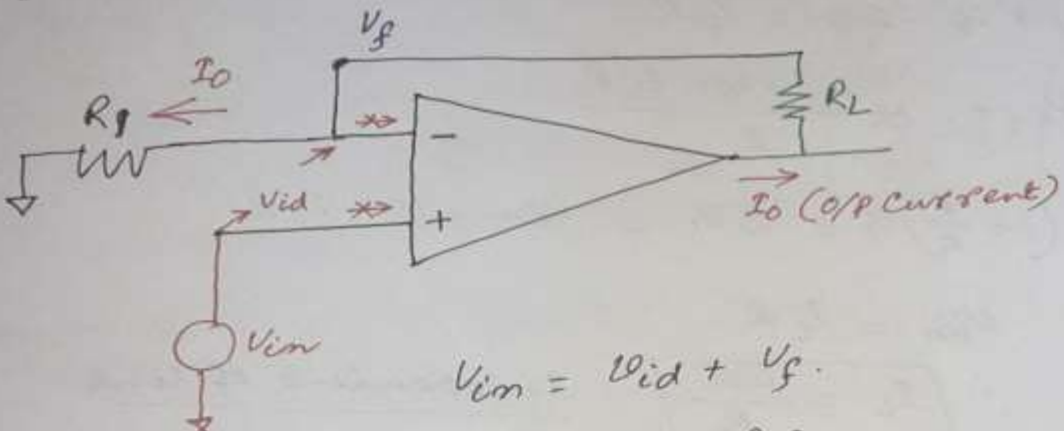
$$\underline{V_0 \propto \Delta R}$$

RTD
Thermistor
Photovoltaic cell
LDR
Strain Gauge
(Analog Weight Scale)

Temperature Indicator, Temperature Controller, Light Intensity meter, Measurement flow & Conductivity, Analog Weight Scale etc.

OP AMP

Voltage to Current Converter with floating load



$$V_{in} = v_{id} + V_f.$$

$V_{id} = 0$,

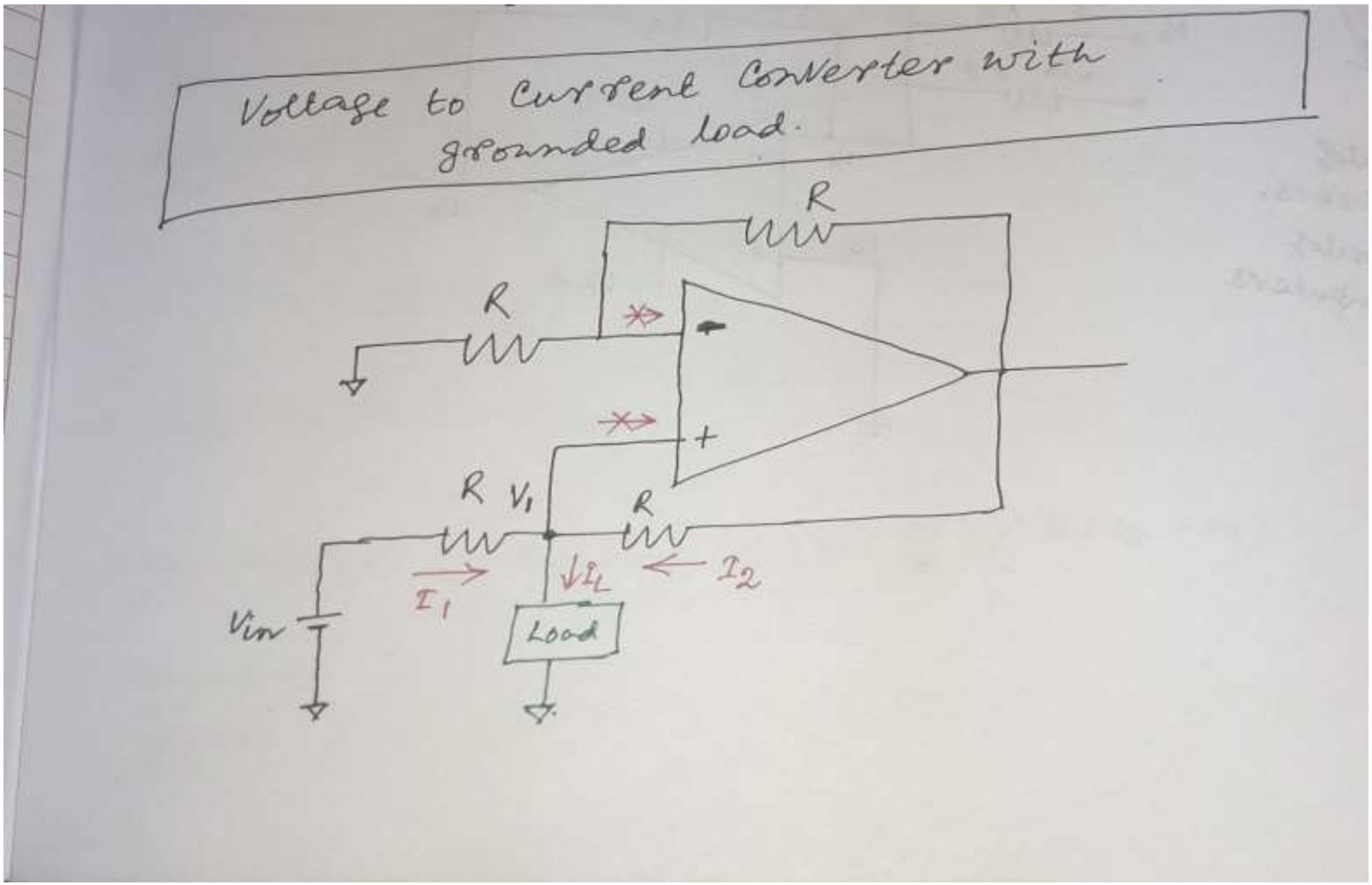
$$V_{in} = V_f. = R_1 I_0.$$

$$\therefore \boxed{I_0 = \frac{V_{in}}{R_1}}$$

Output current is independent of load.

<u>Applications</u> — Low voltage DC Voltmeter, Telemetry System. Low Voltage AC Voltmeter, Zener Diode Tester, Light emitting Diode Tester.

OP AMP


Voltage to Current Converter with grounded load.
R
R
R
V1
R
I1
IL
I2
Vin
Load

OP AMP

$$I_1 + I_2 = I_L$$

$$\therefore \frac{V_{in} - V_1}{R} + \frac{V_0 - V_1}{R} = I_L$$

$$\therefore V_{in} + V_0 - 2V_1 = I_L R$$

$$\therefore V_1 = \frac{V_{in1} + V_0 - I_L R}{2}$$

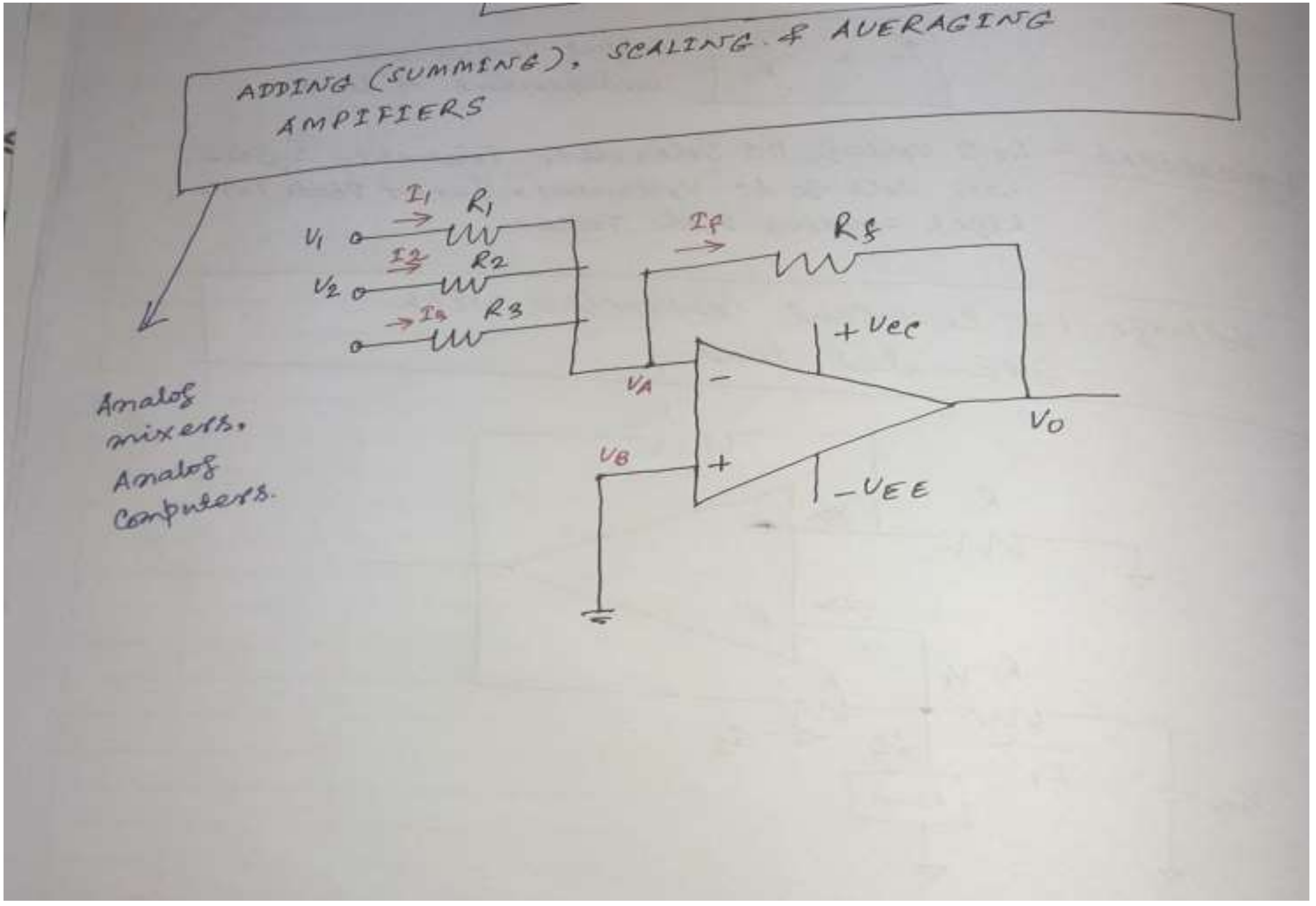
$$\therefore V_0 = \left(1 + \frac{R}{R}\right) V_1 = 2V_1 = V_{in1} + V_0 - I_L R$$

$$\therefore V_{in} = I_L R$$

$$\therefore \boxed{I_L = \frac{V_{in}}{R}}$$

Independent of load.

OP AMP



ADDING (SUMMING), SCALING & AVERAGING AMPIFIERS
Analog mixers. Analog Computers.
I_1
R_1
V_1
I_2
R_2
V_2
I_3
R_3
I_f
R_f
$+V_{CC}$
V_A
V_o
V_B
$-V_{EE}$

OP AMP

$$I_1 + I_2 + I_3 - I_f = 0.$$

$$\therefore \quad V_A = V_B = 0$$

$$\frac{V_1 - V_A}{R_1} + \frac{V_2 - V_A}{R_2} + \frac{V_3 - V_A}{R_3} - \frac{V_A - V_o}{R_f} = 0.$$

$$\therefore \boxed{V_o = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right)}$$

Scaling or Weighting Amplifier

Summing Amplifier

$$R_f = R_2 = R_3 = R$$

$$\therefore \quad V_o = -\left(\frac{R_f}{R_1}\right)(V_1 + V_2 + V_3)$$

OP AMP

Adder

$$R_1 = R_2 = R_3 = R_f = R.$$

$$\therefore V_0 = -(V_1 + V_2 + V_3)$$

Averaging Circuit.

$$R_1 = R_2 = R_3 = R$$

$$\frac{R_f}{R} = \frac{1}{n}.$$

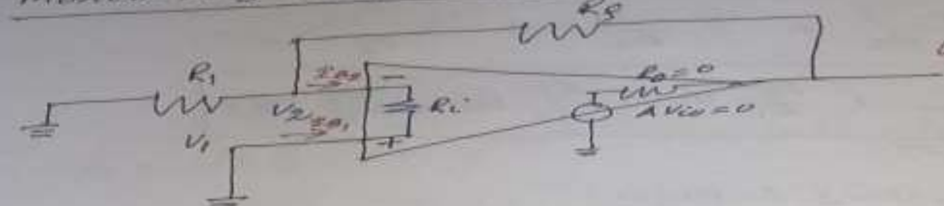
Here $n = 3$, $V_0 = -\frac{V_1 + V_2 + V_3}{3}$

Noninverting? Summing $V_0 = \left(1 + \frac{R_f}{R_1}\right)(V_1 + V_2 + V_3)$

OP AMP

~~OFFSET NULLING TECHNIQ~~

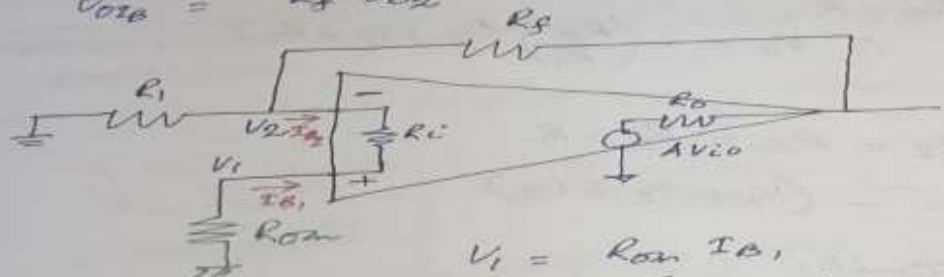
Minimising output offset voltage.



$V_{OIB} = R_f I_{B2}$

$$V_2 = (R_1 \parallel R_f) I_{B2}$$

$$V_{OIB} = R_f I_{B2}$$



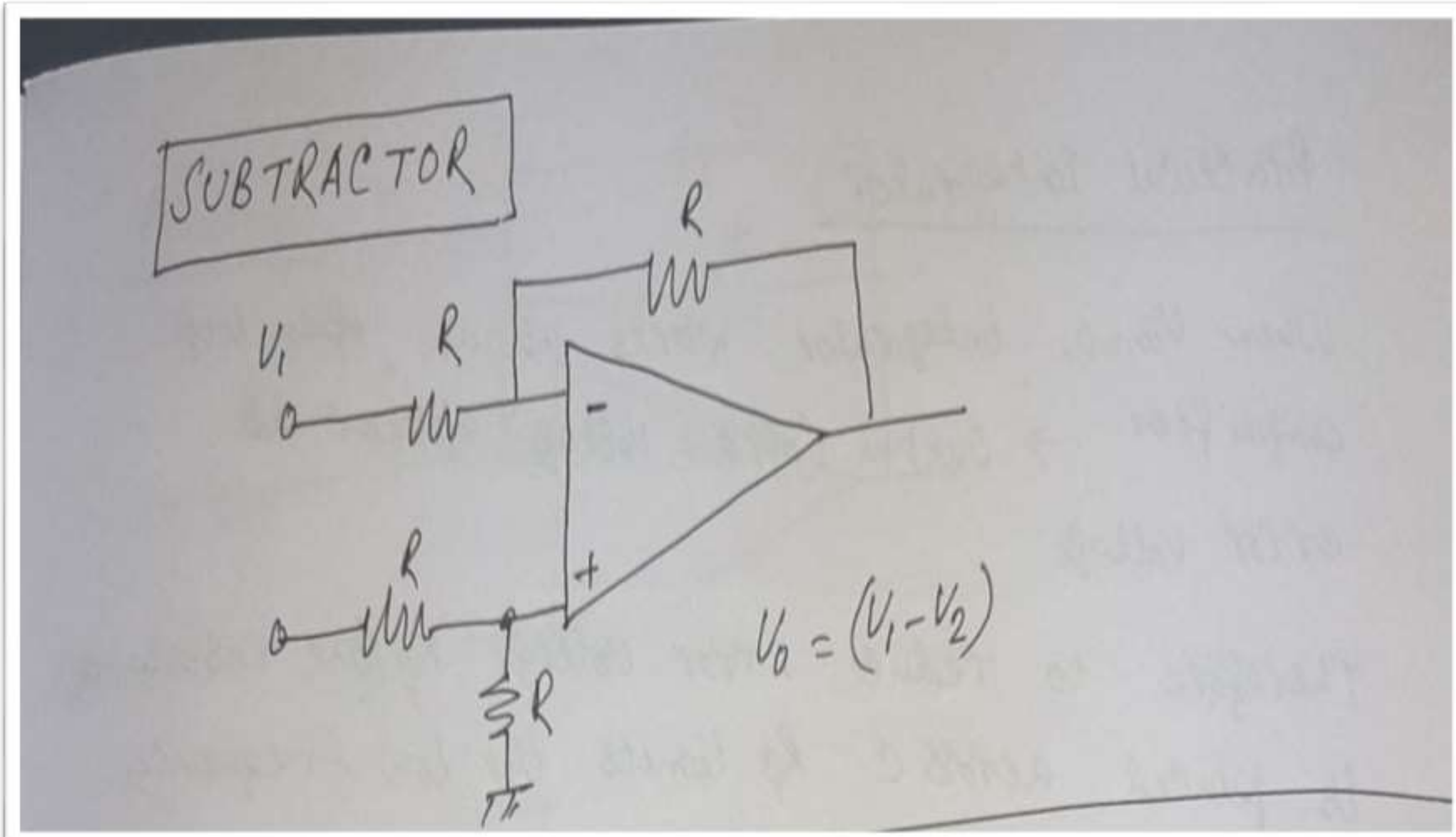
$$V_1 = R_{om} I_{B1}$$

$$V_2 = (R_1 \parallel R_f) I_{B2}$$

$$\therefore \quad R_{om} I_{B1} = (R_1 \parallel R_f) I_{B2}$$

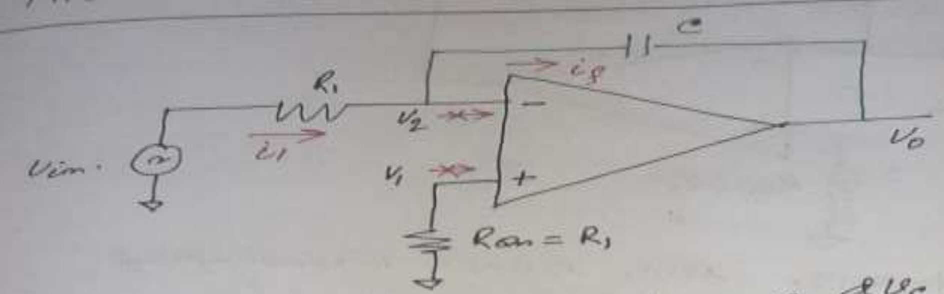
$\underline{I_{B1} = I_{B2}}$ $\quad \therefore \quad \boxed{R_{om} = (R_1 \parallel R_f)}$

OP AMP



OP AMP

THE INTEGRATOR



$$i_1 = i_f. \qquad i_c = C\,\frac{dv_c}{dt}.$$

$$\therefore \quad \frac{V_{in} - v_2}{R_1} = C\,\frac{d}{dt}(v_2 - v_o)$$

$$\therefore \quad \frac{V_{in}}{R_1} = C\,\frac{d}{dt}(-v_o)$$

$$\therefore \quad \int_0^t \frac{V_{in}}{R_1} = \int_0^t C\,\frac{d}{dt}(-v_o)$$

$$= C(-v_o) + v_o\big|_{t=0}.$$

$$\therefore \quad \boxed{v_o = -\frac{1}{R_1 C}\int_0^t V_{in}\,dt + C.}$$

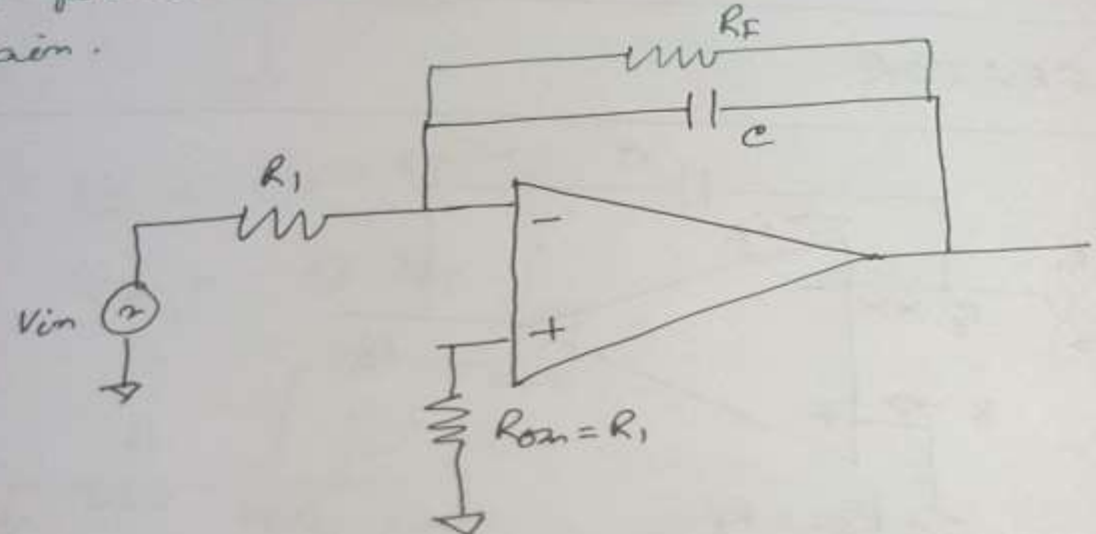
$$f_b = \frac{1}{2\pi R_1 C_F}$$

OP AMP

Practical Integrator

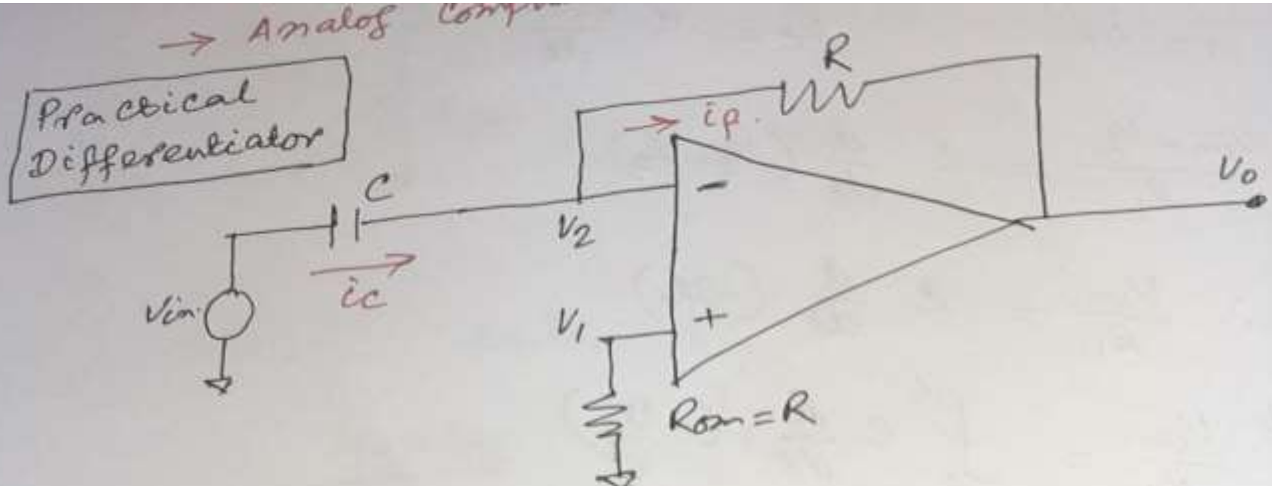
When $V_{in}=0$, integrator works as an open loop amplifier. → Output (offset voltage) appear as error voltage.

Therefore to reduce error voltage R_f (one resistance) is placed across C. R_f limits the low frequency gain.



→ Analog computers, ADC, Signal waveshaping.

OP AMP



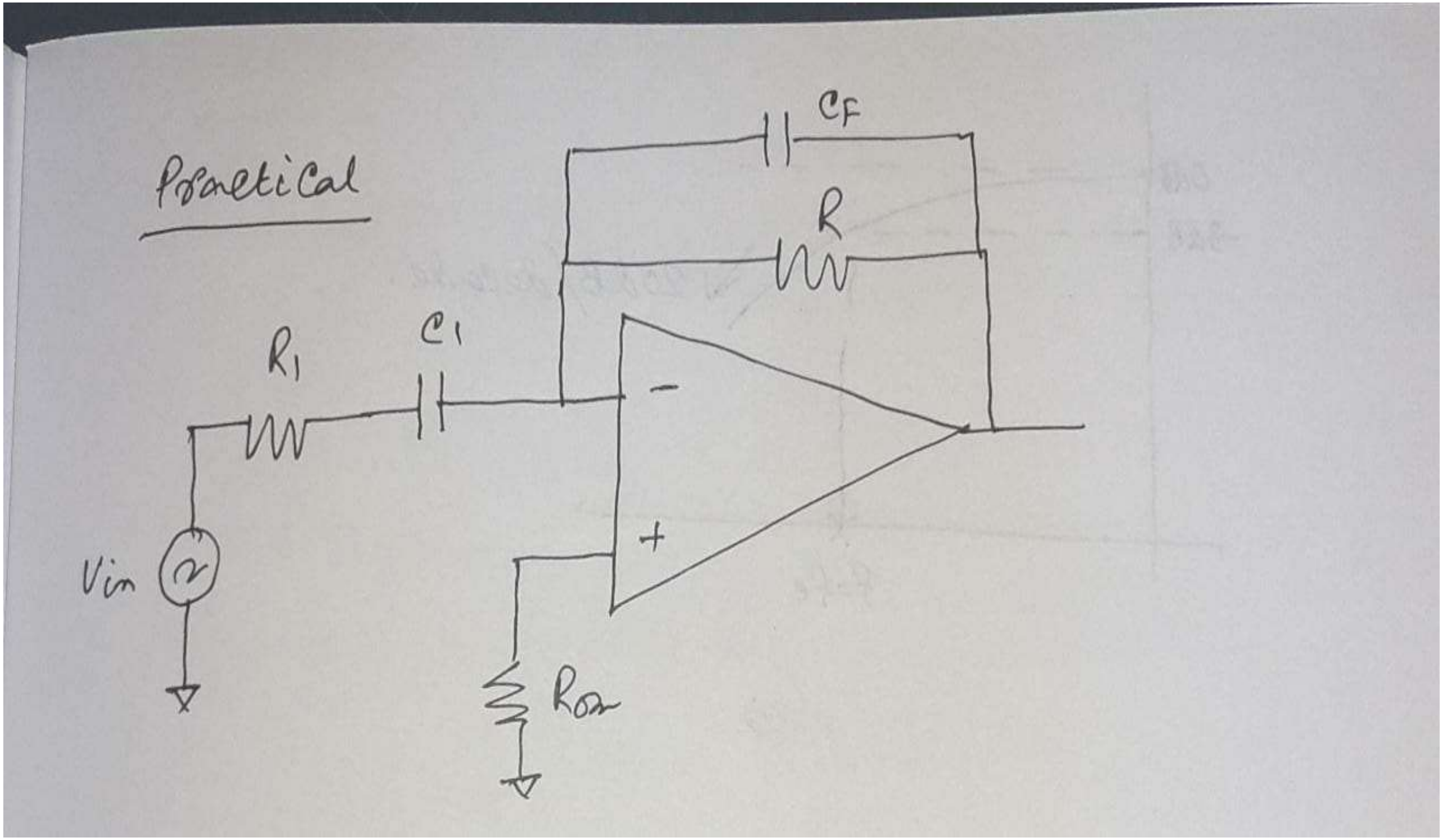
$i_c = i_f$.

$$\therefore C\frac{d}{dt}(V_{in}-V_2) = \frac{V_2-V_0}{R_f}.$$

$$\therefore -\frac{V_0}{R_f} = C\frac{d}{dt}(V_{in}-V_2)$$

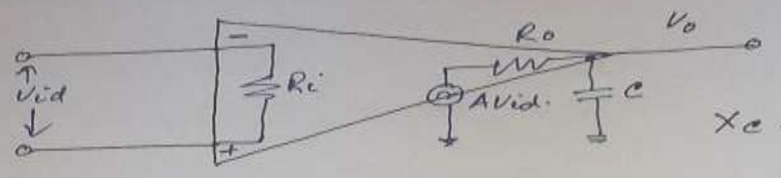
$$\therefore \boxed{V_0 = -RC\frac{dV_{in}}{dt}}$$

OP AMP



OP AMP

FREQUENCY RESPONSE OF AN OPAMP.



$X_C = \frac{1}{2\pi f C}$.

$$\cancel{\boxed{V_o = \frac{jX_C}{R_o - jX_C} \, A V_{id}}}$$

$$V_o = \frac{\frac{1}{j\omega C}}{R_o + \frac{1}{j\omega C}} (A V_{id})$$

$$= \frac{A V_{id}}{1 + j\omega C R_o}.$$

$$= \frac{A V_{id}}{1 + j 2\pi f C R_o}. = \frac{A V_{id}}{1 + j(f/f_C)},$$

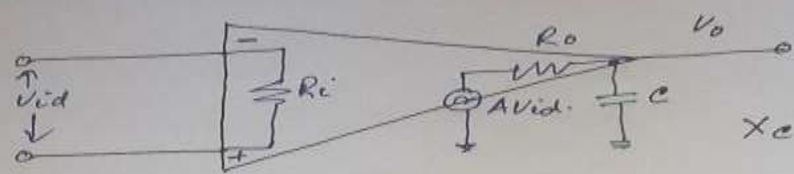
where $f_C = \frac{1}{2\pi C R_o}$

$$\therefore A_f = \frac{V_o}{V_{id}} = \frac{A}{1 + j(f/f_C)}.$$

$$\therefore |A_f| = \frac{A}{\sqrt{1 + (f/f_C)^2}}$$

OP AMP

FREQUENCY RESPONSE OF AN OPAMP.



$X_C = \frac{1}{2\pi f C}$.

$$\boxed{\cancel{V_o = \frac{jX_C}{R_o - jX_C} A V_{id}}}$$

$$V_o = \frac{\frac{1}{j\omega C}}{R_o + \frac{1}{j\omega C}} (A V_{id})$$

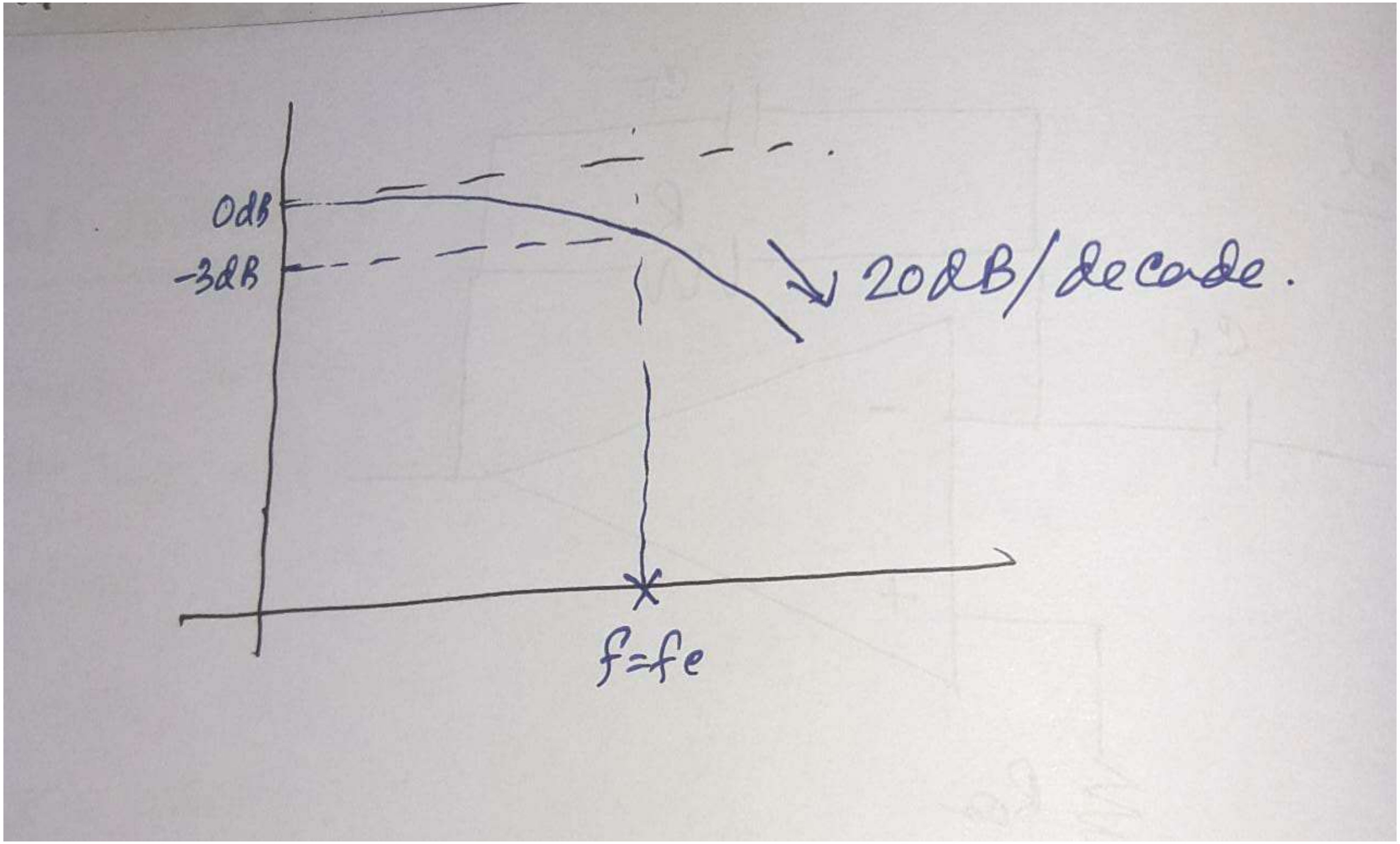
$$= \frac{A V_{id}}{1 + j\omega C R_o}.$$

$$= \frac{A V_{id}}{1 + j 2\pi f C R_o}. = \frac{A V_{id}}{1 + j(f/f_c)},$$ where $f_c = \frac{1}{2\pi C R_o}$

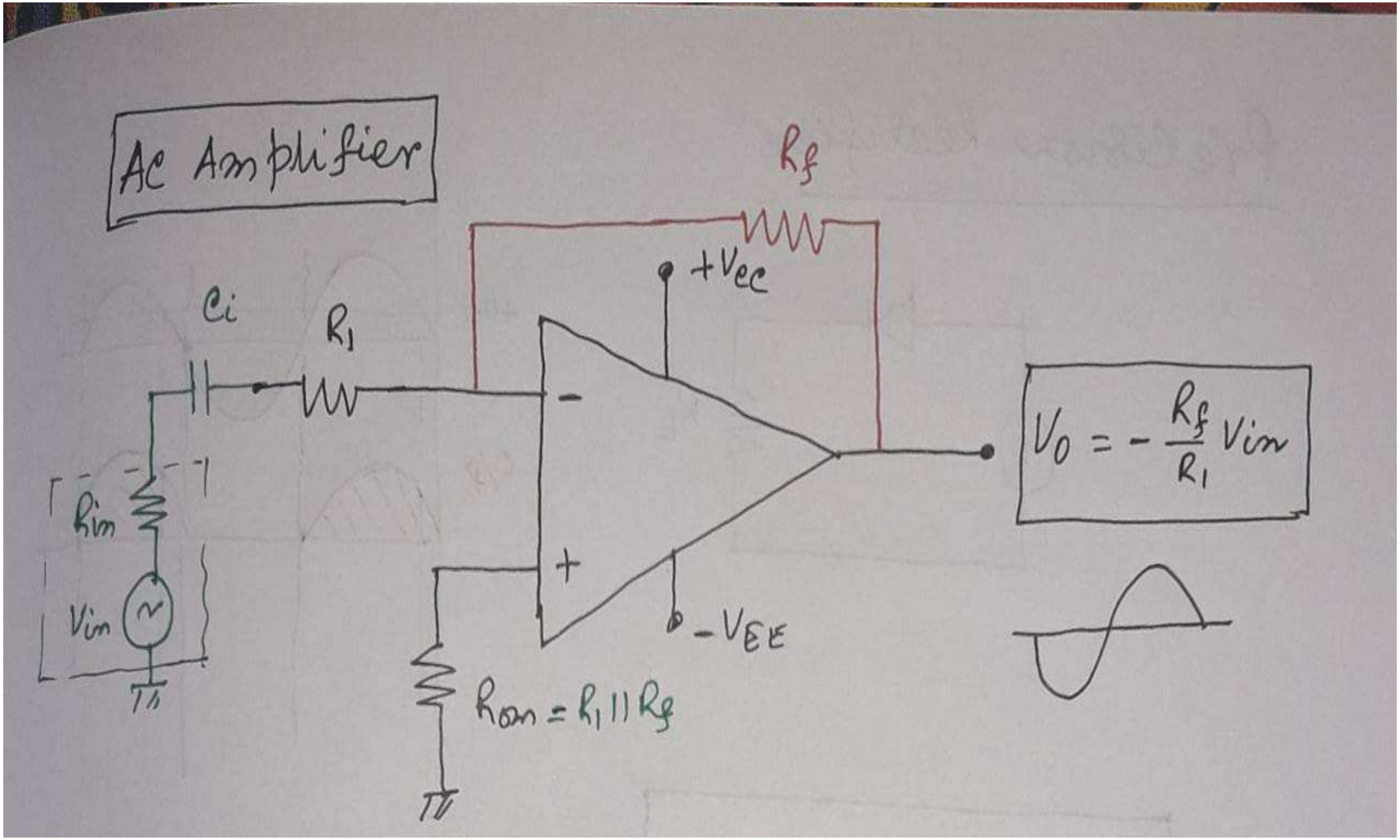
$$\therefore A_f = \frac{V_o}{V_{id}} = \frac{A}{1 + j(f/f_c)}.$$

$$\therefore |A_f| = \frac{A}{\sqrt{1 + (f/f_c)^2}}$$

OP AMP

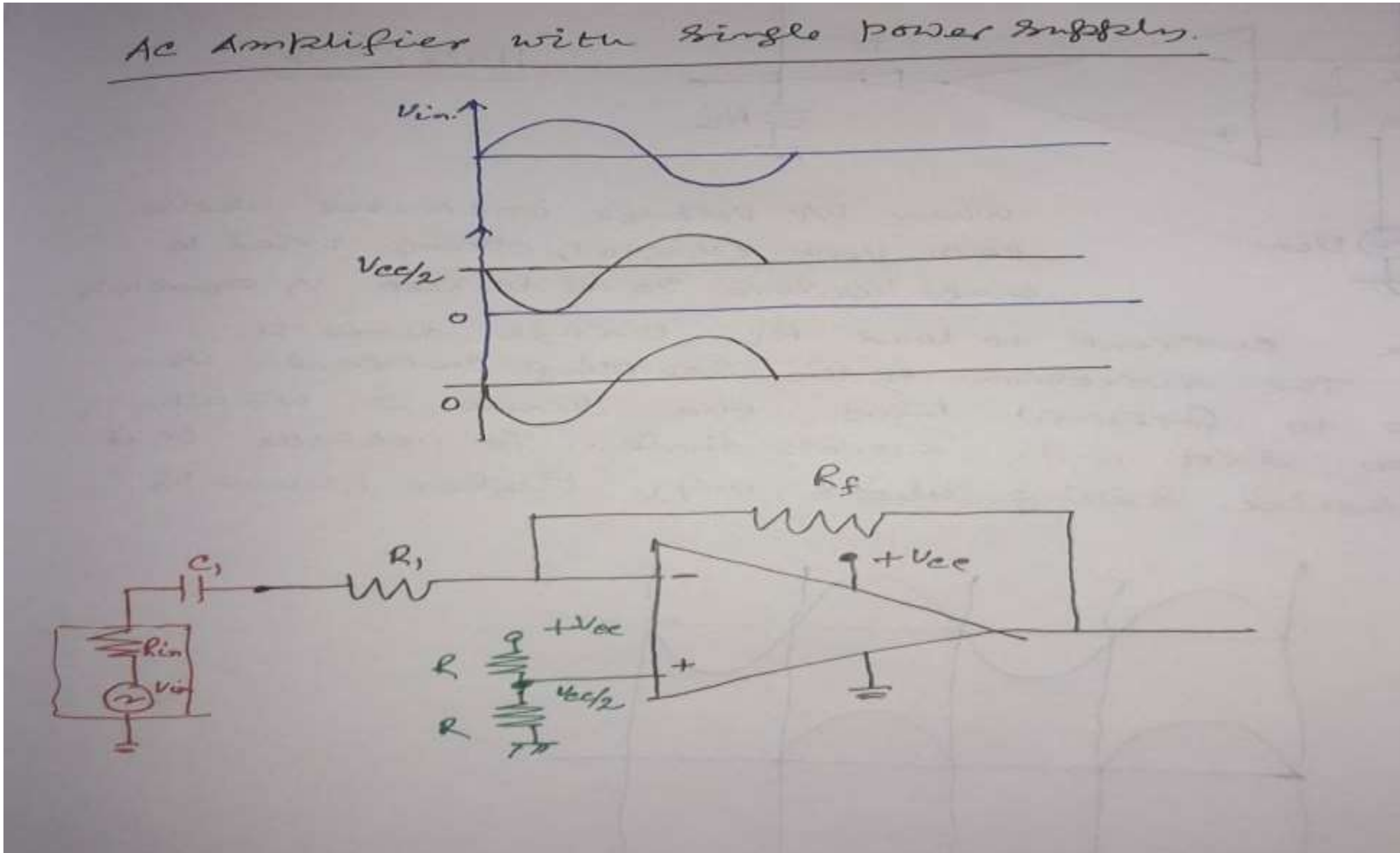


OP AMP



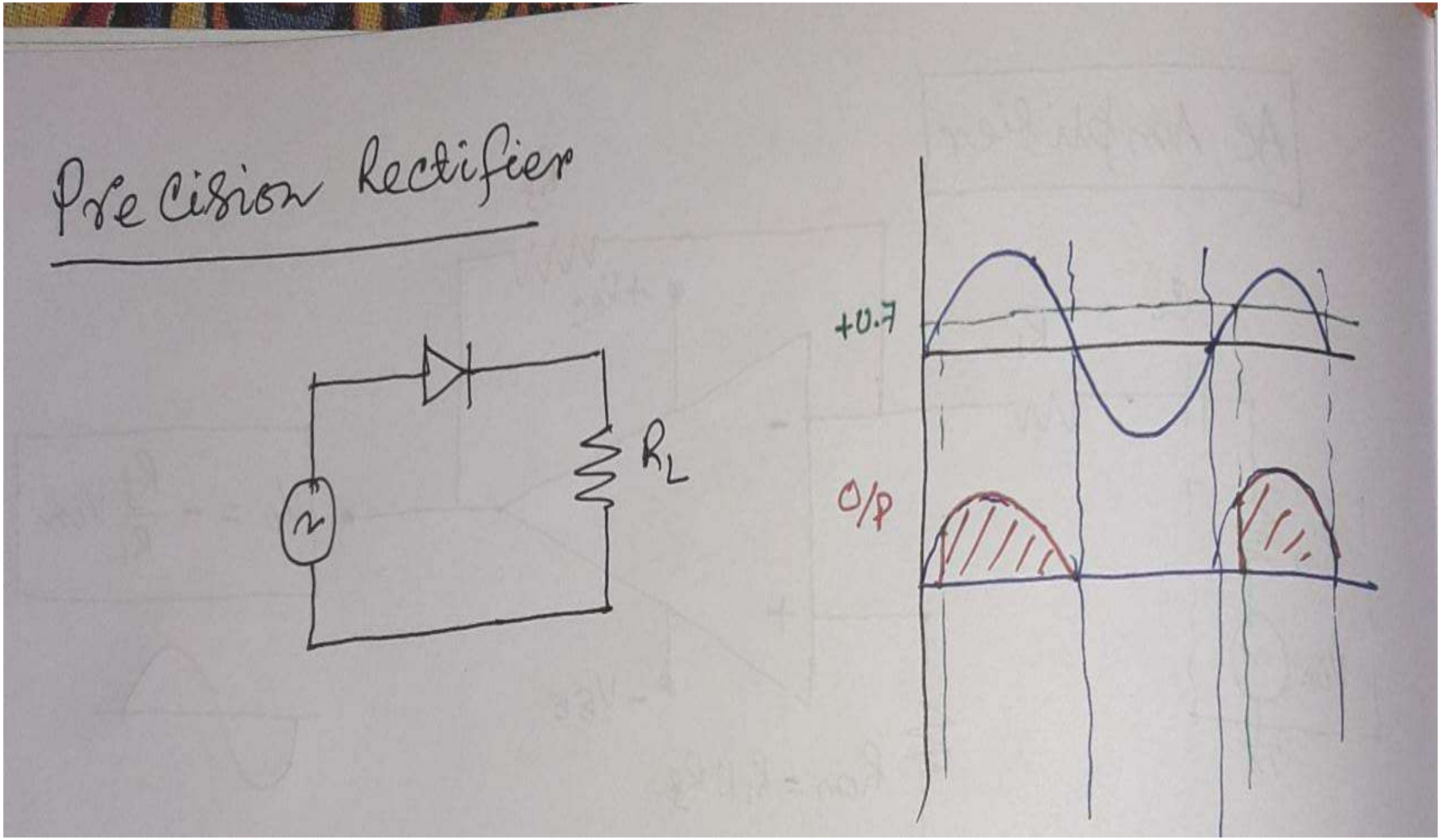
Ac Amplifier
R_f
$+V_{cc}$
C_i
R_1
$-$
$+$
R_{in}
V_{in}
$-V_{EE}$
$R_{om} = R_1 \parallel R_f$
$V_0 = -\frac{R_f}{R_1} V_{in}$

OP AMP

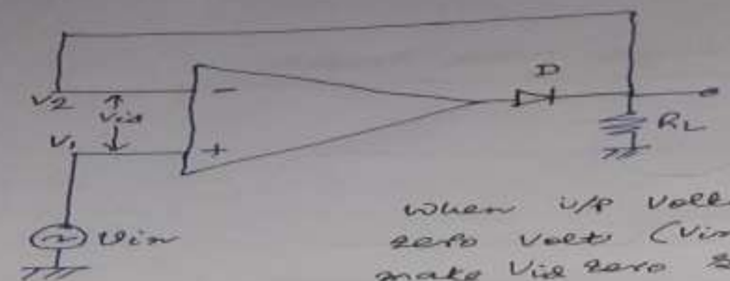


Ac Amplifier with single power supply.
Vin.
Vcc/2
0
0
Rf
C1
R1
+Vcc
+Vcc
R
R
Vcc/2
Rin
Vi

OP AMP



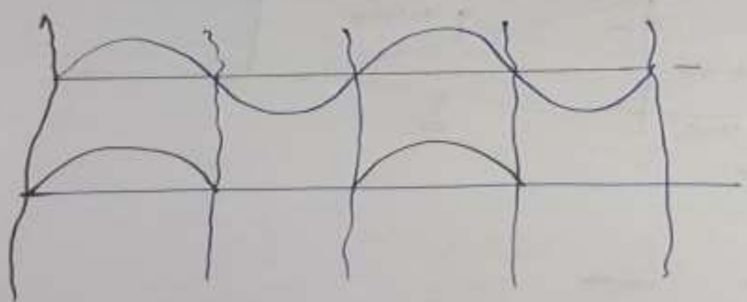
OP AMP



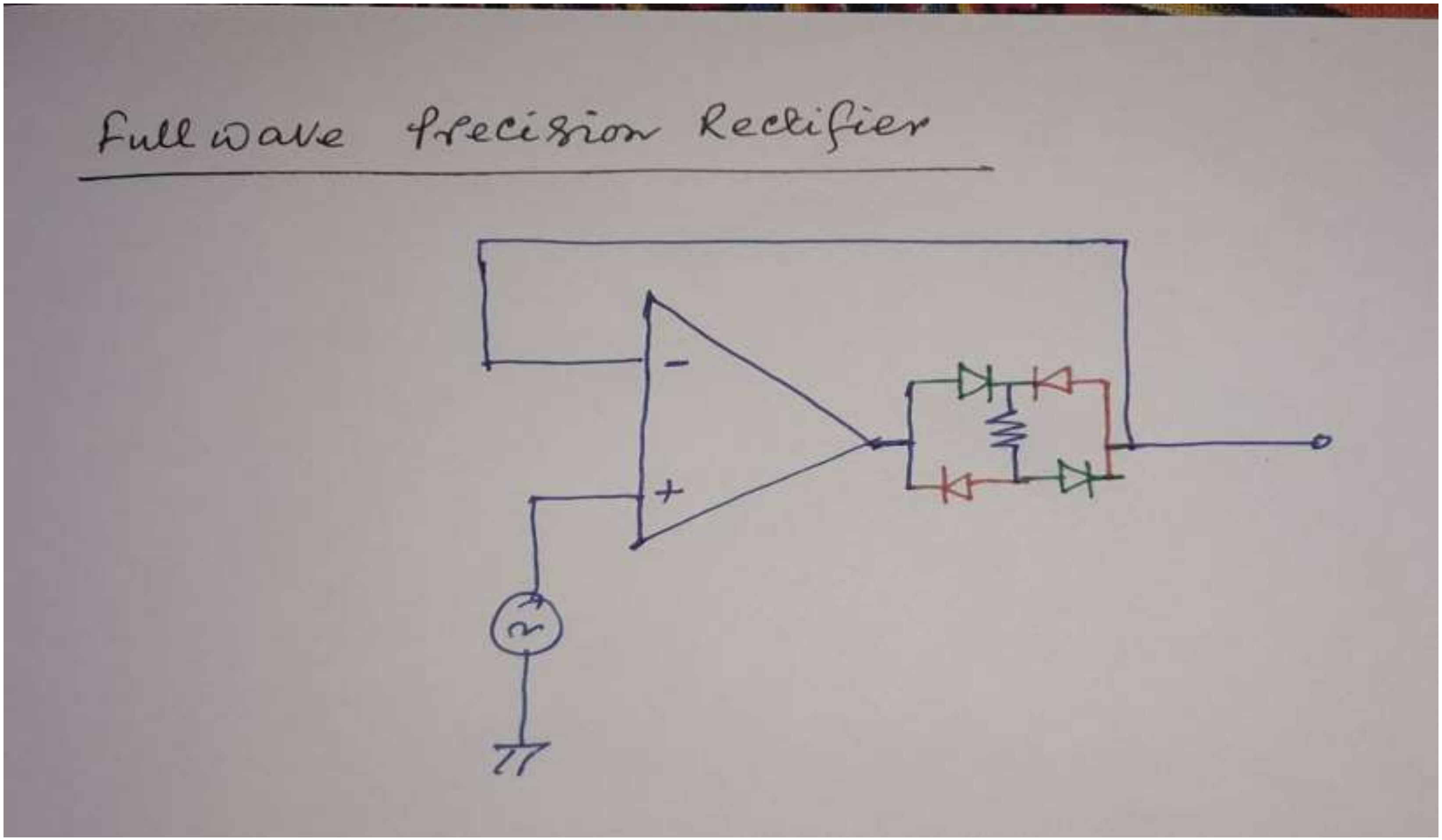
Half wave

When i/p voltage increases above zero volt ($V_{in} > 0$), opamp tried to make V_{id} zero so as to keep V_1 equal to V_2.

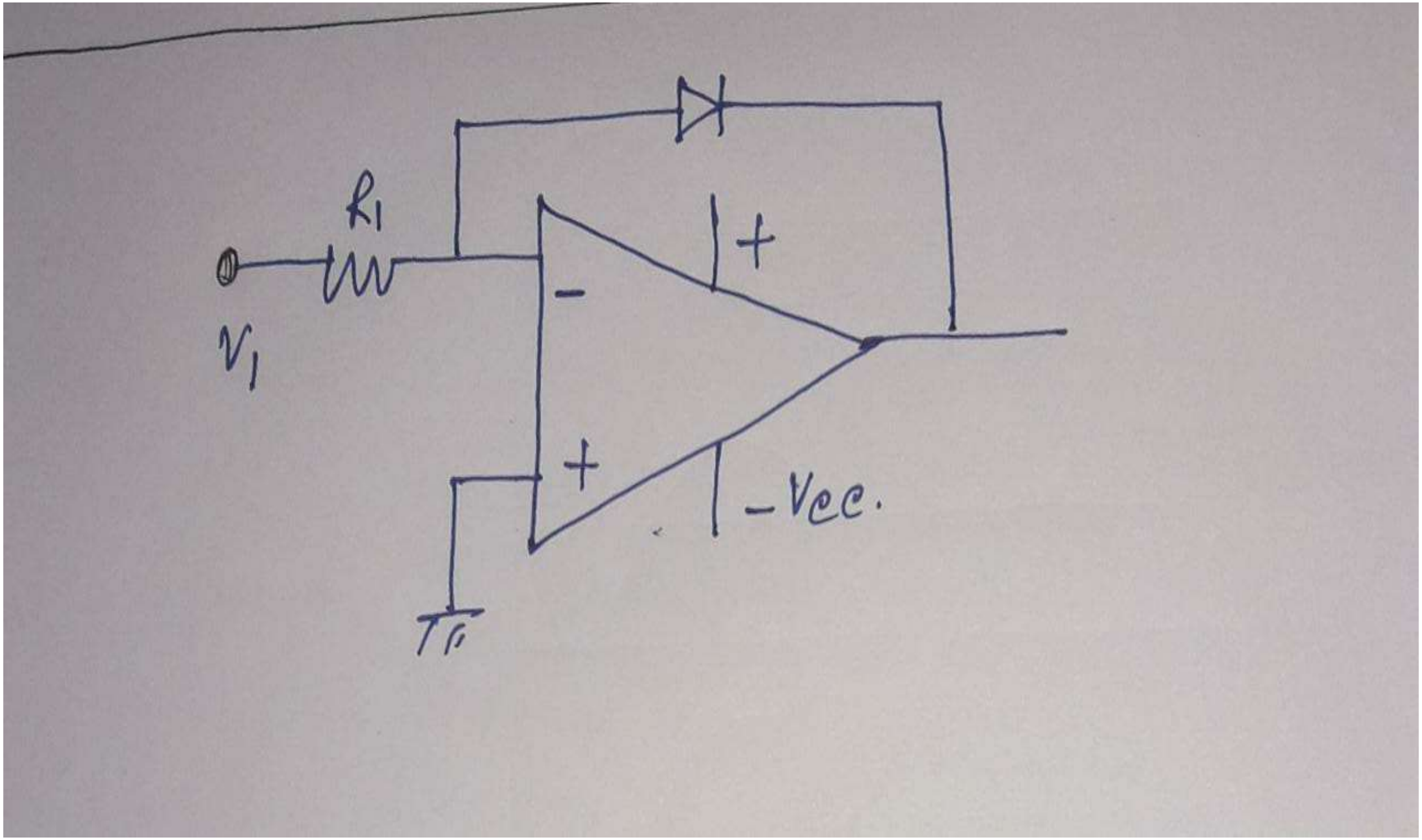
It source current to load R_L through diode D to ground. The direction of the sourcing current is appropriate to forward bias the diode D which develops to drop 0.7V across diode. To achieve this op amp should swing about 0.7V higher than V_o.



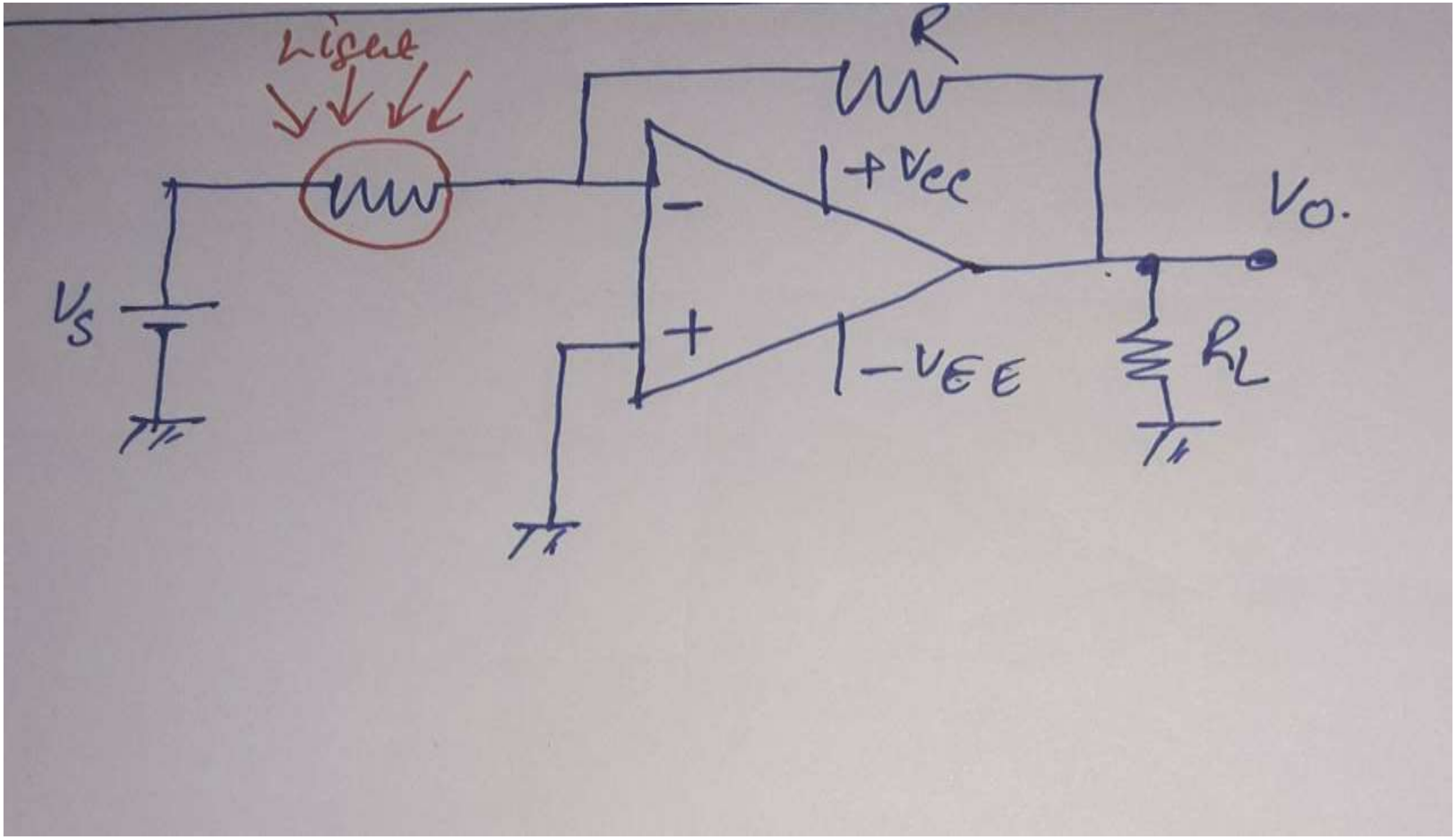
OP AMP



OP AMP

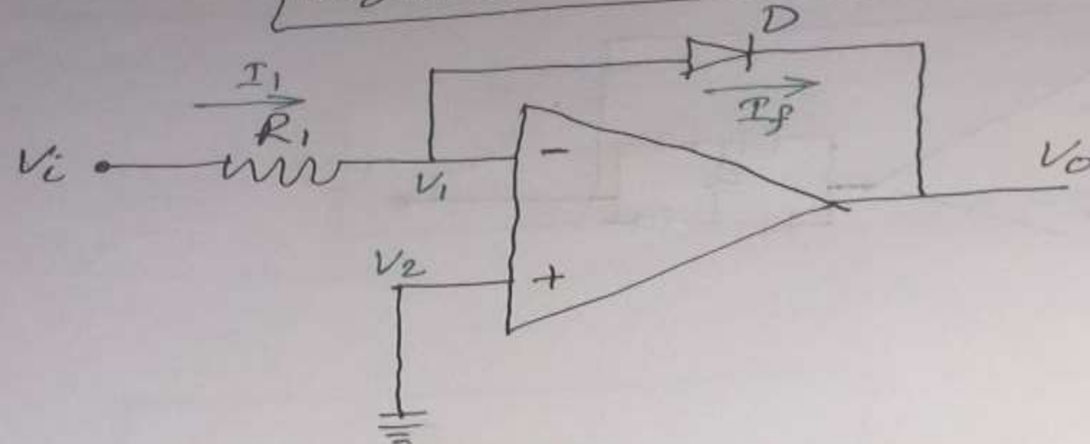


OP AMP



OP AMP

Logarithmic Amplifier



$$I_f = I_1 = V_i/R_1$$

$$I_f = I_s\, e^{(V_f/\eta V_T)}$$

I_s = Saturation Current of the diode

V_f = Voltage Drop across diode, when it is in forward bias

V_T = diode's thermal equivalent Voltage.

OP AMP

$$V_f = -V_o$$

$$\therefore \quad I_f = I_s \, e^{(-V_o/nV_T)}$$

$$\therefore \quad \frac{V_i}{R_1} = I_s \, e^{-(V_o/nV_T)}$$

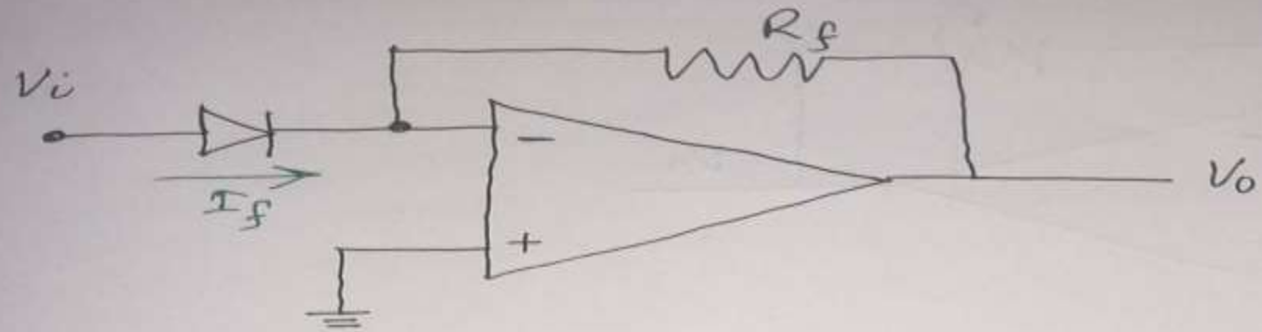
$$\therefore \quad \frac{V_i}{R_1 I_s} = e^{-(V_o/nV_T)}$$

$$\ln\left(\frac{V_i}{R_1 I_s}\right) = -\frac{V_o}{nV_T}$$

$$\therefore \quad \boxed{V_o = -nV_T \ln\left(\frac{V_i}{R_1 I_s}\right)}$$

OP AMP

Anti-logarithmic Amplifier



$$-I_f + \frac{0 - V_o}{R_f} = 0$$

$$\therefore \quad V_o = -R_f I_f$$

$$\therefore \quad I_f = I_s \, e^{(V_f/nV_T)}$$

$$\therefore \quad V_o = -R_f \left\{ I_s \, e^{(V_f/nV_T)} \right\}$$

$$\therefore \quad V_o = -R_f I_s \, e^{(V_f/nV_T)}$$

OP AMP

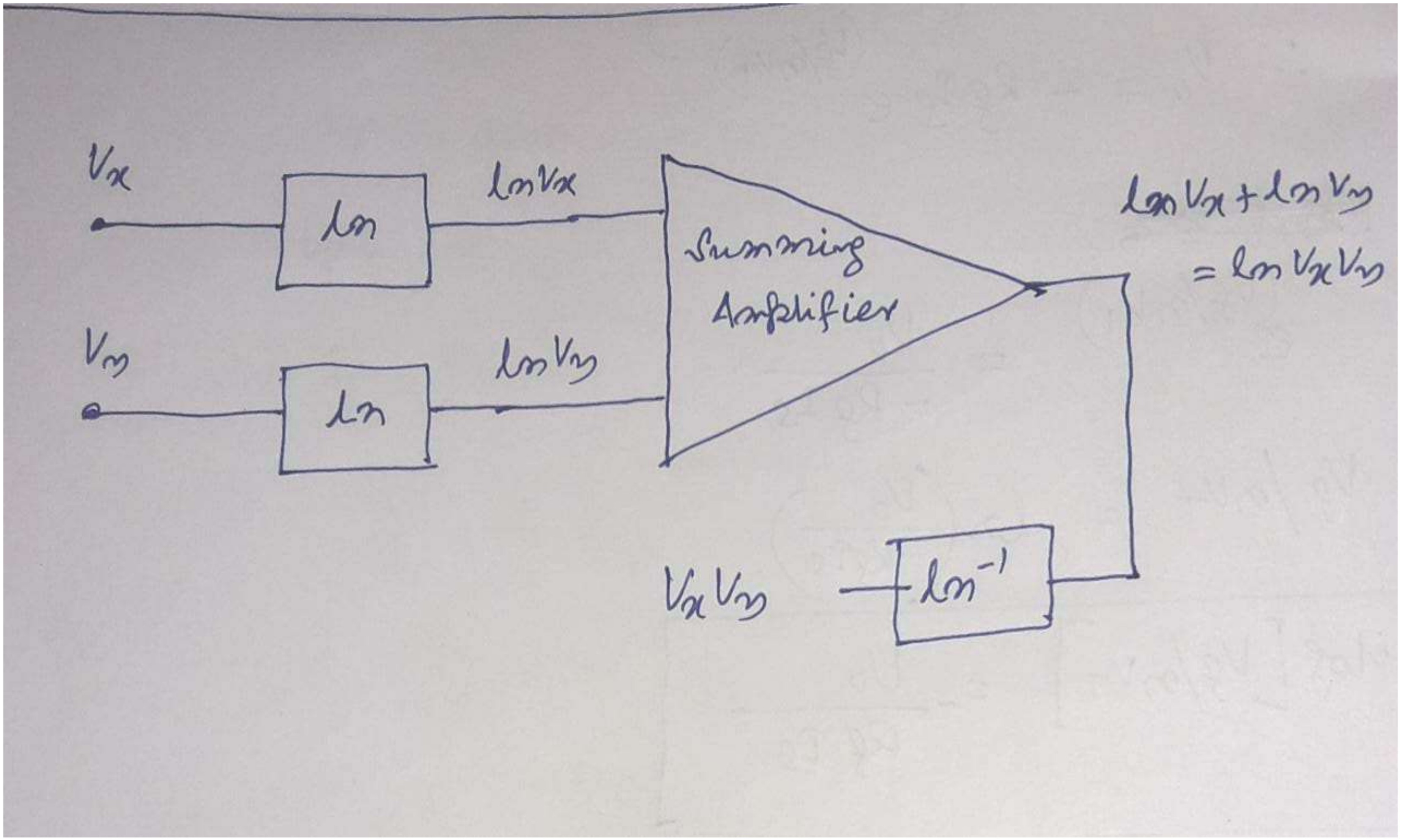
$$e^{(V_f/nV_T)} = \frac{V_o}{-R_f I_s}$$

$$V_f/nV_T = \ln\left(\frac{V_o}{-R_f I_s}\right)$$

$$\boxed{\text{antilog}\left[V_f/nV_T\right] = -\frac{V_o}{R_f I_s}}$$

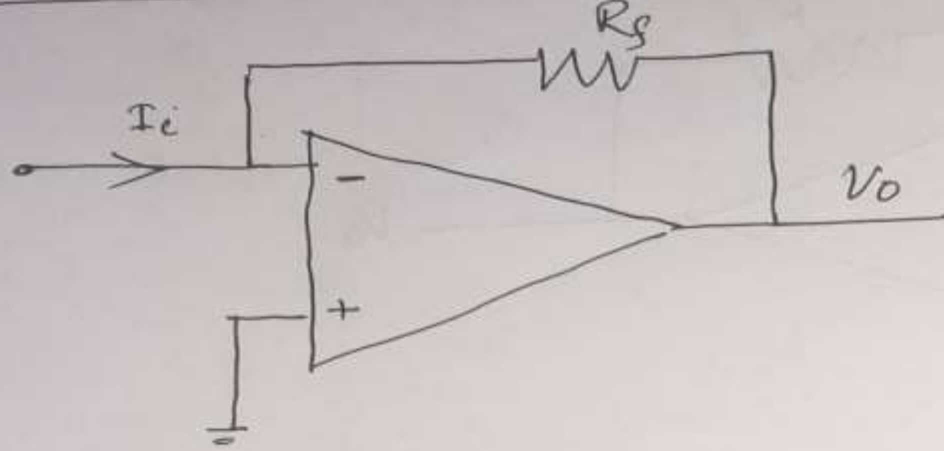
Analog Multiplier

OP AMP


V_x
ln
ln V_x
Summing Amplifier
ln V_x + ln V_y
= ln $V_x V_y$
V_y
ln
ln V_y
$V_x V_y$
ln^{-1}

OP AMP

Current to Voltage Converter



$$-I_i + \frac{0 - V_o}{R_f} = 0$$

$$-I_i = \frac{V_o}{R_f}$$

$$\boxed{V_o = -R_f I_i}$$

OP AMP

Solution to the 2nd Order Differential Equation

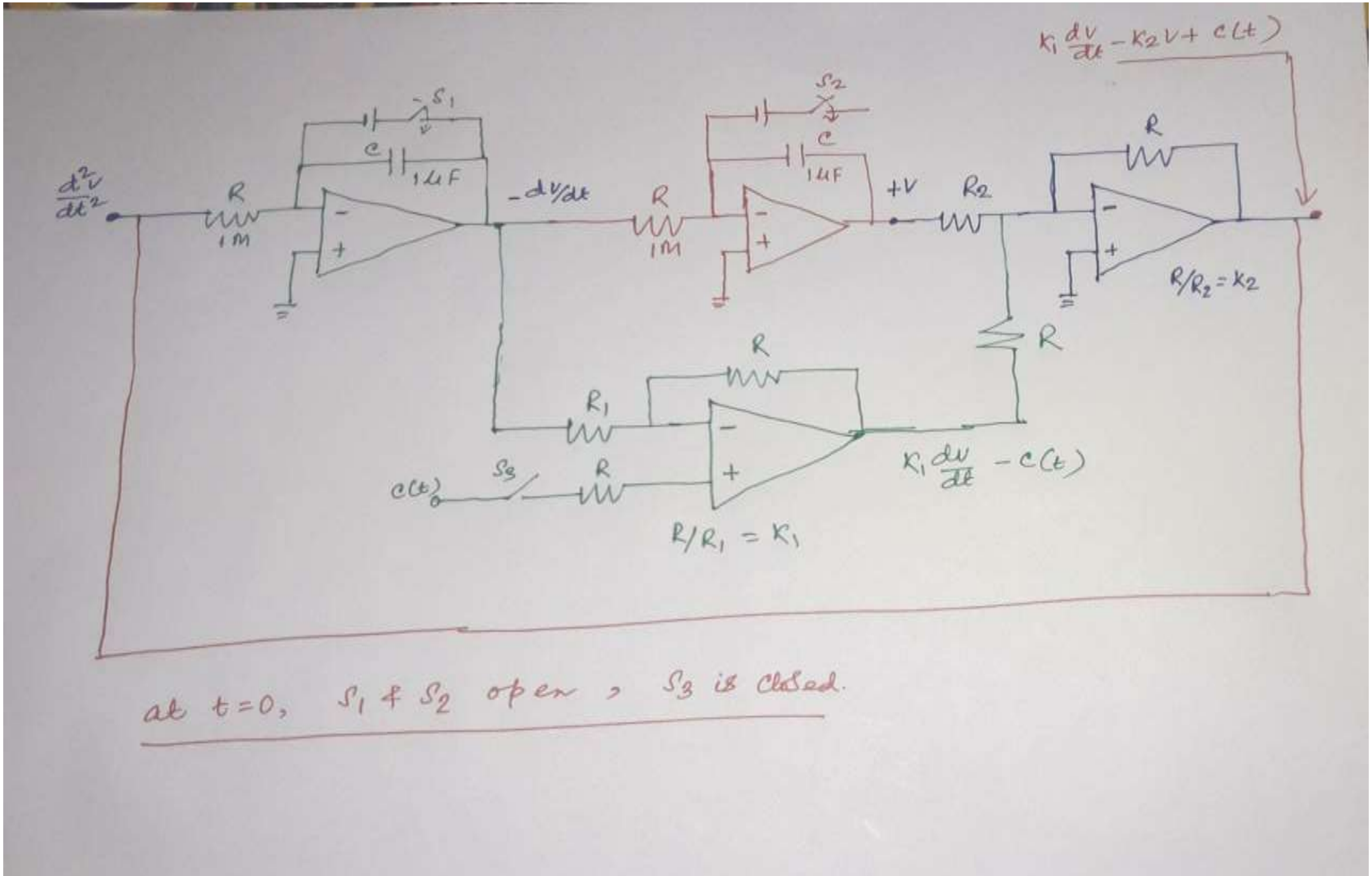
$$\frac{d^2V}{dt^2} + K_1 \frac{dV}{dt} + K_2 V = C(t)$$

with initial conditions

$$V(0) = 0 \quad \& \quad \frac{dV}{dt}(0) = 0.$$

$$\frac{d^2V}{dt^2} = -K_1 \frac{dV}{dt} - K_2 V + C(t)$$

OP AMP



$K_1 \frac{dv}{dt} - K_2 v + c(t)$
S_1
S_2
C
1µF
$\frac{d^2v}{dt^2}$
R
1M
$-dv/dt$
+V
R_2
$R/R_2 = K_2$
R_1
S_3
c(t)
$K_1 \frac{dv}{dt} - c(t)$
$R/R_1 = K_1$
at t=0, S_1 & S_2 open, S_3 is closed.