Today's lect: Introduction

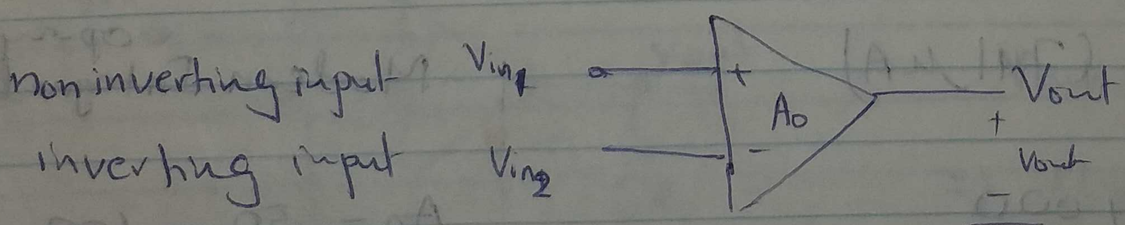
Electronics I
- Diode
- Bipolar & MOS physics
- Large and Small signal models
- Amplifier stages:
  - CB, CE, emitter follower
  - CG, CS, source follower
  - Degeneration
  - Biasing
  - Current source
  - diode connected

Electronics II
1) Op-Amp
2) Advanced circuits topologies:
   * Cascode structure
   * current mirror
   * Differential pair
3) Speed limitations (how fast the system) frequency Response
4) feedback circuits

Today's lect..
- Op-amp Basics
- Amplifiers Using Op-Amps

What is the operational Amplifier:-

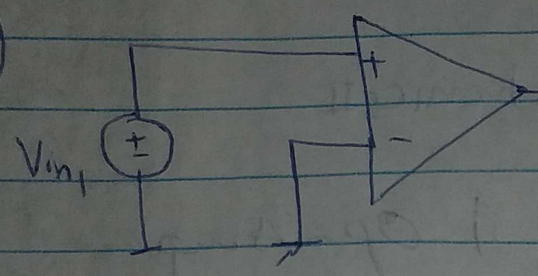
It is amplifier has two inputs and one output



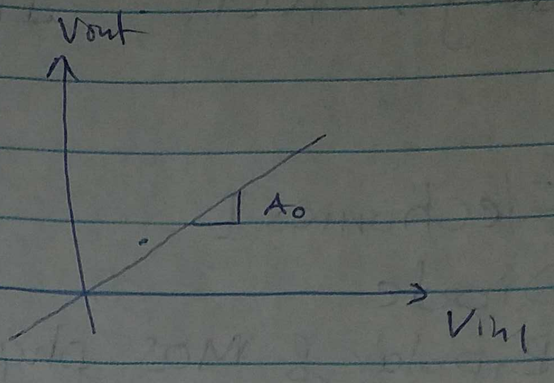
$$V_{out} = A_0 \left(V_{in_1} - V_{in_2} \right)$$

Input/output characteristics

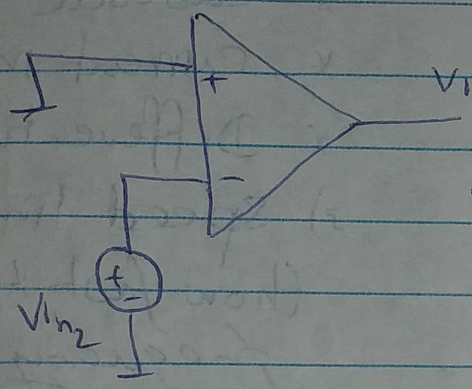
1)



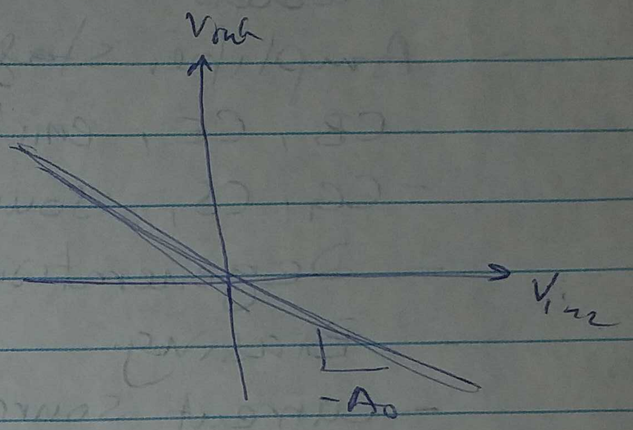
$V_{out} = A_o V_{in_1}$



2)



$V_{out} = -A_o V_{in_2}$



Ideal Op-amp:-

$A_o \longrightarrow \infty$
input impedance ∞
output impedance 0
Speed $BW = \infty$ (very fast)
Power dissipation $= 0$.
Cost $= 0$.

Non ideal op-amp (741 μA)

$A_o = 100,000$
input impedance = several MΩ.
output impedance < 100Ω.
Speed $= 1.5$ MHz.
Power 80 mW
Cost < 1 $.

Modern Integrated op-amp.

$A_o = 50 - 100$
input impedance ≃ several MΩ
output " = several KΩ
Speed GHz
Power 5–10 mW
$ 10^{-5}

Observations

1) If V_{out} is few volt and $A_o = 100,000$

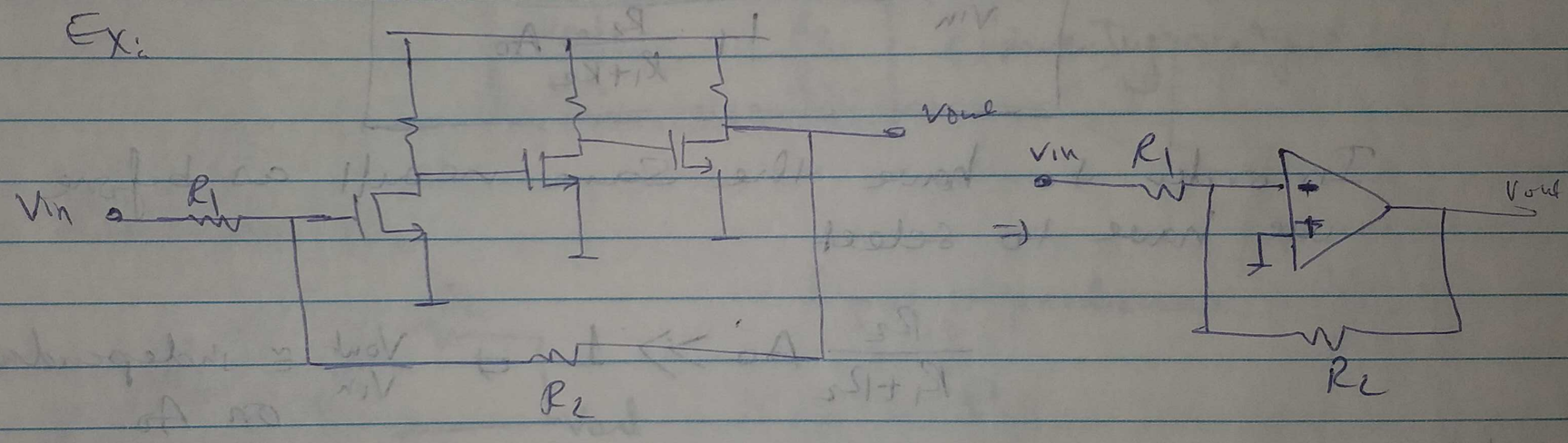
$\Rightarrow V_{in_1} - V_{in_2} =$ few mV (small)

$$V_{out} = A_o (V_{in_1} - V_{in_2})$$

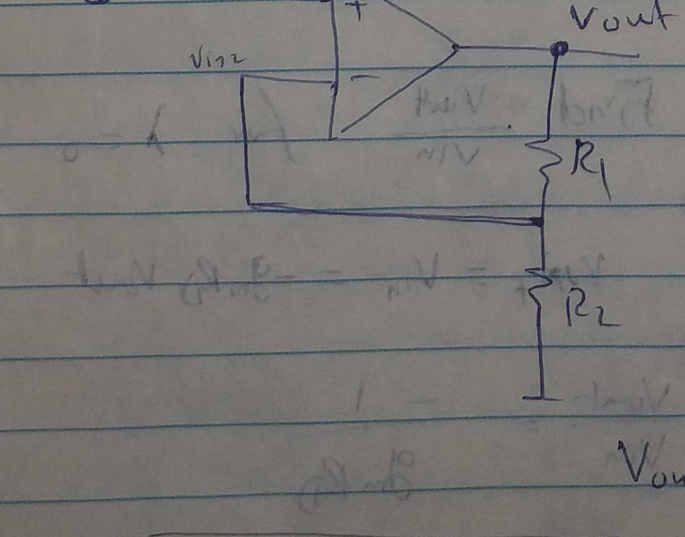
↙ low ↓ large ⇓ very small

2) If we can visualize a complex circuit as op-amp the analysis becomes ~~small~~ simpler.

Ex:



Non Inverting Amplifier:



Case 1: $A_o = \infty$

$$V_{out} = (V_{in_1} - V_{in_2}) A_o$$

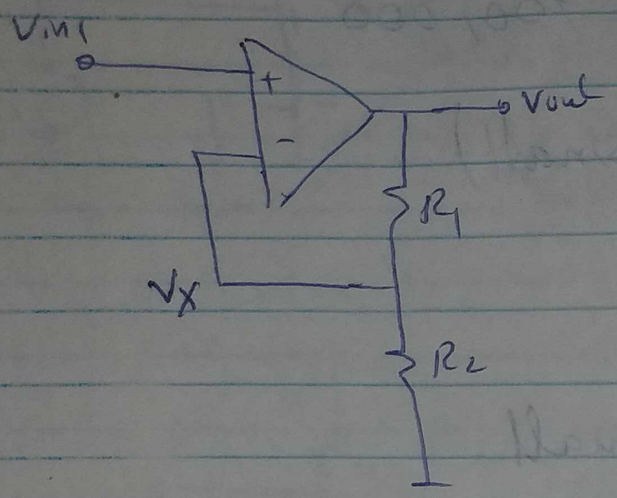
$\Rightarrow V_{in_1} = V_{in_2}$

$$V_{in_2} = V_{in_1} = \frac{R_2}{R_1 + R_2} V_{out} = V_{in}$$

$$V_{out} = \left(\frac{R_1 + R_2}{R_2}\right) V_{in}$$

$$\boxed{\frac{V_{out}}{V_{in}} = 1 + \frac{R_1}{R_2}}$$

Case 2: $A_0 \neq \infty$ (not very high)



$$V_x = \frac{R_2}{R_1+R_2} V_{out}$$

$$V_{out} = (V_{in} - V_x) A_0$$

$$= \left[V_{in} - \frac{R_2}{R_1+R_2} V_{out} \right] A_0$$

$$\boxed{\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + \frac{R_2}{R_1+R_2} A_0}}$$

In order to have the same result as before we have to select

$$\frac{R_2}{R_1+R_2} A_0 \gg 1 \Rightarrow \frac{V_{out}}{V_{in}} \approx \text{independent on } A_0.$$

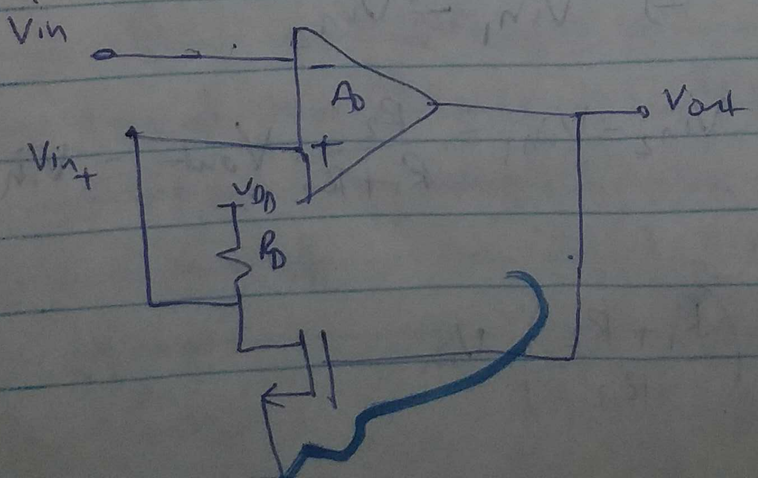
Notations

A_0 : open loop gain.

$\frac{V_{out}}{V_{in}}$: Closed loop gain

Quiz:

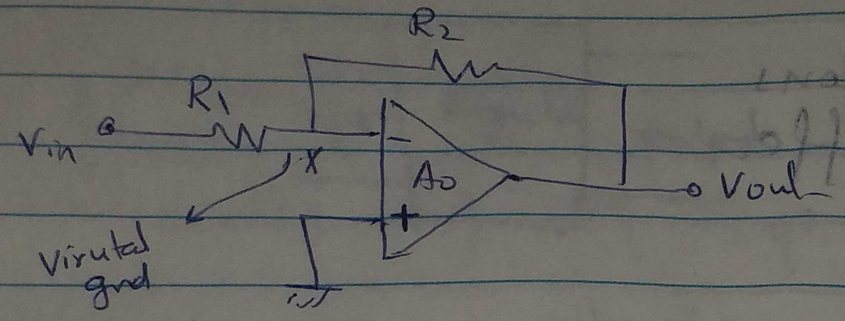
Find $\frac{V_{out}}{V_{in}}$ for $\lambda = 0$



$$V_{in+} = V_{in-} = -g_m R_D V_{out}$$

$$\frac{V_{out}}{V_{in}} = \frac{-1}{g_m R_D}$$

Inverting Op-amp:-



Case 1: $A_0 = \infty$ $\Rightarrow$ $V_{in} = V_{in+} = 0$

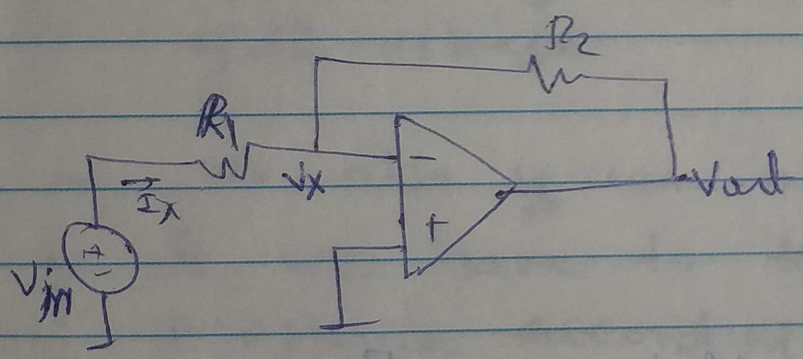
$$I_{R_1} = I_{R_2}$$

$$\frac{V_{in} - V_x}{R_1} = \frac{V_x - V_{out}}{R_2}$$

$$\frac{V_{in}}{R_1} = \frac{-V_{out}}{R_2}$$

$$\boxed{\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}}$$ (Inverting output)

Calculate R_{in}



Input impedance $= \frac{V_x}{I_x}$

$= R_1$

Case 2: $A_0 \neq \infty$

$$V_{out} = A_0(V_{in+} - V_{in-}) = -A_0 V_x$$

$$V_x = \frac{V_{out}}{-A_0}$$

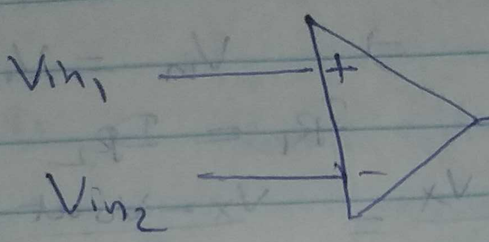
$$I_{R_1} = I_{R_2} \Rightarrow \frac{V_{in} - \left(\frac{V_{out}}{-A_0}\right)}{R_1} = \frac{-\left(\frac{V_{out}}{A_0}\right) - V_{out}}{R_2}$$

$$\boxed{\frac{V_{out}}{V_{in}} = \frac{-1}{\frac{R_1}{R_2} + \frac{1}{A_0}\left(\frac{R_1 + R_2}{R_1}\right)}}$$

Today's lect.

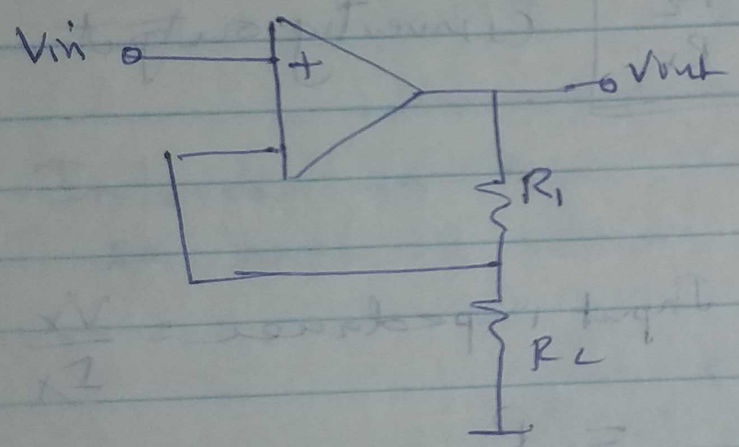
- Example Applications
- Unity gain Buffer
- Integrator
- Differentiator

Review:-



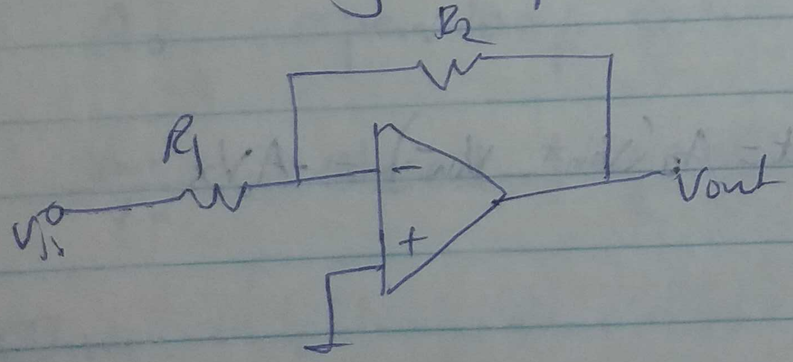
$V_{out} = A_v(V_{in_1} - V_{in_2})$

- Noninverting op-amp



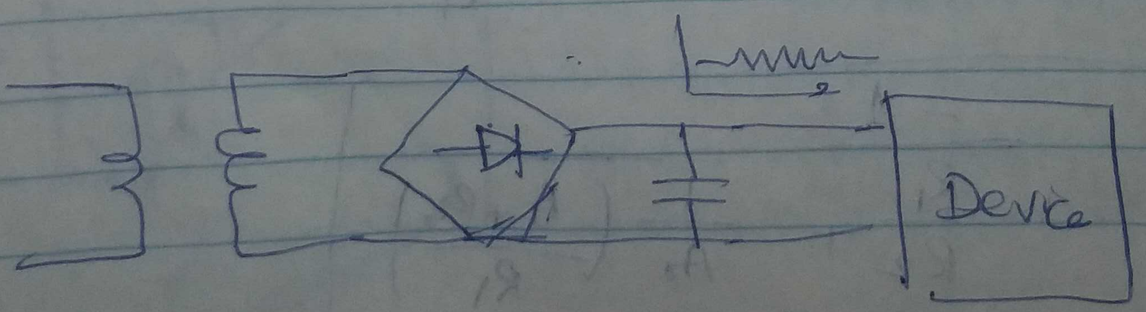
$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_1}{R_2}$$

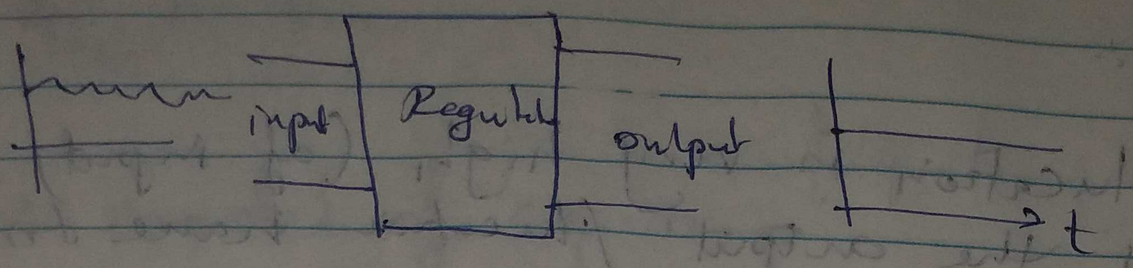
- Inverting op-amp



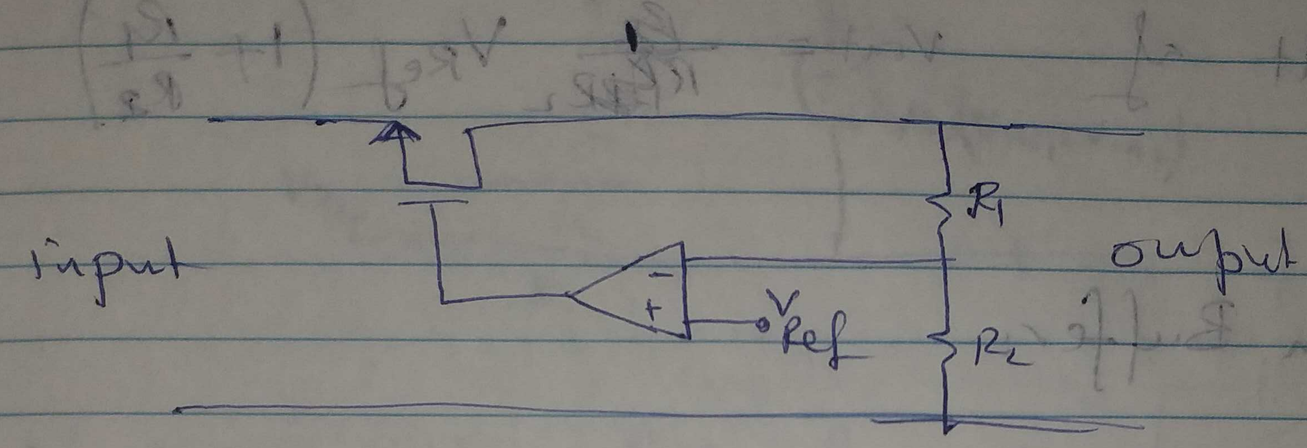
$$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1}$$

* Example of Application : Voltage Regulator





We can build simple regular as follows



- Using MOS work as variable resistance between the input and output
the value of resistance is controlled by its gate voltage.

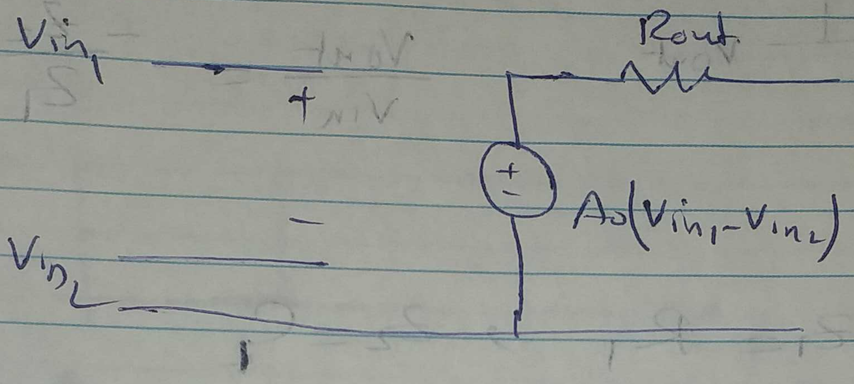
- We also use a voltage divider (R_1, R_2)
- So we have to tell the MOS to adjust its resistance according to output voltage

as example: if the variation is very high so we have to tell MOS to give high resistance that means large attenation.

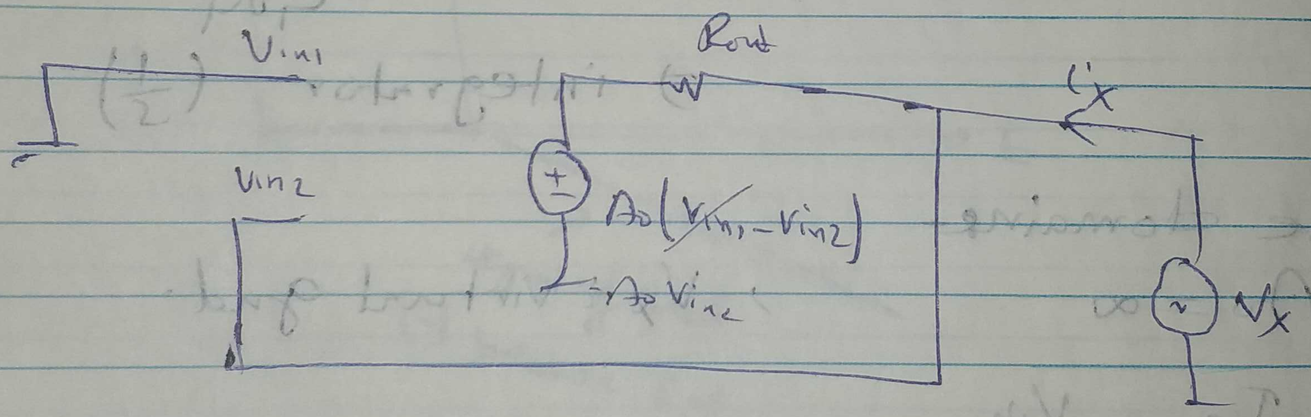
- So in order to have good value on the output we have to Compare it with Reference voltage V_{Ref} using op-amp and compare it with output.

$V_{Ther} = V_{in}$

The model of op-amp



Now Calculation Rth of unity gain Amplifier



$V_{in_2} = V_x$

$$i_x = \frac{V_x + A_0 V_x}{R_{out}}$$

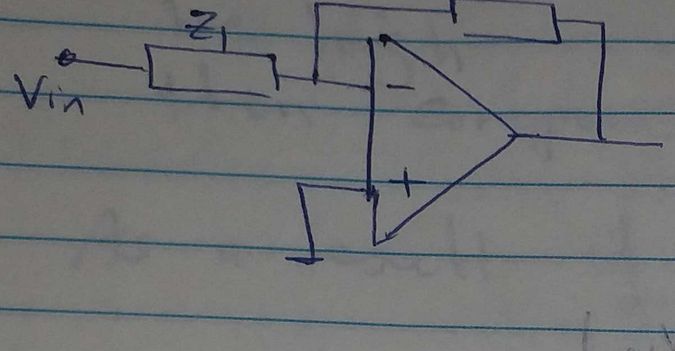
$$\boxed{\frac{V_x}{i_x} = \frac{R_{out}}{A_0 + 1}}$$

that means the resistance becomes smaller that can drive loading resistance.

⇒ good driver.

Integrator:-

general inverting Amplifier

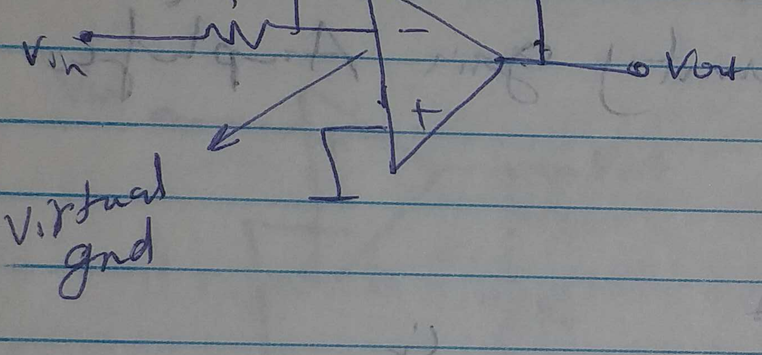


for $A_0 = \infty$

$$\frac{V_{out}}{V_{in}} = -\frac{Z_2}{Z_1}$$

* Integrator:-

If $Z_1 = R_1$, $Z_2 = C_1$



$A_0 = \infty$

$$\frac{V_{out}}{V_{in}} = -\frac{\frac{1}{sC_1}}{R_1}$$

$$= -\frac{1}{sC_1R_1}$$

pole in orginal

$\Rightarrow$ integrator $\left(\frac{1}{s}\right)$

In time domain-

$A_0 = \infty$, V_x i Virtual gnd.

$$I_{R_1} = \frac{V_{in}}{R_1}$$

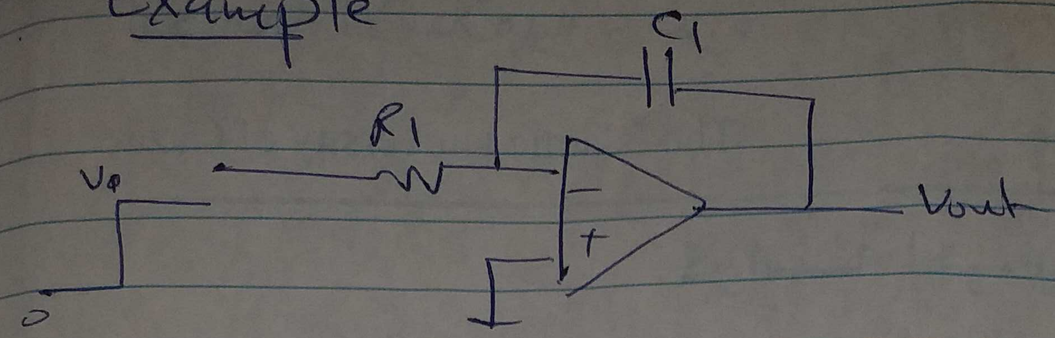
current through $C = C\frac{dV}{dt}$

$$I_{C_1} = -C_1\frac{dV_{out}}{dt}$$

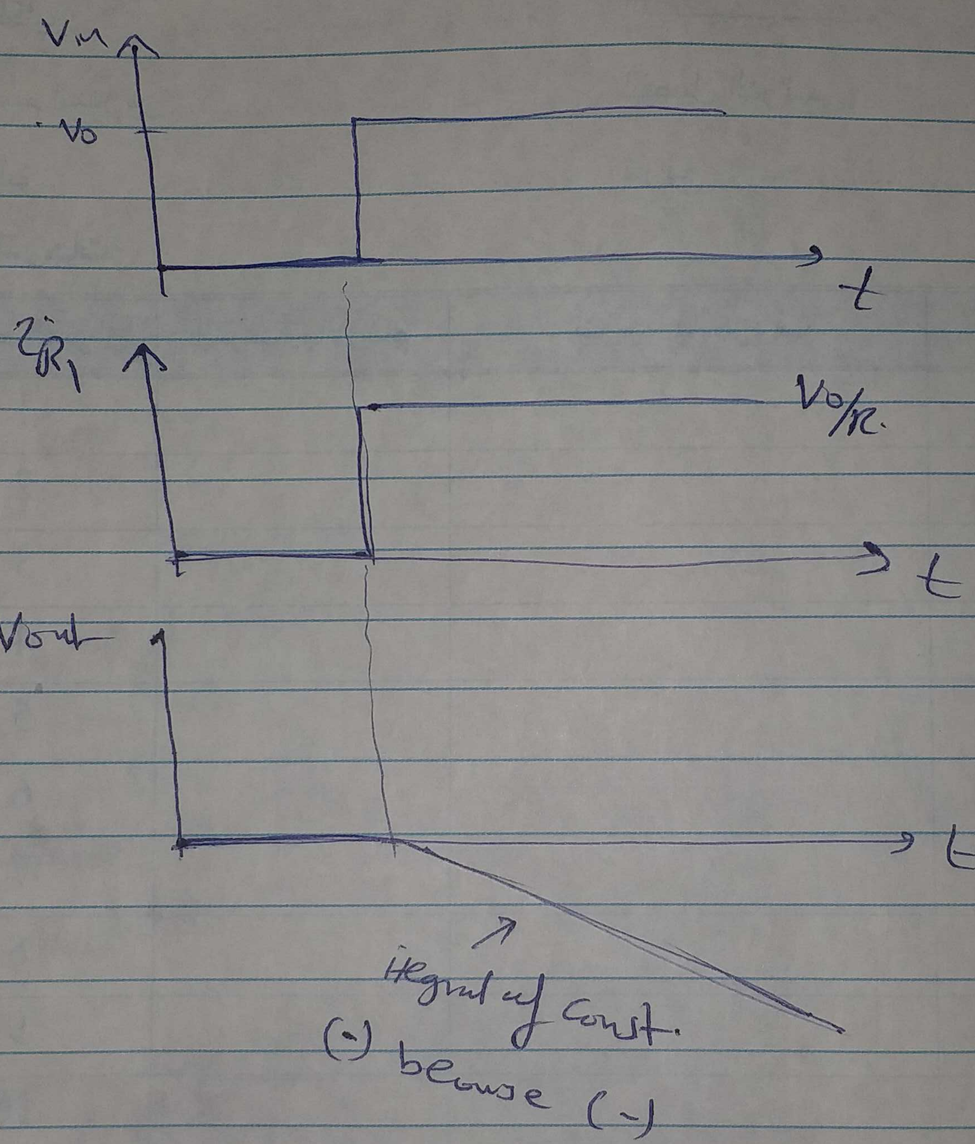
$$\frac{V_{in}}{R_1} = -C_1\frac{dV_{out}}{dt}$$

$$V_{out} = -\frac{1}{R_1C_1}\int V_{in}\,dt$$

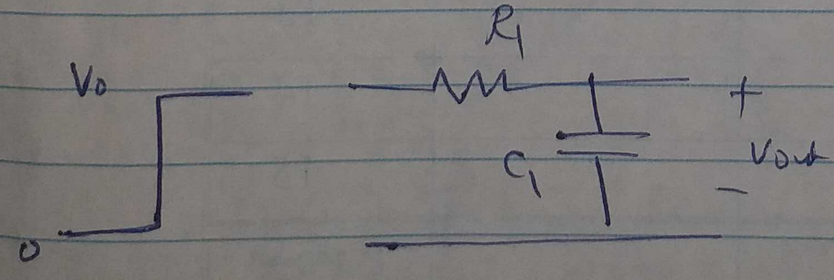
Example



Polt $V_{out} = f(time)$

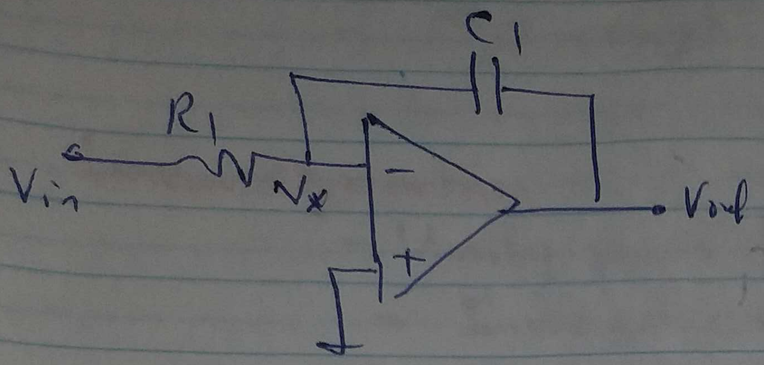


Side Node :-



the difference with integrator there isn't virtual gnd.

* Transfer function if $A_0 \neq \infty$



$$V_x = -\frac{V_{out}}{A_0}$$

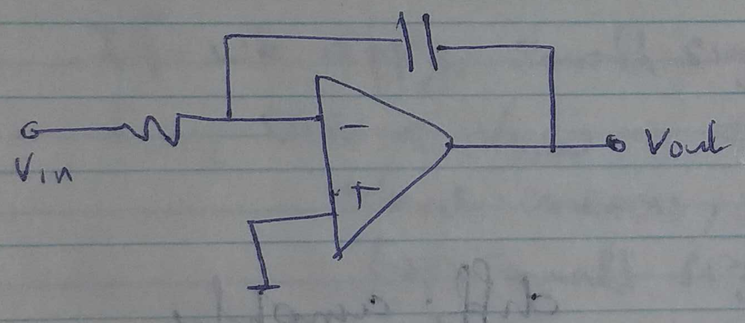
$$I_{R_1} = I_{C_1}$$

$$\frac{V_{in} + \frac{V_{out}}{A_0}}{R_1} = \frac{-\frac{V_{out}}{A_0} - V_{out}}{\frac{1}{sC_1}}$$

$$\Rightarrow \frac{V_{out}}{V_{in}} = \frac{-1}{\frac{1}{A_0} + \left(1 + \frac{1}{A_0}\right) R_1 C_1 s}$$

pole is it @ orginal

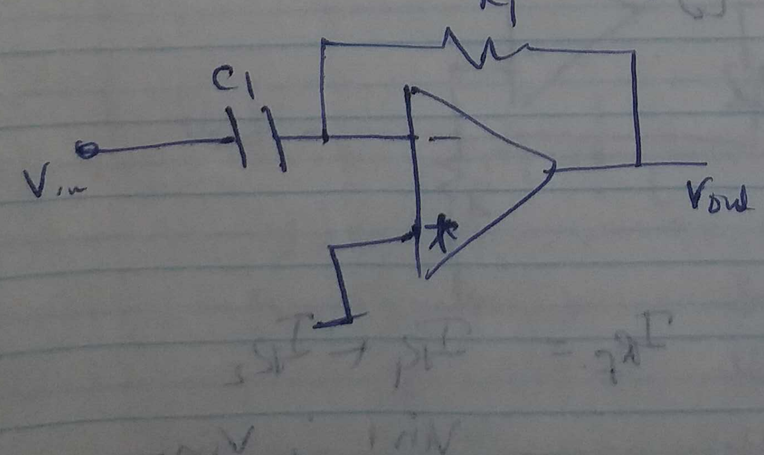
In the Lab:-



doesn't work in the Lab (will be explain later).

Differentiator:-

when Z_1 is Capacitor C_1, Z_2 is resistance R_1



$$\frac{V_{out}}{V_{in}} = -\frac{R_1}{\frac{1}{sC_1}} = -sC_1R_1$$

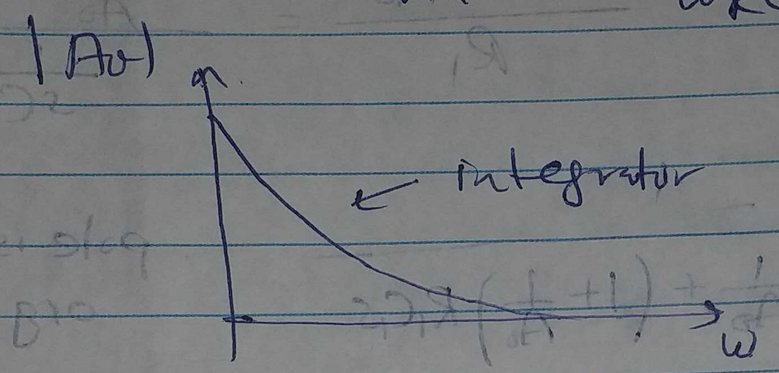
(differentiator)

Plot the frequency Response:

$s = jw$

For integrator $\frac{V_{out}}{V_{in}} = \frac{-1}{sR_1C_1}$

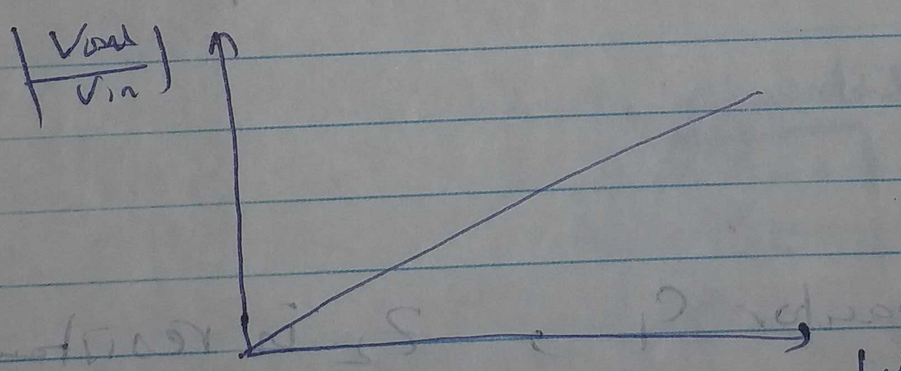
$$\frac{V_{out}}{V_{in}} = \frac{1}{wRC}$$



the gain attenuate at high frequency

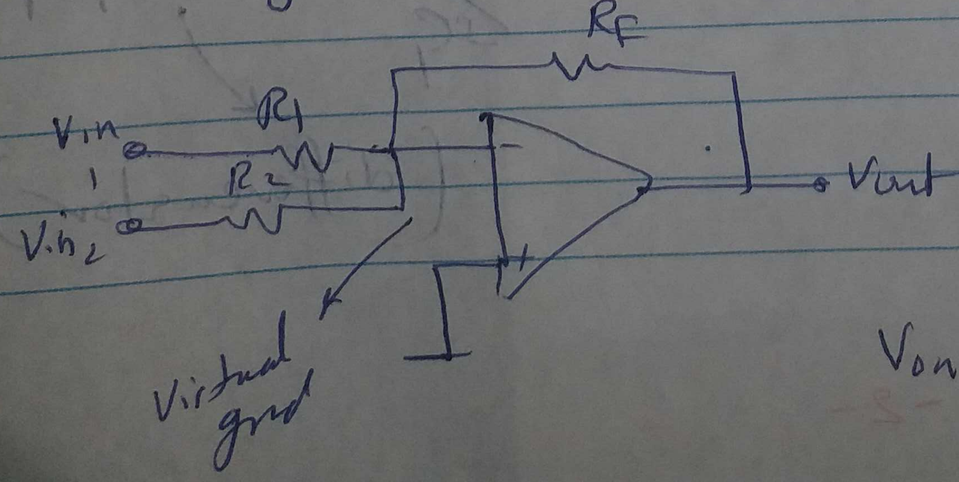
For diffenerator

$$\frac{V_{out}}{V_{in}} = wRC$$



diff: amplify the high fuguency

* Voltage adder (Summer)



$$I_{R_F} = I_{R_1} + I_{R_2}$$

$$= \frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2}$$

$$V_{out} = -R_F\left(\frac{V_{in1}}{R_1} + \frac{V_{in2}}{R_2}\right)$$

Today's lect:-

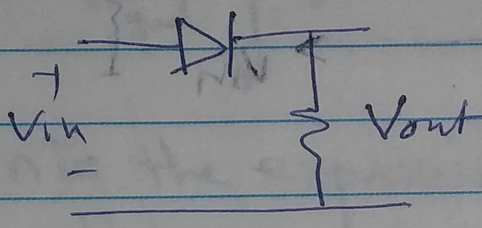
- Nonlinear Functions
- Op-amp Nonidealites

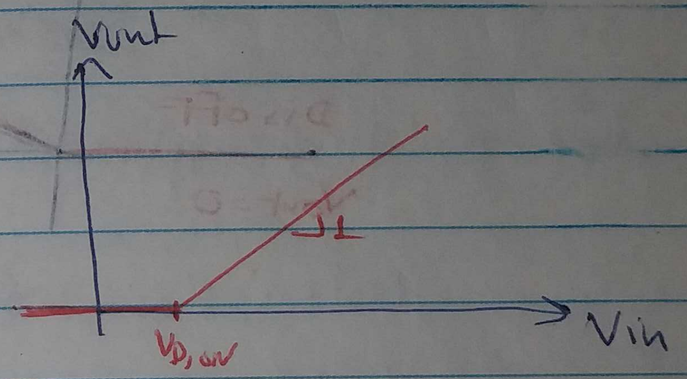
Linear Operation

- Unity gain Buffer
- Integrator
- Differentiator
- Summer

Precision Rectifier:-

- Simple Rectifier



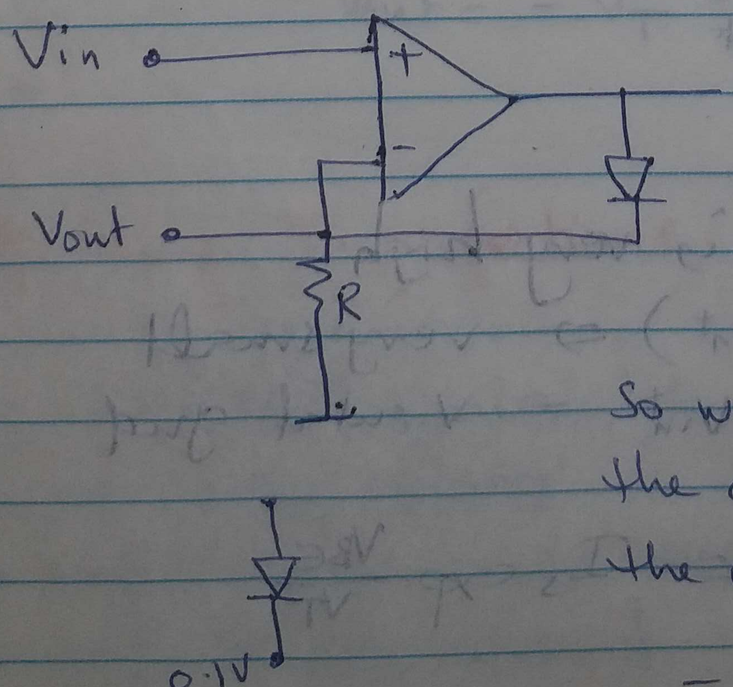


If we apply small signal value;

$V_{in} < V_{D,ON} \Rightarrow V_{out} = 0$

that means, there is no information @ the output for small signal input.

So, we want to design a circuit that work as rectifier with small input.



If $A_o = \infty$ (high)

$\Rightarrow (V_{in} - V_{out})$ is very small

* If $V_{in} = 0 \Rightarrow V_{out} = 0$.
* If $V_{in} = 0.1V \Rightarrow V_{out} = 0.1V$

So we see that V_{out} comes when the diode is ON

the output off op-amp

$= V_{D,ON} + 0.1V$

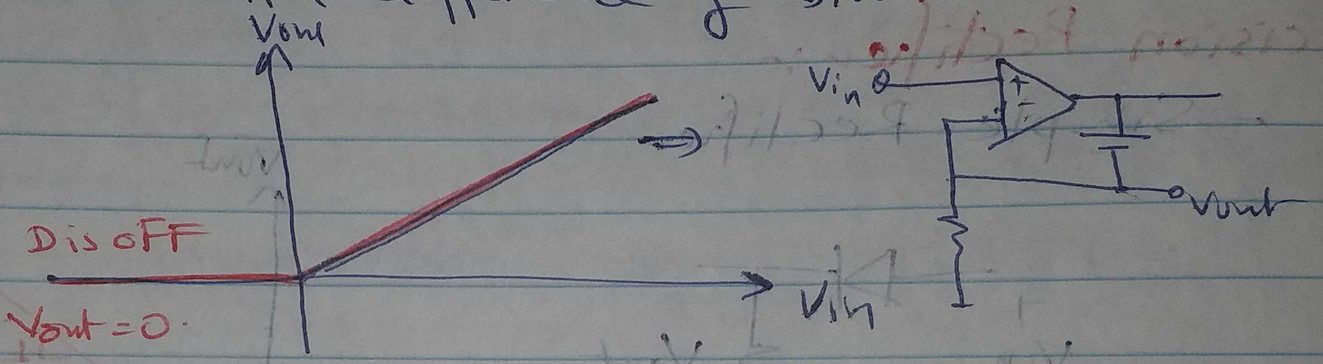
the same if $V_{in} = 0.5V$ ⇒ the $V_{in}^- = 0.5V$
So that the output of op-amp = $V_{D,ON} + 0.5V$

⇒ That means V_{out} of the op increases as the V_{in} increases.

that means

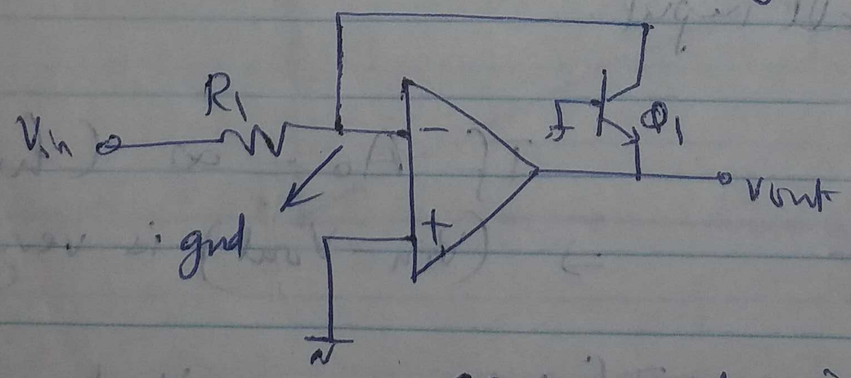
$$V_{out} = V_{out_{of\ op.}} - V_{D,ON}$$

that means V_{out} follows V_{in} with diffenence of $V_{D,ON}$.



* Logarithmtic Amplifei

Logarithmte amplifeir is amplify the small signal by large amount
and amplify the large signal by small amount



assume A_o is very high:

⇒ $(V_{in}^- - V_{in}^+)$ ⇒ very small

$V_{in}^- = V_{in}^+$ = virutal gnd

$$I_{R_1} = \frac{V_{in}}{R_1} = I_Q = I_S \exp \frac{V_{BE}}{V_T}$$

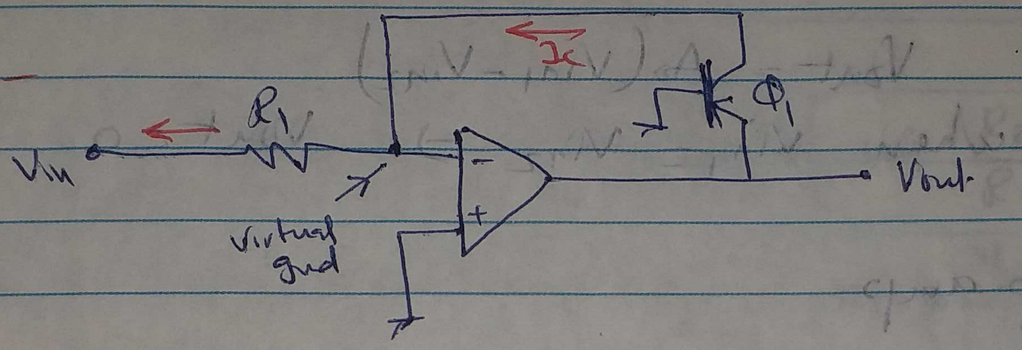
$$V_{BE} = V_B - V_E = -V_E = -V_{out}$$

$$\Rightarrow \frac{V_{in}}{R_1} = I_S \exp \frac{-V_{out}}{V_T}$$

$$\Rightarrow \boxed{V_{out} = -V_T \ln \frac{V_{in}}{R_1 I_S}} = -V_T \ln \frac{V_{in}}{R_1 I_S}$$

If $V_{in} < 0$ $\Rightarrow$ output of op-amp is not defined (saturated)

Quiz:-



Write the expression of V_{out}.

$$I_{R_1} = \frac{-V_{in}}{R_1} = I_{C_1} = I_S \exp\left(\frac{V_{EB}}{V_T}\right)$$

$$V_{out} = V_{EB} = V_E$$

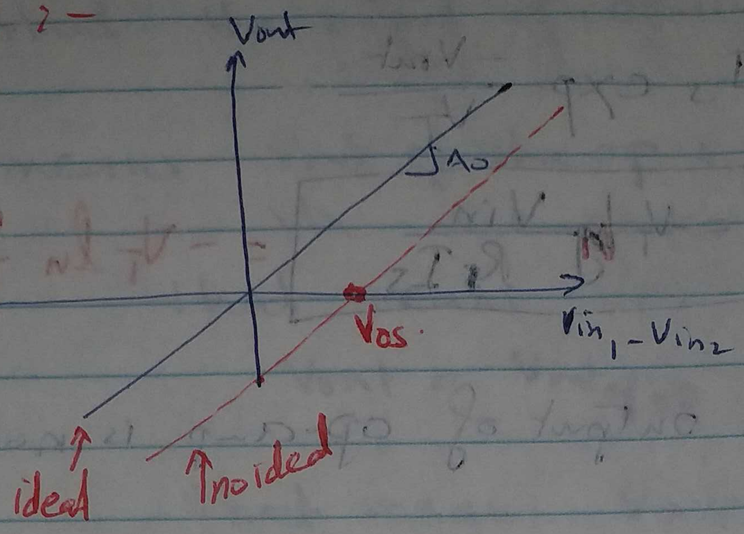
$$\therefore -\frac{V_{in}}{R_1} = I_S \exp \frac{V_{out}}{V_T}$$

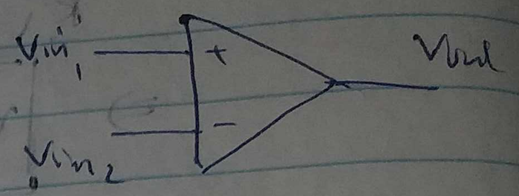
$$V_{out} = -V_T \ln \frac{V_{in}}{R_1 I_S}$$, the input have to be negative all time

Op-amp Imperfections: (problems)

- Finite gain
- DC offsets
- input bias current
- Finite speed

DC offsets :-





If ideal, $V_{out} = A_0(V_{in_1} - V_{in_2})$

when $V_{in_1} = V_{in_2} \Rightarrow V_{out} = 0$

For practical op-amp

when $V_{in_1} = V_{in_2} \Rightarrow V_{out} \neq 0$.

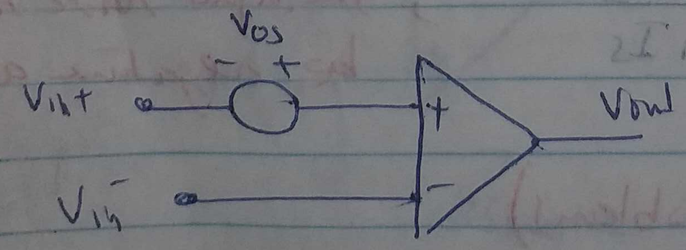
that means there is a voltage difference

$V_{in_1} - V_{in_2} \neq 0 \Rightarrow$ It is called offset voltage

$$V_{os} = V_{in_1} - V_{in_2}$$

The offset creates because the mismatching (mismatching)

How to model offset:

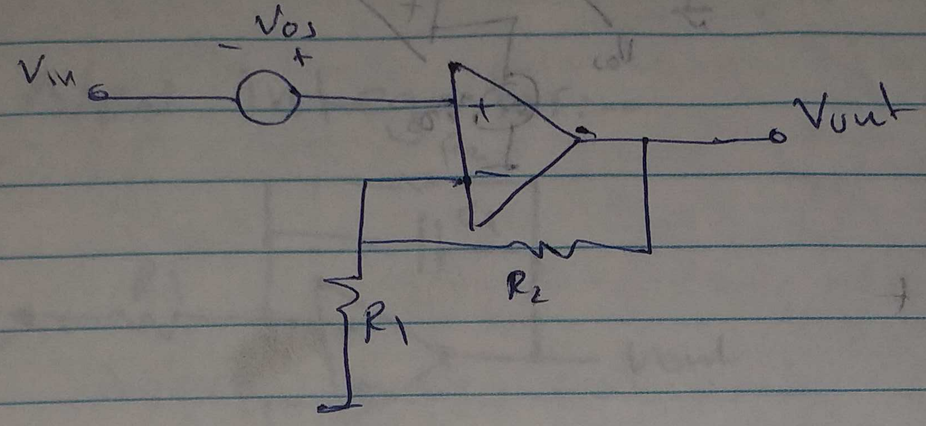


Observations: 1) V_{os} is random (value and sign)

2) V_{os} can be placed in series with either input

Effect of offset on Amplifiers

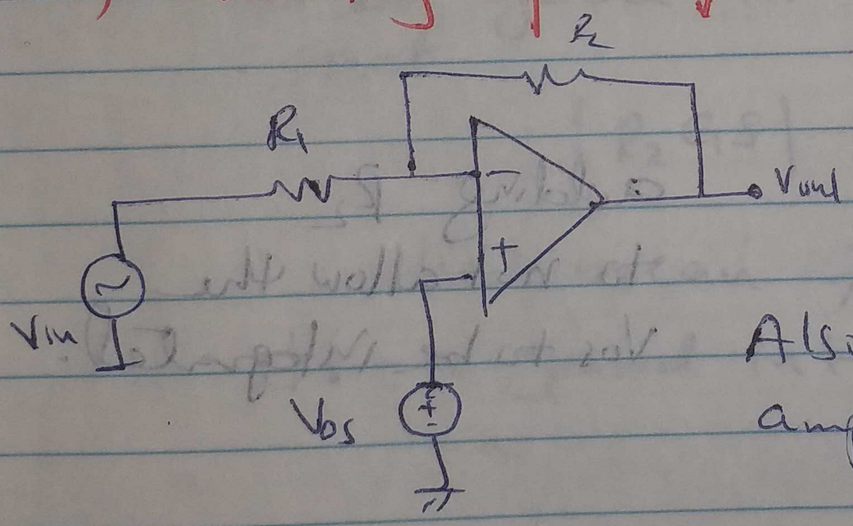
1) Noninverting op-amp:



$$V_{out} = (V_{in} + V_{os})\left[1 + \frac{R_2}{R_1}\right]$$

So, we see that the Vos is amplify by a factor of $\left(1 + \frac{R_2}{R_1}\right)$ ⇒ the output becomes incorrect.

2) Inverting op-amp

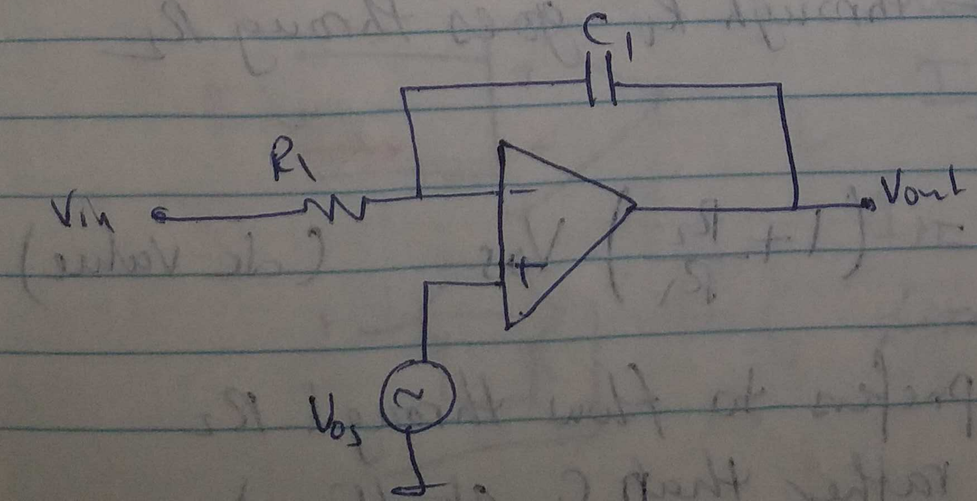


Using Superposition

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

Also, we see that the Vos is amplify by a factor of $\left(1 + \frac{R_2}{R_1}\right)$

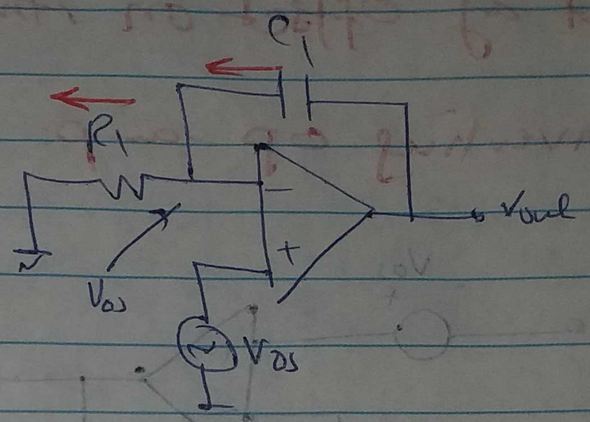
3) DC offset effect on Integrator



Assume $V_{in} = 0$ to see the effect of Vos on the circuit

$A_o = \infty$

$V_{os} = V_{in}^- = V_{in}^+$



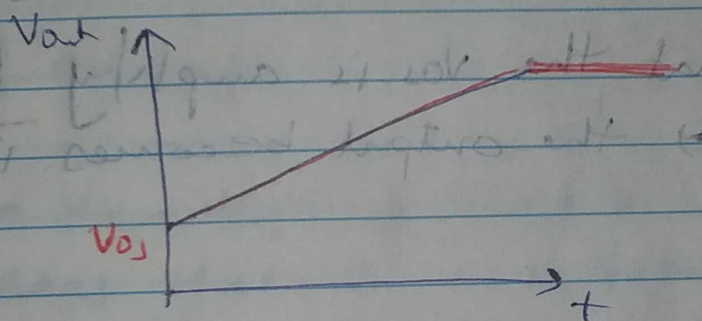
$$I_{R_1} = \frac{V_{os}}{R_1}$$

$$V_c = \frac{1}{C}\int I\,dt$$

$$(V_{out} - V_{os}) = \frac{1}{C_1}\int \frac{V_{os}}{R_1}\,dt$$

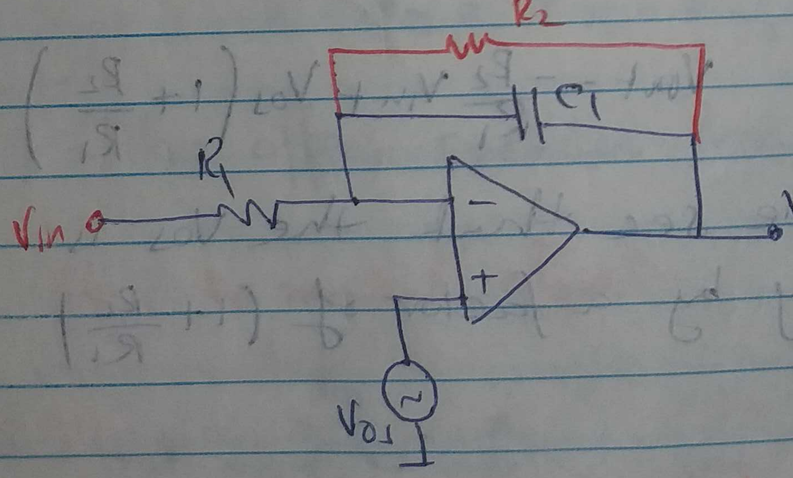
$$\Rightarrow \quad V_{out} = V_{os} + \frac{V_{os}}{R_1 C_1}\,t$$

, we see that the offset is integrated which allows the op-amp to be saturated.



Supply voltage (saturation)

in order to fix the circuit :-



adding R_2 to not allow the Vos to be integrated.

at time ∞ $\Rightarrow$ the current through R_1 goes throug R_2 not on C_1

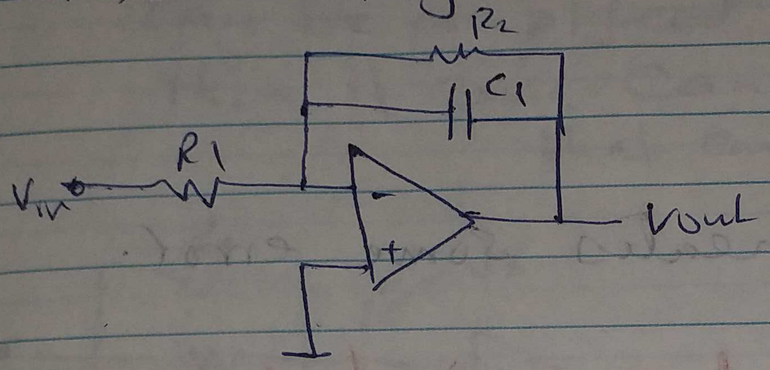
If $V_{in} = 0 \Rightarrow V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{os}$ (dc value)

$\frac{V_{os}}{R_1}$ prefers to flow through R_2 rather than C_1 at $(t = \infty)$

The question becomes, if the circuit still integrator as before.

Ideal integrator Transfer function $= \frac{-1}{sR_1C_1}$

New integrator:-



$$\frac{V_{out}}{V_{in}} = -\frac{Z_2}{Z_1}$$

$$\frac{V_{out}}{V_{in}} = -\frac{\frac{R_2}{1+sR_2C_1}}{R_1} = -\frac{R_2}{R_1(R_2C_1s+1)}$$

In the case where $R_2C_1s \gg 1$

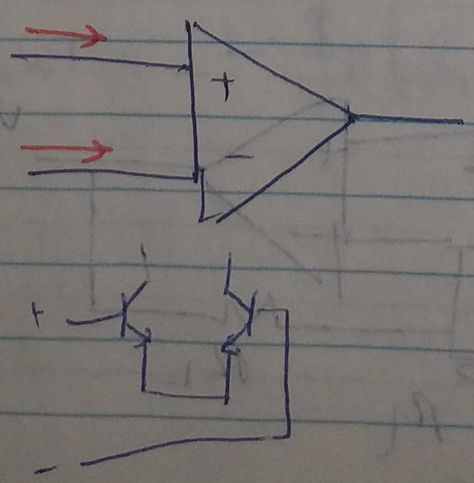
$$\Rightarrow \frac{V_{out}}{V_{in}} = -\frac{1}{sR_1C_1}$$

To be good integrator, the circuit requirement that

$$|R_2C_1s| \gg 1 \qquad s = j\omega$$

that mean for sufficiently high frequency it's a good integrator

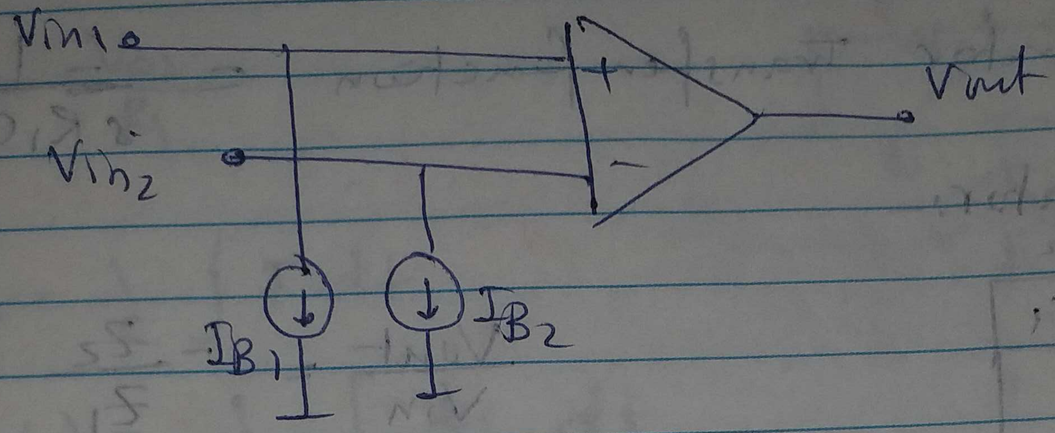
Input Bias Currents:- it happen in BJT op-amp



Using BJT transistor the I_B isn't zero.

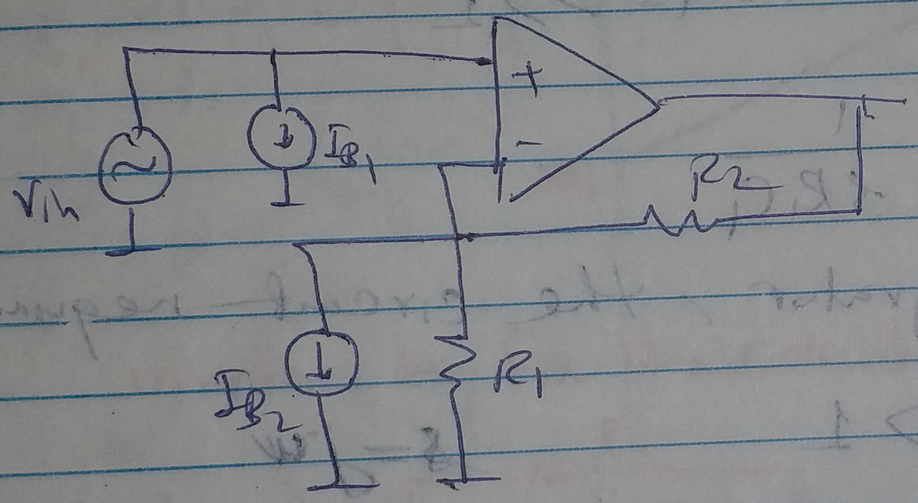
In ideal it has to be zero for input transistors

It can be modeled as:



these I_{B_1} ; I_{B_2} creates some error.

effect of Input bias current on noninverting amp.



* For I_{B_1} is in parrallel with on V_{in}

so I_{B_1} has no effect.

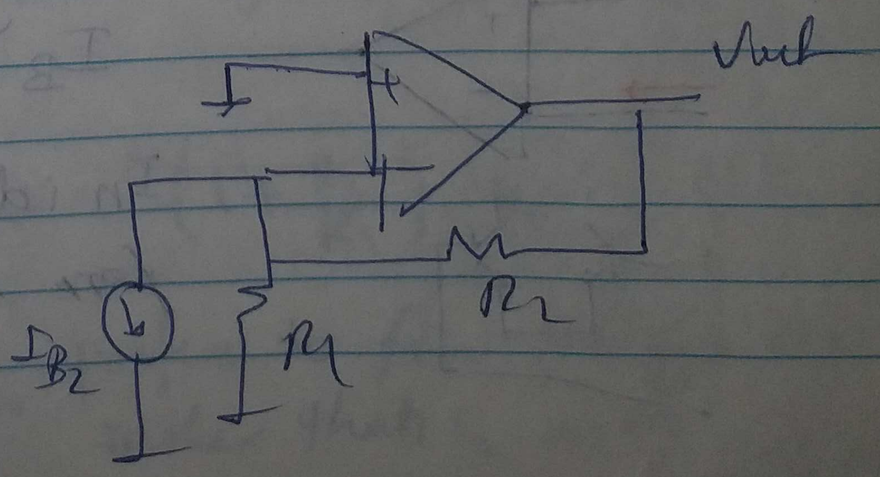
* To Study the effect of I_{B_2} on Vout

Assume $V_{in} = 0$

$V_{R_1} = 0 \Rightarrow I_{R_1} = 0$

I_{B_2} flows through R_2

$V_{out} = I_{B_2} R_2$

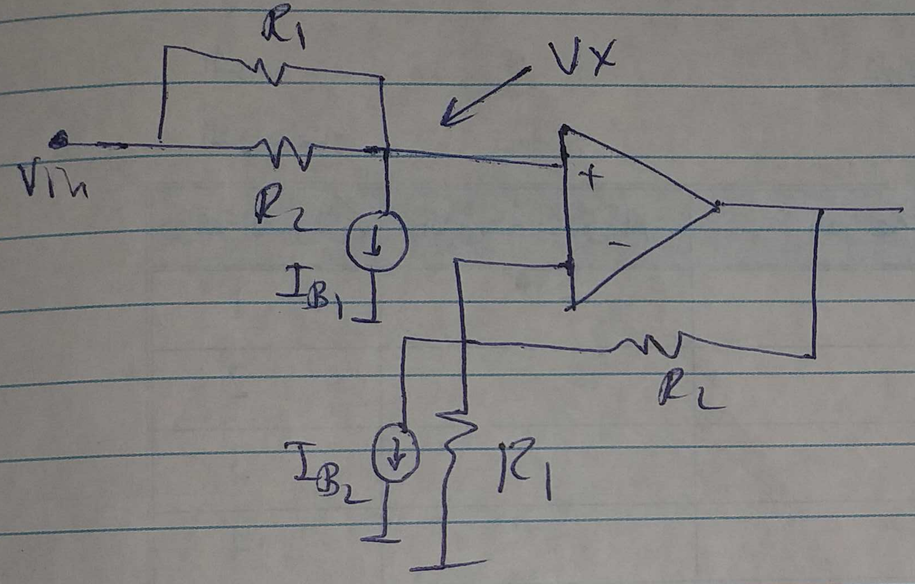


So that I_{B_2} creates error on the output ($R_2 I_{B_2}$)

To fix that: that can be done by adding a voltage on the voltage input, which can be amplified by the amount of ($R_2 I_{B_2}$) then it can cancel that error.

that can done by adding ($R_2 // R_1$)

where $R_1 = R_2$



Set $V_{in} = 0$.

$$V_X = -(I_{B_1})(R_1 // R_2)$$

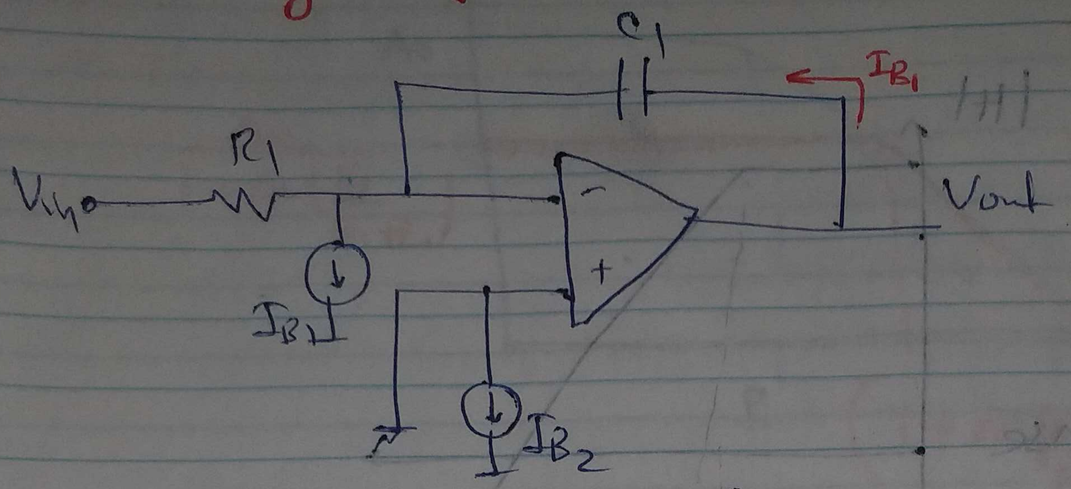
Using superposition :-

$$V_{out}\Big|_{I_{B_1}} = -I_{B_1}(R_1 // R_2)\left[1 + \frac{R_2}{R_1}\right]$$

$$V_{out}\Big|_{I_{B_2}} = R_2 I_{B_2}$$

$$V_{out} = -I_B(R_1 // R_2)\left[1 + \frac{R_2}{R_1}\right] + R_2 I_{B_2} = 0$$

effect of Input Bias current in itegrator:



I_{B2} : has no effect because I_{B2} pass through sc. doesn't

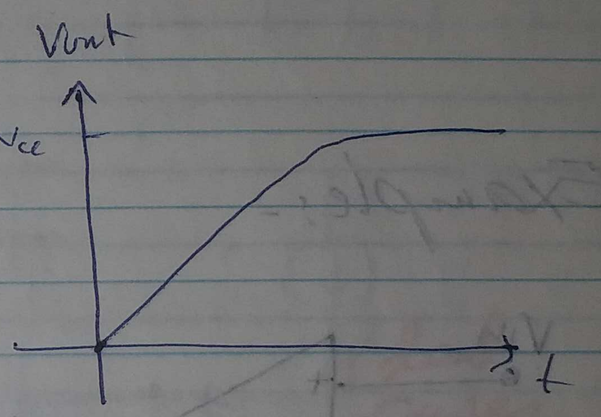
Set $V_{in} = 0$

I_{B1} will be goes through C_1

and $I_{R_1} = 0$ because $V_{in}^- = V_{in}^+ = 0$

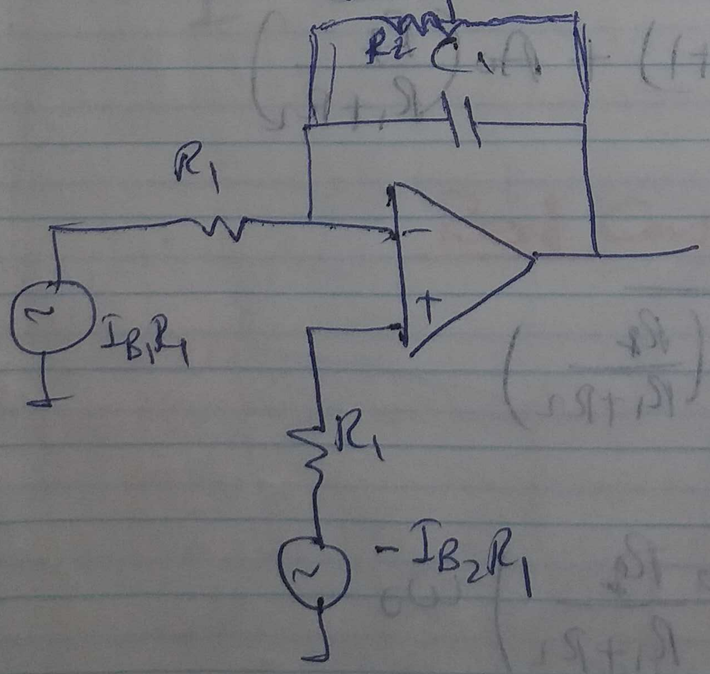
$$V_{out} = \frac{1}{C} I_{B_1} t$$

⇒ Op- saturate.



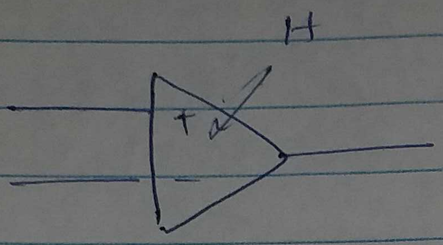
To solve this problem, by adding $R_2 // C_1$ and R_1 ~~in~~ series with the ⊕ input

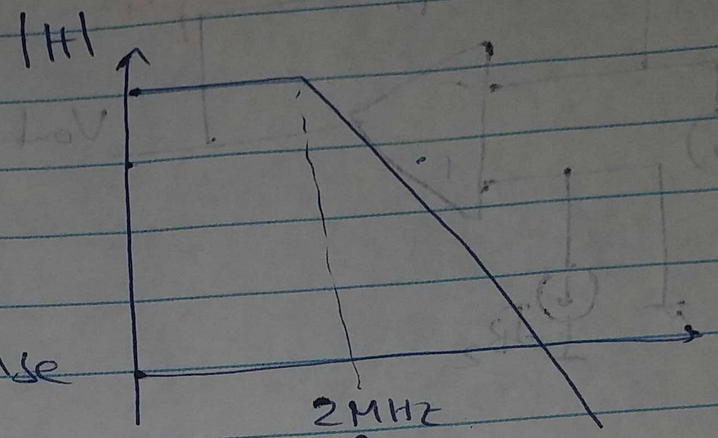
The theven equivalent circuit



I_{B_2} passes through R_1 and creates a voltage if it equal to the voltage ~~and~~ at the negative side so that it can cancel the error.

* Speed limitations:-





The frequency Response as first order syste

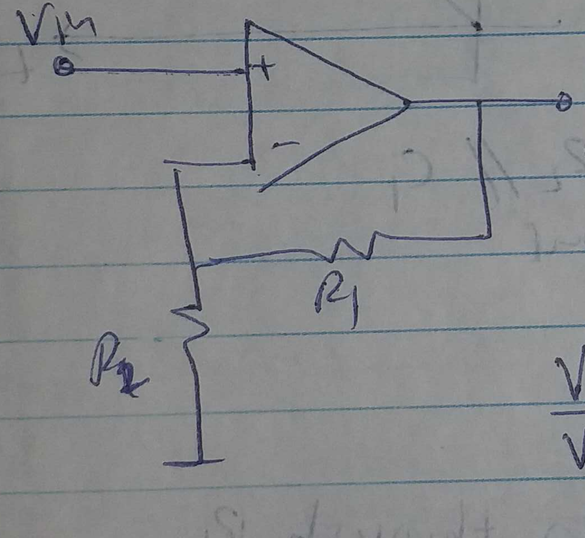
$$|H(s)| = \frac{A_0}{1 + \frac{s}{\omega_0}}$$

$$\omega_0 = 2\pi f_0$$

Example:-

$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + \frac{R_2}{R_1+R_2} A_0}$$

Replace $A_0 \rightarrow \left(\frac{A_0}{1+s/\omega_0}\right)$



$$\frac{V_{out}(s)}{V_{in}} = \frac{\left(\frac{A_0}{1+s/\omega_0}\right)}{1 + \frac{A_0}{1+s/\omega_0}\left(\frac{R_2}{R_1+R_2}\right)}$$

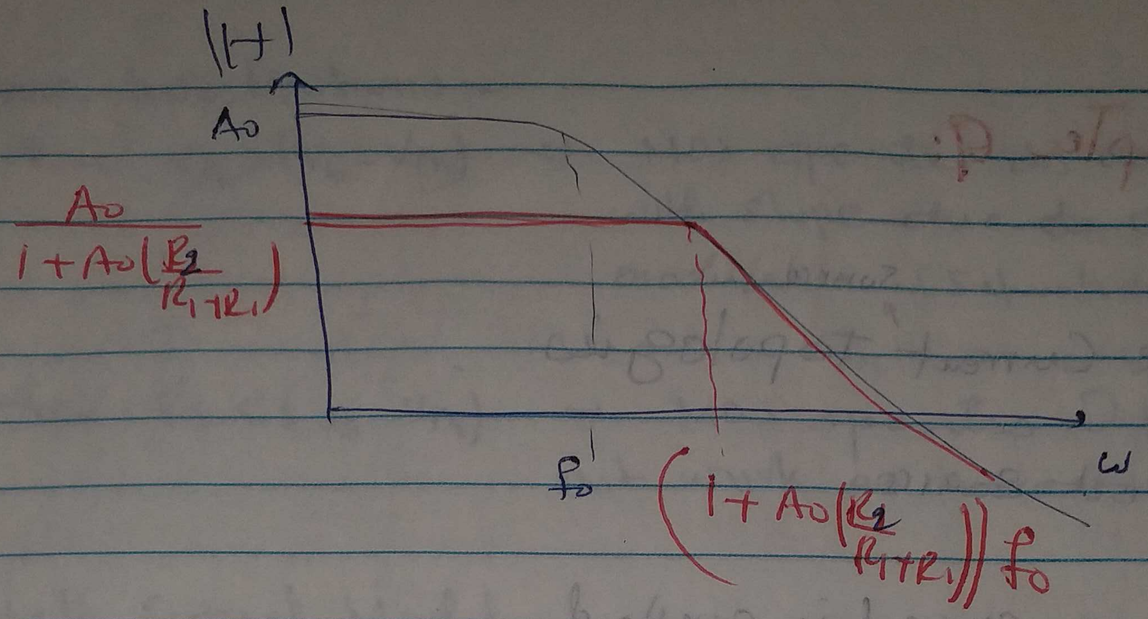
$$\frac{V_{out}}{V_{in}}(s) = \frac{A_0}{\left(\frac{s}{\omega_0}+1\right) + A_0\left(\frac{R_2}{R_1+R_2}\right)}$$

when $s=0$

$$\frac{V_{out}}{V_{in}} = \frac{A_0}{1 + A_0\left(\frac{R_2}{R_1+R_2}\right)}$$

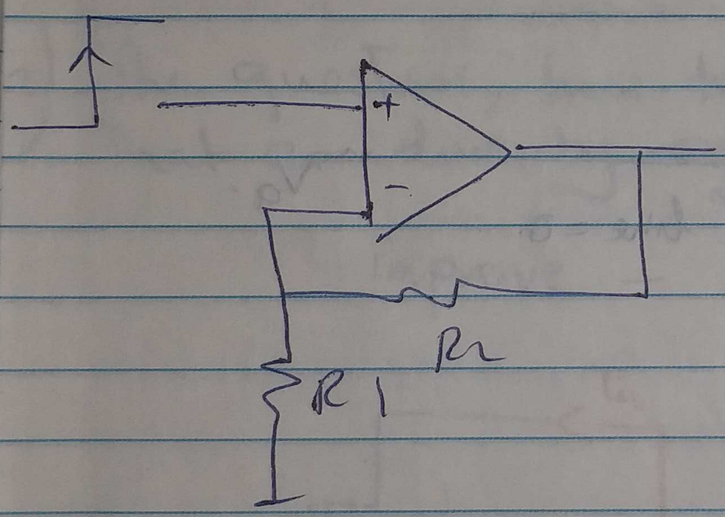
To find the pole

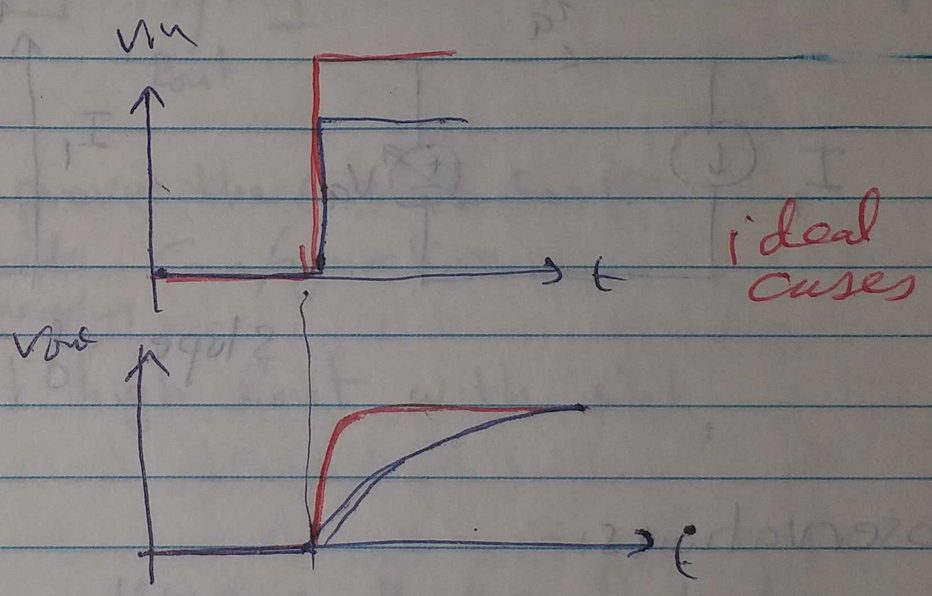
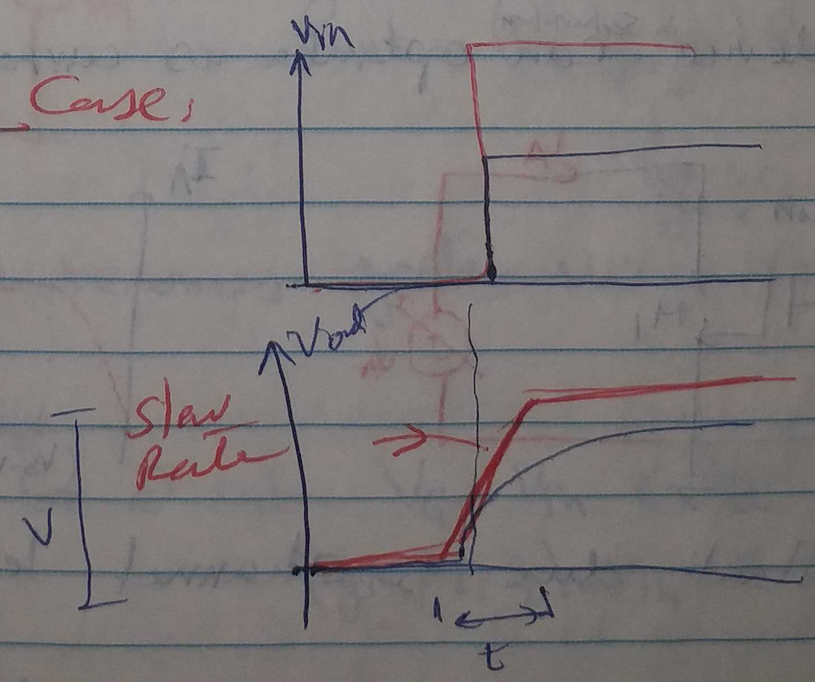
$$= -\left(1 + A_0 \frac{R_2}{R_1+R_2}\right)\omega_0$$



We see that:
the gain is reduces, the BW increases.

* Slew Rate:-





Real Case: