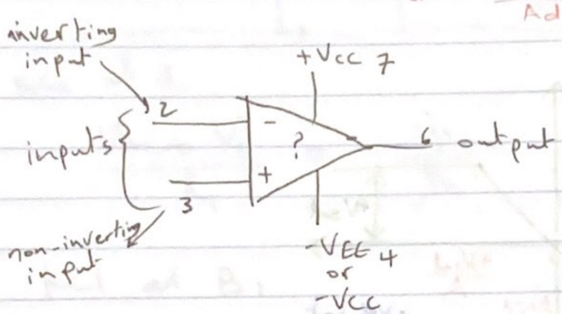
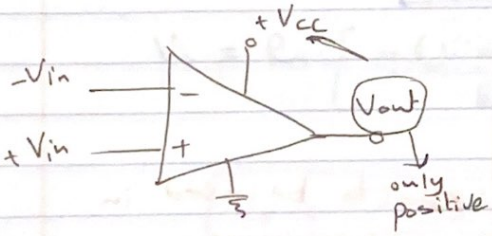
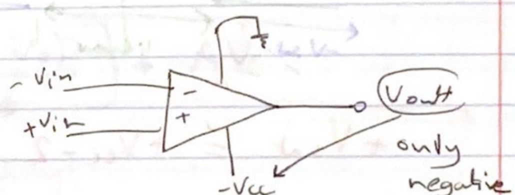
T9: OpAmps

Very High Voltage gain : 200 000
Very High Input Impedence : 10 M ohm
Very small output Impedence : 75 ohm

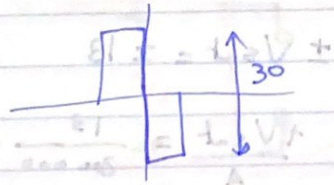
$$V_o = \begin{cases} +V_{sat} & V_d > \frac{V_{sat}}{A_d} \\ A_d V_d & \frac{V_{sat}}{A_d} > V_d > -\frac{V_{sat}}{A_d} \\ -V_{sat} & V_d < \frac{V_{sat}}{A_d} \end{cases}$$



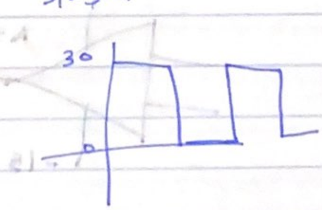


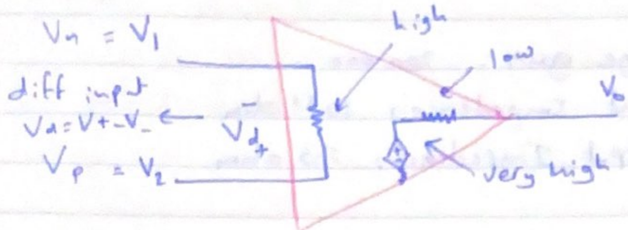


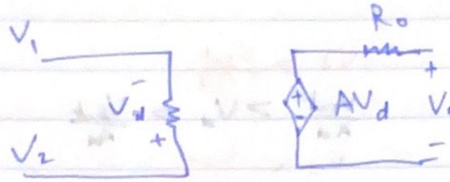
dual:

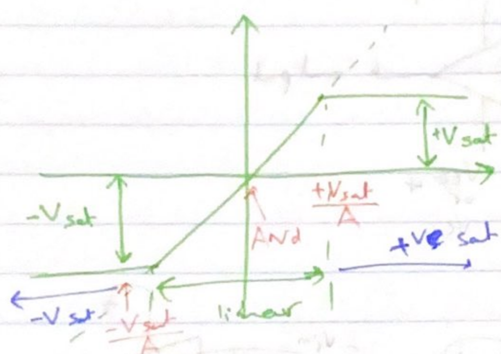


single:



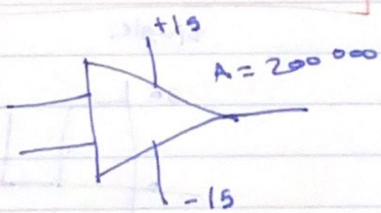






$$\boxed{\begin{aligned} +V_{sat} &\cong +V_{cc} - 2 \\ -V_{sat} &\cong -V_{cc} + 2 \end{aligned}}$$

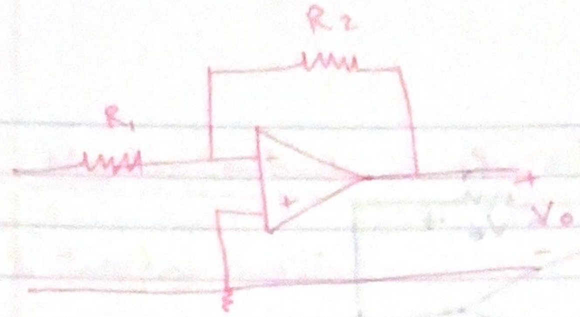
to be used in this course

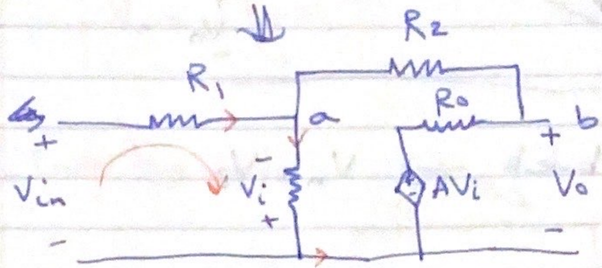


$\pm V_{sat} = \pm 13$

$$\frac{+V_{sat}}{A} = \frac{13}{200\,000} = 65\ \mu V$$

$$\frac{-V_{sat}}{A} = \frac{-13}{200\,000} = -65\ \mu V$$





KCl at A:

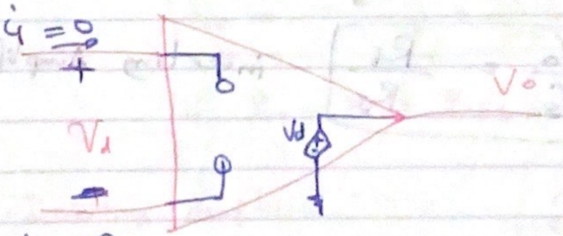
$$\frac{V_{in} + V_i}{R_1} = \frac{-V_i}{R} - \frac{V_i + V_o}{R}$$

KCl at B:

$$V_o = R_o\left[\frac{-(V_i + V_o)}{R_2}\right] + AV_i$$

$$\boxed{V_o = -3.99\,V_{in}}$$

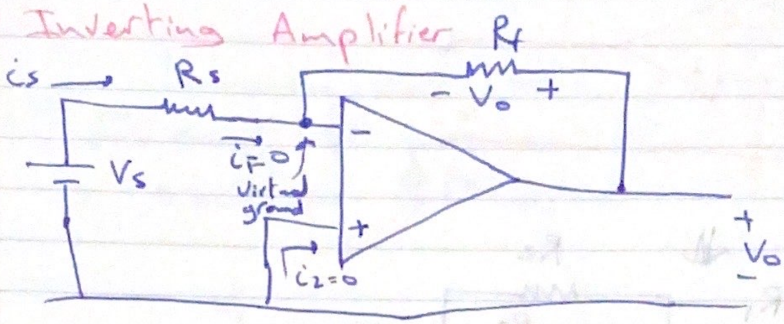
$i_n = i_1 = 0$



$i_p = i_2 = 0$

$V_1 \cong V_2$

① Inverting Amplifier



negative feedback $\Rightarrow V_n = V_p$

but $V_p = 0$

$\therefore V_n = 0$

KCl: $i_s = \cancel{i_1}^{\,0} + i_f$

$i_s = i_f$

$$i_s = \frac{V_s - \cancel{V_1}^{\,0}}{R_s} = \frac{V_s}{R_s} = i_f$$

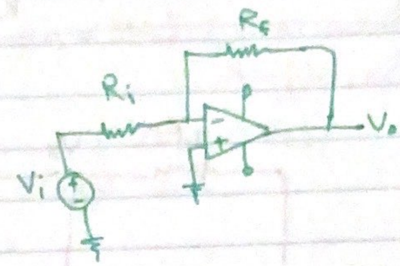
$V_o = -i_f R_f$

$$V_o = \frac{-V_s}{R_s} R_f$$

$$\boxed{\frac{V_o}{V_s} = \frac{-R_f}{R_s}}$$ inverting Amplifier Gain

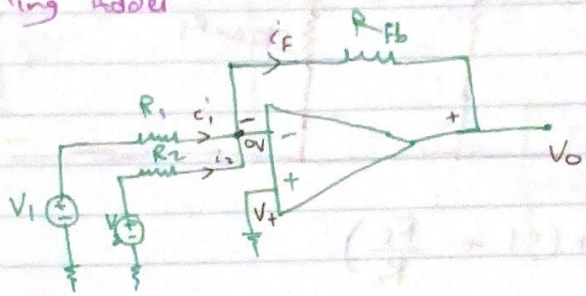
Negative Feedback

1. Inverting Amplifier



$$\boxed{V_o = -\frac{R_F}{R_i} V_i}$$

. Inverting Adder



$V_+ = 0, \quad V_- = V_+ = 0$

$i_1 = \frac{V_1}{R_1}, \quad i_2 = \frac{V_2}{R_2}$

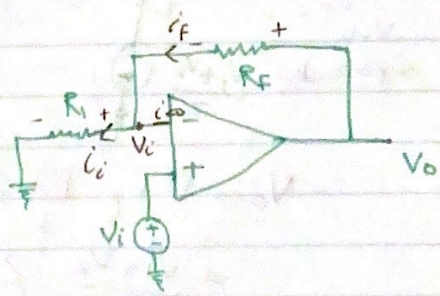
$i_f = i_1 + i_2$

$V_o = -i_f R_{fb} = -(i_1 + i_2) R_{fb}$

$$\boxed{V_o = -\left(\frac{V_1}{R_1} + \frac{V_2}{R_2}\right) R_{fb}}$$

if $R_1 = R_2 = R_{fb} \Rightarrow \boxed{V_o = -(V_1 + V_2)}$

2. Non-Inverting Amplifier



$V_+ = V_-$; but $V_+ = V_i$

$\therefore \quad V_- = V_i$

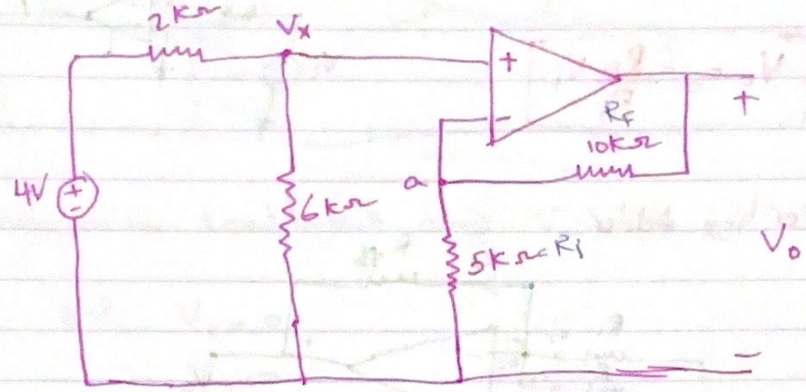
$i_i = \frac{V_i}{R_1} = i_f$

$V_o = i_f R_f + i_i R_1$

$= i_f (R_f + R_1) = \boxed{\frac{V_i}{R_1}(R_f + R_1) = V_i\left(1 + \frac{R_F}{R_1}\right) = V_o}$

$$\boxed{V_o = V_+ \left(1 + \frac{R_F}{R_1}\right)}$$

ex



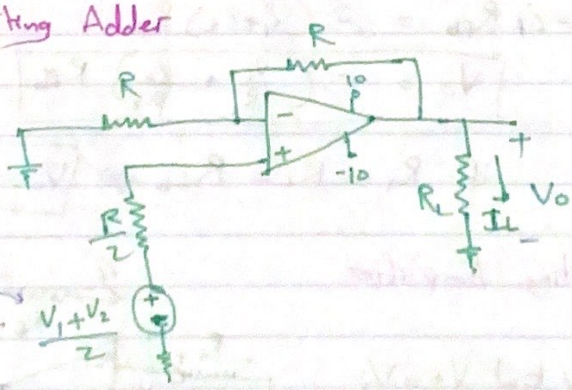
$$V_o = V_+ \left(1 + \frac{R_F}{R_1}\right)$$

$$V_+ = V_x = \frac{6k}{6k+2k} \times 4V = 3V$$

$$V_o = 3\left(1 + \frac{10k}{5k}\right) = 9V$$

$$= -V_{cc} + 2 \leftarrow -V_{sat} < V_o < +V_{sat} \rightarrow +V_{cc} - 2$$

• Non-Inverting Adder



V_{th} superposition $\frac{V_1 + V_2}{2}$

$$V_o = V_+ \left(1 + \frac{R}{R}\right)$$

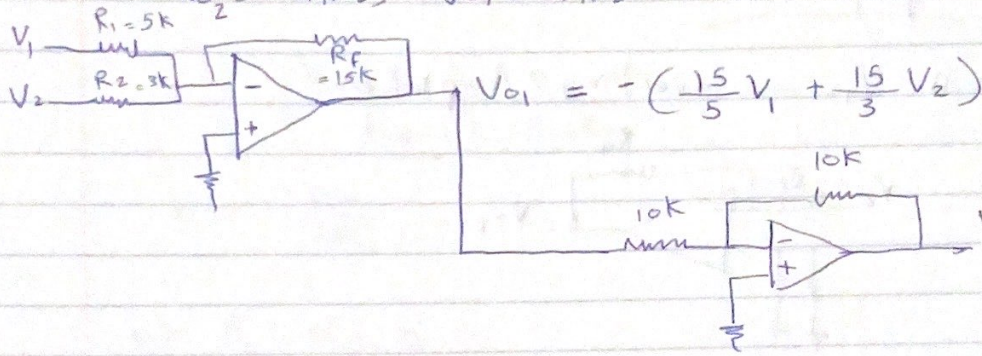
$$= \frac{V_1 + V_2}{2}\left(1 + \frac{R}{R}\right) = \boxed{V_1 + V_2 = V_o}$$

ex Design an amplifier that have 2-input voltages V_1 & V_2 such that the output $V_o = 3V_1 + 5V_2$. (use inverting Amplifiers).

with inverting Amplifier $V_{o_1} = -(3V_1 + 5V_2)$

⇒ we can have a second stage with

$V_{o_2} = -V_{in2}$, $V_{o1} = V_{in2}$

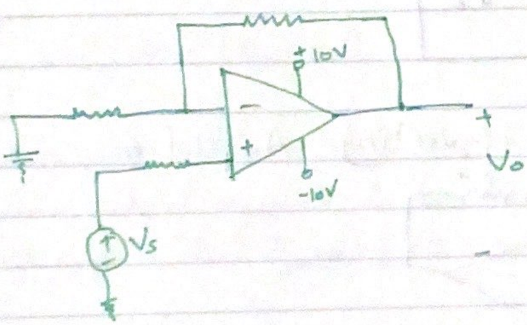


$$V_{o1} = -\left(\frac{15}{5}V_1 + \frac{15}{3}V_2\right)$$

$$V_{o2} = \frac{-10k}{10k}V_{o1}$$

$$= -V_{o1}$$

$$= 3V_1 + 5V_2$$



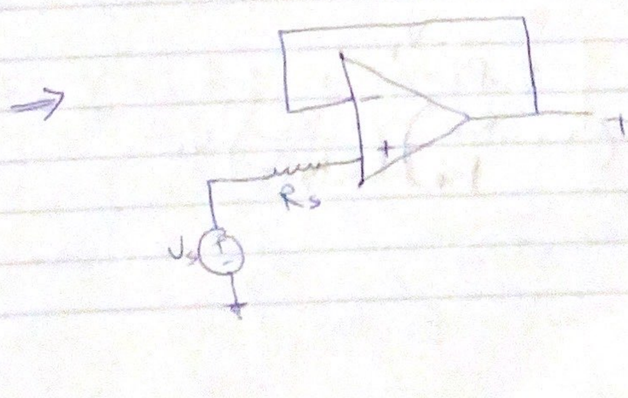
$$V_o = V_+\left(1 + \frac{R_f}{R_1}\right)$$

$$V_o = V_s\left(1 + \frac{R_f}{R_i}\right) \quad = 0$$

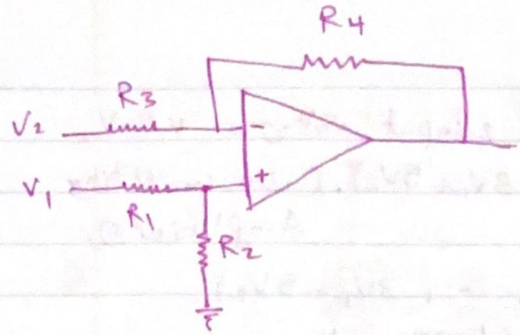
$R_f = 0$

$R_i = \infty$

⇒



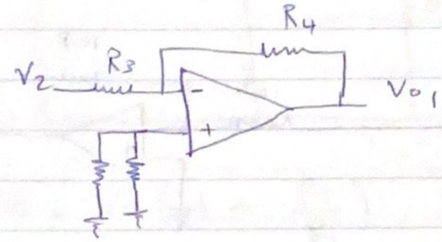
. Difference Amplifier



mix of inverting & non-inverting Amplifier

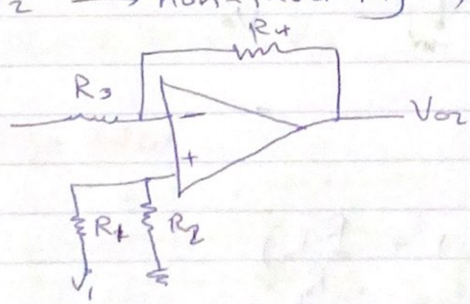
Superposition

1. Kill V_1 → inverting Amplifier



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

2. Kill V_2 → non-inverting Amplifier



$$V_{o2} = \left(1 + \frac{R_4}{R_3}\right) V_+$$

$$V_+ = \frac{R_2}{R_1+R_2} \cdot V_1$$

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

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

$$\boxed{V_o = \left(\frac{R_3 + R_4}{R_3}\right)\left(\frac{R_2}{R_1 + R_2}\right) V_1 - \frac{R_4}{R_3} V_2}$$

$$V_o = a V_1 - b V_2$$

$$a = \left(\frac{R_3 + R_4}{R_3}\right)\left(\frac{R_2}{R_1 + R_2}\right)$$

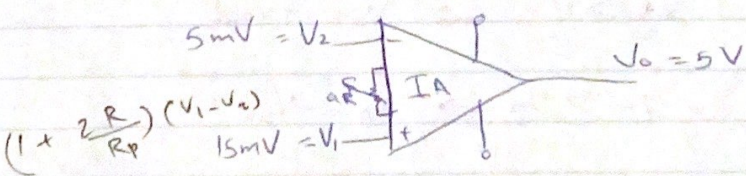
$$b = \frac{R_4}{R_3}$$

let $R_1 = R_3 = R$

$R_2 = R_4 = mR$

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

ex Use a instrumentation amplifier in order to get an output $V_o = 5V$ if $V_1 = 15mV$ (sensor1), $V_2 = 5mV$ (sensor2) & given that internal IA resistance = 20 kΩ



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

$$5 = \left(1 + \frac{2}{a}\right)(15m - 5m)$$

$$5 = \left(1 + \frac{2}{a}\right)(10mV)$$

$$1 + \frac{2}{a} = \frac{5V}{10mV} = \frac{5000mV}{10mV} = 500$$

$$500 = 1 + \frac{2}{a} \Rightarrow \frac{2}{a} = 499 \rightarrow \boxed{a = \frac{2}{499}}$$

$$a R = \frac{2}{499} \times 20k = 80.16\,\Omega$$

So far, circuits with negative feedback

- inverting
- non-inverting
- Difference
- Instrumentation

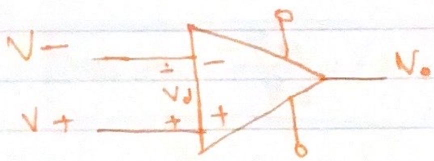
} Amplifiers

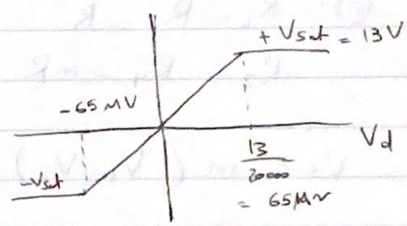
- Voltage to current
- current to voltage

} convertors

2) Open loop $\Rightarrow$ no feedback

Comparator





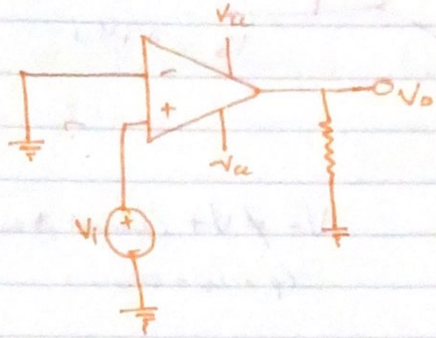
if $V_D = V_+ - V_- > 65\,\mu V$

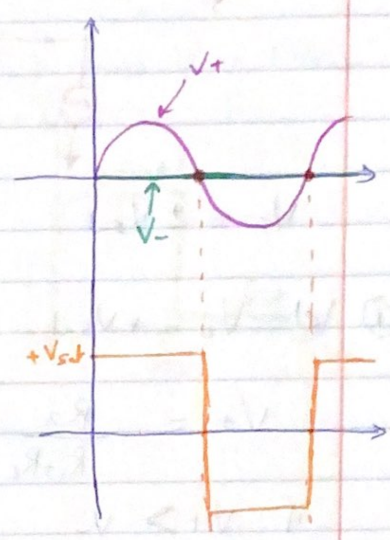
$\Rightarrow V_o = +V_{sat}$

if $V_D < -65\,\mu V$

- If $V_+ > V_- \Rightarrow V_o = +V_{sat}$
- If $V_- > V_+ \Rightarrow V_o = -V_{sat}$

• Comparator : Zero-Level detector





$V_+ > V_- \Rightarrow V_o = +V_{sat}$

$V_- > V_+ \Rightarrow V_o = -V_{sat}$

<u>ex</u> Given how an op amp functions, what do you expect V_o to be if $V_2 = 5V$ when:

1. $V_s = 0V$?

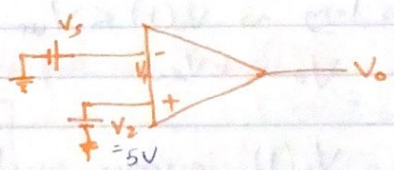
   $+V_{sat}$

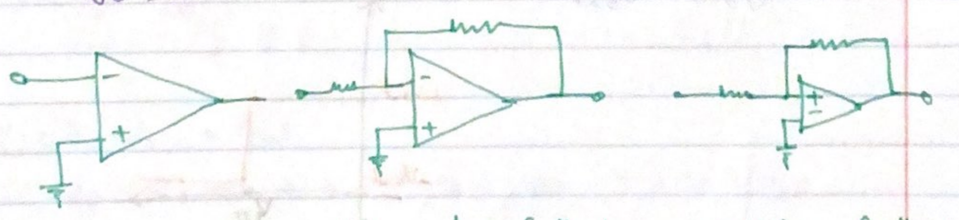
2. $V_s = 6V$?

   $-V_{sat}$

3. $V_s = 5V$?

   $V_o = 0$



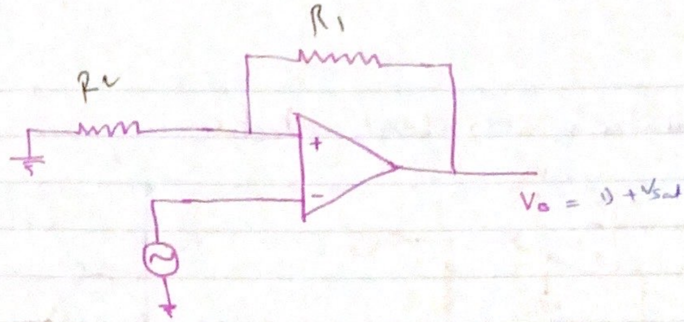


(a) no feedback (open loop comparator circuit)

(b) negative feedback

(c) Positive feedback

ex



$V_o = \pm V_{sat}$ $\qquad$ $V_- \neq V_+$ (cannot be used)

$i_p = i_n = 0$ ✓

① let $V_o = +V_{sat}$

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

if $V_+ > V_-$

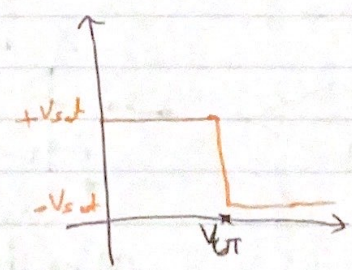
$$\boxed{V_{UT} > V_i(t)} \Rightarrow V_o = +V_{sat}$$

→ as long as $V_i(t) < V_{UT}$

$V_o = +V_{sat}$

→ if $V_i(t)$ increases such that $V_i(t) > V_{UT}$

$V_o = -V_{sat}$



② let $V_o = -V_{sat}$

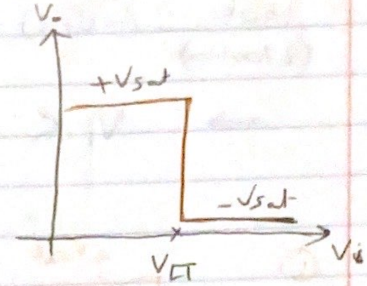
$$V_+ = \left(\frac{R_2}{R_1+R_2}\right)(-V_{sat}) = V_{LT}$$

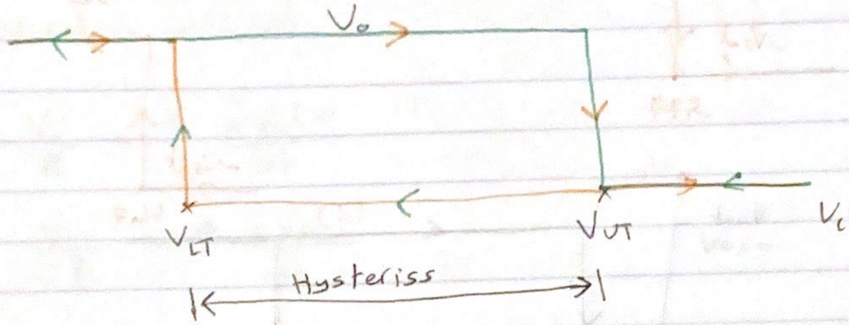
$V_+ - V_- < 0 \Rightarrow V_o = -V_{sat}$

$V_{LT} - V_i(t) < 0 \Rightarrow V_{LT} < V_i(t)$

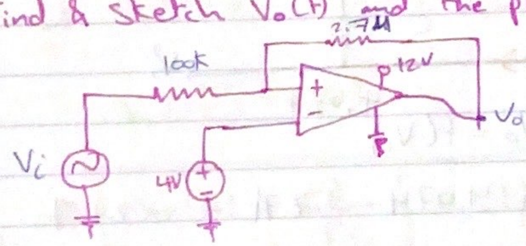
- as long as $V_i(t) > V_{LT} \Rightarrow V_o = -V_{sat}$

- if $V_i(t)$ decreases below $V_{LT} \Longrightarrow V_o = +V_{sat}$





ex Find & sketch $V_o(t)$ and the plot of $V_o = f(V_i)$



$+V_{sat} = 12 - 2 = 10V$

$-V_{sat} = 0 + 2 = 2V$

① let $V_o = +V_{sat}$

$V_D > 0 \Rightarrow V_+ - V_- > 0 \Rightarrow V_+ > V_-$

$V_- = 4V \Rightarrow V_+ > 4V$

$V_+ = \frac{100k}{(2700k + 100k)}(+V_{sat}) + \frac{\cancel{100k}\ 2700k}{(100+2700)k}(V_i)$ by super position

$\frac{100k}{2700k+100k}(10V) + \frac{2700k}{100+2700k}(V_i) > 4V$

$\Rightarrow V_i > \underbrace{3.777V}_{V_{UT}}$ when $V_i < 3.777 \Rightarrow V_o = -V_{sat}$

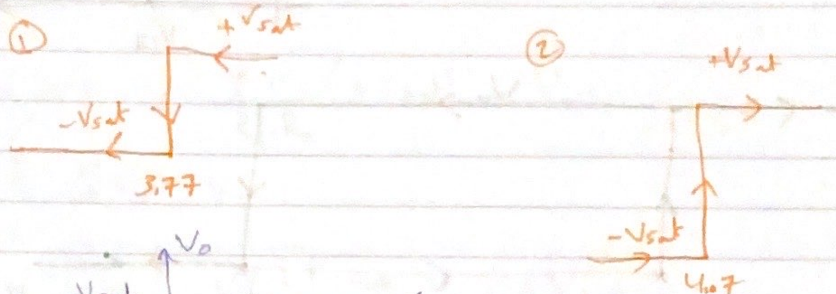
② let $V_o = -V_{sat}$

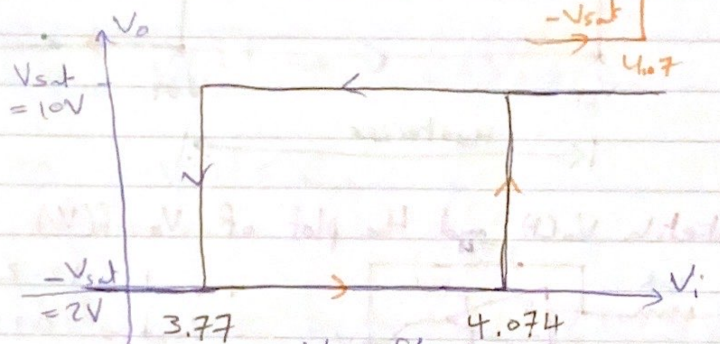
$V_d < 0 \Rightarrow V_+ < V_-$

$$\frac{100k}{(2700+100)k}(-V_{sat}) + \frac{2700k}{(2700+100)k}(V_i) < 4V$$

$\Rightarrow V_i < 4.074$, But when $V_i > \boxed{4.074}$ V_{LT}

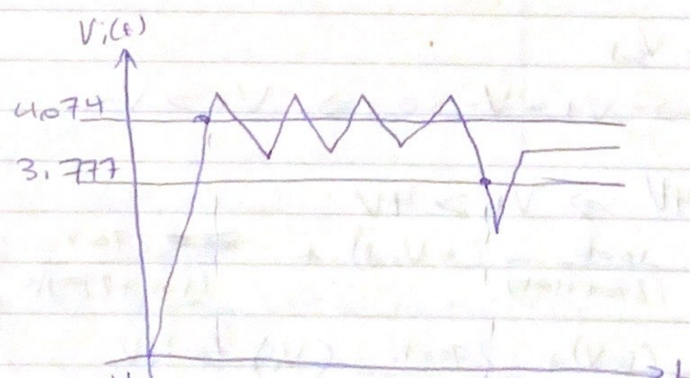
$\Rightarrow V_o = +V_{sat}$

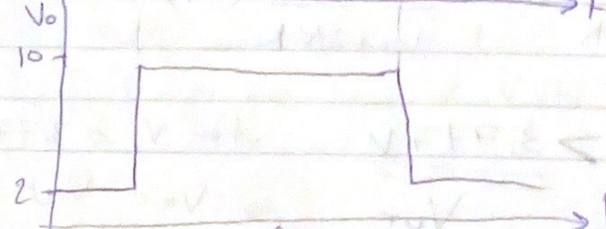




$V_o = f(V_i)$

Hysterisis $= |4.074 - 3.777| = 0.297$

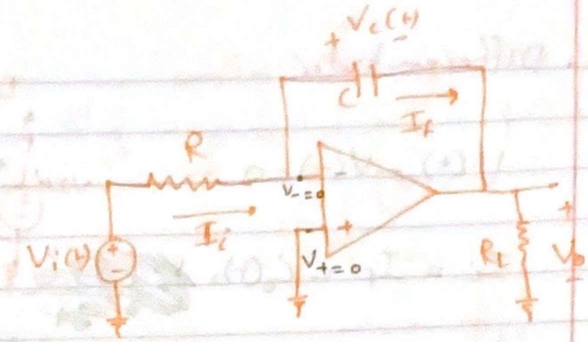




$V_o = f(t)$

Integrator + Differentiator opAmp 4 22137

• Integrator



negative feedback

$V+ = V-$

$i_p = i_n = 0$

$$I_i = \frac{V_i}{R} = I_f$$

$$i_c(t) = C \frac{\partial V_c(t)}{\partial t} = I_f$$

$$V_o(t) = -V_c(t)$$

$$\frac{V_i}{R} = C \frac{\partial V_c(t)}{\partial t}$$

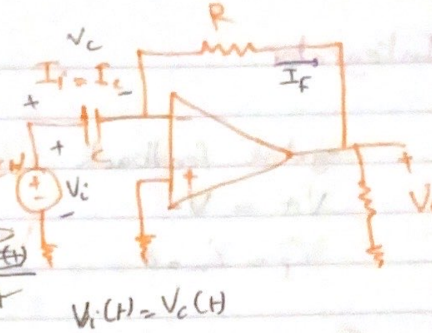
$$\frac{V_i}{CR} = \frac{\partial V_c(t)}{\partial t}$$

$$\Rightarrow V_c(t) = \frac{1}{RC} \int V_i(t)\, \partial t$$

$$V_o(t) = -V_c(t)$$

$$\Rightarrow \boxed{V_o(t) = \frac{-1}{RC} \int V_i(t)\, \partial t}$$

- Differentiator



$V(+) = V(-) = 0$

$I_i = I_f = i_c(t) =$

$V_i(t) = V_c(t)$

$$i_c = C \frac{\partial V_i(t)}{\partial t}$$

$$V_o = -i_f(t) R$$

$$V_o = -C \frac{\partial V_i(t)}{\partial t} (R)$$

$$V_o = -RC \frac{\partial V_i(t)}{\partial t}$$

- Filters

LPF, HPF, BPF, BRF

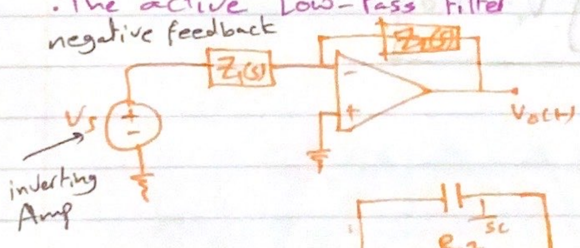
Passive — R, L, C

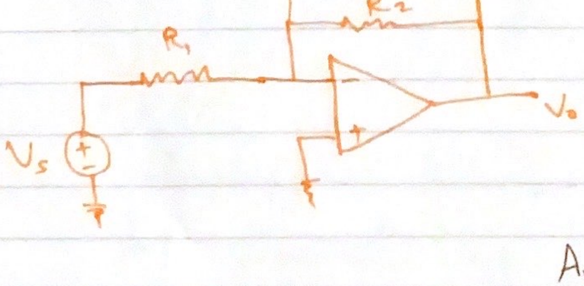
Active — R, C, op-Amp
- no loading effect
- ω_c is will defined & constant

1st order
2nd order
⋮
nth order

- The active Low-Pass Filter

negative feedback





$$H = A_v = -\frac{Z_2(j\omega)}{Z_1(j\omega)}$$

$$Z_2 = \frac{R_2 \frac{1}{sC}}{R_s + \frac{1}{sC}} = \frac{R_2 \frac{1}{j\omega}}{R_2 + \frac{1}{j\omega C}}$$

$$Z_2 = \frac{R_2}{j\omega C R_2 + 1}$$

$$Z_1 = R_1$$

$$A_V = -\frac{R_2}{R_1(1 + j\omega C R_2)}$$ ← complex number

$$A_V = \frac{-K}{1+\frac{j\omega}{\omega_c}}$$

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

$$\omega_c = 2\pi f_c = \frac{1}{R_2C}$$

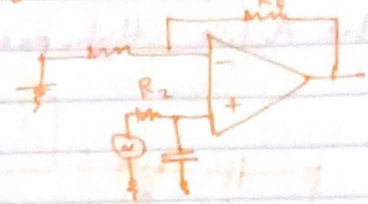
$$\therefore f_c = \frac{1}{2\pi R_2C}$$

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

OR

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

another ~~high~~ low pass filter config.



$$\omega_c = \frac{1}{R_2C}$$

$$K = 1 + \frac{R_f}{R_1}$$

ex $A_V = 40\text{ dB}$, $R_{in} = 5k\Omega$, $f_c = 2\text{ kHz}$

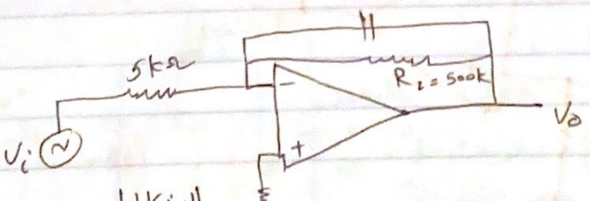
Ideal op-Amp

$$20\log|A_V| = 40\text{ dB}$$

$$\log|A_V| = \frac{40}{20} = 2$$

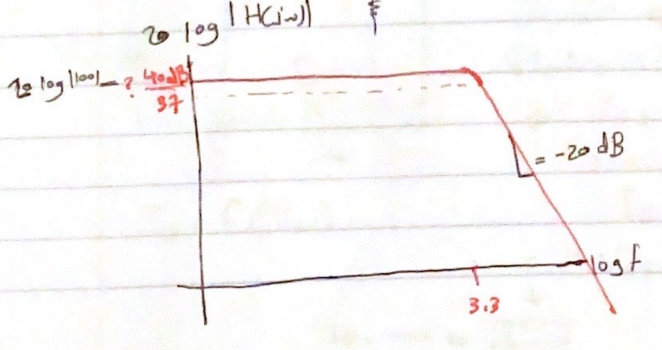
$$|A_V| = 10^2 = 100 \Rightarrow \underset{\text{(cap open)}}{\text{dc gain}} = 100 = \left|\frac{R_2}{R_1}\right|$$

$$\Rightarrow R_2 = 500k\Omega$$



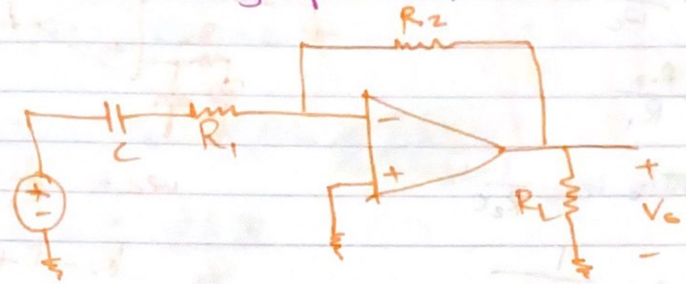
$$\omega_c = \frac{1}{R_2C} = 2\pi f_c$$

$$\Rightarrow C = 159\text{pF}$$



log (2000) = 3.3

* The Active High-pass Filter



$$A_v = -\frac{Z_2}{Z_1} = -\frac{R_2}{\left(R_1 + \frac{1}{j\omega C}\right)}$$

$$A_v = \frac{-K}{\left(1 + \frac{1}{j\omega R_1 C}\right)} \quad ; \quad K = R_2/R_1$$

$$A_v = \frac{-K}{1 + \frac{\omega_c}{j\omega}} \quad , \quad \omega_c = \frac{1}{R_1 C}$$

HPF

$$\Rightarrow |A_v| = \frac{K}{\sqrt{1 + \left(\frac{\omega_c}{\omega}\right)^2}} \xrightarrow[\text{with LPF}]{\text{compare}} |A_v| = \frac{K}{\sqrt{1 + \left(\frac{\omega}{\omega_c}\right)^2}}$$