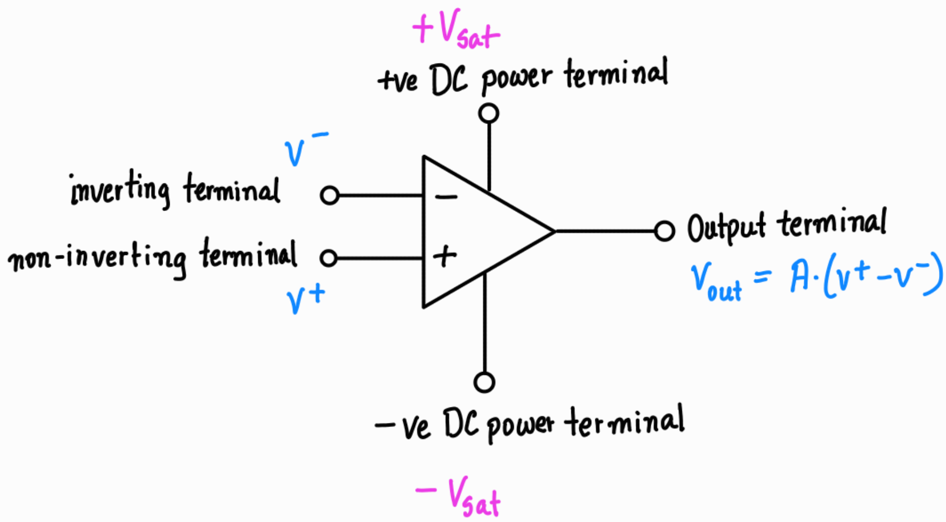
Op-amp (Operational amplifier) is a differential (refers to voltage difference) amplifier.

It has 5 terminals —



The A in $V_{out} = A\,(v^+ - v^-)$ stands for gain. The difference, $v^+ - v^-$ is why op-amp is called a differential amplifier.

The inverting and non-inverting terminals are used as inputs and the output terminal provides the amplified output.

So what do the other 2 terminals do?

What you have to realize is that amplification needs energy beyond the input values as you cannot magically increase the energy of a signal. For op-amps we supply this extra energy through two DC voltage sources — one connected as $+V_{sat}$ (@ +ve DC power terminal) and other connected as $-V_{sat}$ (@ −ve DC power terminal). This DC power allows amplification of the input signal.

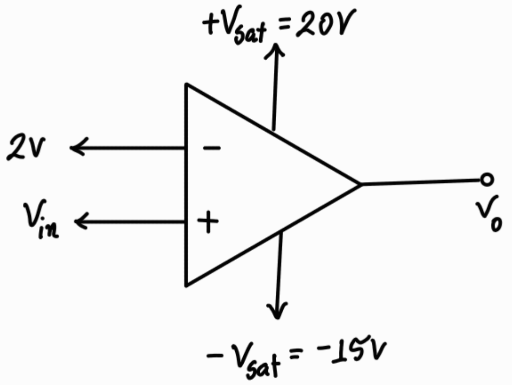
Question — If amplification is dependent on + Vsat & − Vsat, can you ever amplify an input voltage signal beyond the range [−Vsat, + Vsat]?

NO! Remember that you cannot create energy beyond what you supply.

So, for an op-amp,

$$V_{out} = \begin{cases} A(v^+ - v^-) & \text{if } -V_{sat} \leq A(v^+ - v^-) \leq +V_{sat} \\ -V_{sat} & \text{if } A(v^+ - v^-) < -V_{sat} \\ +V_{sat} & \text{if } A(v^+ - v^-) > +V_{sat} \end{cases}$$

Lets take a small example —

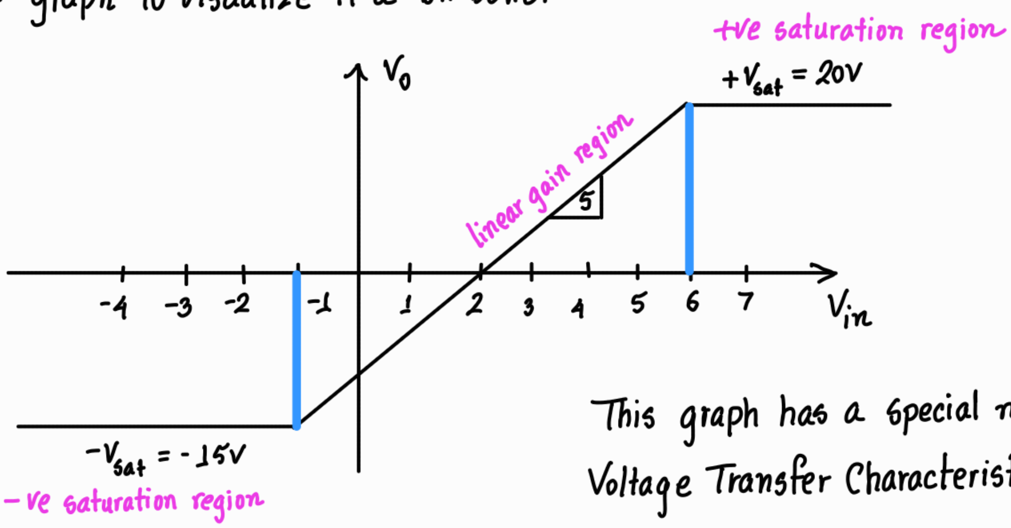


Lets consider $A = 5$

Now lets see how V_0 changes with change in V_{in}

V_{in}	$V_d = v^+ - v^-$	AV_d	V_0	Remarks
−3V	−5V	−25V	−15V	$AV_d < -V_{sat}$, so $V_0 = -V_{sat}$
−2V	−4V	−20V	−15V	"
−1V	−3V	−15V	−15V	$-V_{sat} \leq AV_d \leq +V_{sat}$, so $V_0 = AV_d$
0V	−2V	−10V	−10V	"
1V	−1V	−5V	−5V	"
2V	0V	0V	0V	"
3V	1V	5V	5V	"
4V	2V	10V	10V	"
5V	3V	15V	15V	"
6V	4V	20V	20V	"
7V	5V	25V	20V	$AV_d > +V_{sat}$, so $V_0 = +V_{sat}$
8V	6V	30V	20V	"

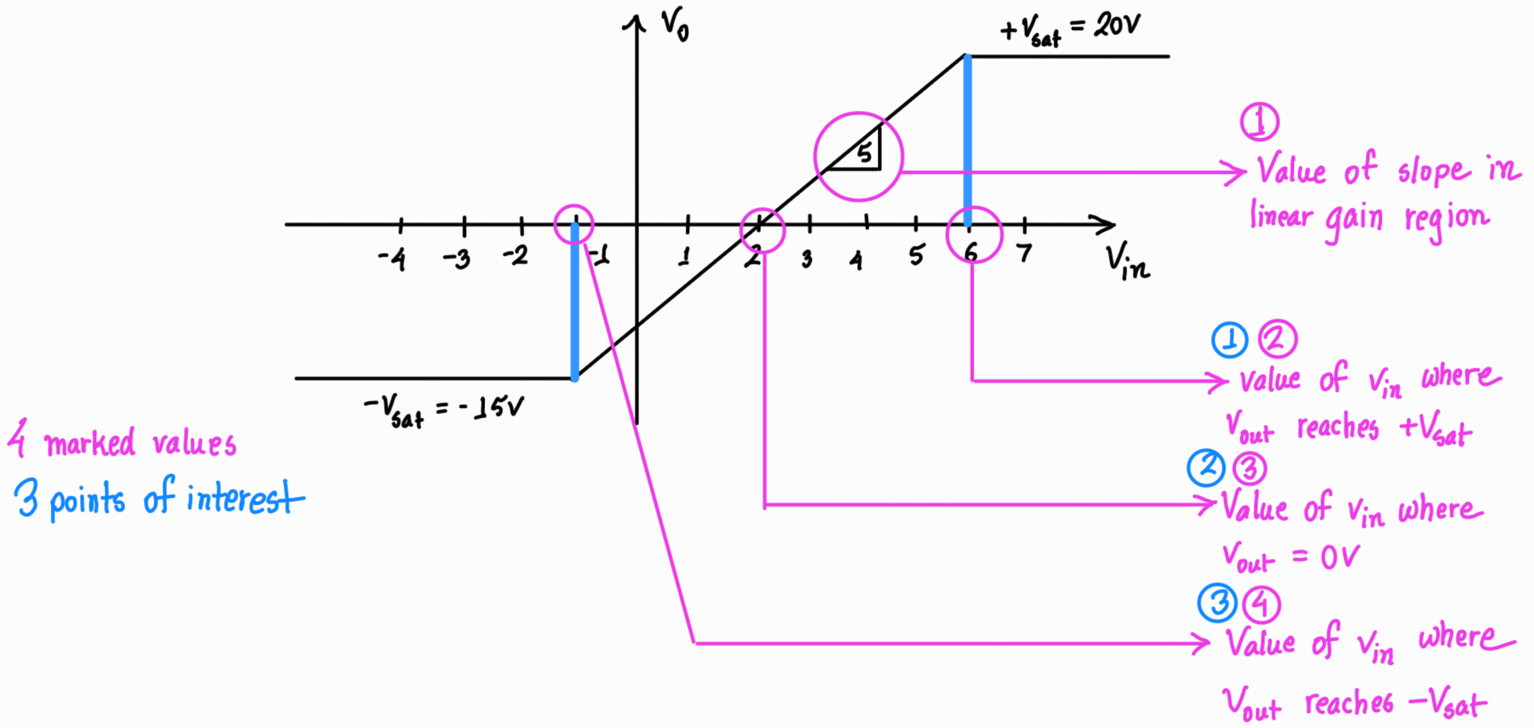
Now understanding the relation from the table maybe a bit hard. Lets try plotting V_0 vs V_{in} on a graph to visualize it a bit better —



This graph has a special name —

Voltage Transfer Characteristics (VTC) graph

The VTCs of an op-amp will always be similar to this graph. To fully define an op-amp VTC, you need to mark 4 things (slope + 3 points of interest). Lets see them in the plotted VTC graph —

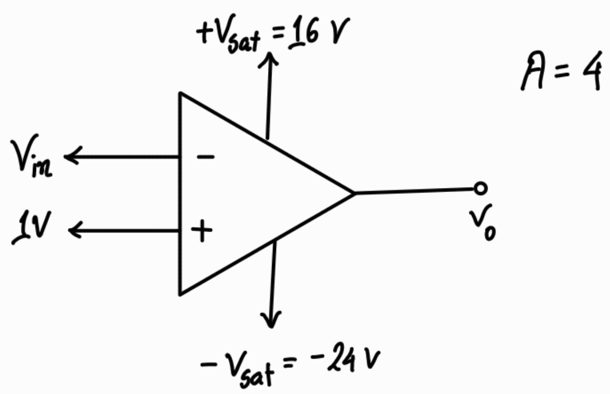


Now you will be asked to draw the VTCs to show relationships between V_{in} & V_{out}.

But it is clearly not feasible to draw the table every time. So can we draw the VTC without constructing the table?

Yes, just use the 3 points of interests.

Let me show you an example —



first find V_o in terms of V_{in} for the linear gain region —

here, $V_o = A(V^+ - V^-) = 4(1 - V_{in})$

$\therefore V_o = 4(1 - V_{in})$ —— (i)

then we use this equation to find the V_{in} value for the 3 points of interest —

① Value of V_{in} when V_o reaches $+V_{sat}$

substitute $V_o = +V_{sat} = 16V$ in equation ⓘ —

$$16 = 4(1 - V_{in}) \Rightarrow V_{in} = -3V$$

② Value of V_{in} when $V_o = 0$

substitute $V_o = 0$ in equation ⓘ —

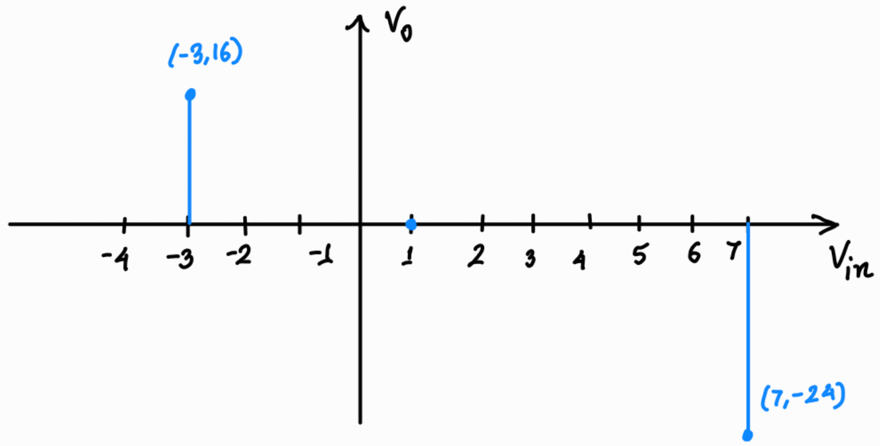
$$0 = 4(1 - V_{in}) \Rightarrow V_{in} = 1V$$

③ Value of V_{in} when V_o reaches $-V_{sat}$

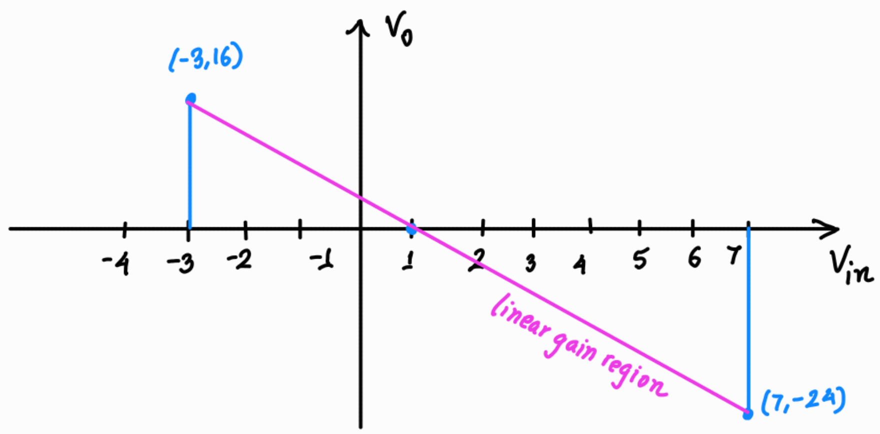
substitute $V_o = -V_{sat} = -24V$ in equation ⓘ —

$$-24 = 4(1 - V_{in}) \Rightarrow V_{in} = 7V$$

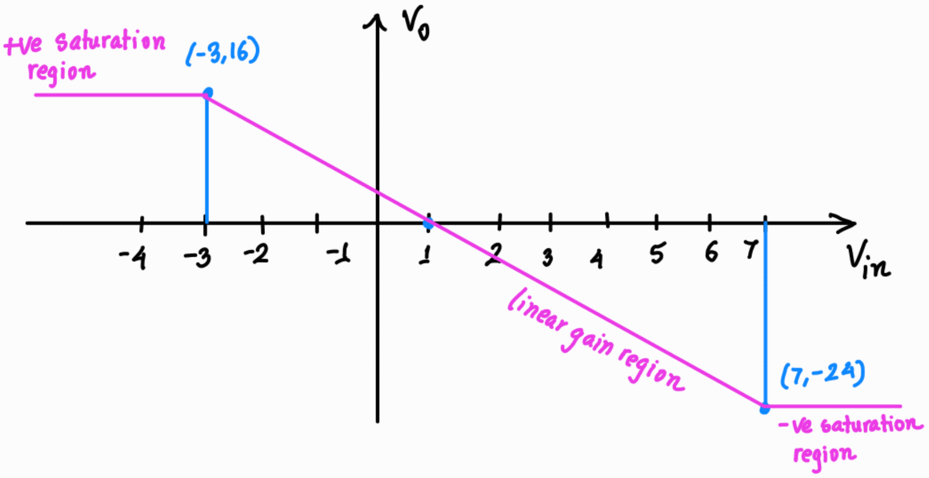
Now plot these points in the graph — $(V_{in}, V_o) \longleftrightarrow \underbrace{(-3, 16)}_{+V_{sat}\text{ point}}, \underbrace{(1, 0)}_{0\text{ point}}, \underbrace{(7, -24)}_{-V_{sat}\text{ point}}$



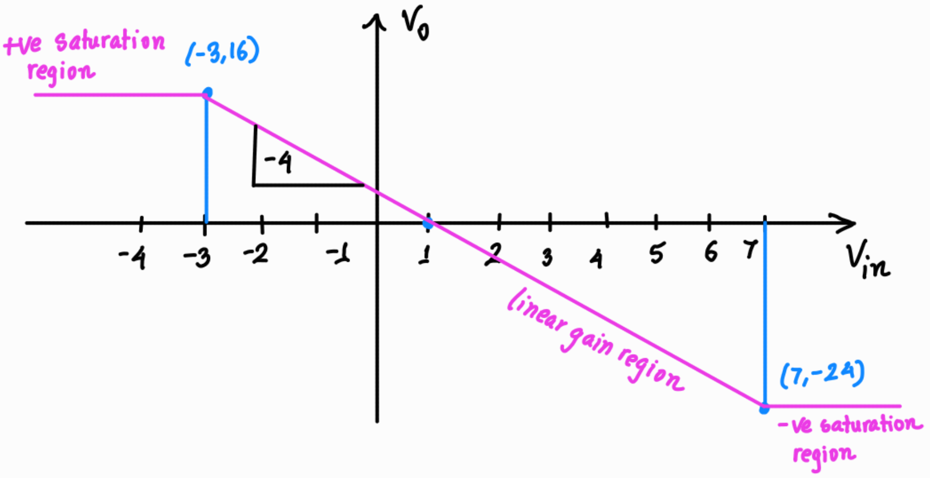
Now join these points to form the linear gain region —



Then complete the +ve & −ve saturation regions —



Finally place the value of the slope and you are done with the VTC —

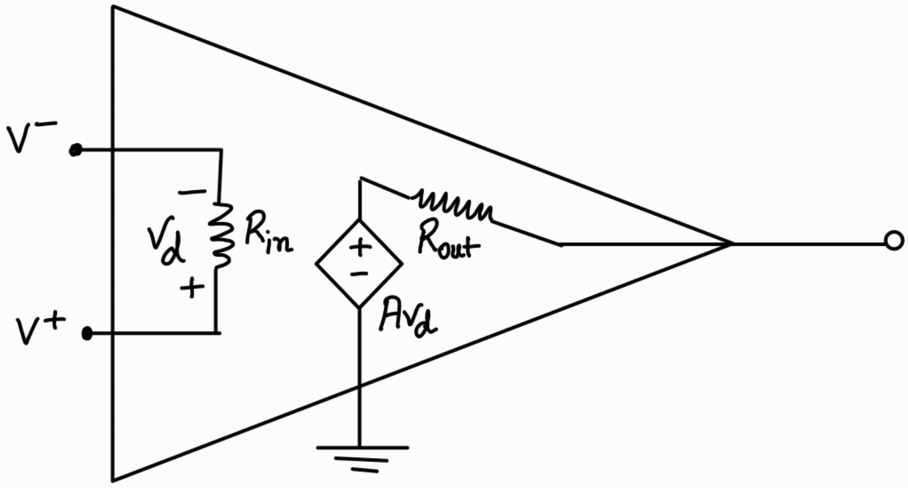


NOTE — This method drawing the VTC and the graph itself is applicable only for finite gain.

For infinite gain (as you will soon see) the VTC is a bit different in the linear gain region.

We will come back to this method when we study closed loop op-amp configs. For now we will talk about open-loop config and comparators after discussing about ideal op-amps.

Op-amp internal ckt simplified —



for an ideal op-amp —

1. $R_{in} = \infty\,\Omega$
2. $A = \infty$
3. $R_{out} = 0\,\Omega$

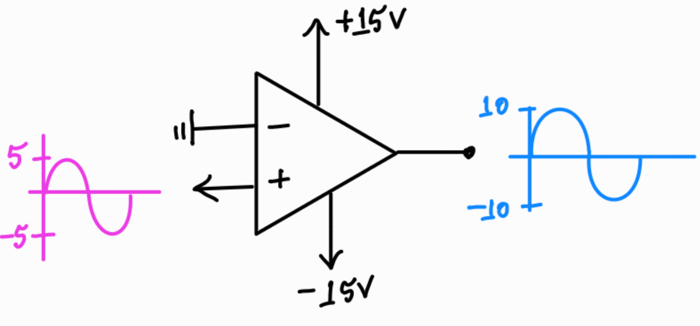
May be asked in the exam

From now on we will only work with ideal op-amps. But in doing so, we get a gain of ∞.

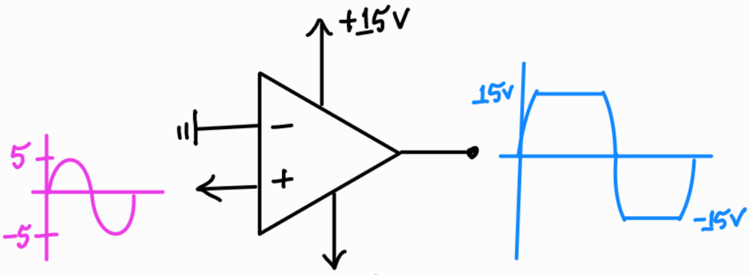
As such if $v^+ - v^- = \Delta v$ such that $\Delta v \longrightarrow 0^+$, V_{out} becomes saturated @ $+V_{sat}$.

and if $v^+ - v^- = \Delta v$ such that $\Delta v \longrightarrow 0^-$, V_{out} becomes saturated @ $-V_{sat}$.

As such we do not get any linear gain region, resulting in no proper amplification. For example —

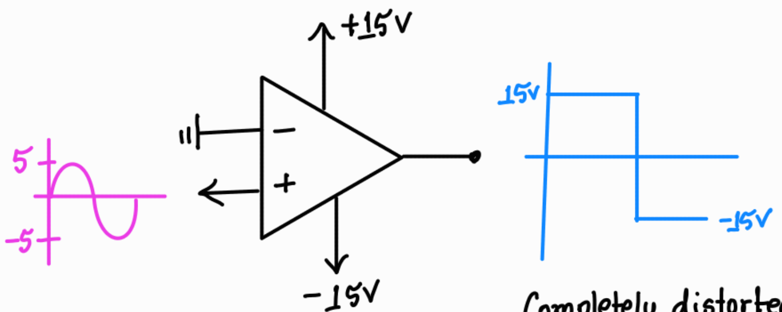


$A = 2$



$A = 5$

High gain distorting output signal

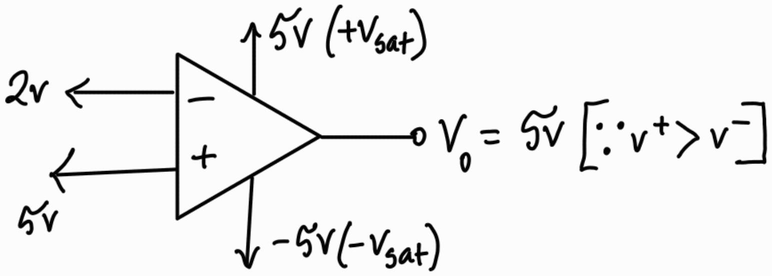


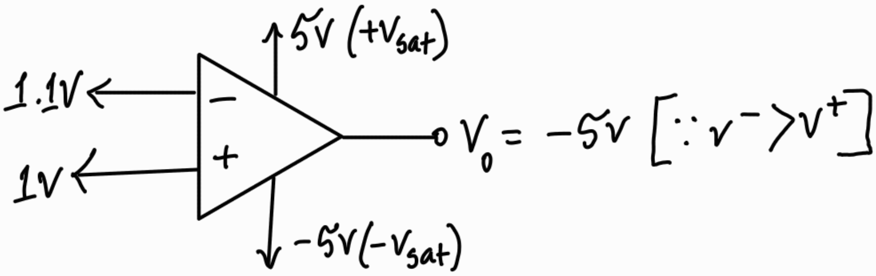
Completely distorted (no semblance of input)

$A = \infty$

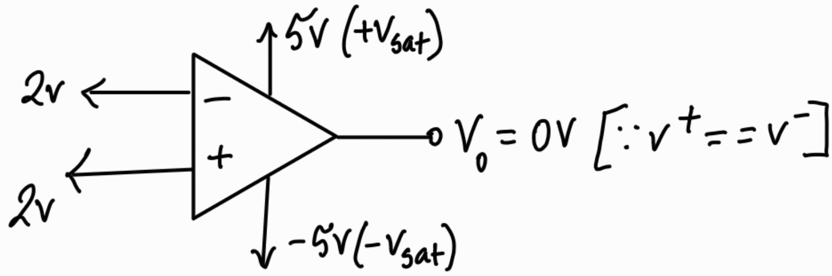
So if we cannot amplify our signal with an ideal op-amp (at least in this configuration), is there even any purpose for this configuration?

Yes, we use this configuration (open loop configuration) as comparator to check which one of v^+ & v^- is larger.

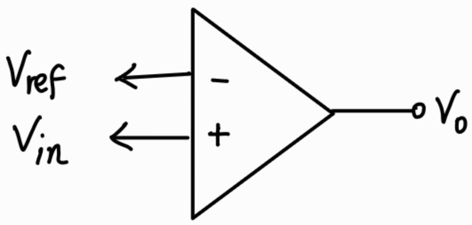




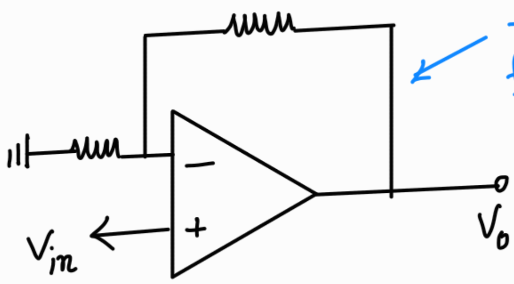
Special case →



NB— for reference —



Open-loop config



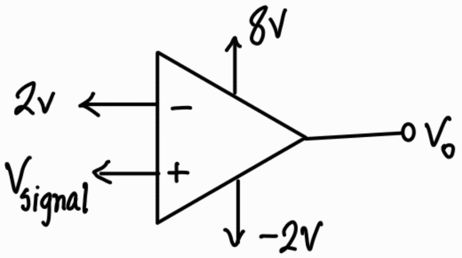
−ve feedback from output

more on this later

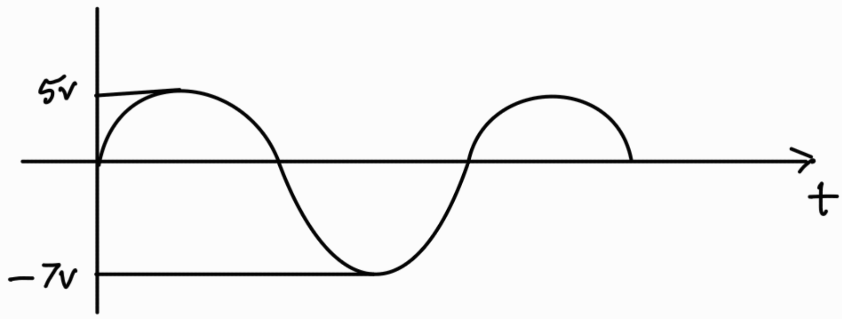
Closed loop config

NB— for an example of comparator ckt in practical sector, go through the smoke detector example in the slides.

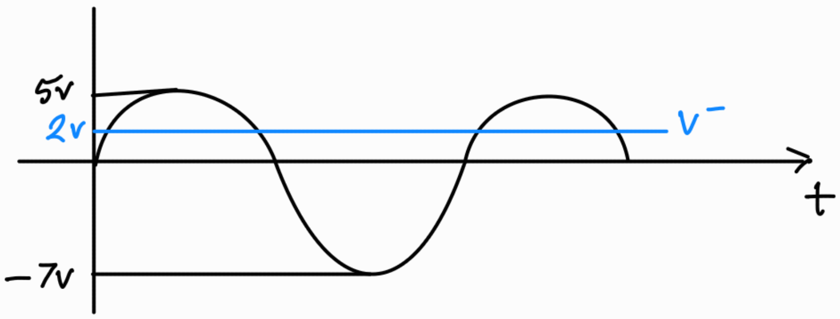
for this note let us look at some examples of comparators —



for V_{signal} graph given below, draw the v_o graph —



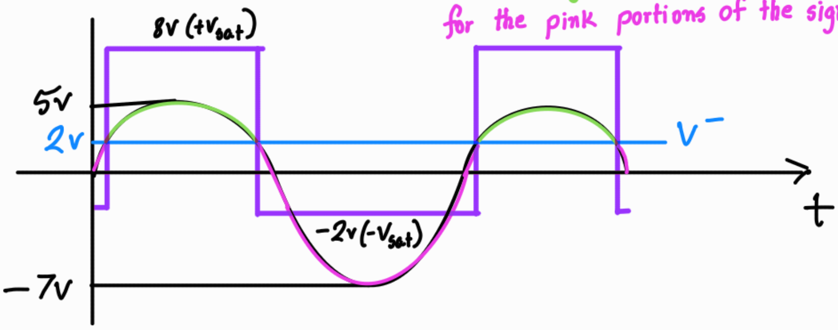
The V_{signal} is basically the v^+. On the same graph plot v^- ——



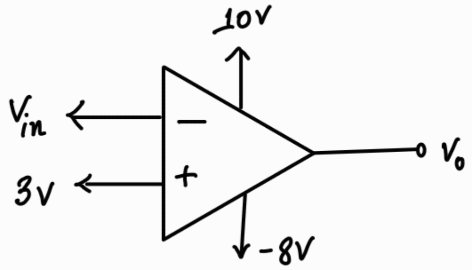
Now for each time point compare v^+ & v^- and draw the output (v_o) on the same graph

for the green portions of the signal $v^+ > v^-$

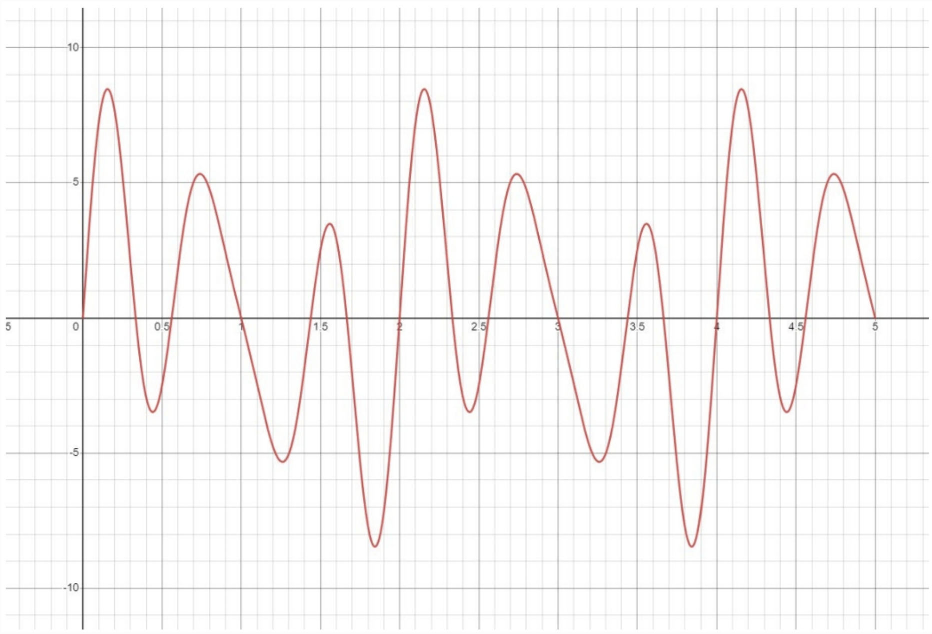
for the pink portions of the signal $v^- > v^+$



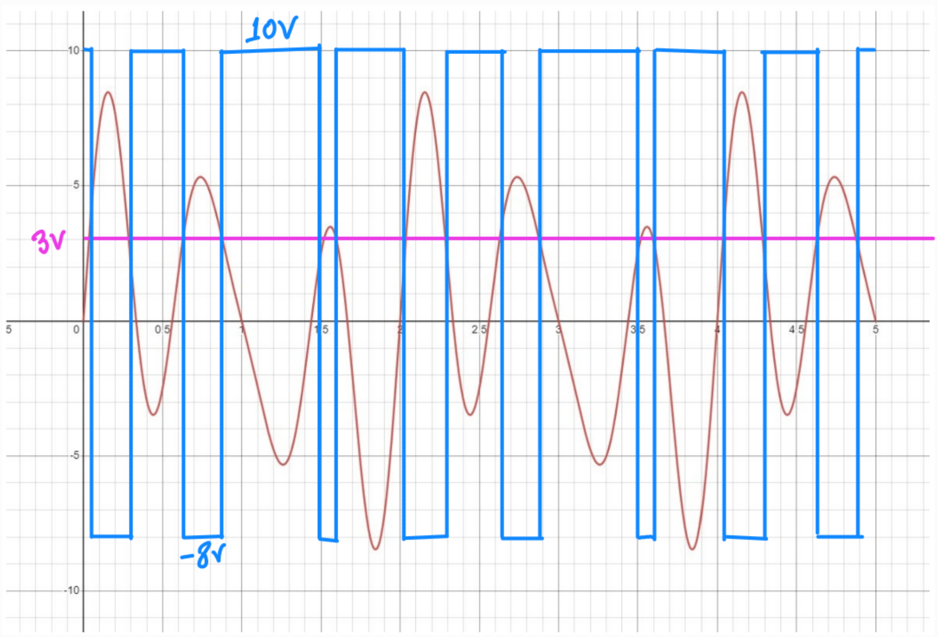
Lets do an example with a more complicated waveshape —



The V_{in} signal ⟶

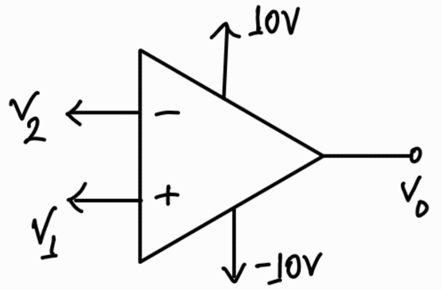


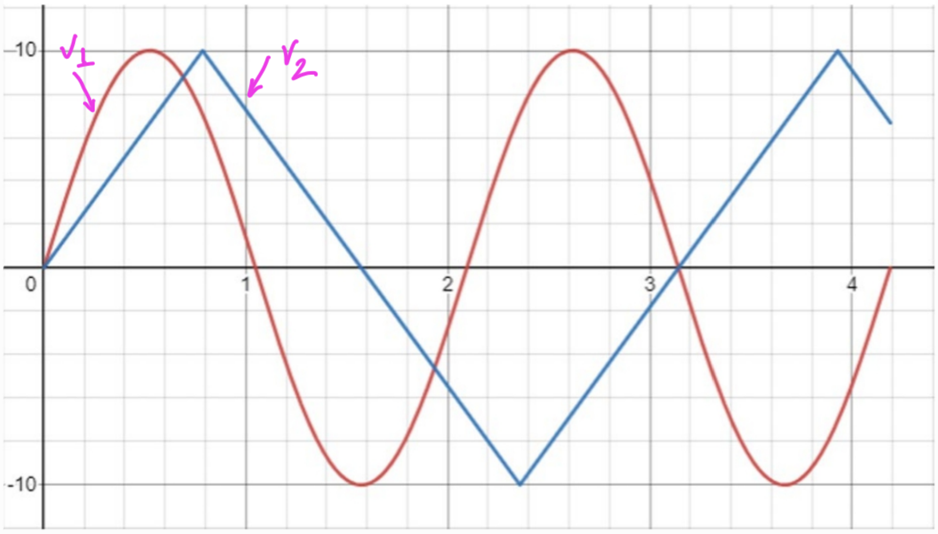
first draw the 3V, V_{ref} on the graph. Also notice V_{ref} is now V^+ and so we adapt accordingly —



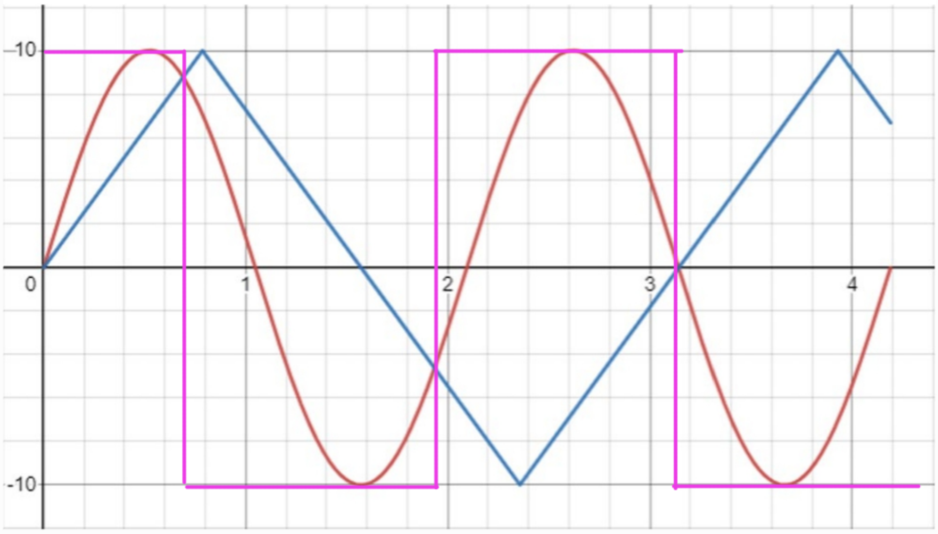
This might feel a bit hard to understand at first but with practice it will become easier for you.

Now lets make V_{ref} an AC signal as well —





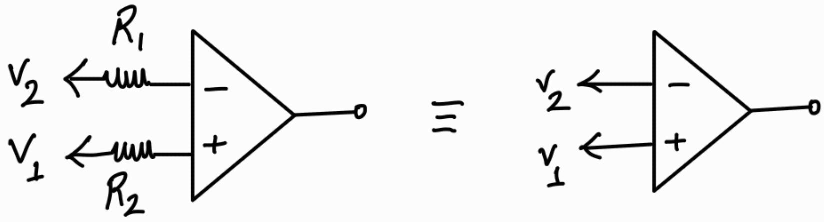
V_1 is the v^+. So to draw the output just check when v_1 is greater than v_2. In such cases $V_o = 10V$ and in other cases $V_o = -10V$



red → v_1 → v^+
blue → v_2 → v^-

Graph-based comparator problems will not be harder than this.

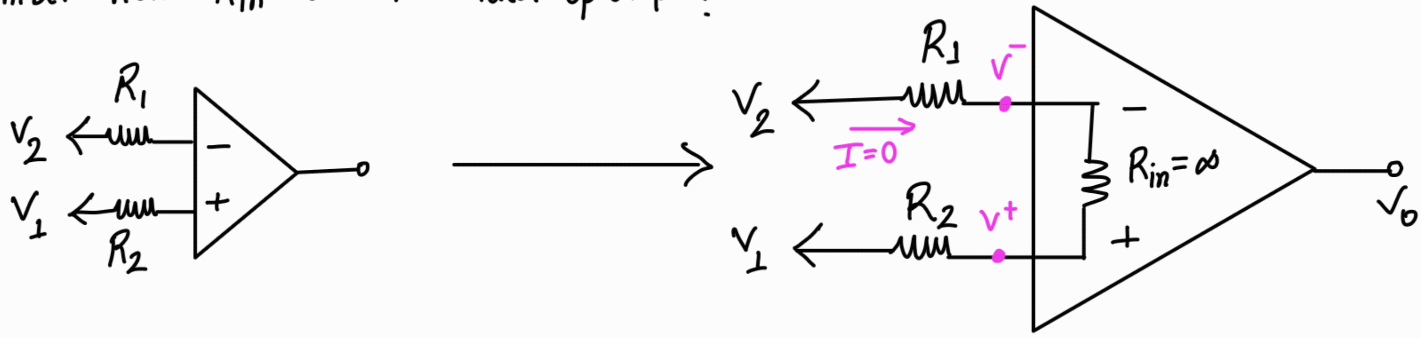
One concept that maybe tested —

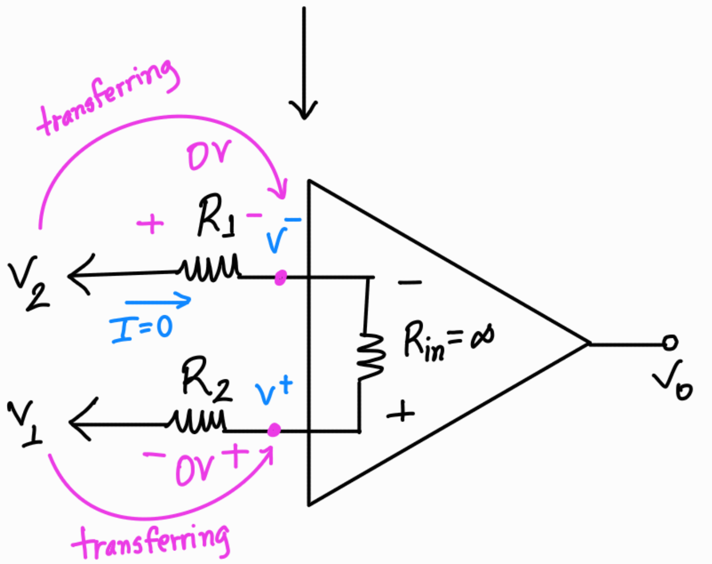


Proof —

Remember how $R_{in} = \infty$ for ideal op-amps?

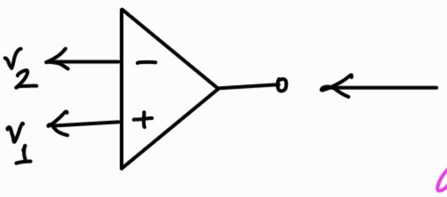
$\therefore$





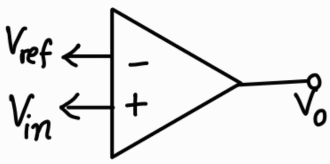
$V^- = V_2 - 0V$
$= V_2$

& $V^+ = V_1 + 0V$
$= V_1$



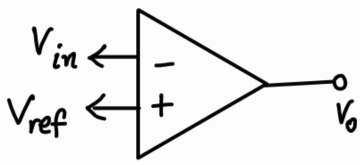
Terminologies regarding comparators —

non-inverting comparator



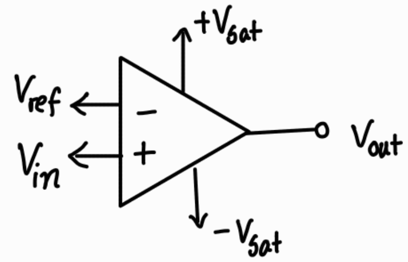
When V_{in} is connected to non-inverting terminal

inverting comparator



When V_{in} is connected to inverting terminal

Finally, the last topic from open loop configs — VTC of a comparator

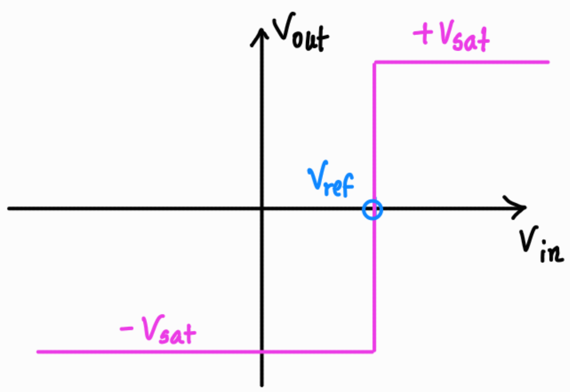


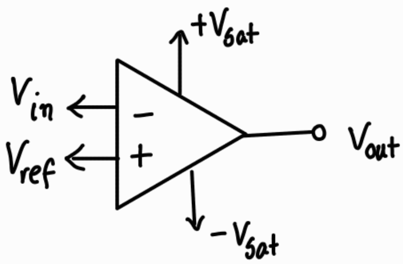
for non-inverting comparator —

when $V_{in} < V_{ref} \longrightarrow V_{out} = -V_{sat}$

when $V_{in} == V_{ref} \longrightarrow V_{out} = 0$

when $V_{in} > V_{ref} \longrightarrow V_{out} = +V_{sat}$



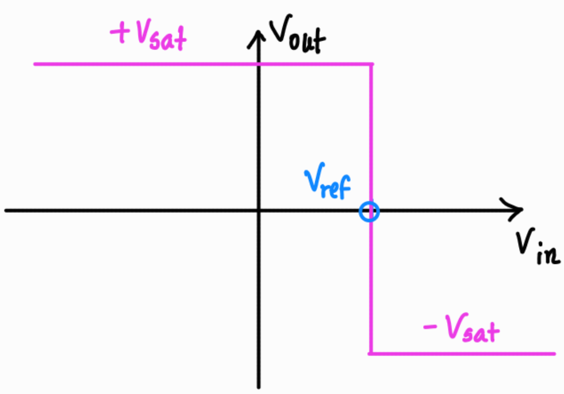


for non-inverting comparator —

when $V_{in} < V_{ref} \longrightarrow V_{out} = +V_{sat}$

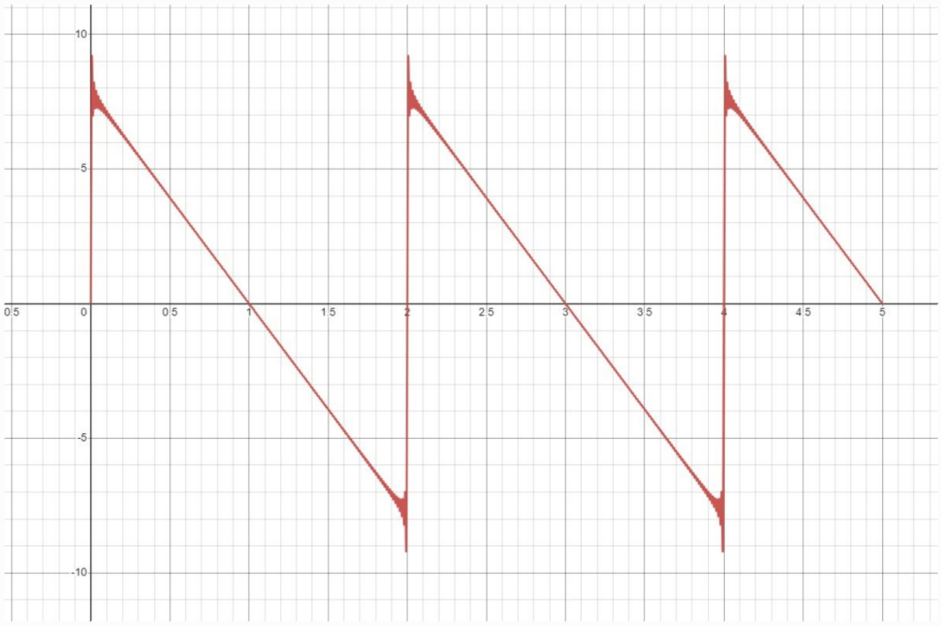
when $V_{in} == V_{ref} \longrightarrow V_{out} = 0$

when $V_{in} > V_{ref} \longrightarrow V_{out} = -V_{sat}$

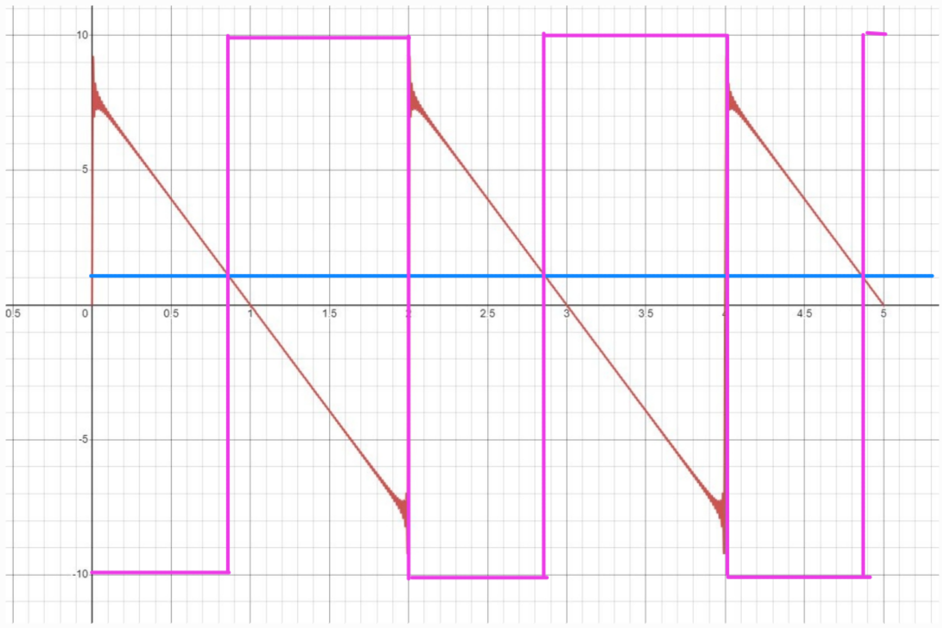


One final example (rare) —

for an inverting op-amp comparator, $V_{ref} = 1V$. If V_{in} is provided in the graph below, draw the V_{out}. $[+V_{sat} = 10V, -V_{sat} = -10V]$



Since the comparator is inverting in nature, $V_{in} = V^-$. So the V_{out} —



final note — even if it isn't mentioned in the question that the op-amp is ideal in nature, for comparators, always consider ideal op-amps.