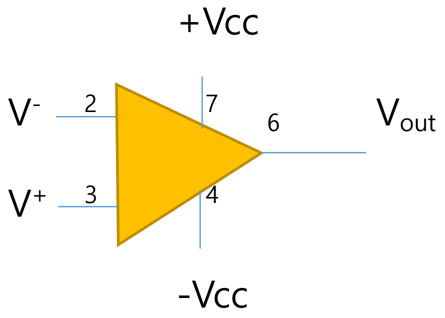
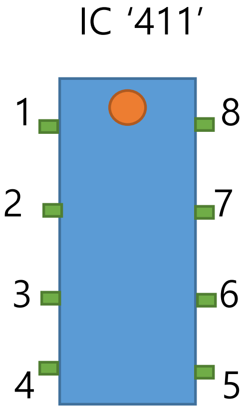
Lecture 12 : Operational Amplifier (OP Amp)

: Integrated Circuit that consists of TRs with feedback circuits

Symbol:





Rules for OP Amp

1. $Z_{in}=\infty$ (or $i^- \fallingdotseq i^+ \fallingdotseq 0$) and Z_{out} is very small ($\fallingdotseq 0$)
2. In open loop (or no feedback)

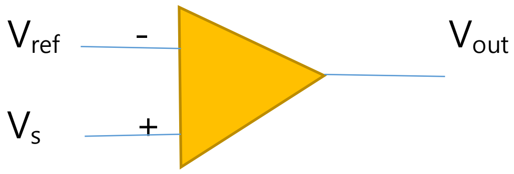
   If $V^+ > V^-$ then $V_{out}=+Vcc$

   If $V^+ < V^-$ then $V_{out}=-Vcc$
3. In closed loop (or negative feedback or feedback to V^-)

   Then $V^- \fallingdotseq V^+$ is always attempted
4. $|V_{out}| \leq +Vcc$. Equality indicates OP Amp saturation (to be avoided)

Application

1. Analog Comparator



IF $V_s > V_{ref}$ THEN V_{out} = Vcc

IF $V_s < V_{ref}$ THEN V_{out} = -Vcc

This OP Amp can be used as an Analog Comparator

that can make comparison between the two analogue voltages

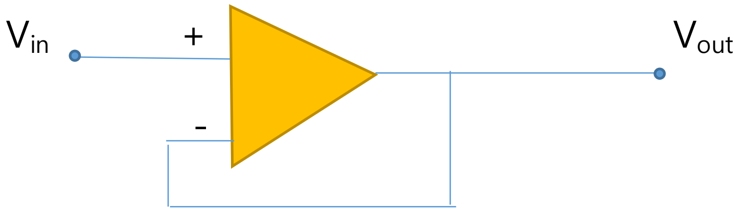
(Q: What happen if $V_s = V_{ref}$ in open loop? A: Never Happen!!)

EX) Logic Circuit, A/D Converter, etc

2. Voltage Follower

:To follow the input voltage with Impedance "Refined"

For better performance in driving or being driven to/from the neighbouring circuit



$V_{in} = V^+ = V^- = V_{out}$ (∵ closed loop with negative feedback)

∴$V_{out} = V_{in}$ ∴ V_{out} follows V_{in} and Gain=V_{out}/V_{in}=1

(Q: Why do we need this circuit ?)

Let's consider the input impedance, Zin, and output impedance, Z_{out}

$Z_{in} = \infty$=Impedance when viewing from Input(V_{in})

$Z_{out} \fallingdotseq 0$ = Impedance when viewing from output (V_{out})

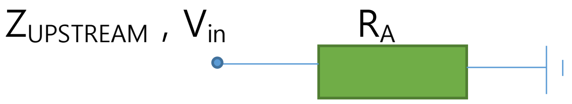
As $Z_{in}=\infty$, this circuit can be driven from any upstream circuit.

As $Z_{out} \fallingdotseq 0$, this circuit can drive any following circuit.

($Z_{out} \ll Z_{in}$ for ideal condition for driving or being driven!!)

Therefore the voltage follower can be a good device to drive or to be driven in practical circuit design application, as Slave and Master!

Ex) For a circuit design to drive A



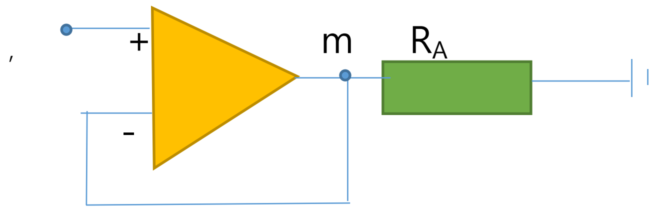
If there exists $Z_{UPSTREAM}$ of zero(0) Ω, A can be driven nicely.

But when there exists unknown $Z_{UPSTREAM}$ as in the fig, the condition of driving may not be satisfied if the $Z_{UPSTREAM}$ is big.

$Z_{UPSTREAM} \ll R_A$ should be satisfied for 10X rule. Thus the voltage follower is better to be located just before the A device, to refine the impedance.

Therefore the design can be modified as follows;

$Z_{UPSTREAM}$, V_{in}



At V_{in} : $Z_{UPSTREAM} \ll Z_{in}$ $(=\infty)$

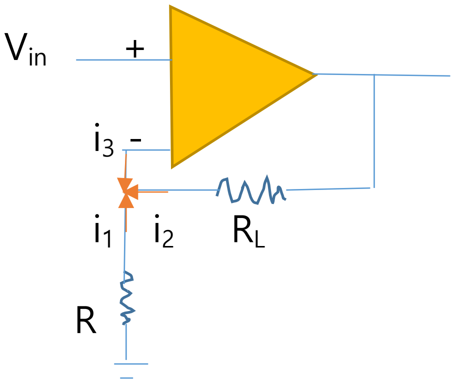
At m; Z_{out} from Op amp $\risingdotseq 0 \ll R_A$

$\therefore$ A can be driven nicely with the OP Amp voltage follower,

even under the uncertain $Z_{UPSTREAM}$

3. Current Source or Current Supply

: To provide constant current supply or current source



At the Junction, $i_1+i_2+i_3=0$ from the Kirchhoff's law.

$i_1=(0 - V^-)/R=-V_{in}/R$ ($\because$ $V^- = V^+ =$ Vin from closed loop)

$i_2=i_L$=current flow from R_L

$i_3= -i^- \fallingdotseq 0$

Thus $i_1+i_2+i_3=(-V_{in}/R)+i_L+0=0$

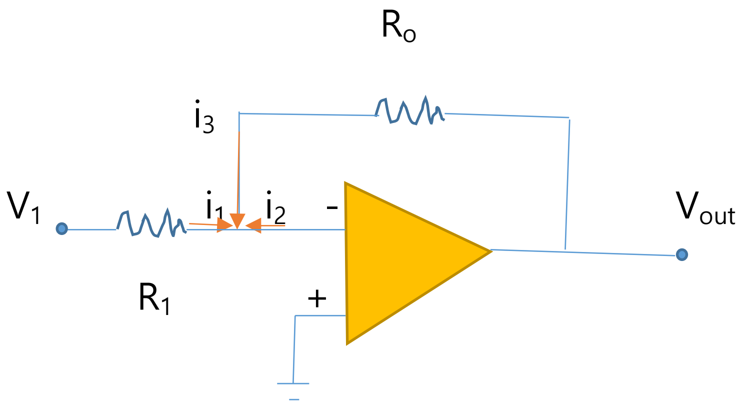
$\therefore$ $i_L=V_{in}/R$ indicates Constant Current to/from R_L , regardless of R_L

$\therefore$ Current Source or Current Supply

This current supply can give wider range of voltage when compared to the TR's version, where $I_E=(V_{in}-0.6)/R_E$ and $V_{in}\geq 0.6$ are assumed.

4. Inverting Amplifier

: To amplify the inverted voltage



At the junction, $i_1+i_2+i_3=0$

$i_1=(V_1 - V^-)/R_1=(V_1 - V^+)/R_1=V_1/R$

$i_2=0$

$i_3=(V_{out} - V^-)/R_o=V_{out}/R_o$

Thus $V_1/R_1+V_{out}/R_o=0$

$\therefore V_{out}=(-R_o/R_1)V_1$

∴ This is inverting amplifier, and Gain = $-R_o/R_1$

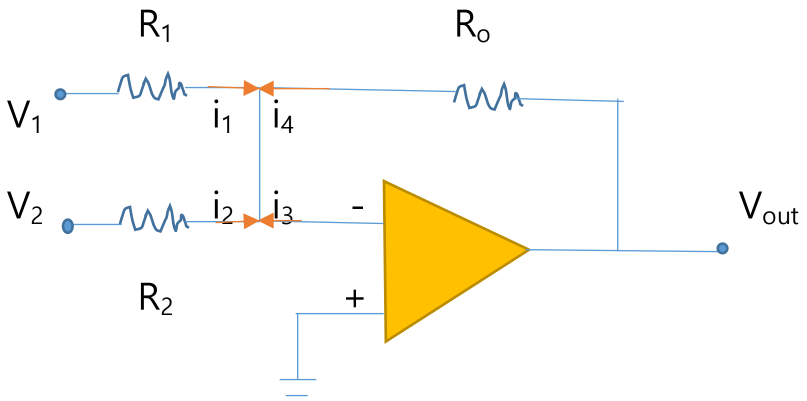
If $R_o>R_1$ then $|Gain|>1$ (Amplification)

If $R_o<R_1$ then $|Gain|<1$ (Attenuation)

If $R_o=R_1$ then Gain=-1 (Inverter or only Sign-change)

5. Summing amplifier

: To sum of voltages amplified



At the junction, $i_1+i_2+i_3+i_4=0$

$i_1=(V_1 - V^-)/R_1=V_1/R_1$; $i_2=(V_2 - V^-)/R_2=V_2/R_2$

$i_3=0$; $i_4=(V_{out} - V^-)/R_o=V_{out}/R_o$

$\therefore i_1+i_2+i_3+i_4=V_1/R_1+V_2/R_2+V_{out}/R_o=0$

Thus $V_{out}=-(R_o/R_1)V_1-(R_o/R_2)V_2 =-\{(R_o/R_1)V_1+(R_o/R_2)V_2\}$

∴ Sum of Voltages amplified

If $R_1=R_2=R_o=R$ then $V_{out}=-V_1-V_2=-(V_1+V_2)$: Adder

and V_1=Vs, V_2=DC_offset, then V_{out}=-(Vs+DC_offset) : DC biasing

If $R_1=R_2=2R$, $R_o=R$ then $V_{out}=-(V_1+V_2)/2$: Average

If $R_1=3R$, $R_2=3R/2$, $R_o=R$ then $V_{out}=-(V_1+2V_2)/3$: Weighing Average

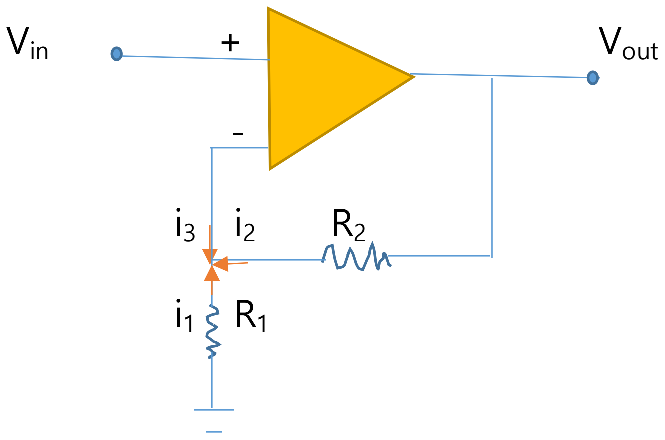
If $R_1=R/a$, $R_2=R/b$, $R_o=R$ then $V_{out}=-(aV_1+bV_2)$: Linear combination

If this circuit is extended to n inputs such as V_n voltage with R_n resistor

Then $V_{out}=-\Sigma(R_o/R_n)V_n$

6. Non-inverting Amplifier

: To amplify non-inverted voltage



At the Junction, $i_1+i_2+i_3=0$

$i_1=(0 - V^-)/R_1=- V_{in}/R_1$

$i_2=(V_{out} - V^-)/R_2=(V_{out} - V_{in}) / R_2$

$i_3=0$

$i_1+i_2+i_3=0= -V_{in}/R_1 + (V_{out} - V_{in}) / R_2$

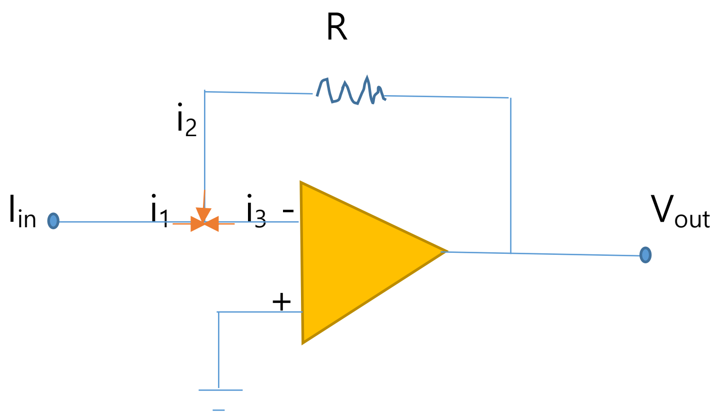
$\therefore V_{out}=(1 + R_2/R_1)V_{in}$

This is Non-inverting amplifier, Gain=$1+R_2/R_1 >1$

Thus the sign is not changed and amplification only

7. Current to Voltage Converter (C/V converter)

: To convert current to voltage with the refined Z_{in} and Z_{out}



At the junction, $i_1+i_2+i_3=0$

$i_1=I_{in}$, $i_2=(V_{out}-0)/R=V_{out}/R$, $i_3=0$

Thus $I_{in}+V_{out}/R=0$

$\therefore V_{out}= - I_{in}R$ and this is the current to voltage converter

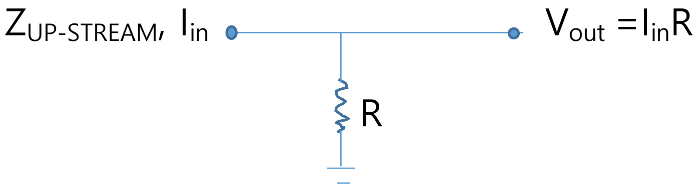
It is of interest to know the input impedance (Z_{in}), and output impedance (Z_{out}).

Input Impedance, $Z_{in}\fallingdotseq\infty$ ($\because Z_{in}\fallingdotseq Z^{-}\fallingdotseq\infty$)

Output Impedance, $Z_{out}\fallingdotseq 0$

$\therefore Z_{out}\ll Z_{in}$ can be achieved and thus it is a good device!

For comparison, a simple C/V (current to voltage) converter is



$Z_{in}=R$, $Z_{out}=Z_{up\text{-}stream} \parallel R$

Q) $Z_{out} \ll Z_{in}$ can be achieved?   Yes or No

Comparison is as follows;

⇒Simple C/V can be nicely driven only when $Z_{UP\text{-}STREAM} \ll Z_{in}$ *(=R)*

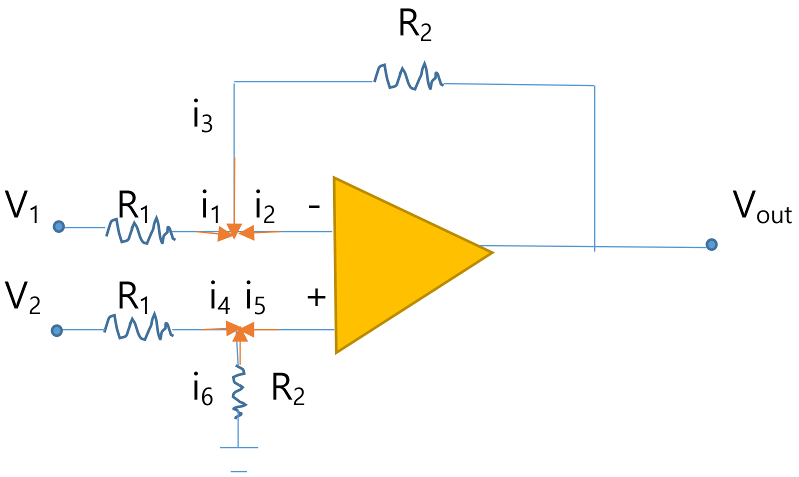
while OP Amp C/V can be driven by any up-stream circuit ($\because Z_{in} \fallingdotseq \infty$*)*

⇒Simple C/V can nicely drive only when $Z_{out} \ll Z_{LOAD}$

while OP Amp C/V can drive any down-stream circuit ($\because Z_{out} \fallingdotseq 0$*)*

∴*OP Amp C/V shows better performance with the "refined" impedance*

8. Differential Amplifier



At Lower Junction: $i_4+i_5+i_6=0$

$i_4=(V_2 - V^+)/R_1$; $i_5=0$; $i_6=(0- V^+)/R_2=-V^+/R_2$

$i_4+i_5+i_6=(V_2 - V^+)/R_1 - V^+/R_2=0 \therefore V^+ = R_2V_2/(R_1+R_2)$

At Upper Junction: $i_1+i_2+i_3=0$

$i_1=(V_1 - V^-)/R_1$; $i_2=0$; $i_3=(V_{out} - V^-)/R_2$

$i_1+i_2+i_3=(V_1 - V^-)/R_1+(V_{out} - V^-)/R_2=0$ and $V^-=V^+$

$\therefore V_{out}=-R_2V_1/R_1+(1+R_2/R_1)V-=(V_2 - V_1)R_2/R_1$

$\therefore$ Differential Amplifier with Gain$=R_2/R_1$

This is to amplify the voltage difference V_2-V_1

Ex) V_2=Signal + DC_offset, V_1=DC_offset

Then V_2-V_1=Signal, and it can be amplified with R_2/R_1 gain.