Operational amplifiers

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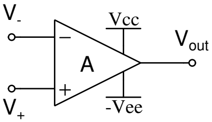
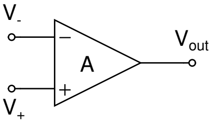
Operational amplifiers (Op-Amp)



$\Longleftrightarrow$

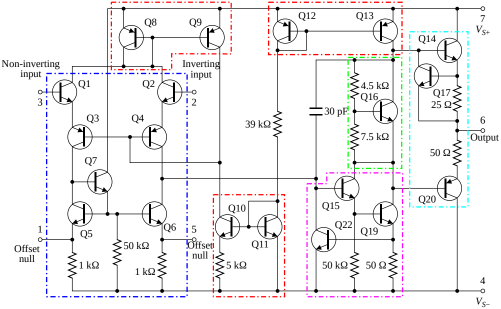


- $V_{out} = A(V_+ - V_-)$ thus sometimes called differential amplifiers
- A is open loop gain
  - A is frequency dependent
  - $A = 10^5 \dots 10^6$ at DC
  - $A \to 0$ at high frequency (roll off)
    this limits operational bandwidth (typically in MHz ... GHz range)
- input impedances are high $10^6 \dots 10^{14}$ Ω
- output impedances are low $0.1 \dots 10$ Ω
  - however output current usually limited to 10 mA
- **it is super easy to design with them**

If Op-Amps are so great why did we learn transistors?

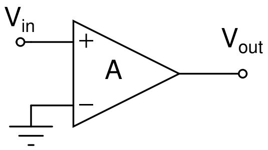
- sometimes one transistor is enough and op-amps are more expensive
- op-amps are made of transistors so to understand their limits we need to know how transistors behave
- op-amps require bipolar power supply
- remember that op-amps cannot source a lot of current/power while transistors can (recall our transistor controlled switch for a bulb)

LM741 (introduced in 1968) internal schematic



So, combine op-amps and transistors for a power circuits. Otherwise do your circuit with op-amps.

Very very bad amplifier !!!



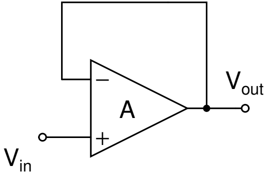
Gain

$$V_{out} = AV_{in}$$

But *A* depends on everything

- temperature
- power supply voltage
- input voltage
- frequency
- …and so on

Follower or Buffer



$$V_{out} = \frac{A}{A+1} V_{in}$$

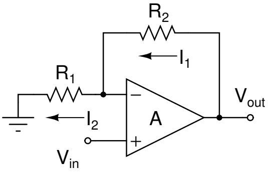
Gain and impedances of ideal Op-Amp ($A \gg 1$)

$$G_{ideal} = 1$$

$$Z_{in} = \infty, Z_{out} = 0$$

notice that with negative feedback $V_+ \approx V_-$

Non-inverting amplifier



$$V_{out} = \left(1 + \frac{R_2}{R1}\right) V_{in} \frac{A}{A + (1 + \frac{R_2}{R_1})}$$

Gain and impedances of ideal Op-Amp ($A \gg 1$)

$$G_{ideal} = 1 + \frac{R_2}{R_1}$$

$$Z_{in} = \infty, Z_{out} = 0$$

notice that with negative feedback $V_+ \approx V_-$

Op-amps golden rules

If negative feedback is applied and $A(f) \gg 1$ (open circuit gain at the frequency of interest) and Op-amp is not in saturation

- there is no current into the inputs
- $V_- = V_+$

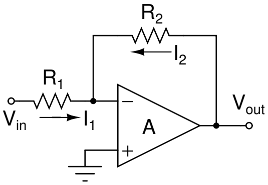
Gain of non ideal Op-Amp ($A \not\gg 1$)

$$G = G_{ideal} || A = \frac{G_{ideal} A}{G_{ideal} + A}$$

How to see if we are in saturation or not. If using above rules we calculate that the expected output voltage is within the supply rails (usually we need to take away a diode voltage drop from each supply level) then we are OK and not in the saturation regime.
All good (no saturation) if

$$-V_{ee} < V_{out_{expected}} < V_{cc}$$

Inverting amplifier



Gain and impedances of ideal Op-Amp ($A \gg 1$)

$$G_{ideal} = -\frac{R_2}{R_1}$$

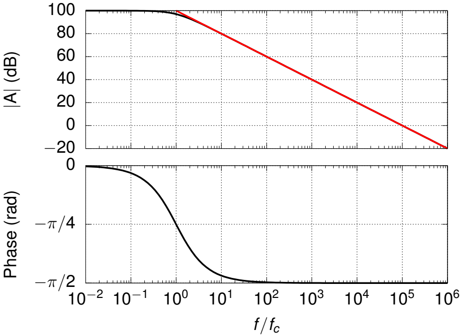
$$Z_{in} = R_1, Z_{out} = 0$$

notice that with negative feedback $V_+ \approx V_-$

Open loop gain

Generally open loop gain has frequency dependence mimicking the low-pass filter

$$A(f) = \frac{A_o}{1 + i\frac{f}{f_c}}$$



Here

A_o is DC gain, i.e. at zero frequency. It is typically greater then 10^5

f_c is the cutoff frequency (knee location in loglog plot), it is typically around 10 Hz

Gain bandwidth (GBW) product

The bandwidth (BW) of the amplifier is the frequency range at which its gain is approximately constant

$$G_{ideal}BW = A_o f_C = GBW$$

The right part $A_o f_c$ depends only on properties of the Op-Amp, and usually is called the gain bandwidth (GBW) product in the data sheets. It is measured in Hz.
Within the bandwidth

$$G(f) \approx G_{ideal}$$

outside the bandwidth

$$G(f) < G_{ideal}$$

and can drop to very low values