Jim Siegrist
Phone: 486-4397
Email: JLSiegrist@lbl.gov
Room (at LBL): 50-4055

Advice:

Today:	lec 7	OP AMP I	
	lec 8	TH	Feb 22
	lec 9	TH	Mar 8 – Note Dates!
	lec 10	TH	Mar 15 – Note Dates!

NB: problems 8.12 – 8.13 → supplementary
Report labs posted.

Concepts

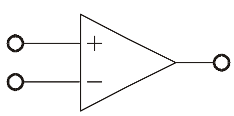
Op-Amps

$IC's\ with\quad R_i > \sim 10^4\,\Omega$

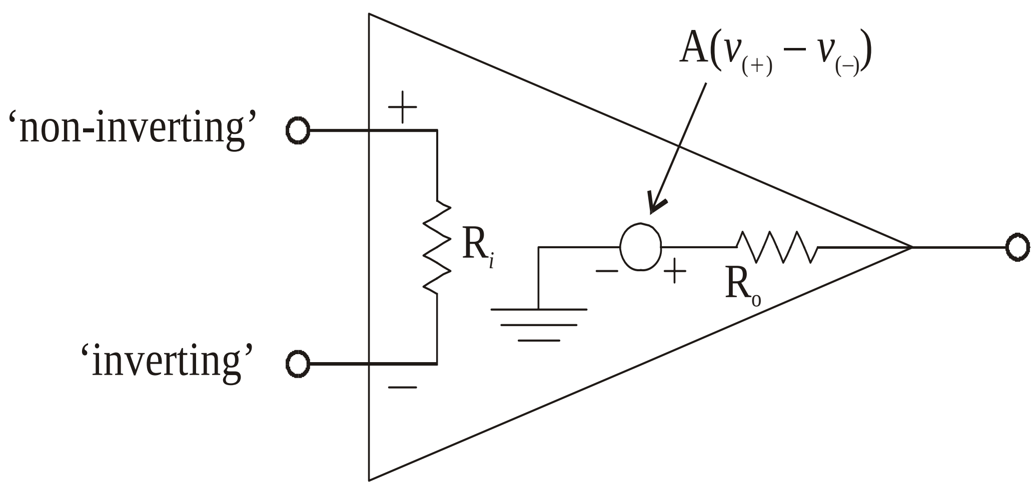
$R_o < \sim 50\Omega$

$gain \sim 10^4\ or\ so$

rugged, inexpensive building block to make actual circuits.

Special Symbol: 

MODEL:



+ Power supply, trim voltage connections, hook up power and ground or nothing happens!!

Feedback

Op-amps usually connected in feedback circuits. Literally, a bit of the output signal is 'fed back' to the input:

Negative Feedback

decrease the output when it is too high
increase the output when it is too low

Positive Feedback

increase output when it is too high
decrease output when it is too low
$\Rightarrow$ oscillations, generally bad

Use of (negative) feedback elements external to the op-amp reduces sensitivity to device variation (as we shall see) – very important.

Path that returns some of the output to the input is the feedback loop $\Rightarrow$ A = 'open loop' gain

To avoid using the detailed model, consider ideal op-amp: A, $R_i \to \infty$, $R_o \to 0$

$\Rightarrow$ Assume potential difference between the two input terminals $v_{(+)} - v_{(-)} = 0$ & the two input currents both = 0.

Why? $|v_{out}|$ is limited by supply voltage. From the model,

$$|v_{out}| = A|v_{(+)} - v_{(-)}| < |V_{supply}|$$

$$\Rightarrow |v_{(+)} - v_{(-)}| < \frac{V_{supply}}{A} \to 0 \quad A \to \infty$$

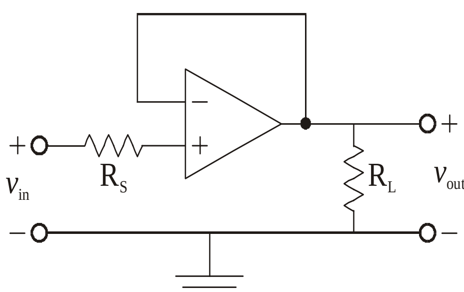
$$\& \quad i_{in} = \frac{v_+ - v_-}{R_i}, \; R_i \to \infty, \; v_+ - v_- \to 0$$

$$\Rightarrow i_{in} = 0$$

Circuit Analysis

Examples

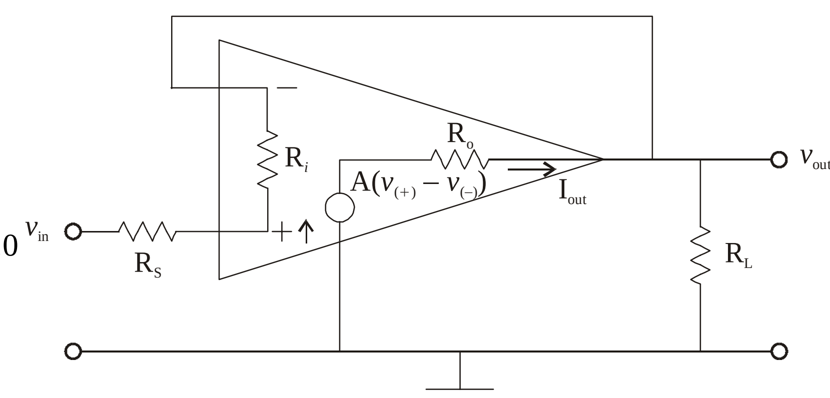
1) Voltage follower:



Note, ideal model:

$$v_{out} = v_- = v_+ = v_{in} \Rightarrow$$

$$A' = \frac{v_{out}}{v_{in}} = \text{`closed loop' gain} = 1.0$$



Exact value? – use model

node equation at + node: $\frac{v_{in} - v_+}{R_S} + \frac{v_+ - v_{out}}{R_i} = 0$ (1)

but $v_{out} = I_{out} \cdot R_L$

$$v_{out} = \frac{A(v_+ - v_-)}{R_o} \cdot R_L$$

but $v_- = v_{out} \Rightarrow v_{out} = A(v_+ - v_{out}) \cdot \frac{R_L}{R_o}$

solve for $v_+ \Rightarrow \frac{R_o}{AR_L} v_{out} + v_{out} = v_+$

substitute into (1) $\Rightarrow \frac{v_{in} - v_{out} - \frac{R_o}{AR_L} v_{out}}{R_S} + \frac{v_{out} + \frac{R_o}{AR_L} v_{out} - v_{out}}{R_i} = 0$

$$\frac{v_{in}}{R_S} - \frac{v_{out}}{R_S} - \frac{R_o}{AR_L R_S} v_{out} + \frac{R_o}{AR_L R_i} v_{out} = 0$$

$$v_{in} = v_{out}\left(1 + \frac{R_o}{AR_L} - \frac{R_o R_S}{AR_L R_i}\right)$$

$$v_{out} = v_{in} \frac{AR_L R_i}{AR_L R_i + R_o R_i - R_o R_S} \Rightarrow$$

$$A' = \frac{v_{out}}{v_{in}} \approx 1 - \frac{R_o(R_i - R_S)}{AR_L R_i} \approx 1$$

$R_o \sim 50\,\Omega$
$R_S \sim 50\,\Omega$
$R_L \sim 1k$
$R_i \sim 10k$
$A \sim 10k$

Note: Let $R_S \to 0$

$\frac{R_o}{R_L} \to 1$ as $R_o \to 0$, $R_L \to \infty$

then my expression reduces to $A' \approx 1 - \frac{1}{A}$, same as equation 8.3, page 311 S&S.

Should note: $A' = 1$ did not depend on op-amp parameters (A, R_i, R_o), so it is very probably accurately enough known by the ideal model.

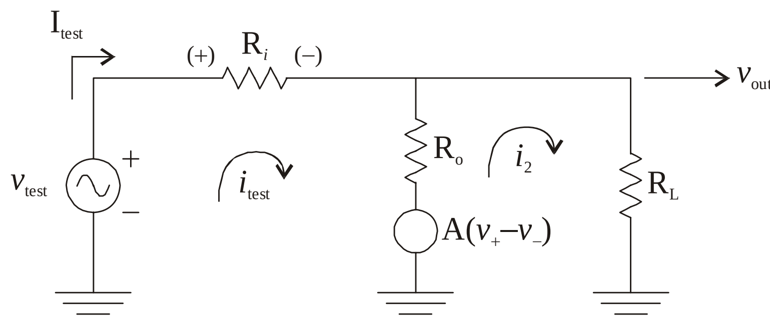
Input & Output Impedance

Input

Apply V_{test} at input terminals; get equivalent input resistance from V_{test}/I_{test}

N.B. This <u>will</u> depend on A, R_i, etc. so we have to resort to the model:
(To see that, $i_{test} = 0$ in ideal model $\Rightarrow R_i = \infty$)

To obtain a better value:
(ignore R_S)



Go around 1st loop:

$$v_{test} - i_{test}R_i - R_o(i_{test} - i_2) - A(v_{(+)} - v_{(-)}) = 0$$

2nd loop:

$$A(v_{(+)} - v_{(-)}) - R_o(i_2 - i_{test}) - i_2 R_L = 0$$

<u>but</u> $v_+ = v_{test}$, $v_{(-)} = v_{test} - i_{test}R_i \Rightarrow$

(1) $v_{test} - i_{test}R_i - R_o(i_{test} - i_2) - A(v_{test} - v_{test} + i_{test}R_i) = 0$

(2) $A(v_{test} - v_{test} + i_{test}R_i) - R_o(i_2 - i_{test}) - i_2 R_L = 0$

solve (2) for $i_2 \Rightarrow$ $i_2 = \dfrac{i_{test}(AR_i + R_o)}{R_o + R_L}$

put back in (1) $\Rightarrow$

$$v_{test} - i_{test}(R_o + (1+A)R_i) + R_o\left[\frac{i_{test}(AR_i + R_o)}{R_o + R_L}\right] = 0$$

$$v_{test} = i_{test}\left[\frac{[R_o + (1+A)R_i](R_o + R_L) - R_o[R_o + AR_i]}{R_o + R_L}\right]$$

$$R_i' = \frac{v_{test}}{i_{test}} = R_o + (1+A)R_i - \frac{R_o}{R_o + R_L}[R_o + AR_i]$$

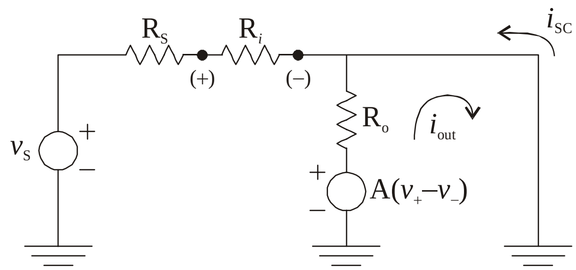
$$= R_i(1+A) + R_o\left[1 - \frac{R_o + AR_i}{R_o + R_L}\right]$$

$$R_i' \approx R_i A \sim 10^{10}\,\Omega \,! \approx \infty$$

<u>Output Impedance</u>

$R'_o = -\frac{v_{oc}}{i_{sc}}$ since $v_+ = v_-$, $v_{oc} = v_{in}$ (ideal model)

i_{sc} is given by:



Note v_- is grounded ⇒

$$i_{out} = -i_{sc} \approx A\frac{(v_+)}{R_o}$$

ignore current from input

$$= A\frac{v_{in}}{R_o}$$

$$\Rightarrow R'_o = -\frac{v_{oc}}{i_{sc}} = \frac{v_{in}}{A[{v_{in}}/{R_o}]}$$

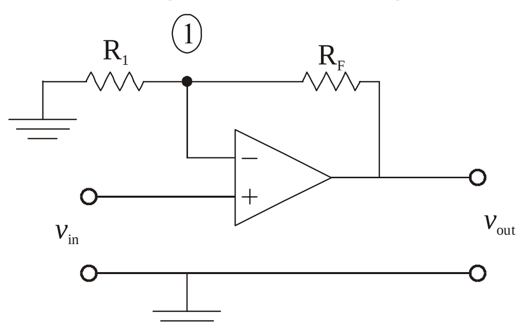
$$= \frac{R_o}{A} \sim 10^{-3}\Omega \approx 0$$

Very good emitter follower.

⇒ Buffer circuit to isolate one part of the circuit from another.

<u>Example 2</u> (1 = follower)

<u>Non-Inverting Amplifier</u> (gives voltage gain)



Like follower, but a voltage divider in the feedback path.

$v_- = v_{in} = v_+$

No current flows into the amp ⇒ at node (1)

$$\frac{v_{in}}{R_1} + \frac{v_{in} - v_{out}}{R_F} = 0$$

$$\Rightarrow v_{out} = \frac{R_1 + R_F}{R_1} v_{in}$$

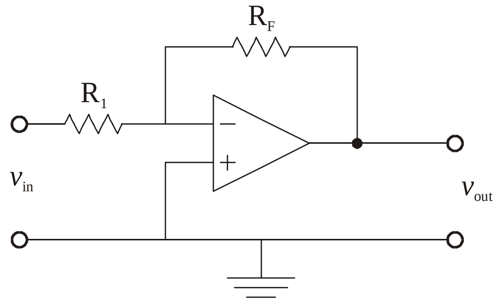
$$\Rightarrow A' = \frac{v_{out}}{v_{in}} = \frac{R_1 + R_F}{R_1}$$

One finds (like follower) $R_i' = \overbrace{AR_i\left(\frac{R_1}{R_1 + R_F}\right)}^{follower\_+\_new\_term}$

$$R_o' = \frac{R_o}{A}\left(\frac{R_1 + R_F}{R_1}\right)$$

Example 3

Inverting Amplifier



Voltage at (−) = 0

⇒ current through R_1 goes through R_F

⇒ (none goes into amplifier)

$$\frac{v_{in}}{R_1} + \frac{v_{out}}{R_F} = 0$$

$$\Rightarrow A' = \frac{v_{out}}{v_{in}} = -\frac{R_F}{R_1} \qquad \text{(inverting amp)}$$

$$v_{out} = -\frac{R_F}{R_1} v_{in} \qquad \overbrace{R_F = R_1 \Rightarrow unity\ \ gain\ inverter}^{\uparrow}$$

Input & Output Impedance:

Input

$$i_{test} = \frac{v_{test}}{R_1} \Rightarrow R_i' = R_1$$

Output

turns out to be $R_o' = \frac{R_o}{A} \frac{(R_F + R_1 + R_S)}{(R_1 + R_S)}$