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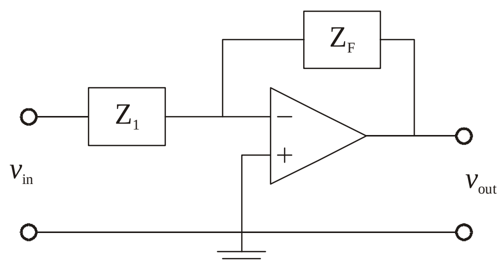
Advice:

Today: lec 9 OP AMP III
lec 10 TH Mar 15
lec 11 TH Mar 22
lec 12 TUE Apr 3 Last Lecture!!

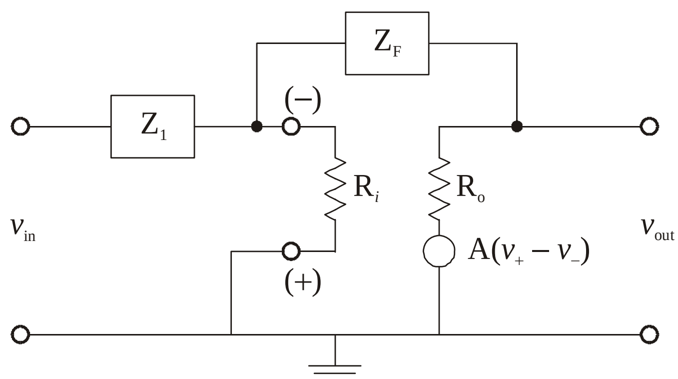
Final project proposals (< ½ page) due Monday, March 19. I sign off, talk to TA's first.
Problems 8.12, 8.13 → supplementary.

Circuit Analyses

Frequency Response, General Circuit



Substitute the op-amp model: (A = A(ω) → small at large ω)



Node equations at v_- and v_{out}:

$$(1)\quad \frac{v_- - v_{in}}{Z_1} + \frac{v_- - v_{out}}{Z_F} + \frac{v_-}{R_i} = 0$$

$$(2)\quad \frac{v_{out} - v_-}{Z_F} + \frac{v_{out} - A(0 - v_-)}{R_o} = 0$$

$$A' = \frac{v_{out}}{v_{in}}$$

Solve (2) for v_- in terms of $v_{\text{out}} \Rightarrow$

$$v_{out}\left(\frac{1}{Z_F}+\frac{1}{R_o}\right)+v_-\left(\frac{A}{R_o}-\frac{1}{Z_F}\right)=0$$

$$\Rightarrow v_- = \frac{v_{out}}{\left(Z_F \parallel R_o\right)\left(\frac{1}{Z_F}-\frac{A}{R_o}\right)}$$

From (1),

$$v_-\left(\frac{1}{Z_1}+\frac{1}{Z_F}+\frac{1}{R_i}\right)-\frac{v_{out}}{Z_F}=\frac{v_{in}}{Z_1}$$

$$\Rightarrow v_{out}\left[\left(\frac{1}{Z_1}+\frac{1}{Z_F}+\frac{1}{R_i}\right)\frac{1}{\left(Z_F \parallel R_o\right)\left(\frac{1}{Z_F}-\frac{A}{R_o}\right)}-\frac{1}{Z_F}\right]=\frac{v_{in}}{Z_1}$$

$$\Rightarrow A' = \frac{v_{out}}{v_{in}} = -\frac{Z_F}{Z_1}\left[\frac{1}{1-\left(\frac{1}{Z_1}+\frac{1}{Z_F}+\frac{1}{R_i}\right)\left(\frac{1}{Z_F}+\frac{1}{R_o}\right)\frac{Z_F}{\left(\frac{1}{Z_F}-\frac{A}{R_o}\right)}}\right]$$

$$= -\frac{Z_F}{Z_1}\left[\frac{1}{1-\left(\frac{1}{Z_1}+\frac{1}{Z_F}+\frac{1}{R_i}\right)\left(R_oZ_F+Z_F^2\right)\frac{1}{\left(R_o-AZ_F\right)}}\right]$$

$$\lim R_o \to 0,\; R_i \to \infty \quad \to$$

$$= -\frac{Z_F}{Z_1}\left[\frac{1}{1+\left(\frac{1}{Z_1}+\frac{1}{Z_F}\right)\frac{Z_F}{A}}\right] = -\frac{Z_F}{Z_1}\left[\frac{A}{A+1+\frac{Z_F}{Z_1}}\right]$$

As gain gets small,

$$A' \sim -\frac{Z_F A}{Z_1}\frac{Z_1}{Z_F + Z_1}$$
$$\sim \frac{-AZ_F}{Z_F + Z_1} \to 0$$

Also, just rearranging terms,

$$A' = \frac{A\left(-\frac{Z_F}{Z_1}\right)\left(\frac{Z_1}{Z_1+Z_F}\right)}{A+\left(\frac{Z_1+Z_F}{Z_1}\right)\left(\frac{Z_1}{Z_1+Z_F}\right)} = \frac{A\left(\frac{-Z_F}{Z_1+Z_F}\right)}{1+A\left(\frac{Z_1}{Z_1+Z_F}\right)}$$

Stability

Instability most often occurs when output appears for no input → oscillations.
Signal suffers a phase shift passing through amp.

Typically,

~ 0 at low frequency
increases at higher frequencies
→ −1 at 180° ⇒
negative feedback at low ν becomes positive at high ν

General form for gain ~

$$A' = \frac{c(\omega)A(\omega)}{1 + A(\omega)f(\omega)}$$

$c(\omega)$ depends on form of circuit
$f(\omega)$ is called feedback coefficient
if $A(\omega)f(\omega) = -1$ (for some ω), instability results

Turns out, if $|Af| \geq 1$ for ω whose phase shift is −180°, instability occurs (Nyquist Criterion)

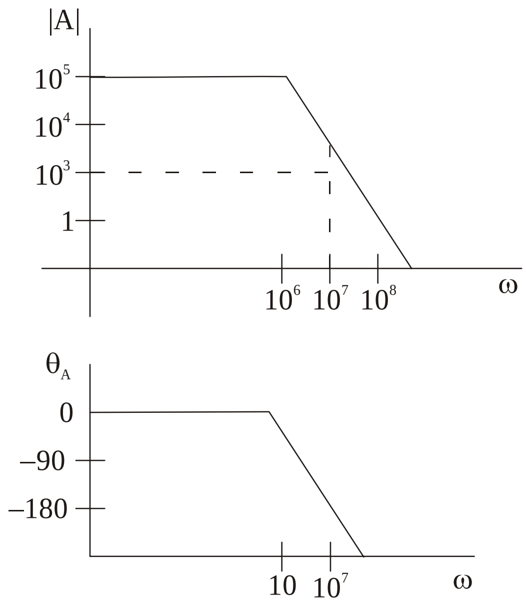
For voltage follower, (last time)

$$A' = \frac{A}{1+A} \Rightarrow c = f = 1$$

$$\& \Rightarrow c = \frac{-Z_F}{Z_1 + Z_F}$$

$$f = \frac{Z_1}{Z_1 + Z_F}$$ for inverter (see previous pg)

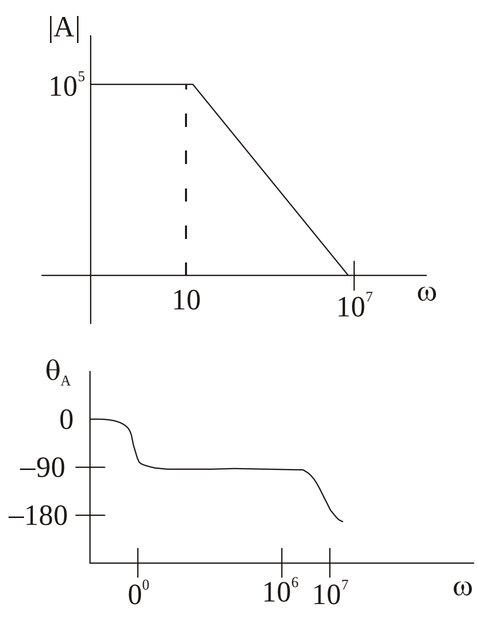
Suppose: (follower)



$-180° \Rightarrow \omega \sim 10^7$

A = gain ~ 10^4 at $10^7 \Rightarrow |Af| >> 1 \Rightarrow$ oscillations

<u>Op-Amp design:</u>



$\omega \sim 10^7$, $|A| \sim +10^{-1} \Rightarrow$ stable

Obtain by putting RC filter someplace in op-amp

(rolloff at $|A|$ 20db/decade, phase shift of 90°)

More phase shifts from stray capacitance at higher ν, but $|A|$ already < 1

emphasize ⇒ <u>why leads must be short, circuits neat</u>

Summary of Op-Amp

- Op amps are cheap, versatile, and form building blocks for circuits

$$A = \infty$$

- Ideal op-amp: $R_i = \infty$

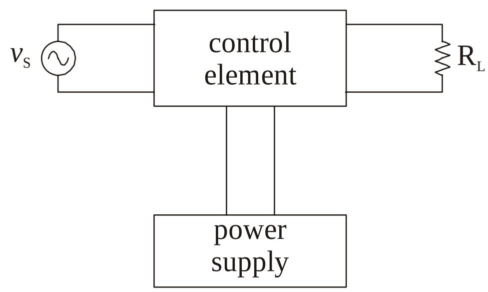
$$R_o = 0$$

- Offsets
- MSR
- Negative feedback provides de-sensitivity of op-amp characteristics
- Limited frequency response – pass band with negative feedback much larger
- Improper feedback ⇒ oscillations

Instruments & Devices

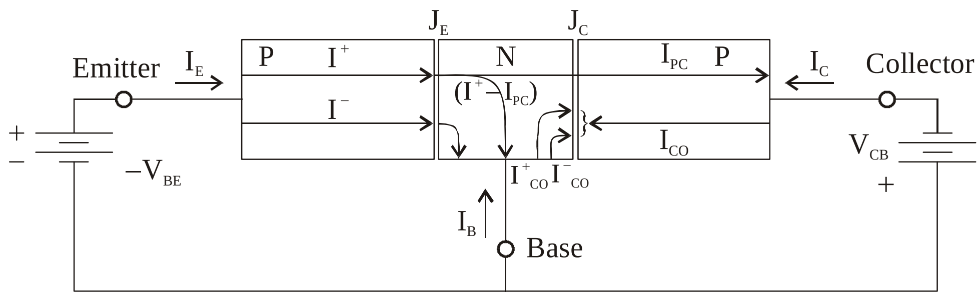
Transistors

Transistors are control elements



Take a small input signal & amplify it, with the power to do so coming from the external DC sources.

Bipolar: current-operated, 3-terminal device consisting of one forward & one reverse biased diode, with base region in common



Emitter-Base is forward biased by (−)V_{BE} ⇒

Majority carriers (hole) are injected into base where they drift to collector. (I^+) (diffusion gradient)

Electron current (I^-) from base to emitter is made small by construction (doping – emitter much more heavily doped)

Total emitter current $= I_E = I^+ + I^-$

Some holes reach collector, rest are recombined in the base.

$I^+ - I_{pc}$ go out though base

I_{pc} go to collector

Reverse current I_{co} from collector to base

I_{co}^+ = holes moving from N to P across J_c

I_{co}^- = electrons moving from P to N across J_C

$-I_{co} = I_{co}^+ + I_{co}^-$ – sign convention so I_{co} in direction I_c

Holes generated thermally within the base

Total collector current:

$I_c = I_{co} - I_{pc} \equiv I_{co} - \alpha I_E$

or

$\alpha \equiv -\frac{I_c - I_{co}}{I_E}$ large-signal current gain

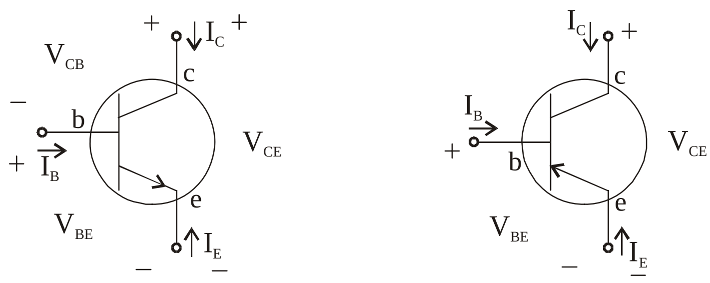
α always > 0, ranges from .90 – .998, varies with I_E, V_{CB}, temperature

Also, $\beta \equiv \frac{\alpha}{1-\alpha}$; in CE configuration,

$I_c \sim \beta I_{base}$

$\Rightarrow \beta$ is current gain of the device; current operated device!!

Circuit Symbols:



N-P-N P-N-P

Identical, arrow opp.

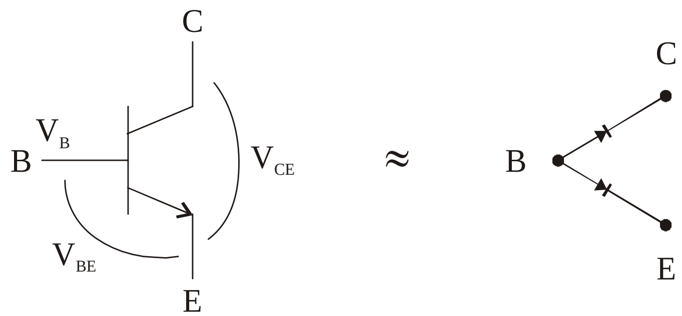
[Current in emitter is positive in the direction of the arrow on the emitter lead]

3 terminals $\Rightarrow$ 6 ways to connect

Closing Comments:

* $V_{CE} > 0$, collector more positive than emitter

*



* max power dissipation, etc.
  limits on I_C, I_B, V_{CE}
  $P_{max} = (I_C\ V_{CE})_{max}$

* $V_B \sim V_E + .6$ in active gain region (when 'on')
  $= V_E + V_{BE}$

* $I_C \approx \beta I_B$

  current operated device

  detailed use of this in lecture 11 – push-pull case