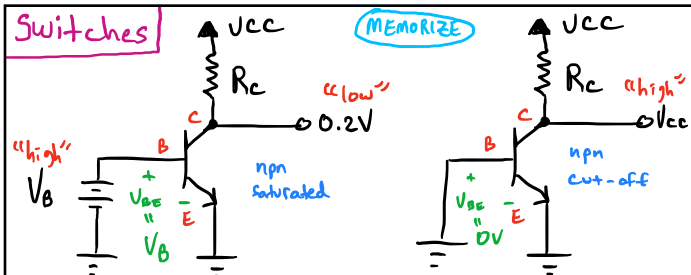
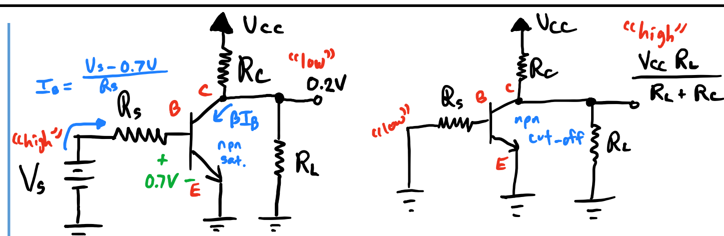
Switches



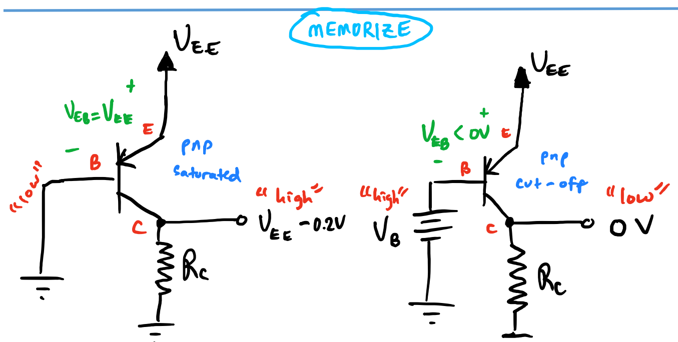
condition for saturation:
$V_B > 0.7\ V$

npn switch (no source/load impedance)



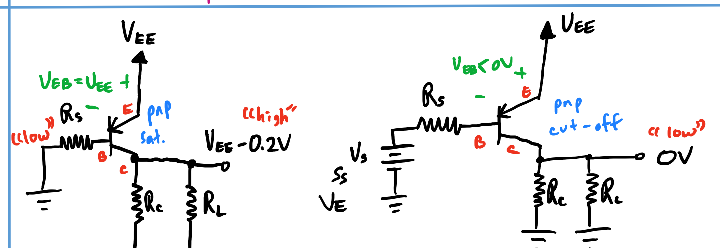
condition for saturation:
$\frac{V_s - 0.7}{R_s}\beta > \frac{V_{cc} - 0.2V}{R_c}$
$\Rightarrow V_s > V_{cc}\left(\frac{R_s}{\beta R_c}\right) + 0.7V$

npn switch (with source/load impedances)



pnp switch (simple)

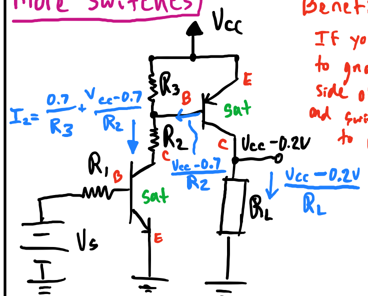
condition for cut-off
$V_B \geq V_{EE}$



condition for cut-off:
$V_s \geq V_{EE} - 0.7\ V$

pnp switch (with source/load impedances)

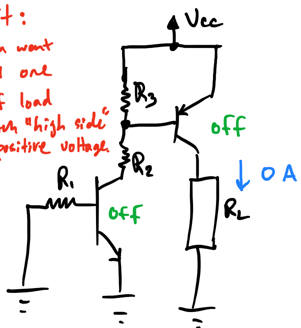
More switches



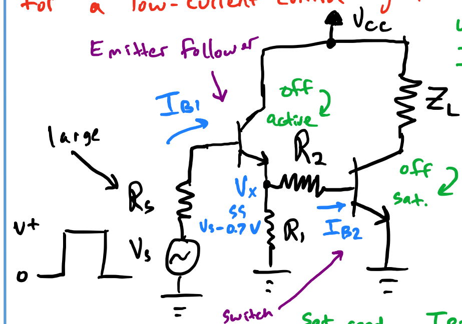
condition for saturation:

$$\frac{V_s - 0.7V}{R_1} > \frac{0.7}{R_3} + \frac{V_{cc}-0.7V}{R_2}$$

Benefit:
If you want to gnd one side of load and switch "high side" to positive voltage



Putting emitter follower in front of switch makes it easy for a low-current control signal to switch a high-current load.



When $V_s = V^+$:

$$I_{B_1} = \frac{V^+ - 0.7\frac{R_1}{R_1+R_2}}{R_s + \beta R_1 \| R_2}$$

$$\simeq \frac{V^+ - 0.7V}{R_s + \beta R_2} \quad (R_1 \gg R_2)$$

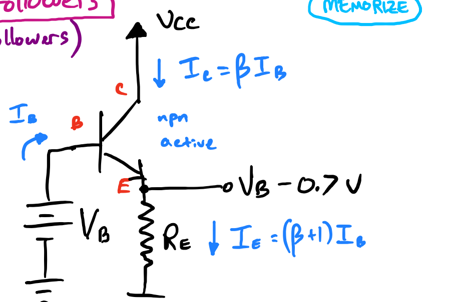
$$V_x \simeq V_s - 0.7\,V$$

$$I_{B2} \simeq \frac{V_s - 1.4V}{R_2}$$

Sat cond. $I_{B2} > V_{cc}/Z_L$

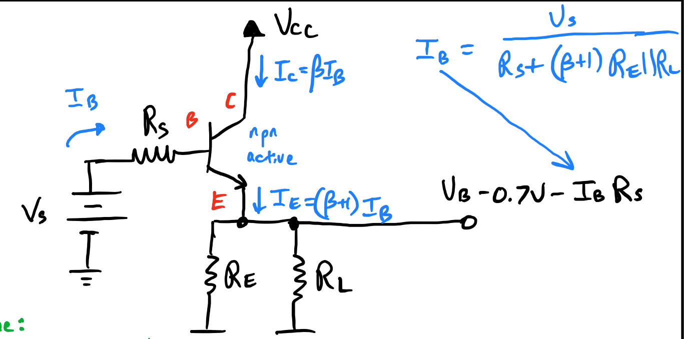
Voltage Followers
(Emitter followers)

MEMORIZE



Assume: $V_B < V_{CC}$, $V_B > 0.7V$

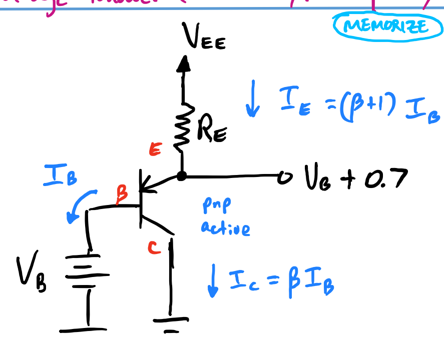
npn voltage follower (no source/load impedances)



Assume: $0.7V < V_s - I_B R_s < V_{CC}$

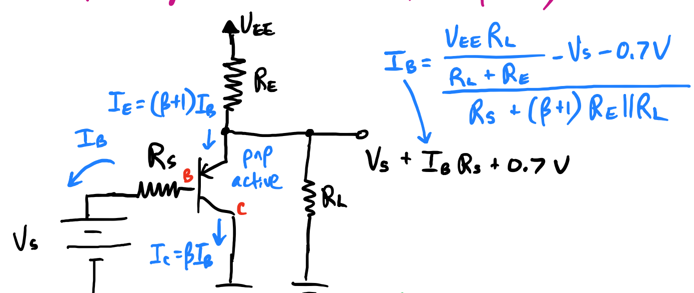
npn voltage follower (with source/load impedances)

MEMORIZE



Assume: $V_B < V_{EE}$

pnp voltage follower (no source/load impedances)



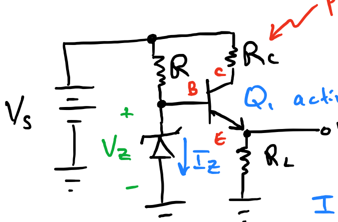
Assume: $0 < V_s + I_B R_s < V_{EE} - 0.7V$

pnp voltage follower (with source/load impedances)

More voltage followers

(Emitter followers)

protect Q_1 by limiting max current



$V_o = V_Z - 0.7V$

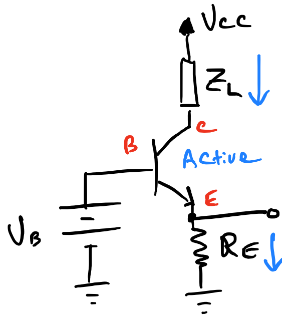
$$I_Z \approx \frac{V_s - V_Z}{R} - \frac{V_Z - 0.7V}{\beta R_L}$$

To keep Q_1 from saturating:

$$\frac{V_Z - 0.7V}{R_L} < \frac{V_S}{R_C}$$

Current sources

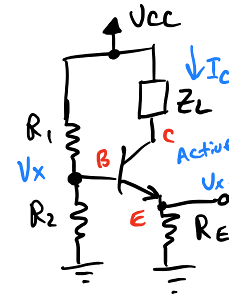
Memorize



$I_C = \alpha I_E \simeq I_E$

$I_E = \frac{V_B - 0.7V}{R_E}$

npn Active condition: $(V_B - 0.7V)/R_E < \frac{V_{CC}}{Z_L}$



If $\beta R_E >> R_1 \| R_2$:

$V_x = \frac{V_{CC} R_2}{R_1 + R_2}$

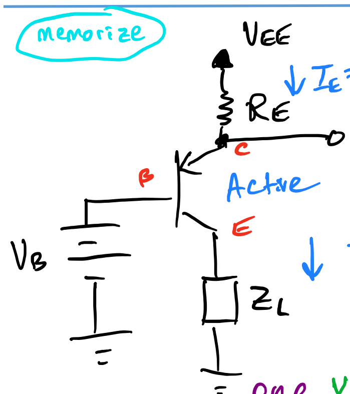
$I_E = \frac{V_x - 0.7V}{R_E}$

$I_C = I_E \cdot \alpha \simeq I_E$

Active condition: $V_x > 0.7V$

npn $(V_x - 0.7V)/R_E < V_{CC}/Z_L$

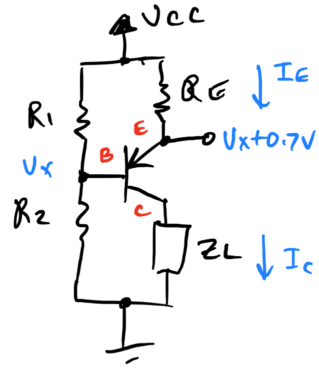
Memorize



$I_E = \frac{V_{EE} - (V_B + 0.7V)}{R_E}$

$I_C = \alpha I_E \simeq I_E$

pnp Active condition: $\frac{V_{EE} - (V_B + 0.7V)}{R_E} < \frac{V_{EE}}{R_E + Z_L}$

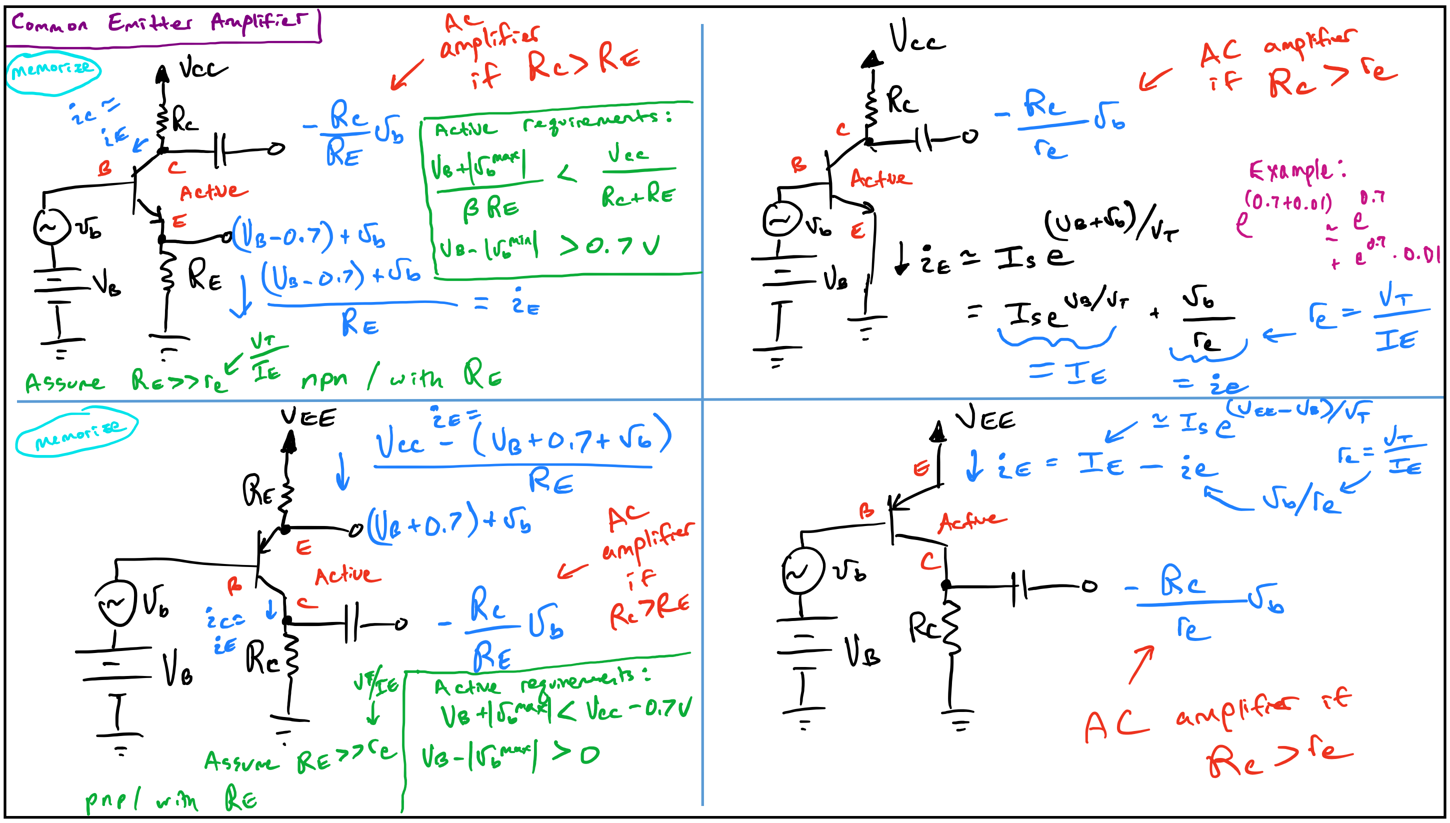


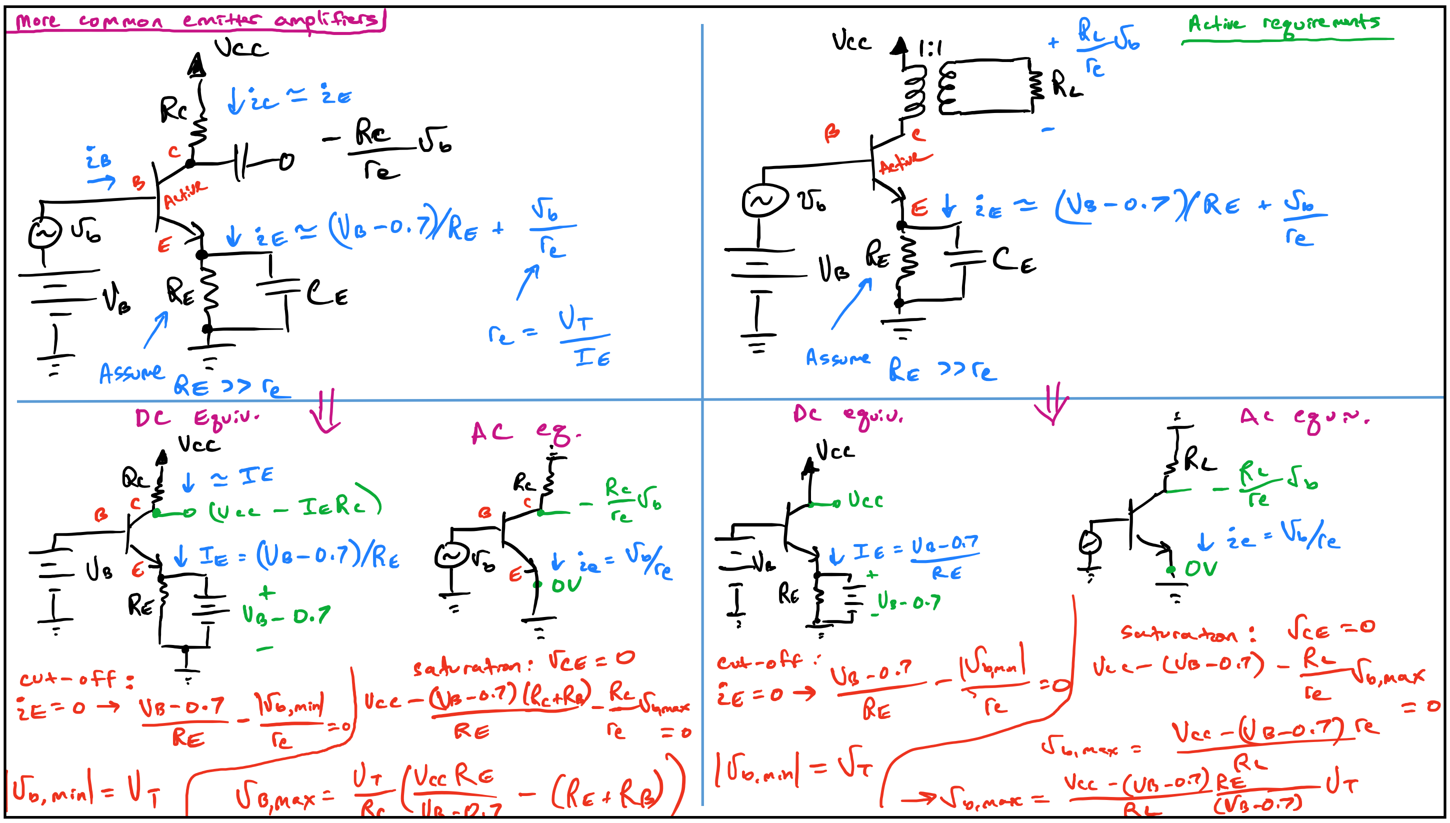
Assume $\beta R_E >> R_1 \| R_2$

$V_x = \frac{V_{CC} R_2}{R_1 + R_2}$

$I_E = \frac{V_{CC} - (V_x + 0.7V)}{R_E}$

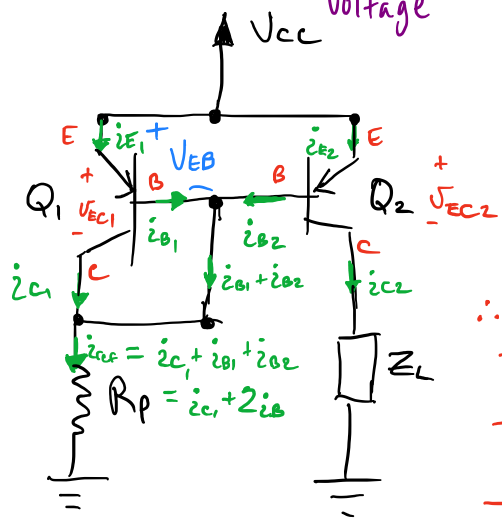
$I_C = I_E \cdot \alpha \simeq I_E$


Common Emitter Amplifier
memorize
Vcc
Rc
iC ≃ iE
B
C
E
Active
vb
VB
RE
−(Rc/RE) vb
AC amplifier if Rc > RE
(VB − 0.7) + vb
↓ ((VB − 0.7) + vb)/RE = iE
Active requirements:
(VB + |vb max|)/(β RE) < Vcc/(Rc + RE)
VB − |vb min| > 0.7 V
Assume RE >> re ← VT/IE
npn / with RE
−(Rc/re) vb
AC amplifier if Rc > re
↓ iE ≃ Is e^((VB+vb)/VT)
= Is e^(VB/VT) + vb/re
= IE
= ie
re = VT/IE
Example:
e^(0.7+0.01) ≃ e^0.7 + e^0.7 · 0.01
memorize
VEE
iE = (Vcc − (VB + 0.7 + vb))/RE
(VB + 0.7) + vb
iC ≃ iE
−(Rc/RE) vb
AC amplifier if Rc > RE
Active requirements:
VB + |vb max| < Vcc − 0.7 V
VB − |vb max| > 0
VT/IE
Assume RE >> re
pnp / with RE
↓ iE = IE − ie
≃ Is e^((VEE−VB)/VT)
vb/re
re = VT/IE
−(Rc/re) vb
AC amplifier if Rc > re


More common emitter amplifiers
Vcc
Rc
iC ≃ iE
iB
B
C
E
Active
− Rc/re vb
vb
VB
RE
CE
iE ≃ (VB − 0.7)/RE + vb/re
re = VT/IE
Assume RE >> re
Vcc
1:1
+ RL/re vb
RL
Active requirements
B
C
Active
E
iE ≃ (VB − 0.7)/RE + vb/re
vb
VB
RE
CE
Assume RE >> re
DC Equiv.
Vcc
Rc
≃ IE
(Vcc − IERc)
IE = (VB − 0.7)/RE
VB
RE
+ VB − 0.7 −
AC eq.
Rc
− Rc/re vb
vb
ie = vb/re
0V
cut-off:
iE = 0 → (VB − 0.7)/RE − |vb,min|/re = 0
|vb,min| = VT
saturation: vCE = 0
Vcc − (VB − 0.7)(Rc + RE)/RE − Rc/re vb,max = 0
vB,max = VT/Rc (Vcc RE/(VB − 0.7) − (RE + RB))
DC equiv.
Vcc
Vcc
IE = (VB − 0.7)/RE
VB
RE
+ VB − 0.7 −
AC equiv.
RL
− RL/re vb
ie = vb/re
0V
cut-off:
iE = 0 → (VB − 0.7)/RE − |vb,min|/re = 0
|vb,min| = VT
Saturation: vCE = 0
Vcc − (VB − 0.7) − RL/re vb,max = 0
vb,max = (Vcc − (VB − 0.7)) re/RL
→ vb,max = (Vcc − (VB − 0.7))/RL · RE/(VB − 0.7) · VT

Current Mirror

ignoring Early voltage



Recall: $i_B = \left(\frac{I_s}{\beta}\right) e^{v_{BE}/V_T}$

since $v_{BE1} = v_{BE2} \rightarrow i_{B1} = i_{B2} \equiv i_B$

$i_{ref} = i_{C1} + i_{B1} + i_{B2}$

$\rightarrow i_{ref} = i_{C1} + 2 i_B$

$v_{EC1} = 0.7\,V \ll |V_A|$

$$i_{C1} = I_s e^{v_{EB1}/V_T}\left(1 + \frac{v_{EC1}}{|V_A|}\right)$$

$$\simeq I_s e^{v_{EB1}/V_T} = \beta i_B$$

$\therefore$

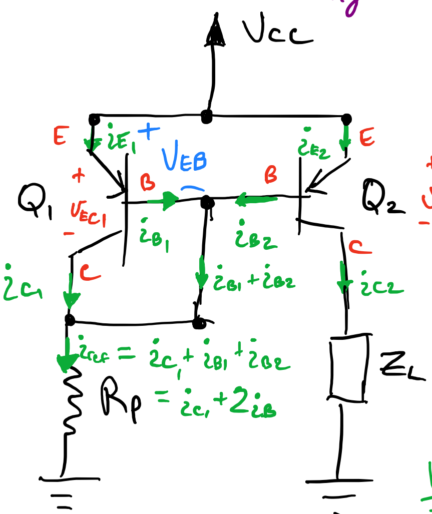
$\rightarrow i_{ref} = i_{C1} + 2 i_B \rightarrow i_{\rho} = (2 + \beta) i_B$

$\rightarrow i_{ref} = \frac{V_{CC} - v_{EB}}{R_P} \quad \rightarrow i_B = \frac{i_{ref}}{2 + \beta}$

$\rightarrow i_{C2} = \beta i_B = \frac{\beta i_{ref}}{2 + \beta} \rightarrow i_{C2} = \frac{i_{ref}}{\frac{2}{\beta} + 1}$

Current Mirror

Taking into account Early voltage



$\rightarrow i_{ref} = i_{C_1} + 2 i_B \rightarrow i_p = (2 + \beta_o) i_B$

$\rightarrow i_{ref} = \dfrac{V_{CC} - v_{EB}}{R_p}$ $\rightarrow i_B = \dfrac{i_{ref}}{2 + \beta_o}$

$\rightarrow i_{C2} = \beta_o i_B \left(1 + \dfrac{v_{EC2}}{|V_A|}\right) = \beta_o i_B \left(1 + \dfrac{V_{CC} - i_{C2} Z_L}{|V_A|}\right)$

$\rightarrow i_{C2} = \dfrac{\beta_o i_B \left(1 + \dfrac{V_{CC}}{|V_A|}\right)}{1 + \dfrac{i_B \beta_o}{|V_A|} Z_L} = \dfrac{\left(\dfrac{1}{\frac{2}{\beta_o}+1}\right) i_{ref} \left(1 + \dfrac{V_{CC}}{V_A}\right)}{1 + \left(\dfrac{1}{\frac{2}{\beta_o}+1}\right) \dfrac{1}{|V_A|} i_{ref} Z_L}$

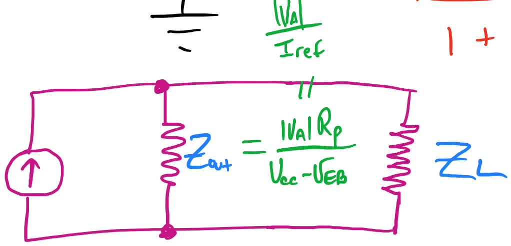
$i_{ref}' = \left(\dfrac{1}{\frac{2}{\beta_o}+1}\right) i_{ref}$

$= \dfrac{i_{ref}' \left(1 + \dfrac{V_{CC}}{V_A}\right)}{1 + i_{ref}' \dfrac{Z_L}{|V_A|}}$ ($\dfrac{V_{CC}}{V_A} \simeq 0$) $= \dfrac{Z_{out}\, i_{ref}'}{Z_{out} + Z_L}$

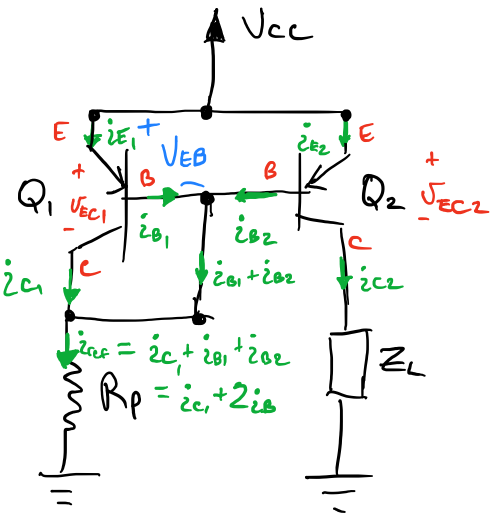
$Z_{out} = \dfrac{|V_A|}{i_{ref}'} = \dfrac{|V_A| R_p}{V_{CC} - v_{EB}}$

$= i_{ref}'$

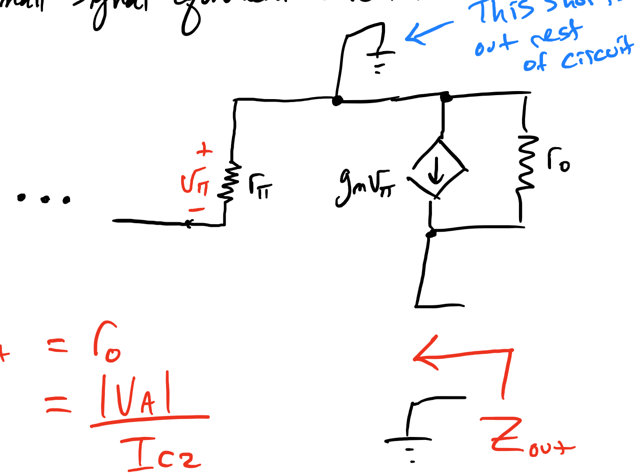
$\left(\dfrac{i_{ref}}{2/\beta_o + 1}\right)$



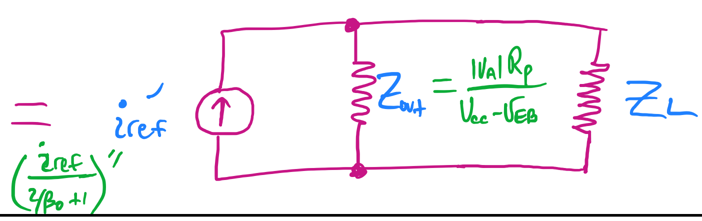
Current Mirror (Taking into account the Early Effect)... using AC small signal model to determine the output impedance.



AC small signal equivalent circuit:



$$Z_{out} = r_o = \frac{|V_A|}{I_{C2}}$$

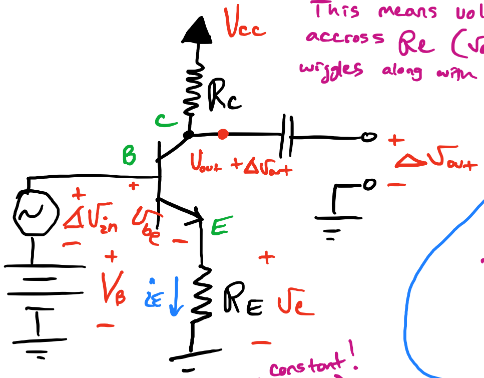


$$\simeq \frac{|V_A|}{I_{ref}}$$

Different ways of analyzing common emitter analyzer...

Method 1: Assume v_{be} = constant $\equiv V_{BE}$

This means voltage accross R_e (v_e) wiggles along with Δv_{in}.



constant! (approx)

$$-V_B - \Delta v_{in} + V_{BE} + (I_E + \Delta i_E)R_E = 0$$

Equate AC and DC components:

$$I_E = (V_B - V_{BE})/R_E$$

$$\Delta i_E = \Delta v_{in}/R_E \implies \Delta v_{out} = -\frac{R_C}{R_E}\frac{\Delta v_{in}}{\alpha} \simeq -\frac{R_C}{R_E}\Delta v_{in}$$

$$\Delta i_C = \Delta i_E/\alpha$$

Method 2: Nonlinear long way... (ignore Early Effect)

$$i_C = \left(\frac{I_S}{\beta}\right)e^{v_{BE}/V_T}$$

$$(V_B + \Delta v_{in}) = v_{BE} + i_E R_E = v_{BE} + \alpha\, i_C R_E$$

$$\rightarrow V_B + \Delta v_{in} = v_{BE} + \alpha R_E I_S e^{v_{BE}/V_T}$$

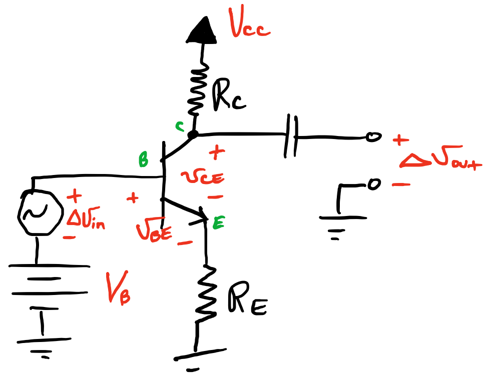
solve for v_{BE} — plug in

$$\rightarrow v_{out} = (V_{CC} - i_C R_C)$$

$$= V_{CC} - \left(I_S e^{v_{BE}/V_T}\right)R_C$$

Different ways of analyzing common emitter analyzer...

method 3: Small signal model



$$v_{BE} = V_{BE} + v_{be}$$

$$i_B = \frac{I_s}{\beta} e^{(V_{BE}+v_{be})/V_T} \simeq I_B + \frac{\partial}{\partial V_{BE}}\left(\frac{I_s}{\beta} e^{V_{BE}/V_T}\right) v_{be}$$

$$= I_B + \frac{I_B}{V_T} v_{be}$$

$$\therefore \; i_B \approx I_B + \frac{1}{r_\pi} v_{be}, \quad r_\pi = V_T / I_B$$

$$i_c = \beta_o i_B \left(1 + v_{CE}/|V_A|\right) = \beta_o \left(I_B + \frac{1}{r_\pi} v_{be}\right)\left(1 + \frac{V_{CE} + v_{ce}}{V_A}\right)$$

$$= \beta_o \left(I_B + \frac{I_B V_{CE}}{|V_A|} + \frac{I_B v_{ce}}{|V_A|} + \frac{1}{r_\pi} v_{be} + \frac{V_{CE} v_{be}}{r_\pi V_A} + \frac{v_{be} v_{ce}}{|V_A| r_\pi}\right) \quad \left(\frac{v_{be} v_{ce}}{|V_A| r_\pi} \simeq 0\right)$$

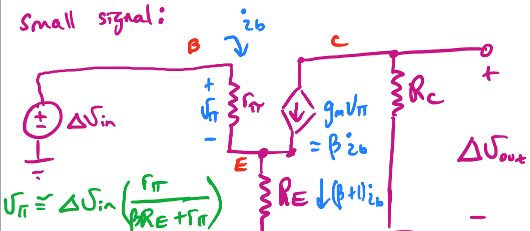
$$= \beta_o I_B \left(1 + \frac{V_{CE}}{|V_A|}\right) + \frac{\beta_o I_B v_{ce}}{|V_A|} + \frac{\beta_o v_{be}}{r_\pi} + \frac{V_{CE} v_{be} \beta_o}{|V_A| r_\pi}$$

$$= I_c + \frac{v_{ce}}{r_o} + g_m v_{be}$$

$$r_o \doteq \frac{|V_A|}{\beta_o I_B} \simeq \frac{|V_A|}{I_c} \qquad g_m \doteq \frac{\beta_o}{r_\pi}\left(1 + \frac{V_{CE}}{|V_A|}\right) = \frac{I_B \beta_o \left(1 + \frac{V_{CE}}{|V_A|}\right)}{V_T} = I_c / V_T$$

$$\therefore \; i_C = I_c + \frac{v_{ce}}{r_o} + g_m v_{be}, \quad r_o = |V_A|/I_c, \quad g_m = I_c/V_T$$

small signal:



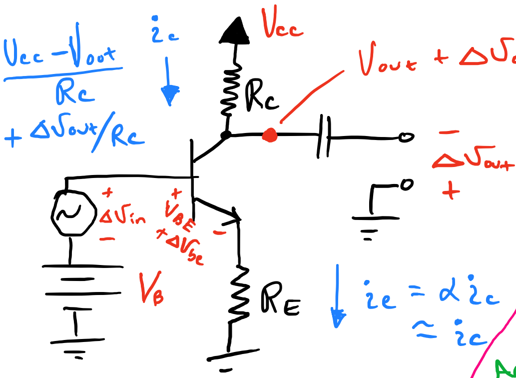
$$v_\pi \cong \Delta v_{in}\left(\frac{r_\pi}{\beta R_E + r_\pi}\right)$$

$$\Delta v_{out} = g_m v_\pi R_c$$

$$= -\Delta v_{in}\left(\frac{g_m R_c r_\pi}{\beta R_E + r_\pi}\right) = \frac{-\beta R_c}{\beta R_E + r_\pi} \approx -\frac{R_c}{R_E}$$

Different ways of analyzing common emitter analyzer...

Method 4: Looking at Feedback

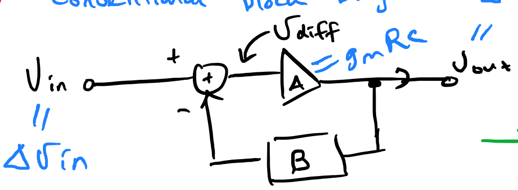


$\frac{V_{cc} - V_{out}}{R_c} + \Delta V_{out}/R_c$

$i_e = \alpha i_c \simeq i_c$

$$\Delta V_{be} = \Delta V_{in} - \frac{R_E}{R_C} \Delta V_{out}$$

Conventional Block Diagram:



$V_{in} = \Delta V_{in}$, $V_{out} = \Delta V_{out}$, $A = g_m R_C$, $B = R_E/R_C$

$A(V_{in} - B V_{out}) = V_{out}$

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

$\rightarrow V_{out} \simeq \frac{V_{in}}{B} \quad (AB \gg 1)$

A_{eff}: effective linear gain

Assume:

$A_{eff} \Delta V_{be} = \Delta i_c = \Delta V_{out}/R_c$

$\longrightarrow \underbrace{R_c A_{eff}}_{= A_{eff}'} \Delta V_{be} = \Delta V_{out}$

$B \equiv R_E/R_C$

$A_{eff}' (\Delta V_{in} - B \Delta V_{out}) = \Delta V_{out}$

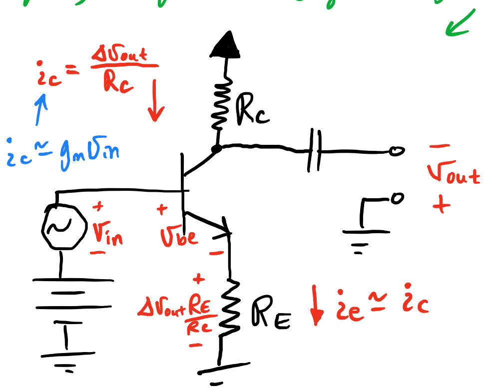
$\rightarrow \Delta V_{out} = \frac{A_{eff}'}{1 + A_{eff}' B} \simeq \frac{1}{B} = \frac{R_C}{R_E}$

A_{eff} is the small signal gain:

$A_{eff} = g_m = I_C / V_T$

Summary of feedback Point of View for common Emitter Amplifier.

ignoring Early Effect: only small signals shown

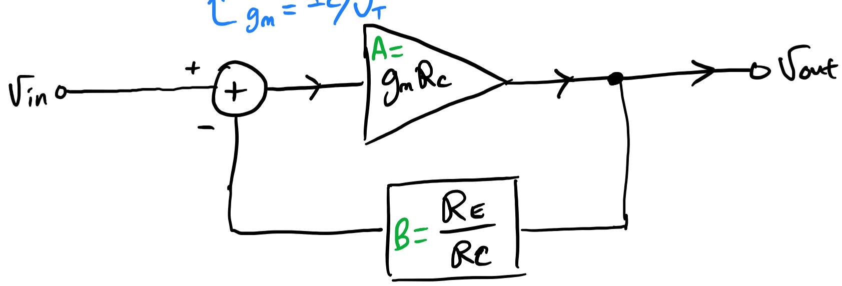


Main Equations:

$$V_{be} = V_{in} - \frac{R_E}{R_C} V_{out}$$

$$V_{out} = g_m R_C V_{be}$$

$g_m = I_C / V_T$



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

where: $A = g_m R_C$ and $B = \frac{R_E}{R_C}$