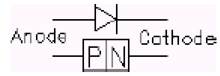
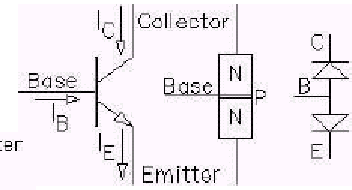
Introduction to Bipolar Junction Transistors (BJTs)

A transistor has three terminals-- the base, the collector, and the emitter. The current flow from the collector to the emitter (through the transistor) is controlled by the current flow from the base to the emitter. A small base current can control a much larger collector current.

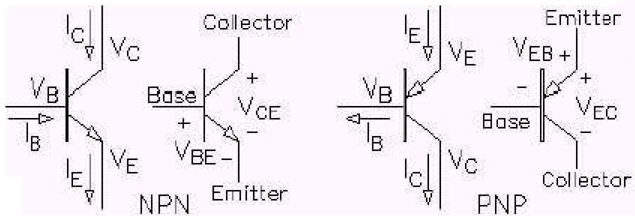
Bipolar junction transistors (BJTs) consist of three layers of doped silicon. The NPN transistor has a thin layer of P-doped silicon sandwiched between two layers of N-doped silicon. Each P-N junction can act like a diode. In fact, this is a fairly good way to check a transistor with an ohmmeter (set to the diode setting).



The base-emitter junction always acts like a diode, but because the base is very thin, it makes the other junction act like a controlled valve (details to come later).



Symbols and conventions



PNP: Replace v_{BE} with v_{EB} and v_{CE} with v_{EC} in equations below

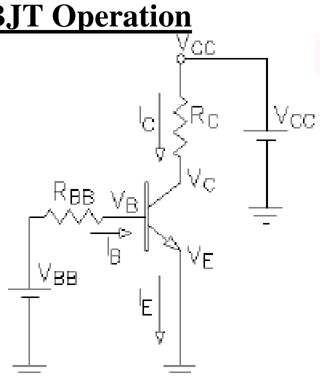
Very High Level Overview of how a transistor works:

- A small amount of base current controls a large emitter (collector) current

Analogy:

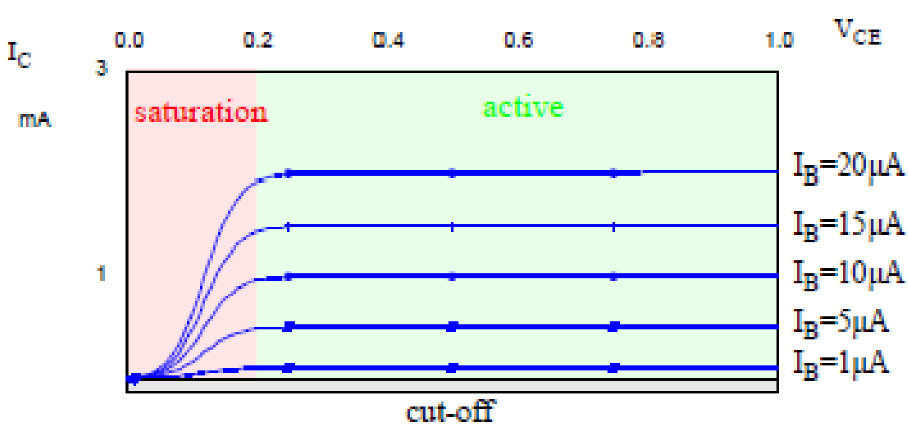
- Think of the transistor as an "electronic" tap able to control a large flow of electrons *(from collector to emitter)* with only a small variation in the "handle" *(base)*
- Water Tap Analogy: (water spigot)
  → Large amounts of H_2O controlled by very small movement of the tap

BJT Operation



Modes or regions of operation (v_{BE} and v_{CE} are approximate)

Cutoff (off)	Active (partially on)	Saturation (fully on)
$v_{BE} < 0.7 \cdot V$	$v_{BE} \simeq 0.7 \cdot V$	$v_{BE} \simeq 0.7 \cdot V$
$i_B = 0$	$i_B > 0$	$i_B > 0$
$i_C = 0$	$v_{CE} \geq 0.7 \cdot V$	$v_{CE} = 0.2$ to $0.7 \cdot V$
	$i_C = \beta \cdot i_B = \alpha \cdot i_E$ controlled by the transistor	$i_C < \beta \cdot i_B$ limited by something outside of the transistor



Summary of BJT Current-Voltage Relationships in the Active Mode:

$i_c = I_S e^{v_{BE}/V_T}$ (n=1 always for BJT) {Ebers-Moll equation}

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

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

Note: For the *pnp* transistor, replace v_{BE} with v_{EB}

$I_C = \alpha I_E = \beta I_B$ $I_E = (\beta+1) I_B$ $\beta = \frac{\alpha}{1-\alpha}$ $\alpha = \frac{\beta}{\beta+1}$

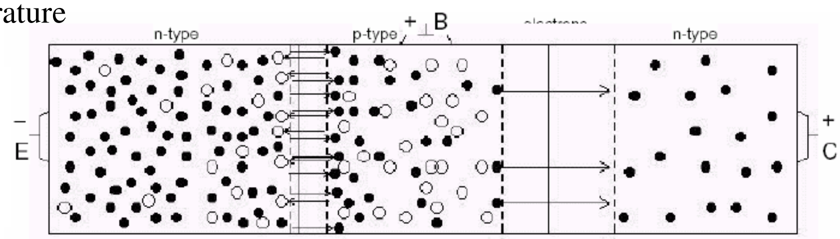
V_T=thermal voltage ≅ ~25mV at room temperature

Temperature dependencies

$v_{BE} = 0.7 \cdot V$ (decreases about 2.1 mV / °C)

at constant I_C: $\Delta V_{BE} = \frac{-2.1 \cdot mV}{degC}$

at constant V_{BE}: I_C increases by 8% per °C (10x per 30°C)



Method for solving DC voltages and currents of a BJT circuit:

1). Start by assuming transistor is in active mode

Either use given values for base-emitter voltage, or use

$V_{BE} = 0.7V$ (npn)

$V_{EB} = 0.7V$ (pnp)

2). Solve for the BJT node voltages and currents

- Voltages: sometimes can read off directly, otherwise use loop equation
- Once you have one current, you can get the other two from the active mode equations

3). Check to see if the solution is consistent!

$V_C \geq V_B > V_E$ npn active more explicitly: $V_{CB} \geq 0$, $V_{BE} \geq 0.7V$

$V_E > V_B \geq V_C$ pnp active more explicitly: $V_{CB} \geq 0$, $V_{EB} \geq 0.7V$

4). If the solution is consistent, stop → you are done

If not, the transistor is either in saturation or cutoff

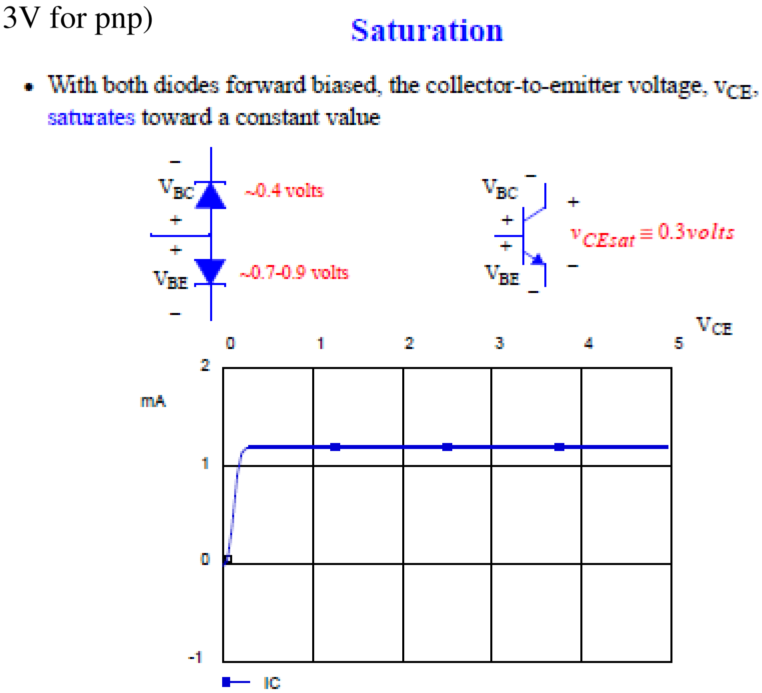
→ go to 2) however active mode equations **do not** apply!

→ Now use: saturation: $v_{BE} \approx 0.7V$ and $v_{CE} \approx 0.3V$ for npn

($v_{EB} \approx 0.7V$ and $v_{EC} \approx 0.3V$ for pnp)

cutoff: set all currents to approximately 0:

$i_C = 0$ $i_E = 0$ $i_B = 0$



NPN ACTIVE AND ON when:

$v_{BE} \geq V_{BEon}$ ($V_{BEon} \cong 0.4V$)

$V_C \geq V_B > V_E$ and $V_{CE} > 0.3V$

PNP ACTIVE AND ON when:

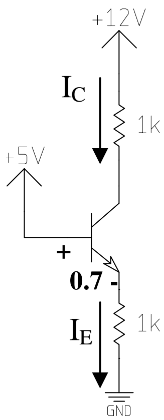
$v_{EB} \geq V_{EBon}$

$V_E > V_B \geq V_C$ and $V_{EC} > 0.3V$

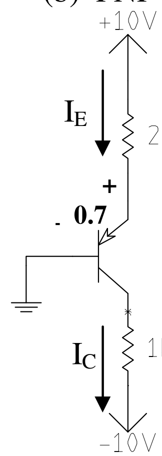
Example 29:

Find V_E and I_c for each circuit. Assume that $|V_{BE}| = 0.7V$ and $\beta = 40$. Both transistors are being operated in the active mode.

(a) NPN

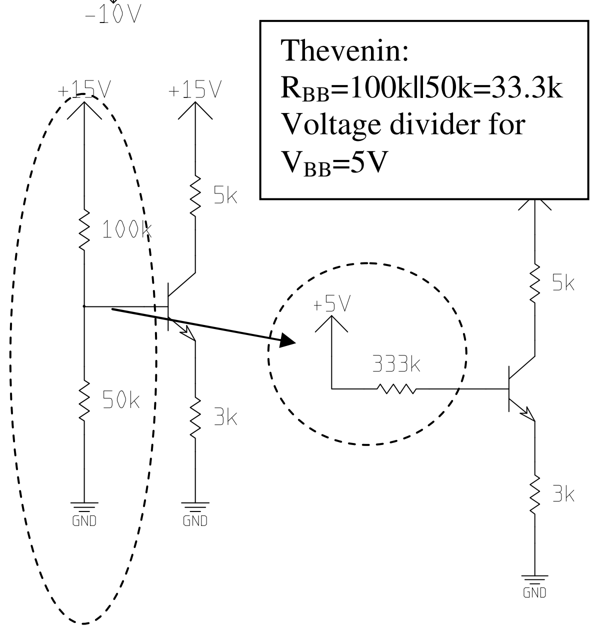


(b) PNP



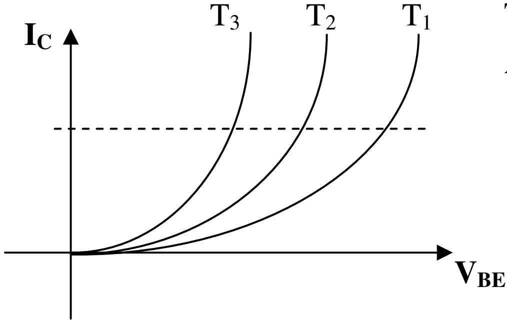
Example 31

$\beta = 100$



Temperature Effects:

NPN Transistor Characteristic



$T_3 > T_2 > T_1$

As $T\uparrow, I\uparrow$ for fixed V_{BE}

Thermal runaway: $T\uparrow \rightarrow I_C\uparrow \rightarrow P_D\uparrow \rightarrow T\uparrow \rightarrow I_C\uparrow \rightarrow P_D\uparrow \rightarrow \cdots$

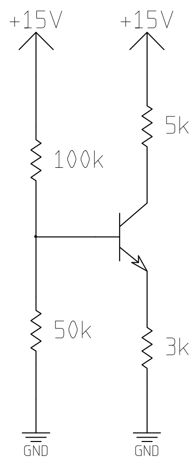
DESIGN

Bias BJT in the ACTIVE region

Goals:

- Stable I_C for any temperature. (Does not go into saturation region - similar to triode region for MosFet)
- Not dependant on the value of β.
- Not dependant on V_{BE}.

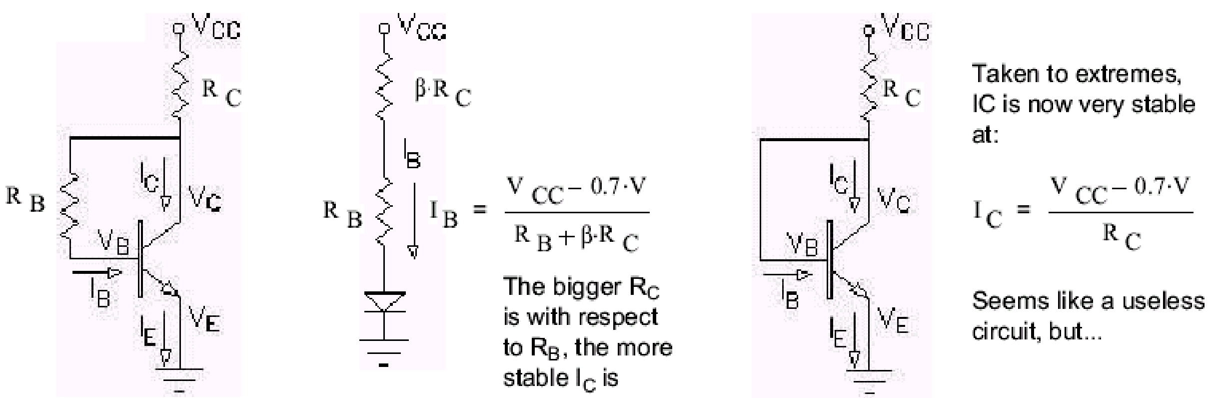
Configurations:



Rules of Thumb:

- $\beta R_E > R_{BB}$

A couple of other bias schemes

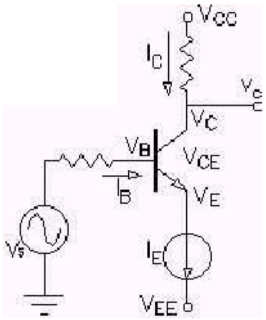


OR

Use Current Mirror:

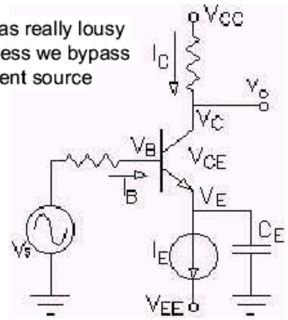
Current source bias: We could make the bias current very stable if we had a current source

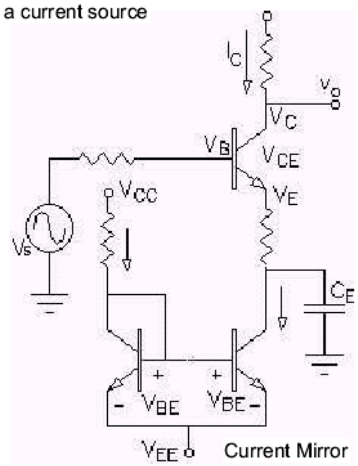
If we can make current sources (drains), then...



For a perfect current source, $R_E = \infty$

which has really lousy gain unless we bypass the current source





Current mirrors A way to make a current source (drain)

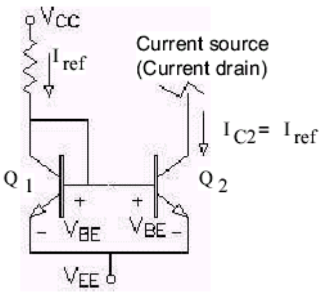
$$I_{C1} = \frac{V_{CC} - V_{EE} - 0.7 \cdot V}{R_C} = I_{ref}$$

Recall that v_{BE} is really not exactly 0.7V, from Ebers-Moll eq.: $I_C = I_S \cdot e^{\frac{v_{BE}}{V_T}}$

Because $V_{BE1} = V_{BE2}$, $I_{C1} = I_{C2}$

We can get a current source (usually called a current drain in this type of configuration). I could make a positive source if I used PNP transistors.

But, the transistors must be identical, and at the same temperature, like in an IC.



BJT basic amplifier:

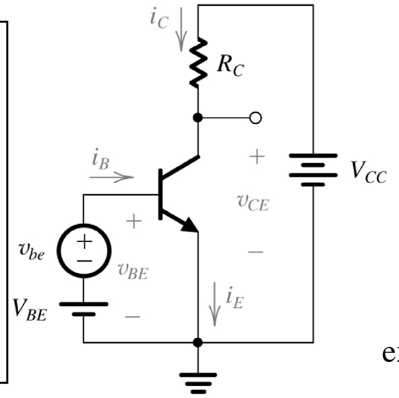
DC:

$$I_C = I_s e^{V_{BE}/V_T}$$

$$I_E = \frac{I_C}{\alpha}$$

$$I_B = \frac{I_C}{\beta}$$

$$V_C = V_{CE} = V_{CC} - I_C R_C$$



(a)

Total (instantaneous -> DC and AC)

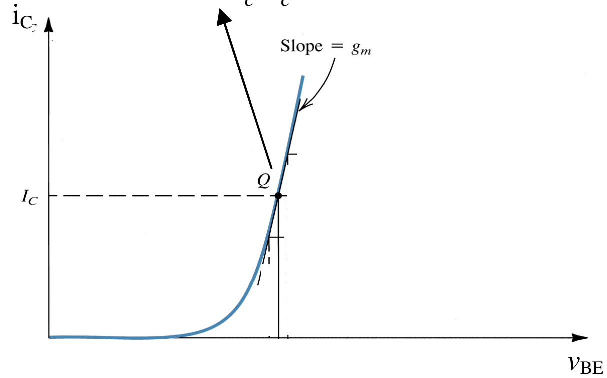
$$i_c = I_s e^{v_{BE}/V_T}$$

$$I_c + i_c = I_s e^{(V_{BE}+v_{be})/V_T} = \underbrace{I_s e^{V_{BE}/V_T}}_{I_c} e^{v_{be}/V_T}$$

$$= I_c e^{v_{be}/V_T} = I_c\left(1+\frac{v_{be}}{V_T}\right) = I_c + \frac{I_c}{V_T} v_{be}$$

expand by $e^x \approx 1 + x$ for x<<1 (V_{be}<<V_T)

$$g_m = \left.\frac{\partial i_c}{\partial v_{BE}}\right|_{i_c = I_c}$$



Look at signal component only:

$$i_c = \frac{I_c}{V_T} v_{be}$$

$$\boxed{g_m = \frac{I_c}{V_T}}$$

Transconductance
Dynamic forward resistance of BE junction

Input Resistance:

a. Input resistance looking in to base (in terms of i_b) – from base to emitter

From above: $i_C = I_c + i_c = I_c + \frac{I_c}{V_T} v_{be}$

$$i_B = \frac{i_C}{\beta} = \frac{I_c}{\beta} + \frac{I_c}{\beta V_T} v_{be}$$

$$i_B = I_B + i_b$$

$$i_b = \frac{I_c}{\beta V_T} v_{be} = \frac{I_B}{V_T} v_{be}$$

$$r_\pi = \frac{V_T}{I_B}$$

if β large($\alpha \approx 1$): good approximation is $r_e \approx \frac{1}{g_m}$

$$\boxed{r_\pi = (\beta+1) r_e}$$

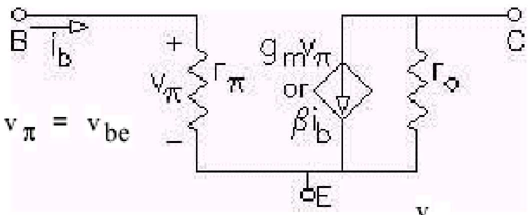
Summary of ac parameters:

$g_m = \frac{I_c}{V_T}$	$r_\pi = \frac{V_T}{I_B} = \frac{\beta}{g_m}$	$i_c = g_m v_{be}$
$r_o \cong \frac{V_A}{I_c}$	$r_e = \frac{V_T}{I_E}$	$\frac{v_c}{v_{be}} = -g_m R_c$

Small-signal equivalent circuit models

Same concept as that of the MOSFET.

- **Hybrid-π** model is used for the BJT:

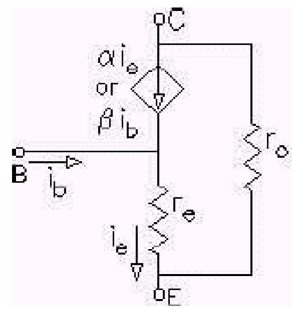


$r_\pi = (\beta + 1)\cdot r_e$ $\quad i_b = \dfrac{v_\pi}{r_\pi}$

$\beta \cdot i_b = \beta \cdot \dfrac{v_\pi}{r_\pi} = \beta \cdot \dfrac{v_\pi}{(\beta+1)\cdot r_e}$

$g_m = \dfrac{\beta}{(\beta+1)\cdot r_e} = \dfrac{\alpha}{r_e} \simeq \dfrac{1}{r_e}$ = transconductance

- T-model – uses r_e instead of r_π

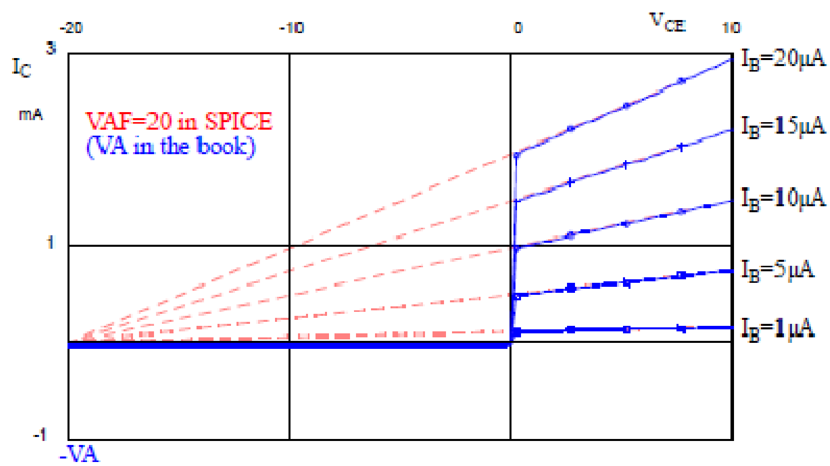


This is equivalent to Hybrid-π:

$r_e (1 + \beta) = r_\pi$

Early Voltage

- The I_C vs. V_{CE} curves in the active region have a finite slope to them due to this i_C dependence on V_{CB}
- *Early* showed that these slopes all converge to one negative voltage point



The actual equation:

$$i_c = I_s e^{\frac{v_{be}}{V_T}}\left(1 + \frac{v_{ce}}{V_A}\right)$$

This means that the output resistance between the collector and emitter is not infinite!

Method for analyzing transistor amplifier circuits:

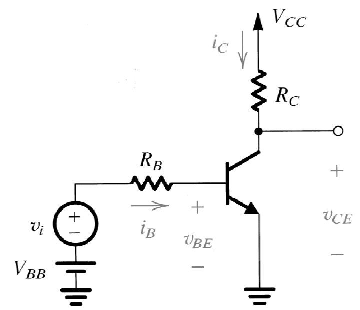
1). Determine dc operating point, specifically I_C
(Set ac sources to 0!!)
Note: Use method for analyzing BJT circuits at DC
2). Calculate small-signal parameters: g_m , r_π, and/or r_e
3). Set dc sources to 0
4). Replace the transistor with one of the equivalent small-signal models
5). Analyze the circuit as usual → linear circuit analysis

Example

Circuit:

$\beta=100$, $V_{BB}=3V$, $R_C=3k$

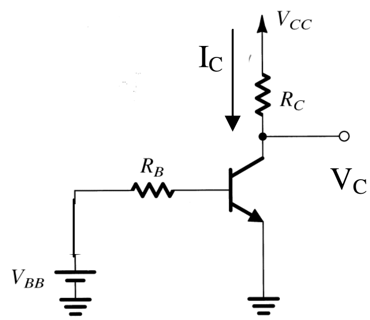
$R_B=100k$, $V_{CC}=10V$



Find the voltage gain, v_o/v_i

1). DC analysis: set v_i to 0 Assume $V_{BE} = 0.7V$ Assume active

Redraw circuit with just dc part:

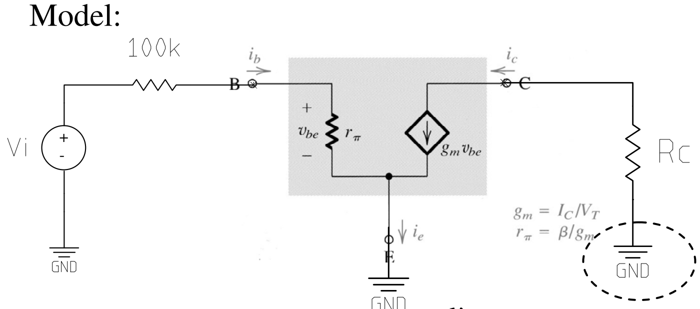


2). Calculate small-signal parameters:

$$g_m = \frac{I_C}{V_T} = \frac{2.3}{25} = 92mA/V \qquad r_e = \frac{V_T}{I_E} = \frac{25}{(2.3/0.99)} = 10.8\Omega \qquad r_\pi = \frac{\beta}{g_m} = \frac{100}{92} = 1.09k\Omega$$

3). And 4). Set dc sources to 0 and replace transistor with equivalent model

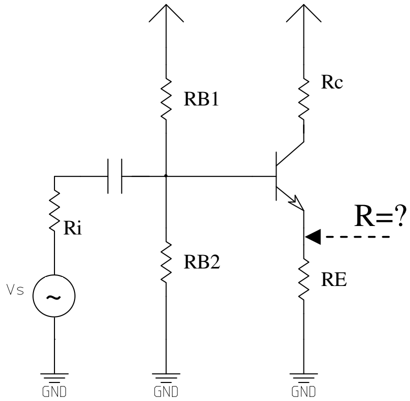
Model:

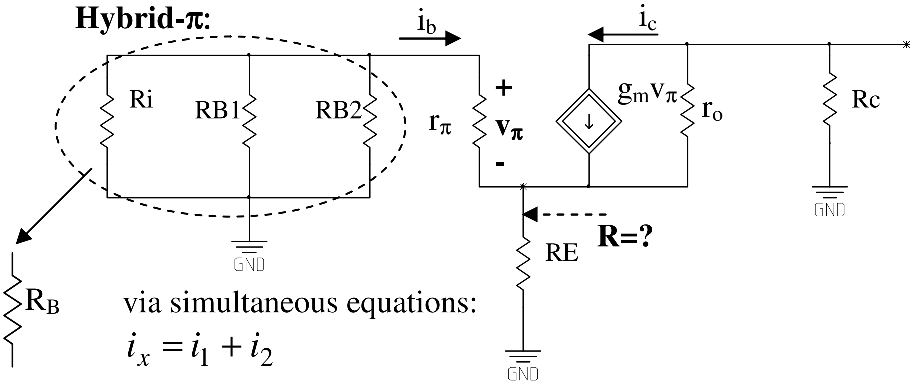


Vcc grounded for ac!

5). Find requested gain: $v_o/v_i = [\frac{v_c}{v_i}]$

Resistance-Reflection Rule Between Base and Emitter:





via simultaneous equations:

$$i_x = i_1 + i_2$$

$$i_1 = \frac{v_x}{R_E}, \quad i_2 = -i_e = -(i_b + i_c) = -i_b(\beta + 1)$$

$$v_\pi = i_b r_\pi, \quad i_c = g_m v_\pi$$

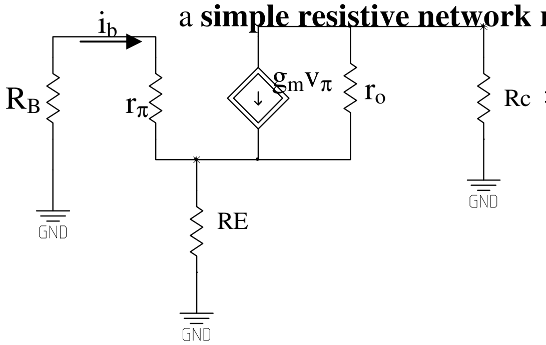
etc.

⋮

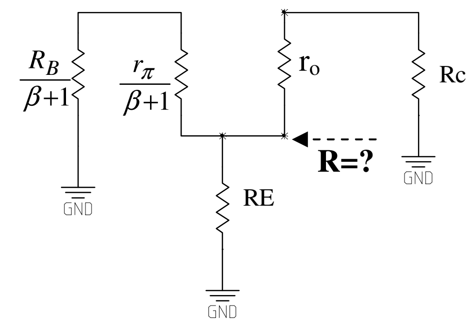
$$R_x = R_E \,||\, \tfrac{r_\pi + R_B}{(\beta+1)} \,||\, (r_o + R_c) \approx R_E \,||\, (r_e + \tfrac{R_B}{(\beta+1)})$$

1. Eliminate VCCS
2. Scale all resistors with i_b through Thevenin by $\frac{1}{(\beta+1)}$ and

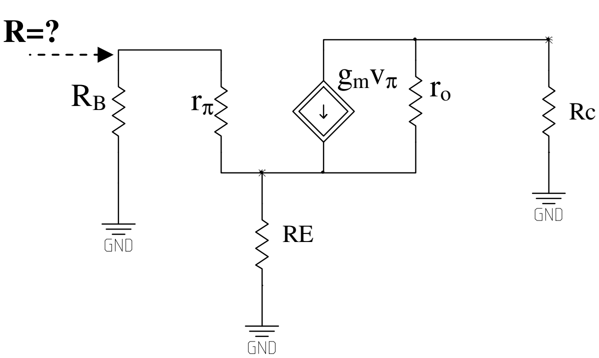
a **simple resistive network remains**



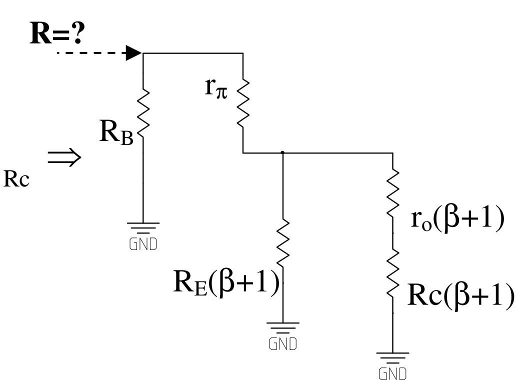
⇒



Same problem, but look into base instead:



⇒



Summary of Resistance-Reflection Rule between base and emitter:
Applies only when you want to reflect a resistor from emitter to base or base to emitter circuit

Review of rule:

1). Temporarily remove dependent source βi_b or $g_m v_{be}$

2). When looking into base: Replace resistors on emitter side with

"R" x (β + 1) or

When looking into emitter: Replace resistors on base side with "R" / (β + 1)

3). Treat circuit as a resistive network and find equivalent resistance

This works because $i_b = \dfrac{i_e}{\beta + 1}$

In a nutshell: To reflect a resistor from:

E→ B multiply by (β + 1)

B→E divide by (β + 1)

Things to keep in mind:

- Rule does NOT work for impedance looking into
- collector – it is a reflection rule between base and emitter
- It works because $i_b = \dfrac{i_e}{\beta + 1}$ which is a relationship
- between the base and emitter current!
- Finding R_{in} or R_{out} → this is just finding Thevenin
- equivalent resistance, R_{Th}

  Possible methods now that you can use:

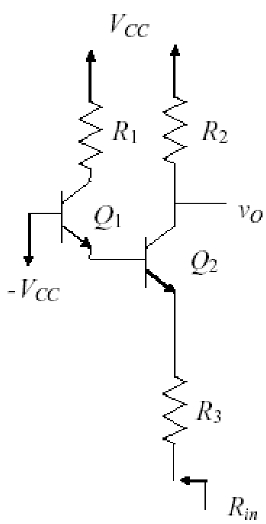
  1). Using the resistance Reflection Rule

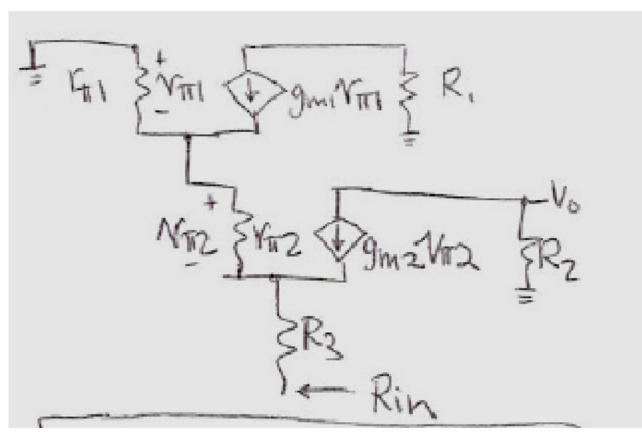
  2). Using Thevenin equivalent methods– use these to double check homework, but on exam will not likely have time
- R_{in} or R_{out} is always between a node and ground – follow all paths to ground from that node

  Applying the Reflection Rule is like turning off dependent sources and multiplying resistances by (β + 1) or dividing resistance by (β + 1) and treating circuit as just a resistive network → Note that this only works because the dependent source is being accounted for through the (β + 1) factor!

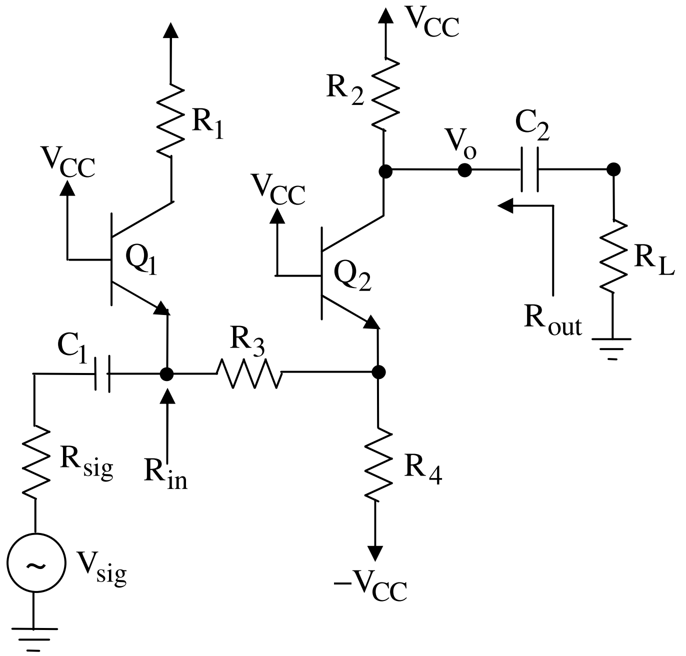
Example: Assume the transistors below have a finite β and an infinite Early voltage.

- Write an expression for the input resistance R_{in} in the circuit shown below. Your expression should include *only* real resistances (R_1, R_2, R_3, or a subset of these) and possibly β, r_{e1} or $r_{\pi1}$, and r_{e2} or $r_{\pi2}$. (Assume both transistors have the same β.) Circle your answer. *Hint: Use Resistance-Reflection rule*



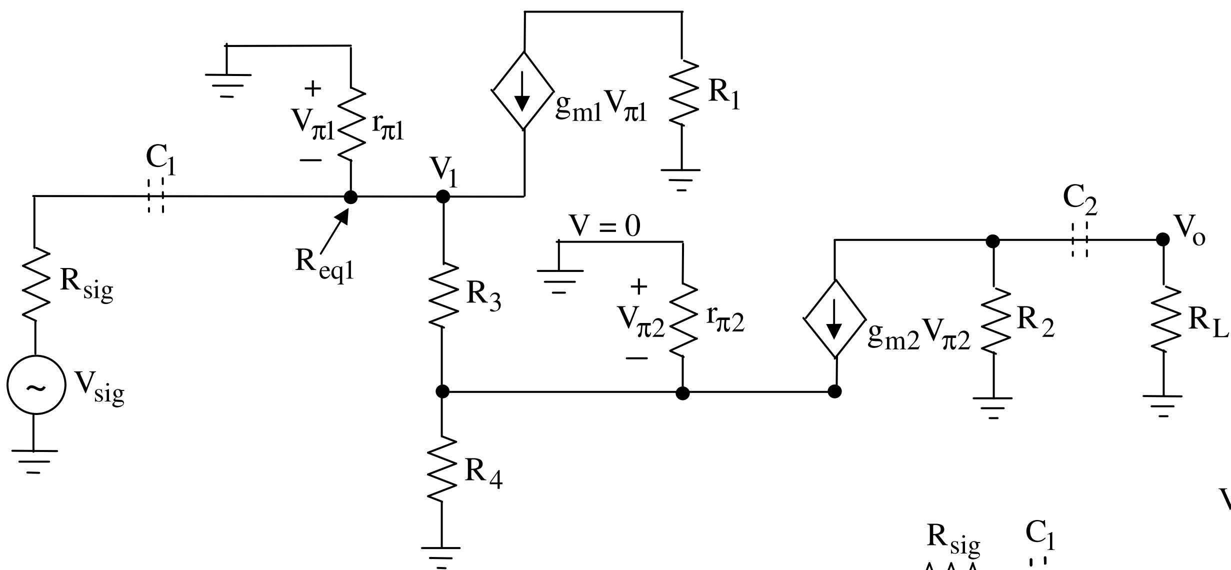


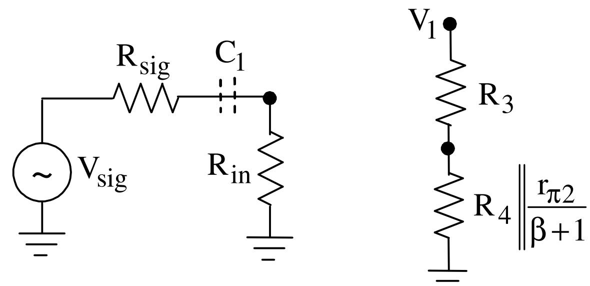
Common-Base



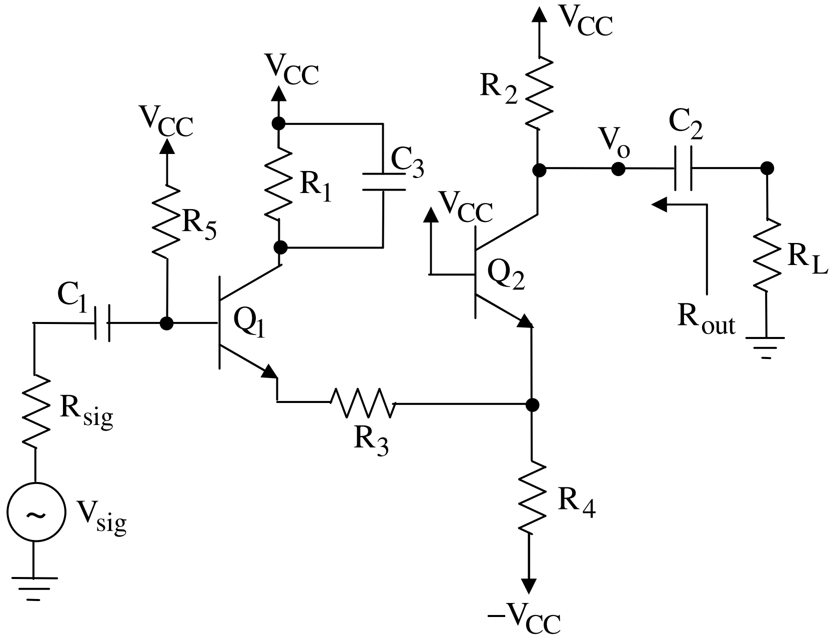
$C_1 = 10\text{ pF}, \quad C_2 = 10\text{ nF}, \quad \beta = 100$

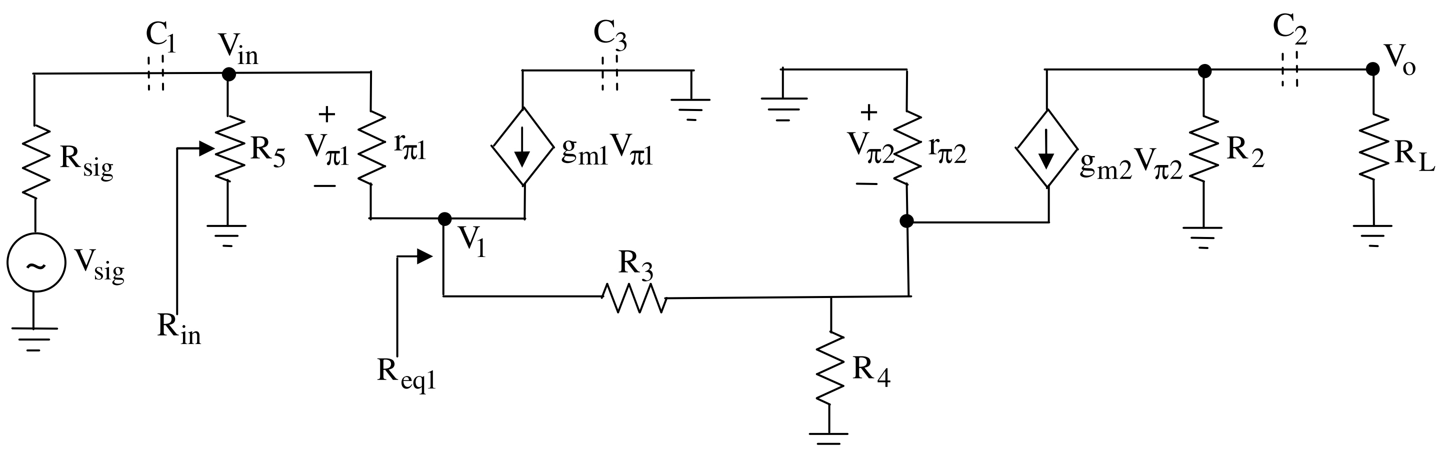
Ignore r_o

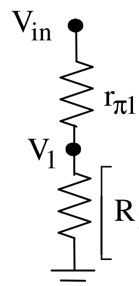




2 Stage ⇒ Common Collector/Common Base

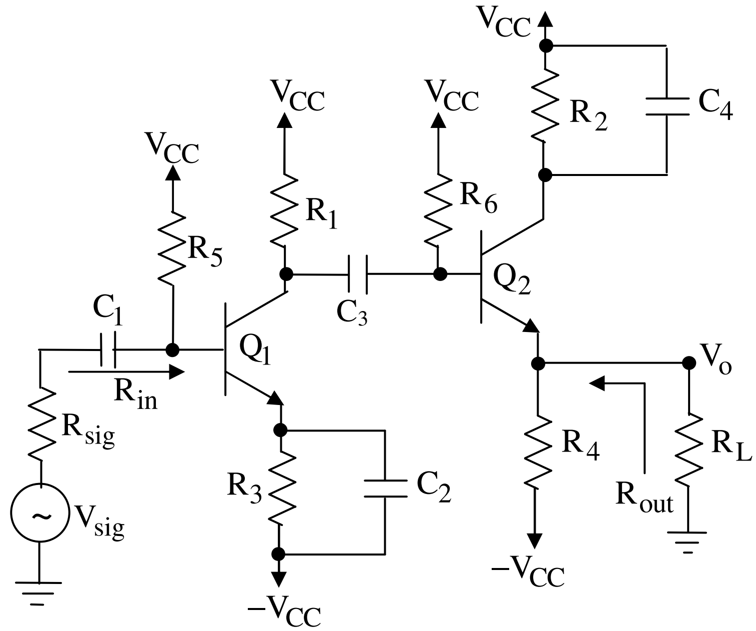


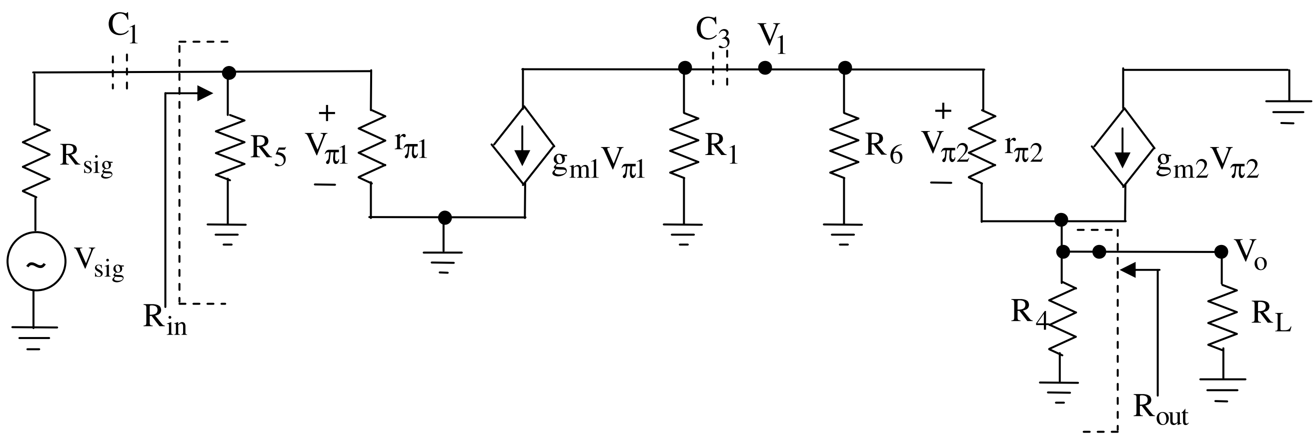


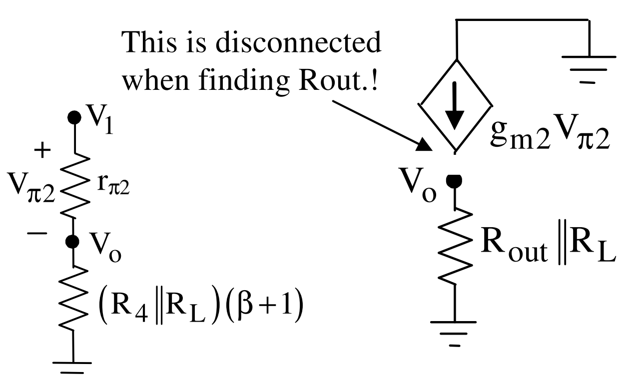


$$\left[R_3 + \left(R_4 \left\| \frac{r_{\pi 2}}{\beta + 1}\right.\right)\right](\beta + 1) = R_{eq1}$$

2 Stage ⇒ Common-Emitter/Common-Collector





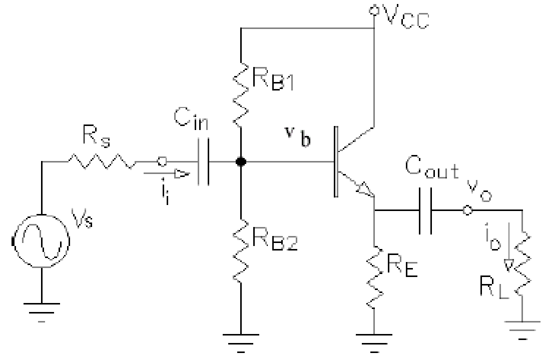


Common collector (CC)

The circuits shown are typical arrangements. Note that V_{EE} is often 0 V (ground). The equations below are for these circuits, adapt them as necessary to fit your actual circuit.

Voltage gain about 1. Good for current gain, or to match a high impedance source to a low impedance load.

The small-signal emitter resistance is right in the emitter of the transistor (where the arrow is).



Recall that the emitter resistor looks β times as big from the base's point-of-view. That's also true for signals

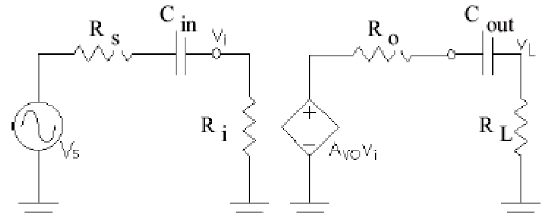
Input impedance: $R_i = R_{B1} \| R_{B2} \| \beta\cdot\left(r_e + R_E \| R_L\right)$

The opposite effect also works, resistors at the base look β times smaller from the emitter's point-of-view.

Output impedance: $R_o = R_E \| \left(r_e + \frac{R_{B1}\|R_{B2}\|R_S}{\beta}\right)$

Low frequency corner frequencies

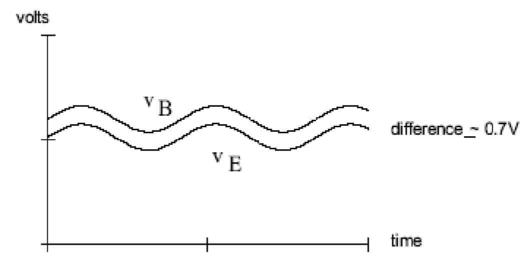
$$f_{CL1} = \frac{1}{2\cdot\pi\cdot\left(R_S + R_i\right)\cdot C_{in}} \qquad f_{CL2} = \frac{1}{2\cdot\pi\cdot\left(R_L + R_o\right)\cdot C_{out}}$$



From the signal analysis, the only thing between the base signal and the output signal is r_e. To find the output, just use the voltage divider equation.

Voltage gain: $A_v = \frac{v_o}{v_b} = \frac{R_E\|R_L}{r_e + R_E\|R_L} \simeq 1$

OR: $\frac{v_o}{v_s} = \frac{R_i}{R_S + R_i}\cdot\frac{R_E\|R_L}{r_e + R_E\|R_L}$

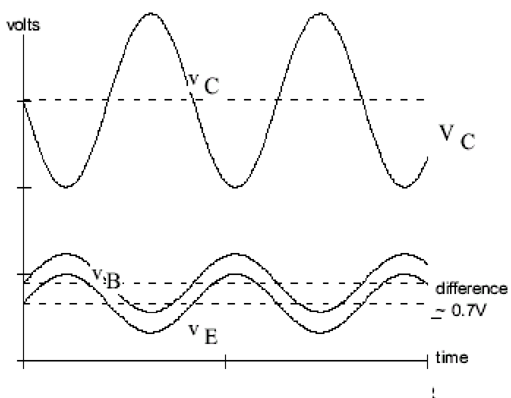


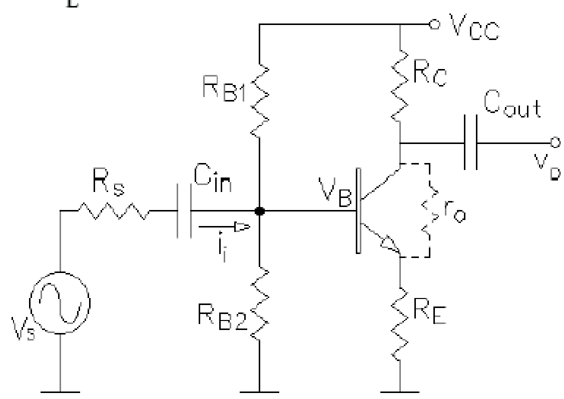
You could think of the ouput as simply 0.7V DC less than the input, which doesn't make the AC signal any less. Of course this doesn't account for the r_e effects.

Current gain: $A_i = \frac{i_o}{i_i} = \frac{R_E\|R_L}{r_e + R_E\|R_L}\cdot\frac{R_i}{R_L} = A_v\cdot\frac{R_i}{R_L} \simeq \frac{R_i}{R_L}$

Common emitter (CE)

Now let's add a resistor in the collector (R_C). Nearly the same current that flows through R_E flows through R_C.



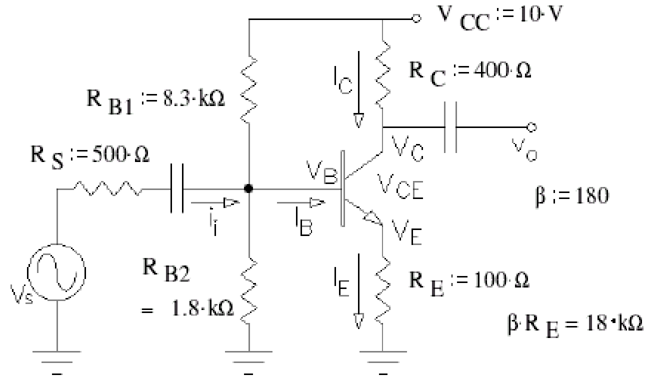


$v_c = -i_c\cdot R_C \qquad v_e = i_e\cdot R_E \simeq v_b$

$i_c \simeq i_e$ so: $\frac{v_c}{v_b} \simeq -\frac{R_C}{R_E}$ gain

Common emitter (CE)

Common Emitter amplifier, example:



Bias:

$V_{BB} := \frac{R_{B2}}{R_{B2}+R_{B1}} \cdot V_{CC}$ $\quad$ $V_{BB} = 1.782 \cdot V$

$R_{BB} := \frac{1}{\left(\frac{1}{R_{B2}}+\frac{1}{R_{B1}}\right)}$ $\quad$ $R_{BB} = 1.479 \cdot k\Omega$

$I_B := \frac{V_{BB} - 0.7 \cdot V}{R_{BB} + \beta \cdot R_E}$ $\quad$ $I_B = 0.056 \cdot mA$

$I_E := \frac{V_E}{R_E}$ $\quad$ $I_C := I_E$ $\quad$ $I_C = 10 \cdot mA$

$V_E := I_B \cdot (\beta \cdot R_E)$ $\quad$ $V_E = 1 \cdot V$

$V_B := V_E + 0.7 \cdot V$ $\quad$ $V_B = 1.7 \cdot V$

$V_C := V_{CC} - I_C \cdot R_C$ $\quad$ $V_C = 6 \cdot V$

What if we put in an AC input signal: $v_B(t) := V_B + 0.5 \cdot V \cdot \cos\left(6280 \cdot \frac{rad}{sec} \cdot t\right)$ $\quad$ $v_E(t) := v_B(t) - 0.7 \cdot V$

$i_C(t) := \frac{v_E(t)}{R_E}$ $\quad$ $v_C(t) := V_{CC} - i_C(t) \cdot R_C$

$\frac{R_C}{R_E} = \frac{400 \cdot \Omega}{100 \cdot \Omega} = 4$

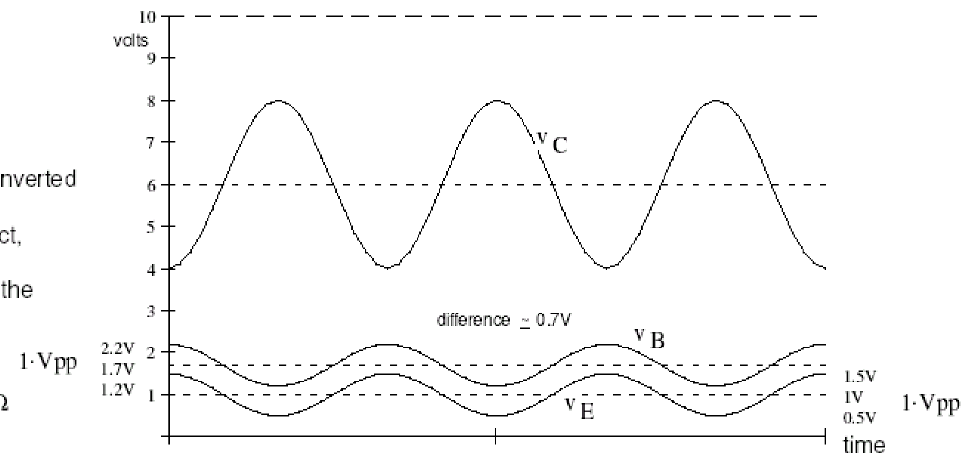
v_C is 4 times bigger and inverted

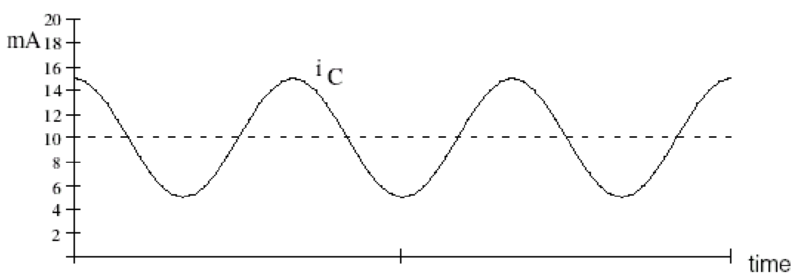
Actually, to be more correct, we should account for the small-signal resistance of the base-emitter junction.

$r_e := \frac{V_T}{I_C}$ $\quad$ $r_e = 2.5 \cdot \Omega$

gain is really:

$\frac{R_C}{R_E + r_e} = 3.902$





Input impedance: $R_i = R_{B1} \| R_{B2} \| \beta \cdot (r_e + R_E)$

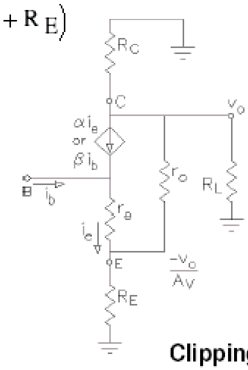
Output impedance: $R_o = R_C \| r_o$

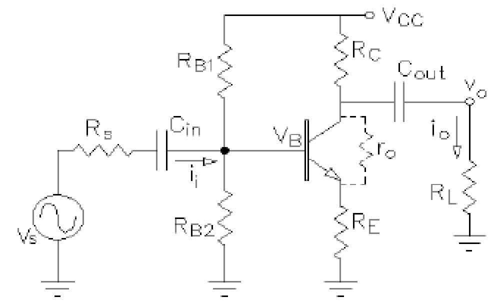
Often neglected $r_o = \dfrac{V_A}{I_C}$ Early voltage. (guess $V_A \simeq 100$ V if no data)

AC collector resistance: $r_c = R_C \| R_L \| r_o$

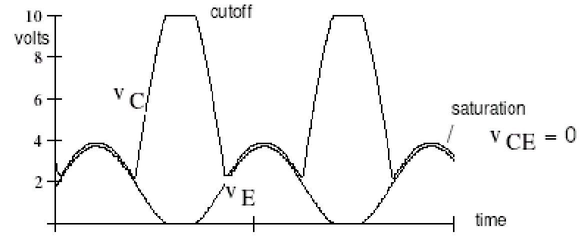
More correct, use: $r_o \cdot \dfrac{A_v}{A_v + 1}$

instead of r_o very rarely done.





Clipping Cutoff clipping: $i_E = 0$



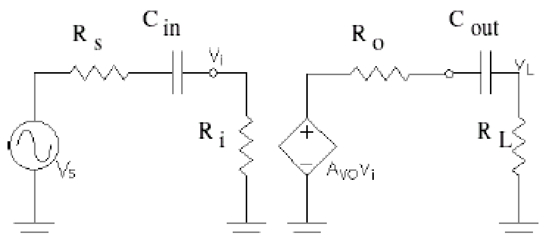
Voltage gain: $A_v = \dfrac{v_o}{v_b} = \dfrac{r_c}{r_e + R_E}$

Current gain: $A_i = \dfrac{i_o}{i_i} = \dfrac{r_c}{r_e + R_E} \cdot \dfrac{R_i}{R_L} = A_v \cdot \dfrac{R_i}{R_L}$

Low frequency corner frequencies

$$f_{CL1} = \frac{1}{2 \cdot \pi \cdot (R_S + R_i) \cdot C_{in}}$$

$$f_{CL2} = \frac{1}{2 \cdot \pi \cdot (R_L + R_o) \cdot C_{out}}$$



With bypass capacitor (C_E)

This basically makes the R_E dissapear at signal frequencies (If the cap is big enough).

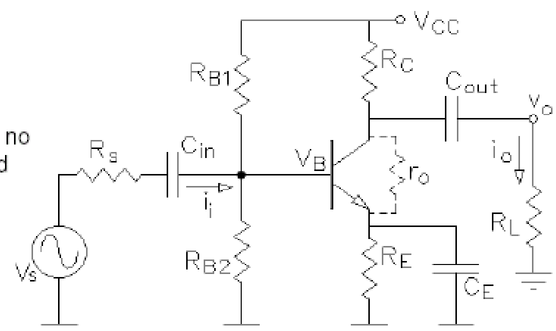
Input impedance: $R_i = R_{B1} \| R_{B2} \| \beta \cdot r_e$ Much lower

Output impedance: $R_o = R_C \| r_o$ Same as above, but no r_o correction needed

AC collector resistance: $r_c = R_C \| R_L \| r_o$

Voltage gain: $A_v = \dfrac{v_o}{v_b} = \dfrac{r_c}{r_e}$

Current gain: $A_i = A_v \cdot \dfrac{R_i}{R_L}$

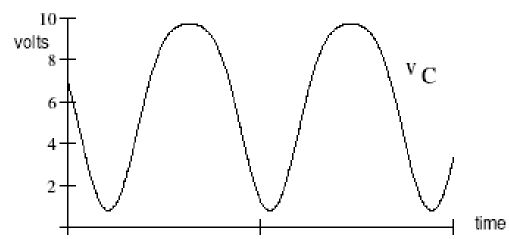


Another low frequency corner frequency:

$$f_{CL3} = \frac{1}{2 \cdot \pi \cdot C_E} \cdot \left(\frac{1}{r_e} + \frac{1}{R_E}\right)$$

Because r_e is so small, this will usually dominate, even when C_E is big.

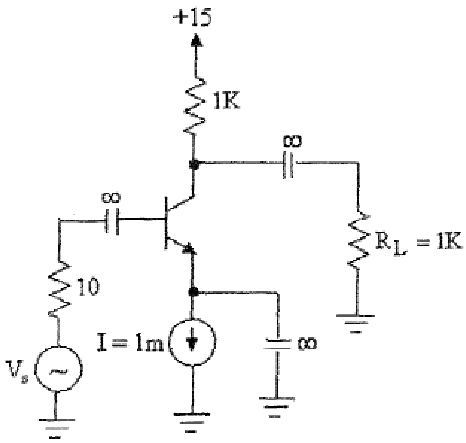
If the output swing is too big you'll get distortion because r_e varies with i_C



Example:

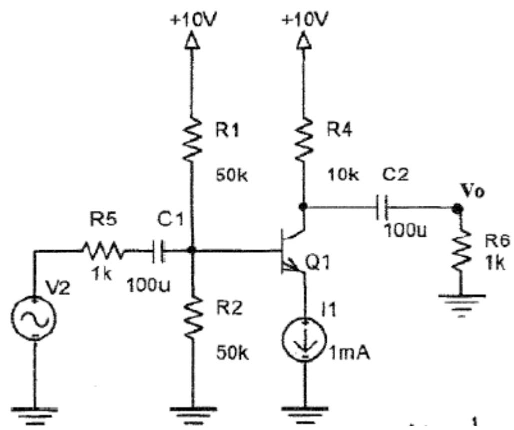
Use $|V_{BE}|=0.7$, $\beta=100$, $V_T=25mV$ (Vs is an ac source), ignore r_o.

Will this circuit work as an amplifier? Why or why not?

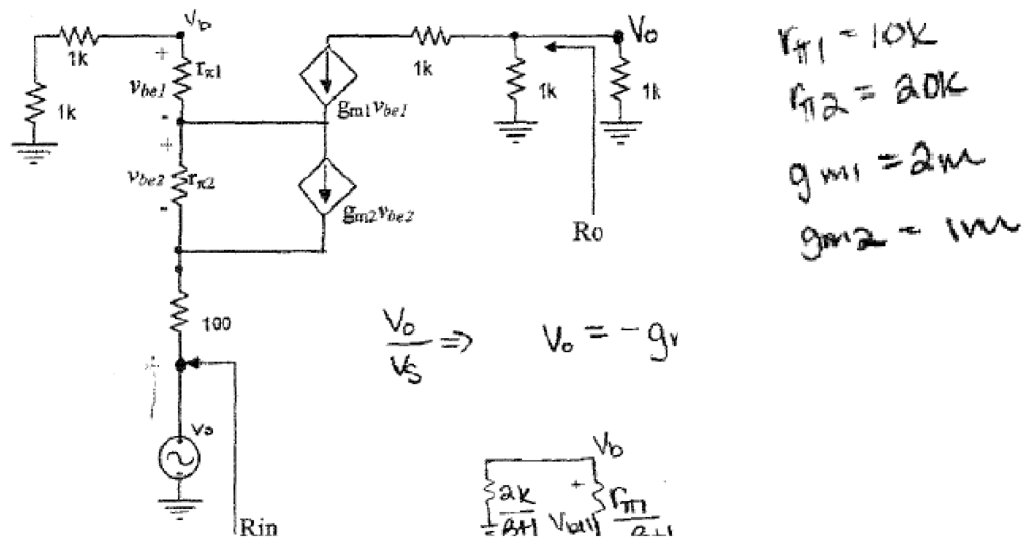


Example:

V2 = 0.1m sin(ωt) and β can vary from 20 to 200. The circuit shown below is suppose to amplify but does not. You expect the output at Vo to amplify V2. When you are testing the circuit, you find that it does not amplify. Explain why it does not and what exact resistor can be changed to allow it to amplify. I1 is not an ideal current source and can have a voltage drop across it.



Example


1k
1k
v_{be1}
$r_{\pi1}$
$g_{m1}v_{be1}$
v_{be2}
$r_{\pi2}$
$g_{m2}v_{be2}$
100
Rin
Ro
1k
1k
1k
Vo
$r_{\pi1}$ = 10K
$r_{\pi2}$ = 20K
g_{m1} = 2m
g_{m2} = 1m

Example:

Use $|V_{BE}|$=0.7, β=20, V_T=25mV (Vs is an ac source), ignore r_o.

This small-signal model circuit is drawn below. The original circuit is also shown below. It was found through a DC analysis that I_{C1}=50μ and I_{C2}=25μ.

(a) Find the ac parameters

a. $r_{\pi 1}$ **(3 points)** $= \frac{\beta}{g_{m1}} = \frac{20}{2m} = \boxed{10K}$

b. $r_{\pi 2}$ **(3 points)** $= \beta/g_{m2} = 20/1m = \boxed{20K}$

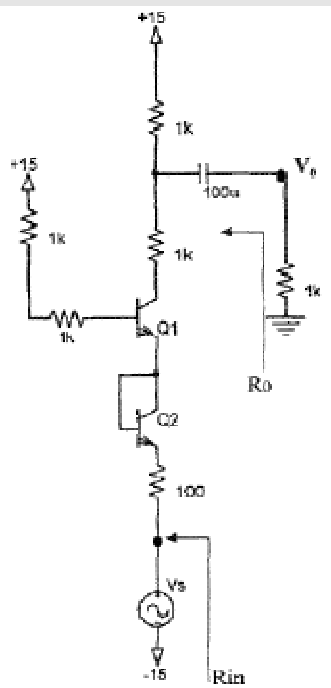
c. gm_1 **(3 points)** $= I_{C1}/V_T = 50\mu/25m = \boxed{2m}$

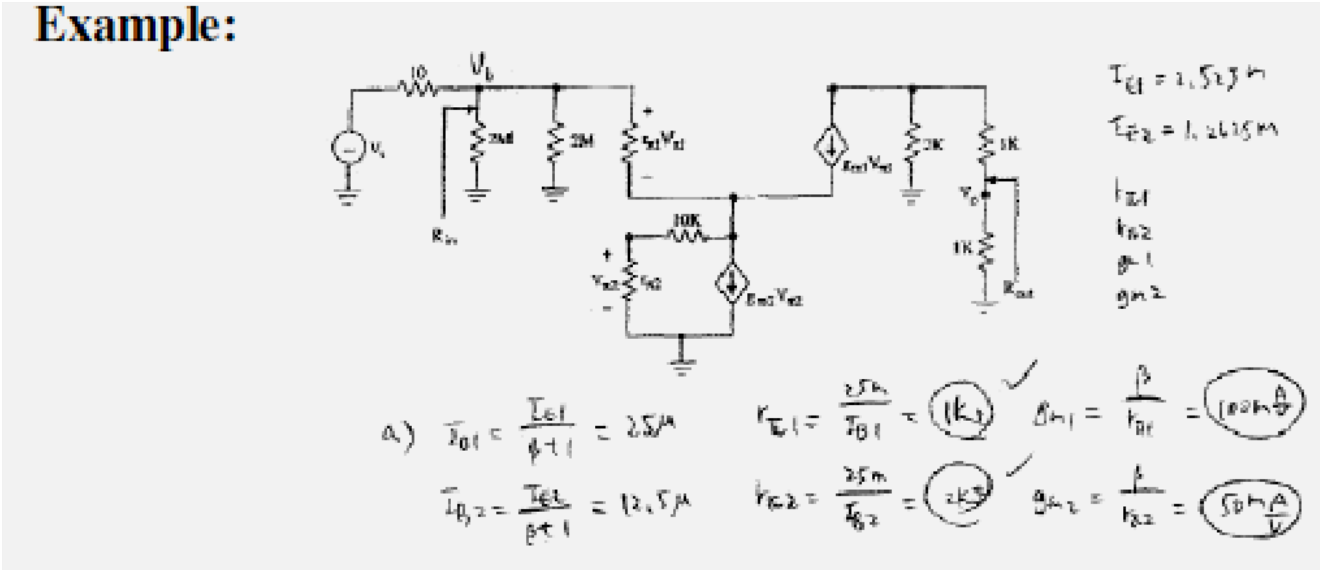
d. gm_2 **(3 points)** $= I_{C2}/V_T = 25\mu/25m = \boxed{1m}$

(b) Find that input resistance, R_{in}. (Ignore the AC input source Vs, include the 100 ohm) **(12 points)**

(c) Find the output resistance, R_o. (Ignore the load resistor of 1k to the right of arrow) **(6 points)**

(d) Find the overall gain, Vo/Vs. **(25 points)**

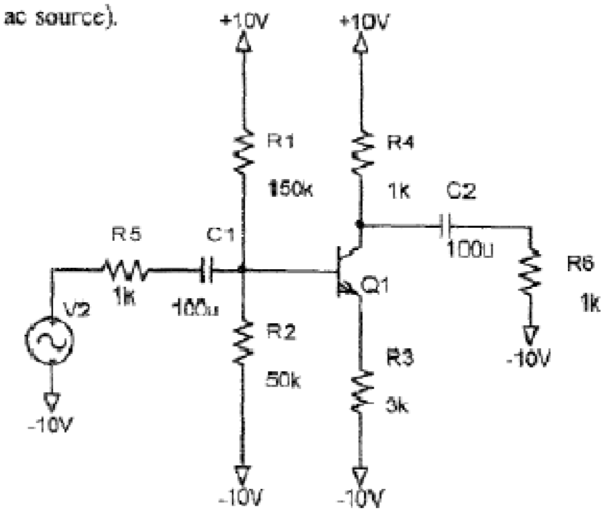



Example:
10
V_b
2M
2M
r_π1 V_π1
g_m1 V_π1
3K
1K
10K
V_π2
r_π2
g_m2 V_π2
1K
V_o
R_in
R_out
I_E1 = 2.525m
I_E2 = 1.2625m
r_π1
r_π2
gm1
gm2
a) I_B1 = I_E1 / β+1 = 25µ
r_π1 = 25m / I_B1 = 1kΩ
gm1 = β / r_π1 = 100m A/V
I_B2 = I_E2 / β+1 = 12.5µ
r_π2 = 25m / I_B2 = 2kΩ
gm2 = β / r_π2 = 50m A/V

Example:

Use $|V_{BE}|=0.7$, $\beta=100$, $V_T=25mV$ (V2 is an ac source).

- Find the DC values for the following
  a. I_{E1} **(15 points)**
  b. I_{C1} **(3 points)**
  c. V_{E1} **(6 points)**
  d. V_{C1} **(6 points)**
  e. V_{B1} **(5 points)**



Thevenin of R_1 and R_2: