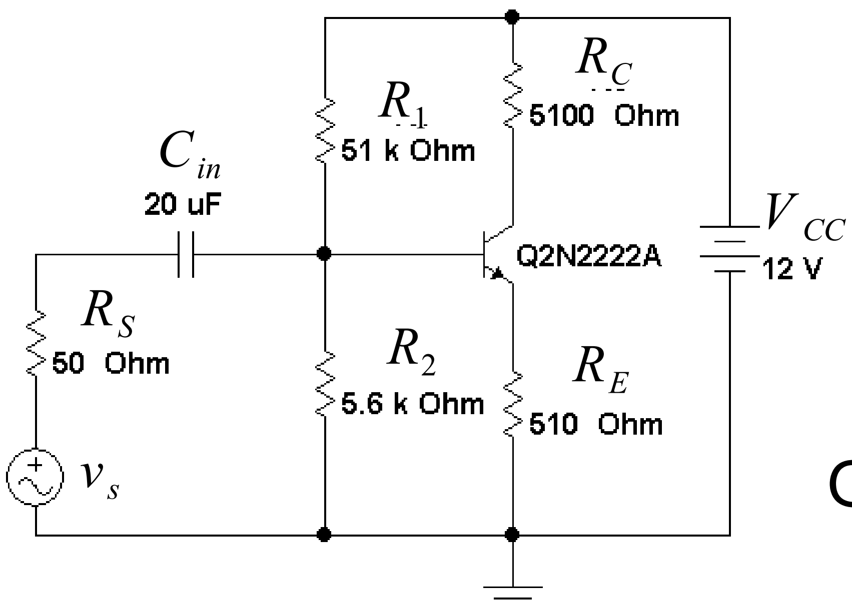
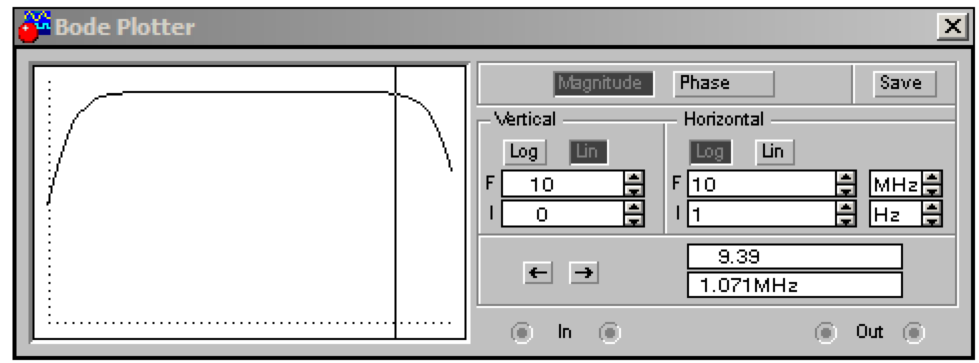
High Frequency BJT Model
Cascode BJT Amplifier

Gain of 10 Amplifier – Non-ideal Transistor

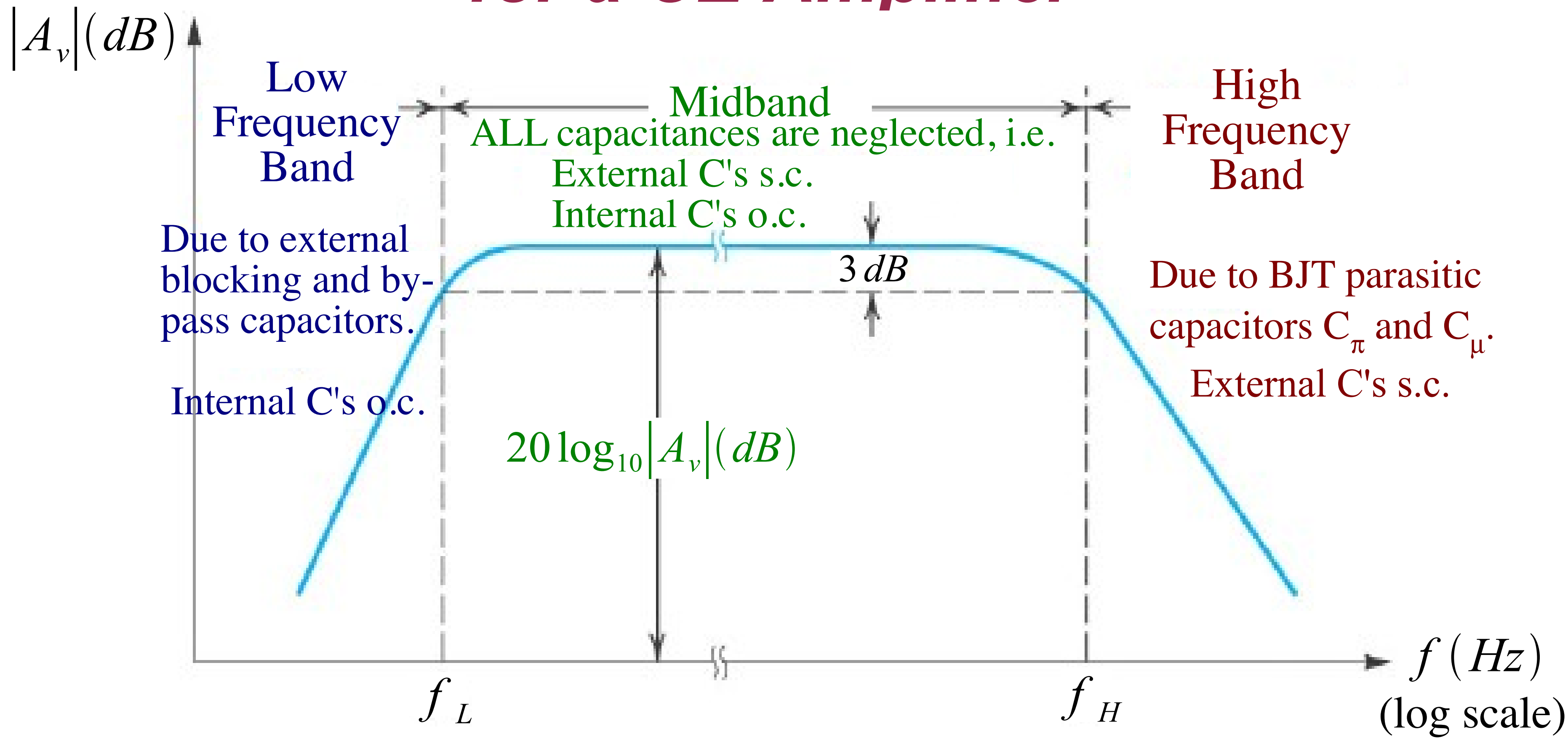




Gain starts dropping at > 1MHz.

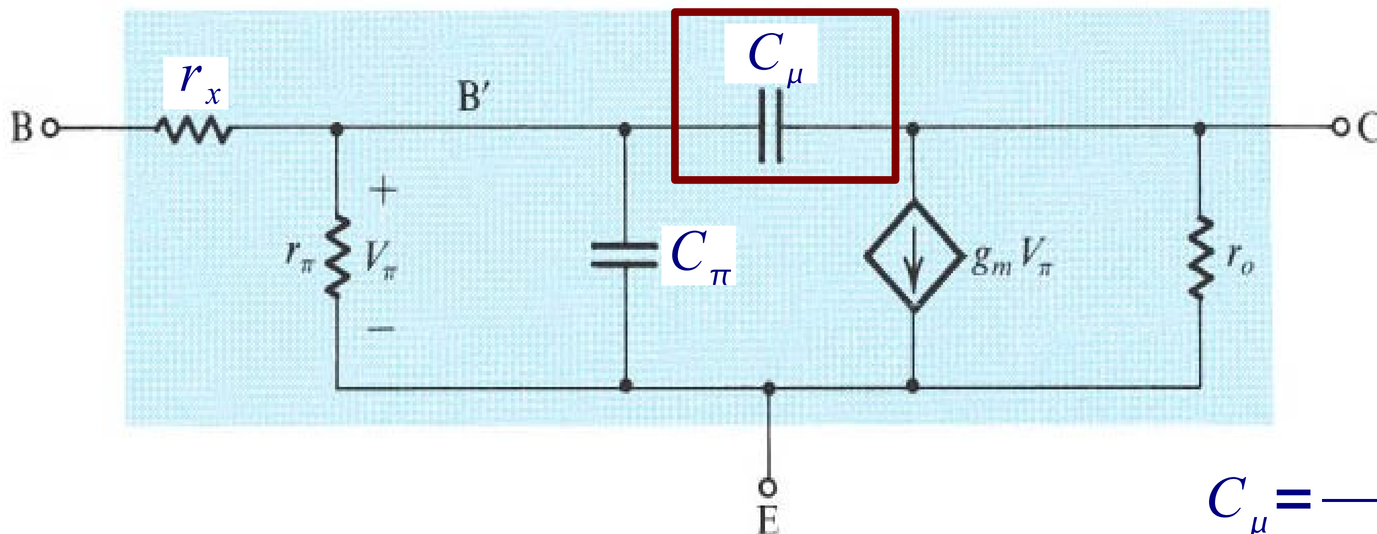
Why!
Because of internal transistor capacitances that we have ignored in our mid-band models.

Sketch of Typical Voltage Gain Response for a CE Amplifier



$BW = f_H - f_L \approx f_H$ $\quad$ $GBP = |A_v| BW$

High Frequency Small-signal Model



SPICE
CJC = $C_{\mu 0}$
CJE = C_{je0}
TF = τ_F
RB = r_x

$$C_\mu = \frac{C_{\mu 0}}{\left(1+\frac{V_{CB}}{V_{0c}}\right)^m}$$

Two capacitors and a resistor added.

A base to emitter capacitor, C_π

A base to collector capacitor, C_μ

A resistor, r_x, representing the base terminal resistance ($r_x << r_\pi$)

$$C_\pi = C_{de} + C_{je} \approx C_{de} + 2C_{je0}$$

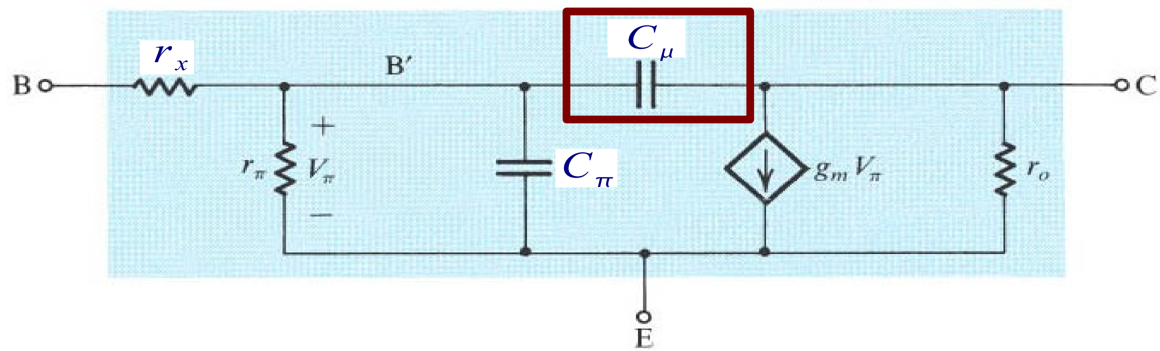
$$C_{de} = \tau_F g_m$$

τ_F = forward-base transit time

High Frequency Small-signal Model

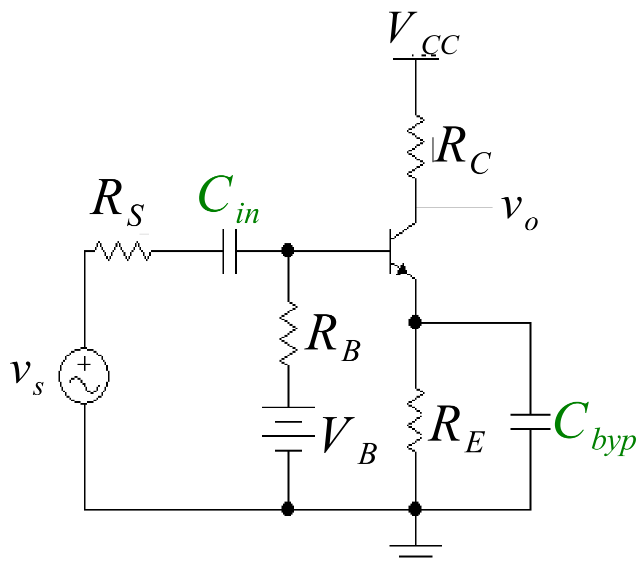
The transistor parasitic capacitances have a strong effect on circuit high frequency performance! They attenuate base signals, decreasing v_{be} since their reactance approaches zero (short circuit) at high frequencies.

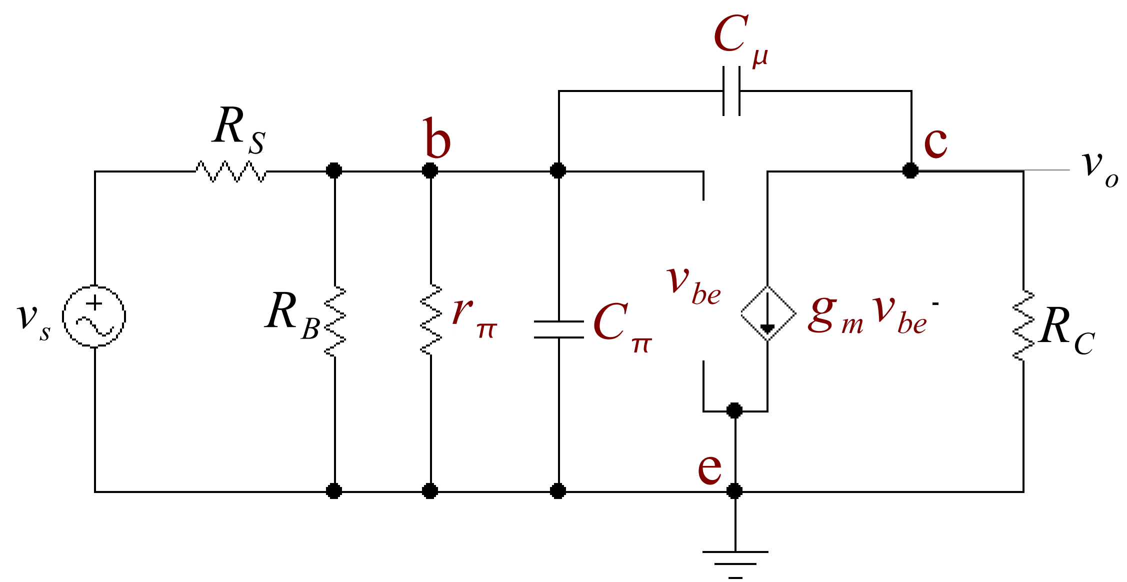
As we will see later C_μ is the principal cause of this gain loss at high frequencies. At the base C_μ looks like a capacitor of value $k\ C_\mu$ connected between base and emitter, where $k > 1$ and may be $>> 1$.



This phenomenon is called the *Miller Effect*.

Prototype Common Emitter Circuit

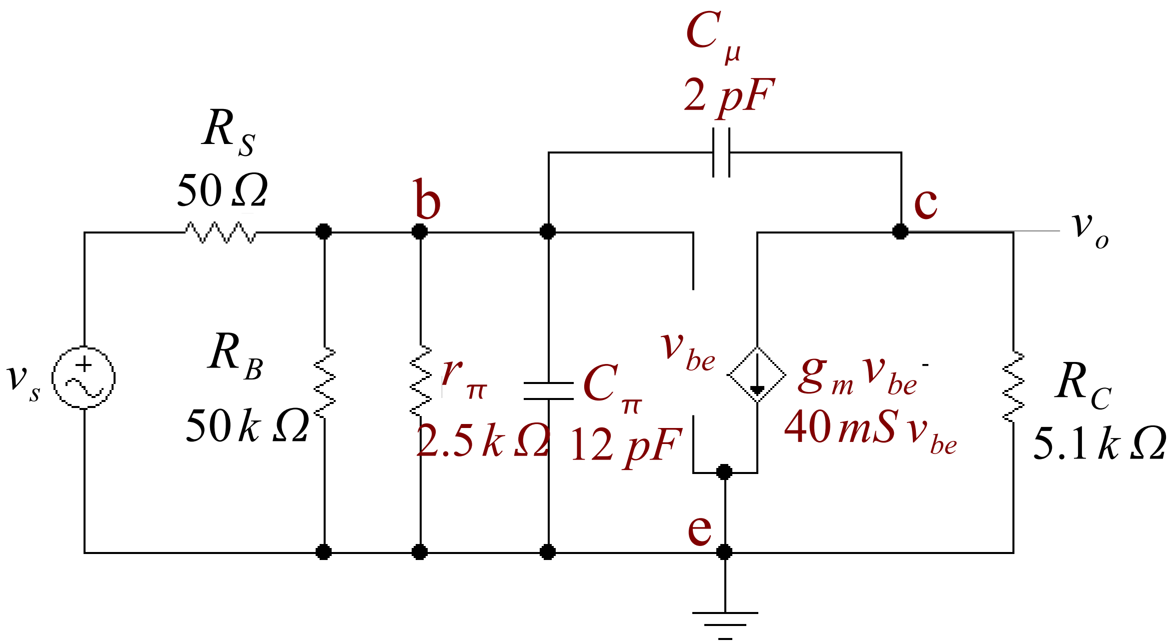


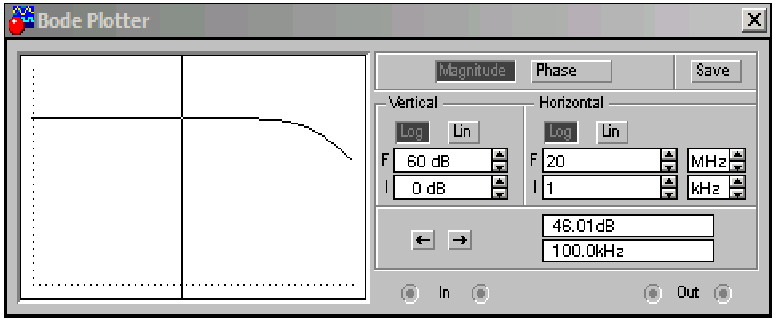


At high frequencies
"low frequency"
capacitors are "short circuits"

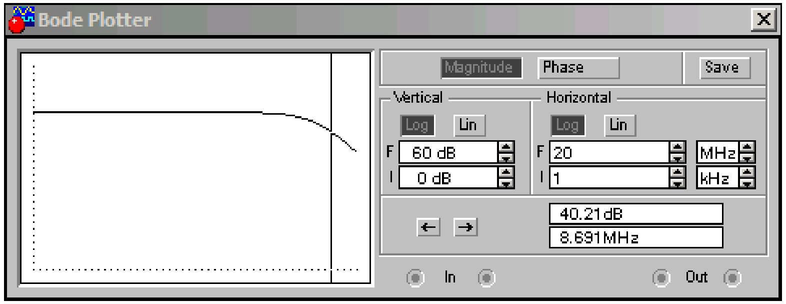
High frequency
small-signal ac model

Multisim Simulation



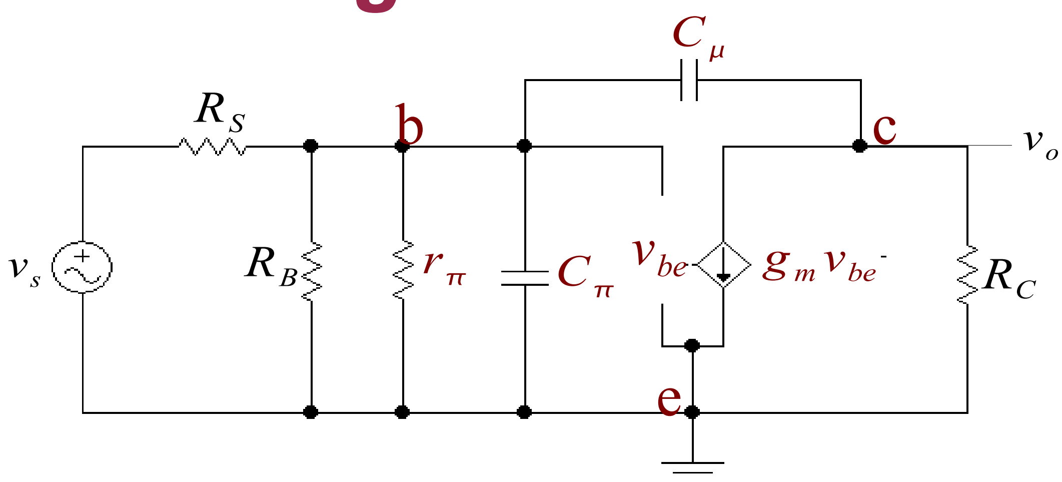


Mid-band gain



Half-gain point

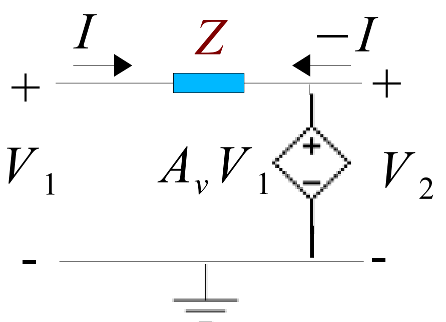
Introducing the Miller Effect



The feedback connection of C_μ between base and collector causes it to appear in the amplifier like a large capacitor $(1-K)C_\mu$ has been inserted Between the base and emitter terminals. This phenomenon is called the "Miller effect" and the capacitive multiplier "$1-K$" acting on C_μ equals the CE amplifier mid-band gain, i.e. $K=A_v=-g_m R_C$.

NOTE: CB and CC amplifiers do not suffer from the Miller effect, since in these amplifiers, one side of C_μ is connected directly to ground.

Miller's Theorem



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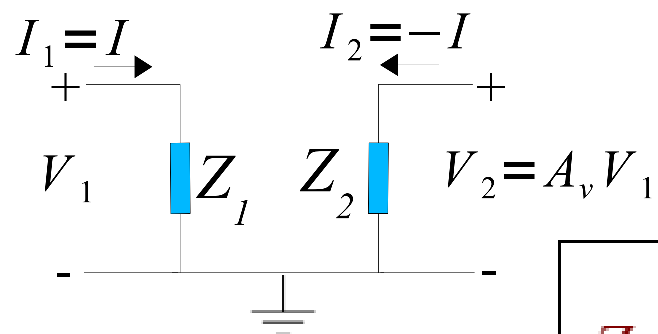


$$I=\frac{V_1-V_2}{Z}=\frac{V_1-A_vV_1}{Z}=\frac{V_1}{\frac{Z}{1-A_v}}\quad \Rightarrow \quad Z_1=\frac{V_1}{I_1}=\frac{V_1}{I}=\frac{Z}{1-A_v}$$

$$Z=\frac{1}{j2\pi f C_\mu}$$

$$Z_1=\frac{1}{j2\pi f C_\mu(1-A_v)}$$

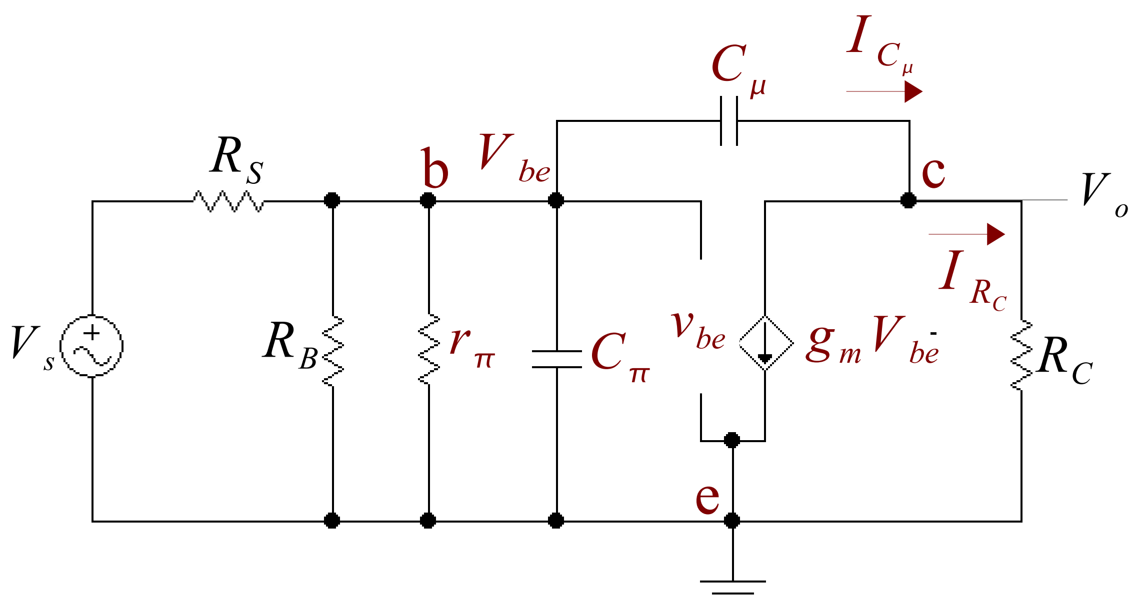
$$-I=\frac{V_2-V_2}{Z}=\frac{V_2-\frac{1}{A_v}V_2}{Z}=\frac{V_2}{\frac{Z}{1-\frac{1}{A_v}}}\quad \Rightarrow \quad Z_2=\frac{V_2}{I_2}=\frac{V_2}{-I}=\frac{Z}{1-\frac{1}{A_v}}\approx Z$$

if $A_v >> 1$

$$Z_2=\frac{V_2}{I_2}=\frac{V_2}{-I}\approx\frac{1}{j2\pi f C_\mu}$$

Ignored in practical circuits

Common Emitter Miller Effect Analysis



Determine effect of C_μ:

Using phasor notation:

$$I_{R_C} = -g_m V_{be} + I_{C_\mu}$$

or

$$V_o = \left(-g_m V_{be} + I_{C_\mu}\right) R_C$$

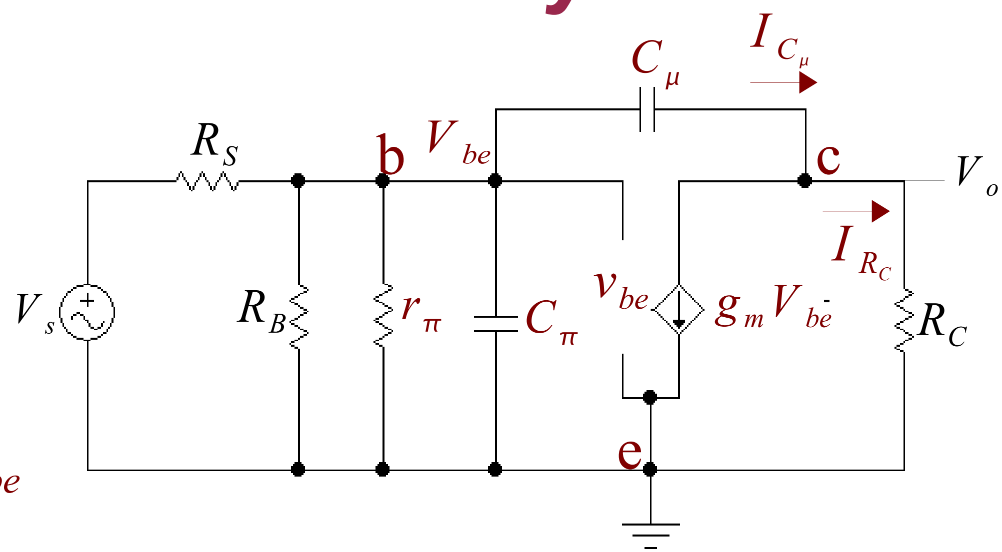
where

$$I_{C_\mu} = \left(V_{be} - V_o\right) s C_\mu$$

$$I_{C_\mu} = \left(V_{be} + \underbrace{g_m V_{be} R_C - I_{C_\mu} R_C}_{V_o}\right) s C_\mu$$

Note: The current through C_μ depends only on V_{be}!

Common Emitter Miller Effect Analysis II



From slide 7:

$$I_{C_\mu} = \left(V_{be} + g_m V_{be} R_C - I_{C_\mu} R_C\right) s C_\mu$$

Collect terms for I_{C_μ} and V_{be}:

$$\left(1 + s R_C C_\mu\right) I_{C_\mu} = \left(1 + g_m R_C\right) s C_\mu V_{be}$$

$$I_{C_\mu} = \frac{\left(1 + g_m R_C\right) s C_\mu}{\left(1 + s R_C C_\mu\right)} V_{be} = \frac{s\left(1 + g_m R_C\right) C_\mu}{\left(1 + s R_C C_\mu\right)} V_{be} \approx s\left(1 + g_m R_C\right) C_\mu V_{be}$$

$\omega R_C C_\mu \ll 1$

Miller Capacitance C_{eq}: $C_{eq} = (1 - A_v) C_\mu = (1 + g_m R_C) C_\mu$

Common Emitter Miller Effect Analysis III

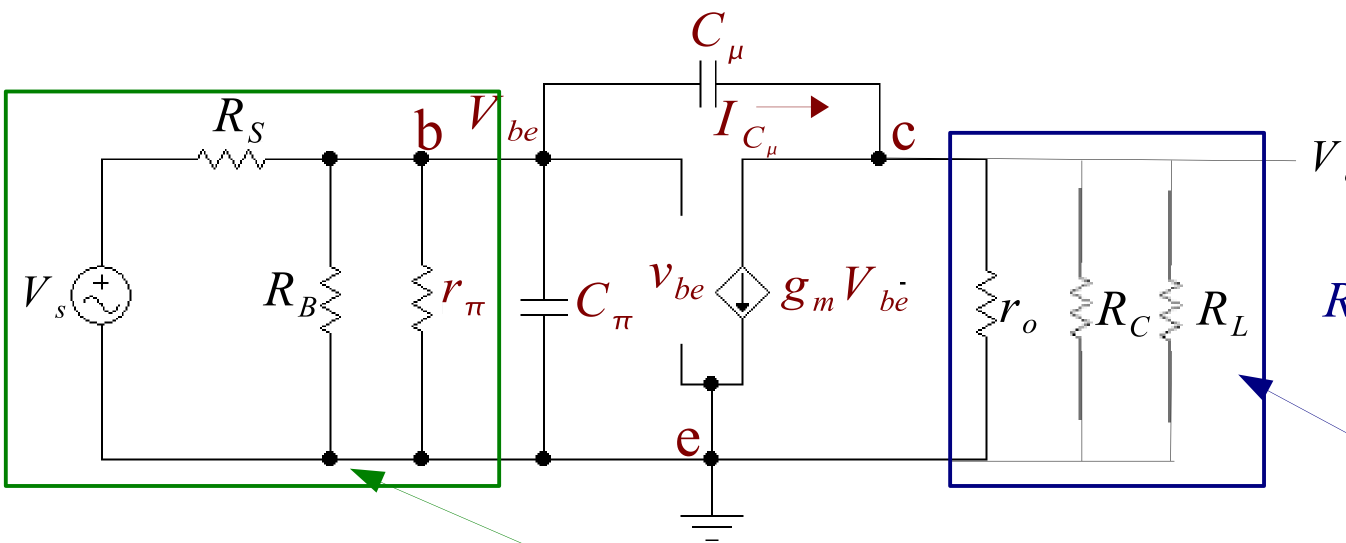
$$C_{eq}=\left(1+g_m R_C\right) C_\mu$$

For our example circuit:

$$1+g_m R_C=1+0.040\cdot 5100=205$$

$$C_{eq}=(205)\cdot 2\ pF\approx 410\ pF$$

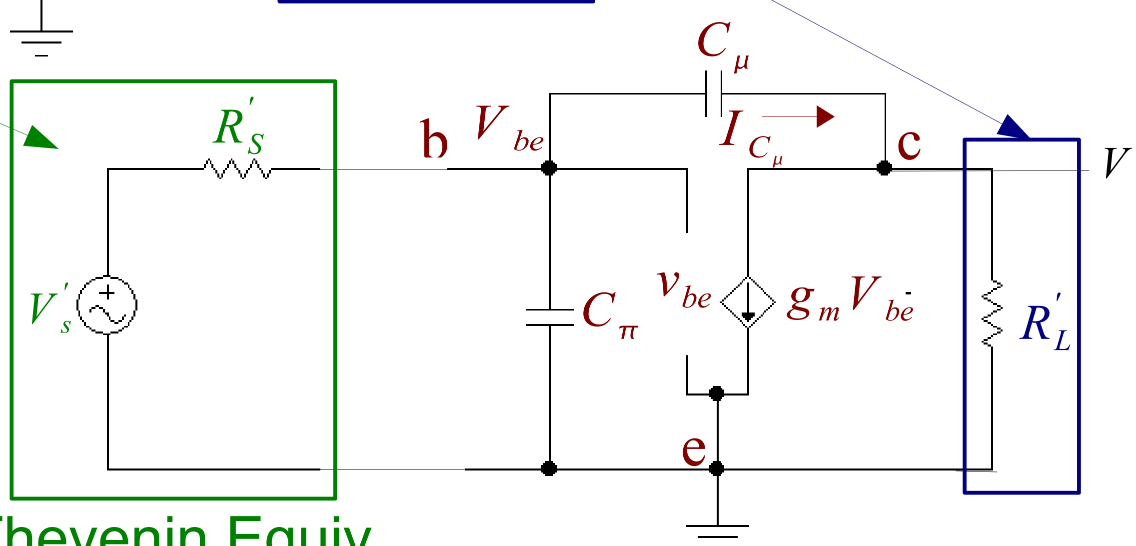
Simplified HF Model



$$R_L' = r_o \| (R_C \| R_L)$$

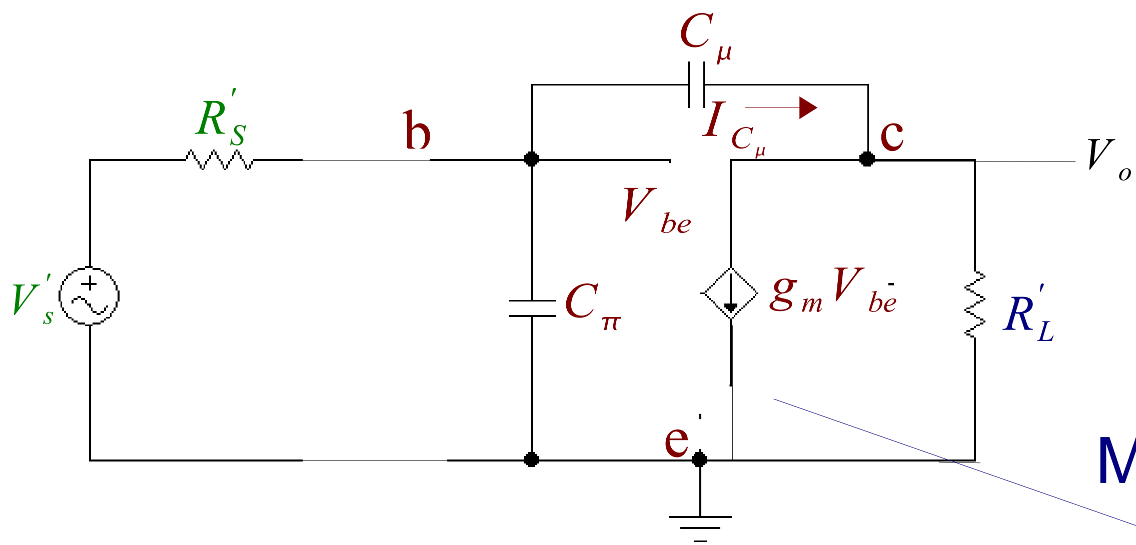
$$V_s' = V_s \frac{R_B \| r_\pi}{R_B \| r_\pi + R_S}$$

$$R_S' = r_\pi \| (R_B \| R_S)$$

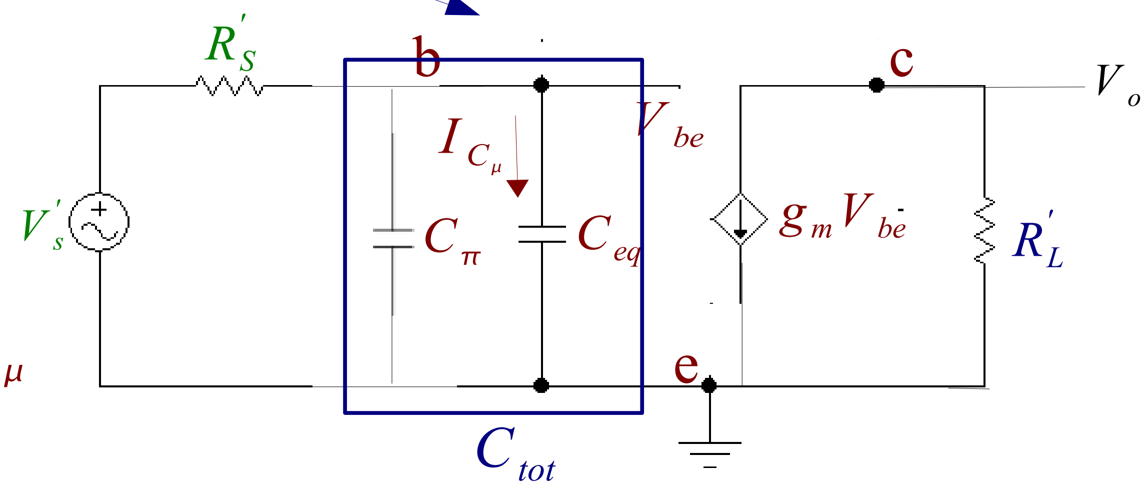


Thevenin Equiv.

Simplified HF Model



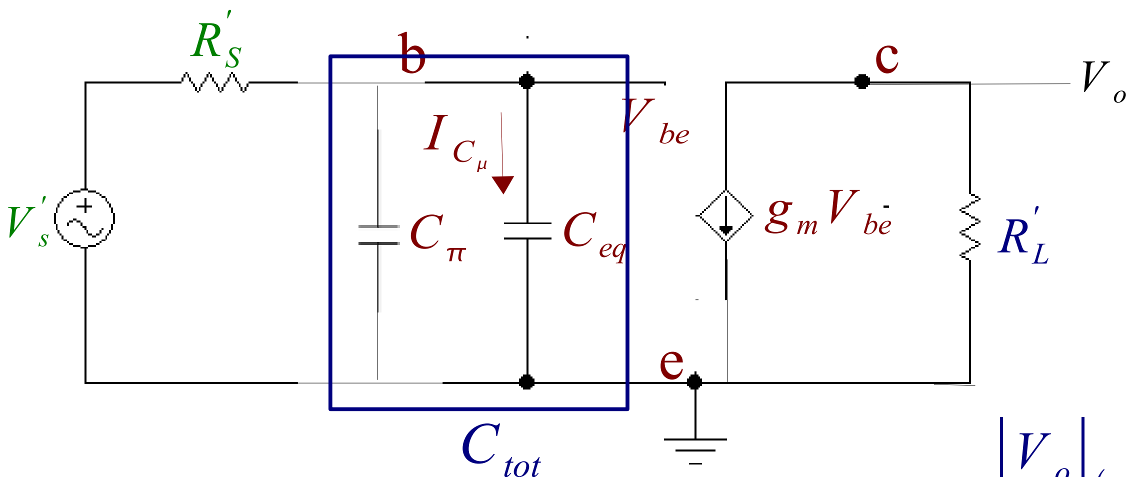
Miller's Theorem



$$C_{eq} = (1 + g_m R_C) C_\mu$$

$$C_{tot} = C_\pi + C_{eq}$$

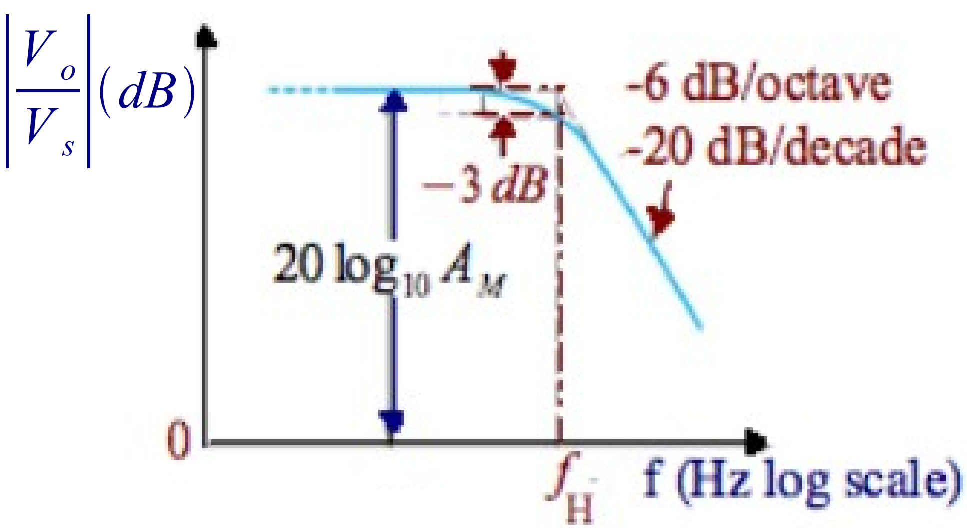
Simplified HF Model



$$C_{tot} = C_\pi + (1 + g_m R_C) C_\mu$$

$$A_v(f) = \frac{V_o}{V_s} \approx \frac{-g_m R_L'}{1 + j 2\pi f C_{tot} R_S'} = \frac{-g_m R_L'}{1 + j \dfrac{f}{f_H}}$$

$$A_M = g_m R_L' \quad \text{and} \quad f_H = \frac{1}{2\pi C_{tot} R_S'}$$



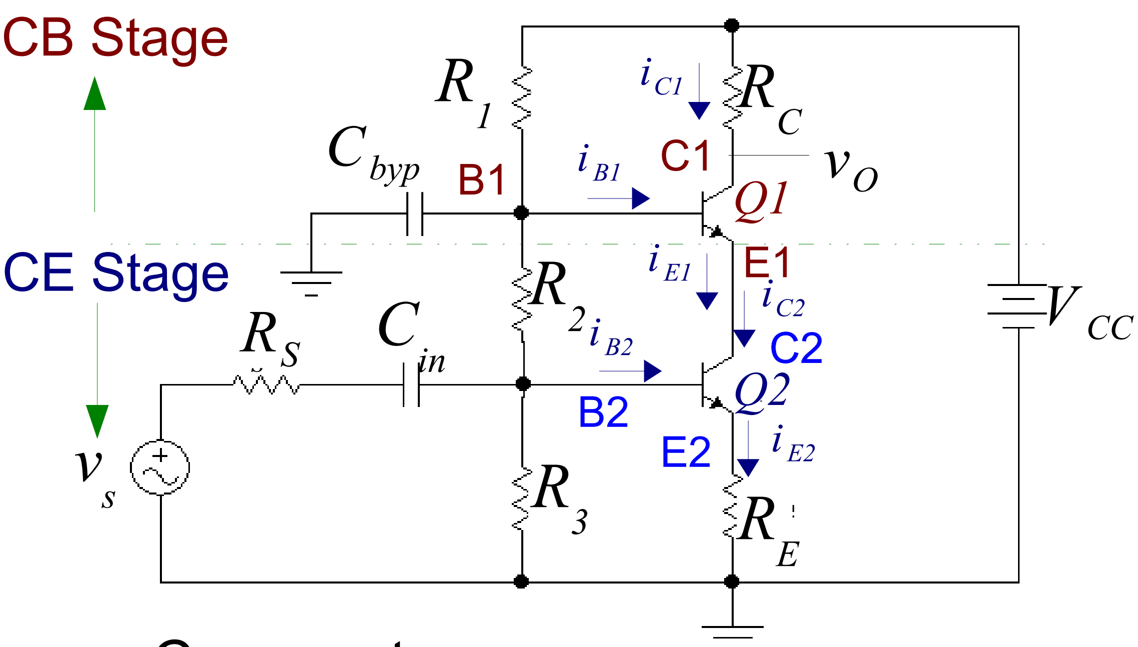
The Cascode Amplifier

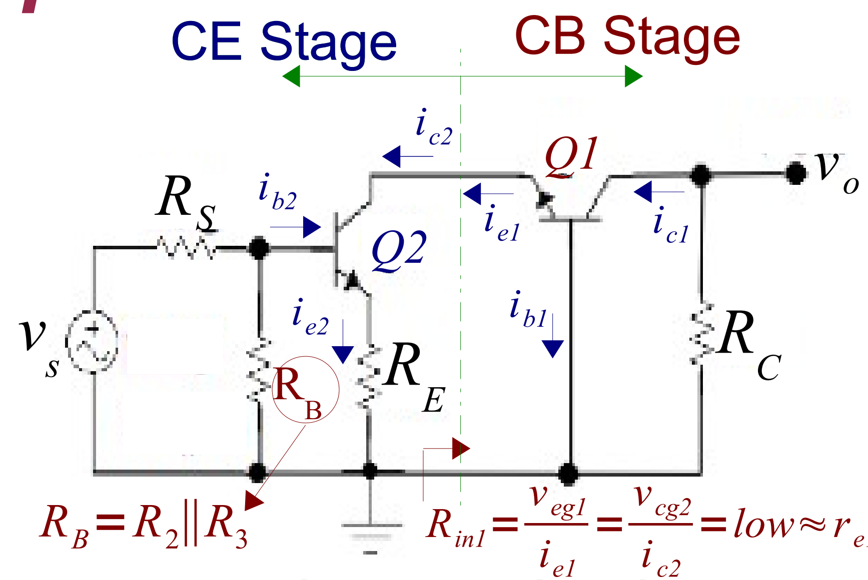
- A two transistor amplifier used to obtain simultaneously:
  1. Reasonably high input impedance.
  2. Reasonable voltage gain.
  3. Wide bandwidth.

- None of the conventional single transistor designs will satisfy all of the criteria above.
- The cascode amplifier will satisfy all of these criteria.
- A cascode is a CE Stage cascaded with a CB Stage.

(**Historical Note:** the cascode amplifier was a cascade of *grounded cathode* and *grounded grid* vacuum tube stages – hence the name “cascode,” which has remained in modern terminology.)

The Cascode Amplifier



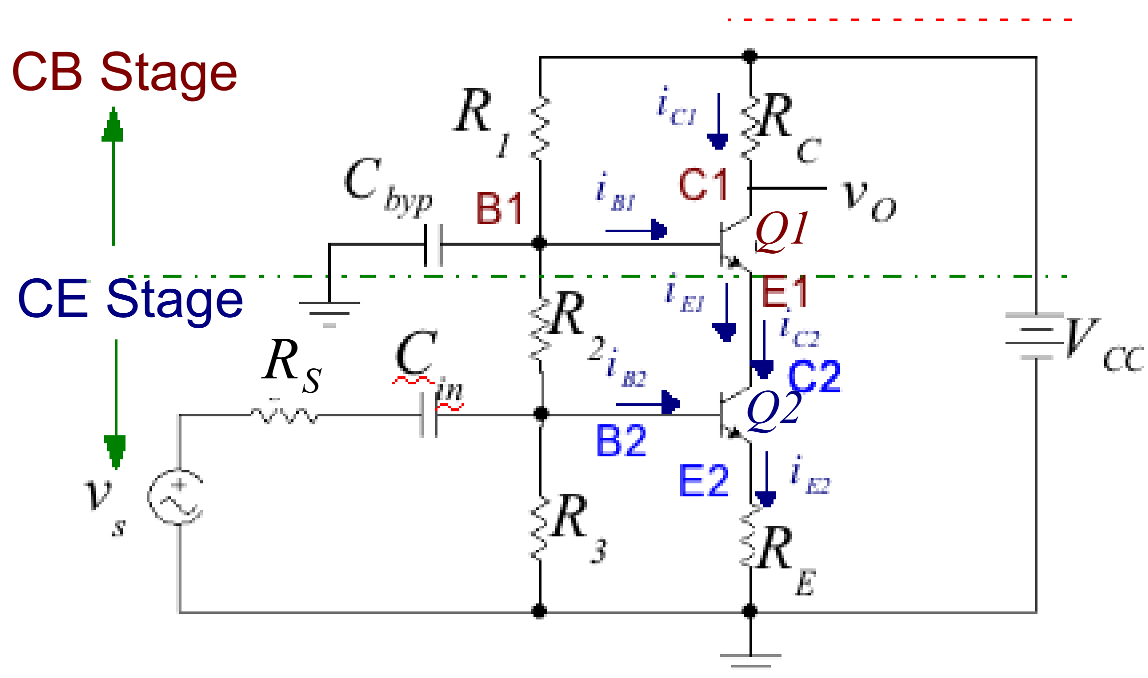


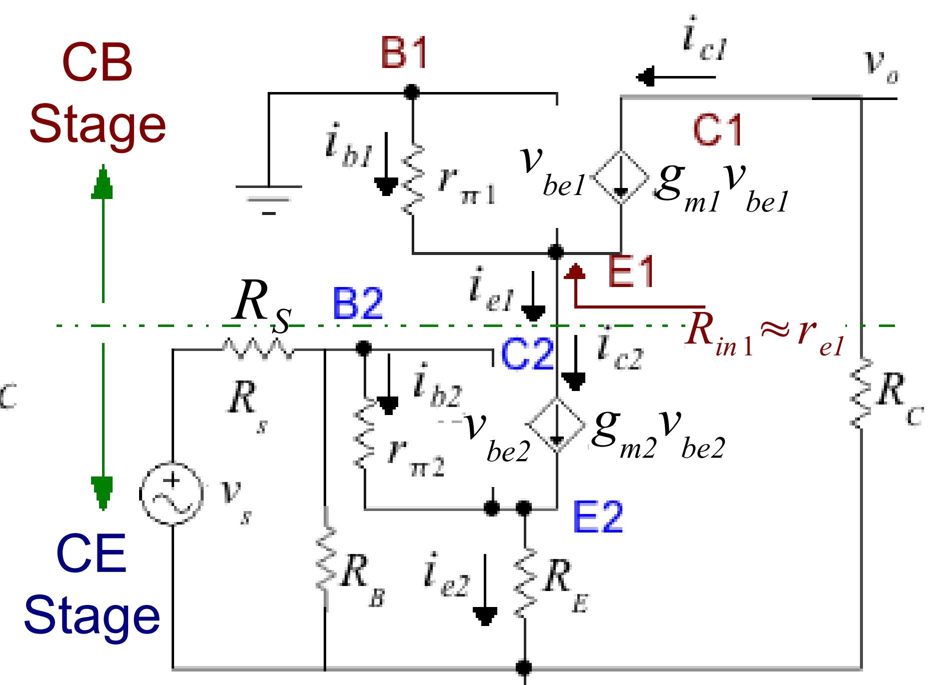
ac equivalent circuit

Comments:

1. R_1, R_2, R_3, and R_C set the bias levels for both Q1 and Q2.
2. Determine R_E for the desired voltage gain.
3. C_{in} and C_{byp} are to act as “open circuits” at dc and act as “short circuits” at all operating frequencies $f > f_{min}$.

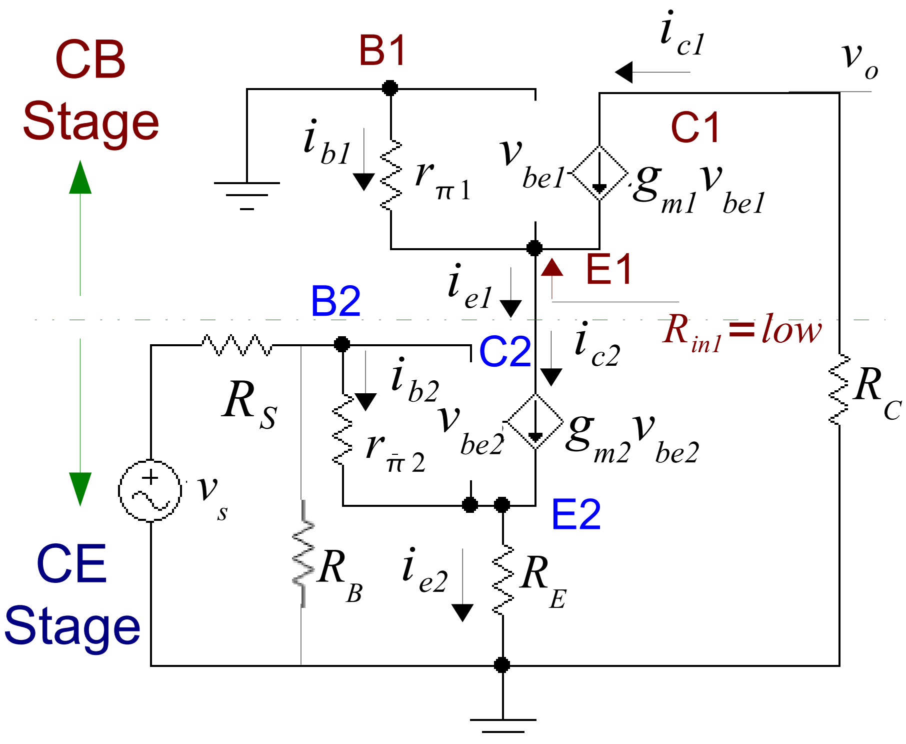
Cascode Mid-Band Small Signal Model





$$R_B = R_2 \| R_3$$

Cascode Small Signal Analysis



$g_{m1} = g_{m2} = g_m$

$r_{e1} = r_{e2} = r_e$

$r_{\pi 1} = r_{\pi 2} = r_\pi$

1. Show reduction in Miller effect
2. Evaluate small-signal voltage gain

OBSERVATIONS

a. The emitter current of the CB Stage is the collector current of the CE Stage. (This also holds for the dc bias current.)

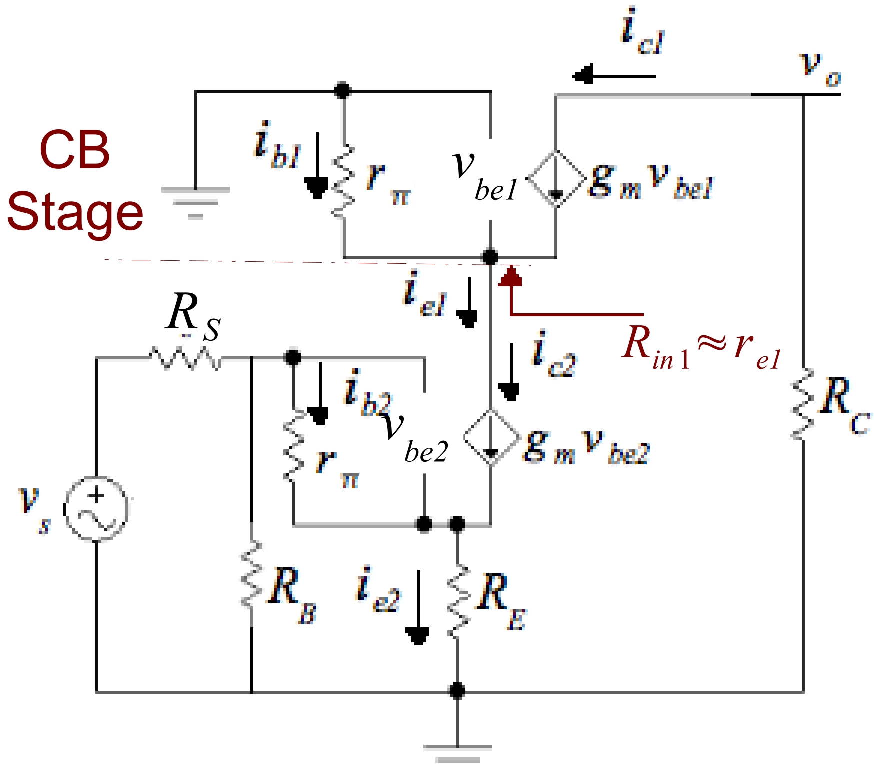
$$i_{e1} = i_{c2}$$

b. The base current of the CB Stage is:

$$i_{b1} = \frac{i_{e1}}{\beta + 1} = \frac{i_{c2}}{\beta + 1}$$

c. Hence, both stages have about same collector current $i_{c1} \approx i_{c2}$ and same g_m, r_e, r_π.

Cascode Small Signal Analysis cont.



The input resistance R_{in1} to the CB Stage is the small-signal "r_{e1}" for the CB Stage, i.e.

$$i_{b1} = \frac{i_{e1}}{\beta+1} = \frac{i_{c2}}{\beta+1}$$

The CE output voltage, the voltage drop from Q2 collector to ground, is:

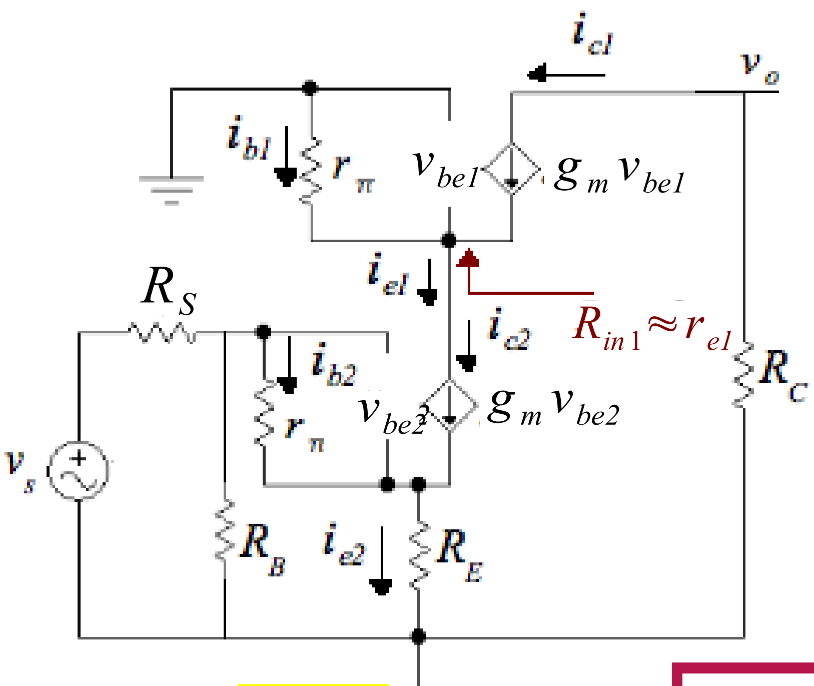
$$v_{c2} = v_{e1} = -r_\pi i_{b1} = -\frac{r_\pi}{\beta+1} i_{c2} = -\frac{r_\pi}{\beta+1} i_{e1}$$

Therefore, the CB Stage input resistance is:

$$R_{in1} = \frac{v_{e1}}{-i_{e1}} = \frac{r_\pi}{\beta+1} = r_{e1}$$

$$A_{vCE-Stage} = \frac{v_{c2}}{v_s} \approx -\frac{R_{in1}}{R_E} = -\frac{r_e}{R_E} < 1 \quad \Rightarrow \quad C_{eq} = \left(1 + \frac{r_e}{R_E}\right) C_\mu < 2\, C_\mu$$

Cascode Small Signal Analysis - cont.



Now, find the CE collector current in terms of the input voltage v_s: Recall $i_{c1} \approx i_{c2}$

$$i_{b2} \approx \frac{v_s}{R_S \| R_B + r_\pi + (\beta+1) R_E}$$

$$i_{c2} = \beta i_{b2} \approx \frac{\beta v_s}{R_S \| R_B + r_\pi + (\beta+1) R_E} \approx \frac{\beta v_s}{(\beta+1) R_E}$$

for bias insensitivity: $(\beta+1) R_E \gg R_S \| R_B + r_\pi$

$$i_{c1} \approx i_{e1} = i_{c2} \approx i_{e2}$$

$$i_{c2} \approx \frac{v_s}{R_E}$$

$$v_o = -i_{c2} R_C$$

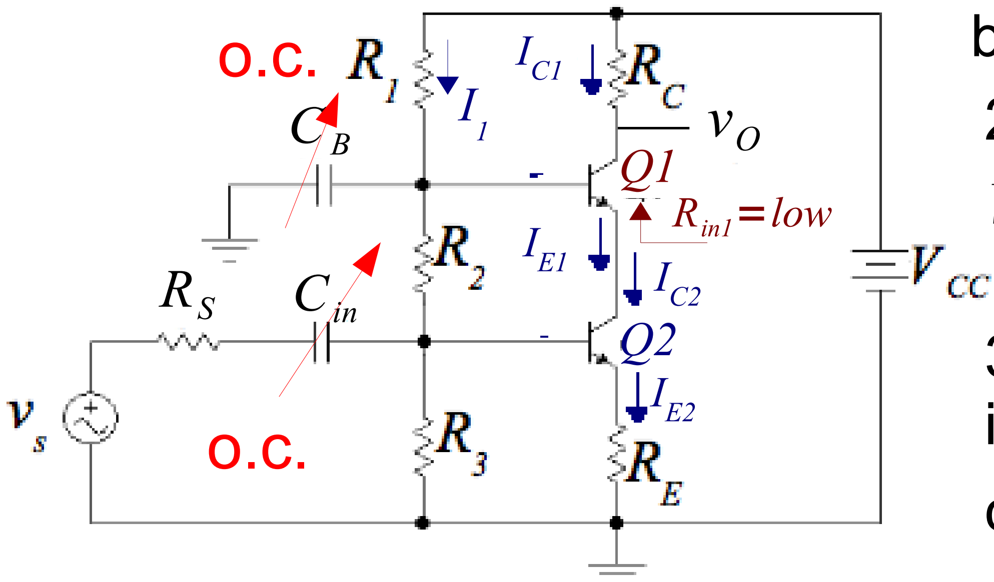
=>

$$A_v = \frac{v_o}{v_s} = \frac{-R_C}{R_E}$$

OBSERVATIONS:

1. Voltage gain A_v is about the same as a stand-along CE Amplifier.
2. HF cutoff is much higher then a CE Amplifier due to the reduced C_{eq}.

Cascode Biasing



$$\alpha_2 I_{E2} = I_{C2} = I_{E1} = \frac{1}{\alpha_1} I_{C1} \Rightarrow I_{C1} \approx I_{E2}$$

1. Choose I_{E1} – make it relatively large to reduce $R_{in1} = r_e = V_T / I_{E1}$ to push out HF break frequencies.

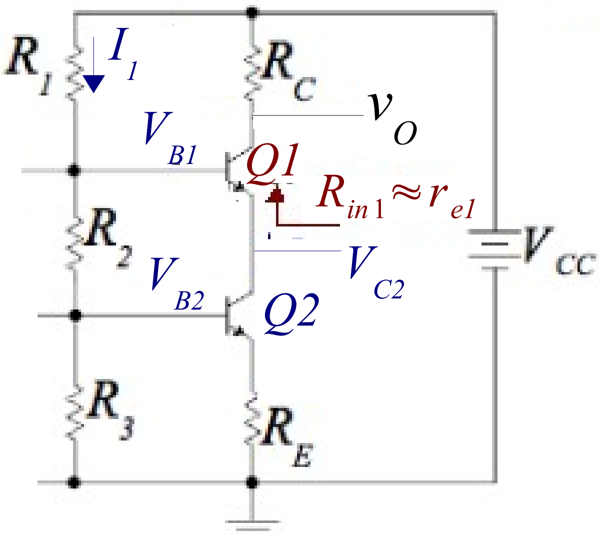
2. Choose R_C for suitable voltage swing V_{C1} and R_E for desired gain.

3. Choose bias resistor string such that its current I_1 is about 0.1 of the collector current I_{C1}.

4. Given R_E, I_{E2} *and* $V_{BE2} = 0.7\ V$ calc. R_3.

5. Need to also determine R_1 & R_2.

Cascode Biasing - cont.



Since the CE-Stage gain is very small:

a. The collector swing of Q2 will be small.

b. The Q2 collector bias $V_{C2} = V_{B1} - 0.7\ V$.

6. Set $V_{B1} - V_{B2} = 1\,V \Rightarrow V_{CE2} = 1\,V$

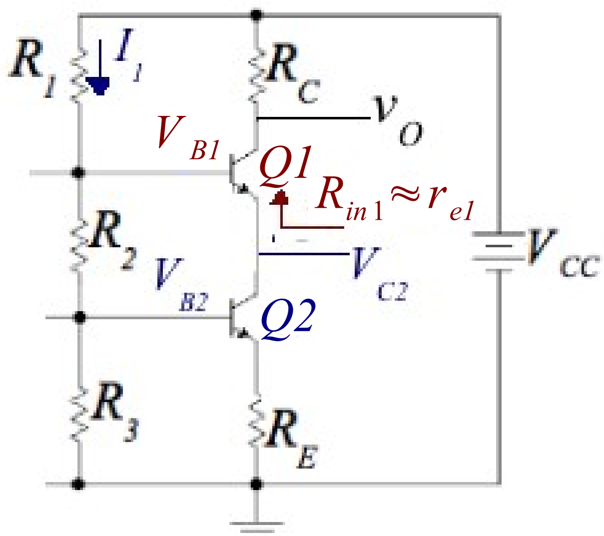
This will limit V_{CB2} $V_{CB2} = V_{CE2} - V_{BE2} = 0.3\,V$ which will keep Q2 forward active.

$$V_{CE2} = V_{C2} - V_{Re} = V_{C2} - (V_{B2} - 0.7\,V)$$
$$= V_{B1} - 0.7\,V - V_{B2} + 0.7\,V$$
$$= V_{B1} - V_{B2}$$

7. Next determine R_2. Its drop $V_{R2} = 1\ V$ with the known current.

$$R_2 = \frac{V_{B1} - V_{B2}}{I_1}$$

Cascode Biasing - cont.



$$R_2 = \frac{V_{B1} - V_{B2}}{I_1} = \frac{1\,V}{I_1}$$

8. Then calculate R_3. $R_3 = \frac{V_{B2}}{I_1}$

where $V_{B2} = 0.7\,V + I_E R_E$

Note: $R_1 + R_2 + R_3 = \frac{V_{CC}}{I_1}$

9. Then calculate R_1.

$$R_1 = \frac{V_{CC}}{0.1\,I_C} - R_2 - R_3$$

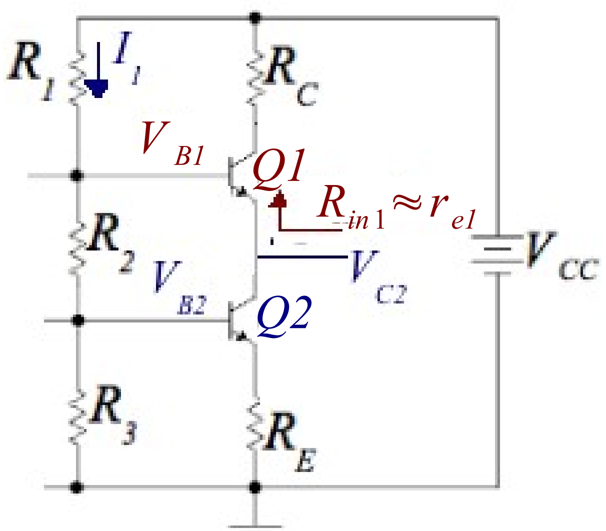
Cascode Bias Summary

SPECIFIED: A_v, V_{CC}, V_{C1} (CB collector voltage);

SPECIFIED: I_E (or I_C) directly or indirectly through BW.

DETERMINE: R_C, R_E, R_1, R_2 and R_3.

SET: $V_{B1} - V_{B2} = 1\,V \Rightarrow V_{CE2} \approx 1\,V$



$$I_{C2} = I_{E1} \approx I_{C1} \approx I_{E2} = I_C$$

STEP1: $R_C = \dfrac{V_{C1}}{I_C}$ $\quad R_E = \dfrac{R_C}{|A_v|}$

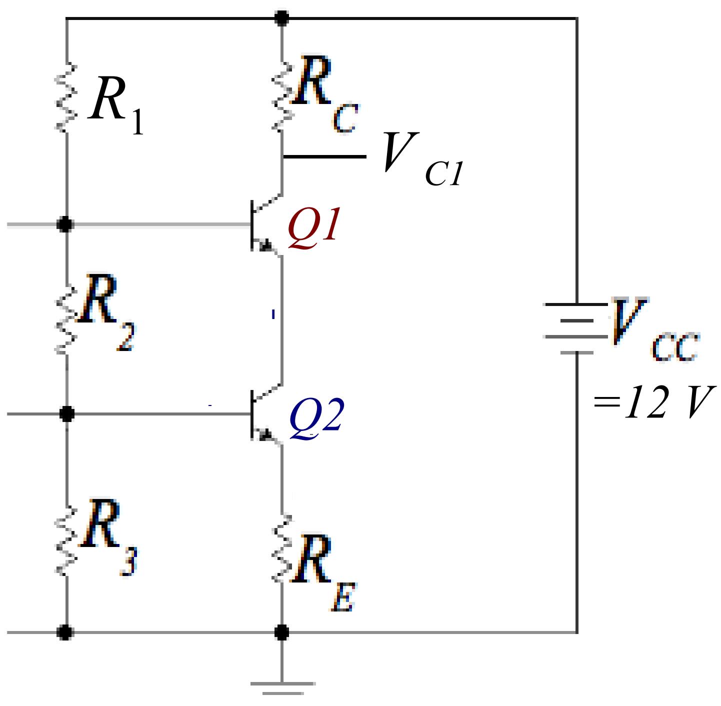
STEP2: $R_2 = \dfrac{V_{B1} - V_{B2}}{I_1} = \dfrac{1\,V}{0.1\,I_C}$

STEP3: $R_3 = \dfrac{V_{B2}}{I_1} = \dfrac{0.7\,V + I_E R_E}{0.1\,I_C}$

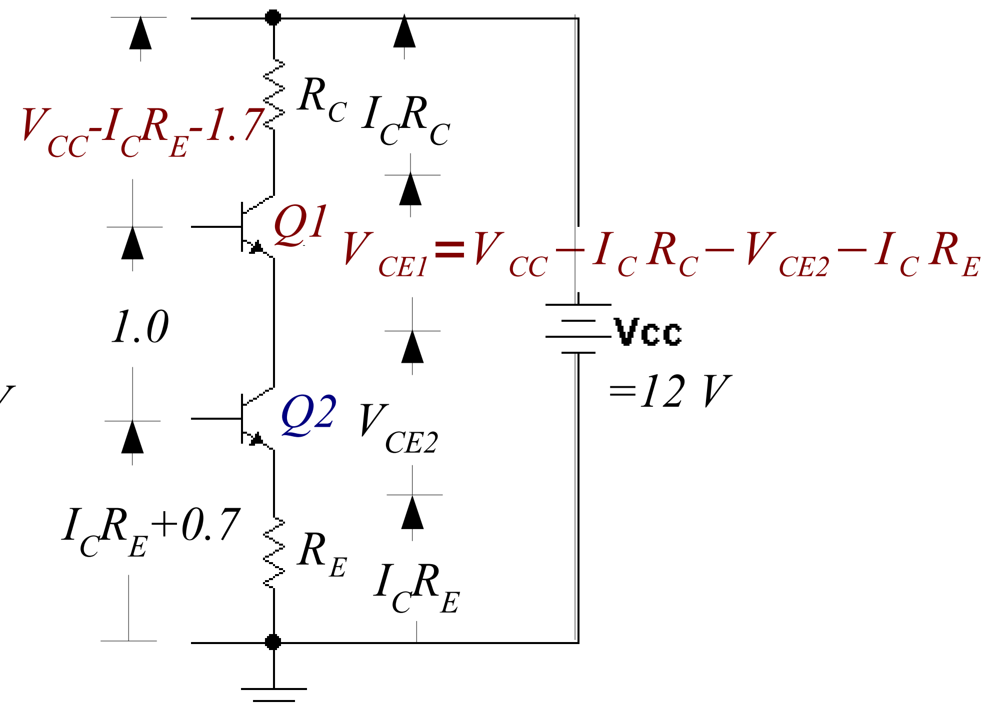
$$R_1 + R_2 + R_3 = \frac{V_{CC}}{I_1} = \frac{V_{CC}}{0.1\,I_C}$$

STEP4: $R_1 = \dfrac{V_{CC}}{0.1\,I_C} - R_2 - R_3$

Cascode Bias Example



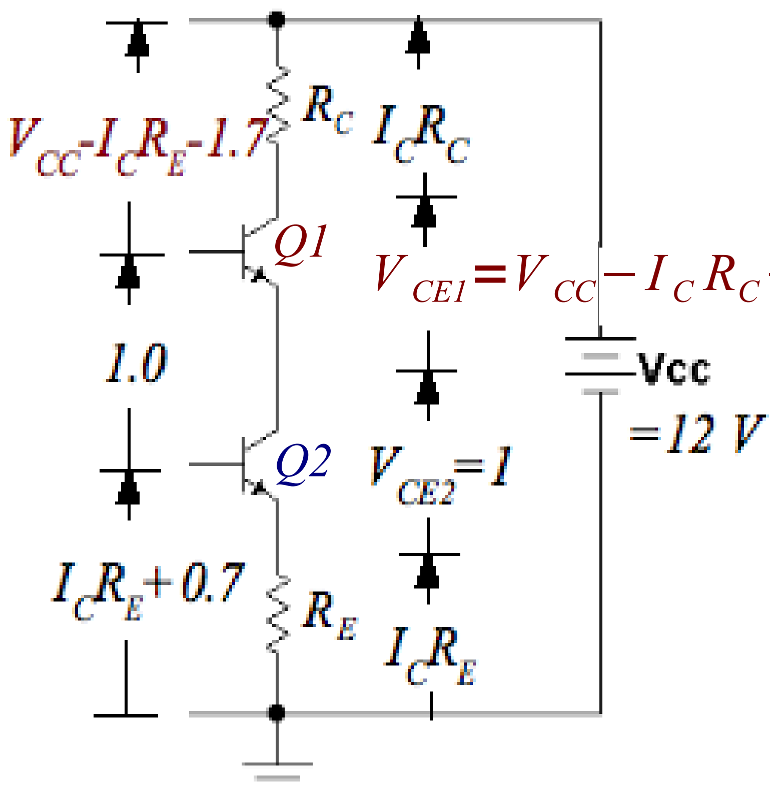
Cascode Amp



$$I_{E2} \approx I_{C2} = I_{E1} \approx I_{C1} \Rightarrow I_{C1} \approx I_{E2}$$

Typical Bias Conditions

Cascode Bias Example cont.

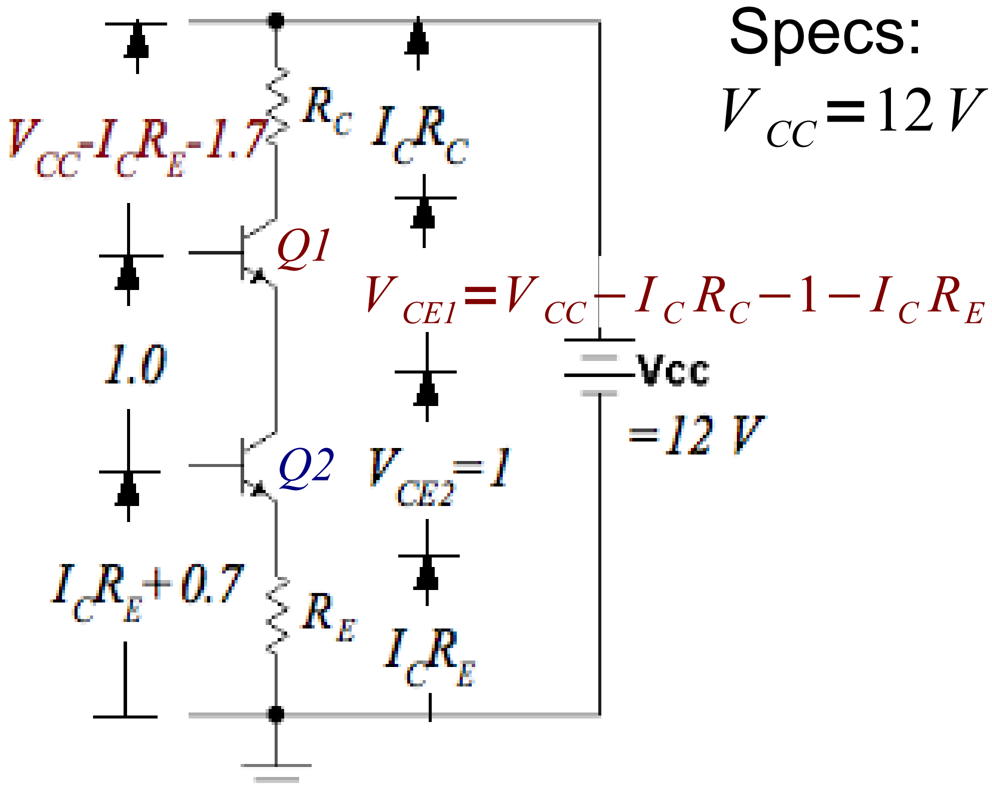


1. Choose I_{E1} – make it a bit high to lower r_e.
Try $I_{E1} = 5\ mA$ => $r_e = 0.025\,V / I_E = 5\,\Omega$.

2. Set desired gain magnitude. For example if $A_V = -10$, then $R_C/R_E = 10$.

3. Since the CE stage gain is very small, V_{CE2} can be small, i.e. $V_{CE2} = V_{B1} - V_{B2} = 1\ V$.

Cascode Bias Example cont.



Specs:

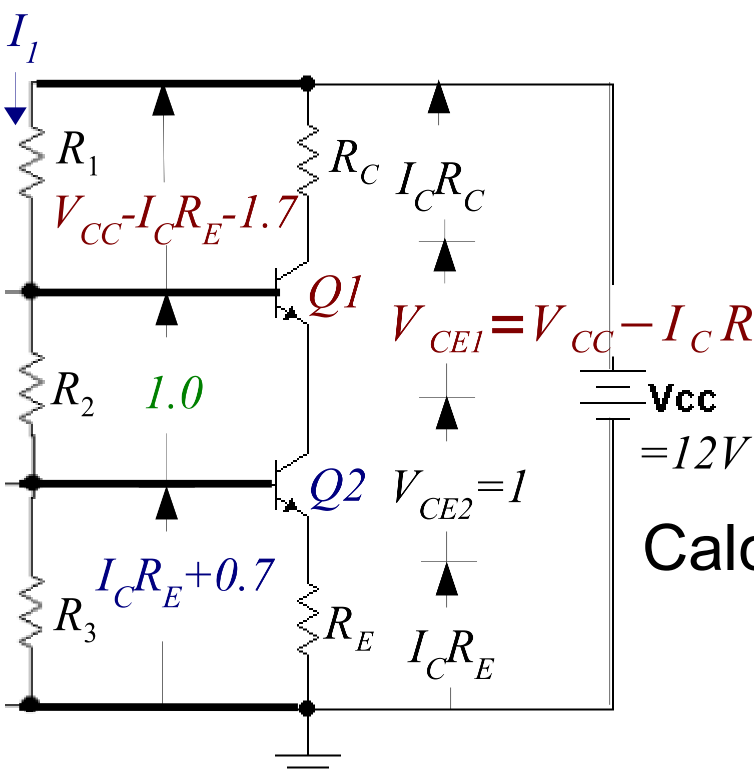
$V_{CC}=12\,V \quad V_{C1}=7\,V \quad I_C=5\,mA \quad |A_v|=\frac{R_C}{R_E}=10$

Determine R_C for $V_{C1} = 7V$.

$$R_C=\frac{V_{CC}-V_{C1}}{5\cdot 10^{-3}\,A}=\frac{5\,V}{5\cdot 10^{-3}\,A}=1000\,\Omega$$

$$R_E=\frac{R_C}{|A_v|}=\frac{R_C}{10}=100\,\Omega$$

Cascode Bias Example cont.



$$V_{CC}=12 \quad R_C=1\,k\,\Omega \quad I_C=5\,mA. \quad R_E=100\,\Omega$$

Make current through the string of bias resistors $I_1 = 0.1\,I_C = 0.5\,mA$.

$$R_1+R_2+R_3=\frac{V_{CC}}{I_1}=\frac{12}{5\cdot 10^{-4}}=24\,k\,\Omega$$

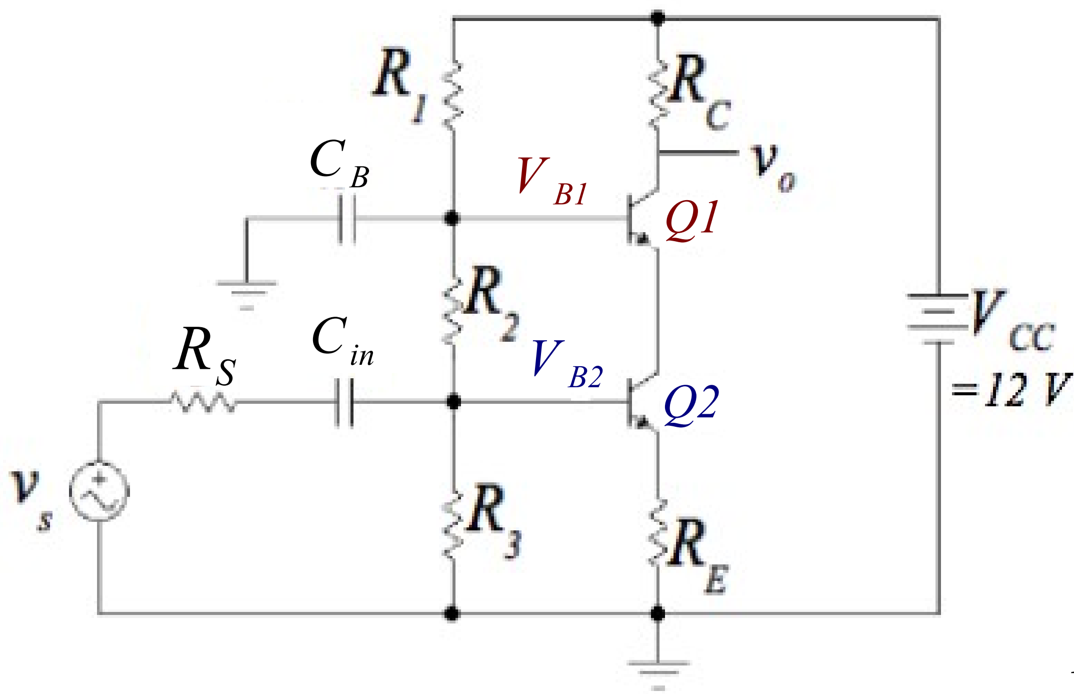
Calculate the bias voltages (base side of Q1, Q2):

$$V_{CC}-I_C R_E-1.7\,V=12\,V-0.5\,V-1.7\,V=9.8\,V$$

$$V_{B1}-V_{B2}=1\,V$$

$$V_{B2}=I_C R_E+0.7=5\cdot 10^{-3}\cdot 100+0.7=1.2\,V$$

Cascode Bias Example cont.



$$V_{B2}=5\cdot 10^{-4}R_3=1.2\,V$$

$$R_3=2.4\,k\,\Omega$$

$$V_{B1}-V_{B2}=5\cdot 10^{-4}R_2=1.0\,V$$

$$R_2=2\,k\,\Omega$$

Recall: $R_1+R_2+R_3=24\,k\,\Omega$

$$R_1=24000-2.400-2000=19.6\,k\,\Omega$$

$V_{CC}=12$, $R_C=1\,k\,\Omega$, $V_{B2}=1.2\,V$,

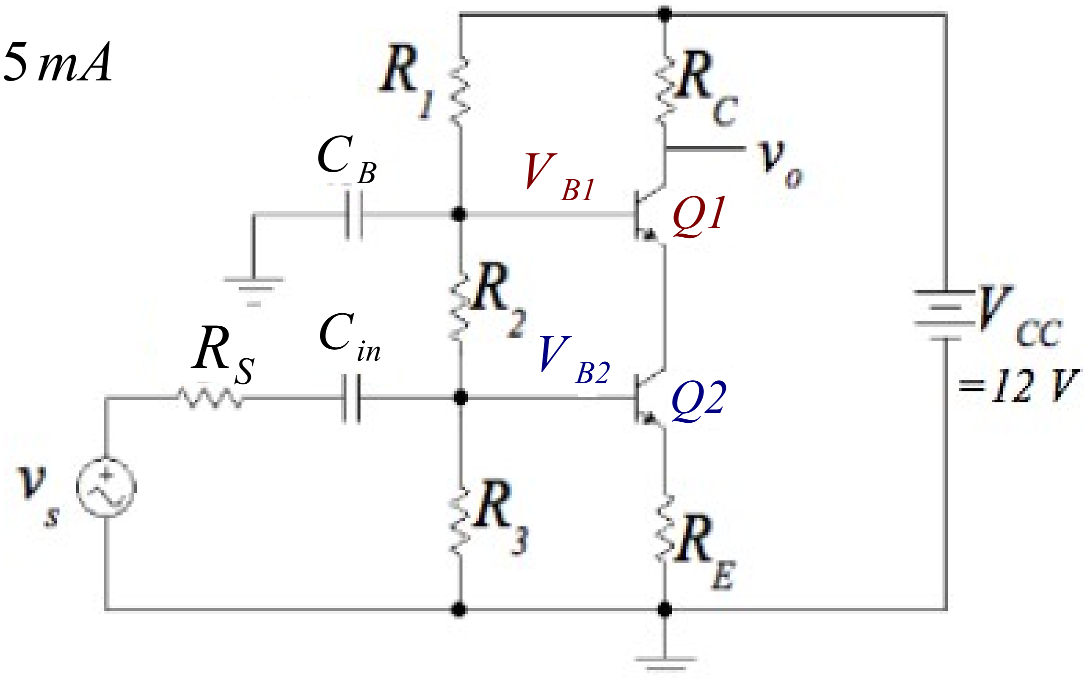
$I_C=5\,mA$, $R_E=100\,\Omega$, $V_{B1}-V_{B2}=1.0\,V$

Completed Design

$r_e = 5\,\Omega \Rightarrow I_C = 5\,mA$

$V_{C1} = 7\,V$

$|A_v| = \frac{R_C}{R_E} = 10$



$R_1 = 19.6\,k\Omega$

$R_2 = 2\,k\Omega$

$R_3 = 2.4\,k\Omega$

$R_C = 1\,k\Omega$

$R_E = 100\,\Omega$

$f_H = \frac{1}{2\pi C_{tot} R'_S}$

$C_{tot} = C_\pi + \left(1 + \frac{r_e}{R_E}\right) C_\mu$

$= C_\pi + 1.05\, C_\mu$

If $C_\pi = 12\,pF$

$C_\mu = 2\,pF$

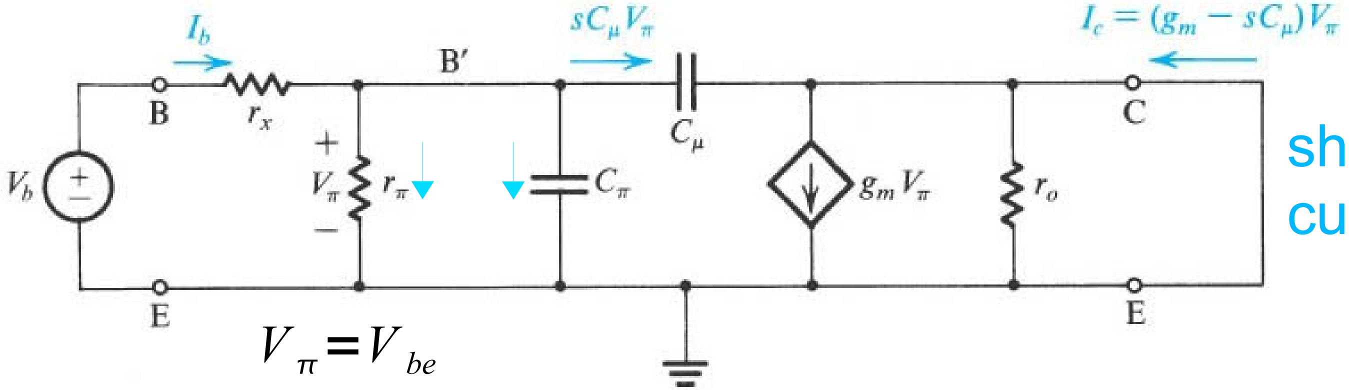
$C_{tot} = 14.1\,pF$

$f_{Hcascode} = 225.8\,MHz$

For CE with $|A_v| = 10$

$f_{HCE} = 94\,MHz$

Frequency-dependent "beta" h_{fe}



short-circuit current

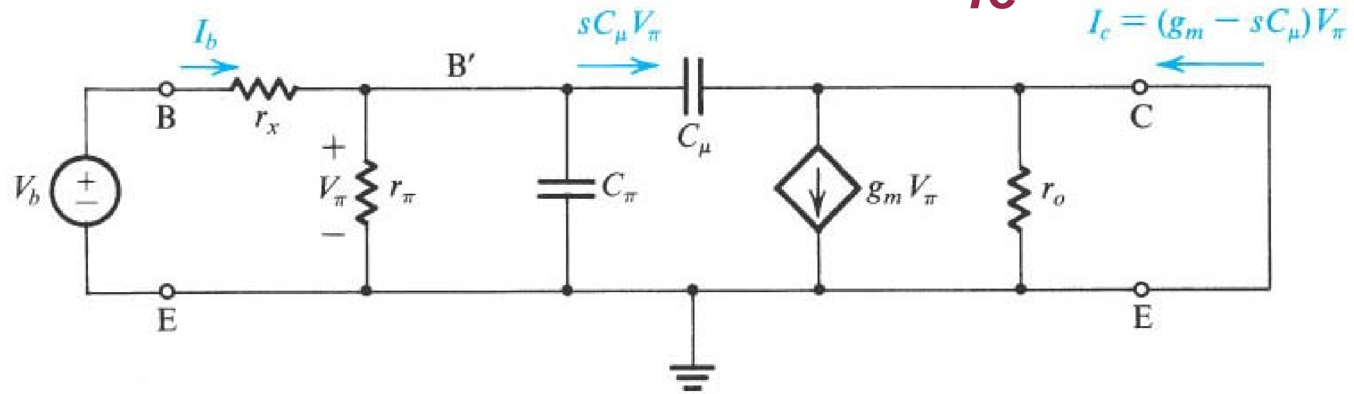
The relationship $i_c = \beta\, i_b$ does not apply at high frequencies $f > f_H$!

Using the relationship – $i_c = f(V_\pi)$ – find the new relationship between i_b and i_c. For i_b (using *phasor notation* (I_x & V_x) *for frequency domain analysis*):

@ node B': $I_b = \left(\frac{1}{r_\pi} + sC_\pi + sC_\mu\right)V_\pi$ where $r_x \approx 0$ (ignore r_x)

NOTE: $s = \sigma + j\omega$, in sinusoidal steady-state $s = j\omega$.

Frequency-dependent h_{fe} or "beta"



$$I_b = \left(\frac{1}{r_\pi} + sC_\pi + sC_\mu\right)V_\pi$$ @ node C: $I_c = (g_m - sC_\mu)V_\pi$ (ignore r_o)

Leads to a new relationship between the I_b and I_c:

$$h_{fe} = \frac{I_c}{I_b} = \frac{g_m - sC_\mu}{\frac{1}{r_\pi} + sC_\pi + sC_\mu}$$

Frequency Response of h_{fe}

$$h_{fe}=\frac{g_m - sC_\mu}{\frac{1}{r_\pi}+sC_\pi+sC_\mu}$$

multiply N&D by r_π and set $s=j\omega$

$$h_{fe}=\frac{(g_m - j\omega C_\mu)r_\pi}{1+j\omega(C_\pi+C_\mu)r_\pi}$$

factor N to isolate g_m

$$h_{fe}=\frac{\left(1-j\omega\frac{C_\mu}{g_m}\right)g_m r_\pi}{1+j\omega(C_\pi+C_\mu)r_\pi}$$

$g_m r_\pi = \beta$

$$g_m=\frac{I_C}{V_T} \qquad r_\pi=\beta\frac{V_T}{I_C}$$

For small $\omega=\omega_{low}$: $\omega_{low}\frac{C_\mu}{g_m}\ll 1<\frac{1}{10}$

and: $\omega_{low}(C_\pi+C_\mu)r_\pi\ll 1<\frac{1}{10}$

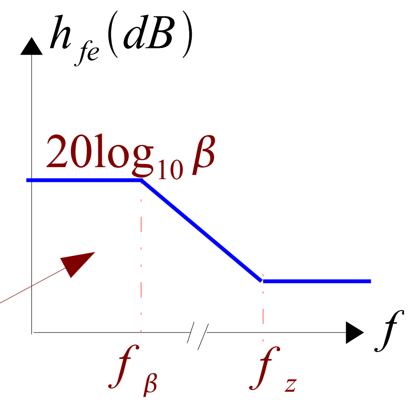
Note: $\omega_{low}(C_\pi+C_\mu)r_\pi=\omega_{low}(C_\pi+C_\mu)\frac{\beta}{g_m}\gg\omega_{low}\frac{C_\mu}{g_m}$

We have: $h_{fe}=g_m r_\pi=\beta$

Frequency Response of h_{fe} cont.

$$h_{fe}=\frac{(1-j\omega\frac{C_\mu}{g_m})g_m r_\pi}{1+j\omega(C_\pi+C_\mu)r_\pi}=\frac{\left(1-j\frac{\omega}{\omega_z}\right)}{\left(1+j\frac{\omega}{\omega_\beta}\right)}g_m r_\pi=\frac{\left(1-j\frac{f}{f_z}\right)}{\left(1+j\frac{f}{f_\beta}\right)}\beta$$

ω_β



$$(C_\pi+C_\mu)r_\pi=(C_\pi+C_\mu)\frac{\beta}{g_m}\gg\frac{C_\mu}{g_m} \Rightarrow f_z\gg f_\beta$$

Hence, the lower break frequency or $-3dB$ frequency is f_β

$$f_\beta=\frac{1}{2\pi(C_\pi+C_\mu)r_\pi}=\frac{g_m}{2\pi(C_\pi+C_\mu)\beta}$$ the upper: $$f_z=\frac{1}{2\pi C_\mu/g_m}=\frac{g_m}{2\pi C_\mu}$$

where $f_z>10f_\beta$

Frequency Response of h_{fe} cont.

Using Bode plot concepts, for the range where: $f < f_\beta$

$$h_{fe} = g_m r_\pi = \beta$$

For the range where: $f_\beta < f < f_z$ s.t. $|1 - j f / f_z| \approx 1$

We consider the frequency-dependent numerator term to be 1 and focus on the response of the denominator:

$$h_{fe} = \frac{g_m r_\pi}{\left(1 + j\dfrac{f}{f_\beta}\right)} = \frac{\beta}{\left(1 + j\dfrac{f}{f_\beta}\right)}$$

Frequency Response of h_{fe} cont.

Neglecting numerator term: $$h_{fe} = \frac{g_m r_\pi}{\left(1 + j\frac{f}{f_\beta}\right)} = \frac{\beta}{\left(1 + j\frac{f}{f_\beta}\right)}$$

And for $f/f_\beta >> 1$ (but $< f/f_z$): $$|h_{fe}| \approx \frac{\beta}{\left(\frac{f}{f_\beta}\right)} = \beta\frac{f_\beta}{f}$$

Unity gain bandwidth: $$|h_{fe}| = 1 \Rightarrow \beta\frac{f_\beta}{f}\Big|_{f = f_T} = 1 \Rightarrow f_T = \beta f_\beta$$

$$f_T = \frac{\omega_T}{2\pi} = \beta f_\beta$$

BJT unity-gain frequency or GBP

Frequency Response of h_{fe} cont.

$$\beta = 100 \quad r_\pi = 2500\,\Omega \quad C_\pi = 12\,pF \quad C_\mu = 2\,pF \quad g_m = 40\cdot 10^{-3}\,S$$

$$\omega_\beta = \frac{1}{(C_\pi + C_\mu) r_\pi} = \frac{10^{12}\cdot 10^{-3}}{(12+2)\cdot 2.5} = 28.57\cdot 10^6\,rps$$

$$f_\beta = \frac{\omega_\beta}{2\pi} = \frac{28.57}{6.28} 10^6\,Hz = 4.55\,MHz$$

$$f_T = \beta f_\beta = 455\,MHz$$

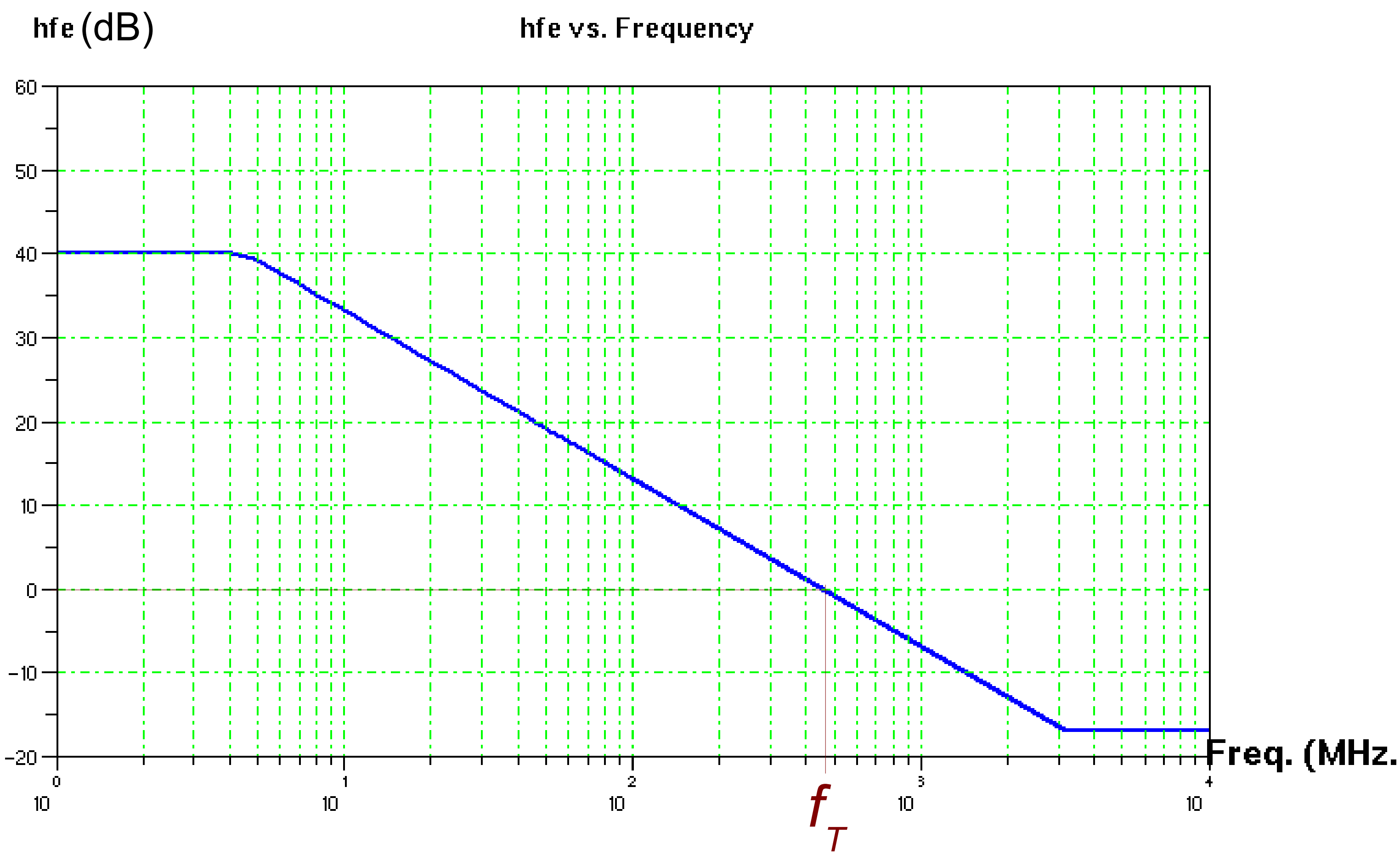
$$\omega_z = \frac{g_m}{C_\mu} = \frac{40\cdot 10^{-3}\cdot 10^{12}}{2}\,Hz = 20\cdot 10^9\,rps$$

$$f_z = \frac{\omega_z}{2\pi} = 3.18\cdot 10^9\,Hz = 3180\,MHz$$

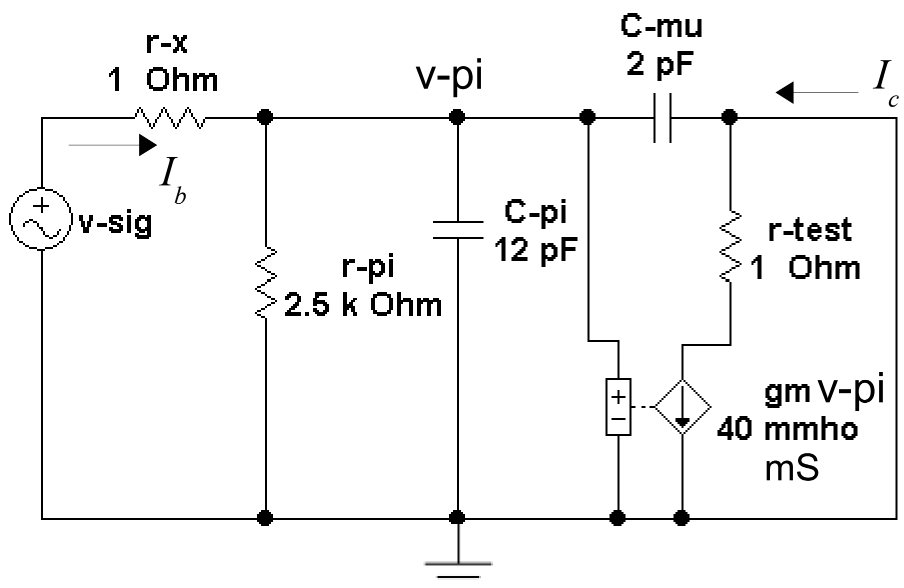
Scilab f_T Plot

```
//fT Bode Plot
Beta=100;
KdB= 20*log10(Beta);
fz=3180;
fp=4.55;
f= 1:1:10000;
term1=KdB*sign(f); //Constant array of len(f)
term2=max(0,20*log10(f/fz));   //Zero for f < fz;
term3=min(0,-20*log10(f/fp));  //Zero for f < fp;
BodePlot=term1+term2+term3;
plot(f,BodePlot);
```

h_{fe} Bode Plot



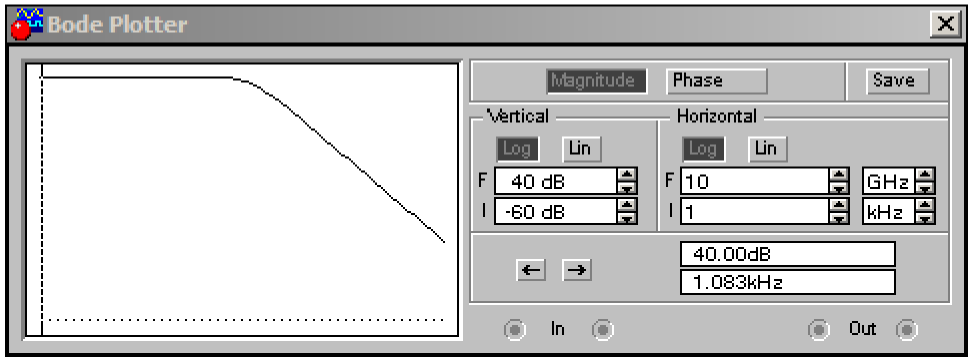
Multisim Simulation



Insert 1 ohm resistors – we want to measure a current ratio.

$$h_{fe}=\frac{I_c}{I_b}=\frac{g_m-sC_\mu}{\frac{1}{r_\pi}+s(C_\pi+C_\mu)}$$

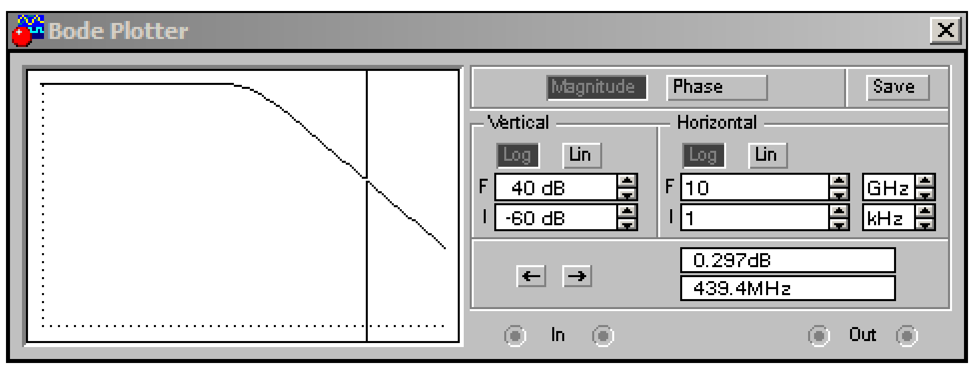
Simulation Results



Low frequency $|h_{fe}|$

Theory:

$f_T = \beta f_\beta = 455\ MHz$



Unity Gain frequency about 440 MHz.