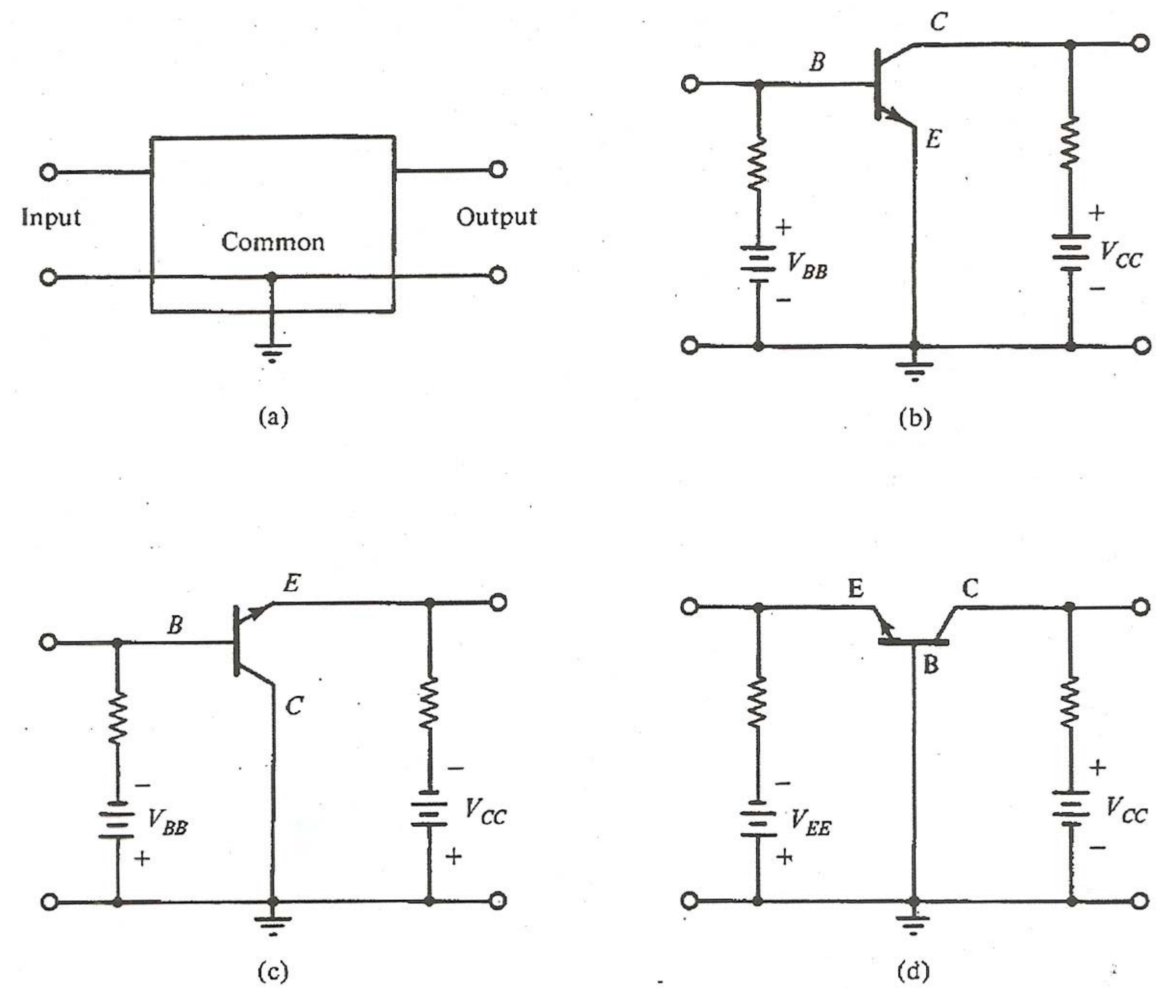
- BJT Circuits & Limitations
- LTspice

Tue 2/18: Mon schedule
Lab: Sun closed
    Mon 1-11:45pm
Handouts:
    lecture notes,
    pset 2,
    lab 2

Acnowledgements:
Neamen, Donald: Microelectronics Circuit Analysis and Design, 3rd Edition

General Configuration

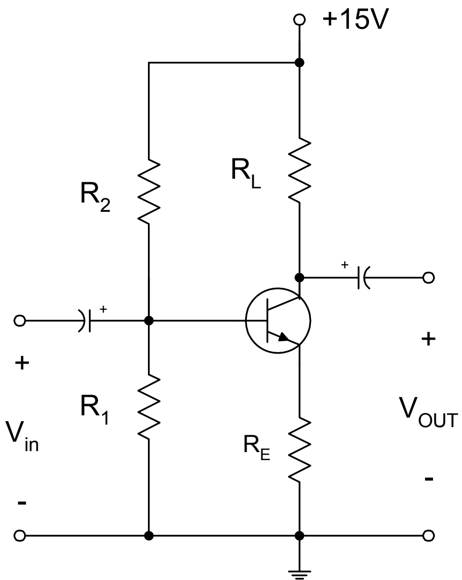


Common Emitter

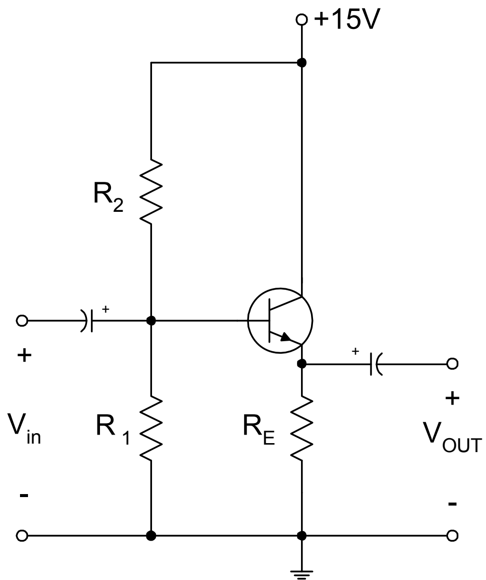
Common Collector

Common Base

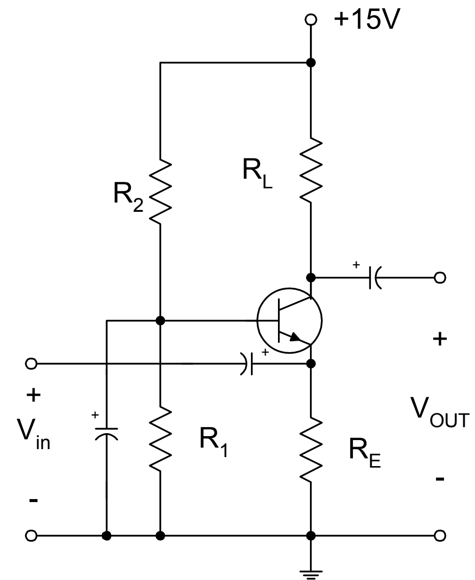
Transistor Configurations



[a] Common Emitter Amplifier

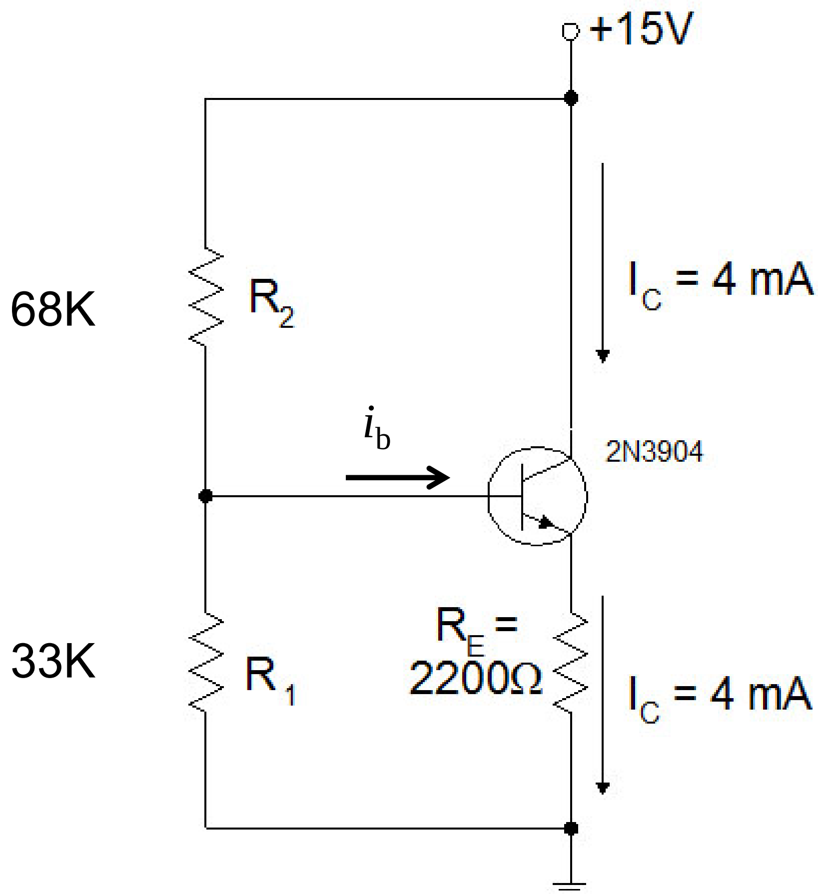


[b] Common Collector [Emitter Follower] Amplifier



[c] Common Base Amplifier

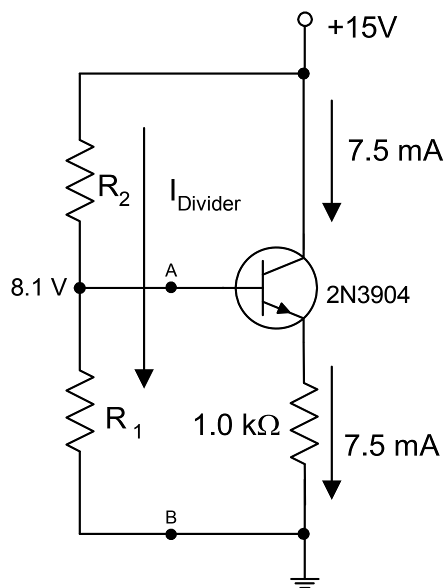
Base Current – Resistor Divider



I_C	β_F
3.7 mA	50
4.0 mA	100
4.2 mA	200
4.3 mA	300
ΔI_C=0.6 mA	

Make i_b small compared to the current through R_2

Common Collector – Emitter Follower Biasing



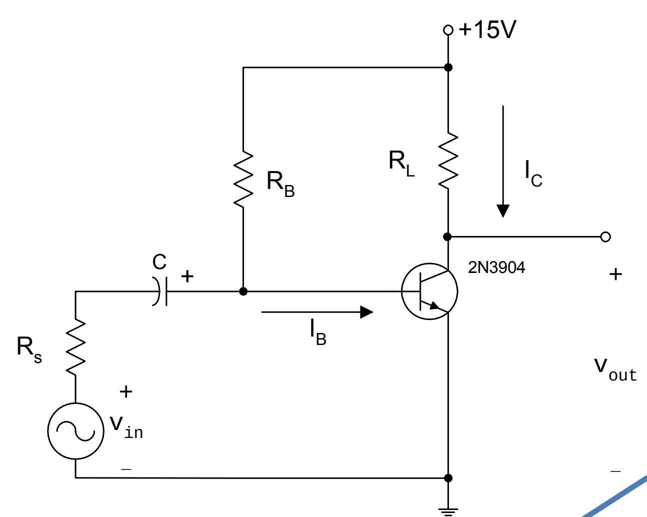
- With R1 = 24kΩ, R2 = 16 kΩ, the current through the voltage divider is 15 ÷ [40 kΩ] = 375 µA.
- The 75 µA base current is 20% of 375 µA.
- With R1 = 2 kΩ, will need a divider current that is ~ 4.1 mA. (75 µA is only ~2% of 4.1 mA, which is negligible)
- The voltage drop across R2 will be [15 V – 8.1 V] = 6.9 V; R2 = 1.7 kΩ
- But input impedance will be low = ~890Ω
- Use bootstrapping configuration

= 24.4 kΩ (use 24 kΩ)

Commom Emitter – Hybrid π

TRANSISTOR AMPLIFIER CONFIGURATIONS WITH HYBRID-Π EQUIVALENT CIRCUITS

COMMON EMITTER AMPLIFER

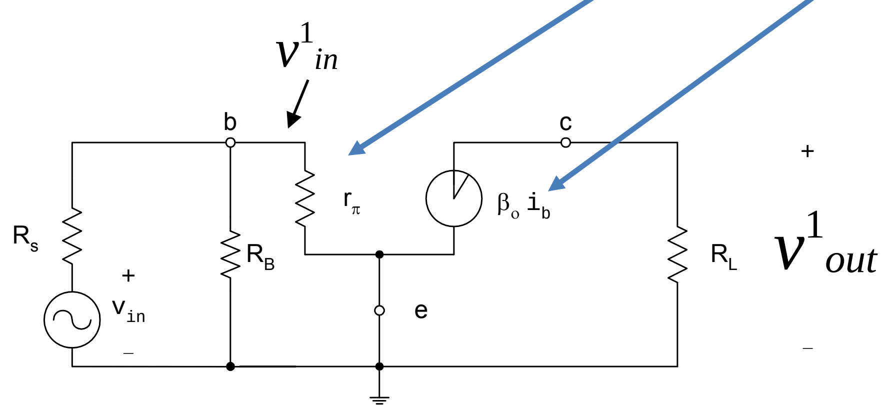


$$\beta_0 = g_m r_\pi$$

$$g_m = \frac{I_{CQ}}{V_{TH}} \qquad V_{TH} = 26mv$$

v_π

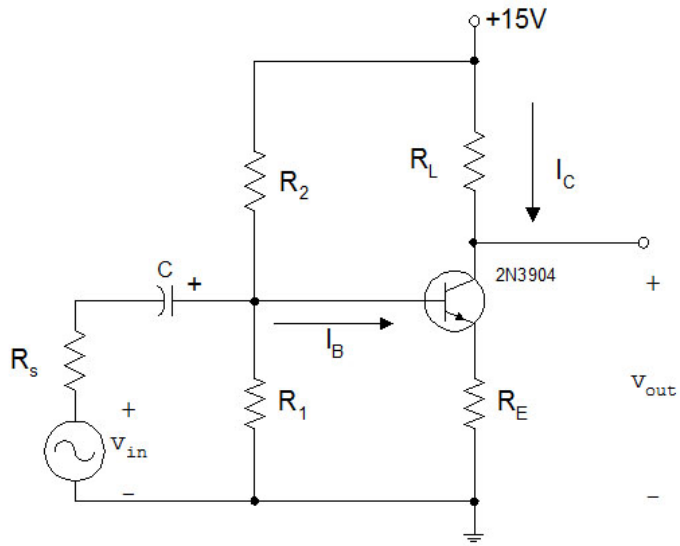
$g_m v_\pi$



$$A_v = \frac{v^1{}_{out}}{v^1{}_{in}} = \frac{-\beta_o i_b R_L}{i_b[r_\pi]} = \frac{-\beta_o R_L}{r_\pi}$$

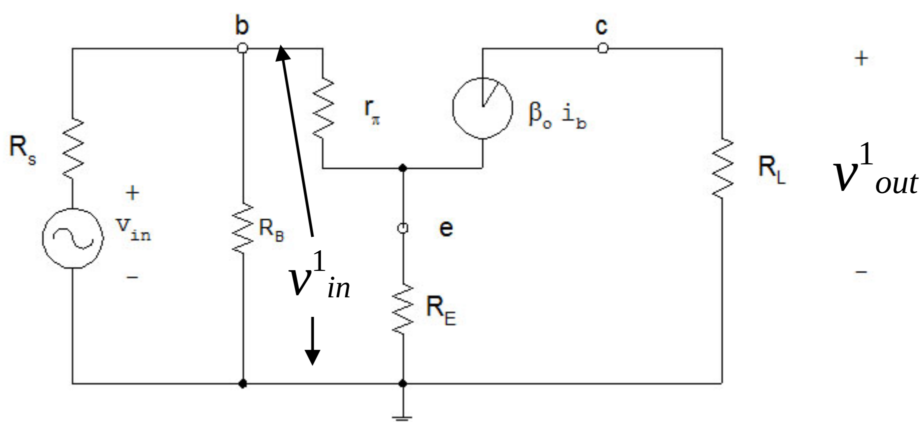
$$then\ A_v = \frac{-\beta_o R_L}{\frac{\beta_o}{g_m}} = -g_m R_L$$

Common Emitter with Emitter Degeneration



$$A_v = \frac{v^1{}_{out}}{v^1{}_{in}} = \frac{-\beta_o i_b R_L}{i_b\left[r_\pi + (\beta_o + 1)R_E\right]} = \frac{-\beta_o R_L}{r_\pi + (\beta_o + 1)R_E};$$

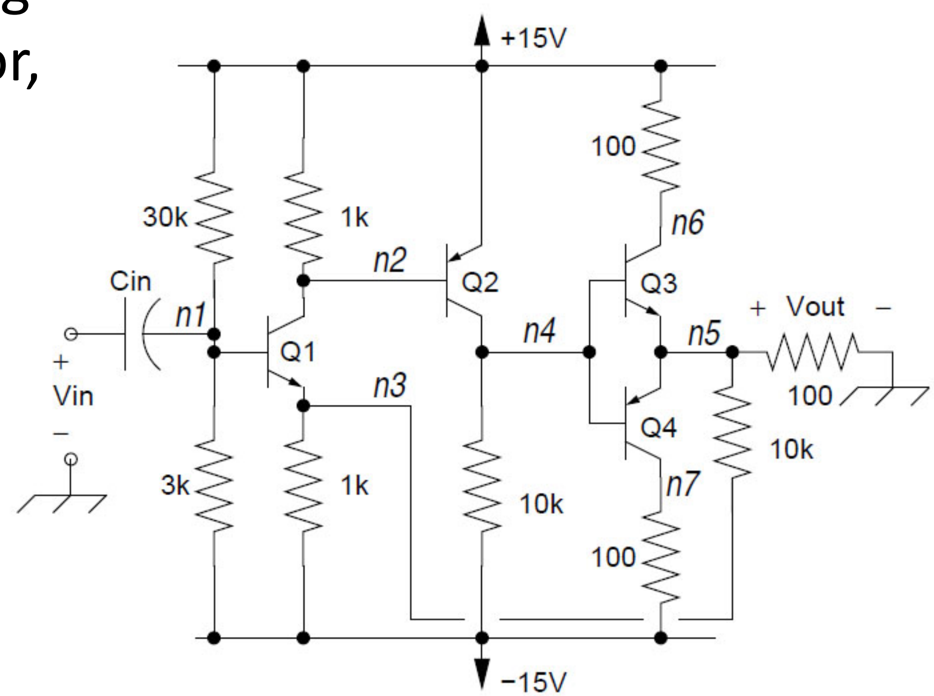
$$if \quad r_\pi << (\beta_o + 1)R_E; \qquad then\, A_v \approx -R_L / R_E$$



- Input resistance $(\beta+1)R_E$
- Voltage gain reduced by $(g_m R_E)$
- Voltage gain less dependent on β (linearity)

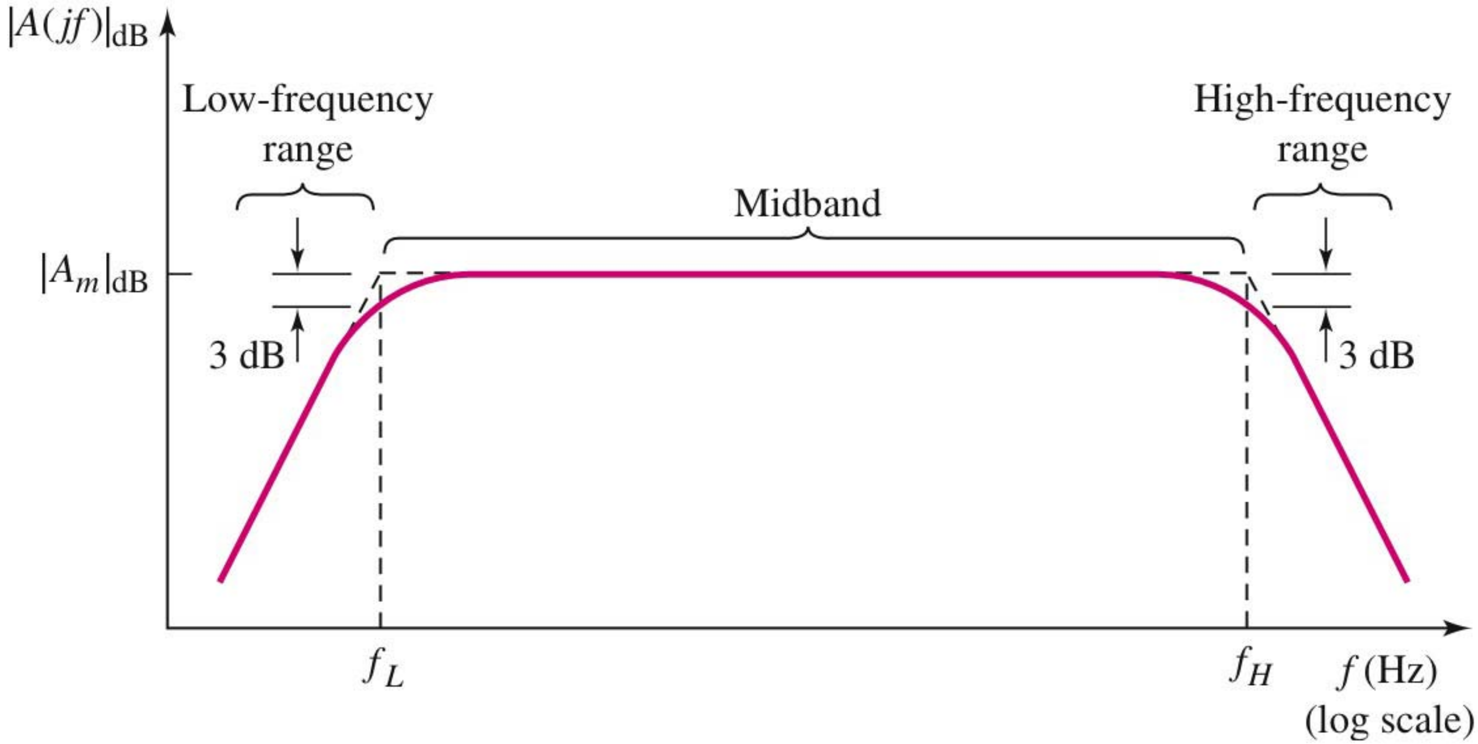
AC Coupled vs DC Coupled Amplifiers

- AC Coupling
  - Advantage: easy cascading with DC blocking capacitor, bias stability and stage independent
  - Disadvantage: lot's of R's and C's, no DC gain, need large C for low freqency

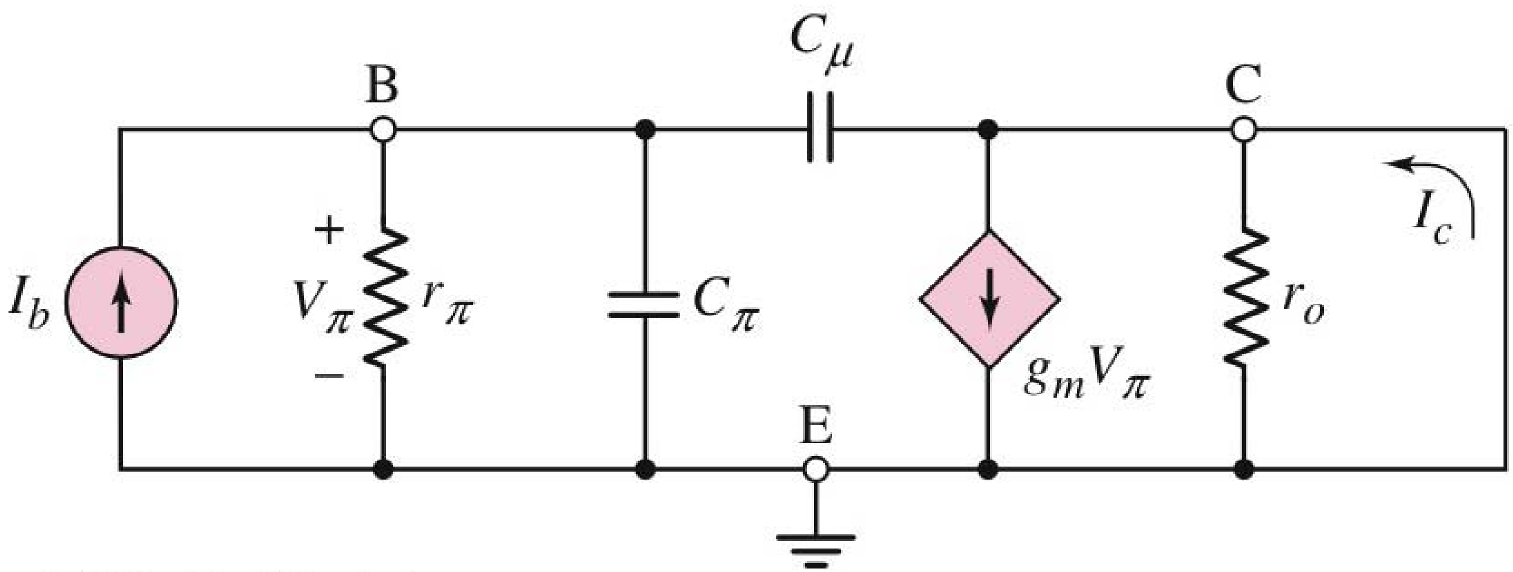


- DC coupling
  - Some gain at DC
  - Fewer R's C's

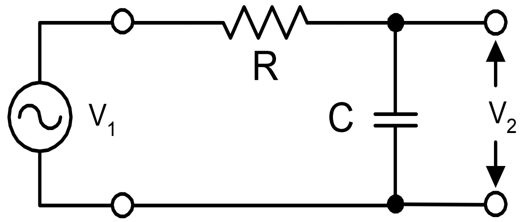
Gain vs Frequency

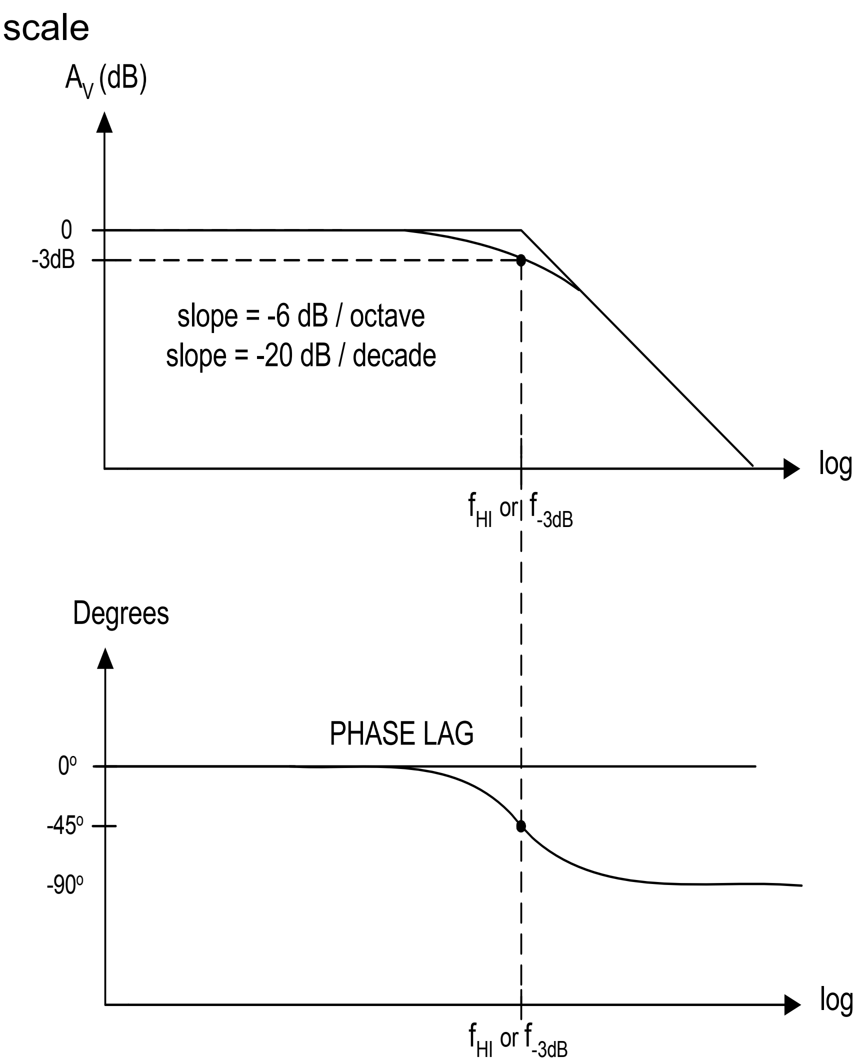


Cutoff Frequency Analysis



Low Pass Filter LPF





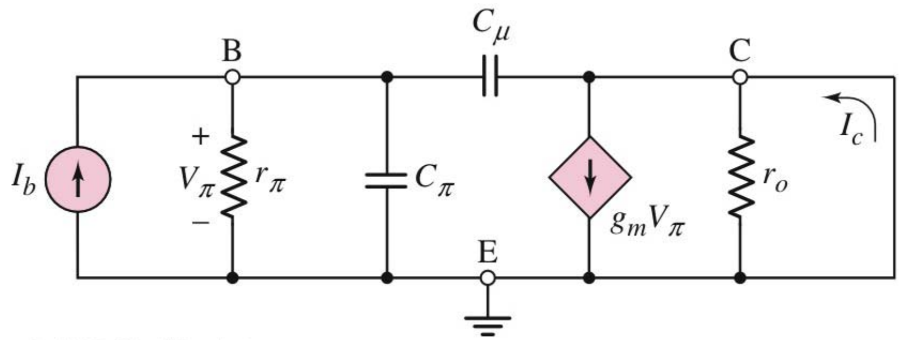
$$A_v = \frac{V_2}{V_1} = \frac{j\,X_C}{R + j\,X_C} = \frac{\frac{1}{j\,\omega C}}{R + \frac{1}{j\,\omega C}} = \frac{1}{j\,\omega RC + 1}$$

$$A_v = \frac{1}{sRC + 1}$$

$$\textit{High frequency cutoff}\ \ f_\beta = \frac{1}{2\pi RC}$$

Cutoff Frequency Analysis

$$3db \quad f_{3db} = f_{\beta} = \frac{1}{2\pi RC} = \frac{1}{2\pi r_{\pi}(C_{\pi}+C_{\mu})}$$



$$i_b = \frac{v_{be}}{r_{\pi}} + v_{be} j\omega\,(C_{\pi}+C_{\mu})$$

$$v_{\pi} = v_{be}$$

$$h_{fe} = \frac{g_m v_{be}}{i_b} = \frac{g_m r_{\pi}}{1 + j\omega\, r_{\pi}(C_{\pi}+C_{\mu})} = \frac{\beta}{1 + j\omega\, r_{\pi}(C_{\pi}+C_{\mu})}$$

This incorrectly ignores the Miller effect on Cμ

$$h_{fe} = \frac{\beta}{1 + j(\frac{f}{f_{\beta}})} \qquad f_t = h_{fe} = 1 \quad or \quad f_t = \frac{g_m}{2\pi r_{\pi}(C_{\pi}+C_{\mu})}$$

Cutoff Frequency Parameters

$$g_m = \left(\frac{q}{kT}\right)\left|I_C\right|$$

$$\beta_0 = h_{fe} \ \ (datasheet)$$

$$C_\mu = C_{ob} \ \ (datasheet)$$

$$\frac{g_m}{2\pi(C_\pi + C_\mu)} = f_T \ \ (transit \ \ frequency \ \ datasheet)$$

$$C_\pi = \frac{g_m}{2\pi f_T r_\pi} - C\mu$$

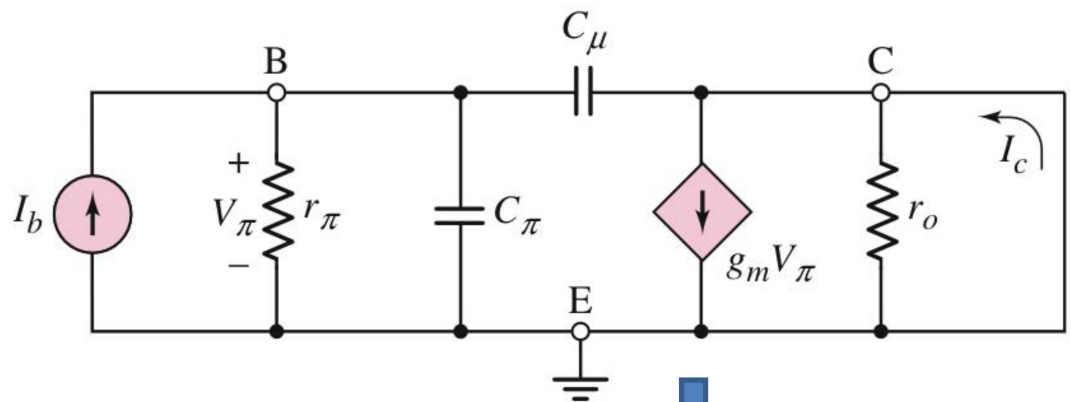
2N3903 2N3904

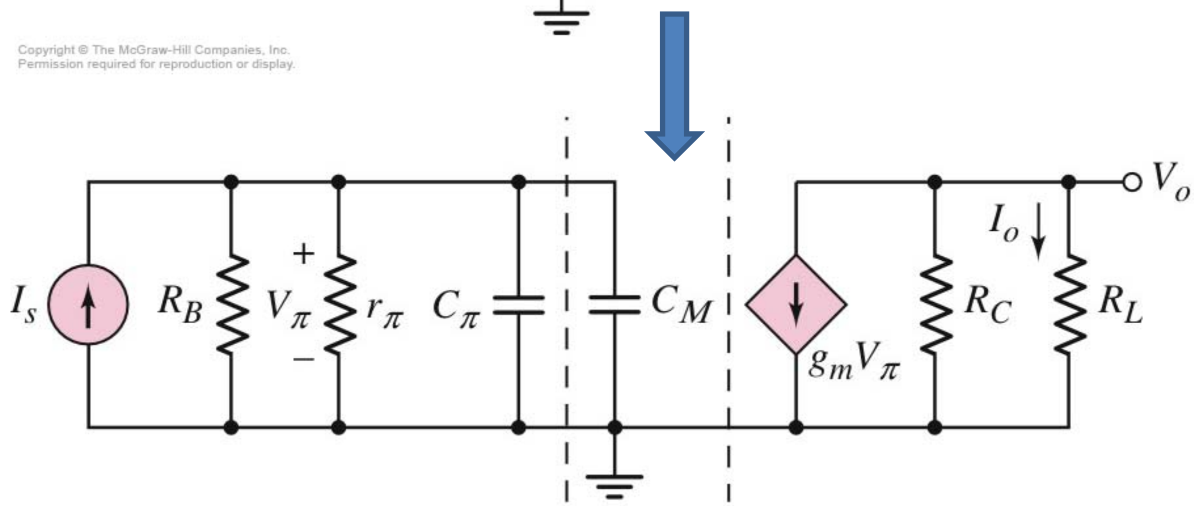
ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted) (Continued)

Characteristic		Symbol	Min	Max	Unit
ON CHARACTERISTICS					
DC Current Gain[1]		h_{FE}			—
(I_C = 0.1 mAdc, V_{CE} = 1.0 Vdc)	2N3903		20	—	
	2N3904		40	—	
(I_C = 1.0 mAdc, V_{CE} = 1.0 Vdc)	2N3903	β	35	—	
	2N3904		70	—	
(I_C = 10 mAdc, V_{CE} = 1.0 Vdc)	2N3903		50	150	
	2N3904		100	300	
(I_C = 50 mAdc, V_{CE} = 1.0 Vdc)	2N3903		30	—	
	2N3904		60	—	
(I_C = 100 mAdc, V_{CE} = 1.0 Vdc)	2N3903		15	—	
	2N3904		30	—	
Collector–Emitter Saturation Voltage[1]		$V_{CE(sat)}$			Vdc
(I_C = 10 mAdc, I_B = 1.0 mAdc)			—	0.2	
(I_C = 50 mAdc, I_B = 5.0 mAdc			—	0.3	
Base–Emitter Saturation Voltage[1]		$V_{BE(sat)}$			Vdc
(I_C = 10 mAdc, I_B = 1.0 mAdc)			0.65	0.85	
(I_C = 50 mAdc, I_B = 5.0 mAdc)			—	0.95	
SMALL–SIGNAL CHARACTERISTICS					
Current–Gain — Bandwidth Product		f_T			MHz
(I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz)	2N3903		250	—	
	2N3904		300	—	
Output Capacitance (V_{CB} = 5.0 Vdc, I_E = 0, f = 1.0 MHz)		C_{obo}	—	4.0	pF
Input Capacitance (V_{EB} = 0.5 Vdc, I_C = 0, f = 1.0 MHz)		C_{ibo}	—	8.0	pF
Input Impedance		h_{ie}			k Ω
(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	2N3903		1.0	8.0	
	2N3904		1.0	10	
Voltage Feedback Ratio		h_{re}			X 10^{-4}
(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	2N3903		0.1	5.0	
	2N3904		0.5	8.0	
Small–Signal Current Gain		h_{fe}			—
(I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	2N3903		50	200	
	2N3904		100	400	
Output Admittance (I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)		h_{oe}	1.0	40	μmhos
Noise Figure		NF			dB
(I_C = 100 μAdc, V_{CE} = 5.0 Vdc, R_S = 1.0 k Ω, f = 1.0 kHz)	2N3903		—	6.0	
	2N3904		—	5.0	

Use max for worst case c_u

Miller Effect* – Common Emitter





$$C_M = C_\mu[1 + g_m(R_C \| R_L)]$$

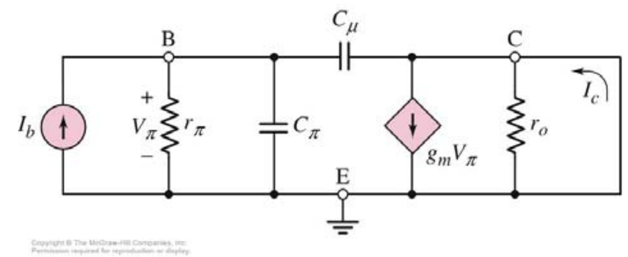
- Neamen, Microlectronics 3rd Edition p 514

Miller Effect

$$R_C = R_L = 4k \quad r_\pi = 2.6k \;\; R_B = 200k$$

$$C_\pi = 4\,pF \quad C_\mu = 0.2\,pF \;\; g_m = 38.5ma/V$$

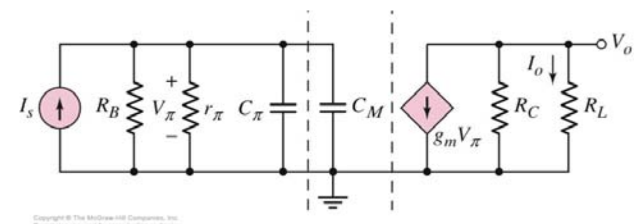
$$f_{3db} = f_\beta = \frac{1}{2\pi\left(r_\pi \| R_B\right)(C_\pi + C_\mu)} = 15.5MHz$$



$$with\,Miller\;\;Effect$$

$$C_M = C_\mu[1 + g_m(R_C \| R_L)]$$

$$f_{3db} = f_\beta = \frac{1}{2\pi\left(r_\pi \| R_B\right)(C_\pi + C_M)} = 3.16MHz$$

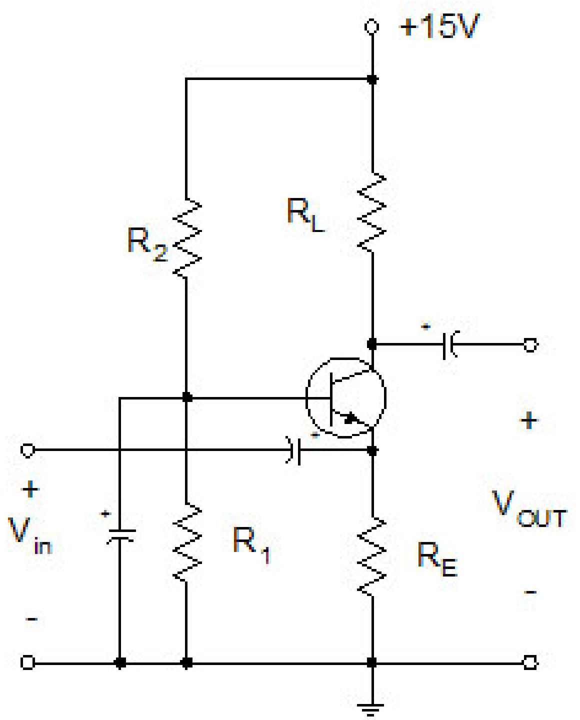


*Neamen, Microlectronics 3rd Edition p 515

Equation	Example 1 – 1 mA bias	Example 2 – 10 mA bias
$g_m = 40\lvert I_C \rvert$	40x1mA = 40 mmho	40x10mA = 400 mmho
β_o = h_{fe} from spec sheet	Approx. 120 @ 1 mA	Approx. 160 @ 10 mA
R_{INCE} = $r_\pi = \beta_o \div g_m$ R_{INCB} = $r_\pi \div (\beta_o + 1)$	120/40 x 10^{-3} = 3000 Ω 3000/121 = 25Ω	160/0.4 = 400 Ω 400/161 = 2.5 Ω
r_x	estimate; ≈ 25Ω	estimate; ≈ 25Ω
CE LF Gain: $A_v = -g_m R_L$	-300 [R_L= 7.5k]	-300 [R_L= 750Ω]
C_μ=C_{ob} [from spec sheet]	1.8 pF at V_{cb} = -7.0 v	1.8 pF at V_{cb} = -7.0 v
f_T from spec sheet	300 MHz	300 MHz
$C_\pi = \frac{g_m}{2\pi f_T} - C_\mu$	=21.2pF – 1.8pF ≈ 20pF	212pF
$C_T = C_\pi + (g_m R_L + 1)C_\mu$ Not good above ≈ 150 /400 MHz!	=20pF + 301 x 1.8pF = 562 pF	=212pF + 301x1.8pF =754 pF
$f_{hi} = \frac{1}{2\pi\, R_S \Vert R_{IN} C_T}$ R_s'= R_s + r_x = 50Ω + 25Ω = 75Ω]	$= \frac{1}{6.28 \times 73.2\Omega \times 562 pF}$ f_{hi} = 3.9 MHz	$= \frac{1}{6.28 \times 63\Omega \times 754 pF}$ f_{hi}=3.3 MHz
Add shunt the input resistance (r_x+r_π // C_T) with a 51Ω resistance for maximum power transfer: [note –6dB gain loss]	$= \frac{1}{6.28 \times 49\Omega \times 562 pF}$ f_{hi} = 5.8 MHz	$= \frac{1}{6.28 \times 44\Omega \times 754 pF}$ f_{hi}=4.8 MHz

2N3904
CE configuration,
V_{CC} +15v

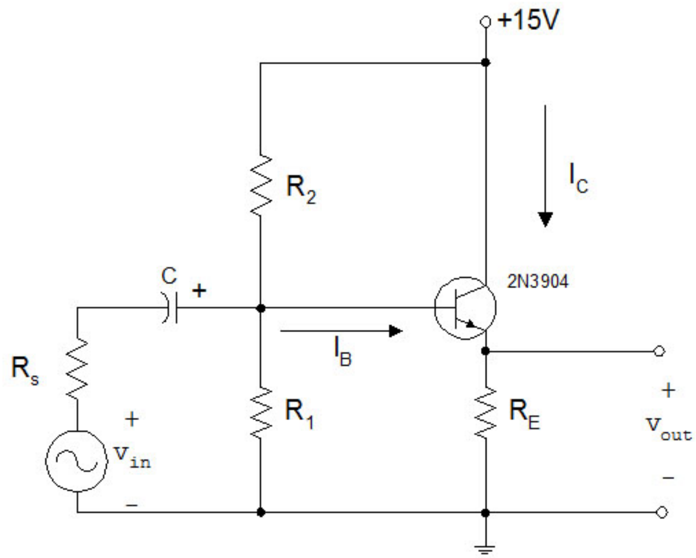
Common Base Configuration



[c] Common Base Amplifier

Equation	Example 1 – 1 mA bias	Example 2 – 10 mA bias
CB input time constant: [no 51Ω] $f_{hi} = \frac{1}{2\pi\ R_S \| R_{IN} C_\pi}$	$= \frac{1}{6.28 \times 12.4\Omega \times 20pF}$ f_{hi} = 640 MHz	$= \frac{1}{6.28 \times 2.3\Omega \times 212pF}$ f_{hi} = 332 MHz
CB output time constant: $f_{hi} = \frac{1}{2\pi\ R_L C_\mu}$	$= \frac{1}{6.28 \times 7500\Omega \times 1.8pF}$ f_{hi} = 11.8 MHz	$= \frac{1}{6.28 \times 750\Omega \times 1.8pF}$ f_{hi} = 118 MHz

Common Collector (Emitter Follower)

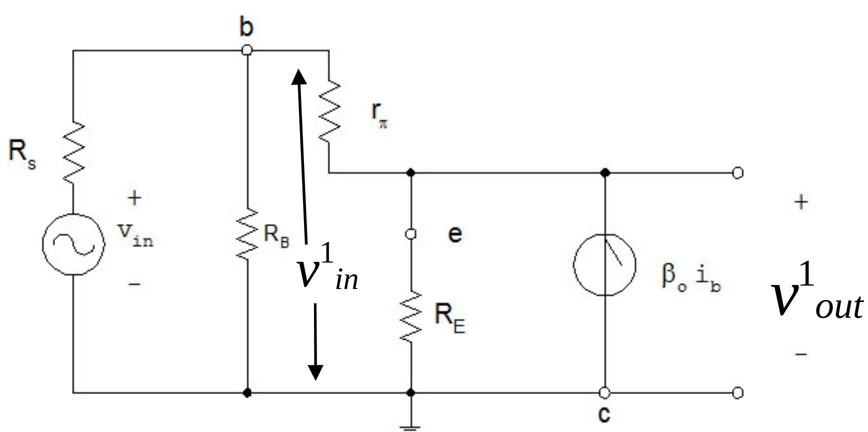


$$\beta_0 = g_m r_\pi$$

$$g_m = \frac{I_{CQ}}{V_{TH}} \qquad V_{TH} = 26mv$$

$$A_v = \frac{v^1{}_{out}}{v^1{}_{in}} = \frac{(\beta_o + 1) i_b R_E}{i_b\left[R'_s + r_\pi + (\beta_o + 1) R_E\right]} = \frac{(\beta_o + 1)\ R_E}{R'_s + r_\pi + (\beta_o + 1) R_E};$$

$$if \quad r_\pi << (\beta_o + 1) R_E; \qquad then \ \ A_v \approx 1$$



- Buffer with unity gain
- High input resistance driving low output resistance (current gain).

Low Frequency Hybrid-π Equation Chart

Characteristic	Common Emitter	CE with R_E	CC [E. Follower]	Common Base
Voltage Gain [if $r_o >> R_L$]	$A_v = -g_m R_L$	$A_v \approx -\frac{R_L}{R_E}$	$A_v \approx 1$	$A_v = \frac{\beta_o R_L}{r_\pi // R_B + (\beta_o + 1) R_s}$
Current Gain	β_o	β_o	β_o+1	$\frac{\beta_o}{\beta_o + 1}$
Input Impedance	$r_\pi // R_B$	$[r_\pi + (\beta_o + 1) R_E] // R_B$	$[r_\pi + (\beta_o + 1) R_E] // R_B$	$\frac{r_\pi}{\beta_o + 1}$
Output Impedance	R_L [if $r_o >> R_L$]	R_L [if $r_o >> R_L$]	$\left[\frac{(r_\pi + R_s // R_B)}{\beta_o + 1}\right] // R_E$	R_L [if $r_o >> R_L$]
Phase Reversal?	Yes	Yes	No	No

High gain applications Moderate input resistance High output resistance	Unity gain, low output resistance High input resist.	High gain, better high frequency response Low input resistance