Chapter 9:
BJT and FET Frequency Response

9.2 General Frequency Considerations

- The mid-range frequency response of an amplifier refers to the frequency range in which the amplifier will operate with negligible effects from capacitors and capacitance in devices. This range of frequencies can be called the **mid-range**.
- At frequencies above and below the midrange, capacitance and any inductance will affect the gain of the amplifier.

- At low frequencies the coupling and bypass capacitors lower the gain.

- At high frequencies stray capacitances associated with the active device lower the gain.

- Also, cascading amplifiers limits the gain at high and low frequencies.

9.2 General Frequency Considerations

Bode Plot

- A Bode plot indicates the frequency response of an amplifier.
- The horizontal scale indicates the frequency (in Hz and log scale) and the vertical scale indicates the gain (in dB).

Cutoff Frequencies

The mid-range frequency of an amplifier is called the **bandwidth** of the amplifier.

The **bandwidth** is defined by the lower and upper cutoff frequencies.

f_1: lower cutoff frequency

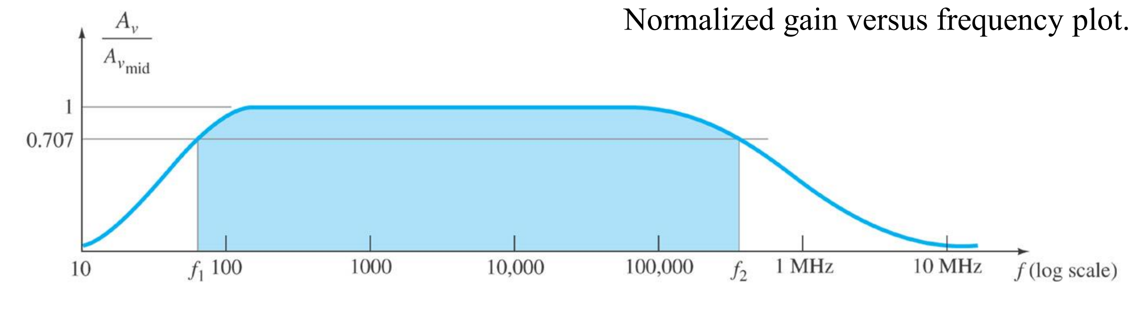
f_2: upper cutoff frequency

bandwidth(BW)= $f_2 - f_1$

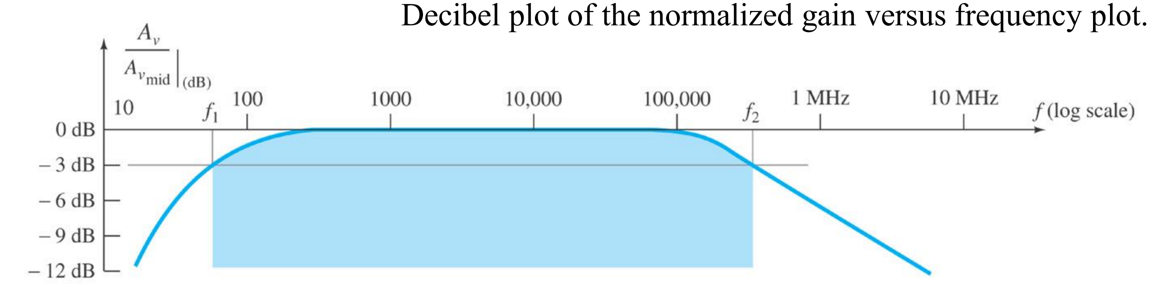
Cutoff frequency at which the gain has dropped by:

0.5 power
0.707 voltage
-3dB

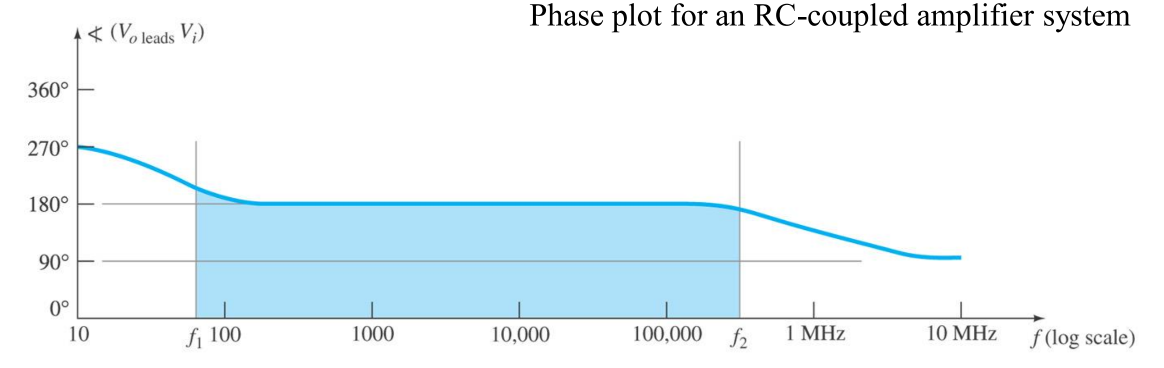
Normalized gain versus frequency plot.



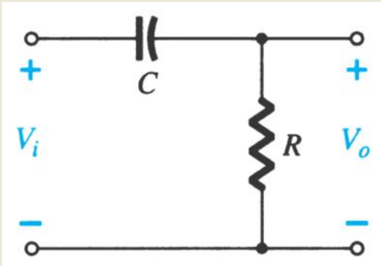
Decibel plot of the normalized gain versus frequency plot.



Phase plot for an RC-coupled amplifier system



9.3 Bode Plot



$$A_v = \frac{V_o}{V_i} = \frac{R}{R + \frac{1}{j2\pi fC}} \qquad f_1 = \frac{1}{2\pi RC}$$

$$A_v = \frac{V_o}{V_i} = \frac{1}{1 - j\frac{1}{2\pi fCR}} = \frac{1}{1 - j\frac{f_1}{f}}$$

$$|A_v| = \frac{1}{\sqrt{1+\left(f_1/f\right)^2}} \rightarrow |A_v|_{dB} = 20\log_{10}\frac{1}{\sqrt{1+\left(f_1/f\right)^2}}$$

$$|A_v|_{dB} \approx -3dB \qquad f = f_1$$

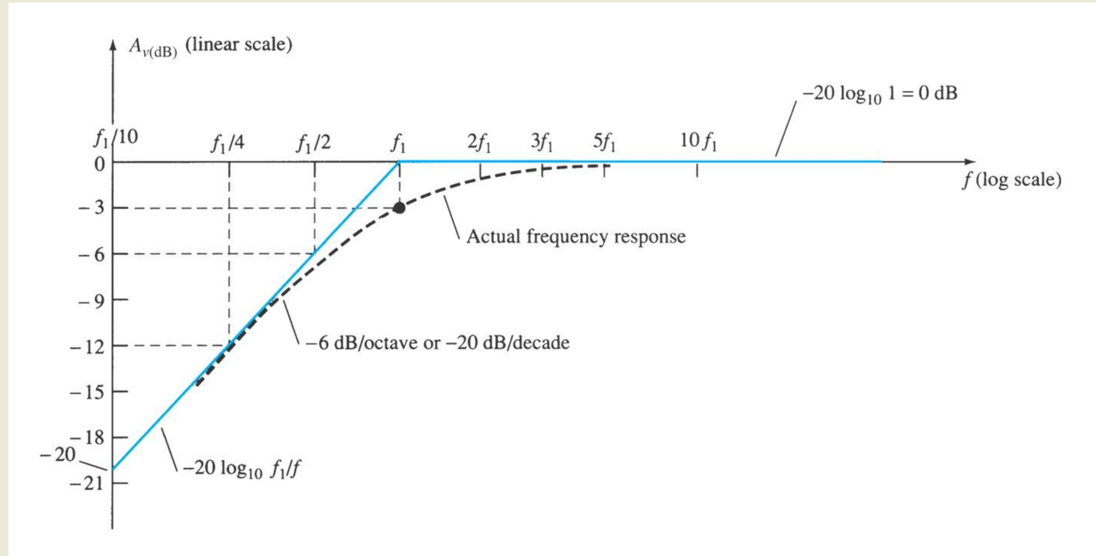
$$|A_v|_{dB} \approx -20\log_{10}\frac{f_1}{f} \qquad f << f_1$$

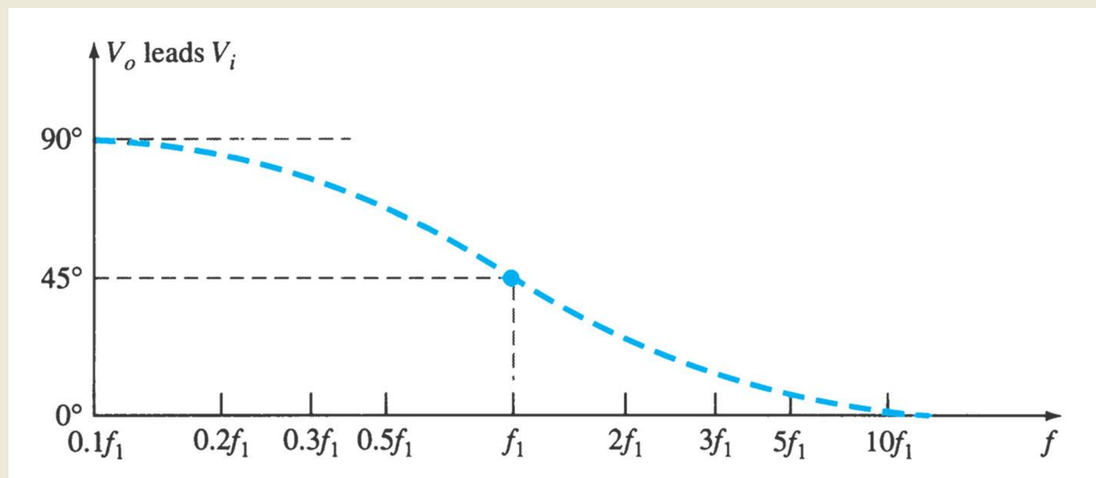
$$\theta_{A_v} = \tan^{-1}\left(f_1/f\right)$$

$$\theta_{A_v} = 45^o \qquad f = f_1$$

$$\theta_{A_v} = 90^o \qquad f << f_1$$

$$\theta_{A_v} = 0^o \qquad f >> f_1$$





9.4 Low Frequency Response—BJT Amplifier

At low frequencies coupling capacitors (C_S, C_C) and bypass capacitors (C_E) will have capacitive reactances (X_C) that affect the circuit impedances.

Coupling Capacitor—C_S

The cutoff frequency due to C_S can be calculated by $f_{Ls} = \dfrac{1}{2\pi(R_s + R_i)C_s}$

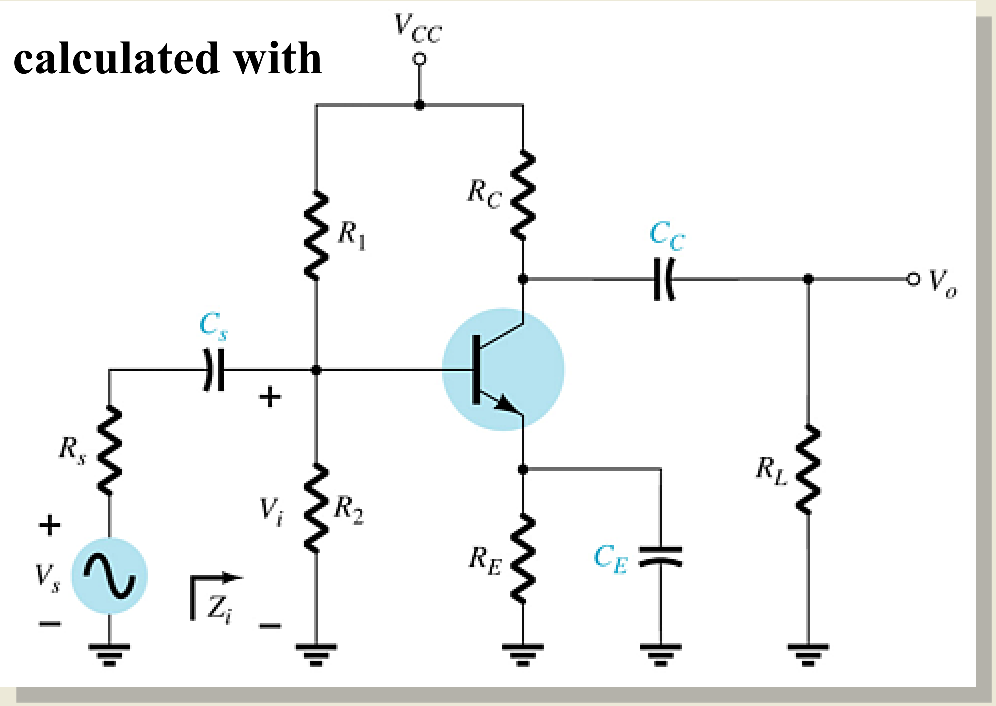
and $R_i = R_1 \parallel R_2 \parallel \beta r_e$

Coupling Capacitor—C_C

The cutoff frequency due to C_C can be calculated with

$$f_{LC} = \frac{1}{2\pi(R_o + R_L)C_c}$$

and $R_o = R_C \parallel r_o$



Bypass Capacitor—C_E

The cutoff frequency due to C_E can be calculated with

$$f_{LE} = \frac{1}{2\pi R_e C_E}$$

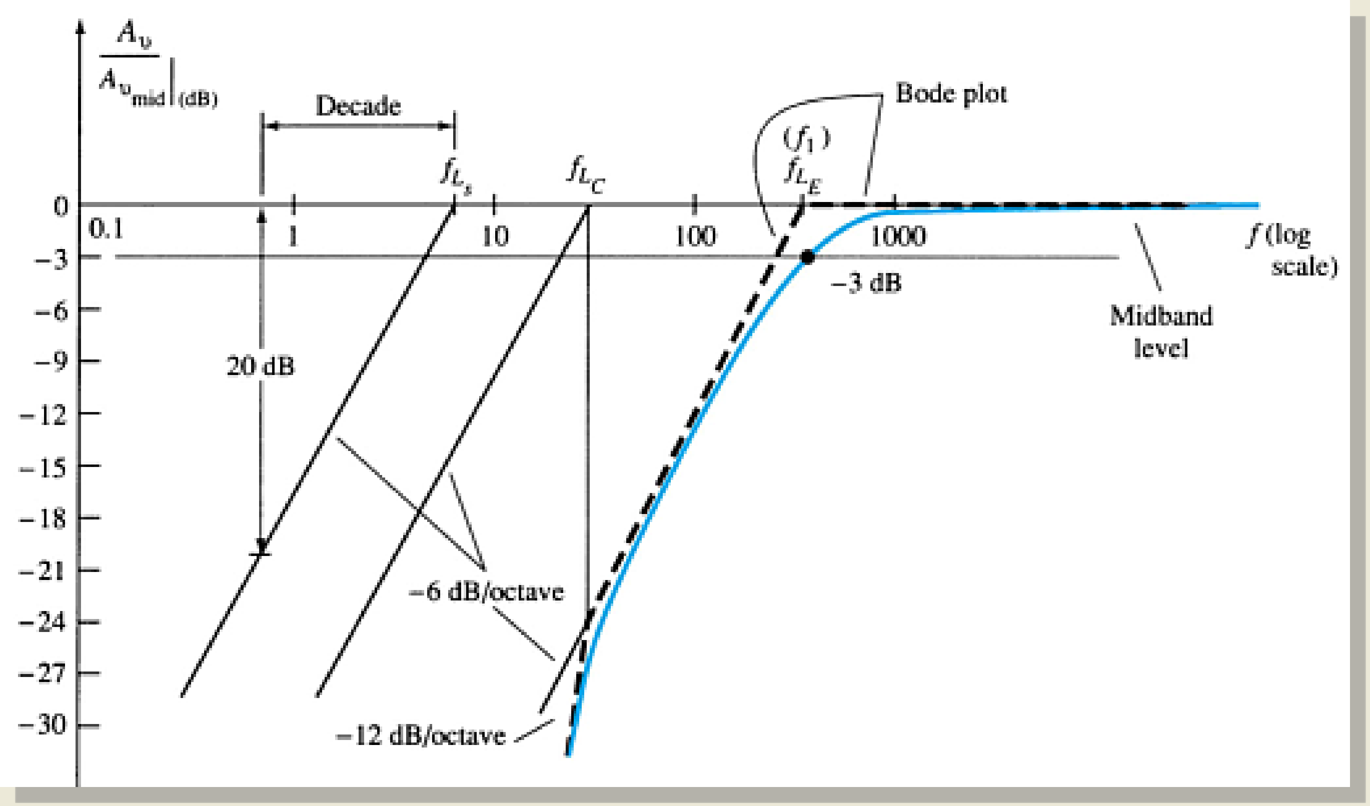
and

$$R_e = R_E \parallel \left(\frac{R_s'}{\beta} + r_e\right) \quad \text{where} \quad R_s' = R_s \parallel R_1 \parallel R_2$$

Bode Plot of Low-Frequency Response—BJT Amplifier

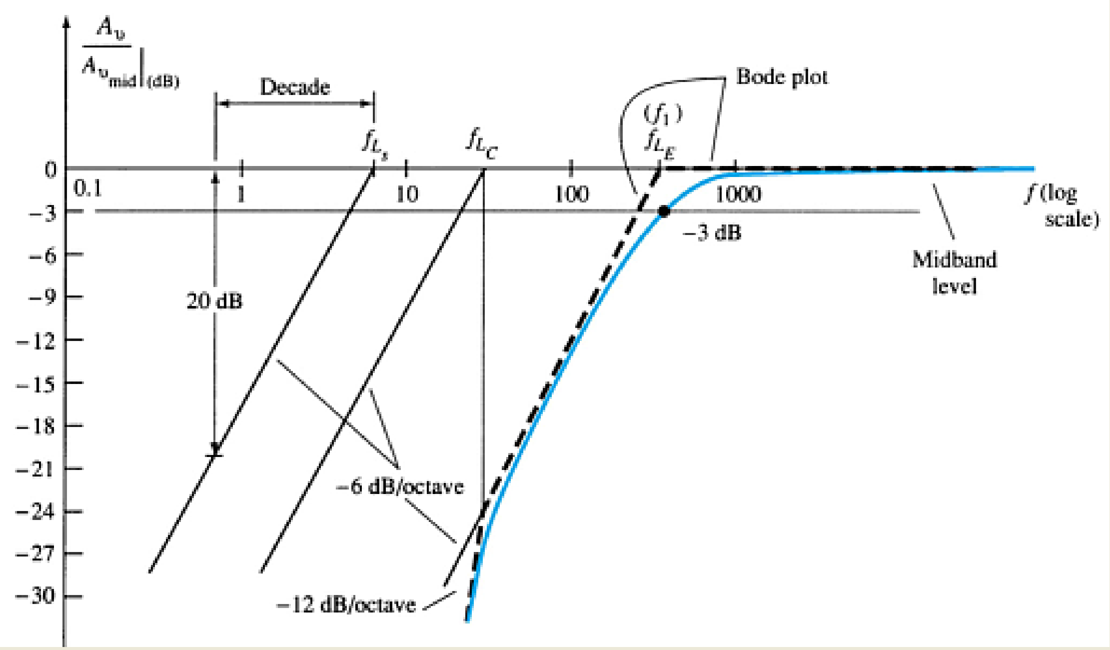
The Bode plot indicates that each capacitor may have a different cutoff frequency.

It is the device that has the *highest* lower cutoff frequency (f_L) that dominates the overall frequency response of the amplifier.



Roll-Off of Gain in the Bode Plot

The Bode plot not only indicates the cutoff frequencies of the various capacitors it also indicates the amount of attenuation (loss in gain) at these frequencies.



The amount of attenuation is sometimes referred to as **roll-off**.

The roll-off is described as dB loss-per-octave or dB loss-per-decade.

-dB/decade refers to the attenuation for every 10-fold change in frequency.

-dB/octave refers to the attenuation for every 2-fold change in frequency.

9.5 Low Frequency Response—FET Amplifier

At low frequencies coupling capacitors (C_G, C_C) and bypass capacitors (C_S) will have capacitive reactances (X_C) that affect the circuit impedances.

Coupling Capacitor—C_G

The cutoff frequency due to C_G can be calculated by $f_{LC} = \dfrac{1}{2\pi(R_{sig} + R_i)C_G}$

where $R_i = R_G$

Coupling Capacitor—C_C

The cutoff frequency due to C_C can be calculated with

$$f_{LC} = \frac{1}{2\pi(R_o + R_L)C_C}$$

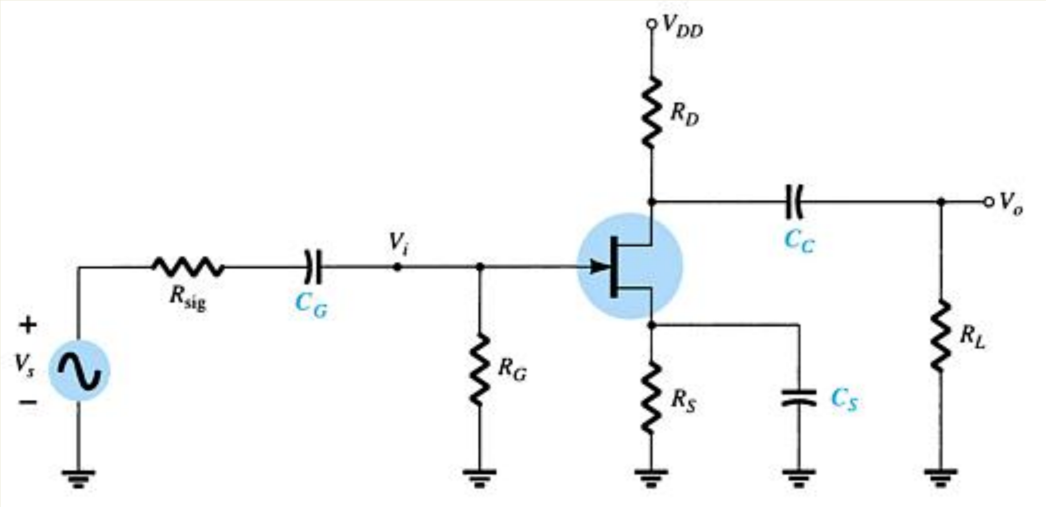
where $R_o = R_D \parallel r_d$

Bypass Capacitor—C_S

The cutoff frequency due to C_S can be calculated with

$$f_{LS} = \frac{1}{2\pi R_{eq} C_S}$$

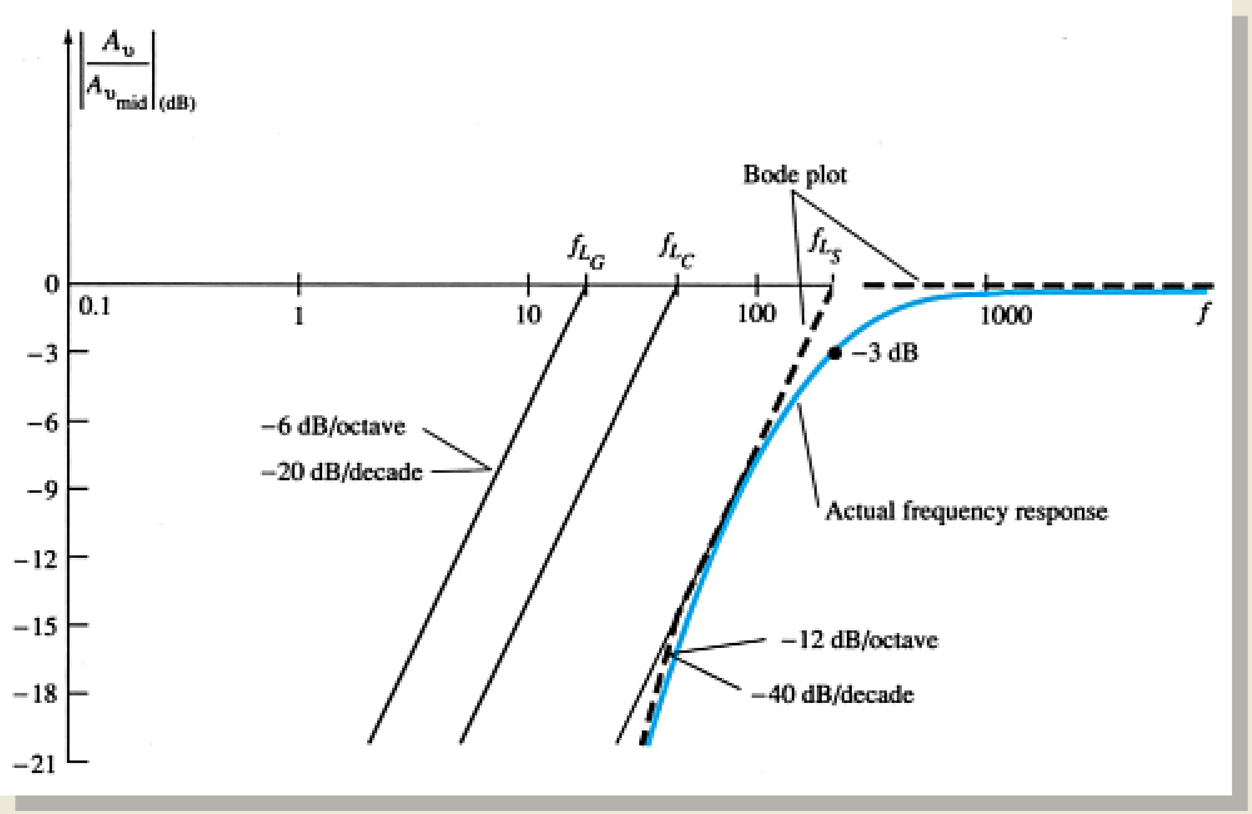
where $R_{eq} = R_S \parallel \left.\dfrac{1}{g_m}\right|_{r_d \cong \infty\Omega}$



Bode Plot of Low-Frequency Response—FET Amplifier

The Bode plot indicates that each capacitor may have a different cutoff frequency.

The capacitor that has the *highest* lower cutoff frequency (f_L) is closest to the actual cutoff frequency of the amplifier.



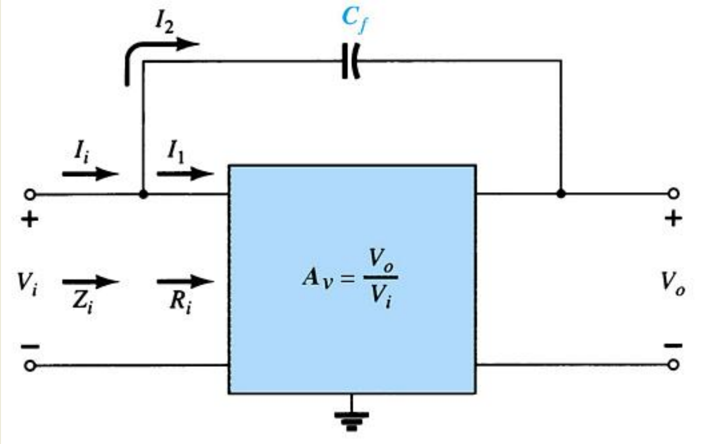
9.6 Miller Effect Capacitance

Any *p-n* junction can develop capacitance.
This capacitance becomes noticeable between:

- The base-collector junction at high frequencies in common-emitter BJT amplifier configurations
- The gate-drain junction at high frequencies in common-source FET amplifier configurations.

It is called the **Miller Capacitance**, and it affects the input and output circuits.

Miller Input Capacitance (C_{Mi})



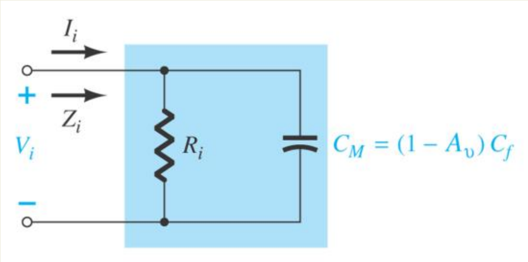
$$C_{Mi} = (1 - A_v)C_f$$

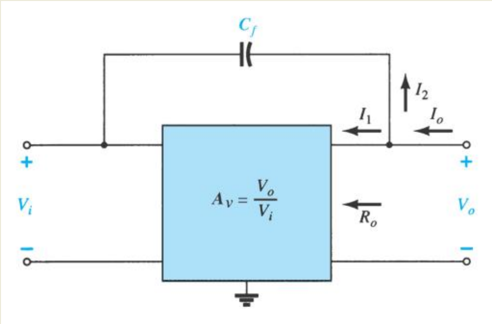
Note that the amount of Miller capacitance is dependent on interelectrode capacitance from input to output (C_f) and the gain (A_v).

Miller Output Capacitance (C_{Mo})

If the gain (A_v) is considerably greater than 1, then

$$C_{Mo} \cong C_f$$

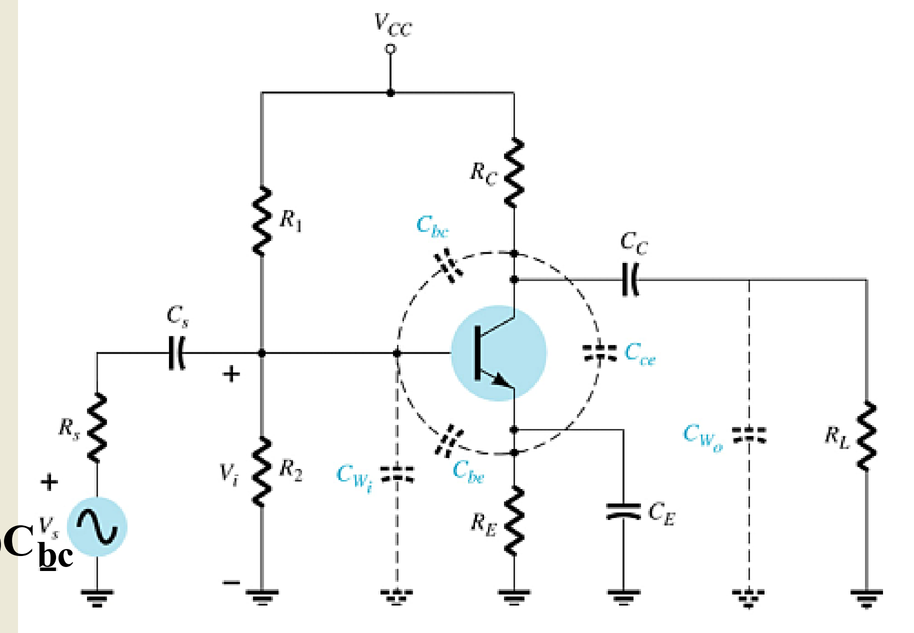




9.7 High-Frequency Response —BJT Amplifiers

Dominant capacitances that affect the high-frequency response are:

- **Parasitic capacitances: C_{be}, C_{bc}, C_{ce}**
- **Wiring capacitances: C_{wi}, C_{wo}**



High-Frequency Cutoff—Input Network (f_{Hi})

$$f_{Hi} = \frac{1}{2\pi R_{Thi} C_i}$$

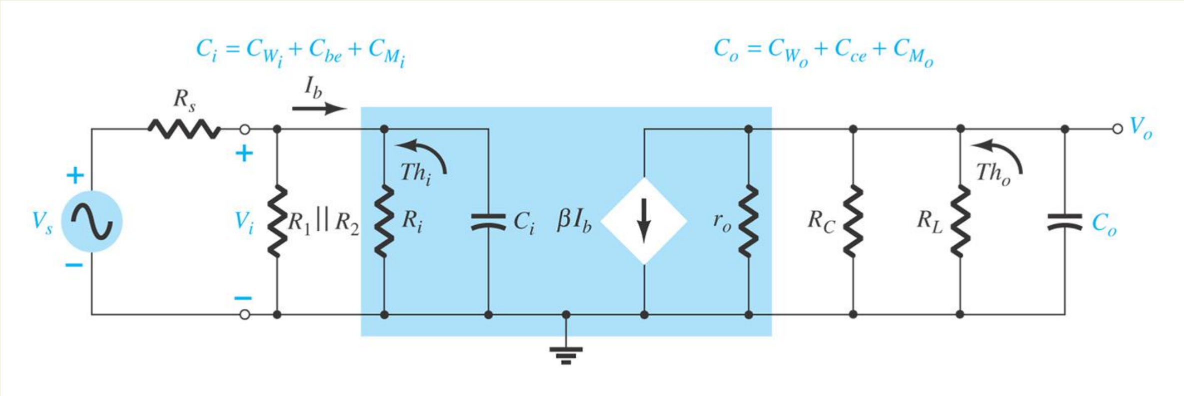
where

$$R_{Thi} = R_s \| R_1 \| R_2 \| R_i$$

and

$$C_i = C_{Wi} + C_{be} + C_{Mi} = C_{Wi} + C_{be} + (1 - A_v)C_{bc}$$

High-Frequency Cutoff —Output Network (f_{Ho})

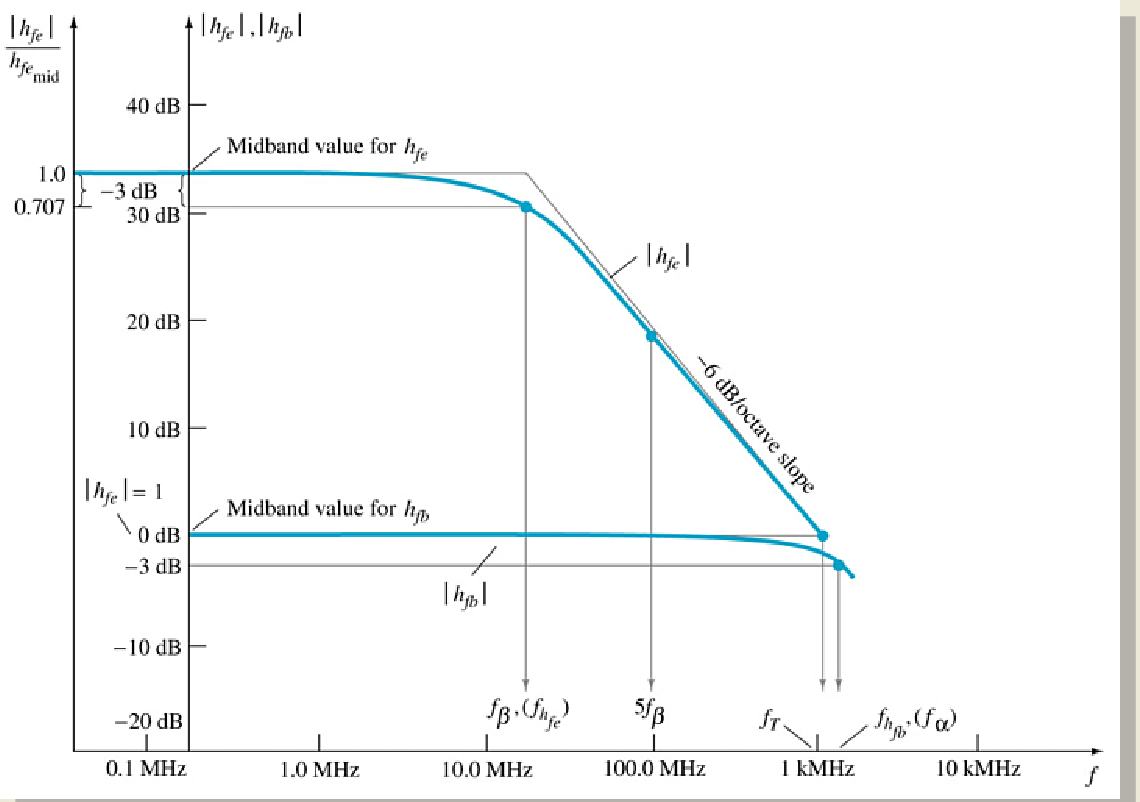


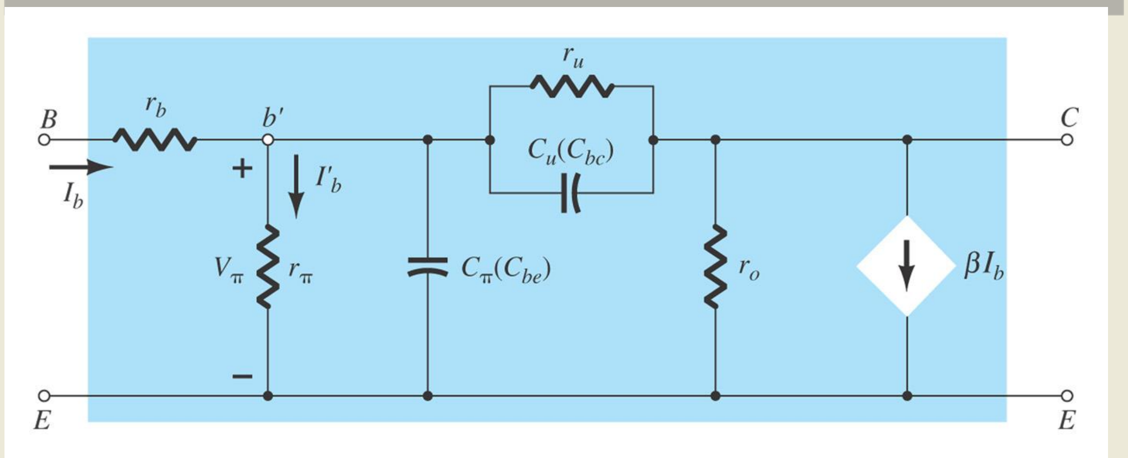
$$f_{Ho} = \frac{1}{2\pi R_{Tho} C_o}$$

where $R_{Tho} = R_C \| R_L \| r_o$

and $C_o = C_{Wo} + C_{ce} + C_{Mo}$

h_{fe} (or β) Variation





The h_{fe} parameter (or β) of a transistor varies with frequency

$$\beta(\text{or } h_{fe}) = \frac{\beta_{mid}}{1 + j(f/f_\beta)}$$

$$\mathbf{f_\beta \cong \frac{1}{2\pi\beta_{mid} r_e (C_{be} + C_{bc})}}$$

$$|\beta(f_\beta)| = 0.707\beta_{mid}$$

$$|\beta(f_T)| = 1$$

$$f_T \cong \beta_{mid} f_\beta$$

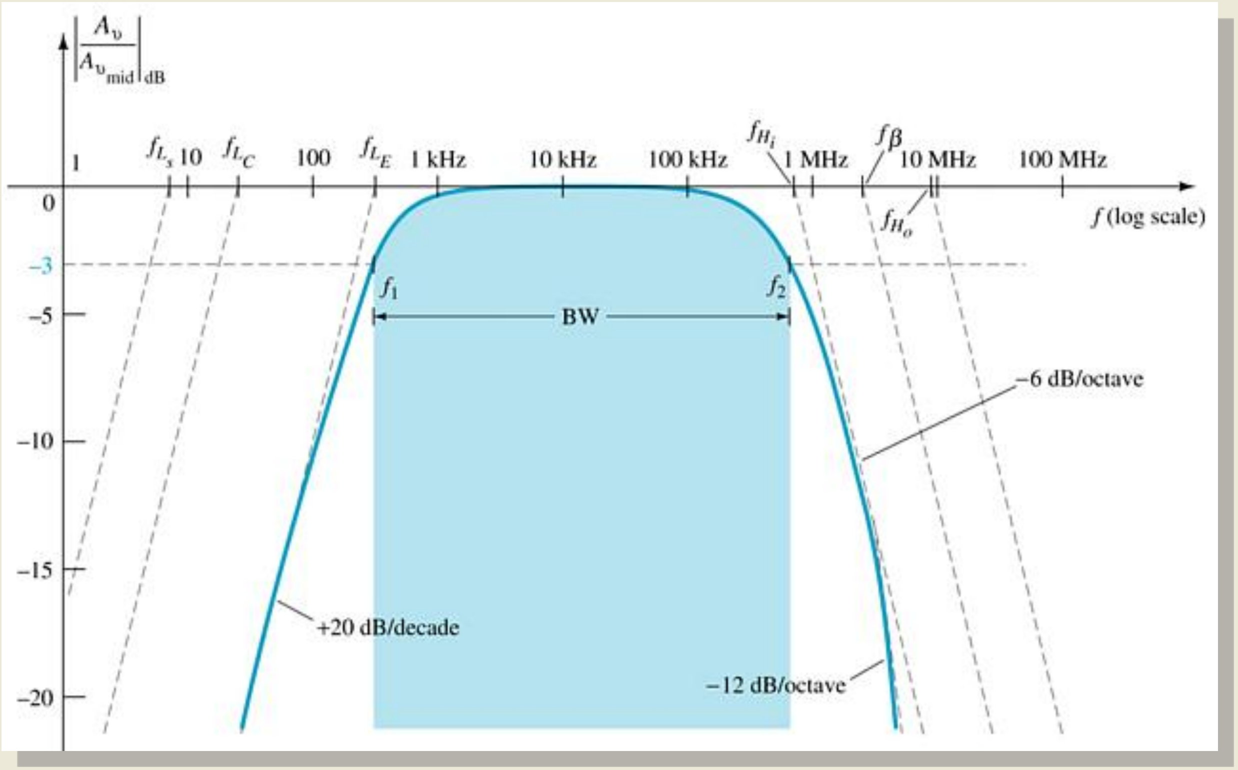
$$\alpha(\text{or } h_{fb}) = \frac{\alpha_{mid}}{1 + j(f/f_\alpha)}$$

$$\alpha = \frac{\beta}{1+\beta}$$

$$f_\alpha = (1 + \beta_{mid}) f_\beta$$

$$f_\beta < f_T < f_\alpha$$

Full Frequency Response of a BJT Amplifier



Middle-frequency region: resistance features by short and open equivalents of capacitances

Low-frequency region: coupling and bypass capacitors determin lower cutoff frequency

High-frequency region: network capacitance (parasitic and introduced) and the frequency dependance of h_{fe} or h_{fb} define the upper cutoff frequency

Note the *highest* lower cutoff frequency (f_L) and the *lowest* upper cutoff frequency (f_H) are closest to the actual response of the amplifier.

9.8 High-Frequency Response—FET Amplifier

High-Frequency Cutoff—Input Network (f_{Hi})

$$f_{Hi} = \frac{1}{2\pi R_{Thi} C_i}$$

$$C_i = C_{Wi} + C_{gs} + C_{Mi}$$

$$C_{Mi} = (1 - A_v) C_{gd}$$

$$R_{Thi} = R_{sig} \parallel R_G$$

Dominant capacitances that affect the high-frequency response are

- Parasitic capacitances: C_{gs}, C_{gd}, C_{ds}
- Wiring capacitances: C_{wi}, C_{wo}

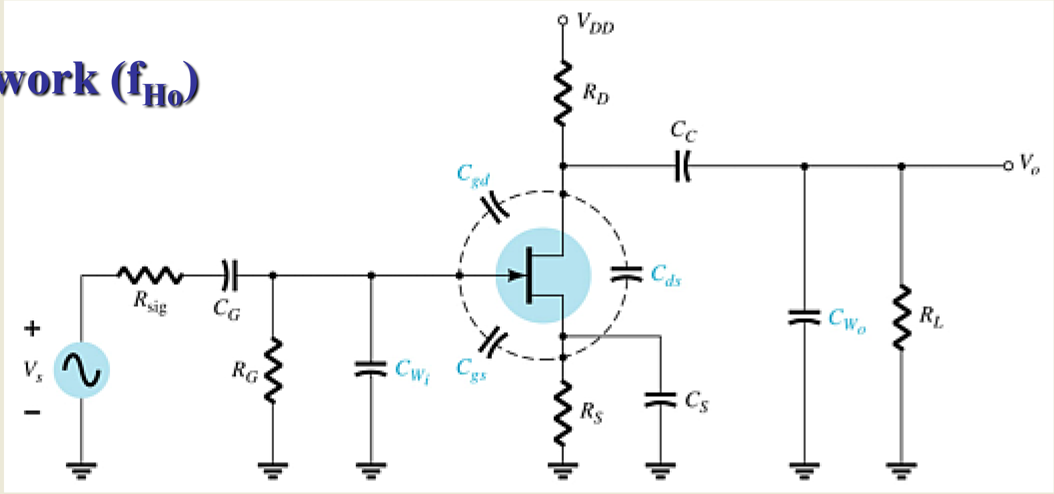
High-Frequency Cutoff —Output Network (f_{Ho})

$$f_{Ho} = \frac{1}{2\pi R_{Tho} C_o}$$

$$C_o = C_{Wo} + C_{ds} + C_{Mo}$$

$$C_{Mo} = \left(1 - \frac{1}{A_v}\right) C_{gd}$$

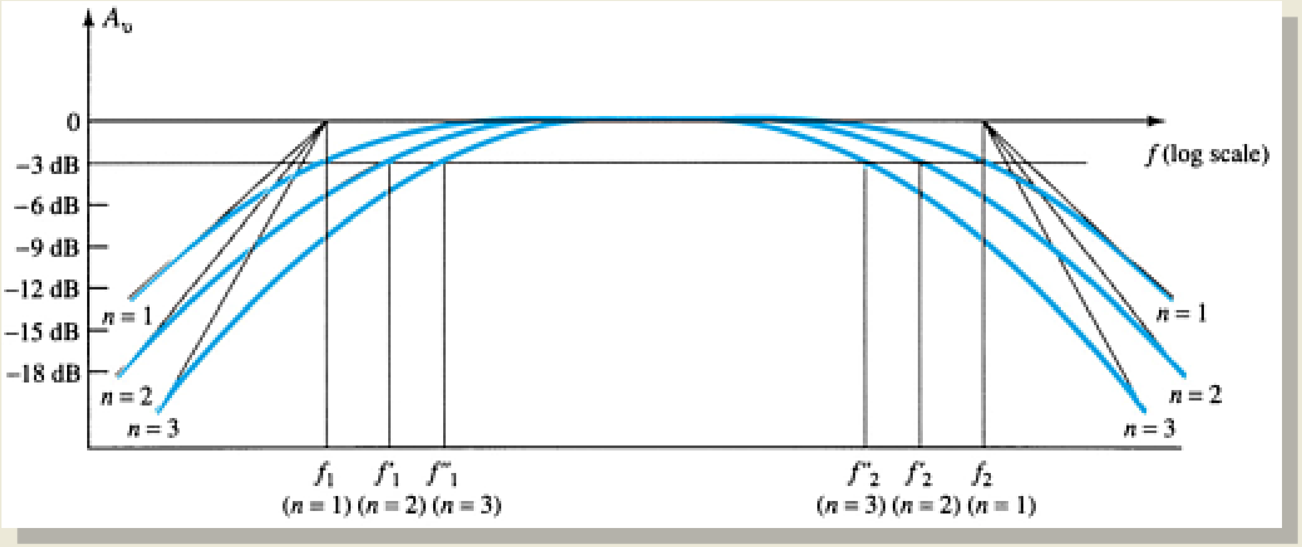
$$R_{Tho} = R_D \parallel R_L \parallel r_d$$



9.9 Multistage Frequency Effects

Each stage will have its own frequency response. But the output of one stage will be affected by capacitances in the subsequent stage. This is especially so when determining the high frequency response. For example, the output capacitance (C_o) will be affected by the input Miller Capacitance (C_{Mi}) of the next stage.

Total Frequency Response of a Multistage Amplifier



Once the cutoff frequencies have been determined for each stage (taking into account the shared capacitances), they can be plotted.

Note the *highest* lower cutoff frequency (f_L) and the *lowest* upper cutoff frequency (f_H) are closest to the actual response of the amplifier.

Summary of Chapter 9

Dominant capacitances that affect the high-frequency response are:

- **Junction and parasitic capacitances: C_{be}, C_{bc}, C_{ce}**
- **Wiring capacitances: C_{wi}, C_{wo}**

Dominant capacitances that affect the low-frequency response are:

- **Coupling capacitances: C_S, C_C**
- **Bypass capacitance: C_E**

Bode plot is required to present frequency response, and determine

- **Cutoff frequencies**
- **Bandwidth**

Miller Effect of CE (or CS) configuration

- **How to increase the bandwidth of CE amplifier**