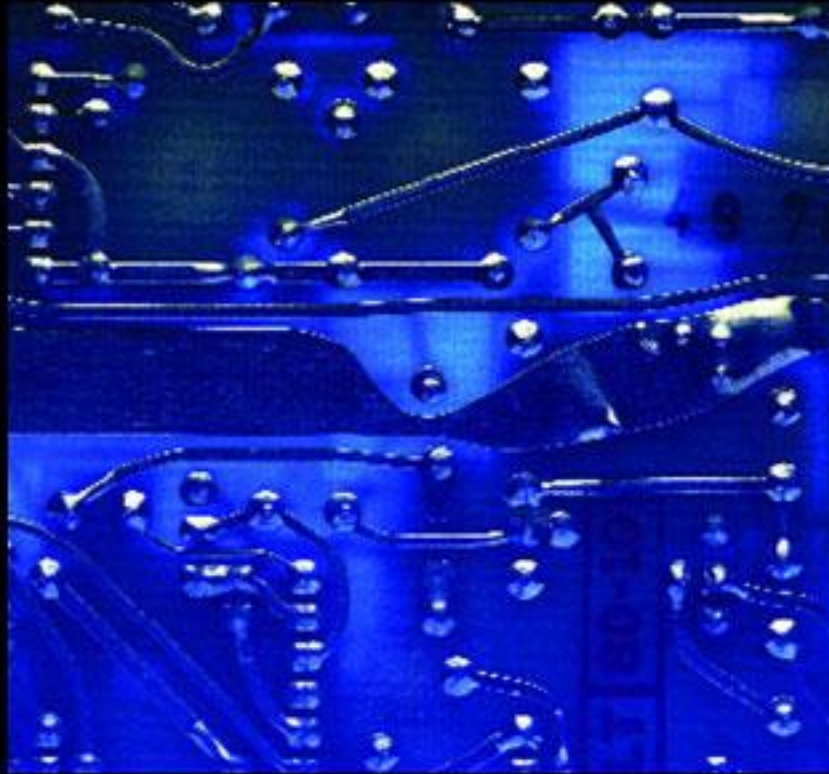


ELECTRONIC DEVICES AND CIRCUIT THEORY

TENTH EDITION



BOYLESTAD

PEARSON

Chapter 9: BJT and FET Frequency Response

General Frequency Considerations

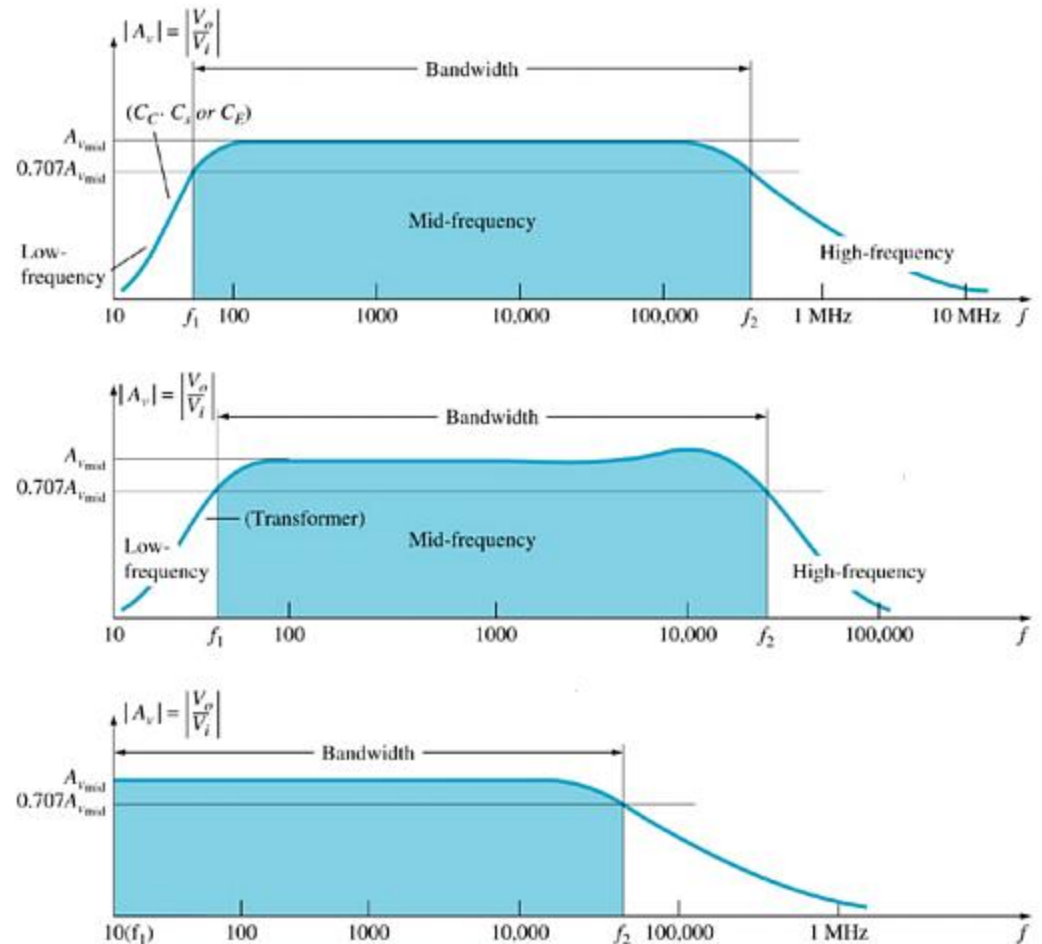
The **frequency response** of an amplifier refers to the frequency range in which the amplifier will operate with negligible effects from capacitors and device internal capacitance. This range of frequencies can be called the **mid-range**.

- 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.

Bode Plot

A Bode plot indicates the frequency response of an amplifier.

The horizontal scale indicates the frequency (in Hz) and the vertical scale indicates the gain (in dB).

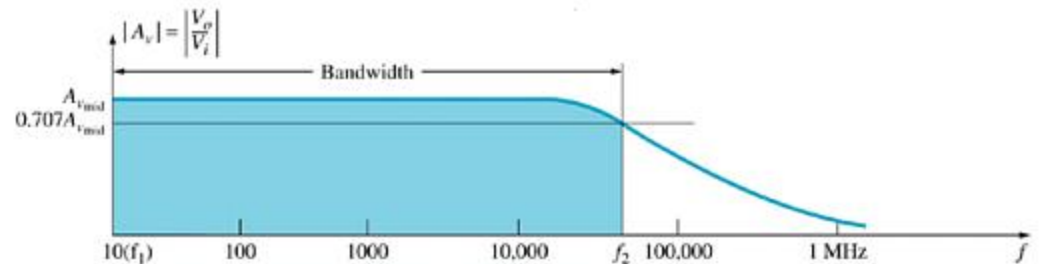
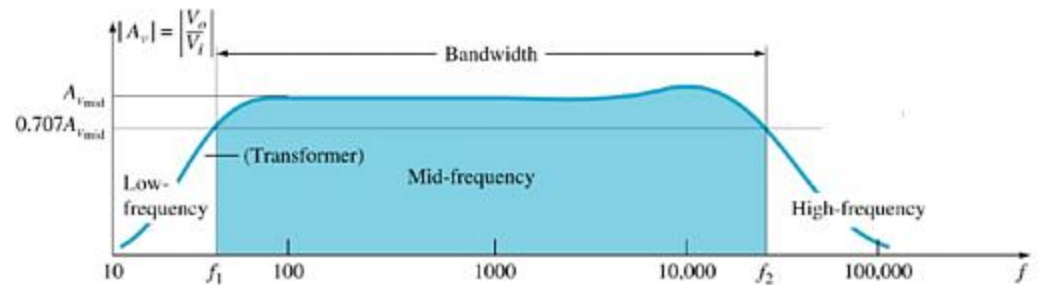
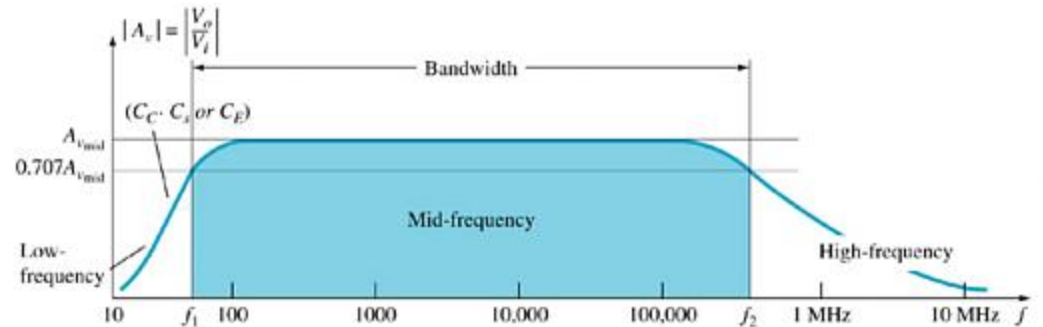


Cutoff Frequencies

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

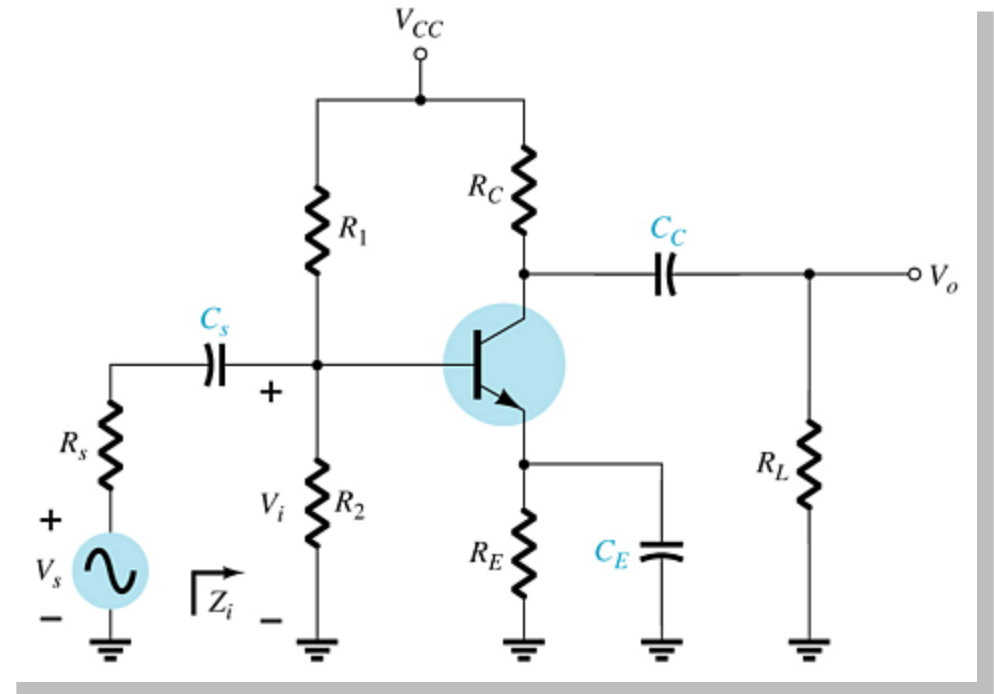
The **bandwidth** is defined by the lower and upper cutoff frequencies.

Cutoff – any frequency at which the gain has dropped by 3 dB.



BJT Amplifier Low-Frequency Response

At low frequencies, coupling capacitor (C_S , C_C) and bypass capacitor (C_E) reactances affect the circuit impedances.



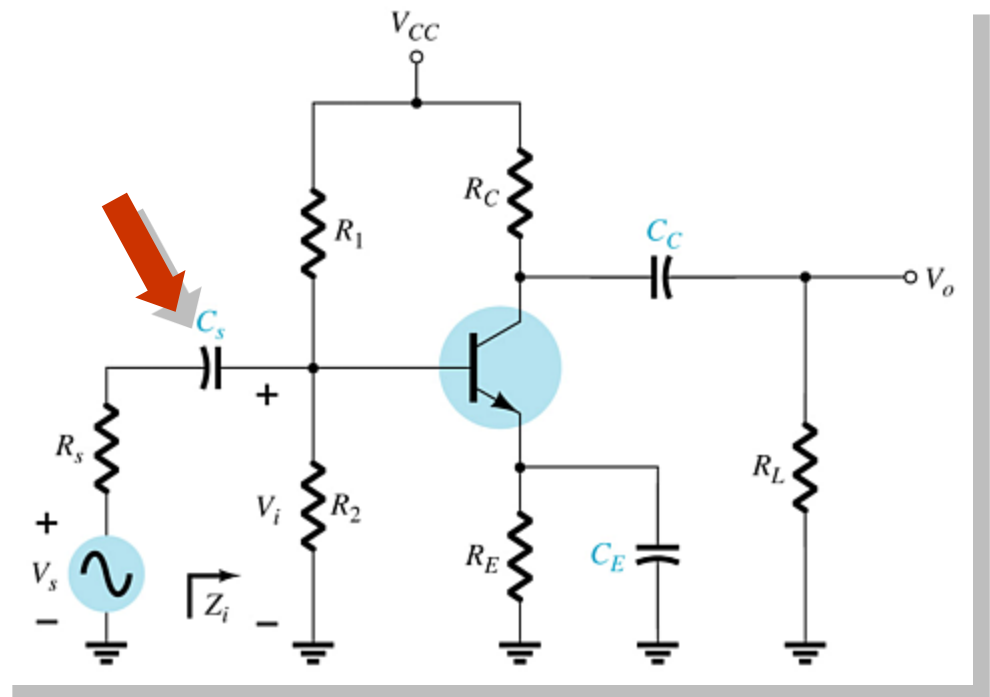
Coupling Capacitor (C_s)

The cutoff frequency due to C_s can be calculated by

$$f_{Ls} = \frac{1}{2\pi(R_s + R_i)C_s}$$

where

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



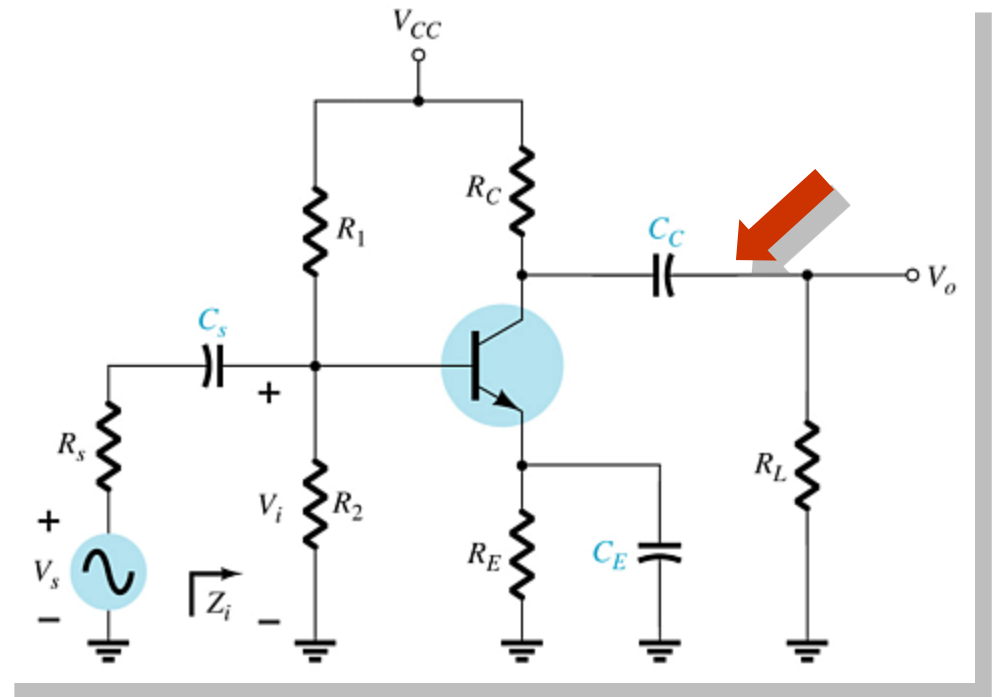
Coupling Capacitor (C_C)

The cutoff frequency due to C_C can be calculated with

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

where

$$R_o = R_C \parallel r_o$$



Bypass Capacitor (C_E)

The cutoff frequency due to C_E can be calculated with

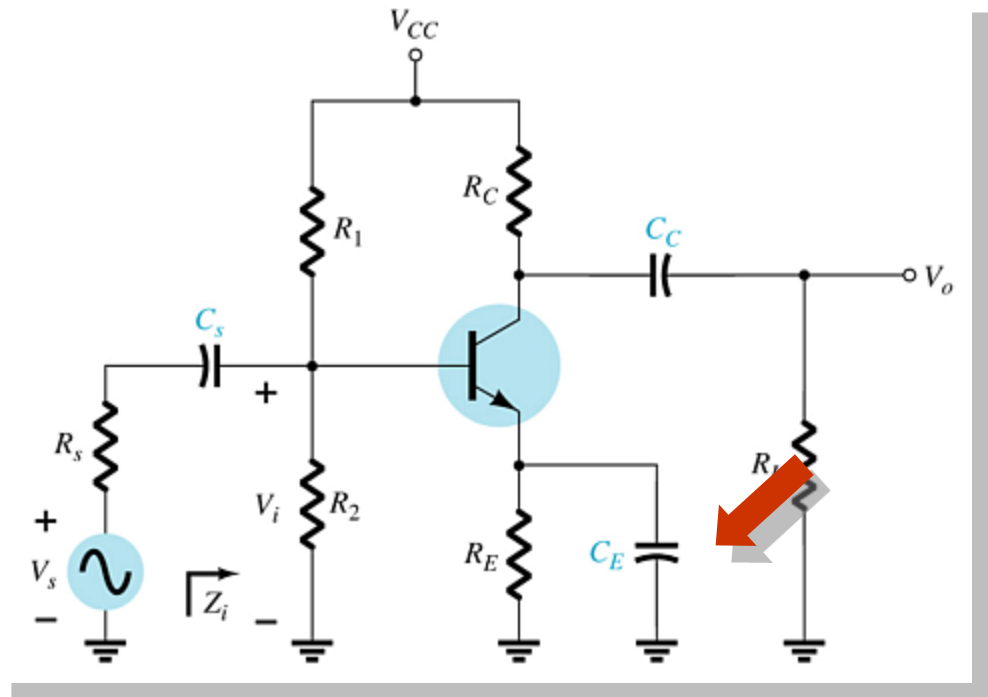
$$f_{LE} = \frac{1}{2\pi R_e C_E}$$

where

$$R_e = R_E \parallel \left(\frac{R'_s}{\beta} + r_e \right)$$

and

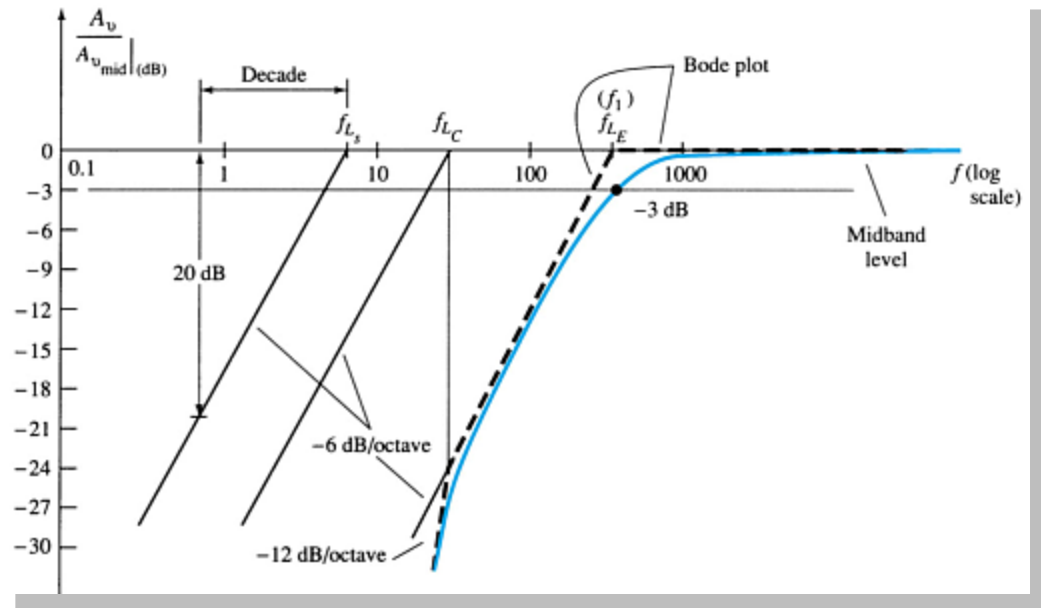
$$R'_s = R_s \parallel R_1 \parallel R_2$$



BJT Amplifier Low-Frequency Response

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.

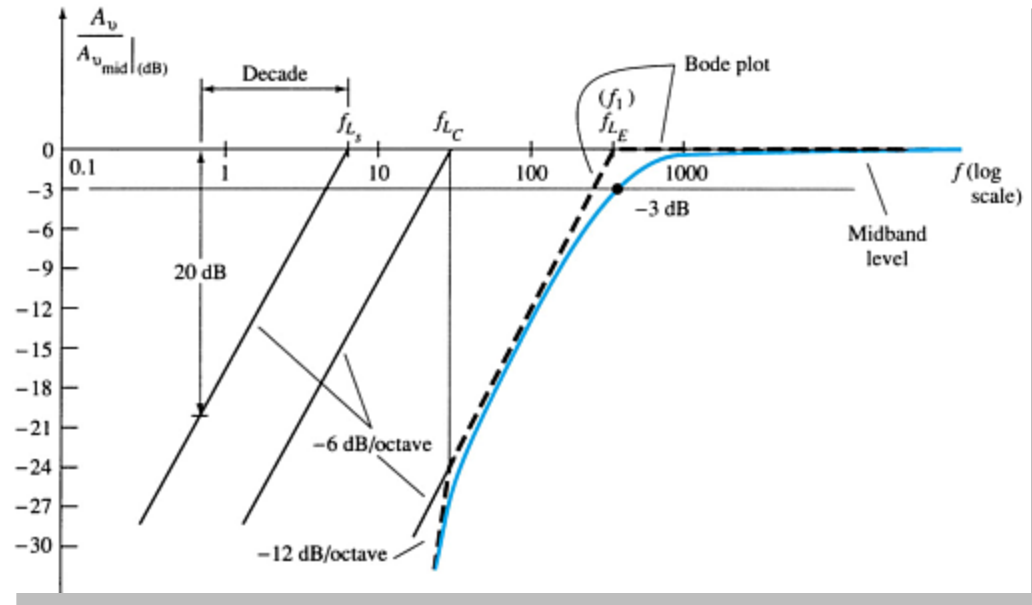


Roll-Off of Gain in the Bode Plot

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**.

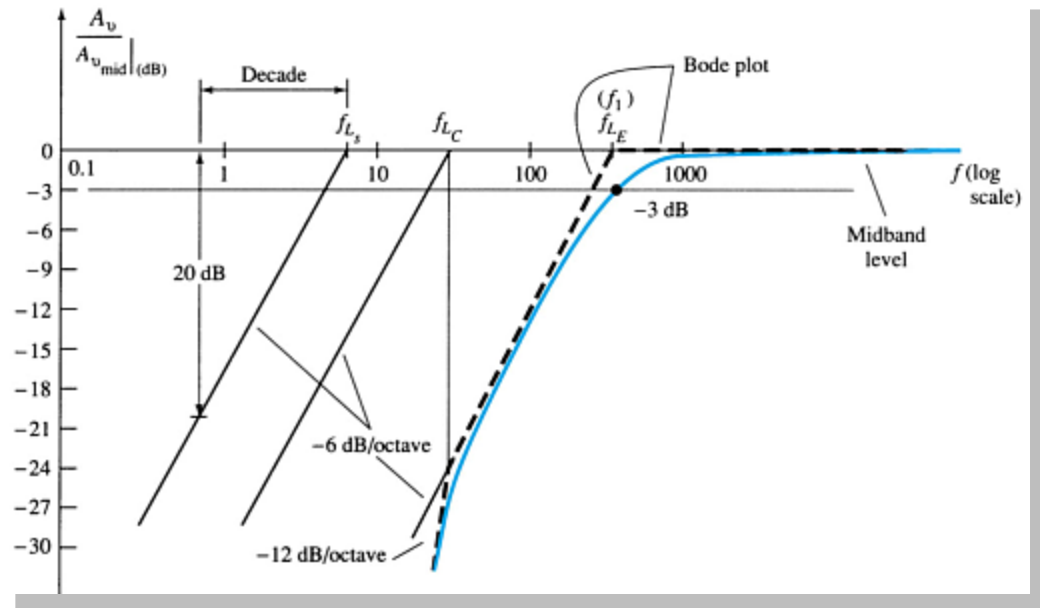
The roll-off is described as dB loss-per-octave or dB loss-per-decade.



Roll-off Rate (-dB/Decade)

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

For attenuations at the low-frequency end, it refers to the loss in gain from the lower cutoff frequency to a frequency that is one-tenth the cutoff value.



In this example:

$f_{LS} = 9\text{kHz}$ gain is 0dB

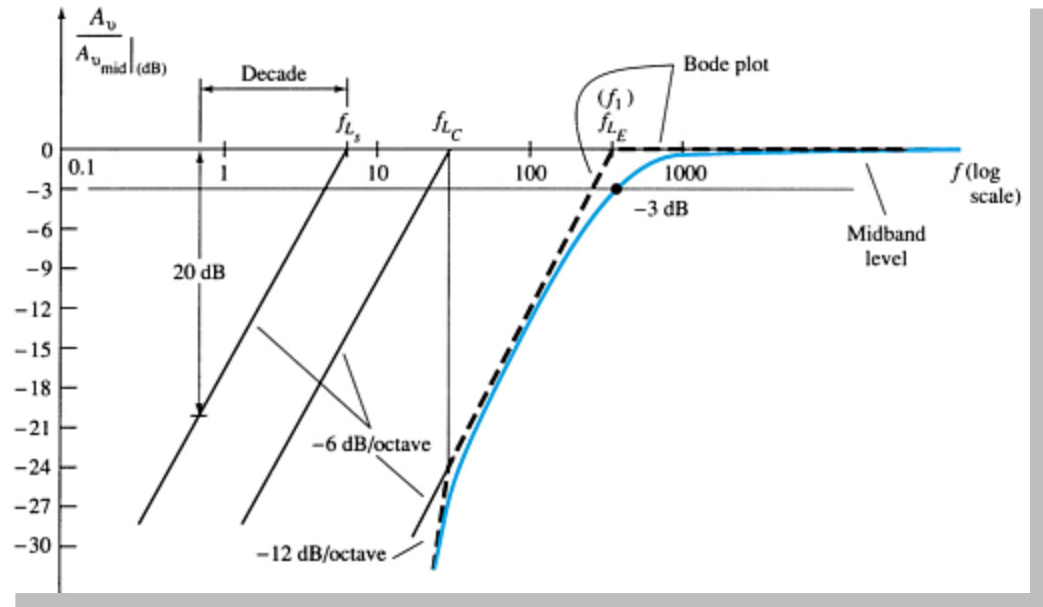
$f_{LS}/10 = .9\text{kHz}$ gain is -20dB

Thus the roll-off is 20dB/decade

The gain decreases by -20dB/decade

Roll-Off Rate (-dB/Octave)

-dB/octave refers to the attenuation for every 2-fold change in frequency. For attenuations at the low-frequency end, it refers to the loss in gain from the lower cutoff frequency to a frequency one-half the cutoff value.



In this example:

$f_{LS} = 9\text{kHz}$ gain is 0dB

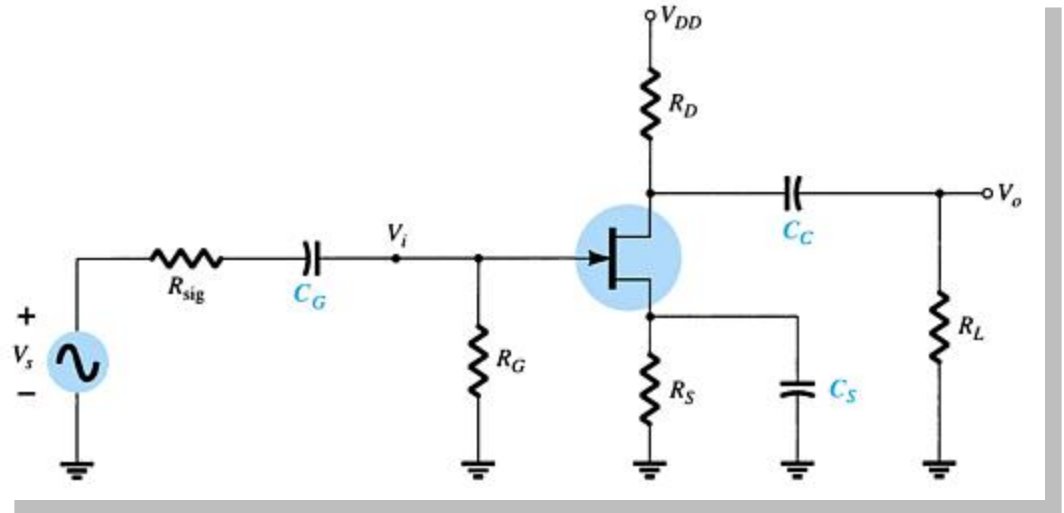
$f_{LS} / 2 = 4.5\text{kHz}$ gain is -6dB

Therefore the roll-off is 6dB/octave.

This is a little difficult to see on this graph because the horizontal scale is a logarithmic scale.

FET Amplifier Low-Frequency Response

At low frequencies, coupling capacitor (C_G , C_C) and bypass capacitor (C_S) reactances affect the circuit impedances.



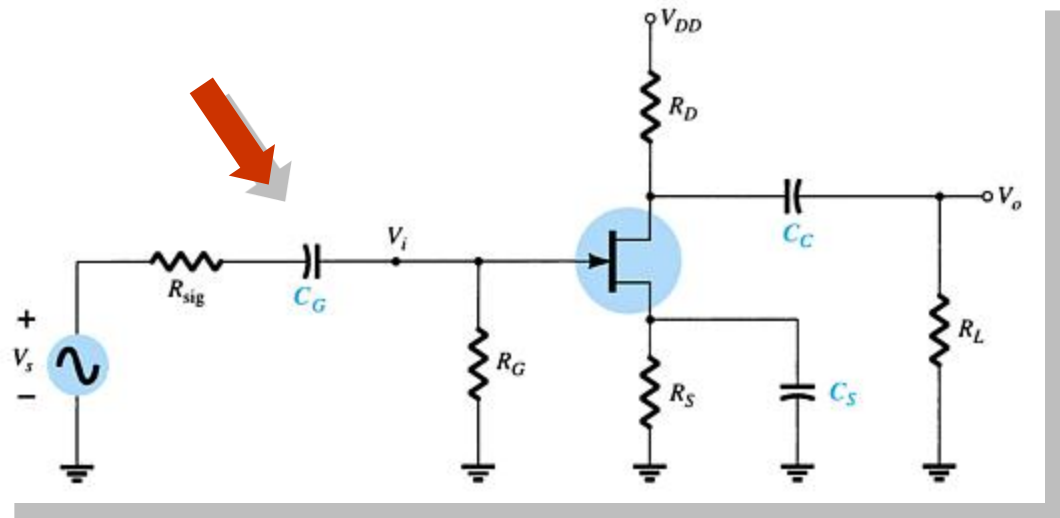
Coupling Capacitor (C_G)

The cutoff frequency due to C_G can be calculated with

$$f_{LC} = \frac{1}{2\pi(R_{sig} + R_i)C_G}$$

where

$$R_i = R_G$$



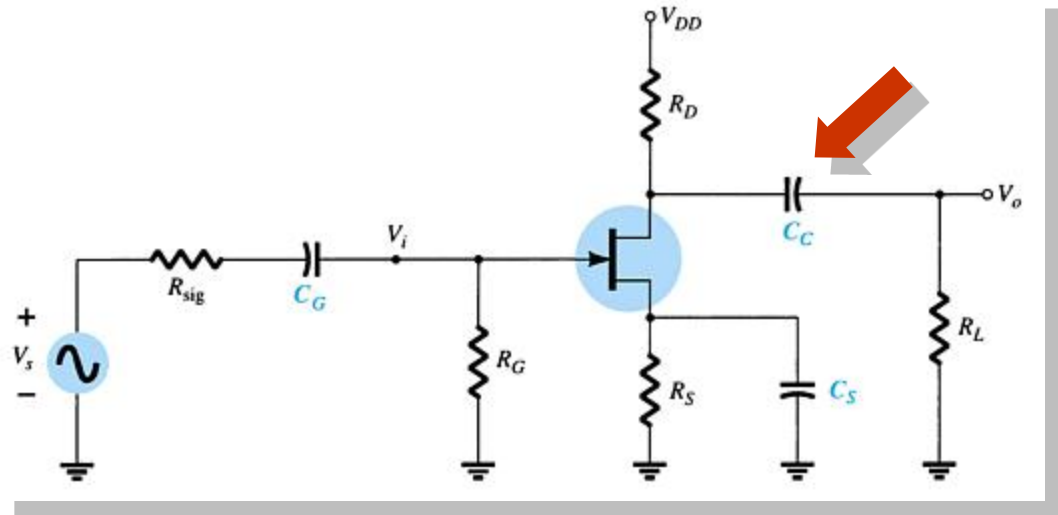
Coupling Capacitor (C_C)

The cutoff frequency due to C_C can be calculated with

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

where

$$R_o = R_D \parallel r_d$$



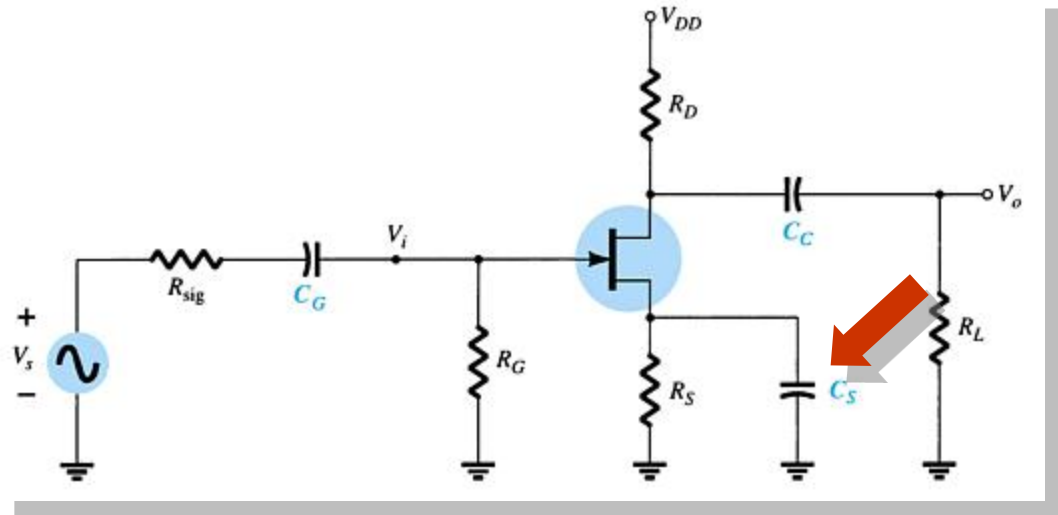
Bypass Capacitor (C_S)

The cutoff frequency due to C_S can be calculated with

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

where

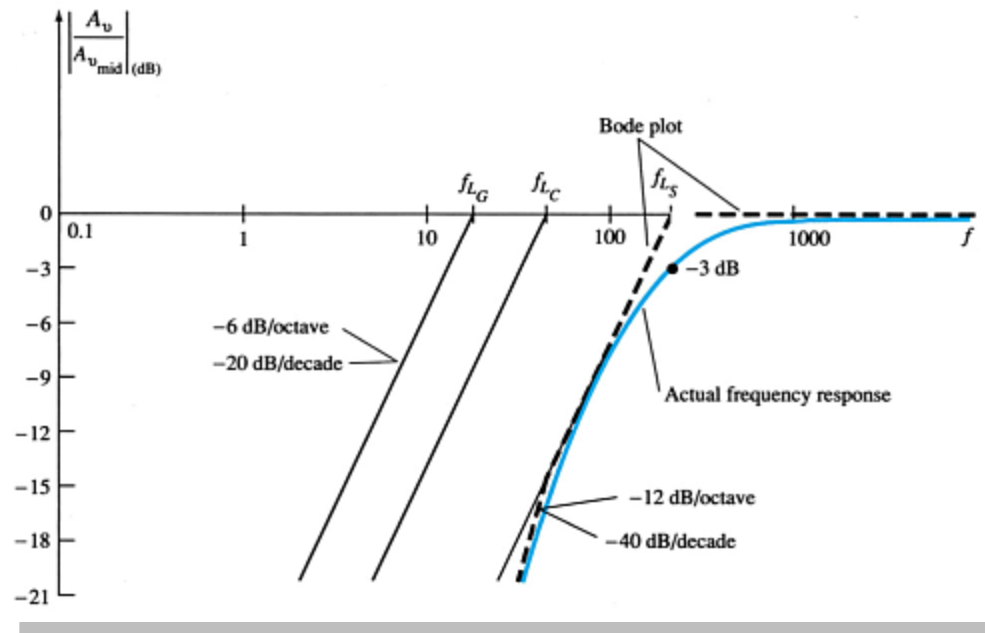
$$R_{eq} = R_S \parallel \frac{1}{g_m} \Big|_{r_d \cong \infty \Omega}$$



FET Amplifier Low-Frequency Response

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.



Miller Capacitance

Any $p-n$ junction can develop capacitance. In a BJT amplifier, this capacitance becomes noticeable across:

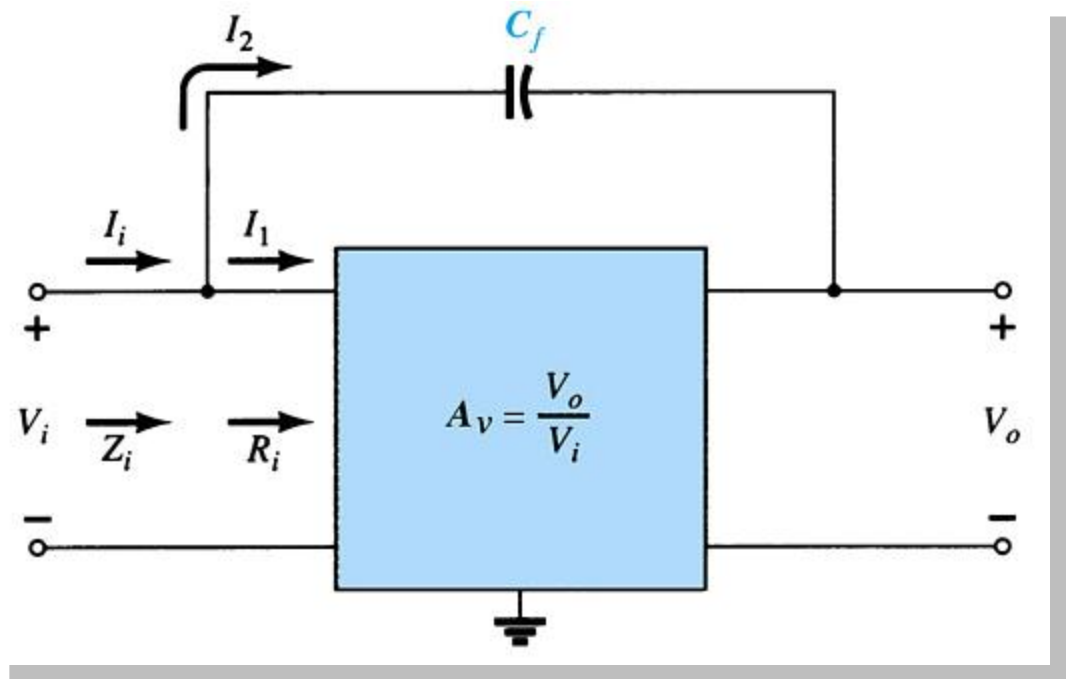
- **The base-collector junction at high frequencies in common-emitter BJT amplifier configurations**
- **The gate-drain junction at high frequencies in common-source FET amplifier configurations.**

These capacitances are represented as separate input and output capacitances, called the **Miller Capacitances.**

Miller Input Capacitance (C_{Mi})

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

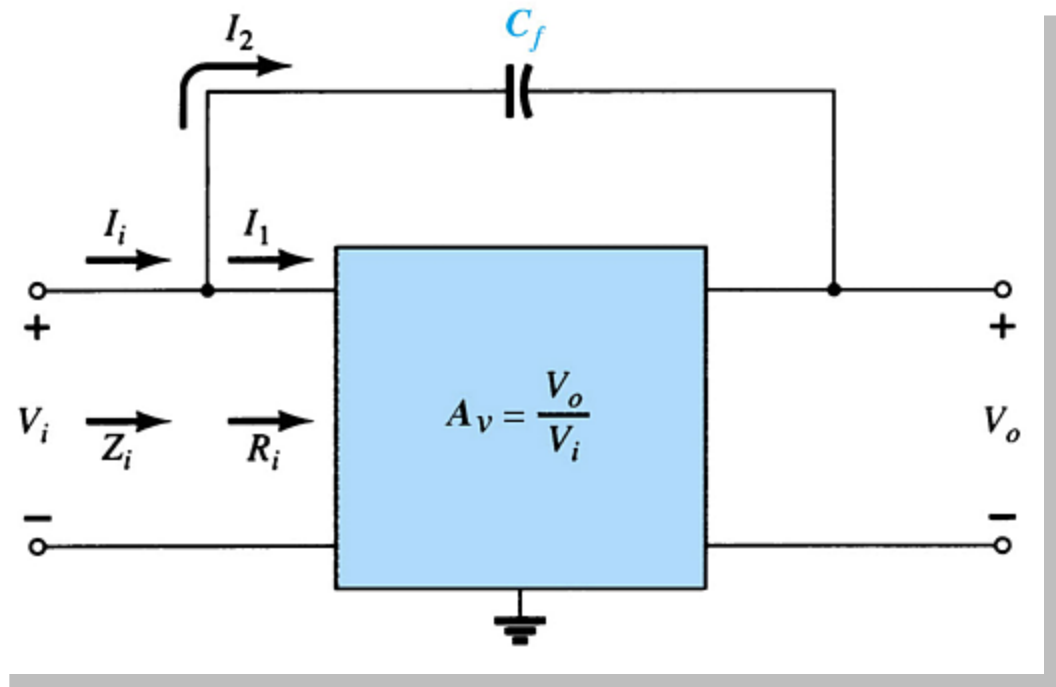
Note that the amount of Miller capacitance is dependent on inter-electrode capacitance from input to output (C_f) and the gain (A_v).



Miller Output Capacitance (C_{M_o})

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

$$C_{M_o} \cong C_f$$



BJT Amplifier High-Frequency Response

Capacitances that affect the high-frequency response are

- **Junction capacitances**

$$C_{be}, C_{bc}, C_{ce}$$

- **Wiring capacitances**

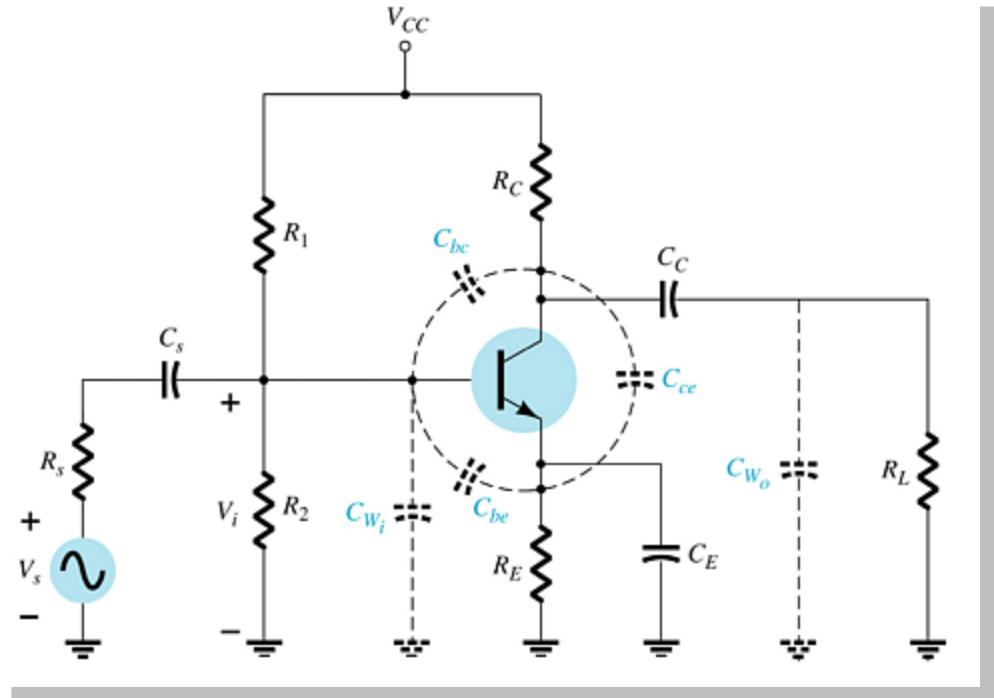
$$C_{wi}, C_{wo}$$

- **Coupling capacitors**

$$C_S, C_C$$

- **Bypass capacitor**

$$C_E$$



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

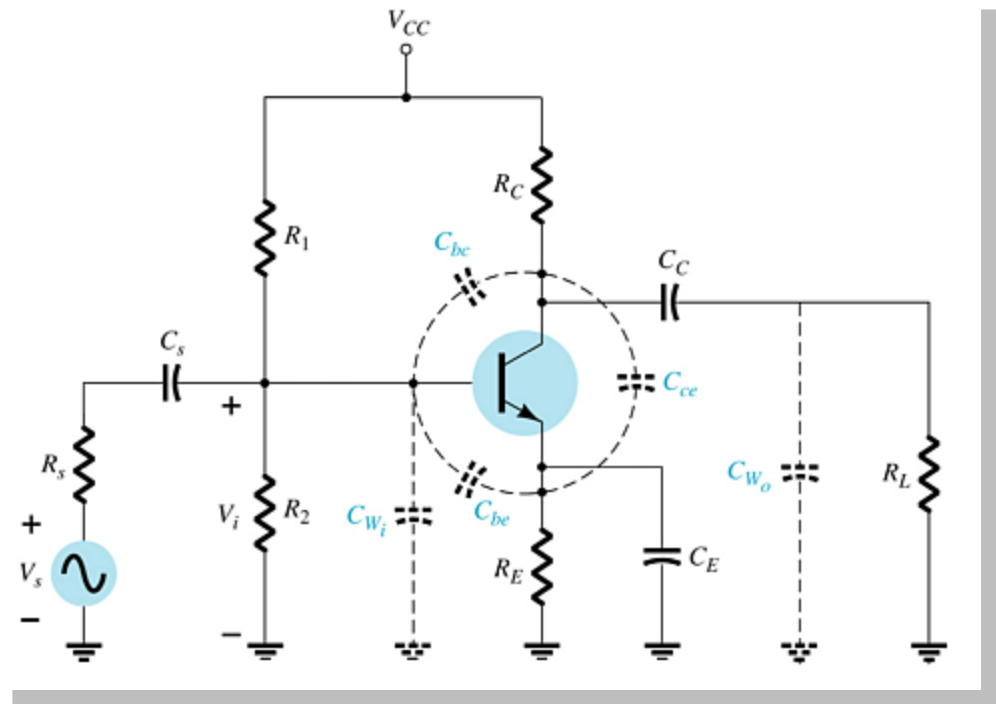
$$f_{Hi} = \frac{1}{2\pi R_{Thi} C_i}$$

where

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

and

$$\begin{aligned} C_i &= C_{Wi} + C_{be} + C_{Mi} \\ &= C_{Wi} + C_{be} + (1 - A_v) C_{bc} \end{aligned}$$



Output Network (f_{H_o}) High-Frequency Cutoff

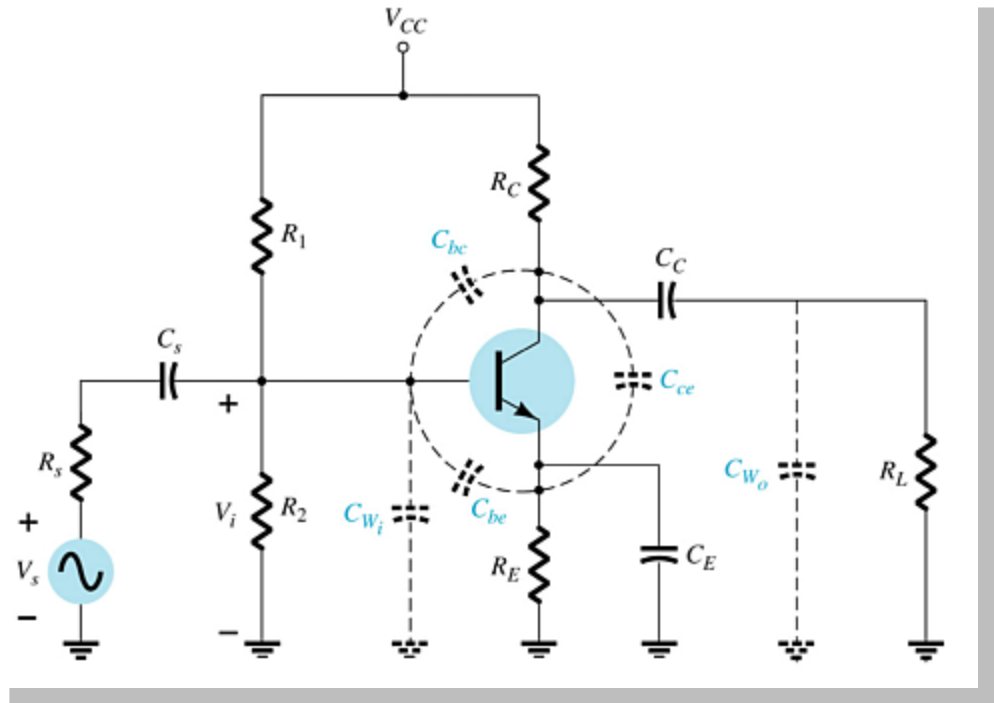
$$f_{H_o} = \frac{1}{2\pi R_{Th_o} C_o}$$

where

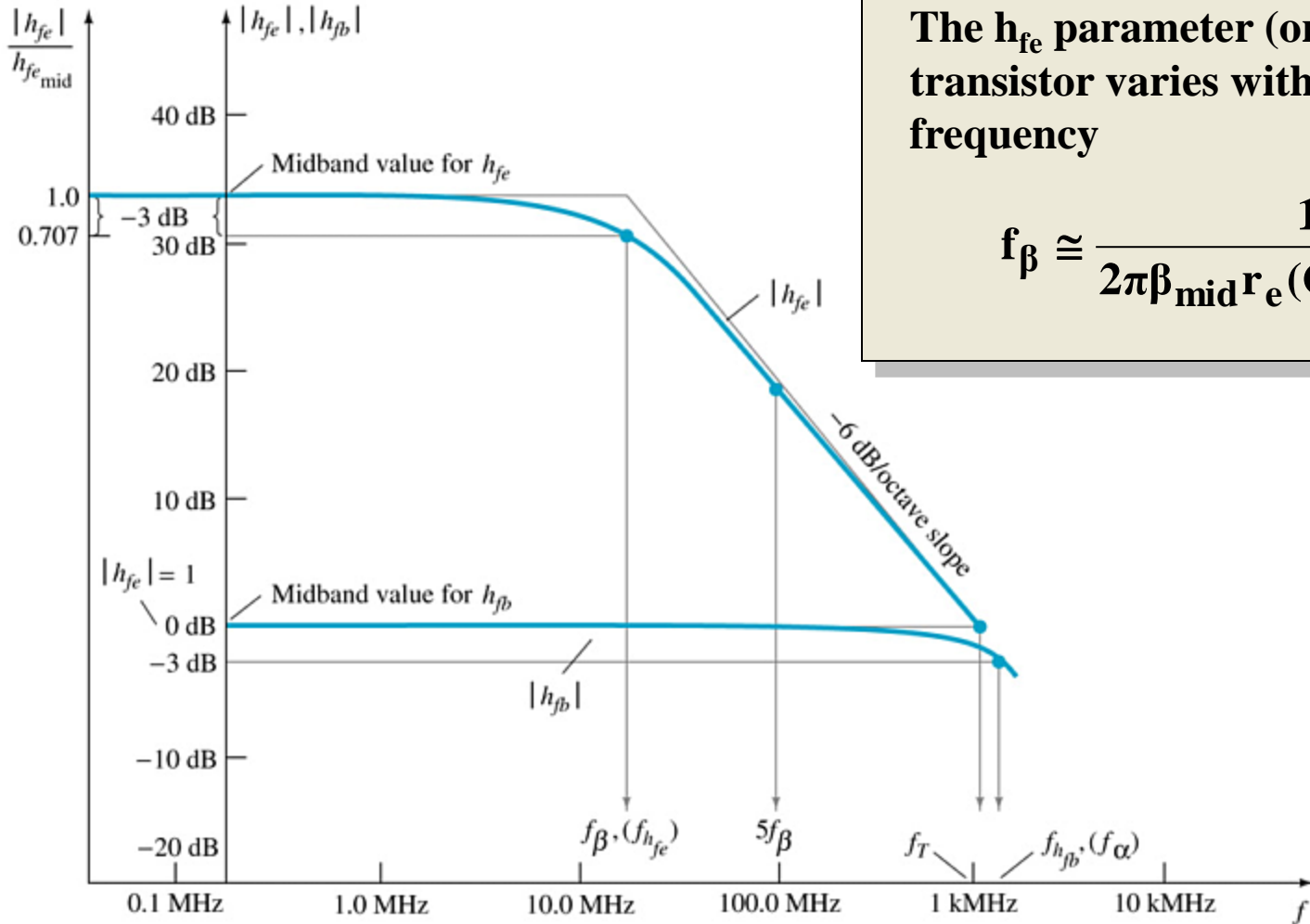
$$R_{Th_o} = R_C \parallel R_L \parallel r_o$$

and

$$C_o = C_{W_o} + C_{c_e} + C_{M_o}$$



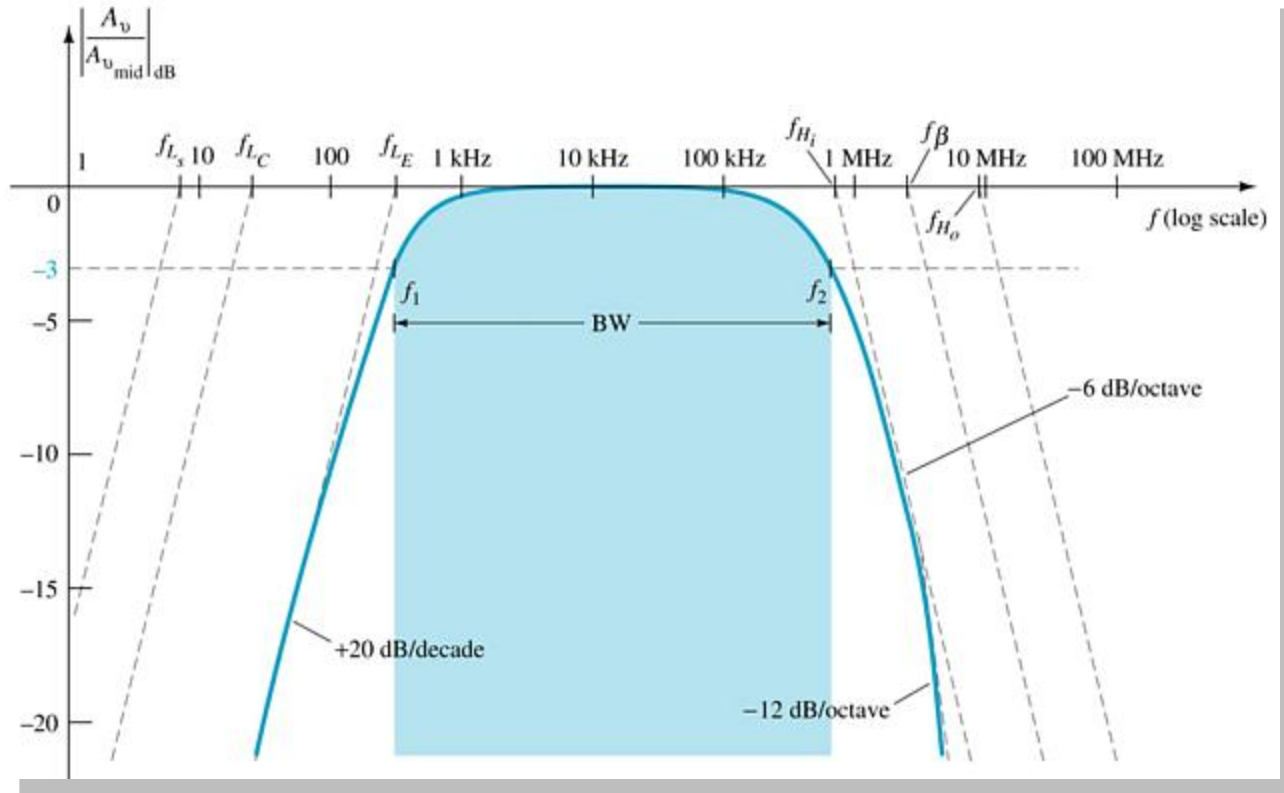
h_{fe} (or β) Variation



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

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

BJT Amplifier Frequency Response



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.

FET Amplifier High-Frequency Response

Capacitances that affect the high-frequency response are

- Junction capacitances

$$C_{gs}, C_{gd}, C_{ds}$$

- Wiring capacitances

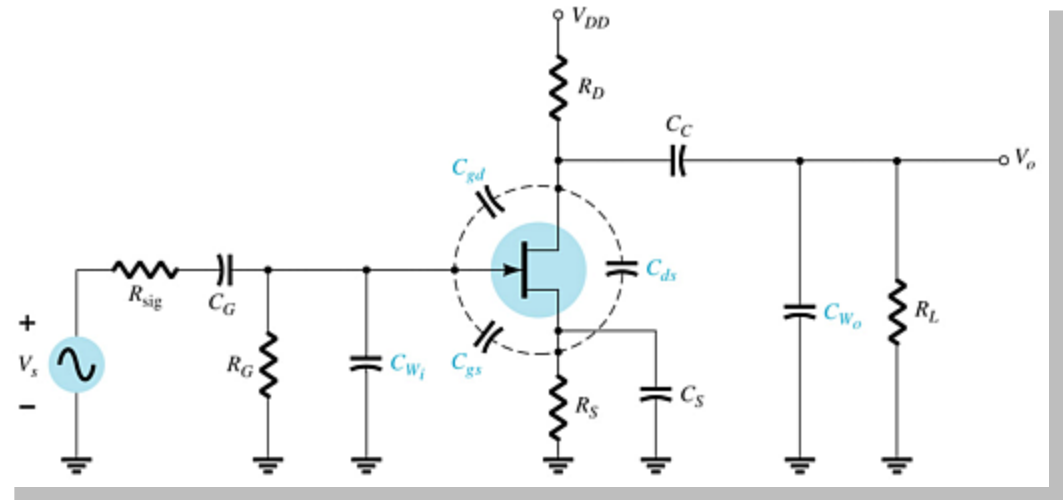
$$C_{wi}, C_{wo}$$

- Coupling capacitors

$$C_G, C_C$$

- Bypass capacitor

$$C_S$$



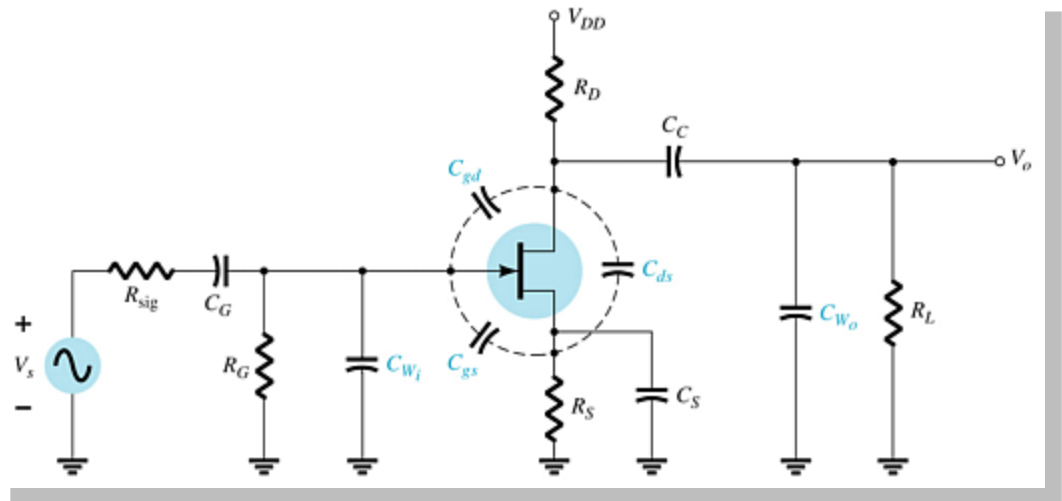
Input Network (f_{Hi}) High-Frequency Cutoff

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

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

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

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



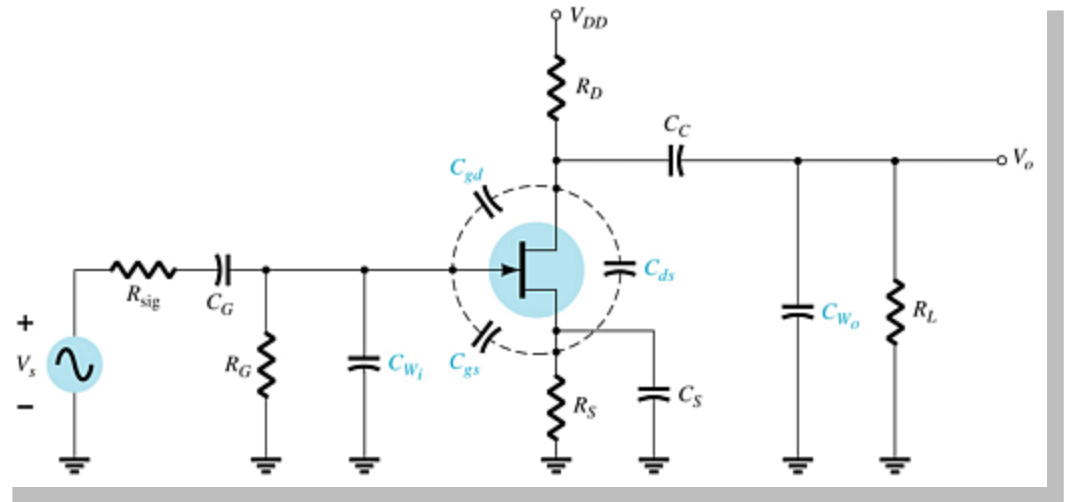
Output Network (f_{H_o}) High-Frequency Cutoff

$$f_{H_o} = \frac{1}{2\pi R_{Th_o} C_o}$$

$$C_o = C_{W_o} + C_{ds} + C_{M_o}$$

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

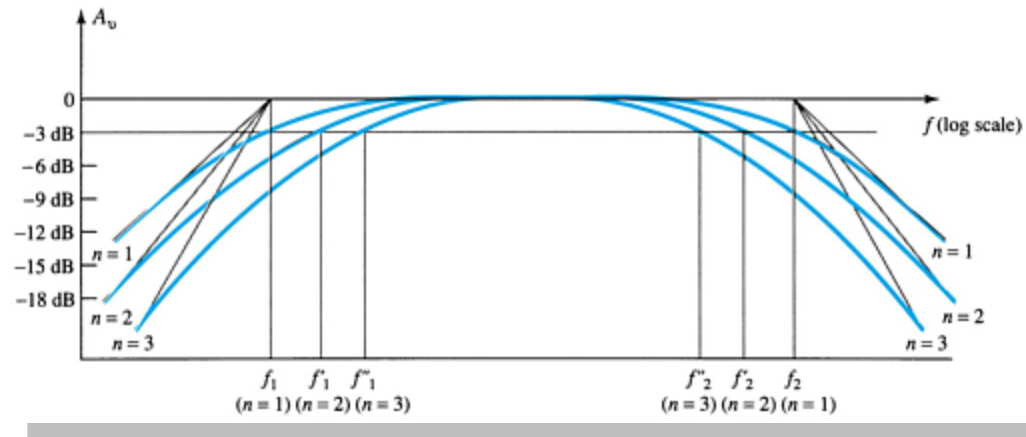
$$R_{Th_o} = R_D \parallel R_L \parallel r_d$$



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.

Multistage Amplifier Frequency Response



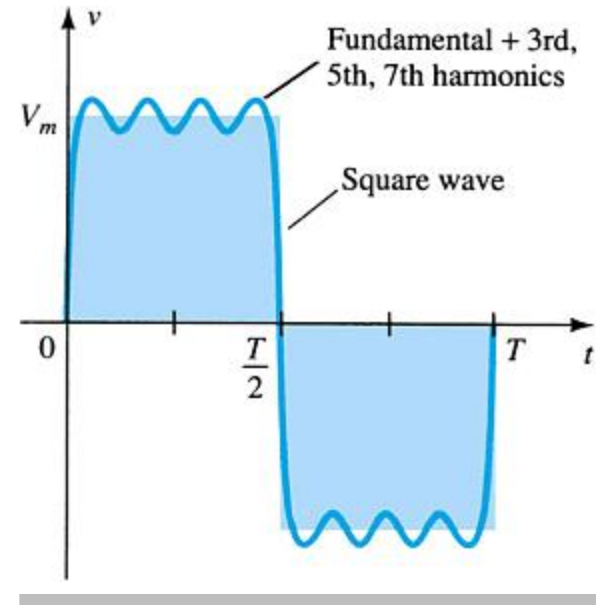
Once the cutoff frequencies have been determined for each stage (taking into account the shared capacitances), they can be plotted.

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.

Square Wave Testing

In order to determine the frequency response of an amplifier by experimentation, you must apply a wide range of frequencies to the amplifier.

One way to accomplish this is to apply a square wave. A square wave consists of multiple frequencies (by Fourier analysis: it consists of odd harmonics).



Square Wave Response Waveforms

If the output of the amplifier is not a perfect square wave then the amplifier is 'cutting' off certain frequency components of the square wave.

