BME 202 Electronics

Lecture 13: BJT and JFET Frequency Response

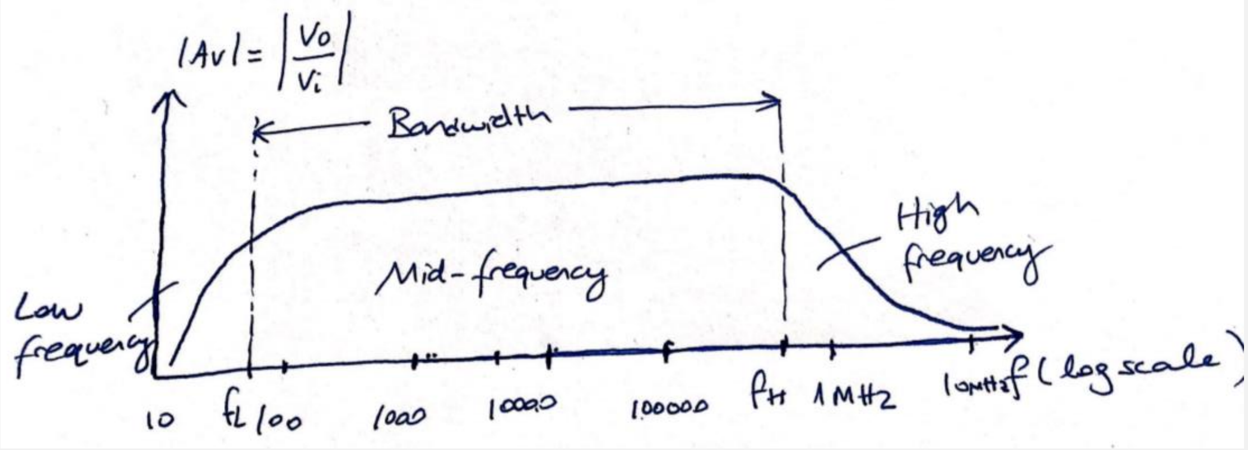
General Frequency Considerations

Frequency Response: The frequency range in which an amplifier will operate with negligible effects from capacitors and device internal capacitances; often called the mid-range.

- At frequencies below mid-range, the coupling and bypass capacitors lower the gain.
- At frequencies above mid-range, 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 illustrates the frequency respons of an amplifier.



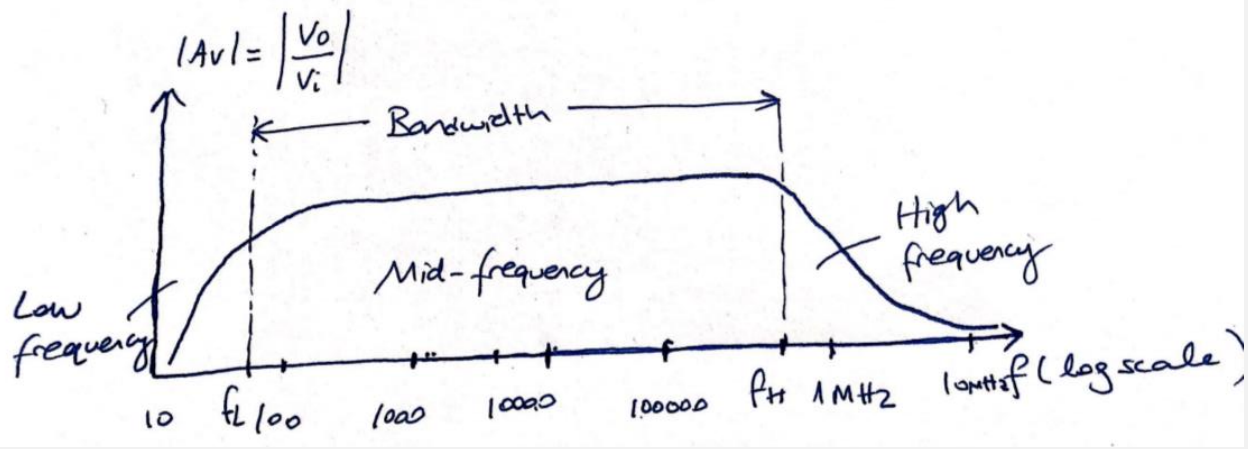
The horizontal scal indicates the frequency (in Hz) and the vertical scale indicates the gain (in dB).

Cutoff Frequencies

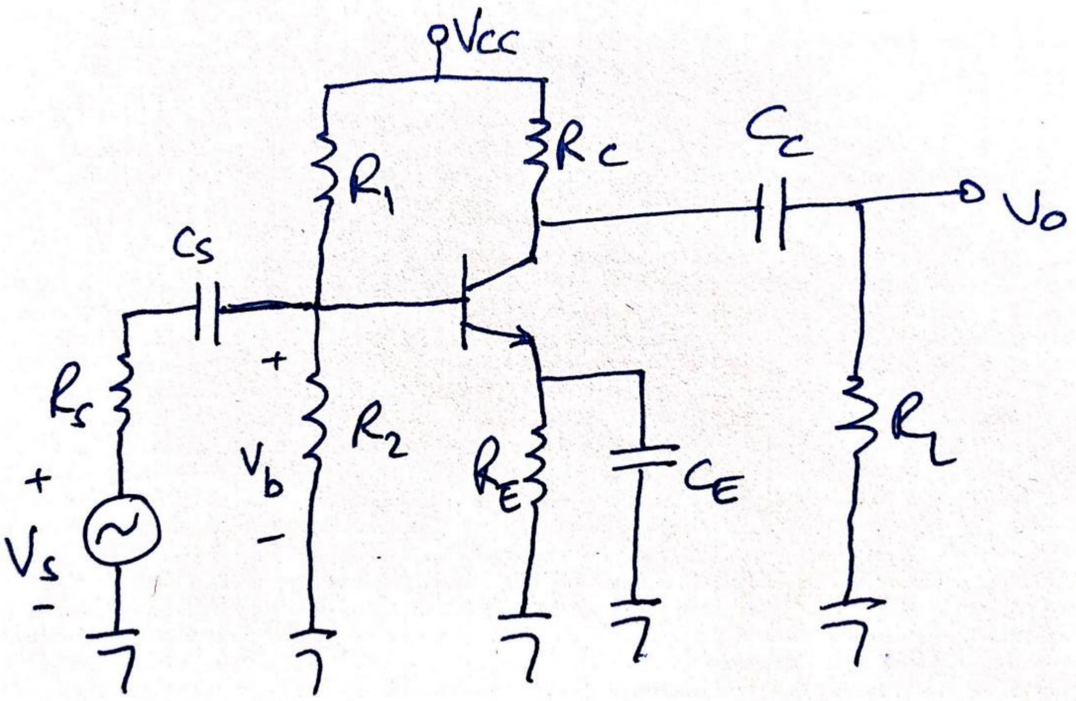
The mid-range of an amplifier is called the **bandwidth** of the amplifier.

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

Cutoff frequency – any frequency at which the gain has dropped by 3 dB from its mid-range value



BJT Amplifier Low-Frequency Response



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

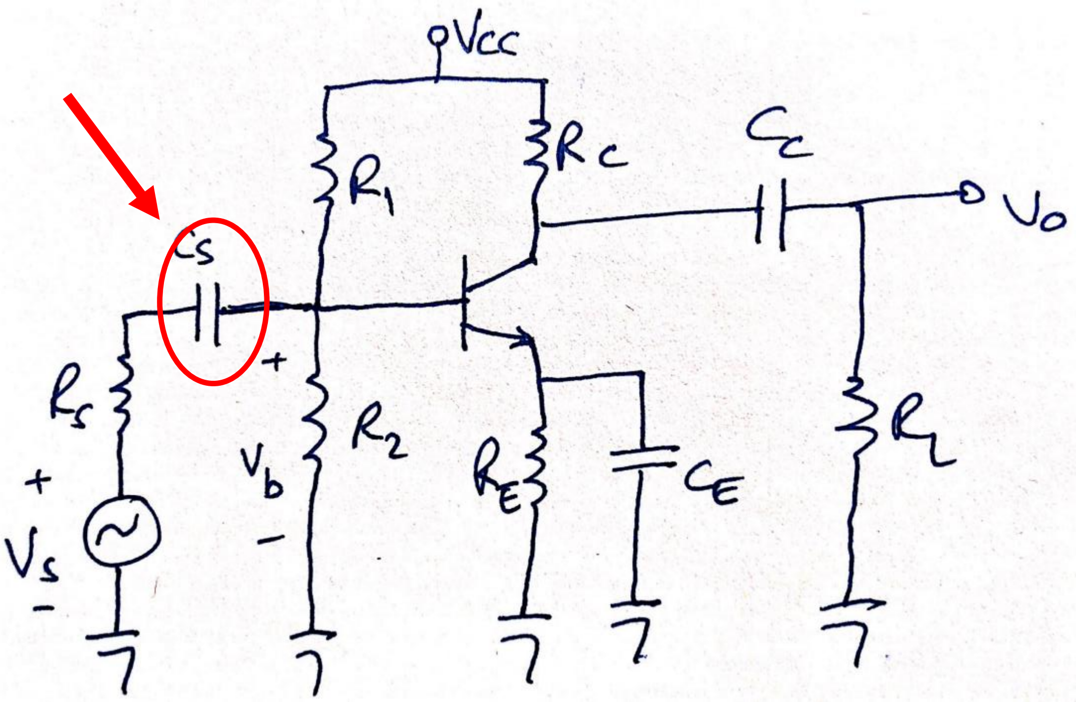
Coupling Capacitor (C_S)

The cutoff frequency due to C_S can be calculated using

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

where

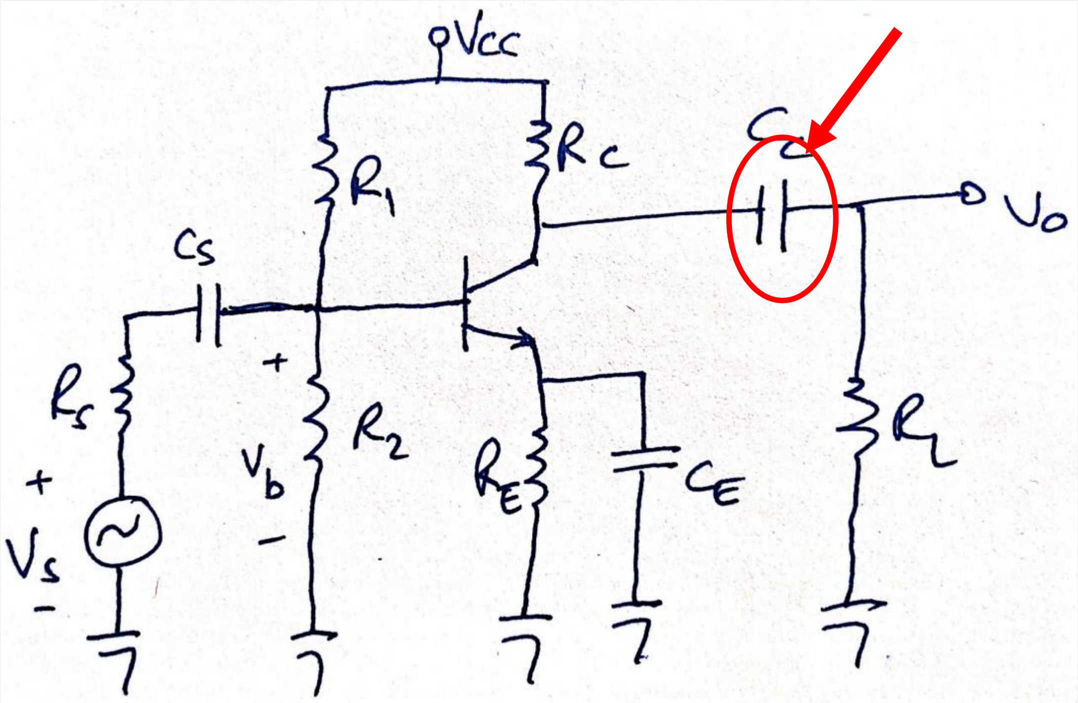
$$R_i = R_1 \| R_2 \| \beta R_e$$



Coupling Capacitor (C_C)

The cutoff frequency due to C_C can be calculated using

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



where

$$R_o = R_C \| r_o$$

Bypass Capacitor (C_E)

The cutoff frequency due to C_E can be calculated using

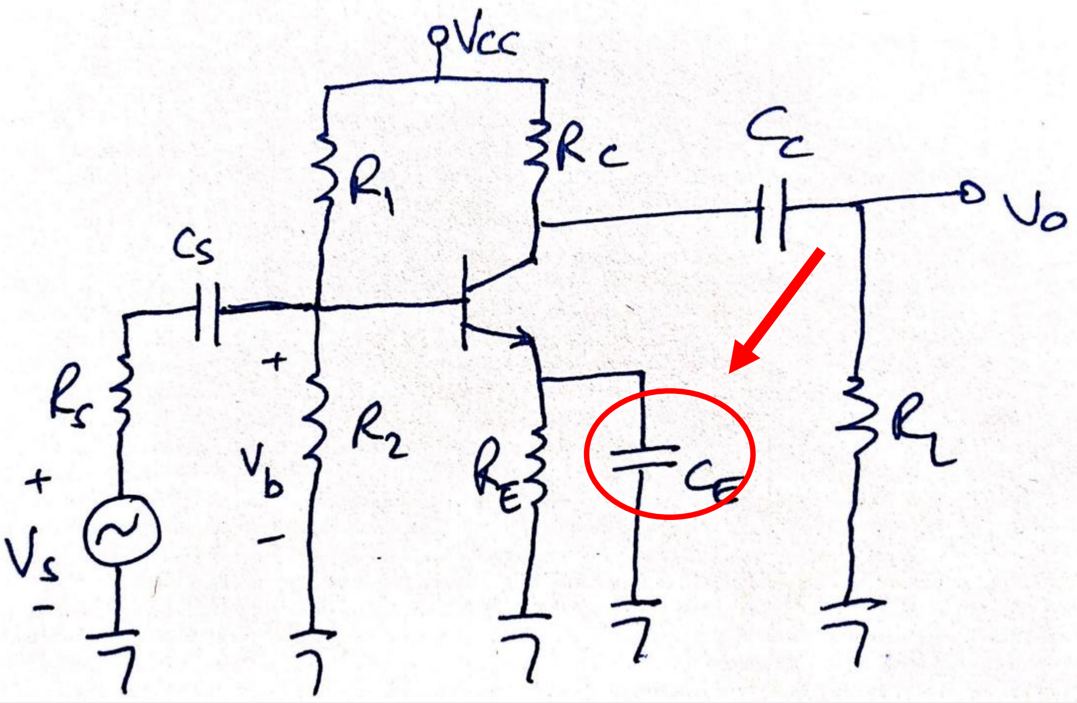
$$f_{LE} = \frac{1}{2\pi R_e C_E}$$

where

$$R_e = R_E || (\frac{R_s'}{\beta} + r_e)$$

and

$$R_s' = R_s || R_1 || R_2$$



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 low-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 rate of attenuation is sometimes referred to as **roll-off**.

The roll-off is measured in dB-per-octave or dB-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.

f_{LS} = 9kHz gain is 0dB
$f_{LS}/10$ = .9kHz gain is –20dB
Thus the roll-off is −20dB/decade

Roll-Off Rate (-dB/Octave)

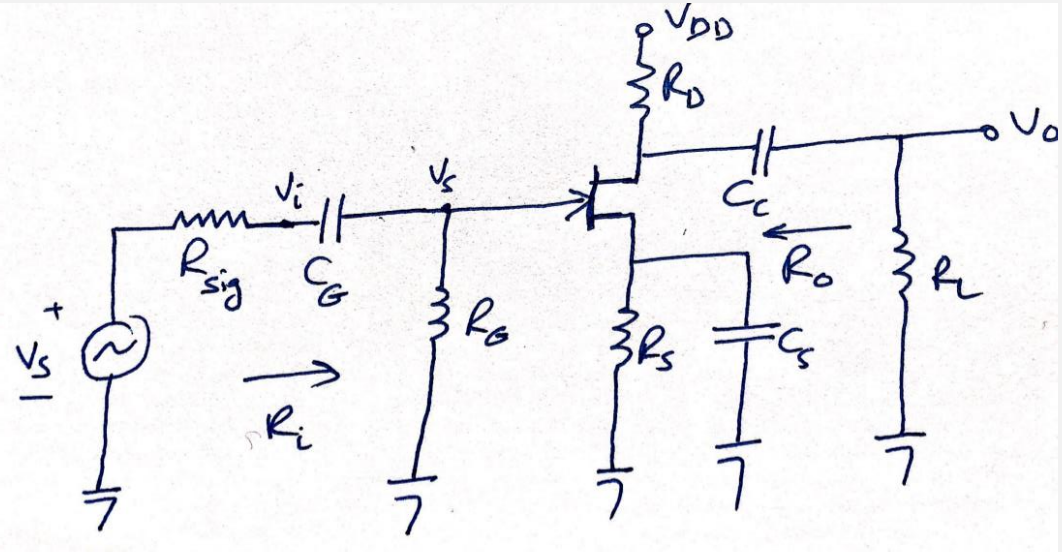
-dB/octave refers to the attenuation for every 2-fold change in frequency.
For attenuations at the low-frequency end, it refers to the loss in gain from the lower cutoff frequency to a frequency one-half the cutoff value.

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

f_{LS} = 9kHz gain is 0dB
f_{LS} / 2 = 4.5kHz gain is –6dB
Therefore the roll-off is 6dB/octave.

FET Amplifier Low-Frequency Response

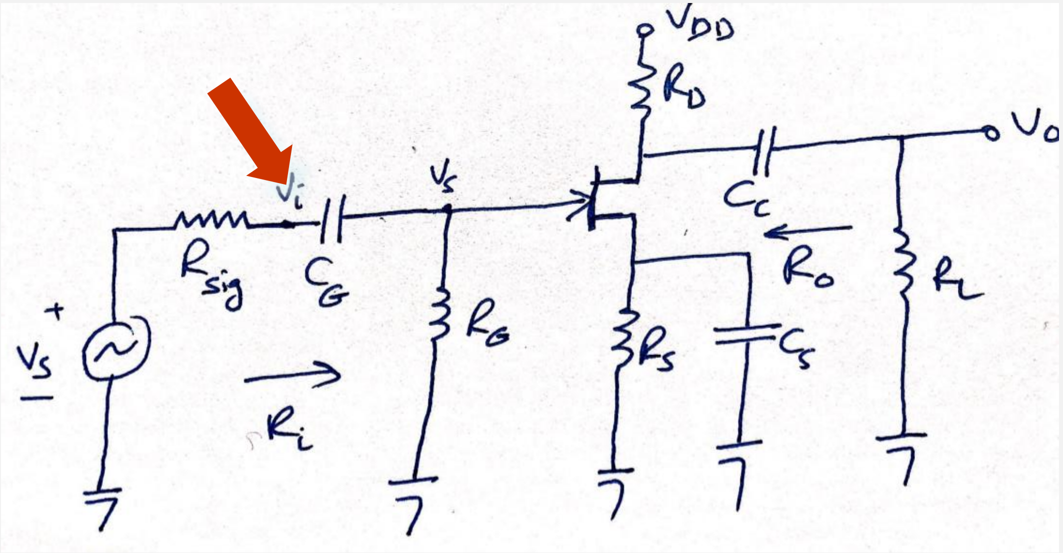
At low frequencies, the reactances of the coupling capacitors (C_G, C_C) and the bypass capacitor (C_S) affect the circuit impedances.



Coupling Capacitor (CG)

The cutoff frequency due to C_G can be calculated with

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



where

$$R_i = R_G$$

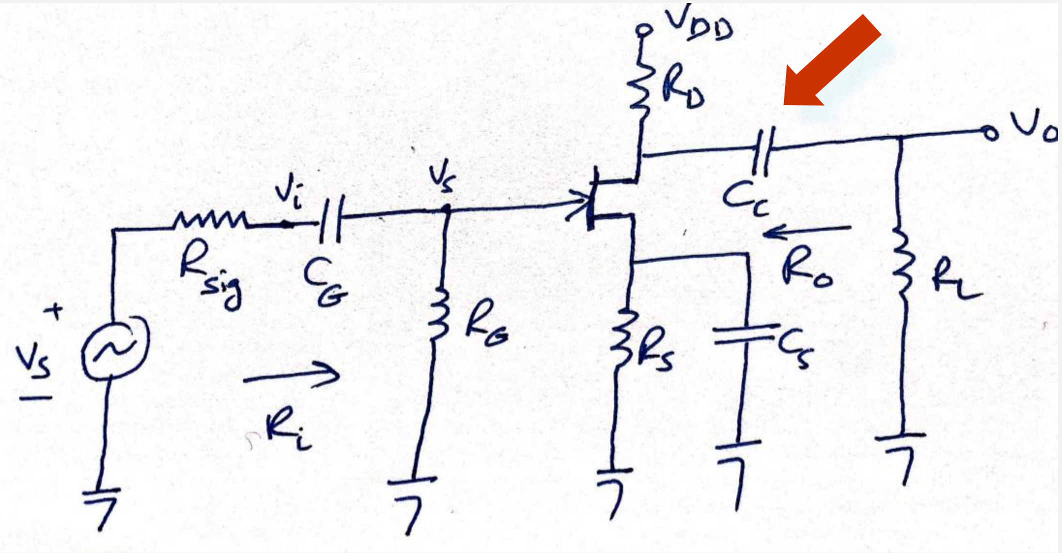
Coupling Capacitor (CC)

The cutoff frequency due to C_C can be calculated with

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

where

$$R_o = R_D \| r_d$$



Bypass Capacitor (CS)

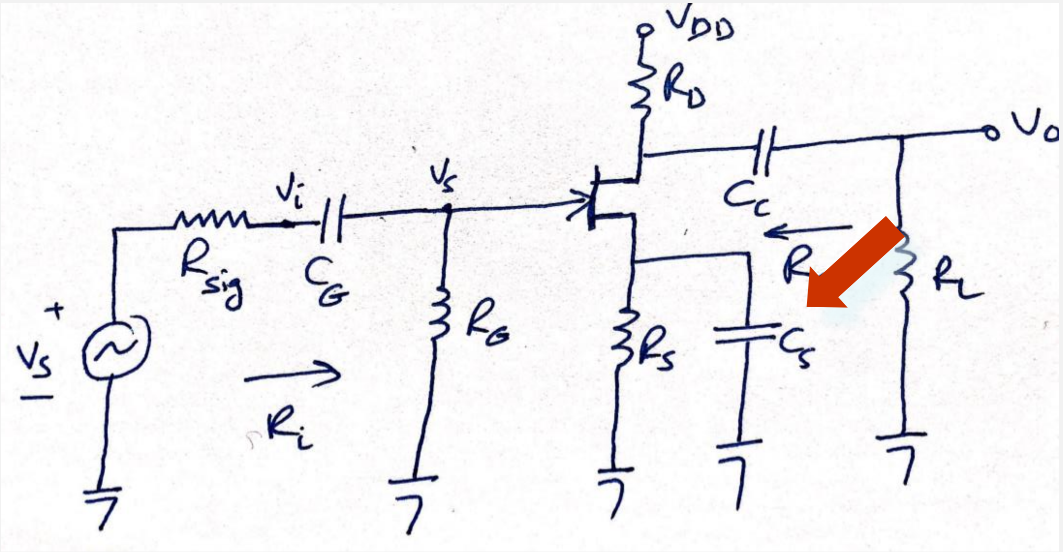
Bypass Capacitor (C_S)

The cutoff frequency due to C_S can be calculated with

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

where

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



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. This capacitance becomes noticeable across:

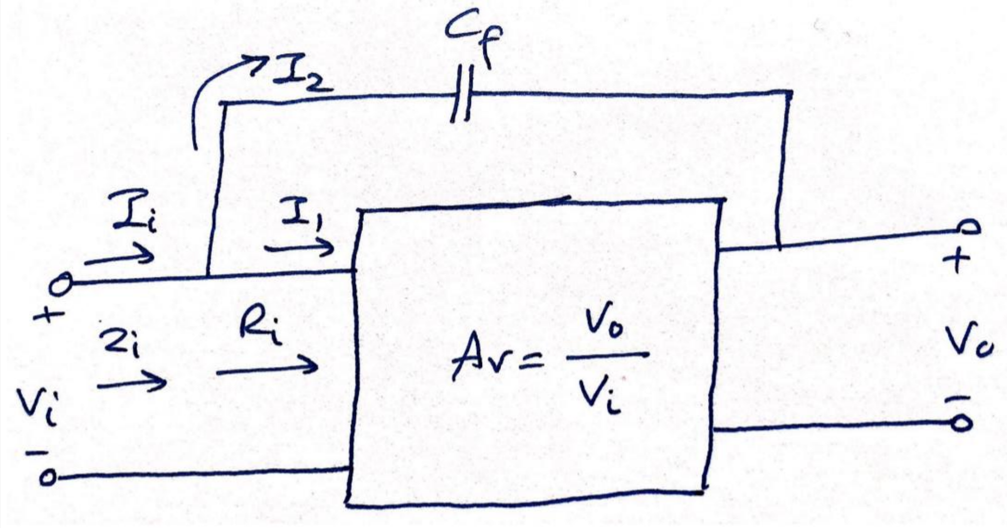
- The BJT base-collector junction in a common-emitter amplifier operating at high frequencies
- The FET gate-drain junction in a common-source amplifier at high frequencies

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

Miller Input Capacitance (C_{MI})

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

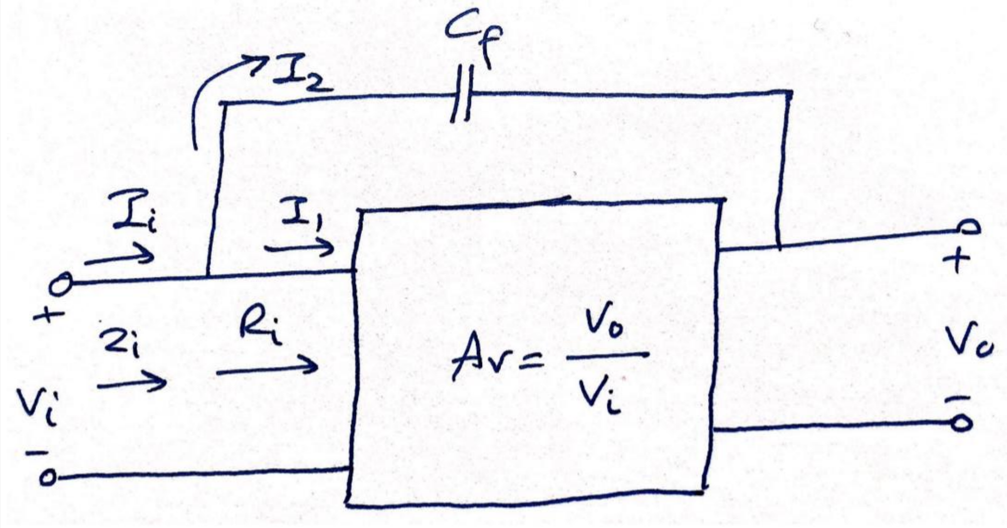
Note that the amount of Miller capacitance is dependent on inter-electrode capacitance from input to output (C_f) and the gain (A_v).



Miller Output Capacitance (C_{MO})

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

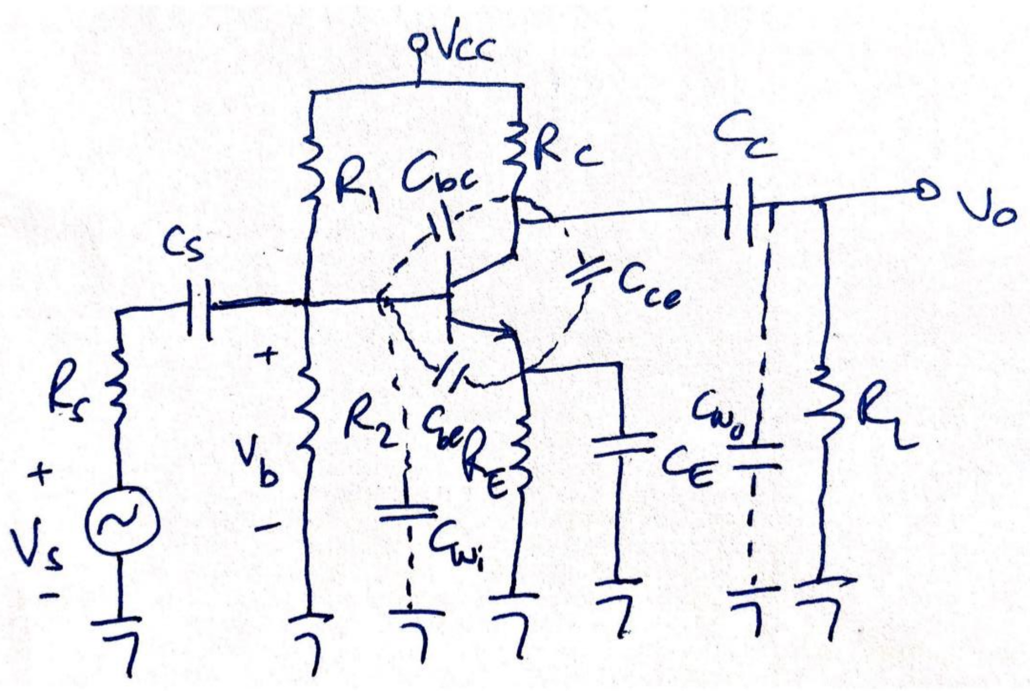
$$C_{MO} \cong C_f$$



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 High-Frequency Cutoff (fHi)

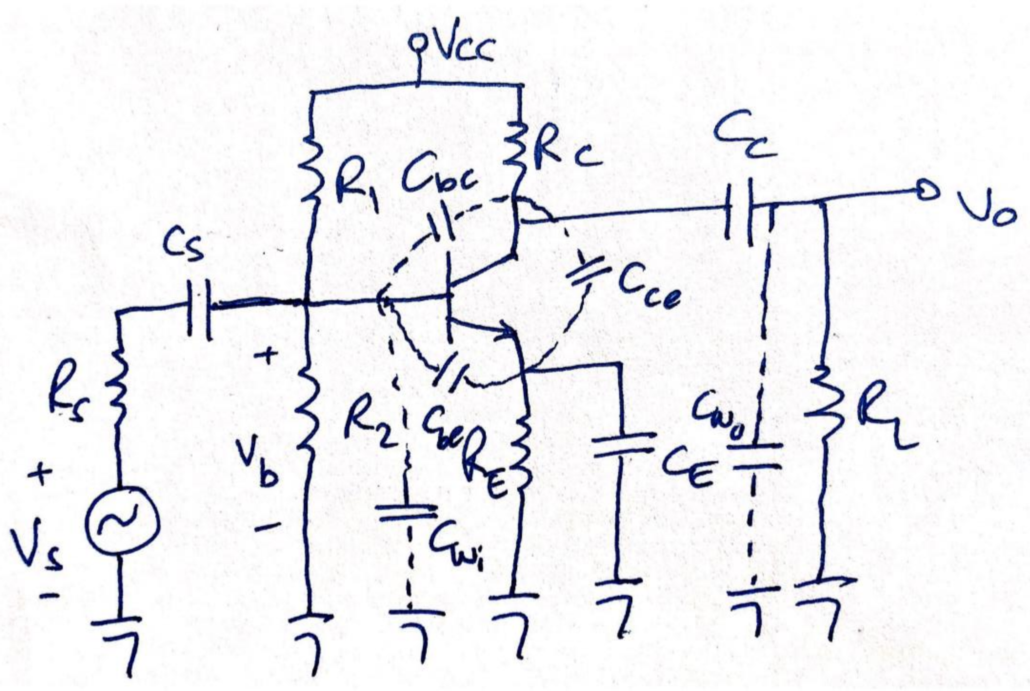
$$f_{Hi} = \frac{1}{2\pi R_{Thi} C_i}$$

where

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

and

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



Output High-Frequency Cutoff (fHo)

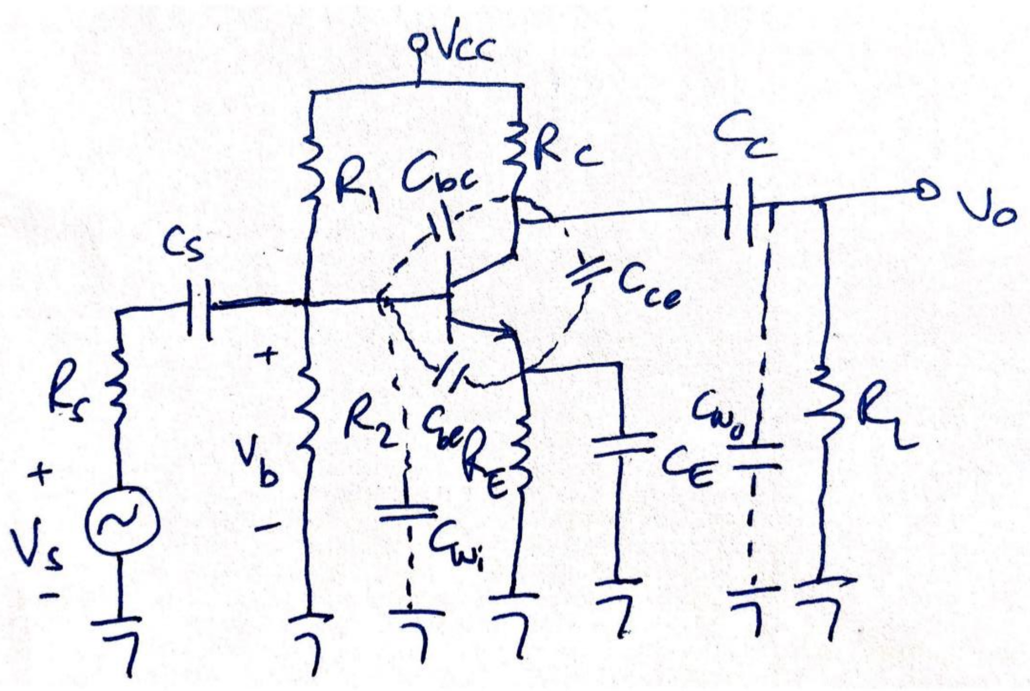
$$f_{Ho} = \frac{1}{2\pi R_{Tho} C_o}$$

where

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

and

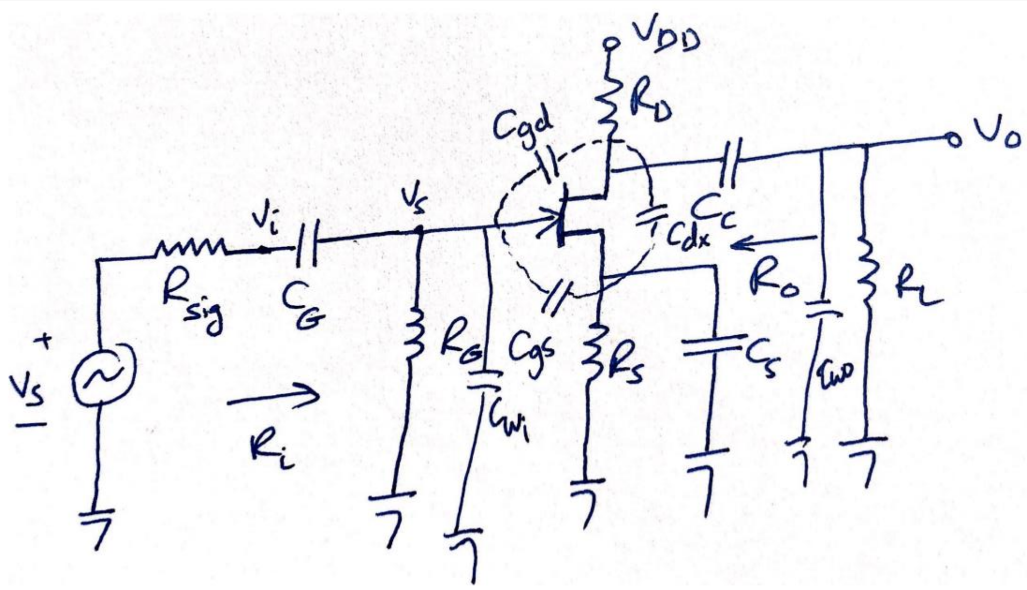
$$C_o = C_{Wo} + C_{ce} + C_{Mo}$$



FET Amplifier High-Frequency Response

Capacitances that affect the high-frequency response:

- Junction capacitances
  - C_{gs}, C_{gd}, C_{ds}
- Wiring capacitances
  - C_{wi}, C_{wo}
- Coupling capacitors
  - C_G, C_C
- Bypass capacitor
  - C_S



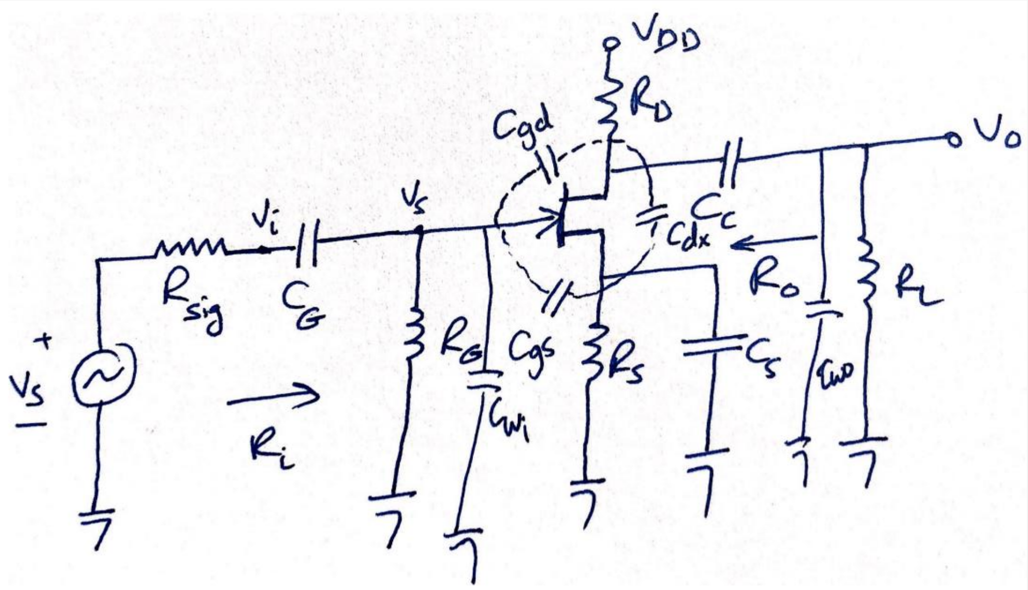
Input High-Frequency Cutoff (f_{Hi})

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

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

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

$$R_{Thi} = R_{sig} || R_G$$



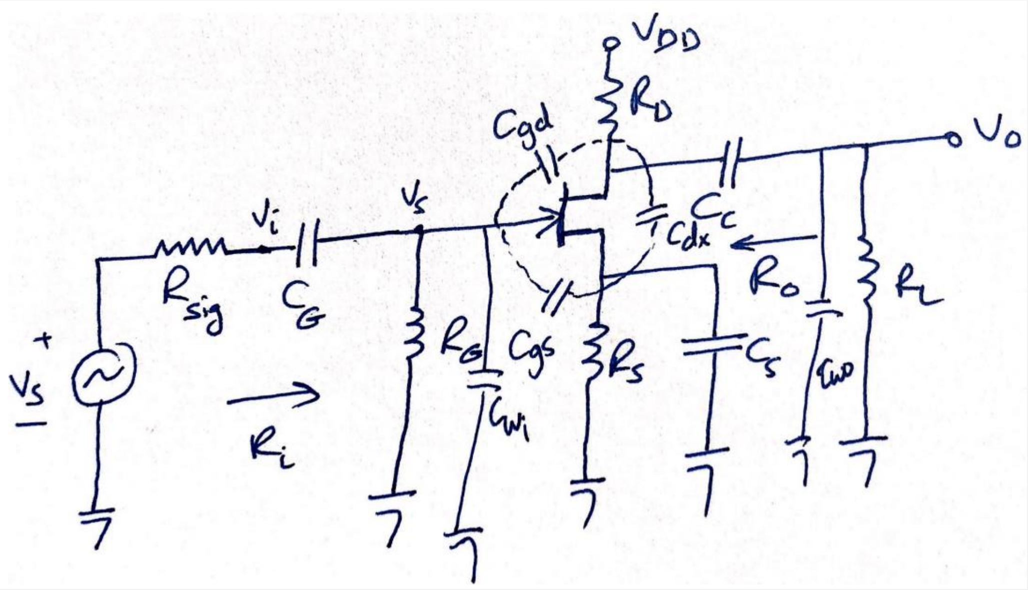
Output High-Frequency Cutoff (f_{Ho})

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

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

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

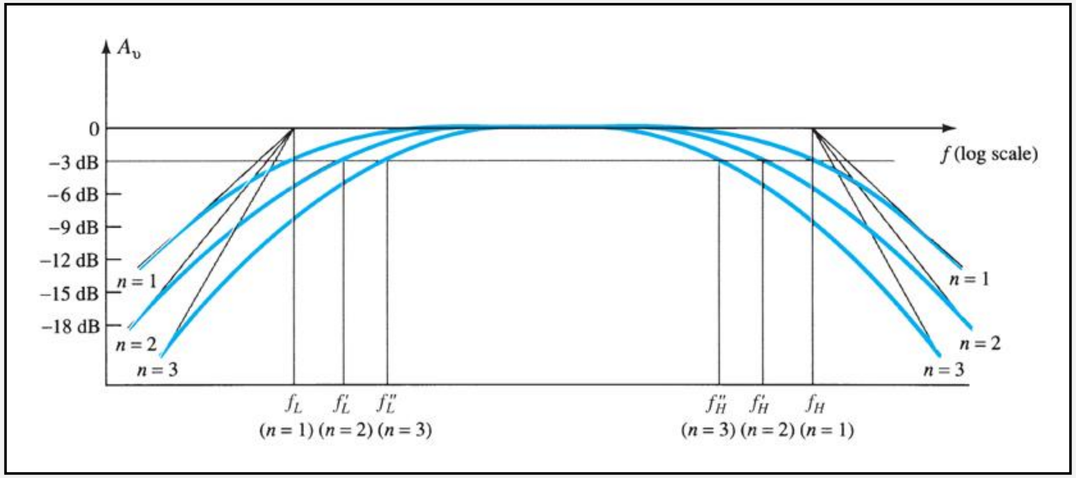
$$R_{Tho} = R_D || R_L || r_d$$



Multistage Frequency Effects

Each stage has its own frequency response, but the output of each stage is affected by capacitances in the subsequent stage. For example, the output capacitance (C_o) is affected by the input Miller Capacitance (C_{Mi}) of the next stage.

Multistage Amplifier 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.