ELECTRONICS II

School of EE-ECE-COE

Mapua Institute of Technology

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Course Content

- Small-Signal BJT Amplifiers
- Power Amplifiers
- Field-Effect Transistor Biasing
- Small-Signal FET Amplifiers
- Amplifier Frequency Response
- General Feedback Theory

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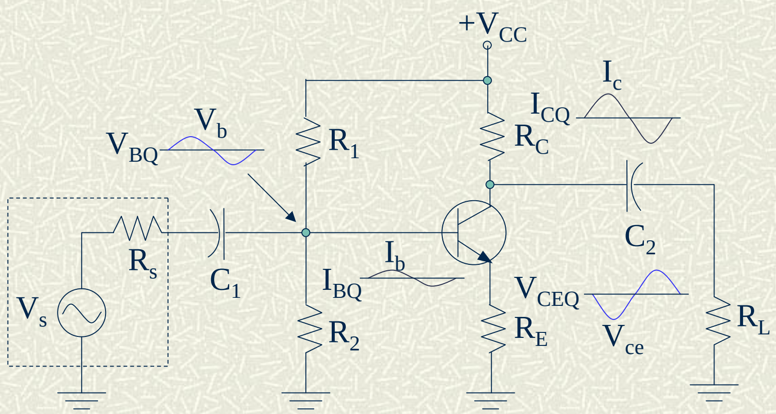
Intro to Small-Signal Amplifiers

- The Q-point of a transistor is set by dc biasing
- Small-signal amplifiers are designed to handle small ac signals that cause relatively small variations about the Q-point.
- Convention used for dc and ac values:
  - dc values, e.g. I_E , R_E
  - ac values, e.g. I_e (rms is assumed unless otherwise stated), R_e , r'_e (internal r of t'sistor)
  - instantaneous values, e.g. i_e

Basic Small-Signal Amplifier



C_1 and C_2 block dc voltage but pass ac signal.

Small-Signal Amplifier Operation

- Coupling capacitors C_1 and C_2 prevent R_s and R_L from changing the dc bias voltages
- V_s causes V_b and I_b to vary slightly which in turn produces large variations in I_c due to β
- As I_c increases, V_{ce} decreases and vice versa
- Thus, V_c (output to R_L) is 180^o out of phase with V_b

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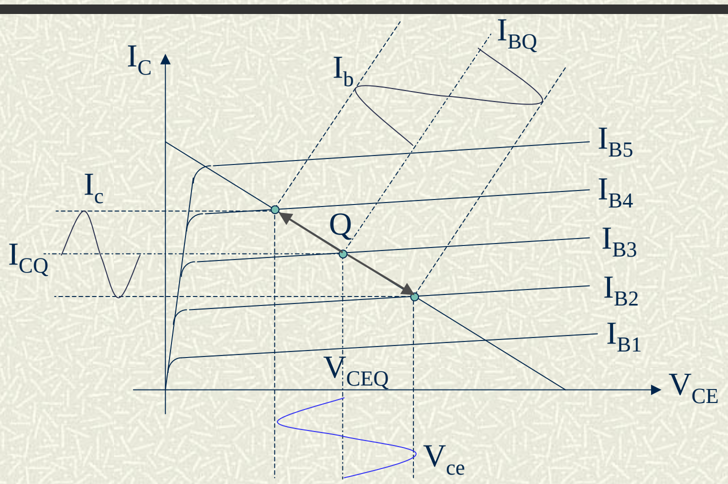
Graphical Picture



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h Parameters

- h (hybrid) parameters are typically specified on a manufacturer's data sheet.
  - h_i: input resistance; output shorted
  - h_r : voltage feedback ratio, input open
  - h_f : forward current gain; output shorted
  - h_o : output conductance; input open
- Each h parameter has a 2nd subscript letter to designate configuration, e.g. h_{fe}, h_{fc}, h_{fb}

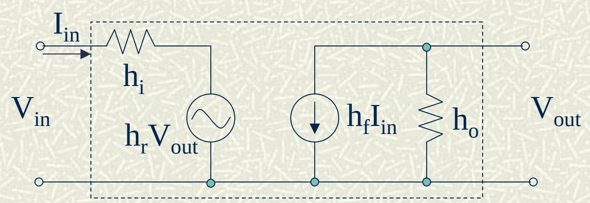
Amplifier Configurations

- Common-emitter amplifier: emitter is connected to ground, input is applied to base, and output is on collector
- Common-collector: collector is grounded, input is at base, and output is on emitter
- Common-base: base is grounded, input is at emitter, and output is on collector

h-parameter Ratios

Common-Emitter	Common-Base	Common-Collector
$h_{ie} = V_b/I_b$	$h_{ib} = V_e/I_b$	$h_{ic} = V_b/I_b$
$h_{re} = V_b/V_c$	$h_{rb} = V_e/V_c$	$h_{rc} = V_b/V_e$
$h_{fe} = I_c/I_b$	$h_{fb} = I_c/I_e$	$h_{fc} = I_e/I_b$
$h_{oe} = I_c/V_c$	$h_{ob} = I_c/V_c$	$h_{oc} = I_e/V_e$

h-parameter Equivalent Circuit



- The above diagram is the general form of the *h*-parameter equivalent circuit for a BJT.
- For the three different amplifier configurations, just add the appropriate second subscript letter.

r Parameters

- The resistance, *r*, parameters are perhaps easier to work with
  - α_{ac} : ac alpha (I_c/I_e)
  - β_{ac} : ac beta (I_c/I_b)
  - r_e' : ac emitter resistance
  - r_b' : ac base resistance
  - r_c' : ac collector resistance

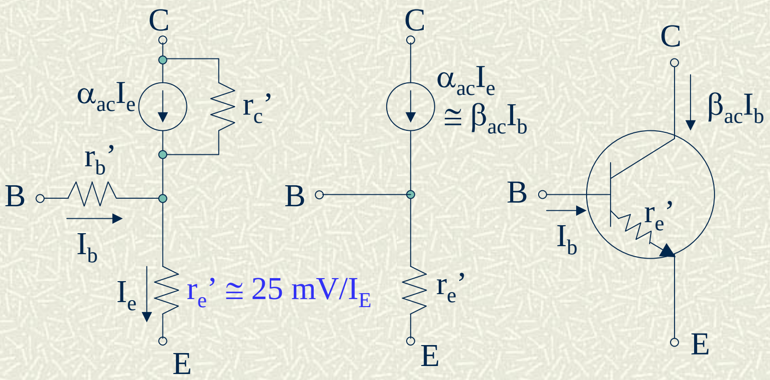
Relationships of *h* and *r* parameters:

$$\alpha_{ac} = h_{fb}\ ;\ \beta_{ac} = h_{fe}$$

$$r_e' = \frac{h_{re}}{h_{oe}};\quad r_c' = \frac{h_{re}+1}{h_{oe}}$$

$$r_b' = h_{ie} - \frac{h_{re}}{h_{oe}}(1+h_{fe})$$

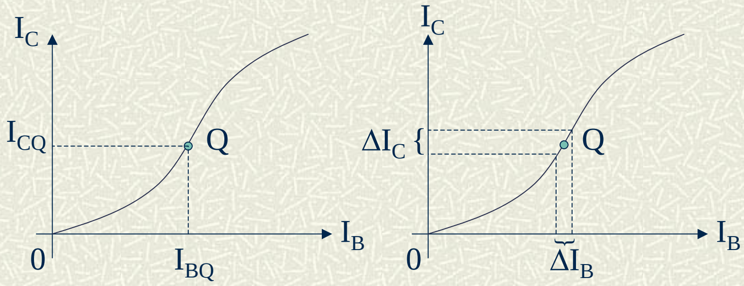
r-Parameter Equivalent Circuits



Generalized r-parameter equivalent circuit for BJT

Simplified r-parameter equivalent circuit and symbol of BJT

Difference between β_{ac} and β_{DC}



$\beta_{DC} = I_{CQ}/I_{BQ}$ $\beta_{ac} = \Delta I_C/\Delta I_B$

β_{DC} and β_{ac} values will generally not be identical and they also vary with the Q-point chosen.

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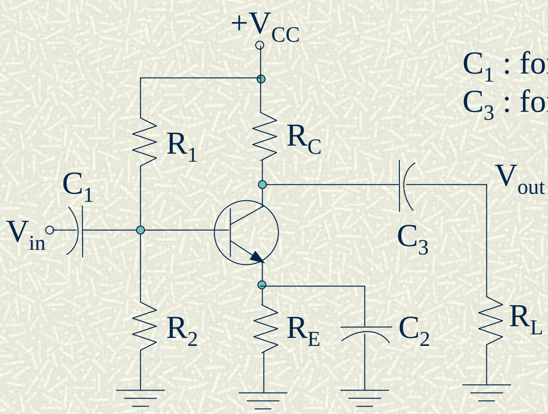
Common-Emitter Amplifier



C_1 : for input coupling
C_3 : for output coupling

C_2 : for emitter bypass

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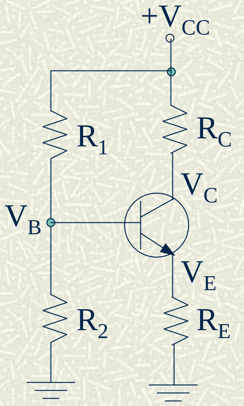
DC Analysis of CE Amplifier



$$V_B = \left(\frac{R_2 // \beta_{DC} R_E}{R_1 + R_2 // \beta_{DC} R_E} \right) V_{CC}$$

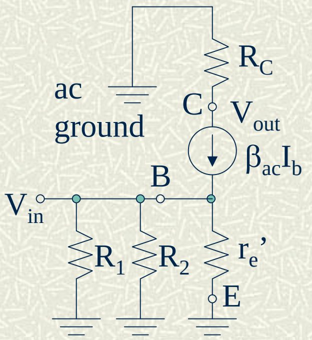
If $\beta_{DC}R_E = R_{IN(base)} >> 10R_2$, then

$$V_B \cong \left(\frac{R_2}{R_1 + R_2} \right) V_{CC}$$

$V_E = V_B - V_{BE}$; $I_C \cong I_E = \frac{V_E}{R_E}$

$V_C = V_{CC} - I_C R_C$

AC Analysis of CE Amplifier



C_1, C_2, and C_3 are replaced by shorts assuming $X_C \cong 0$

Input and output resistance:

$R_{in(tot)} = R_1//R_2//R_{in(base)}$

where $R_{in(base)} = \beta_{ac} r_e'$

$R_{out} \cong R_C$ (not including R_L)

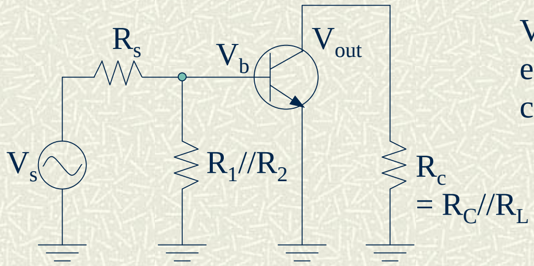
Voltage gain of CE amplifier:

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_c}{V_b} = \frac{-I_c R_C}{I_e r_e'} = -\frac{R_C}{r_e'}$$

If R_L is included: $R_{out} = R_C//R_L$, and

$$A_v = -\frac{R_C // R_L}{r_e'}$$

Overall Voltage Gain of CE Amplifier



Voltage gain without emitter bypass capacitor, C_2 :

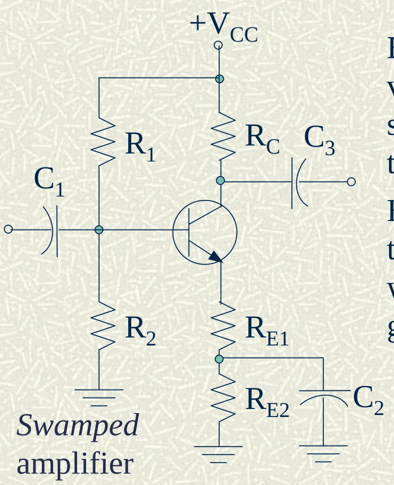
$$A_v = -\frac{R_c}{r_e' + R_E}$$

Rule of thumb on emitter bypass capacitor:

$X_{C2} > R_E/10$

$$A_v' = \frac{V_b}{V_s} A_v = \frac{R_{in(tot)}}{R_s + R_{in(tot)}} A_v$$

Stability of Voltage Gain



Swamped amplifier

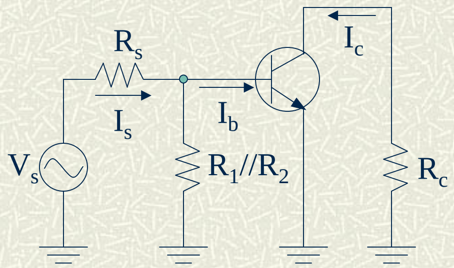
Bypassing R_E produces max. voltage gain but it is less stable since r_e' is dependent on I_E and temperature.

By choosing $R_{E1} > 10\ r_e$', the effect of r_e' is minimized without reducing the voltage gain too much:

$A_v = -R_c/R_{E1}$

$R_{in(base)} = \beta_{ac}(r_e' + R_{E1})$

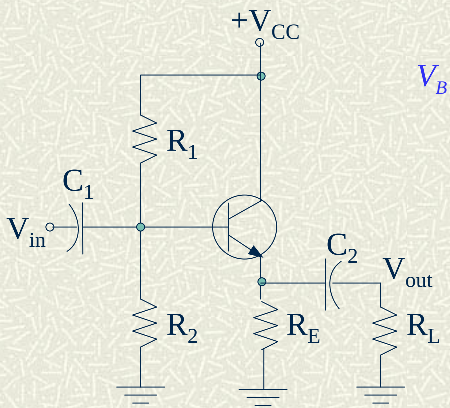
Current Gain and Power Gain



Base to collector current gain is β_{ac} but overall current gain is $A_i = I_c/I_s$ where $I_s = \dfrac{V_s}{R_{in(tot)} + R_s}$

Overall power gain is: $A_p = A_v' A_i$

Common-Collector Amplifier



DC analysis:

$$V_B = \left(\frac{R_2 // \beta_{DC} R_E}{R_1 + R_2 // \beta_{DC} R_E} \right) V_{CC}$$

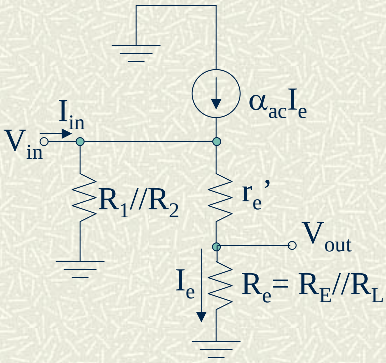
$V_E = V_B - V_{BE}$

$I_E = V_E / R_E$

$V_C = V_{CC}$

The CC amplifier is also known as an emitter-follower since V_{out} follows V_{in} in phase and voltage.

AC Analysis of CC Amplifier



$V_{in} = I_e(r_e' + R_e)$
$V_{out} = I_eR_e$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{R_e}{(r_e' + R_e)}$$

$$R_{in(base)} \cong \beta_{ac}(r_e' + R_e)$$

If $R_e >> r_e'$, then, $A_v = 1$, and $R_{in(base)} = \beta_{ac}R_e$

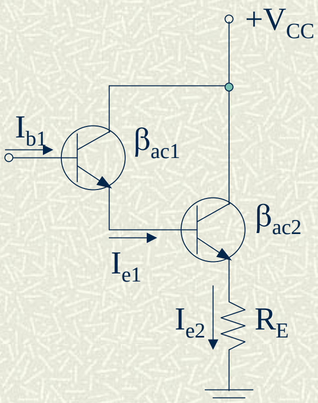
$R_{in(tot)} = R_1//R_2//R_{in(base)}$

$R_{out} = (R_s/\beta_{ac})//R_e$ (very low)

$A_i = I_e/I_{in}$
$= \beta_{ac}$ (if $R_1//R_2 >> \beta_{ac}R_e$)

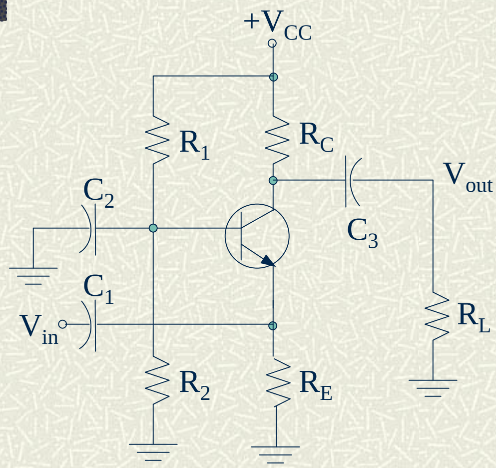
$A_p = A_vA_i = A_i$

Darlington Pair



- $I_{e2} = \beta_{ac2}I_{e1} = \beta_{ac1}\beta_{ac2}I_{e1}$
- So, $\beta_{ac(overall)} = \beta_{ac1}\beta_{ac2}$
- Assuming $r_e' << R_E$, $R_{in} = \beta_{ac1}\beta_{ac2}R_E$
- Darlington pair has very high current gain, very high R_{in}, and very low R_{out} - ideal as a *buffer*

Common-Base Amplifier

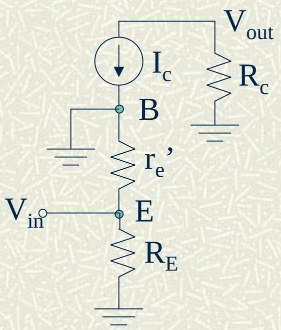


CB amplifier provides high A_v with a max. A_i of 1.

There is no phase inversion between V_{out} and V_{in}.

DC formulas are identical to those for CE amplifier.

AC Analysis of CB Amplifier



$$A_v = \frac{V_{out}}{V_{in}} = \frac{I_c R_c}{I_e (r_e' // R_E)} \cong \frac{R_c}{r_e' // R_E}$$

$R_{in(emitter)} = r_e'//R_E$

If $R_E >> r_e'$, then

$$A_v \cong \frac{R_c}{r_e'}; \quad R_{in(emitter)} = r_e'$$

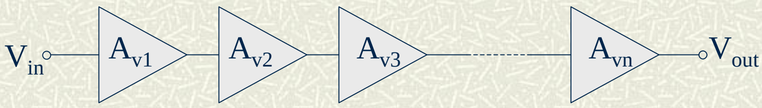
$R_{out} = R_c$

$A_i = 1$; and $A_p = A_v$

Comparing CE, CC, & CB Amplifiers

	CE	CC	CB
A_v	High ($-R_c/r_e'$)	Low ~ 1	High (R_c/r_e')
$A_{i(max)}$	High (β_{ac})	High (β_{ac})	Low ~ 1
A_p	Very high (A_vA_i)	High A_i	High A_v
$R_{in(max)}$	Low ($\beta_{ac}r_e'$)	High ($\beta_{ac}R_e$)	Very low (r_e')
R_{out}	High (R_c)	Very low ($(R_s/\beta_{ac})//R_e$)	High (R_c)

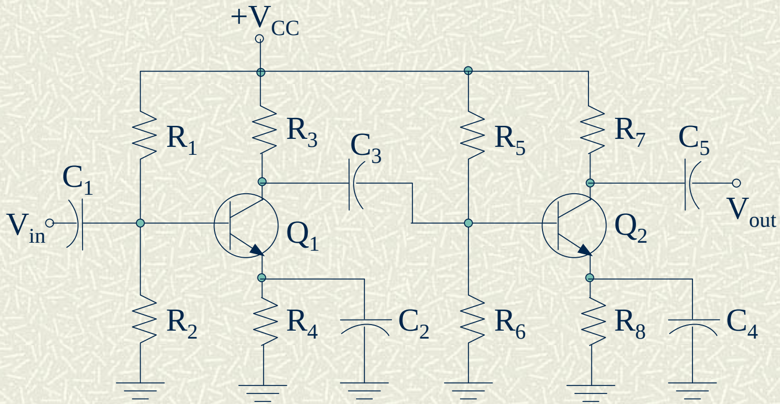
Multistage Amplifiers



n amplifier stages in *cascade*

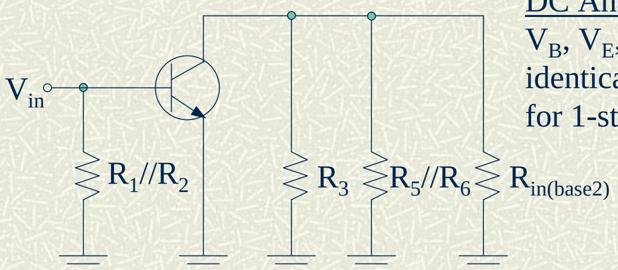
- Overall voltage gain, $A_{vT} = A_{v1}A_{v2}A_{v3} \ldots A_{vn} = V_{out}/V_{in}$
- Overall gain in dB, $A_{vT(dB)} = A_{v1(dB)}+A_{v2(dB)} + \ldots +A_{vn(dB)}$ where, $A_{v(dB)} = 20 \log A_v$
- The purpose of a multistage arrangement is to increase the overall voltage gain.

Two-stage CE Amplifier



Capacitive coupling prevents change in dc bias

Analysis of 2-stage CE Amplifier



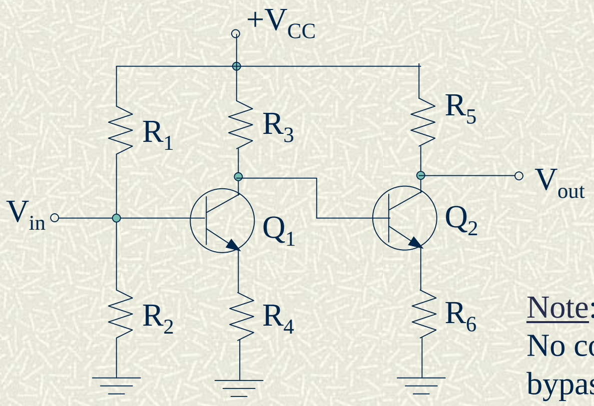
<u>DC Analysis</u>:
V_B, V_E, V_C and I_C are identical to those for 1-stage CE ampl.

<u>AC Analysis</u>:

$R_{c1} = R_3//R_5//R_6//R_{in(base2)}$; $A_{v1} = -\frac{R_{c1}}{r_e'}$; $A_{v2} = -\frac{R_{c2}}{r_e'} = -\frac{R_7}{r_e'}$

$A_{vT} = A_{v1}A_{v2}$

2-stage Direct-Coupled Amplifier



Note:
No coupling or bypass capacitors

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Notes on Direct-Coupled Amplifier

- DC collector voltage of first stage provides base-bias voltage for second stage
- Amplification down to 0 Hz is possible due to absence of capacitive reactances
- Disadvantage - small changes in dc bias voltages due to temperature or power-supply variations are amplified by succeeding stages

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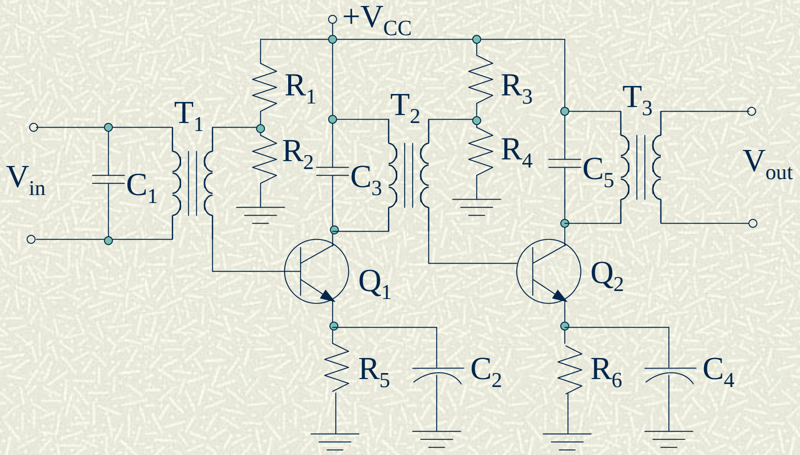
Transformer-Coupled Multistage Amplifier



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Notes On T'former-Coupled Amplifiers

- Transformer-coupling is often used in high-frequency amplifiers such as those in RF and IF sections of radio and TV receivers.
- Transformer size is usually prohibitive at low frequencies such as audio.
- Capacitors are usually connected across the primary windings of the transformers to obtain resonance and increase selectivity.

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Typical Troubleshooting Process

- Identify the symptom(s).
- Perform a power check.
- Perform a sensory check.
- Apply a signal-tracing technique to isolate the fault to a single circuit.
- Apply fault-analysis to isolate the fault further to a single component or group of components.
- Use replacement or repair to fix the problem.

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Power Amplifiers

- Power amplifiers are large-signal amplifiers
- They are normally used as the final stage of a communications receiver or transmitter to provide signal power to speakers or to a transmitting antenna.
- Four classes of large-signal amplifiers will be covered: class A, class B, class AB, and class C.

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Class A Amplifier Characteristics

- Q-point is centred on ac load line.
- Operates in linear region (i.e. no cutoff or saturation) for full 360° of input cycle.
- Output voltage waveform has same shape as input waveform except amplified.
- Can be either inverting or noninverting.
- Maximum power efficiency is 25%.

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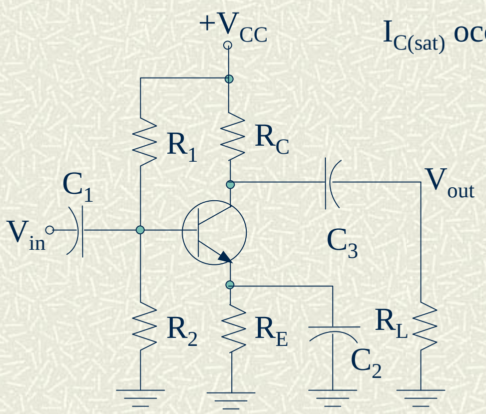
Class A Operation: DC Load Line

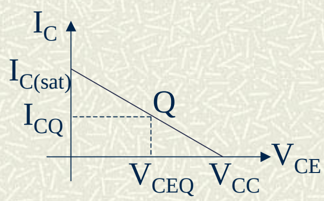


$I_{C(sat)}$ occurs when $V_{CE} \to 0$, so

$$I_{C(sat)} \cong \frac{V_{CC}}{R_C + R_E}$$

$V_{CE(cutoff)}$ occurs when $I_C \to 0$, so

$V_{CE(cutoff)} \to V_{CC}$



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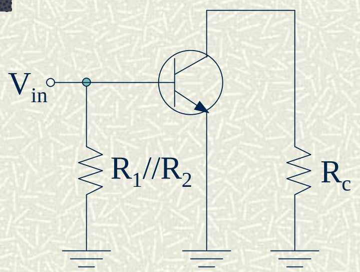
Class A Operation: AC Load Line

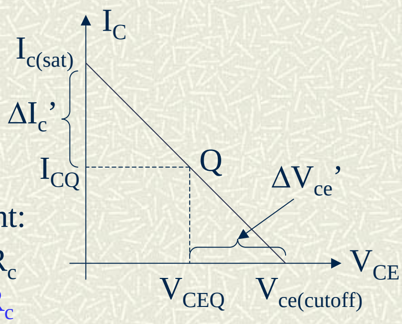


$R_c = R_C//R_L$

From Q-point to cutoff point:

$\Delta I_c = I_{CQ}$; ⑧ $\Delta V_{ce}' = I_{CQ}R_c$

$V_{ce(cutof)} = V_{CEQ} + I_{CQ}R_c$

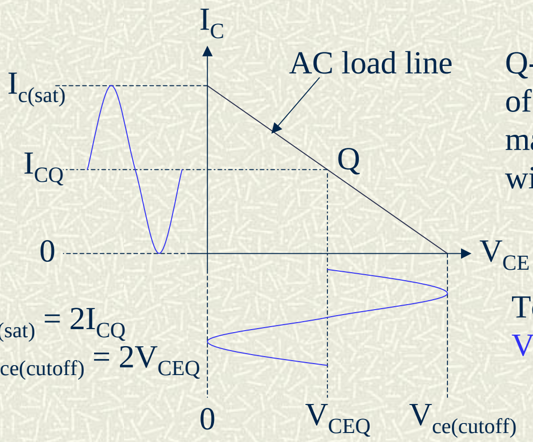


From Q-point to saturation point:

$\Delta V_{ce} = V_{CEQ}$; ⑧ $\Delta I_c' = V_{CEQ}/R_c$

$I_{c(sat)} = I_{CQ}+\Delta I_c' = I_{CQ} + V_{CEQ}/R_c$

Maximum Class A Operation



$I_{c(sat)} = 2I_{CQ}$

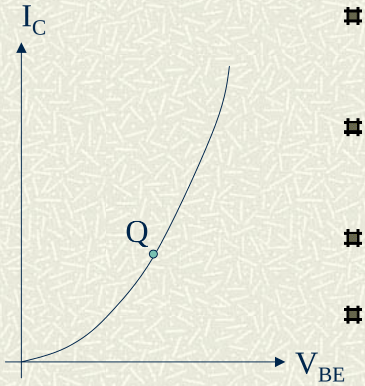
$V_{ce(cutoff)} = 2V_{CEQ}$

Q-point is at centre of ac load line for max. voltage swing with no clipping.

To centre Q-point:

$V_{CEQ} = I_{CQ}R_c$

Non-linearity of r_e’



- For large voltage swings, $r_e' \cong 25mV/I_E$ is not valid.
- Instead, the average value of $r_e' = \Delta V_{BE}/\Delta I_C$ should be used for A_v formula.
- Non-linearity of r_e’ leads to distortion at output.
- Reduce distortion by setting Q-point higher or use swamping resistor in the emitter.

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Power & Efficiency: Class A Amplifier

- Power gain, $A_p = A_i A_v \cong \beta_{DC} R_c / r_e'$
- Quiescent power, $P_{DQ} = I_{CQ} V_{CEQ}$
- Output power, $P_{out} = V_{ce} I_c = V_{out(rms)} I_{out(rms)}$
  - when Q-point is centred, $P_{out(max)} = 0.5 V_{CEQ} I_{CQ}$
- Efficiency, $\eta = P_{out}/P_{DC} = P_{out}/(V_{CC} I_{CQ})$
- When Q-point is centred, $\eta_{max} = 0.25$
- Max. load power, $P_{L(max)} = 0.5(V_{CEQ})^2/R_L$

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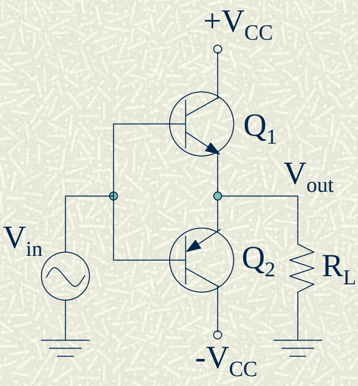
Class B Amplifier Characteristics

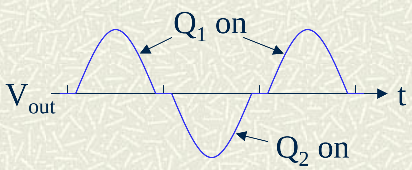
- Biased at cutoff - it operates in the linear region for 180^o and cutoff for 180^o.
- *Class AB* amplifier is biased to conduct slightly more than 180^o.
- Advantage of class B or class AB amplifier over class A amplifier - more efficient.
- Disadvantage - more difficult to implement circuit for linear reproduction of input wave

Push-pull Class B Operation

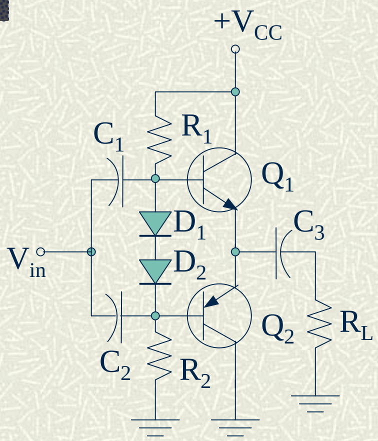


Complementary amplifier

An npn transistor and a matched pnp transistor form two emitter-followers that turn on alternately. Since there is no dc base bias, Q_1 and Q_2 will turn on only when $|V_{in}|$ is greater than V_{BE}. This leads to *crossover distortion*.

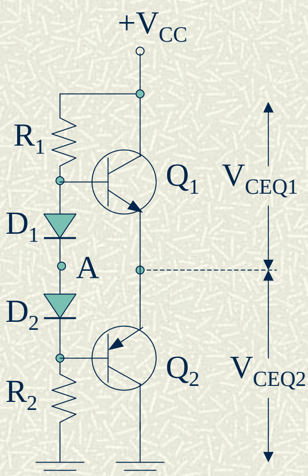


Class AB Operation



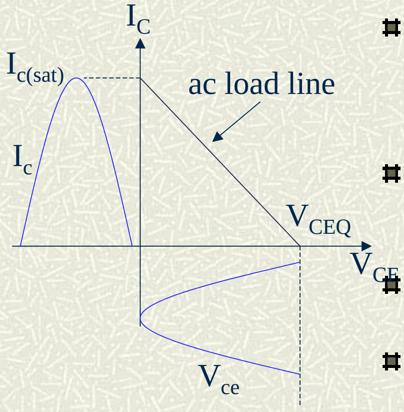
- The push-pull circuit is biased slightly above cutoff to eliminate crossover distortion.
- D_1 and D_2 have closely matched transconductance characteristics of the transistors to maintain a stable bias.
- C_3 eliminates need for dual-polarity supplies.

Class AB Amplifier: DC Analysis



- Pick $R_1 = R_2$, therefore $V_A=V_{CC}/2$
- Assuming transconductance characteristics of diodes and transistors are identical, $V_{CEQ1}=V_{CEQ2}=V_{CC}/2$
- I_{CQ} ☞ 0 (cutoff)

Class AB Amplifier: AC Analysis



- For max. output, Q_1 and Q_2 are alternately driven from near cutoff to near saturation.
- V_{ce} of both Q_1 and Q_2 swings from $V_{CEQ} = V_{CC}/2$ to 0.
- I_c swings from 0 to $I_{c(sat)} = V_{CEQ}/R_L$ ☞ $I_{out(pk)}$
- Input resistance, $R_{in} = \beta_{ac}(r_e' + R_L)$

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Power & Efficiency: Class B Amplifier

- Average output power, $P_{out} = V_{out(rms)} I_{out(rms)}$
- For max. output power, $V_{out(rms)} = 0.707 V_{CEQ}$ and $I_{out(rms)} = 0.707 I_{c(sat)}$; therefore, $P_{out(max)} = 0.5 V_{CEQ} I_{c(sat)} = 0.25\ V_{CC} I_{c(sat)}$
- Since each transistor draws current for a half-cycle, dc input power, $P_{DC} = V_{CC} I_{c(sat)}/\pi$
- Efficiency, $\eta_{max} = P_{out}/P_{DC} = 0.25\pi$ ☞ 0.79
- The efficiency for class AB is slightly less.

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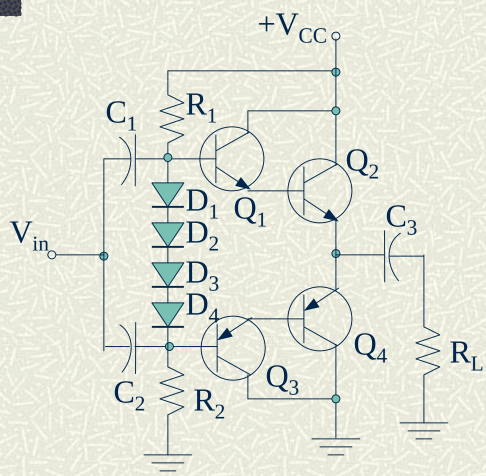
Darlington Class AB Amplifier



In applications where the load resistance is low, Darlingtons are used to increase input resistance presented to driving amplifier and avoid reduction in A_v. 4 diodes are required to match the 4 base-emitter junctions of the darlington pairs.

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Class C Amplifier Characteristics

- Biased below cutoff, i.e. it conducts less than 180º.
- More efficient than class A, or push-pull class B and class AB.
- Due to severe distortion of output waveform, class C amplifiers are limited to applications as tuned amplifiers at radio frequencies (RF).

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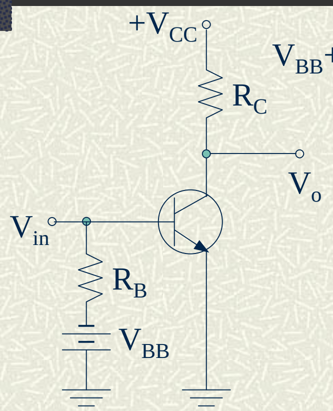
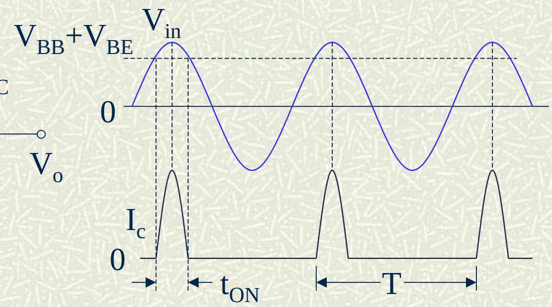
Basic Class C Operation



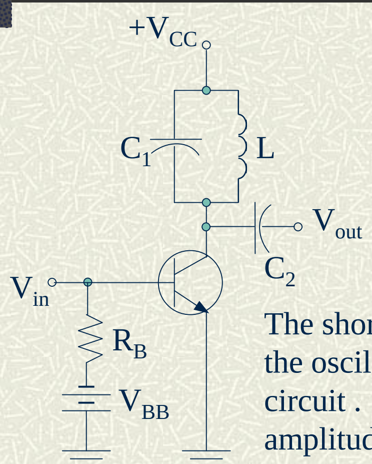


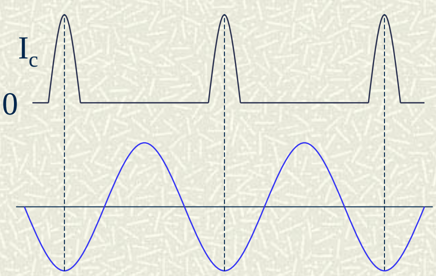
The transistor turns on when

$V_{in} > V_{BB} + V_{BE}$

Duty cycle = t_{ON} / T

Tuned Operation





The short pulse of I_c initiates and sustains the oscillation of the parallel resonant circuit . The output sinewave has a pk-pk amplitude of approximately $2V_{CC}$.

Power & Efficiency: Class C Amplifier

- Using simplification where current is $I_{C(sat)}$ and voltage is $V_{CE(sat)}$ at turn on, and assuming the entire load line is used, then

  $P_{D(avg)} = (t_{ON}/T)V_{CE(sat)}I_{C(sat)}$
- Max. output power for tuned operation,

  $P_{out(max)} = (0.707V^2_{CC}) / R_c \quad = 0.5\, V^2_{CC} / R_c$
- Efficiency, $\eta = P_{out} / (P_{out} + P_{D(avg)})$
- When $P_{out} >> P_{D(avg)}$, η approaches 100%.

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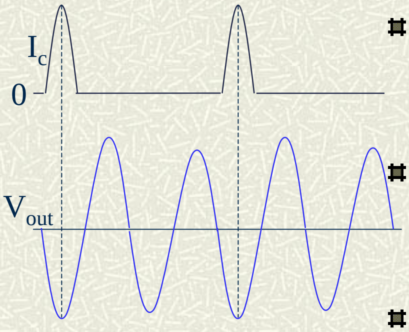
Frequency Multiplier



Output of tank circuit tuned to 2nd harmonic frequency

- Frequency "doubling" is obtained by tuning tank circuit to second harmonic of input frequency.
- By tuning tank circuit to higher harmonics, further frequency multiplication factors are achieved.
- Amplitude of each alternate peak drops due to energy loss in circuit.

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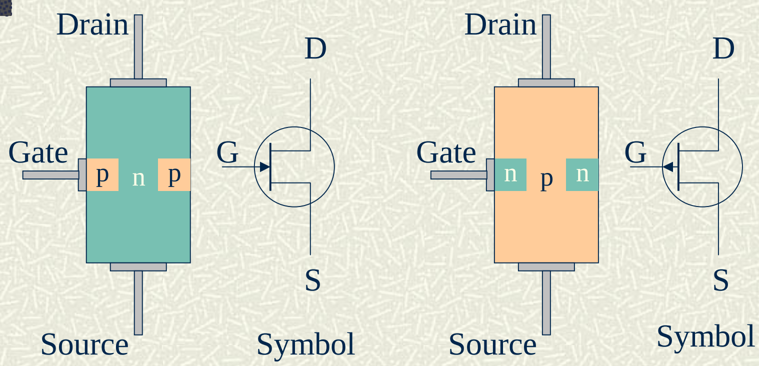
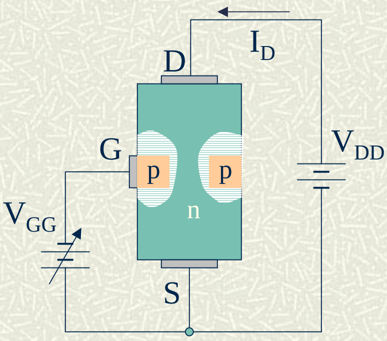
Junction Field-Effect Transistor



n-channel p-channel

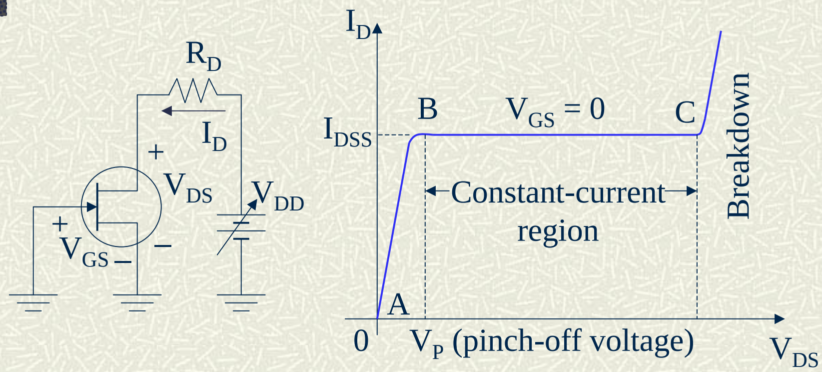
Basic Operation of JFET



JFET is always operated with V_{GG} reverse-biased

- Depletion region in n-channel increases its resistance.
- Channel width and channel resistance can be controlled by varying V_{GG} (or V_{GS}), thereby controlling drain current, I_D.

JFET Characteristics For V_{GS}=0



Between points A and B, I_D α V_{DS} - ohmic region.
I_{DSS} - max. I_D for a given JFET regardless of external circuit.

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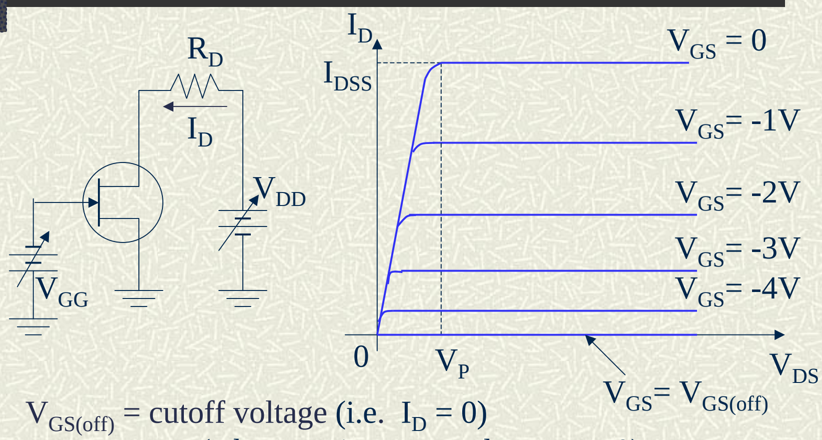
Controlling I_D With V_{GS}



$V_{GS(off)}$ = cutoff voltage (i.e. I_D = 0)
$V_{GS(off)}$ = $-V_P$ (where V_P is measured at V_{GS} = 0)

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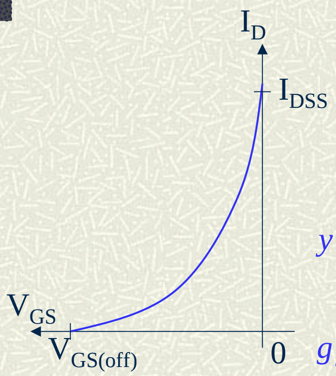
JFET Transfer Characteristics



Shockley's equation:

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)^2$$

Forward transconductance:

$$y_{fs} \text{ or } g_m = \frac{\Delta I_D}{\Delta V_{GS}} = g_{m0}\left(1 - \frac{V_{GS}}{V_{GS(off)}}\right)$$

$$g_{m0} = \frac{2I_{DSS}}{|V_{GS(off)}|}$$ is value of g_m at $V_{GS} = 0$

Note: g_m is max. at $V_{GS} = 0$ and min. at $V_{GS(off)}$

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Other JFET Parameters

- JFET's input resistance, $R_{IN} = |V_{GS}/I_{GSS}|$ is very high since its gate-source junction is reverse-biased.
- Input capacitance, C_{iss} is typically a few pF.
- Output conducutance, g_{os}, or output admittance, y_{os}, is typically 10 mS, and is the inverse of drain-to-source resistance, $r'_{ds} = \Delta V_{DS}/\Delta I_D$

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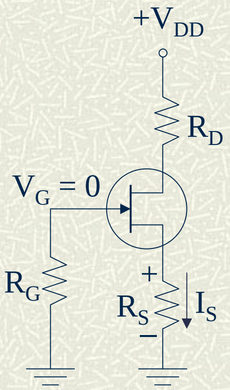
JFET With Self-Biasing



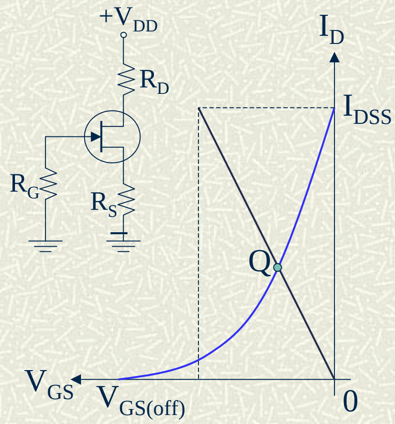
- Large R_G is required to prevent shorting of input signal to ground and to prevent loading on the driving stage.
- $V_{GS} = -I_D R_S$
- $V_D = V_{DD} - I_D R_D$
- $V_{DS} = V_D - V_S$
  $= V_{DD} - I_D(R_D + R_S)$

Setting Q-Point of JFET

- First, determine I_D for a desired value of V_{GS} either by using transfer characteristic curve or Shockley's equation.
- Then calculate $R_S = |V_{GS}/I_D|$
- For midpoint bias (i.e. $I_D = 0.5\ I_{DSS}$), make $V_{GS} \approx V_{GS(off)}/3.4$
- To set $V_D = 0.5\ V_{DD}$, pick $R_D = V_{DD}/(2I_D)$

Graphical Analysis of Self-Biased JFET

- First obtain transfer characteristic curve from data sheet or plot using Shockley's equation.
- Draw dc load line by starting with $V_{GS} = 0$ when $I_D = 0$, and then $V_{GS} = -I_{DSS}R_S$ when $I_D = I_{DSS}$.



Voltage-Divider Bias

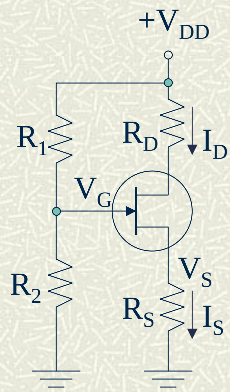
To keep the gate-source junction reverse-biased, $V_S > V_G$

$V_S = I_D R_S$

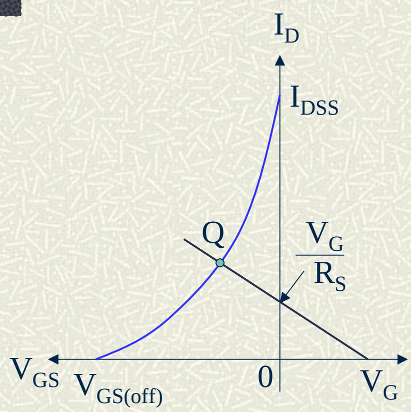
$$V_G = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD}$$

$V_S = V_G - V_{GS}$

$$I_D = \frac{V_S}{R_S} = \frac{V_G - V_{GS}}{R_S}$$



Graphical Analysis of Voltage-Divider Biased JFET



For $I_D = 0$, $V_S = I_D R_S = 0$, and $V_{GS} = V_G - V_S = V_G$

For $V_{GS} = 0$,

$$I_D = \frac{V_G - V_{GS}}{R_S} = \frac{V_G}{R_S}$$

Draw the dc load line by joining the two points and extend it to intersect the curve to get the Q-point.

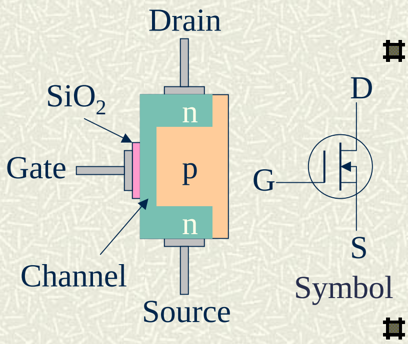
Q-Point Stability

- The transfer characteristic of a JFET can differ considerably from one device to another of the same type.
- This can cause a great variation of the Q-point, and consequently, I_D and V_{GS}.
- With voltage-divider bias, the dependency of I_D on the range of Q-points is reduced (i.e. more stable) because the slope is less than for self-bias, although V_{GS} varies quite a bit for both circuits.

Metal Oxide Semiconductor FET

- The MOSFET differs from the JFET in that it has no *pn* junction structure.
- The gate of the MOSFET is insulated from the channel by a silicon dioxide layer.
- The two basic types of MOSFETs are depletion (D) and enhancement (E).
- Because of the insulated gate, these devices are sometimes called IGFETs.

Depletion MOSFET



Basic structure of *n*-channel D-MOSFET

- *n*-channel D-MOSFET is usually operated in the *depletion mode* with $V_{GS} < 0$ and in the *enhancement mode* with $V_{GS} > 0$.
- *p*-channel D-MOSFET uses the opposite voltage polarity

Depletion/Enhancement MOSFET

- Depletion Mode: negative gate voltage applied to *n* channel depletes channel of electrons, thus increasing its resistivity. At $V_{GS(off)}$, $I_D = 0$, just like *n*-channel JFET.
- Enhancement mode: when $V_{GS} > 0$, electrons are attracted into channel, thus increasing (enhancing) the channel conductivity.

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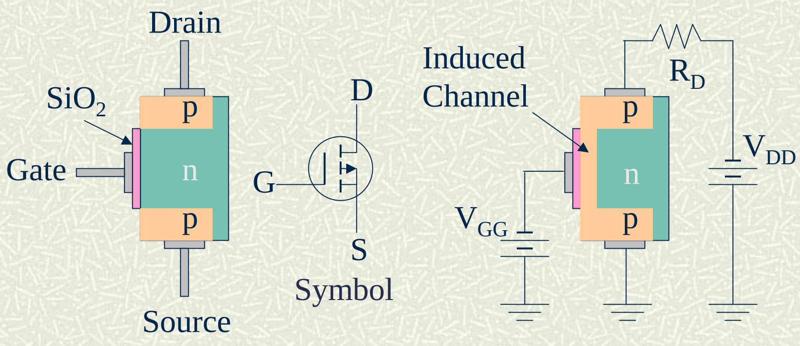
Enhancement MOSFET



E-MOSFET construction and operation (*p*-channel)

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Notes On E-MOSFET

- The E-MOSFET operates *only* in the enhancement mode.
- For a *p*-channel device, a negative gate voltage above a threshold value induces a channel by creating a layer of positive charges in the substrate region adjacent to the SiO_2 layer.
- Channel conductivity increases with V_{GS}.

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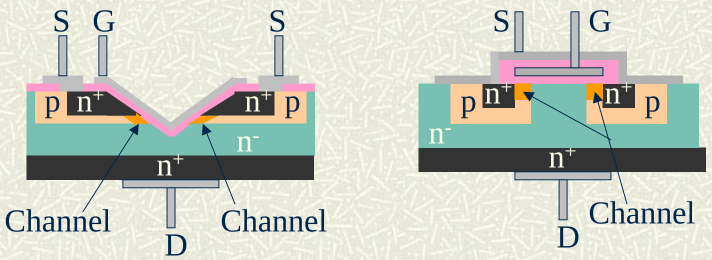
VMOS & TMOS Power MOSFETs



VMOS (V-groove MOSFET) creates a short and wide induced channel to allow for higher currents and greater power dissipation. Frequency response is also improved.

TMOS is similar to VMOS except it is easier to manufacture

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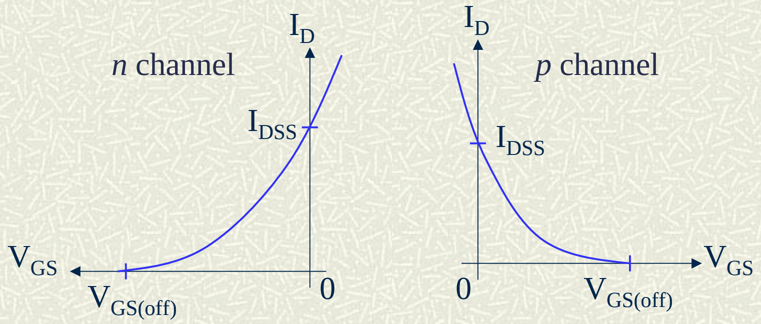
D-MOSFET Transfer Characteristic



D-MOSFET can operate with either +ve or -ve gate voltage. Shockley's equation for the JFET curve also applies to the D-MOSFET curve.

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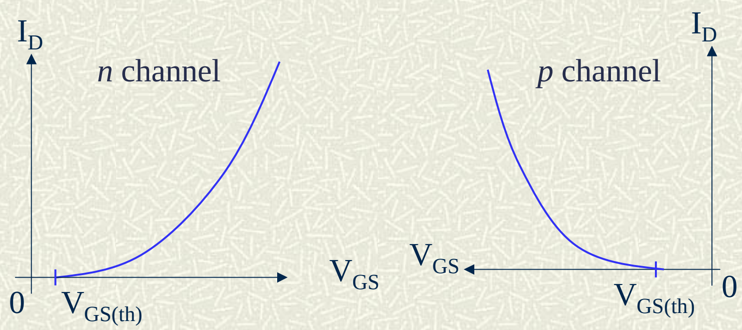
E-MOSFET Transfer Characteristic



E-MOSFET uses only channel enhancement. Ideally $I_D = 0$ until $V_{GS} > V_{GS(th)}$. Transfer equation: $I_D = K(V_{GS} - V_{GS(th)})^2$, where K depends on the particular MOSFET.

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MOSFET Handling Precautions

- All MOS devices are subject to damage from *electrostatic discharge* (ESD).
- To avoid damage from ESD:
  - ship/store MOS devices in conductive foam
  - ground all instruments and metal benches
  - ground assembler's/handler's body via resistor
  - never remove MOS device from live circuit
  - do not apply signals while dc supply is off

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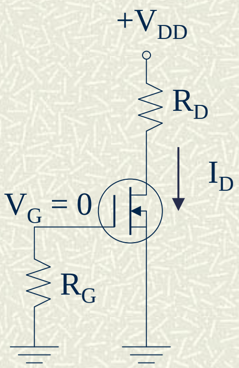
D-MOSFET With Zero-Bias



- Since $V_{GS} = 0$, $I_D = I_{DSS}$.
- $V_{DS} = V_{DD} - I_{DSS}R_D$
- The value of R_G is chosen arbitrarily large to prevent loading of the previous stage and isolate any ac input signal from ground.

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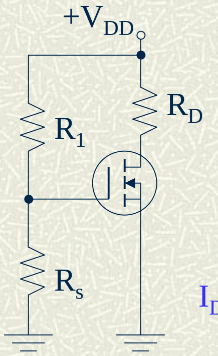
E- or D-MOSFET Bias

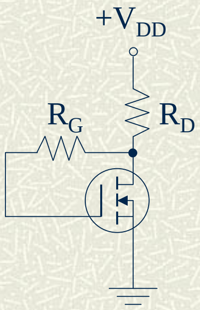


Voltage-divider bias

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD}$$

$$V_{DS} = V_{DD} - I_D R_D$$

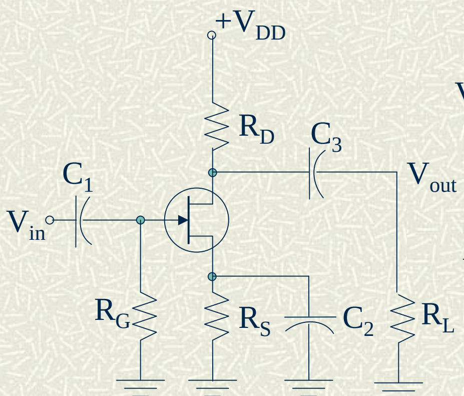
$$I_D = K(V_{GS} - V_{GS(th)})^2$$



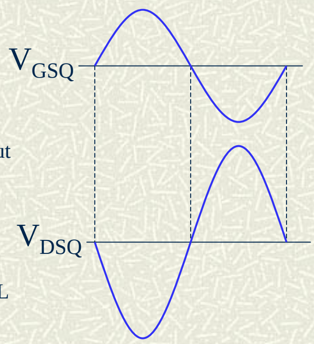
Drain-feedback bias

Since $I_G \approx 0$, $V_{GS} = V_{DS}$

Small-Signal JFET Amplifier

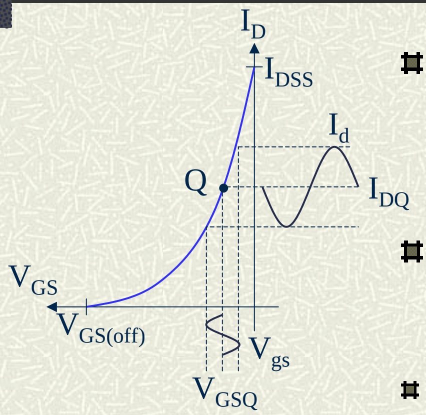


Common-source amplifier



Voltage waveforms

JFET Transfer Characteristic Curve



Signal operation with *n*-channel JFET

- As V_{gs} swings from its Q-point to a more -ve value, I_d decreases from its Q-point.
- When V_{gs} swings to a less -ve value, I_d increases.
- Similar diagrams can be drawn for MOSFETs.

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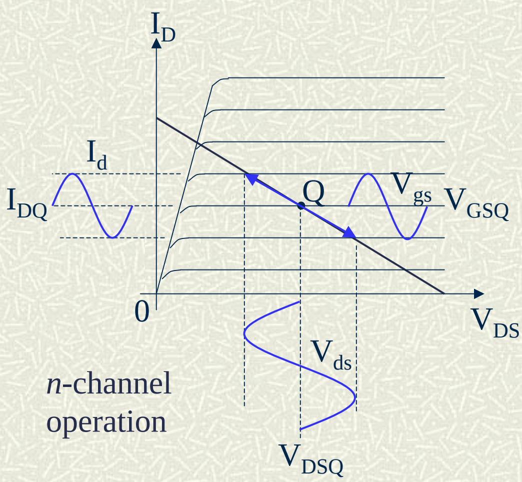
JFET Drain Characteristic Curve



n-channel operation

This is an alternative view of the JFET amplifier operation showing the varia -tion of I_d with the corresponding change in V_{gs} & V_{ds}. Note that the CS amplifier is equi- valent to the CE amplifier.

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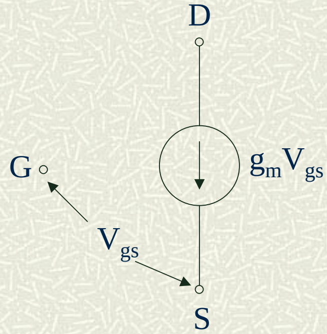
FET Simplified Equivalent Circuit

- Transconductance is defined as $g_m = \Delta I_D / \Delta V_{GS}$ (siemens)
- In ac quantities, $g_m = I_d / V_{gs}$
- Rearranging the terms, $I_d = g_m V_{gs}$



r'_{gs} and r'_{ds} are assumed to be very large

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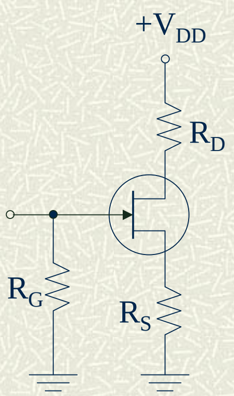
DC Analysis of Common-Source Amplifier



DC Equivalent circuit

If the circuit is biased at midpoint, $I_D = I_{DSS}/2$

Otherwise, solve for I_D either graphically or by finding the root of the quadratic equation:

$$I_D = I_{DSS}\left(1 - \frac{I_D R_S}{|V_{GS(off)}|}\right)^2$$

where V_{GS} has been substituted by $I_D R_S$.

Then, $V_{DS} = V_D - V_S = V_{DD} - I_D(R_D + R_S)$

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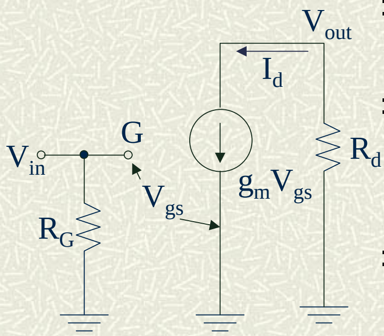
AC Analysis of CS Amplifier

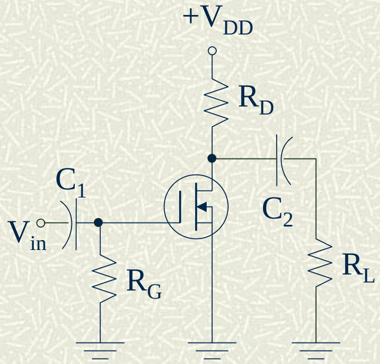


AC equivalent circuit

- Since R_{in} is very high, $V_{gs} = V_{in}$
- $A_v = V_{out}/V_{in}$
  $= -I_d R_d / V_{gs} = -g_m R_d$
  where, $R_d = R_D // R_L$
- $V_{out} = A_v V_{in}$
  $= -g_m R_d V_{in}$

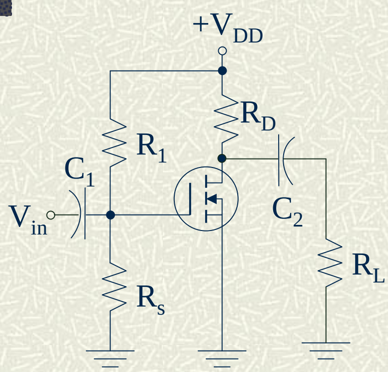
$$R_{in} = R_G // \left(\frac{V_{GS}}{I_{GSS}} \right)$$

Common-Source D-MOSFET Amplifier



- DC analysis is easier than for a JFET because $I_D = I_{DSS}$ at $V_{GS} = 0$
- Once I_D is known, $V_D = V_{DD} - I_D R_D$
- AC analysis is the same as for JFET
- Thus, $A_v = -g_m R_d$

Common-Source E-MOSFET Amplifier



$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD}$$

DC analysis:

- $I_D = K(V_{GS} - V_{GS(th)})^2$
- $V_{DS} = V_{DD} - I_D R_D$

AC analysis is same as JFET and D-MOSFET

- i.e., $A_v = -g_m R_d$
- $R_{in} = R_1 // R_2 // R_{INIgate)}$
- $R_{IN(gate)} = V_{GS}/I_{GSS}$

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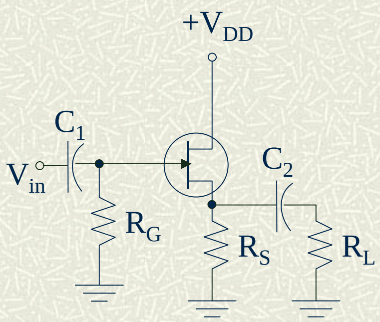
Common-Drain Amplifier



CD amplifier is comparable to the CC amplifier.

- $R_{in} = R_G // R_{IN(gate)}$
- $V_{out} = I_d R_s = g_m V_{gs} R_s$, where $R_s = R_S // R_L$
- $V_{in} = V_{gs} + I_d R_s = V_{gs} + g_m V_{gs} R_s = V_{gs}(1 + g_m R_s)$

$$\therefore A_v = \frac{V_{out}}{V_{in}} = \frac{g_m R_s}{1 + g_m R_s}$$

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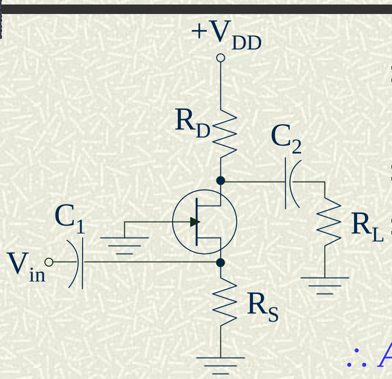
Common-Gate Amplifier



- $R_{in} = R_{in(source)} // R_S$
  where $R_{in(source)} = 1/g_m$
- $V_{in} = V_{gs}$
- $V_{out} = I_d R_d = g_m V_{gs} R_d$
  where $R_d = R_D // R_L$

$$\therefore A_v = \frac{V_{out}}{V_{in}} = \frac{g_m V_{gs} R_d}{V_{gs}} = g_m R_d$$

CG amplifier is comparable to the CB amplifier

Amplifier Frequency Response

- In the previous discussion of amplifiers, X_C of the coupling and bypass capacitors was assumed to be 0 Ω at the signal frequency.
- Also, the internal transistor capacitances were assumed to be negligible.
- These capacitances, however, do affect the gain and phase shift of the amplifier over a specified range of input signal frequencies.

Effect At Low Frequency

- Since $X_C = 1/(2\pi fC)$, when f is low (e.g. <10 Hz), $X_C >> 0$. The voltage drop across the input and output coupling capacitors become significant, leading to a drop in A_v. Also, a phase shift is introduced because the coupling capacitor form a *lead* (or RC) circuit at the input and the output.
- At low f, the significant X_C across R_E (or R_S) makes the emitter (or source) no longer at ground potential, again reducing A_v.

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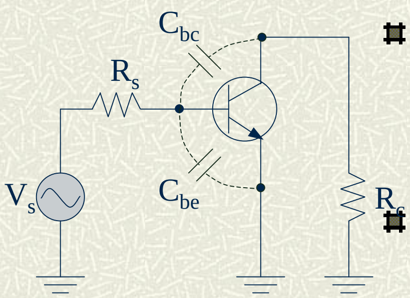
Effect At High Frequency



C_{bc} and C_{be} are internal junction capacitances which are usually a few pF.

- At high f, C_{be} causes a drop in signal voltage due to the voltage divider effect with R_S.
- At high f, C_{bc} allows negative feedback from output to cancel the input partially.
- A_v drops in each case.

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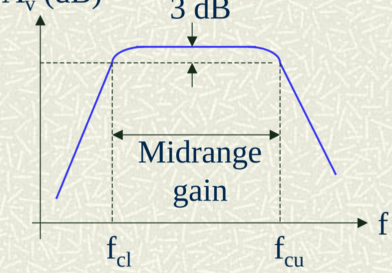
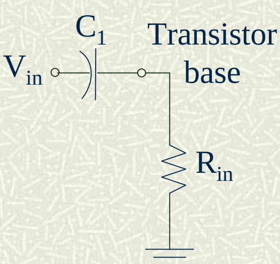
General Frequency Response Curve

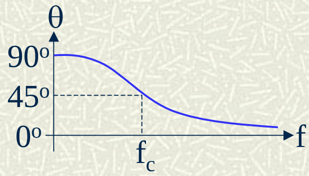


f_{cl} = lower cutoff frequency
f_{cu} = upper cutoff frequency
Gain is max. at midrange, often referenced as 0 dB.

- A_v (dB) = 20 log A_v
- *Cutoff*, *critical*, or *corner frequency* is the frequency when A_v or A_p drops by 3 dB. This corresponds to $0.707A_{v(max)}$ or 0.5 $A_{p(max)}$ (*half-power point*) respectively.

Input RC Circuit At Low Frequency





$R_{in} = R_1//R_2//R_{in(base)}$

Critical frequency for this circuit is:

$$f_c = \frac{1}{2\pi \, R_{in} C_1}$$

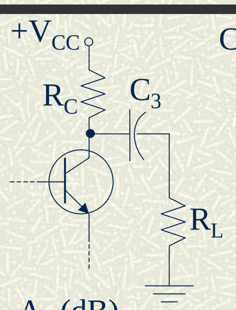
$V_{R(in)}$ leads V_{in} by: $\theta = \tan^{-1}\left(\frac{X_{C1}}{R_{in}}\right)$

Note: At f_c, $X_{C1} = R_{in}$, ⑧ $\theta = 45^o$.

If R_s of input source is included:

$$f_c = \frac{1}{2\pi \, (R_s + R_{in}) C_1}$$

Output RC Circuit At Low Frequency



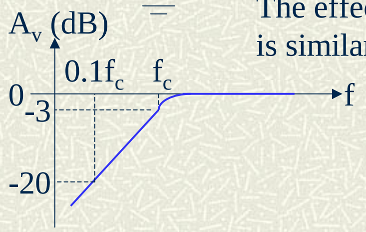
Critical frequency for the output RC circuit:

$$f_c = \frac{1}{2\pi\,(R_C + R_L)C_3}$$

The phase shift at the output:

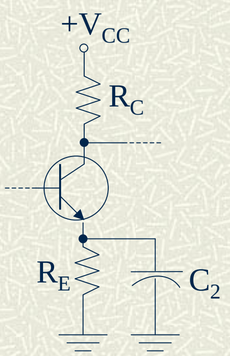
$$\theta = \tan^{-1}\left(\frac{X_{C3}}{R_C + R_L}\right)$$

The effect of the output RC circuit on A_v is similar to that of the input RC circuit.



Drop in A_v for each RC circuit is 20 dB/decade or 6 dB/octave

Bypass RC Circuit At Low Frequency



At low frequency, the impedance at the emitter is $Z_e = R_E // X_{C2}$, and A_v becomes:

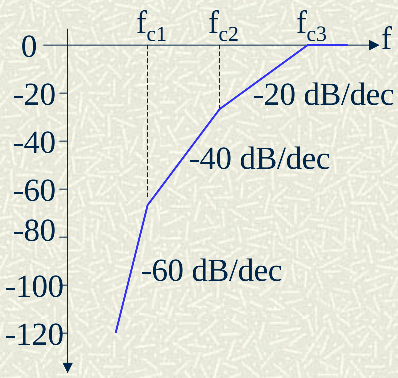
$$A_v = \frac{R_c}{r'_e + Z_e}$$

The critical frequency is:

$$f_c = \frac{1}{2\pi[(r'_e + R_{th}/\beta_{ac}) // R_E]C_2}$$

where $R_{th} = R_1 // R_2 // R_s$ is the equivalent Thevenin resistance looking from the base toward the input source.

Total Low-Frequency Response



Bode plot of amplifier's low-frequency response

- f_{c1}, f_{c2}, and f_{c3} are the critical frequencies of the bypass, output and input RC circuits (not necessarily in that order).
- The RC circuit giving f_{c3} is known as the *dominant* RC circuit.

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Direct-Coupled Amplifiers

- Since direct-coupled amplifiers don't have coupling or bypass capacitors, their frequency response can extend down to dc.
- Because of this, they are commonly used in linear ICs.
- Although their gain is not as high as amplifiers with emitter bypass, A_v stays constant at lower frequencies.

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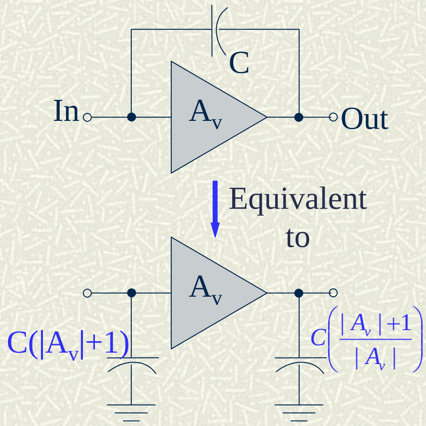
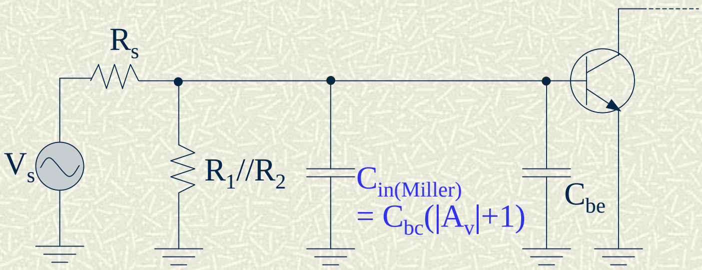
Miller's Theorem

- Miller's theorem can be used to simplify the analysis of inverting amplifiers at high frequencies.
- C in the diagram can represent either C_{bc} of a BJT or C_{gd} of a FET.



Input RC Circuit At High Frequency



Critical frequency:

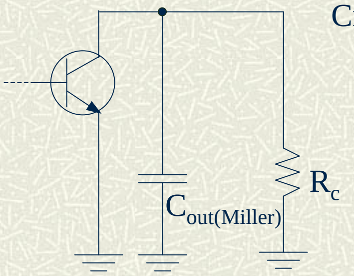
$$f_c = \frac{1}{2\pi R_{tot} C_{tot}}$$

Phase shift:

$$\theta = \tan^{-1}\left(\frac{R_{tot}}{X_{C(tot)}}\right)$$

where $R_{tot} = R_s//R_1//R_2//\beta_{ac}r'_e$; and $C_{tot} = C_{be}+C_{in(Miller)}$

Output RC Circuit At High Frequency



Critical frequency:

$$f_c = \frac{1}{2\pi R_c C_{out(Miller)}}$$

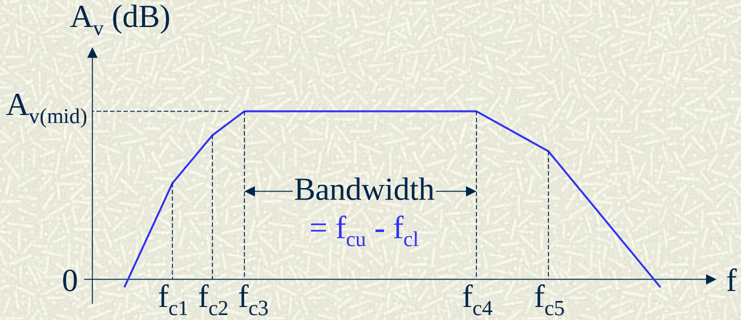
Phase shift:

$$\theta = \tan^{-1}\left(\frac{R_c}{X_{C_{out(Miller)}}}\right)$$

$$C_{out(Miller)} = C_{bc}\left(\frac{|A_v|+1)}{|A_v|}\right)$$

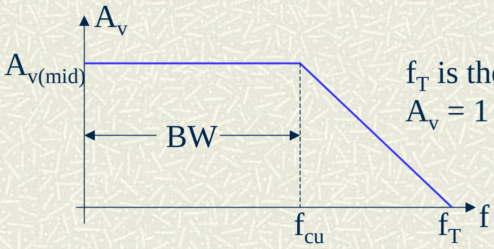
If $|A_v| \geq 10$, $C_{out(Miller)} \approx C_{bc}$

Total Amplifier Frequency Response



f_{c3} and f_{c4} are the two dominant critical frequencies where A_v is 3 dB below its midrange value. f_{c3} is the *lower cutoff frequency*, f_{cl}, and f_{c4} is the *upper cutoff frequency*, f_{cu}.

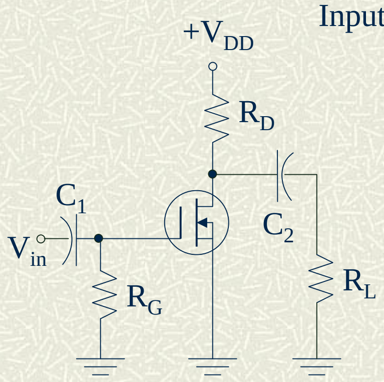
Gain-Bandwidth Product



f_T is the frequency at which $A_v = 1$ (unity gain) or 0 dB.

- For a given amplifier, its *gain-bandwidth product* is a constant when the roll-off is -20 dB/dec.
- If $f_{cu} >> f_{cl}$, then $BW = f_{cu} - f_{cl}$ ☞ f_{cu}.
- *Unity-gain frequency*, $f_T = A_{v(mid)} BW = A_{v(mid)} f_{cu}$.

FET Amplifier At Low Frequency



$R_{in(gate)} = |V_{GS} / I_{DSS}|$

Input RC circuit:
$$f_c = \frac{1}{2\pi R_{in} C_1}$$
$$\theta = \tan^{-1}\left(\frac{X_{C1}}{R_{in}}\right)$$
where $R_{in} = R_G // R_{in(gaate)}$

Output RC circuit:
$$f_c = \frac{1}{2\pi (R_D + R_L) C_2}$$
$$\theta = \tan^{-1}\left(\frac{X_{C2}}{R_D + R_L}\right)$$

FET Amplifier At High Frequency

The high frequency analysis of an FET amplifier is very similar to that of a BJT amplifier. The basic differences are the specs of C_{gd} (= C_{rss}), and the determination of R_{in}.

Input RC circuit:

$$f_c = \frac{1}{2\pi R_s C_{tot}}; \theta = \tan^{-1}\left(\frac{R_s}{X_{C_{tot}}}\right)$$

where $C_{tot} = C_{gs} + C_{in(Miller)}$; $C_{in(Miller)} = C_{gd}(|A_v| + 1)$

Output RC circuit:

$$f_c = \frac{1}{2\pi R_d C_{out(Miller)}}; \theta = \tan^{-1}\left(\frac{R_d}{X_{C_{out(Miller)}}}\right); C_{out(Miller)} = C_{gd}\left(\frac{|A_v|+1}{|A_v|}\right)$$

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Multistage Amplifiers

For an amplifier formed by cascading several stages, the overall bandwidth is: $BW_{tot} = f'_{cu} - f'_{cl}$

If all the stages have the same f_{cl} and f_{cu}, then:

$$f'_{cl} = \frac{f_{cl}}{\sqrt{2^{1/n} - 1}} \quad \text{and} \quad f'_{cu} = f_{cu}\sqrt{2^{1/n} - 1}$$

If each stage has a different f_{cl} and a different f_{cu}, then f'_{cl} is determined by the stage with the highest f_{cl}, and f'_{cu} is determined by the stage with the lowest f_{cu}.

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