EE105 – Fall 2014
Microelectronic Devices and Circuits

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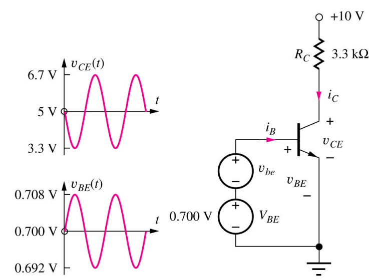
Introduction to Amplifiers

- **Amplifiers: transistors biased in the flat-part of the i-v curves**
  - **BJT: forward-active region**
  - **MOSFET: saturation region**
- **In these regions, transistors can provide high voltage, current and power gains**
- **Bias is provided to stabilize the operating point (the Q-Point) in the desired region of operation**
- **Q-point also determines**
  - **Small-signal parameters of transistor**
  - **Voltage gain, input resistance, output resistance**
  - **Maximum input and output signal amplitudes**
  - **Power consumption**

Transistor Amplifiers
BJT Amplifier Concept

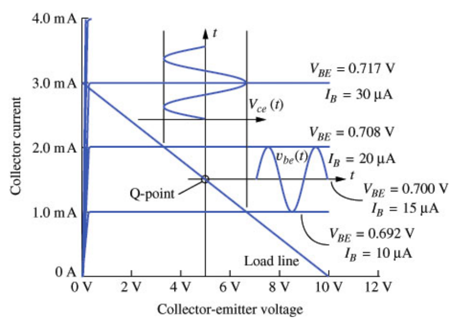


The BJT is biased in the active region by dc voltage source V_{BE}. e.g., Q-point is set at (I_C, V_{CE}) = (1.5 mA, 5 V) with I_B = 15 μA (β_F = 100)

Total base-emitter voltage is: $v_{BE} = V_{BE} + v_{be}$

Collector-emitter voltage is: $v_{CE} = V_{CC} - i_C R_C$ This is the load line equation.

Transistor Amplifiers
BJT Amplifier (cont.)



8 mV peak change in v_{BE} gives 5 mA change in i_B and 0.5 mA change in i_C.

0.5 mA change in i_C produces a 1.65 V change in v_{CE} .

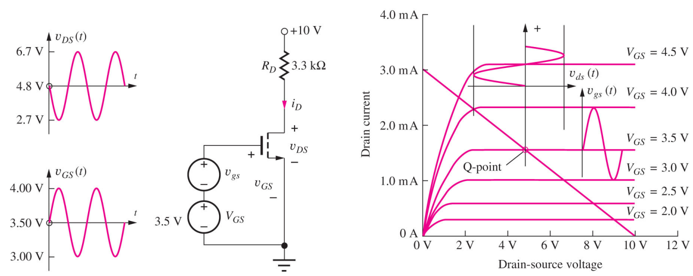
If changes in operating currents and voltages are small enough, then i_C and v_{CE} waveforms are undistorted replicas of the input signal.

A small voltage change at the base causes a large voltage change at collector. Voltage gain is given by:

$$A_v = \frac{V_{ce}}{V_{be}} = \frac{1.65\angle 180^o}{0.008\angle 0^o} = 206\angle 180^o = -206$$

Minus sign indicates 180° phase shift between the input and output signals.

Transistor Amplifiers
MOSFET Amplifier Concept



$$A_v = \frac{V_{ds}}{V_{gs}}$$

$$A_v = \frac{4\angle 180^o}{1\angle 0^o}$$

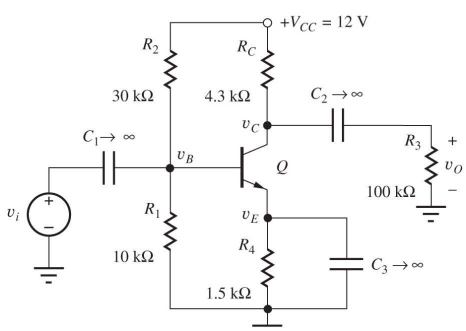
$$A_v = -4.00$$

MOSFET is biased in active region by dc voltage source V_{GS}. e.g., Q-point is set at (I_D, V_{DS}) = (1.56 mA, 4.8 V) with V_{GS} = 3.5 V

Total gate-source voltage is: $v_{GS} = V_{GS} + v_{gs}$

1 $V_{p\text{-}p}$ change in v_{GS} yields 1.25 $mA_{p\text{-}p}$ change in i_D and a 4 $V_{p\text{-}p}$ change in v_{DS}

Transistor Amplifiers
Coupling and Bypass Capacitors



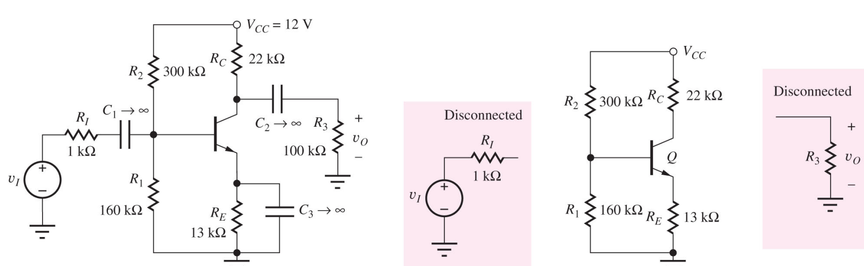
- **ac coupling through capacitors is used to inject ac input signal and extract output signal without disturbing Q-point**

- **Capacitors are designed to provide negligible impedance at frequencies of interest and provide open circuits at dc.**
- **C_1 and C_2 are low impedance coupling capacitors or dc blocking capacitors whose reactance at the signal frequency is designed to be negligible.**
- **C_3 is a bypass capacitor that provides a low impedance path for ac current from emitter to ground, thereby removing R_E (required for good Q-point stability) from the circuit when ac signals are considered.**

Transcistor Amplifiers
dc and ac Analysis – Two Step Analysis

- **dc analysis:**
  - **Find dc equivalent circuit by replacing all capacitors by open circuits and inductors by short circuits.**
  - **Find Q-point from dc equivalent circuit by using appropriate large-signal transistor model.**
- **ac analysis:**
  - **Find ac equivalent circuit by replacing all capacitors by short circuits, inductors by open circuits, dc voltage sources by ground connections and dc current sources by open circuits.**
  - **Replace transistor by its small-signal model**
  - **Use small-signal ac equivalent to analyze ac characteristics of amplifier.**
  - **Combine end results of dc and ac analysis to yield total voltages and currents in the network.**

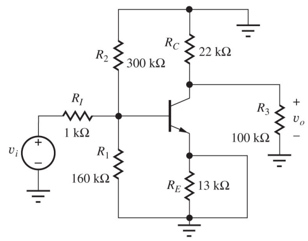
Transistor Amplifiers
dc Equivalent Circuit for BJT Amplifier



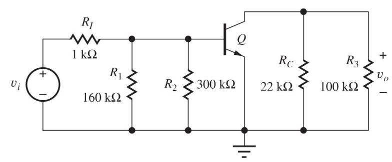
- **All capacitors in the original amplifier circuit are replaced by open circuits, disconnecting v_I, R_I, and R_3 from circuit.**

Transistor Amplifiers
ac Equivalent Circuit for BJT Amplifier

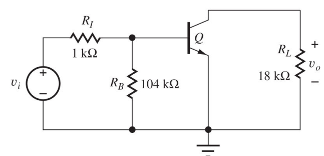
Capacitors are replaced by short circuits



(c)



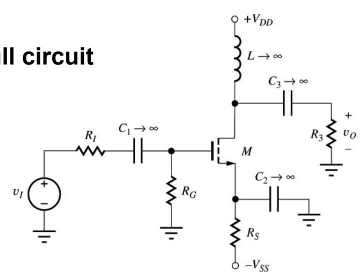
(d)



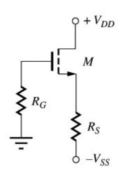
$$R_B = R_1 \| R_2 = 100\text{k}\Omega \| 300\text{k}\Omega$$
$$R = R_C \| R_3 = 22\text{k}\Omega \| 100\text{k}\Omega$$

Transistor Amplifiers
dc and ac Equivalents for a MOSFET Amplifier

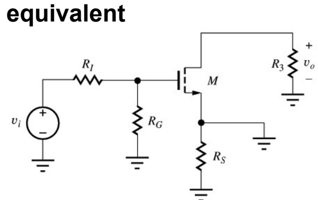
Full circuit



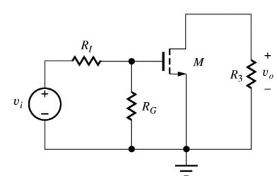
dc equivalent



ac equivalent

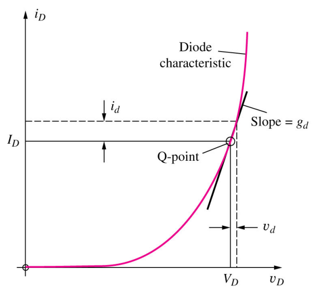


Simplified ac equivalent



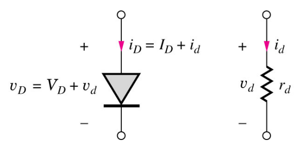
Small-Signal Operation
Diode Small-Signal Model

- **The slope of the diode characteristic at the Q-point is called the diode conductance and is given by:**



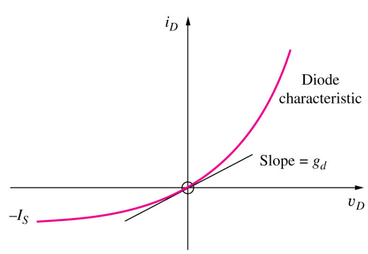
$$g_d = \left.\frac{\partial i_D}{\partial v_D}\right|_{Q-\text{point}} = \frac{I_S}{V_T}\exp\left(\frac{V_D}{V_T}\right) \approx \frac{I_D}{V_T}$$

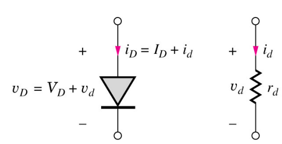
- **Diode resistance is given by:**



$$r_d = \frac{1}{g_d}$$

Small-Signal Operation
Diode Small-Signal Model (cont.)

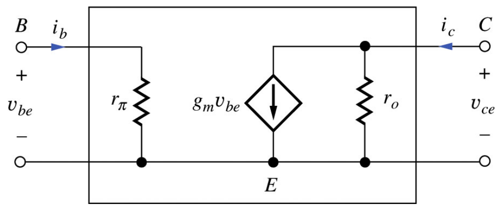




- **g_d is small but non-zero for $I_D = 0$ because slope of diode equation is nonzero at the origin.**
- **At the origin, the diode conductance and resistance are given by:**

$$g_d = \frac{I_S}{V_T} \quad \text{and} \quad r_d = \frac{V_T}{I_S}$$

Small-Signal Operation
BJT Hybrid-Pi Model



- The hybrid-pi small-signal model is the intrinsic representation of the BJT.
- Small-signal parameters are controlled by the Q-point and are independent of geometry of the BJT

Transconductance:

$$g_m = \frac{I_C}{V_T} \cong 40 I_C$$

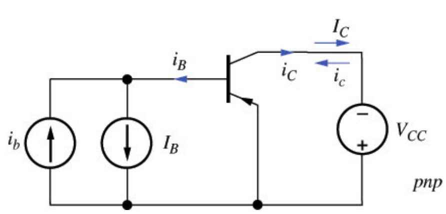
Input resistance:

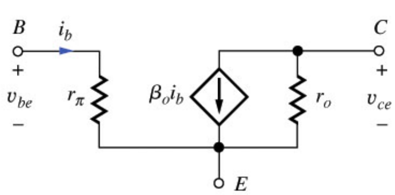
$$r_\pi = \frac{\beta_o V_T}{I_C} = \frac{\beta_o}{g_m} \quad \text{or} \quad \beta_o = g_m r_\pi$$

Output resistance:

$$r_o = \frac{V_A + V_{CE}}{I_C} \cong \frac{V_A}{I_C}$$

BJT Small-Signal Operation
Small-Signal Model for pnp Transistor



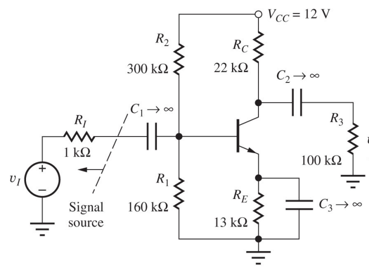


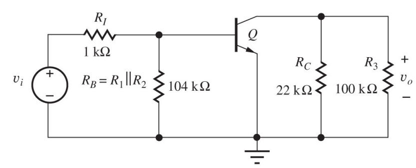
- For the pnp transistor

$$i_B = I_B - i_b$$
$$i_C = I_C - i_c = \beta_F I_B - \beta_F i_b$$

- Signal current injected into base causes decrease in total collector current which is equivalent to increase in signal current entering collector.
- So the small-signal models for the npn and pnp devices are identical!

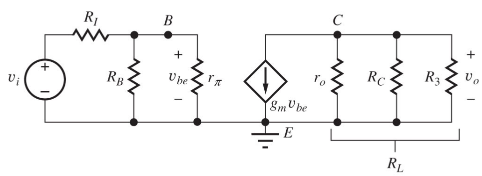
Common-Emitter Amplifiers
Small-Signal Analysis - ac Equivalent Circuit

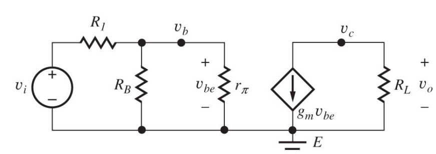




- ac equivalent circuit is constructed by assuming that all capacitances have zero impedance at signal frequency and dc voltage sources are ac ground.
- Assume that Q-point is already known.

Common-Emitter Amplifiers
Small-Signal Equivalent Circuit

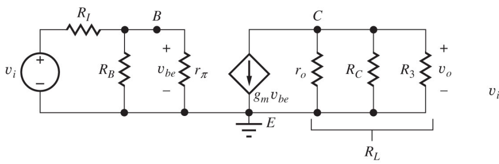


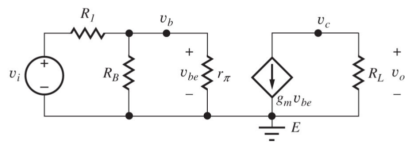


- Input voltage is applied to the base terminal
- Output signal appears at collector terminal
- Emitter is *common* to both input and output signals
  Thus circuit is termed a Common-Emitter (C-E) Amplifier.
- The terminal gain of the C-E amplifier is the gain from the base terminal to the collector terminal

$$A_{vt}^{CE} = \frac{v_c}{v_b} = -g_m R_L \qquad R_L = r_o \| R_C \| R_3$$

Common-Emitter Amplifiers
Input Resistance and Signal Source Gain





Define R_{iB} as the input resistance looking into the base of the transistor: $$R_{iB} = \frac{v_b}{i_b} = r_\pi$$

The input resistance presented to v_i is: $$R_{in} = R_I + R_B \| R_{iB} = R_I + R_B \| r_\pi$$

The signal source voltage gain is: $$A_v^{CE} = \frac{v_o}{v_i} = \frac{v_o}{v_b}\frac{v_b}{v_i} = A_{vt}^{CE}\frac{R_B \| r_\pi}{R_I + R_B \| r_\pi}$$

Common-Emitter Amplifiers
"Rule of Thumb" Design Estimate

$$A_v^{CE} = A_{vt}^{CE}\frac{R_B \| r_\pi}{R_I + R_B \| r_\pi} \cong A_{vt}^{CE} \qquad A_{vt}^{CE} = -g_m R_L \qquad R_L = r_o \| R_C \| R_3$$

Typically: $r_o >> R_C$ and $R_3 >> R_C$ $\qquad A_v^{CE} \cong -g_m R_C = -40 I_C R_C$

$I_C R_C$ represents the voltage dropped across collector resistor R_C

A typical design point is $I_C R_C = \frac{V_{CC}}{3}$

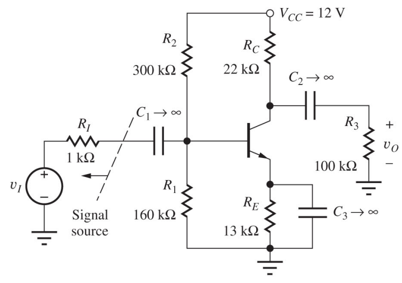
$$\therefore A_v^{CE} \cong -40\frac{V_{CC}}{3} = -13.3V_{CC}$$

To help account for all the approximations and have a number that is easy to remember, our "rule-of-thumb" estimate for the voltage gain becomes

$$A_v^{CE} \cong -10V_{CC}$$

Common-Emitter Amplifiers
Voltage Gain Example

- **Problem: Calculate voltage gain, input resistance and maximum input signal level for a common-emitter amplifier**
- **Given data: β_F = 100, V_A = 75 V, Q-point is (0.245 mA, 3.39 V)**
- **Assumptions: Transistor is in active region, $\beta_O = \beta_F$. Signals are low enough to be considered small signals. Room temperature.**



- **Analysis:**

$$g_m = 40I_C = 40(0.245mA) = 9.80\ mS \qquad r_\pi = \frac{\beta_o}{g_m} = \frac{100}{9.8mS} = 10.2\ k\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = \frac{75V + 3.39V}{0.245mA} = 320\ k\Omega \qquad R_B = R_1 \| R_2 = 160k\Omega \| 300k\Omega = 104\ k\Omega$$

$$R_L = r_o \| R_C \| R_L = 320k\Omega \| 22k\Omega \| 100k\Omega = 17.1\ k\Omega \qquad R_B \| r_\pi = 104k\Omega \| 10.2k\Omega = 9.29\ k\Omega$$

Common-Emitter Amplifiers
Voltage Gain Example (cont.)

$$A_v = -g_m R_L \left(\frac{R_B \| r_\pi}{R_I + R_B \| r_\pi} \right) = -9.8mS(17.1k\Omega)\left(\frac{9.29k\Omega}{1k\Omega + 9.29k\Omega} \right) = -168(0.903) = -151$$

$$R_{in} = R_I + R_B \| r_\pi = 10.3\ k\Omega$$

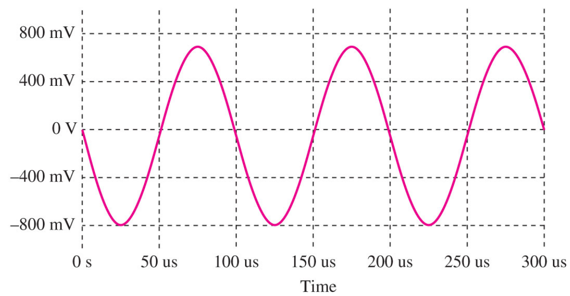
$$v_{be} = v_i \left(\frac{R_B \| r_\pi}{R_I + R_B \| r_\pi} \right) \qquad \therefore v_{be} \le 0.005V \to v_i \le 5mV \left(\frac{10.3k\Omega}{9.29k\Omega} \right) = 5.54\ mV$$

Check the rule-of-thumb estimate: $A_v^{CE} \cong -10(12) = -120$ (ballpark estimate)

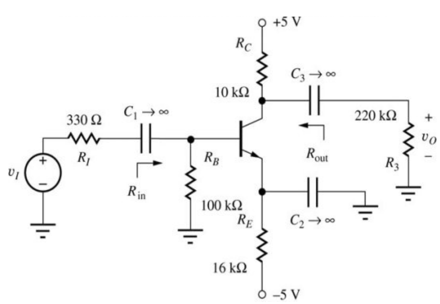
What is the maximum amplitude of the output signal: $v_o \le 5.54mV(-151) = 0.837\ V$

Common-Emitter Amplifiers
Voltage Gain Example (cont.)

- **Simulation Results: The graph below presents the output voltage for an input voltage that is a 5-mV, 10-kHz sine wave.**
- **Note that although the sine wave at first looks good, the positive and negative peak amplitudes are different indicating the presence of distortion. The input is near our small-signal limit for linear operation.**



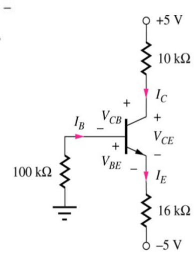
Common-Emitter Amplifiers
Dual Supply Operation - Example



- **Problem: Find voltage gain, input and output resistances for the circuit above**
- **Given: β_F = 65, V_A = 50 V**
- **Assumptions: Active-region operation, V_{BE} = 0.7 V, small signal operating conditions.**

Analysis: To find the Q-point, the dc equivalent circuit is constructed.

$$10^5 I_B + V_{BE} + (\beta_F + 1) I_B (1.6\times10^4) = 5$$



$$\therefore I_B = 3.71\ \mu A$$

$$I_C = 65 I_B = 241\ \mu A$$

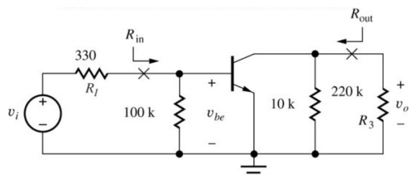
$$I_E = 66 I_B = 245\ \mu A$$

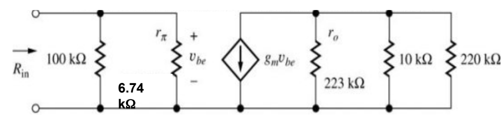
$$5 - 10^4 I_C - V_{CE} - (1.6\times10^4) I_E - (-5) = 0$$

$$\therefore V_{CE} = 3.67\ V$$

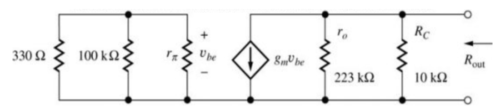
Common-Emitter Amplifiers
Dual Supply Operation - Example (cont.)

- **Next we construct the ac equivalent and simplify it.**





$$R_{in} = R_B \| r_\pi = 6.31\ k\Omega$$



$$g_m = 40 I_C = 9.64\times10^{-3}\ S$$

$$r_\pi = \frac{\beta_o}{40 I_C} = 6.74\ k\Omega$$

$$r_o = \frac{V_A + V_{CE}}{I_C} = 223\ k\Omega$$

$$R_{out} = R_C \| r_o = 9.57\ k\Omega$$

$$A_v^{CE} = \frac{v_o}{v_i} = -g_m \left(R_{out} \| R_3\right)\left(\frac{R_{in}}{R_I + R_{in}}\right) = -84.0$$

Gain Estimate: $A_v^{CE} \cong -10\left(V_{CC} + V_{EE}\right) = -100$