EE105 – Fall 2014
Microelectronic Devices and Circuits

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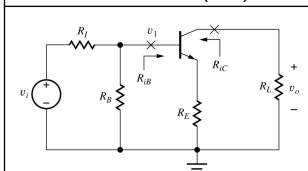
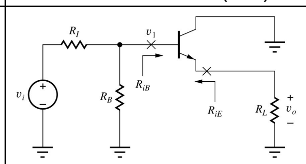
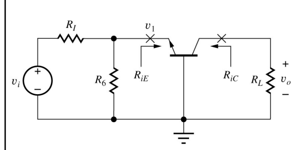
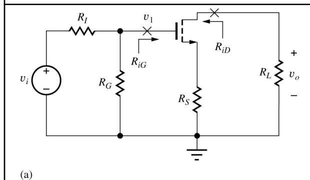
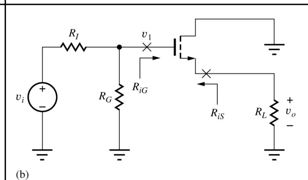
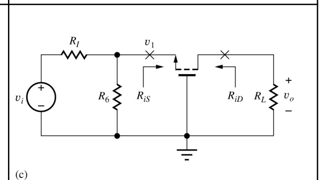
Terminal Gain and I/O Resistances of BJT Amplifiers

Common Emitter (CE)	Common Collector (CC)	Common Base (CB)
	 (b)	 (c)
$A_{V,t} = -\frac{g_m R_L}{1+g_m R_E}$ $R_i = r_\pi + (\beta+1)R_E$ $R_o = \left[r_o\left(1+g_m R_E\right)\right]$ $A_{I,t} = \beta$ Without degeneration: Simply set $R_E = 0$	$A_{V,t} = \frac{R_L}{\frac{1}{g_m}+R_L}$ $R_i = r_\pi + (\beta+1)R_L$ $R_o = \frac{r_\pi + R_{th}}{1+\beta} \approx \frac{1}{g_m} + \frac{R_{th}}{\beta}$ $A_{I,t} = \beta + 1$	$A_{V,t} = g_m R_L \beta$ $R_i = \frac{1}{g_m}$ $R_o = \left[r_o\left(1+g_m R_E\right)\right]$ $A_{I,t} \approx 1$

For the gain, R_i, R_o of the whole amplifier, you need to include voltage/ current dividers at input and output stages

Terminal Gain and I/O Resistances of MOS Amplifiers

Common Source (CS)	Common Drain (CD)	Common Gate (CG)
		
$A_{V,t} = -\dfrac{g_m R_L}{1+g_m R_S}$ $R_i = \infty$ $R_o = \left[r_o\left(1+g_m R_E\right)\right]$ $A_{I,t} = \infty$ Without degeneration: Simply set $R_S = 0$	$A_{V,t} = \dfrac{R_L}{\dfrac{1}{g_m} + R_L}$ $R_i = \infty$ $R_o = \dfrac{1}{g_m}$ $A_{I,t} = \infty$	$A_{V,t} = g_m R_L$ $R_i = \dfrac{1}{g_m}$ $R_o = \left[r_o\left(1+g_m R_E\right)\right]$ $A_{I,t} \approx 1$

For the gain, R_i, R_o of the whole amplifier, you need to include voltage/ current dividers at input and output stages

Summary of Single-Transistor Amplifiers

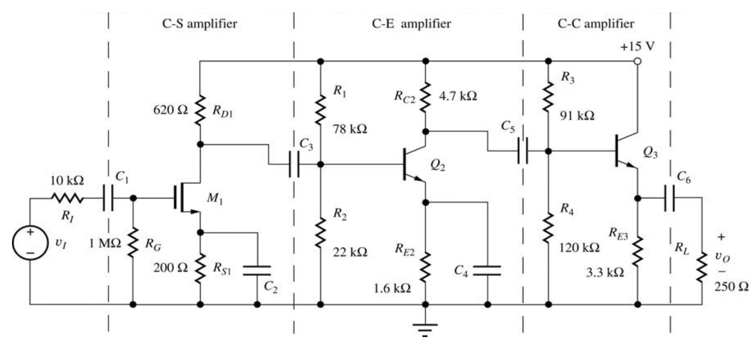
BJT	Ideal Voltage Amplifiers	Common Emitter	Common Emitter with Deg.	Common Collector	Common Base
R_i	∞	Moderate	Large	Large	Small
R_o	0	Large	Very Large	Small	Large
A_V	∞	Large	Moderate	~ 1	Large
f_H	∞	Small	Moderate	Large	Large

MOS	Ideal Voltage Amplifiers	Common Source	Common Source with Deg.	Common Drain	Common Gate
R_i	∞	Very Large	Very Large	Large	Small
R_o	0	Large	Very Large	Small	Large
A_V	∞	Moderate	Small	~ 1	Moderate
f_H	∞	Small	Moderate	Large	Large

Need for Multistage Amplifiers

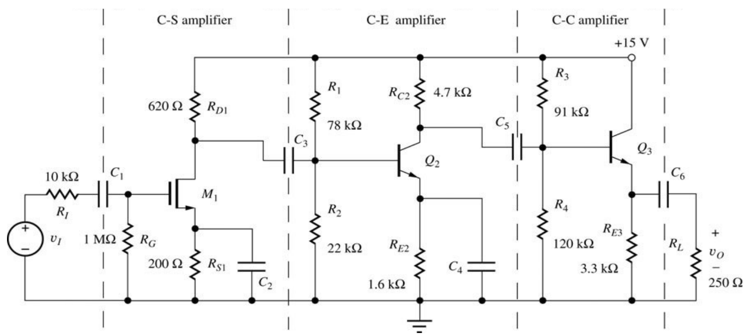
- Typical spec for a general purpose operational amplifier
  - Input resistance ~ 1MΩ
  - Output resistance ~ 100Ω
  - Voltage gain ~ 100,000
- No single transistor amplifier can satisfy the spec
- Cascading multiple stages of amplifiers to meet the spec
- Usually
  - An input stage to provide required input resistance
  - A middle stage(s) to provide gain
  - An output stage to provide required output resistance
- It is important to note that the input resistance of the follow -on stage becomes the load of the previous stage

A 3-Stage ac-coupled Amplifier Circuit



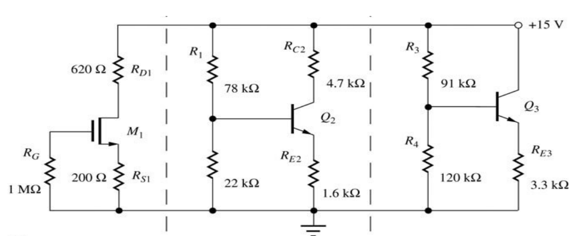
- MOSFET M_1operating in the C-S configuration provides high input resistance and moderate voltage gain.
- BJT Q_2 in a C-E configuration, the second stage, provides high gain.
- BJT Q_3, an emitter-follower gives low output resistance and buffers the high gain stage from the relatively low value of load resistance.

A 3-Stage ac-coupled Amplifier Circuit



- Input and output of overall amplifier is ac-coupled through capacitors C_1 and C_6.
- Bypass capacitors C_2 and C_4 are used to get maximum voltage gain from the two inverting amplifiers.
- Interstage coupling capacitors C_3 and C_5 transfer ac signals between amplifiers but provide isolation at dc and prevent Q-points of the transistors from being affected.
- In the ac equivalent circuit, bias resistors are replaced by $R_{B2} = R_1||R_2$ and $R_{B3} = R_3||R4$

dc Equivalent Circuit



Transistor Parameters

$M_1: K_n = 10\ mA/V^2,\ V_{TN} = -2\ V,\ \lambda = 0.02V^{-1}$

$Q_2: \beta_F = 150,\ V_A = 80V,\ V_{BE} = 0.7V$

$Q_3: \beta_F = 80,\ V_A = 60V,\ V_{BE} = 0.7V$

Q - Points

$M_1: (5.00\text{ mA},\ 10.9\text{ V})$

$Q_2: (1.57\text{ mA},\ 5.09\text{ V})$

$Q_3: (1.99\text{ mA},\ 8.36\text{ V})$

Small - Signal Parameters

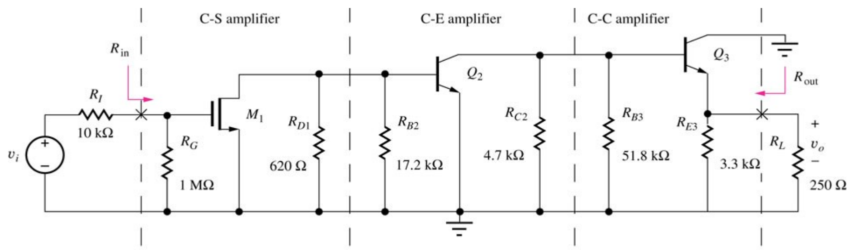
$M_1: g_{m1} = 10.0\ mS,\ r_{o1} = 12.2\ k\Omega$

$Q_2: g_{m2} = 62.8\ mS,\ r_{\pi 2} = 2.39\ k\Omega,\ r_{o2} = 54.2\ k\Omega$

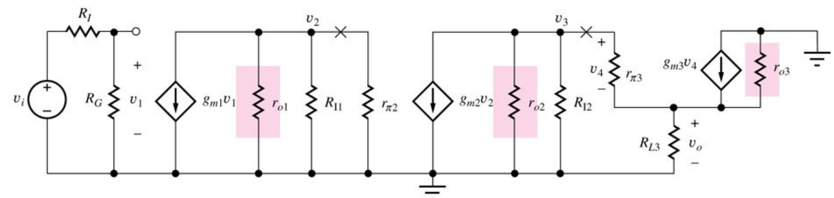
$Q_3: g_{m3} = 79.6\ mS,\ r_{\pi 3} = 1.00\ k\Omega,\ r_{o3} = 34.4\ k\Omega$

At dc, the capacitors isolate each individual transistor stage from the others. Thus, the bias point for each transistor may be found using the single transistor analysis methods already discussed.

ac and Small-Signal Equivalent Circuits

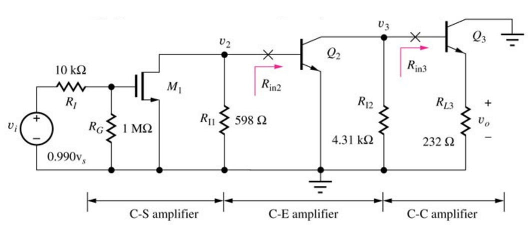


ac Equivalent



Small-signal Equivalent

Input Resistance and Voltage Gain



$$A_v = A_{vt3}A_{vt2}A_{vt1}\frac{R_{in}}{R_I + R_{in}}$$

$$A_{vt1} = \frac{v_2}{v_1} = -g_{m1}R_{L1} = -0.01S(0.478k\Omega) = -4.78$$

$$v_1 = v_i\frac{R_{in}}{R_I + R_{in}} = v_i\frac{1M\Omega}{10k\Omega + 1M\Omega} = 0.990v_i$$

$$R_{L2} = R_{I2}\|R_{in3} = R_{I2}\|\left[r_{\pi 3} + (\beta_{o3}+1)R_{L3}\right] = 3.54k\Omega$$

$$A_{vt2} = \frac{v_3}{v_2} = -g_{m2}R_{L2} = -62.8S(3.54k\Omega) = -222$$

$$A_{vt3} = \frac{v_o}{v_3} = \frac{(\beta_{o3}+1)R_{L3}}{r_{\pi 3} + (\beta_{o3}+1)R_{L3}} = 0.950$$

$$A_v = A_{vt3}A_{vt2}A_{vt1}\frac{R_G}{R_I + R_G} = +998$$

$R_{I1} = 620\Omega\|17.2k\Omega = 598\Omega$

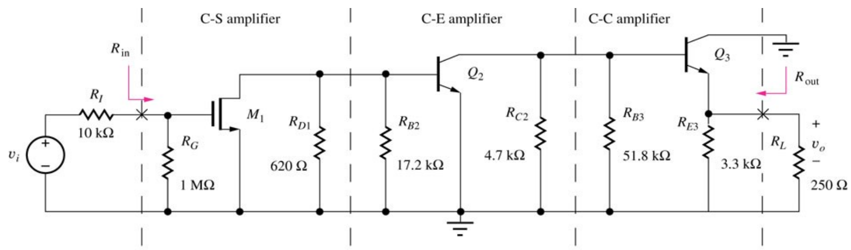
$R_{I2} = 4.7k\Omega\|51.8\Omega = 4.31k\Omega$

$R_{I3} = 3.3k\Omega\|250\Omega = 232\Omega$

$R_{L1} = R_{I1}\|R_{in2} = 598\Omega\|r_{\pi 2} = 598\Omega\|2390\Omega = 478\Omega$

$R_{in} = R_G = 1M\Omega$

Output Resistance



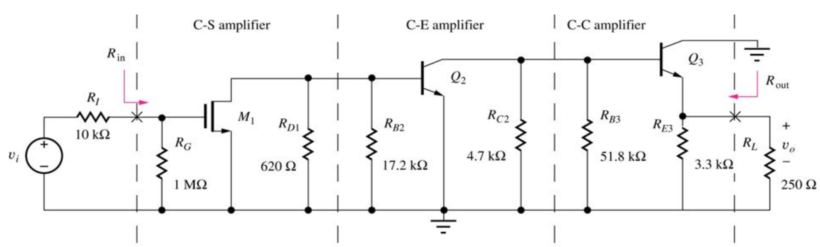
$$R_{o3} = \frac{r_\pi + R_{th}}{1+\beta} \approx \frac{1}{g_m} + \frac{R_{th}}{\beta}$$

$$R_{th} = R_{I2} \,\|\, r_{o2} = 4.31k\Omega \,\|\, 54.2k\Omega = 4k\Omega$$

$$R_{o3} = \frac{1}{79.6mS} + \frac{4k\Omega}{80} = 12.6\Omega + 50\Omega = 62.6\Omega$$

$$R_{out} = R_{E3} \,\|\, R_{o3} = 3.3k\Omega \,\|\, 62.6\Omega = 61.3\Omega$$

Current and Power Gain



The input signal current delivered to the amplifier from source v_i is

$$i_i = \frac{v_i}{R_I + R_{in}} = 9.90x10^{-7} v_i$$

and the signal current delivered to the load resistor is

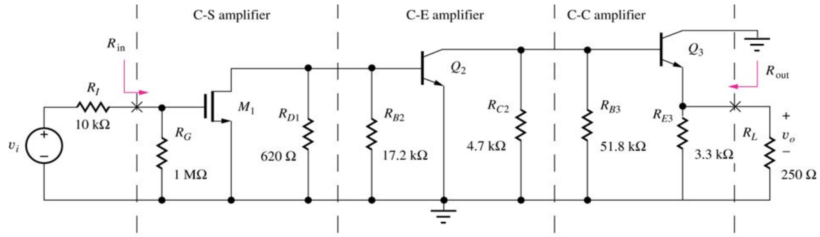
$$i_o = \frac{v_o}{R_L} = \frac{A_v v_i}{250\Omega} = \frac{998 v_i}{250\Omega} = 3.99 v_i$$

Current Gain: $A_i = \frac{i_o}{i_i} = 4.03x10^6$ (132 dB)

Voltage Gain: $A_v = \frac{v_o}{v_i} = 9.98x10^2$ (60 dB)

Power Gain: $A_P = \frac{P_o}{P_i} = \left|\frac{v_o i_o}{v_i i_i}\right| = A_v A_i = 4.02x10^9$ (96 dB)

Input and Output Signal Range



For the first stage: $|v_1| \le 0.2(V_{GS} - V_{TN}) \quad \rightarrow \quad |v_i| \le \dfrac{0.2(-1+2)V}{0.99} = 0.202\ V$

For the second stage: $|v_{be2}| = |v_2| = |A_{v1}v_1| \le 5mV$

$$|v_1| \le \frac{5mV}{A_{v1}} = \frac{5mV}{4.78} = 1.05mV \quad \rightarrow \quad |v_i| \le \frac{1.05mV}{0.99} = 1.06\ \text{m}V$$

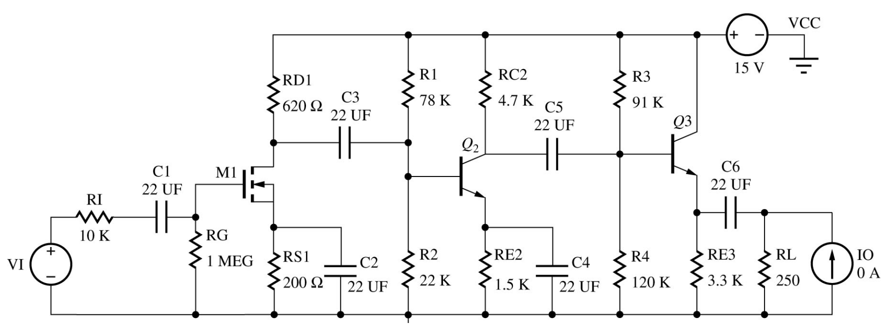
For the third stage: $v_{be3} \cong \dfrac{v_3}{1+g_{m3}R_{L3}} = \dfrac{A_{v1}A_{v2}(0.990v_i)}{1+g_{m3}R_{L3}} \le 5mV$

$$|v_i| \le \frac{1+g_{m3}R_{L3}}{A_{v1}A_{v2}(0.990)} 5mV = 92.7\ \mu V$$

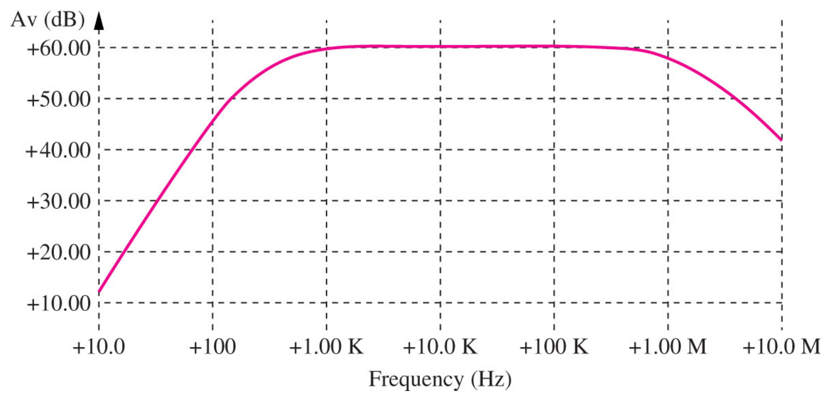
Overall: $|v_i| \le \min(202mV, 1.06mV, 92.7\mu V) = 92.7\mu V$

$$|v_o| \le A_v(92.7\mu V) = 998(92.7\mu V) = 92.5\ mV$$

SPICE Simulation Circuit



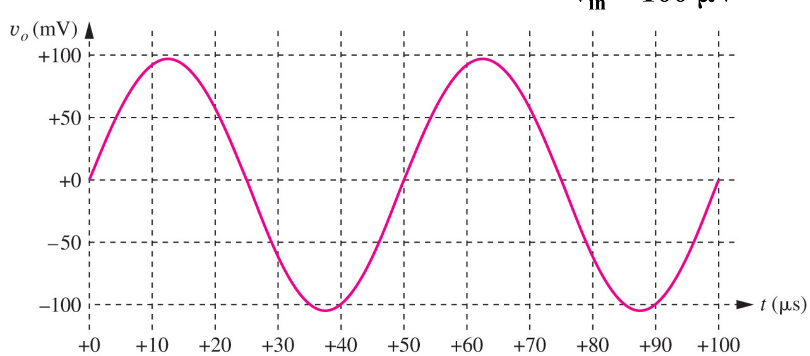
SPICE Simulation Results



$A_v = 1000$ $f_L = 500$ Hz $f_H = 500$ kHz

SPICE Simulation Results

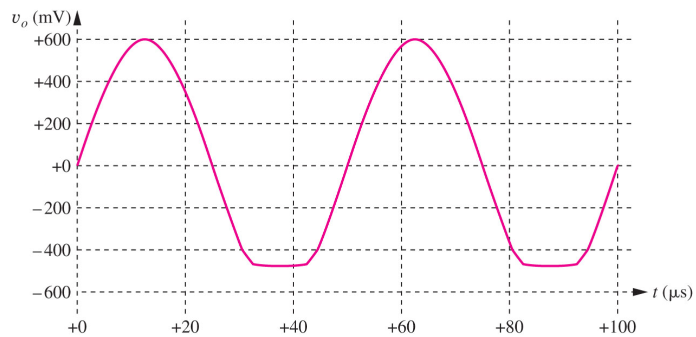
$v_{in} = 100\ \mu V$



Simulation with undistorted output and gain of 1000.

SPICE Simulation Results

v_{in} = 750 μV



Distorted output with amplitude exceeding output voltage capability of amplifier.

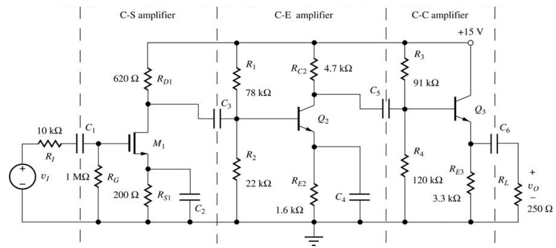
Short-Circuit Time Constant Estimate for f_L

An estimate for the lower cutoff frequency for an amplifier with multiple coupling and bypass capacitors is given by the sum of the reciprocals of the "short-circuit" time constants:

$$f_L \cong \frac{1}{2\pi}\sum_{i=1}^{n}\frac{1}{R_{iS}C_i}$$

where R_{iS} is the resistance at the terminals of the ith capacitor with all the other capacitors shorted.

Short-Circuit Time Constant Estimate for f_L



C_1: $R_{1S} = R_I + R_G = 1.01\ M\Omega$

C_2: $R_{2S} = R_{S1} \| R_{iS1} = R_{S1} \| \frac{1}{g_{m1}} = 200\Omega \| \frac{1}{0.01S} = 66.7\ \Omega$

C_3: $R_{3S} = R_{D1} + R_{I1} \| R_{iB2} = R_{D1} + R_{I1} \| r_{\pi 2} = 620\Omega + 17.2k\Omega \| 2.39k\Omega = 2.72\ \text{k}\Omega$

C_4: $R_{4S} = R_{E2} \| R_{iE2} = R_{E2} \| \frac{r_{\pi 2} + R_{th2}}{\beta_{o2} + 1} = 1.5k\Omega \| \frac{2.39k\Omega + 17.2k\Omega \| 0.620k\Omega}{151} = 19.2\ \Omega$

C_5: $R_{5S} = R_C + R_{I2} \| R_{iB3} = R_L + R_{I2} \| r_{\pi 3}(1 + g_{m3} R_{L3})$

$R_{5S} = 4.7k\Omega + 51.8k\Omega \| 1.0k\Omega\left[1 + 0.0796S(232\Omega)\right] = 18.9\ \text{k}\Omega$

C_6: $R_{6S} = R_L + R_{E3} \| R_{iE3} = R_L + R_{E3} \| \frac{r_{\pi 3} + R_{th3}}{\beta_{o3} + 1}$

$R_{6S} = 250\Omega + 3.3k\Omega \| \frac{1.0k\Omega + 51.8k\Omega \| 4.7k\Omega}{81} = 315\ \Omega$

Short-Circuit Time Constant Estimate for f_L

$$f_L \cong \frac{1}{2\pi}\left[\frac{1}{1.01M\Omega(22\mu F)} + \frac{1}{66.7\Omega(22\mu F)} + \frac{1}{2.72k\Omega(22\mu F)} + \frac{1}{19.2\Omega(22\mu F)} + \frac{1}{18.9k\Omega(22\mu F)} + \frac{1}{315\Omega(22\mu F)}\right] = 511\ Hz$$