

Lecture 22

OUTLINE

- Differential Amplifiers
 - General considerations
 - BJT differential pair
 - Qualitative analysis
 - Large-signal analysis
 - Small-signal analysis
 - Frequency response

- Reading: Chapter 10.1-10.2

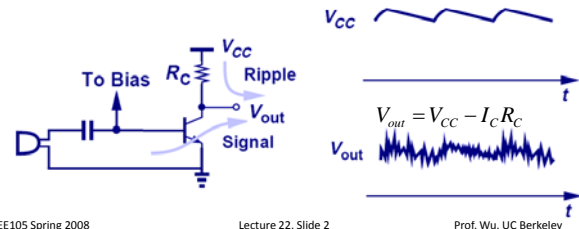
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“Humming” Noise in Audio Amplifier

- Consider the amplifier below which amplifies an audio signal from a microphone.
- If the power supply (V_{CC}) is time-varying, it will result in an additional (undesirable) voltage signal at the output, perceived as a “humming” noise by the user.



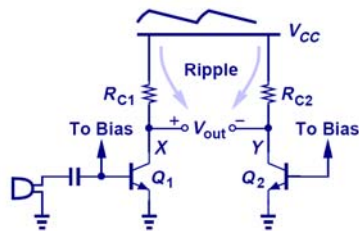
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Supply Ripple Rejection

- Since node X and Y each see the voltage ripple, their voltage difference will be free of ripple.



$$v_X = A_v v_{in} + v_r$$

$$v_Y = v_r$$

$$v_X - v_Y = A_v v_{in}$$

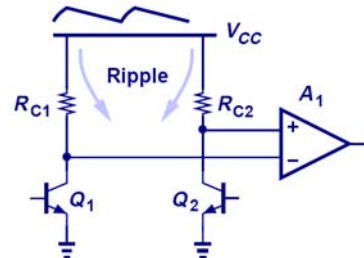
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Ripple-Free Differential Output

- If the input signal is to be a voltage difference between two nodes, an amplifier that senses a **differential signal** is needed.



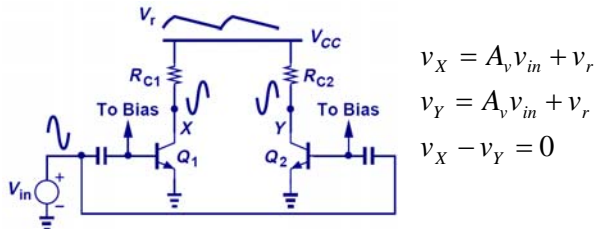
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Common Inputs to Differential Amp.

- The voltage signals applied to the input nodes of a differential amplifier cannot be in phase; otherwise, the differential output signal will be zero.



$$v_X = A_v v_{in} + v_r$$

$$v_Y = A_v v_{in} + v_r$$

$$v_X - v_Y = 0$$

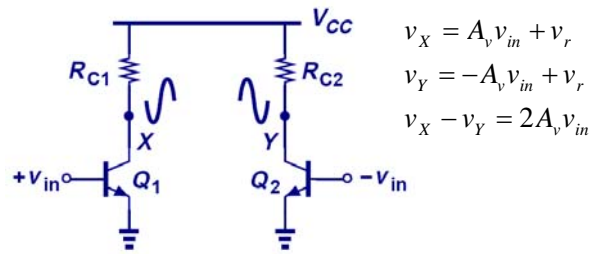
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Differential Inputs to Differential Amp.

- When the input voltage signals are 180° out of phase, the resultant output node voltages are 180° out of phase, so that their difference is enhanced.



$$v_X = A_v v_{in} + v_r$$

$$v_Y = -A_v v_{in} + v_r$$

$$v_X - v_Y = 2A_v v_{in}$$

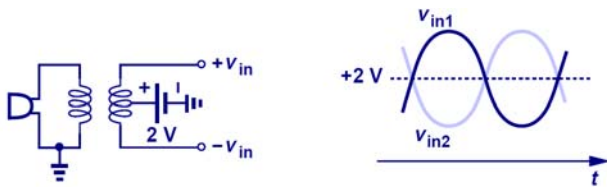
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Differential Signals

- Differential signals share the same average DC value and are equal in magnitude but opposite in phase.
- A pair of differential signals can be generated, among other ways, by a transformer.

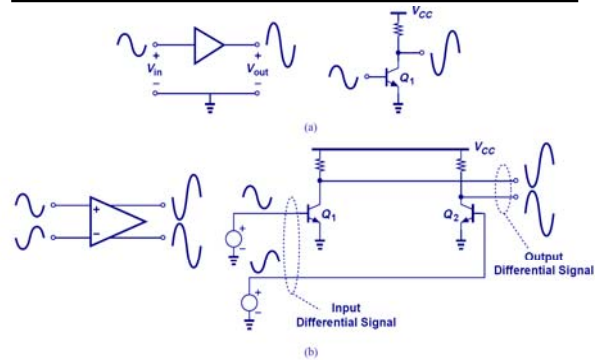


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Single-Ended vs. Differential Signals

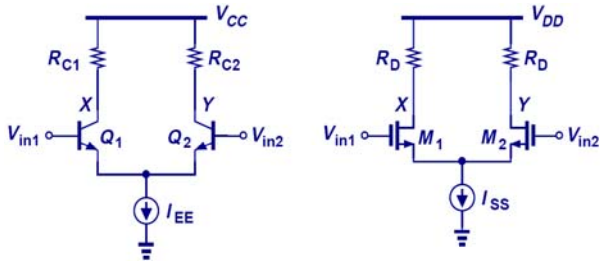


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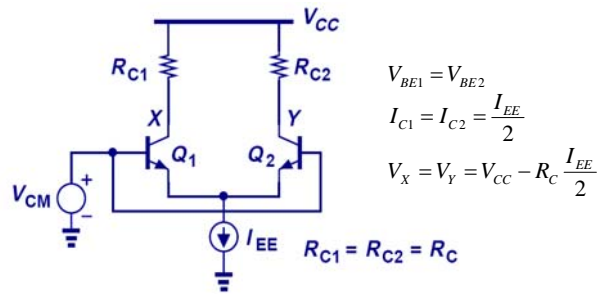
Differential Pair



- With the addition of a tail current, the circuits above operate as an elegant, yet robust differential pair.

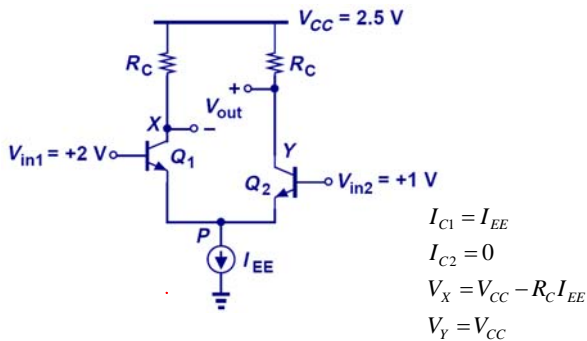
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Common-Mode Response



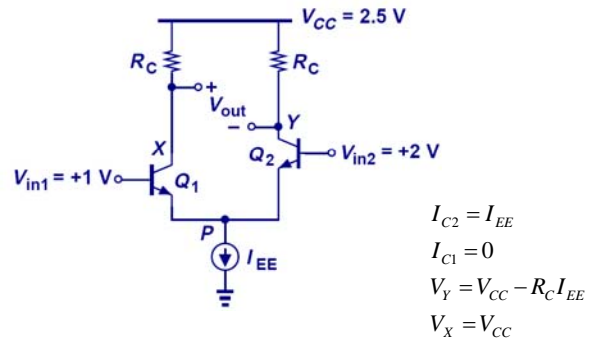
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Differential Response



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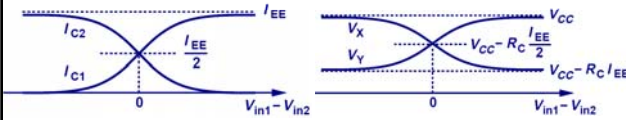
Differential Response (cont'd)



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Differential Pair Characteristics

- A differential input signal results in variations in the output currents and voltages, whereas a common-mode input signal does not result in any output current/voltage variations.



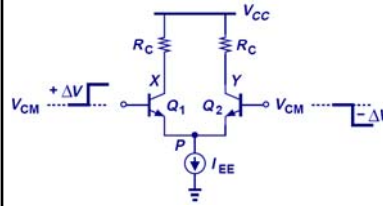
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Virtual Ground

- For small input voltages ($+\Delta V$ and $-\Delta V$), the g_m values are \sim equal, so the increase in I_{C1} and decrease in I_{C2} are \sim equal in magnitude. Thus, the voltage at node P is constant and can be considered as AC ground.



$$I_{C1} = \frac{I_{EE}}{2} + \Delta I$$

$$I_{C2} = \frac{I_{EE}}{2} - \Delta I$$

$$\Delta I_{C1} = g_m (\Delta V - \Delta V_P)$$

$$\Delta I_{C2} = g_m (-\Delta V - \Delta V_P)$$

$$\Delta I_{C1} = -\Delta I_{C2}$$

$$\Rightarrow \Delta V_P = 0$$

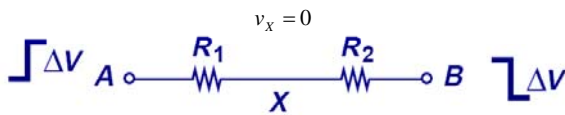
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Extension of Virtual Ground

- It can be shown that if $R_1 = R_2$, and the voltage at node A goes up by the same amount that the voltage at node B goes down, then the voltage at node X does not change.



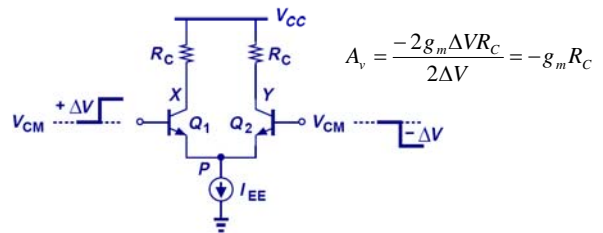
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Small-Signal Differential Gain

- Since the output signal changes by $-2g_m \Delta V R_C$ when the input signal changes by $2\Delta V$, the small-signal voltage gain is $-g_m R_C$.
- Note that the voltage gain is the same as for a CE stage, but that the power dissipation is doubled.

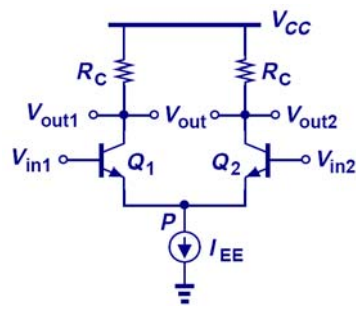


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Large-Signal Analysis



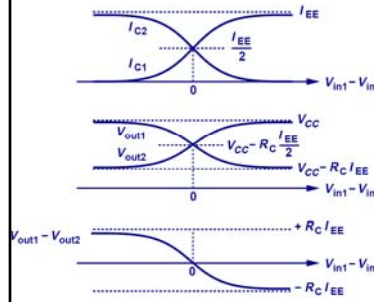
$$\begin{aligned}
 V_{in1} - V_{in2} &= V_{BE1} - V_{BE2} \\
 &= V_T \ln\left(\frac{I_{C1}}{I_S}\right) - V_T \ln\left(\frac{I_{C2}}{I_S}\right) \\
 &= V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right) \\
 I_{C1} + I_{C2} &= I_{EE} \\
 I_{C1} &= \frac{I_{EE} e^{\frac{V_{in1} - V_{in2}}{V_T}}}{1 + e^{\frac{V_{in1} - V_{in2}}{V_T}}} \\
 I_{C2} &= \frac{I_{EE}}{1 + e^{\frac{V_{in1} - V_{in2}}{V_T}}}
 \end{aligned}$$

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Input/Output Characteristics



$$\begin{aligned}
 V_{out1} - V_{out2} &= (V_{CC} - I_{C1}R_C) - (V_{CC} - I_{C2}R_C) \\
 &= (I_{C2} - I_{C1})R_C \\
 &= -R_C I_{EE} \tanh\left(\frac{V_{in1} - V_{in2}}{2V_T}\right)
 \end{aligned}$$

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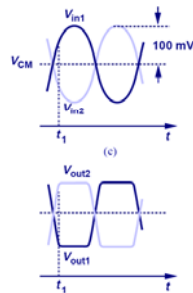
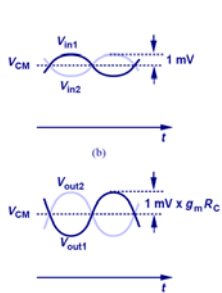
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Linear/Nonlinear Regions of Operation

Amplifier operating in linear region

Amplifier operating in non-linear region

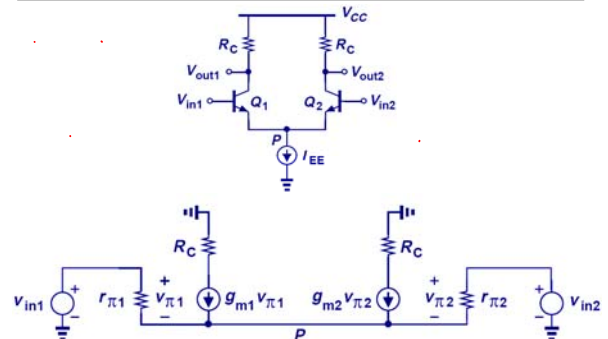


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Small-Signal Analysis



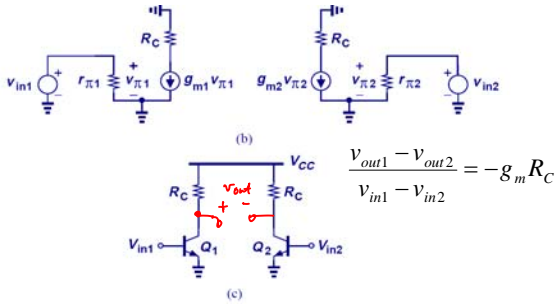
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Half Circuits

- Since node P is AC ground, we can treat the differential pair as two CE "half circuits."

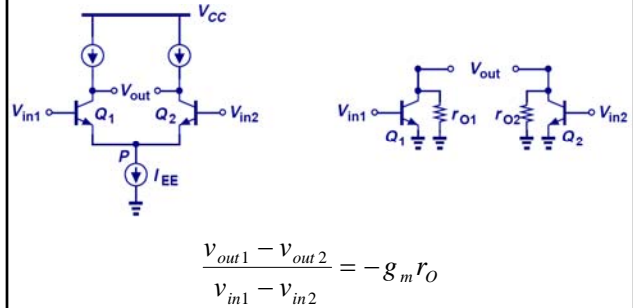


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Half Circuit Example 1

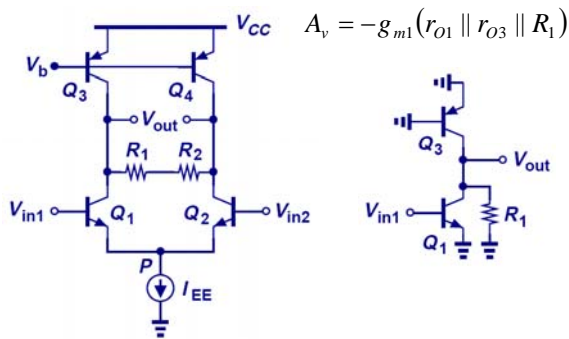


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Half Circuit Example 2

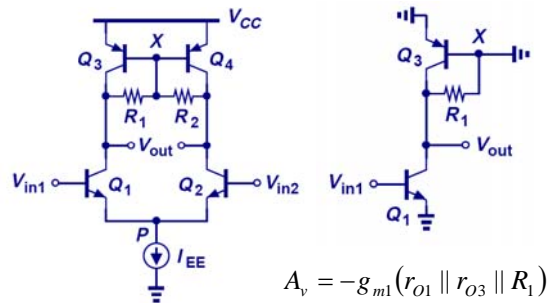


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Half Circuit Example 3

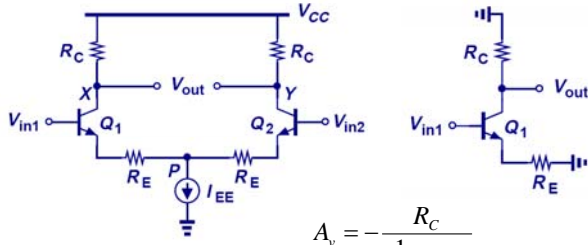


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Half Circuit Example 4



$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}$$

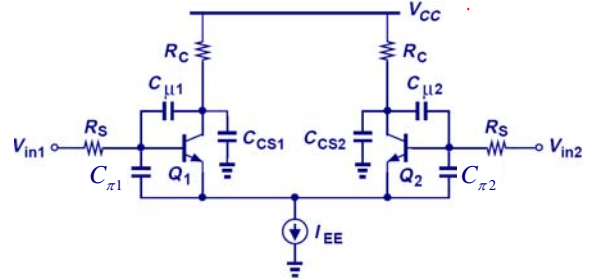
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Differential Pair Frequency Response

- Since the differential pair can be analyzed using its half circuit, its transfer function, I/O impedances, locations of poles/zeros are the same as that of its half circuit.



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