## Lecture 22

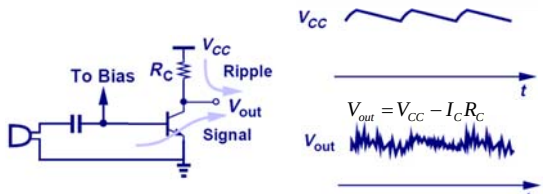
OUTLINE

- Differential Amplifiers
  - General considerations
  - BJT differential pair
    - Qualitative analysis
    - Large-signal analysis
    - Small-signal analysis
    - Frequency response
- Reading: Chapter 10.1-10.2



## "Humming" Noise in Audio Amplifier

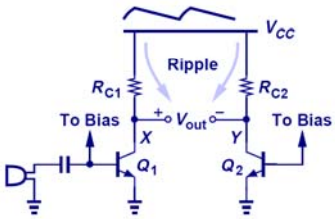
- Consider the amplifier below which amplifies an audio signal from a microphone.
- If the power supply ($V_{CC}$) is time-varying, it will result in an additional (undesirable) voltage signal at the output, perceived as a "humming" noise by the user.






## Supply Ripple Rejection

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

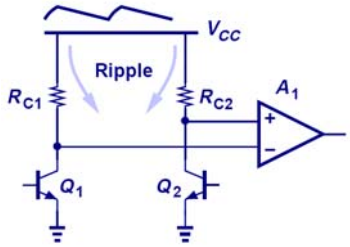



$$v_X = A_v v_{in} + v_r$$
$$v_Y = v_r$$
$$v_X - v_Y = A_v v_{in}$$



## Ripple-Free Differential Output

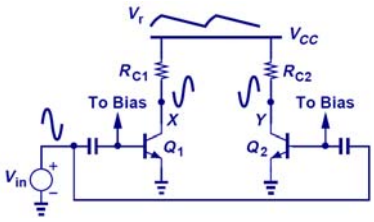
- If the input signal is to be a voltage difference between two nodes, an amplifier that senses a ***differential signal*** is needed.






## 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.

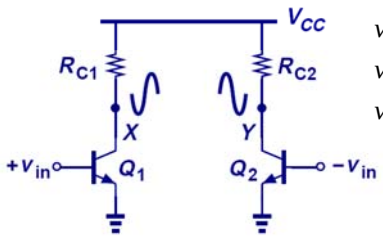



$$v_X = A_v v_{in} + v_r$$
$$v_Y = A_v v_{in} + v_r$$
$$v_X - v_Y = 0$$



## Differential Inputs to Differential Amp.

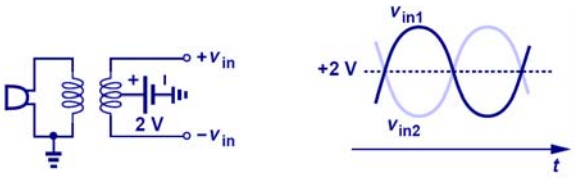
- When the input voltage signals are 180° out of phase, the resultant output node voltages are 180° out of phase, so that their difference is enhanced.




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

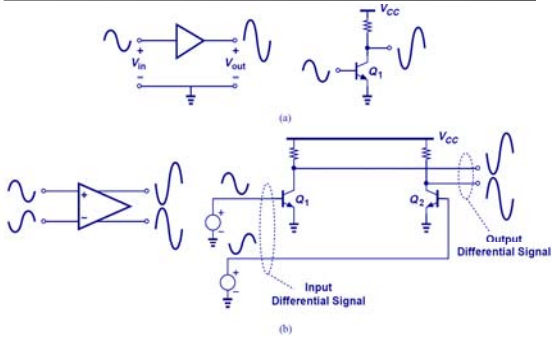
## Differential Signals

- 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.



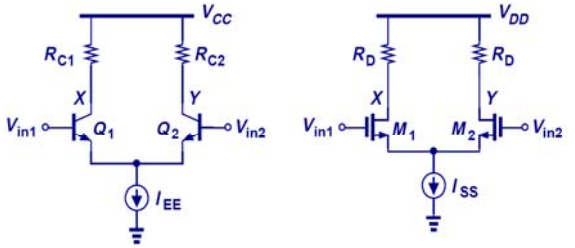



## Single-Ended *vs*. Differential Signals





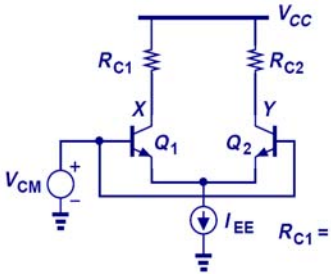

## Differential Pair




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



## Common-Mode Response




$$V_{BE1} = V_{BE2}$$

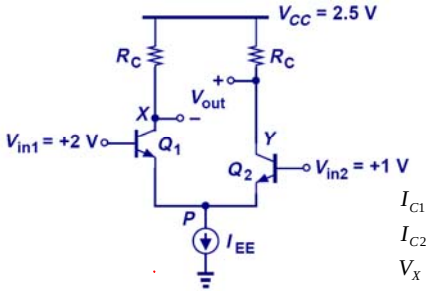
$$I_{C1} = I_{C2} = \frac{I_{EE}}{2}$$

$$V_X = V_Y = V_{CC} - R_C \frac{I_{EE}}{2}$$

$R_{C1} = R_{C2} = R_C$



## Differential Response




$$I_{C1} = I_{EE}$$

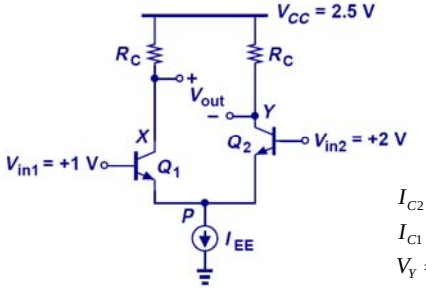
$$I_{C2} = 0$$

$$V_X = V_{CC} - R_C I_{EE}$$

$$V_Y = V_{CC}$$



## Differential Response (cont'd)




$$I_{C2} = I_{EE}$$

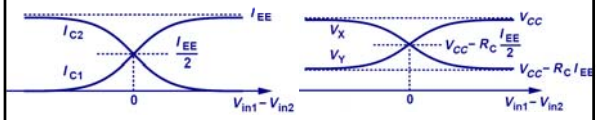
$$I_{C1} = 0$$

$$V_Y = V_{CC} - R_C I_{EE}$$

$$V_X = V_{CC}$$

## Differential Pair Characteristics

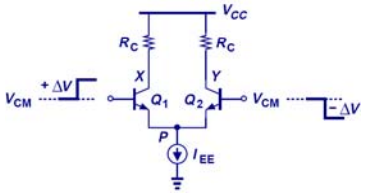
- A differential input signal results in variations in the output currents and voltages, whereas a common-mode input signal does not result in any output current/voltage variations.






## Virtual Ground

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

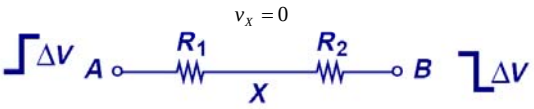



$$I_{C1}=\frac{I_{EE}}{2}+\Delta I$$
$$I_{C2}=\frac{I_{EE}}{2}-\Delta I$$
$$\Delta I_{C1}=g_m\left(\Delta V-\Delta V_P\right)$$
$$\Delta I_{C2}=g_m\left(-\Delta V-\Delta V_P\right)$$
$$\Delta I_{C1}=-\Delta I_{C2}$$
$$\Rightarrow \Delta V_P=0$$



## Extension of Virtual Ground

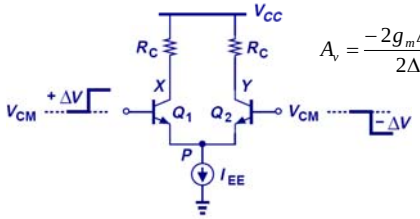
- It can be shown that if $R_1 = R_2$, and the voltage at node *A* goes up by the same amount that the voltage at node *B* goes down, then the voltage at node *X* does not change.






## Small-Signal Differential Gain

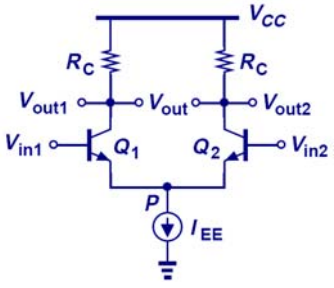
- Since the output signal changes by $-2g_m\Delta V R_C$ when the input signal changes by $2\Delta V$, the small-signal voltage gain is $-g_m R_C$.
- Note that the voltage gain is the same as for a CE stage, but that the power dissipation is doubled.




$$A_v=\frac{-2g_m\Delta V R_C}{2\Delta V}=-g_m R_C$$



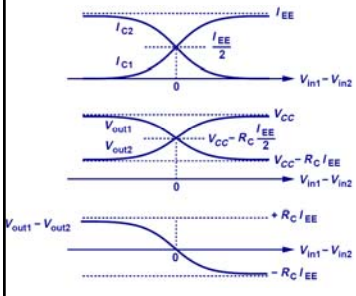
## Large-Signal Analysis




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



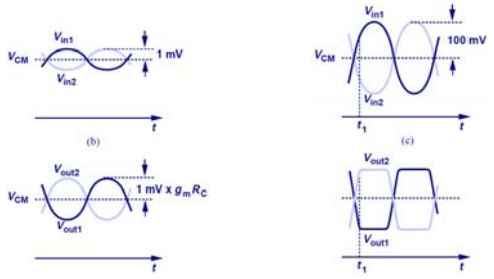
## Input/Output Characteristics




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

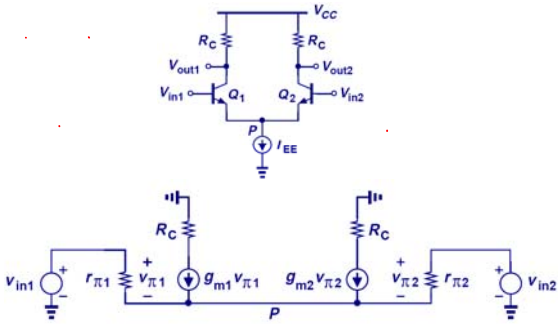
## Linear/Nonlinear Regions of Operation

**Amplifier operating in linear region** | **Amplifier operating in non-linear region**





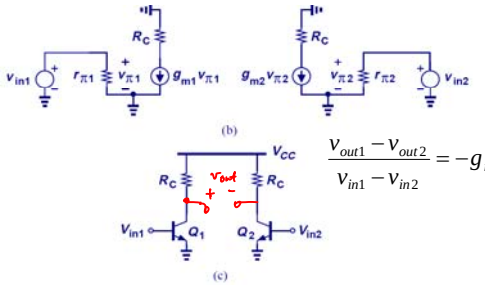

## Small-Signal Analysis






## Half Circuits

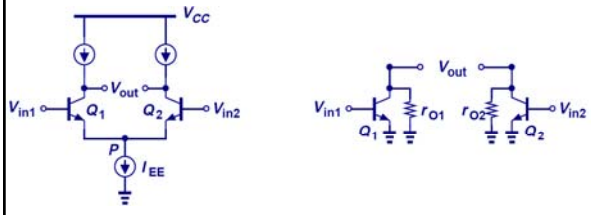
- Since node *P* is AC ground, we can treat the differential pair as two CE "half circuits."




$$\frac{v_{out1} - v_{out2}}{v_{in1} - v_{in2}} = -g_m R_C$$



## Half Circuit Example 1

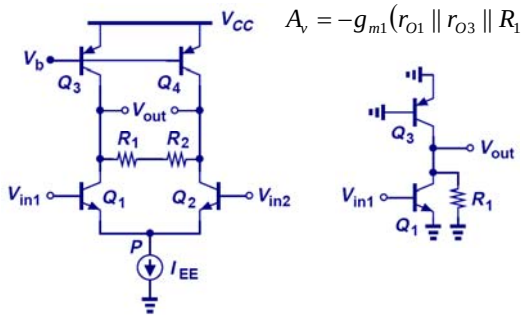



$$\frac{v_{out1} - v_{out2}}{v_{in1} - v_{in2}} = -g_m r_O$$



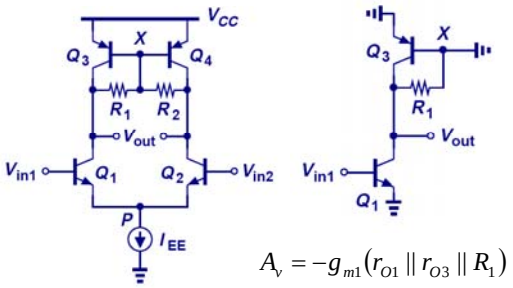
## Half Circuit Example 2

$$A_v = -g_{m1}(r_{O1} \| r_{O3} \| R_1)$$



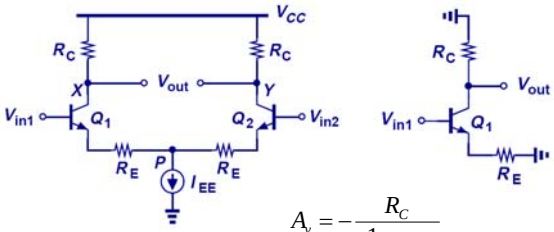



## Half Circuit Example 3




$$A_v = -g_{m1}(r_{O1} \| r_{O3} \| R_1)$$

## Half Circuit Example 4




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



## 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.