Lecture 22

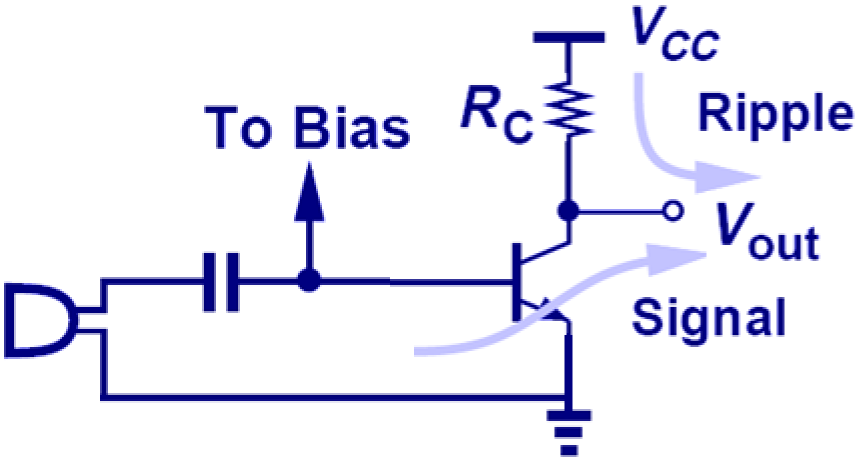
OUTLINE

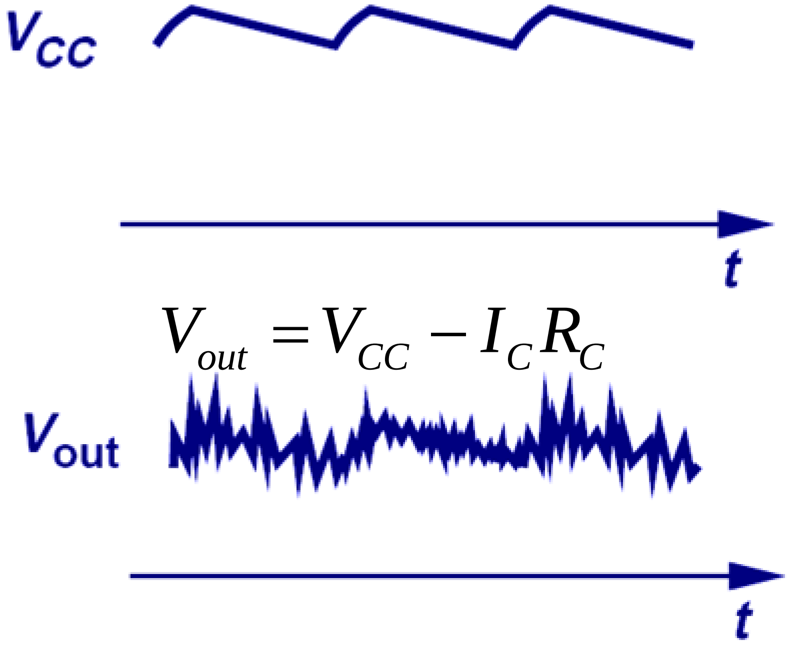
- Differential Amplifiers
  - General considerations
  - BJT differential pair
    - Qualitative analysis
    - Large-signal analysis
    - Small-signal analysis
    - Frequency response

- 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.

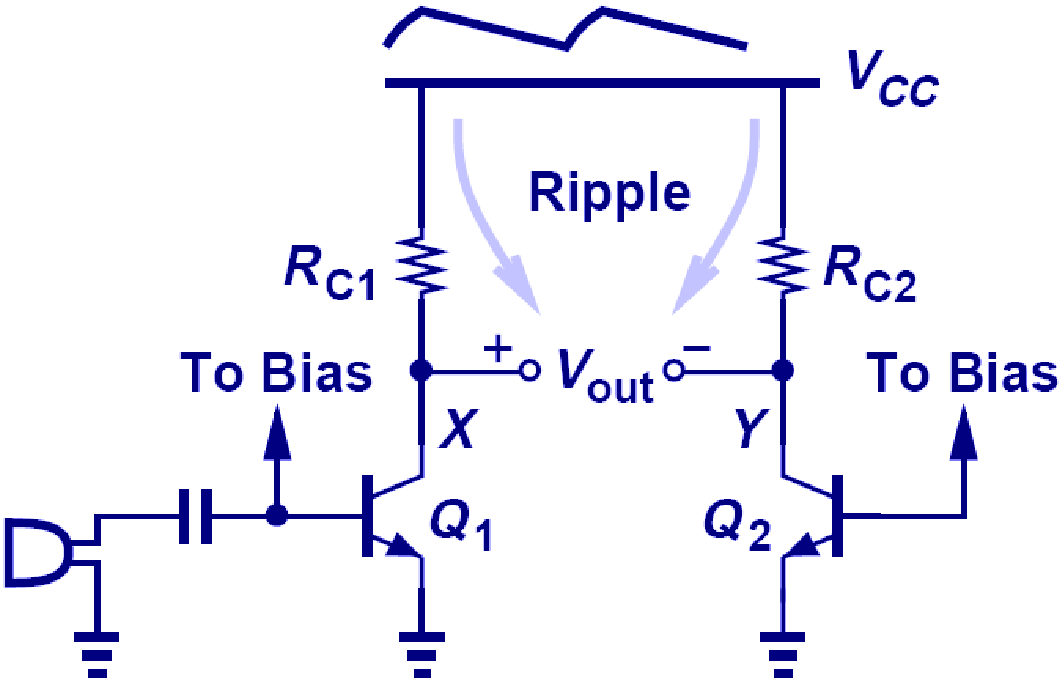




$$V_{out} = V_{CC} - I_C R_C$$

Supply Ripple Rejection

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



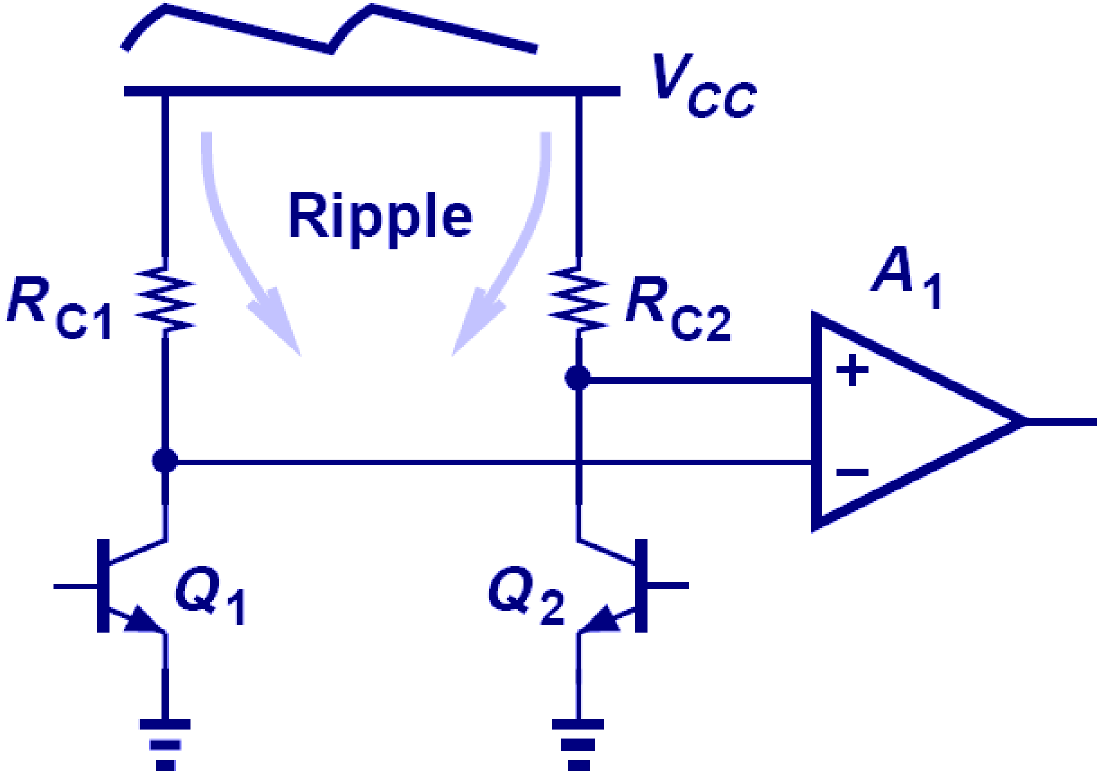
$$v_X = A_v v_{in} + v_r$$

$$v_Y = v_r$$

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

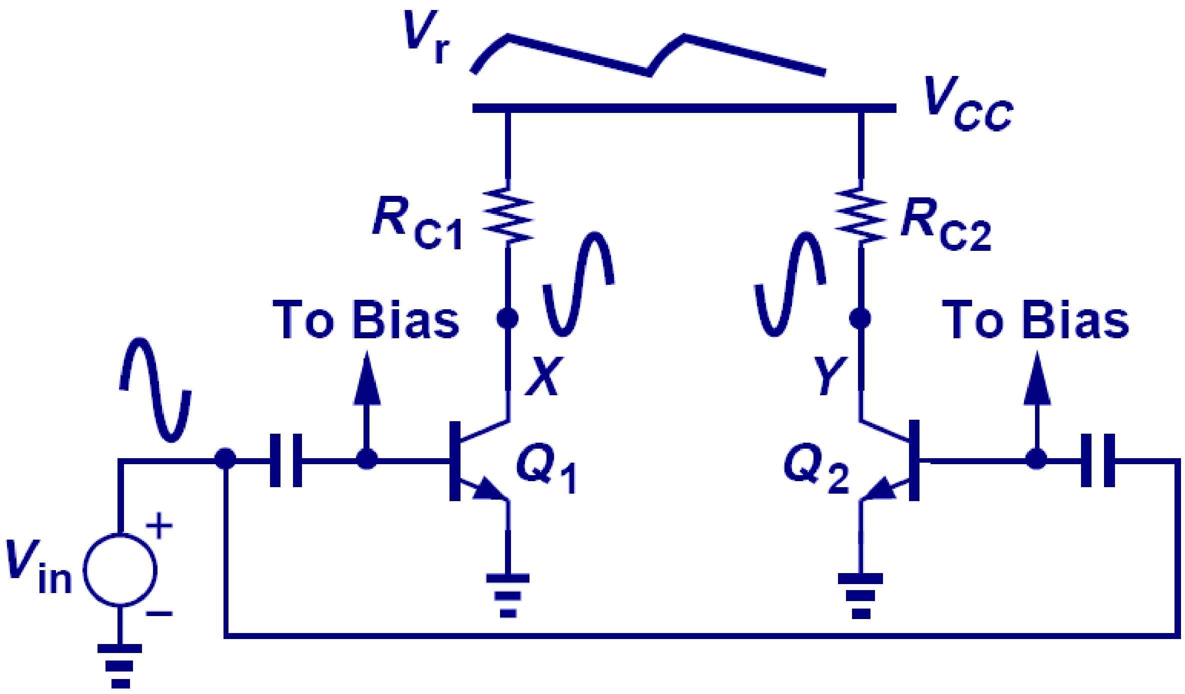
Ripple-Free Differential Output

- 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.



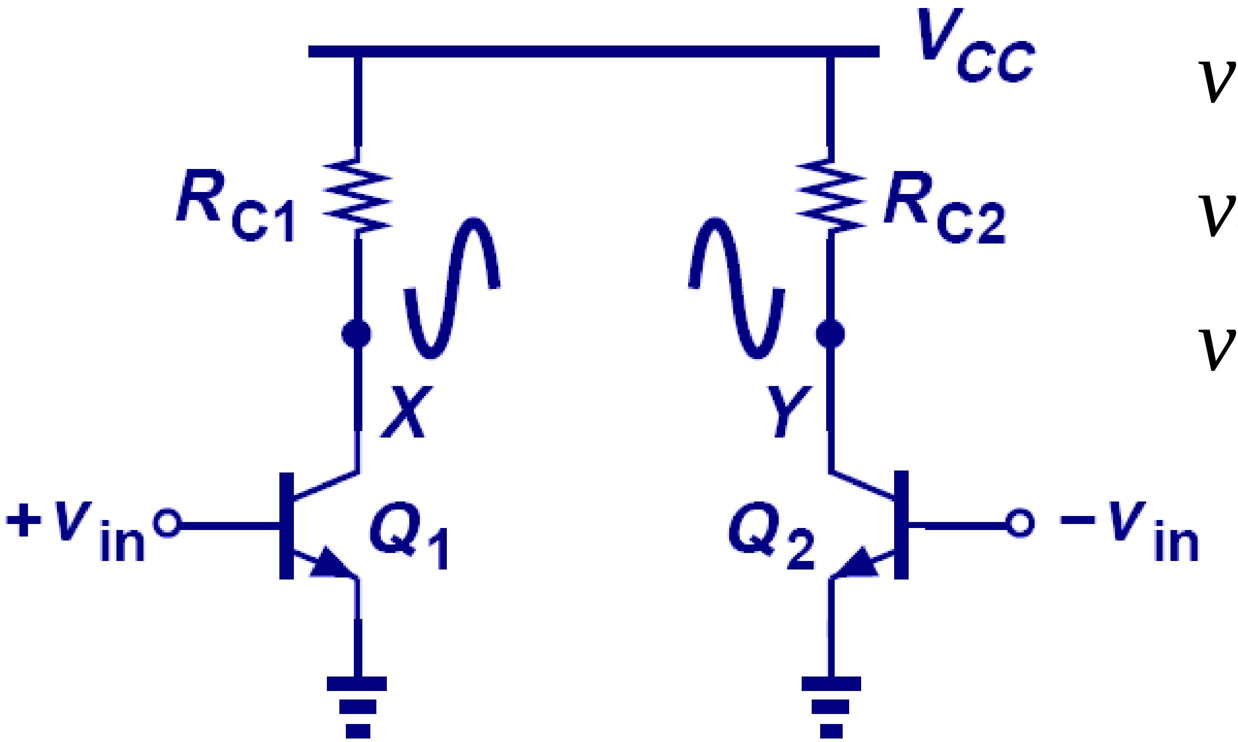
$$v_X = A_v v_{in} + v_r$$

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

$$v_X - v_Y = 0$$

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.



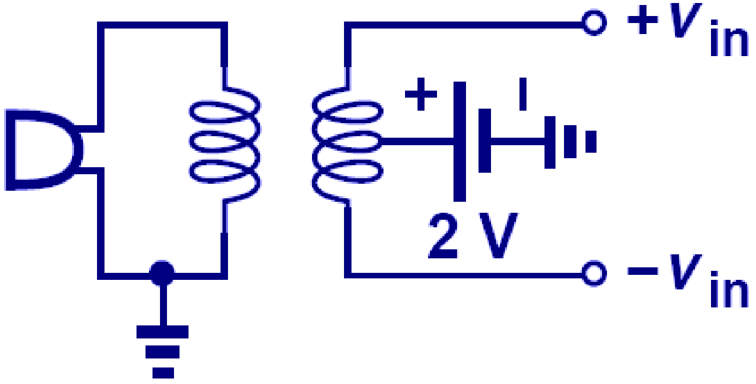
$$v_X = A_v v_{in} + v_r$$

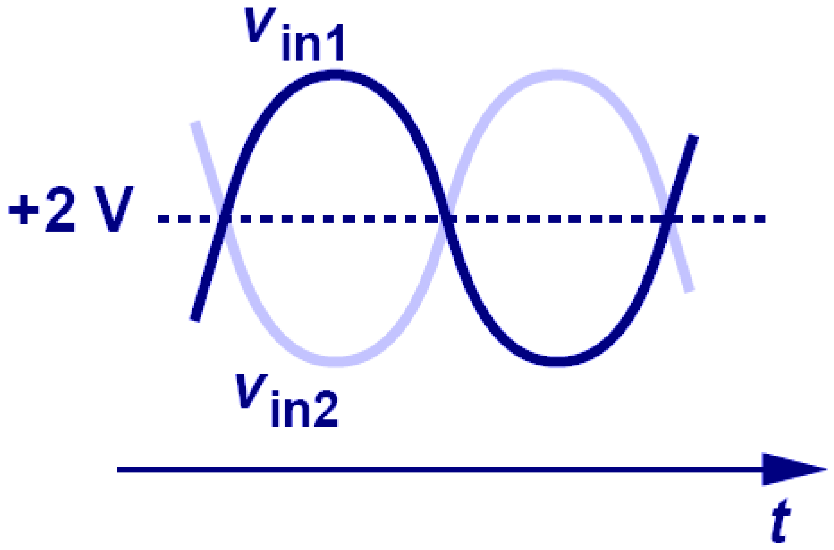
$$v_Y = -A_v v_{in} + v_r$$

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

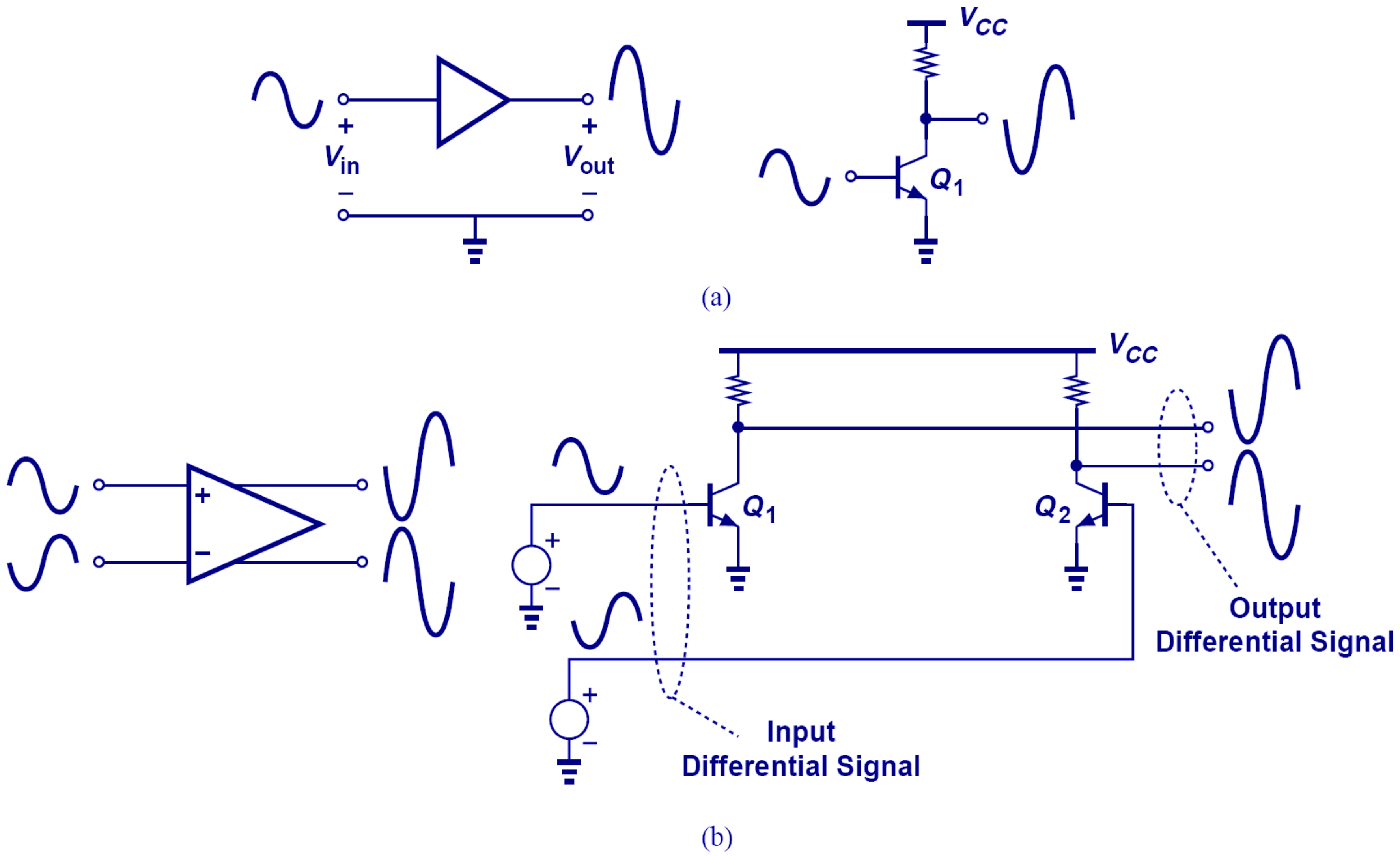
Differential Signals

- 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.

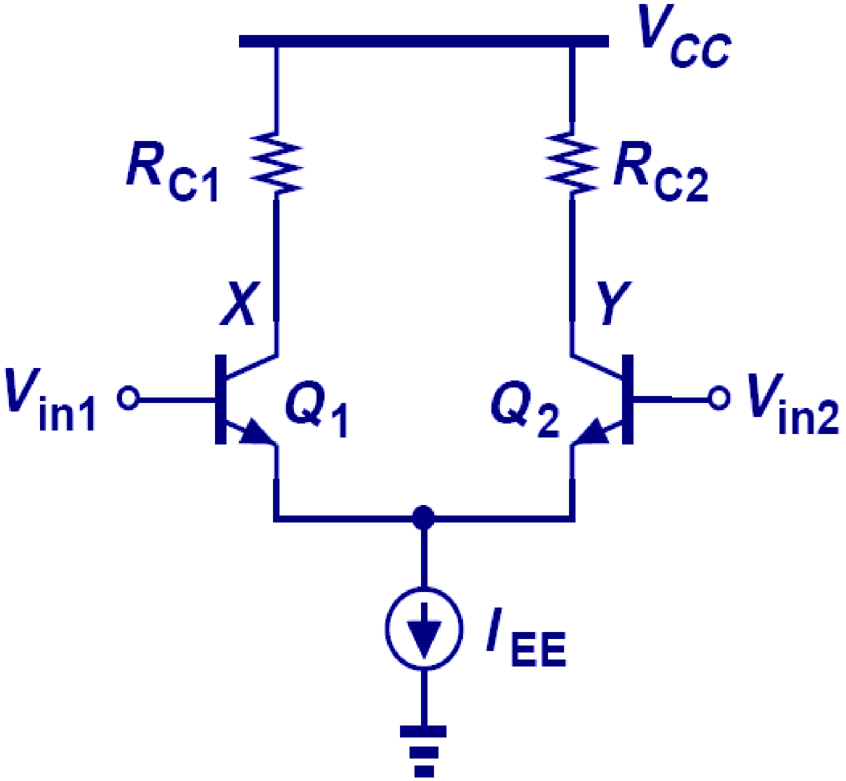


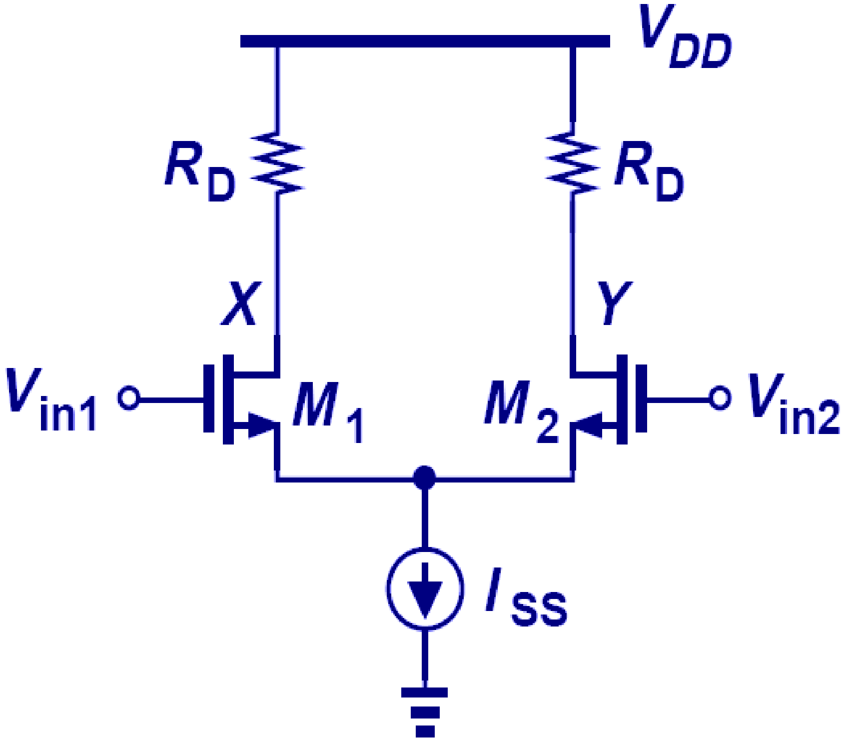


Single-Ended *vs*. Differential Signals



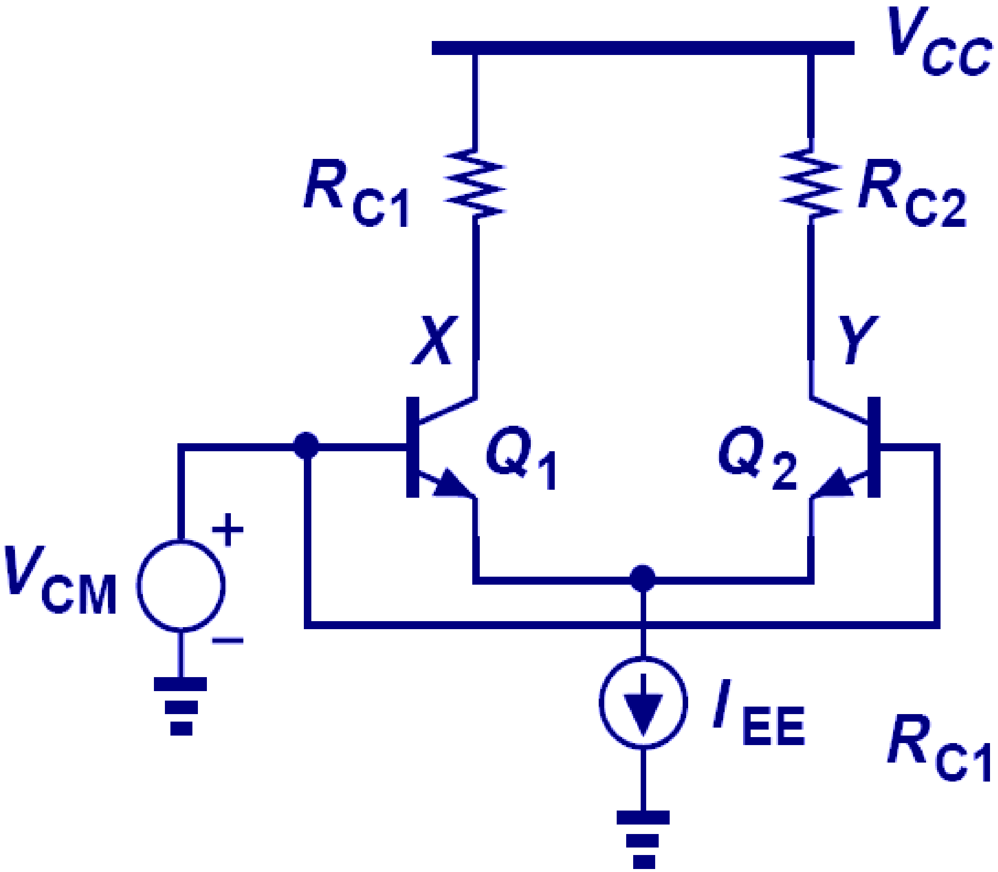
Differential Pair





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

Common-Mode Response



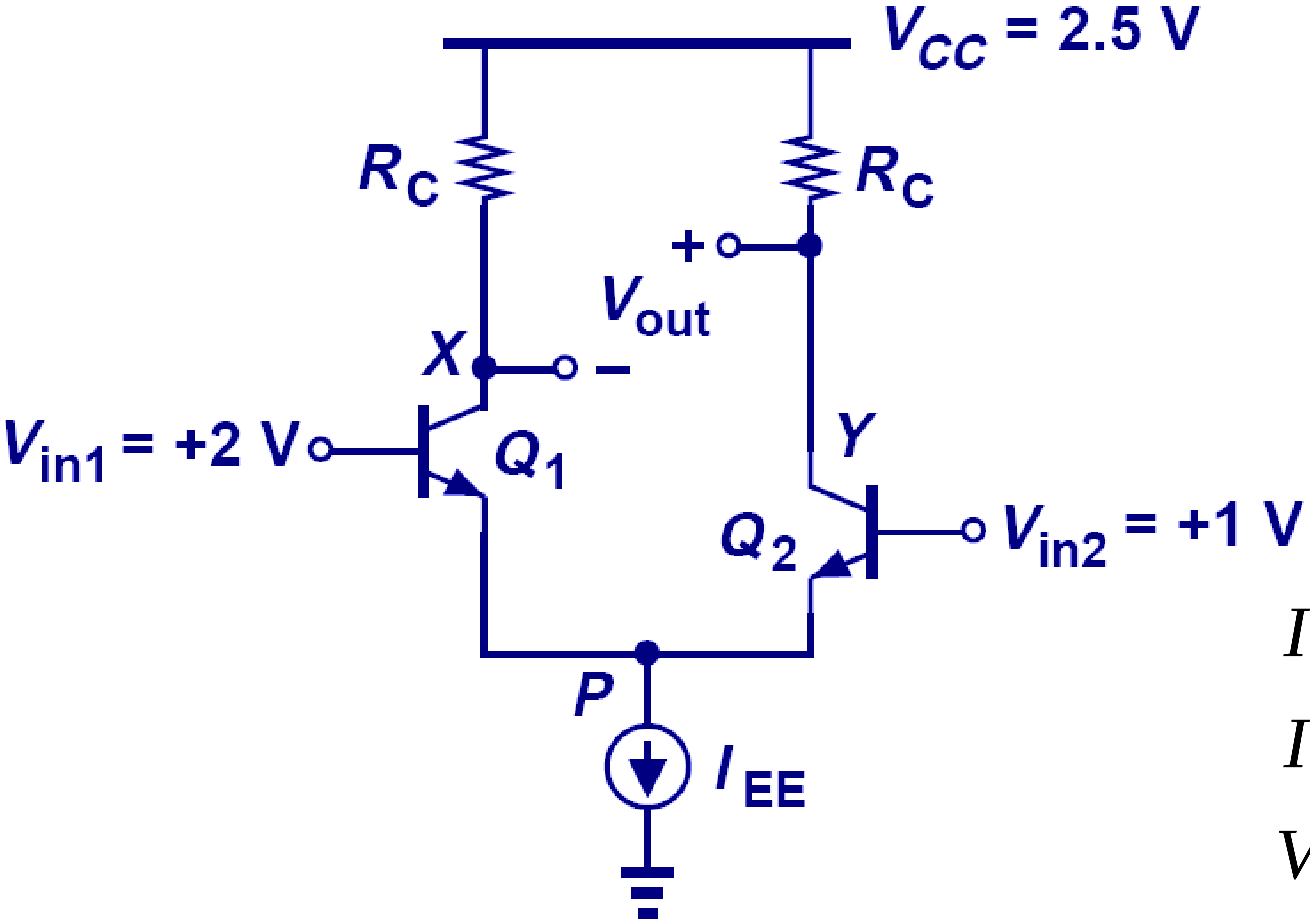
$$V_{BE1} = V_{BE2}$$

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

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

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

Differential Response



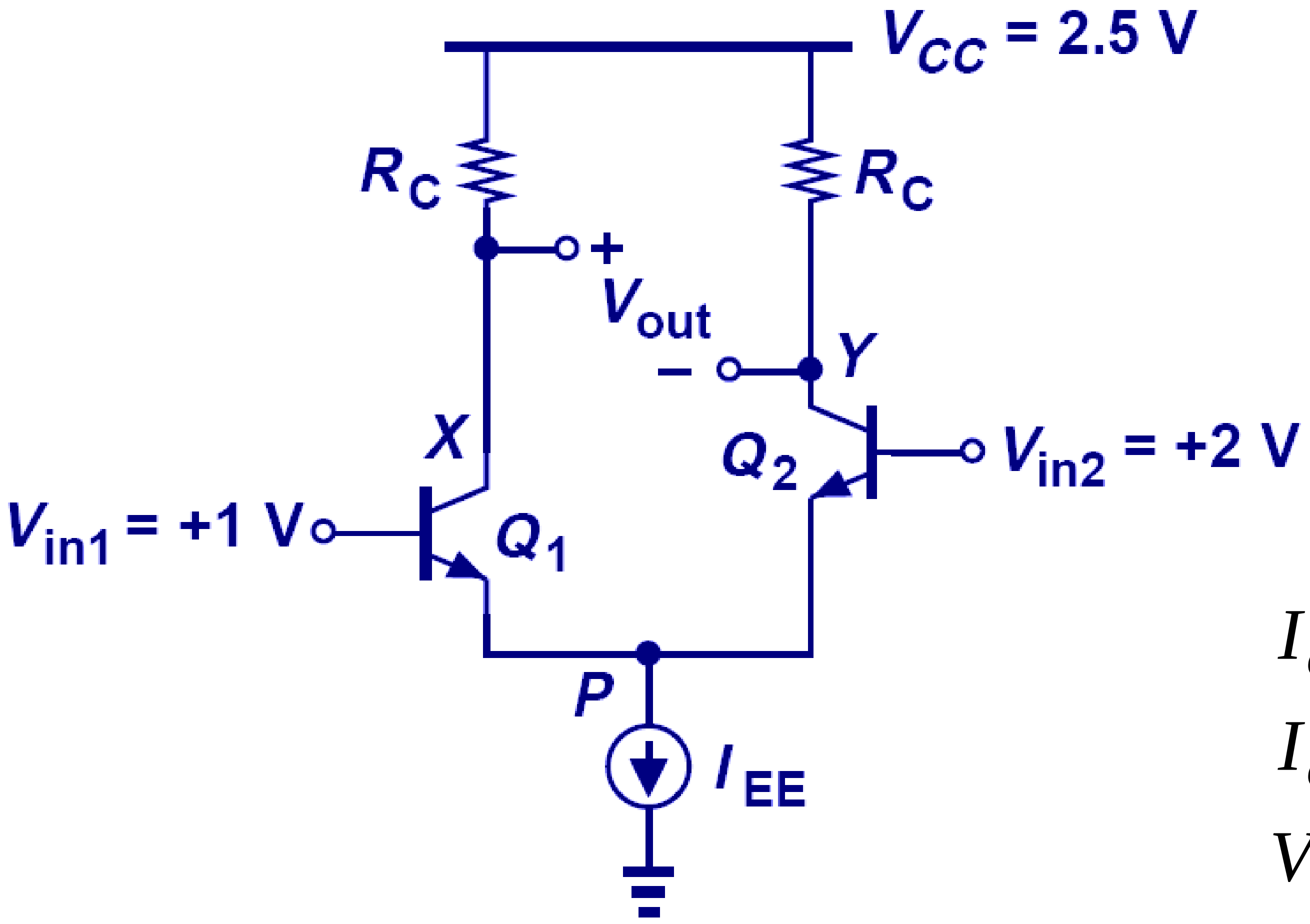
$$I_{C1} = I_{EE}$$

$$I_{C2} = 0$$

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

$$V_Y = V_{CC}$$

Differential Response (cont’d)



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

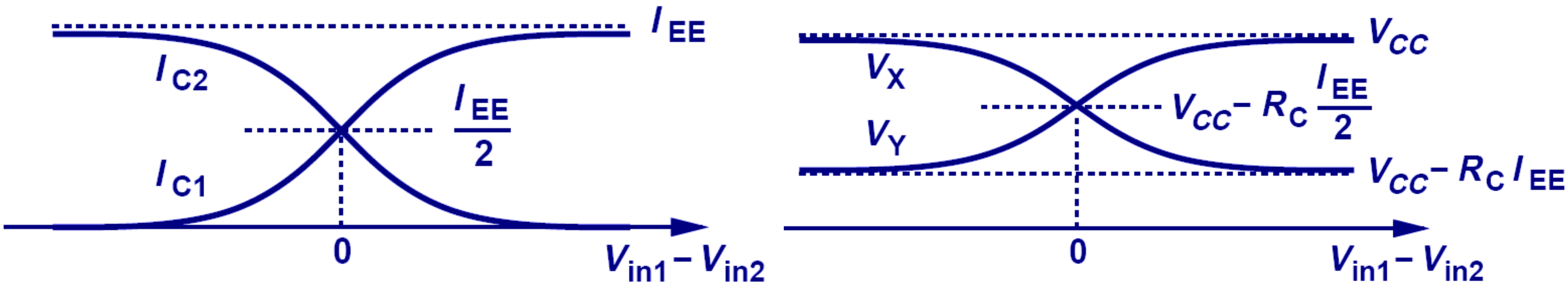
$$I_{C1} = 0$$

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

$$V_X = V_{CC}$$

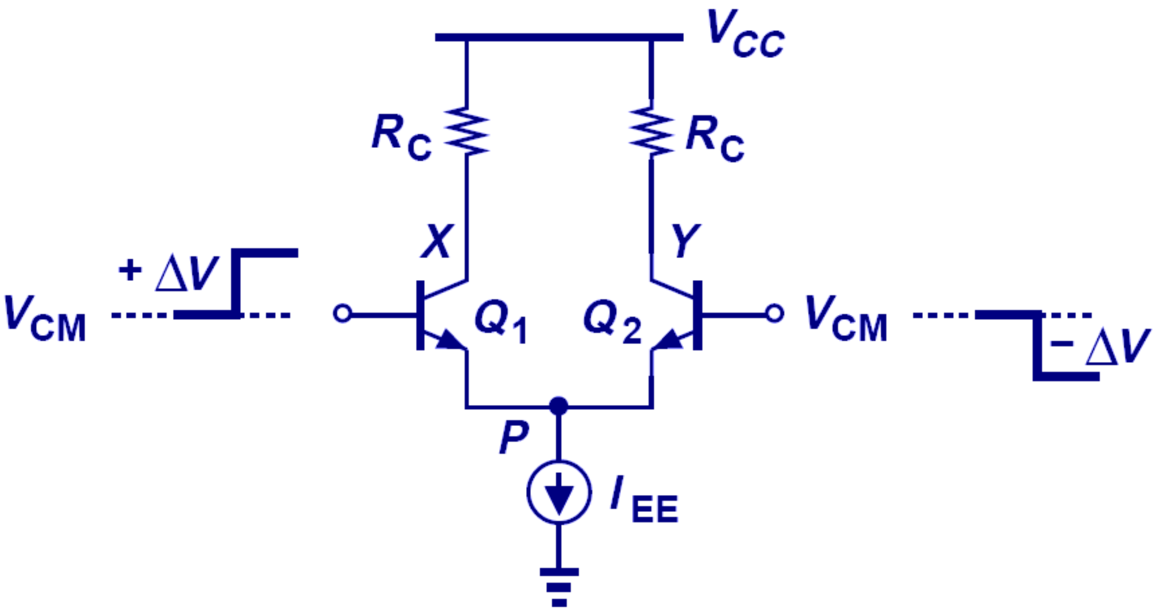
Differential Pair Characteristics

- 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 (+ΔV and -ΔV), 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.



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

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

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

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

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

$$\Rightarrow \Delta V_P = 0$$

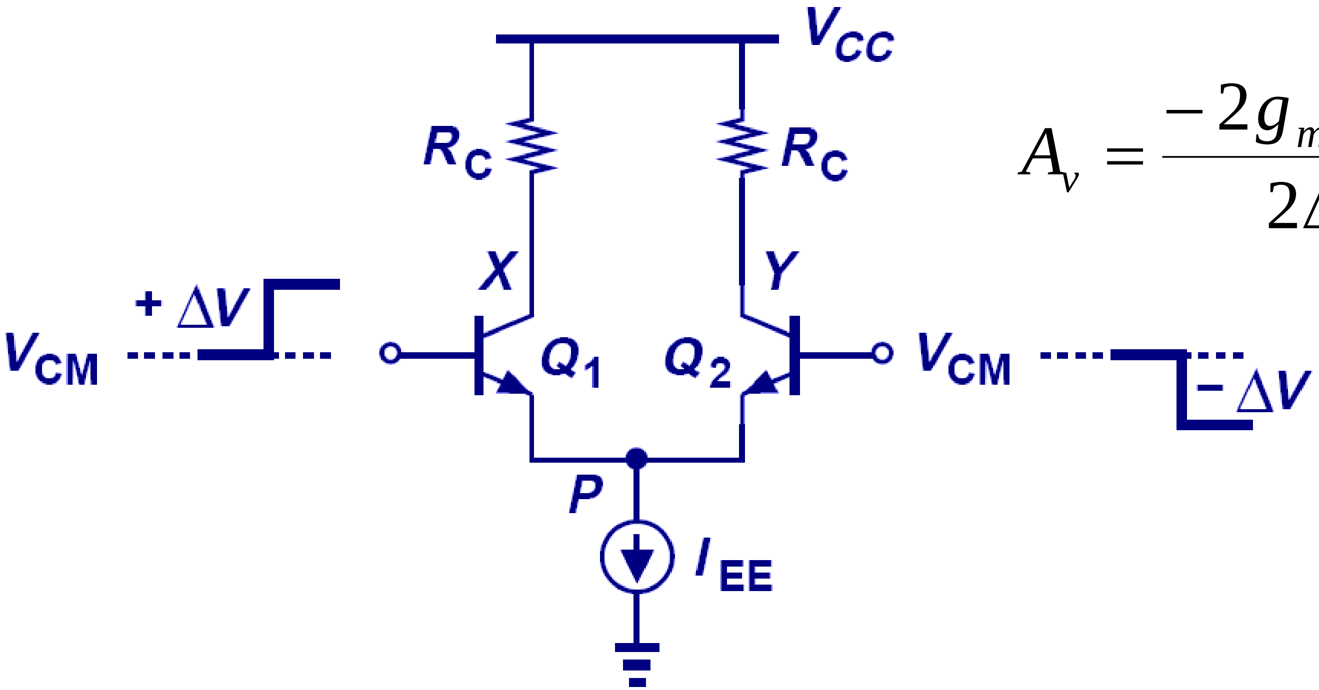
Extension of Virtual Ground

- 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.

$$v_X = 0$$

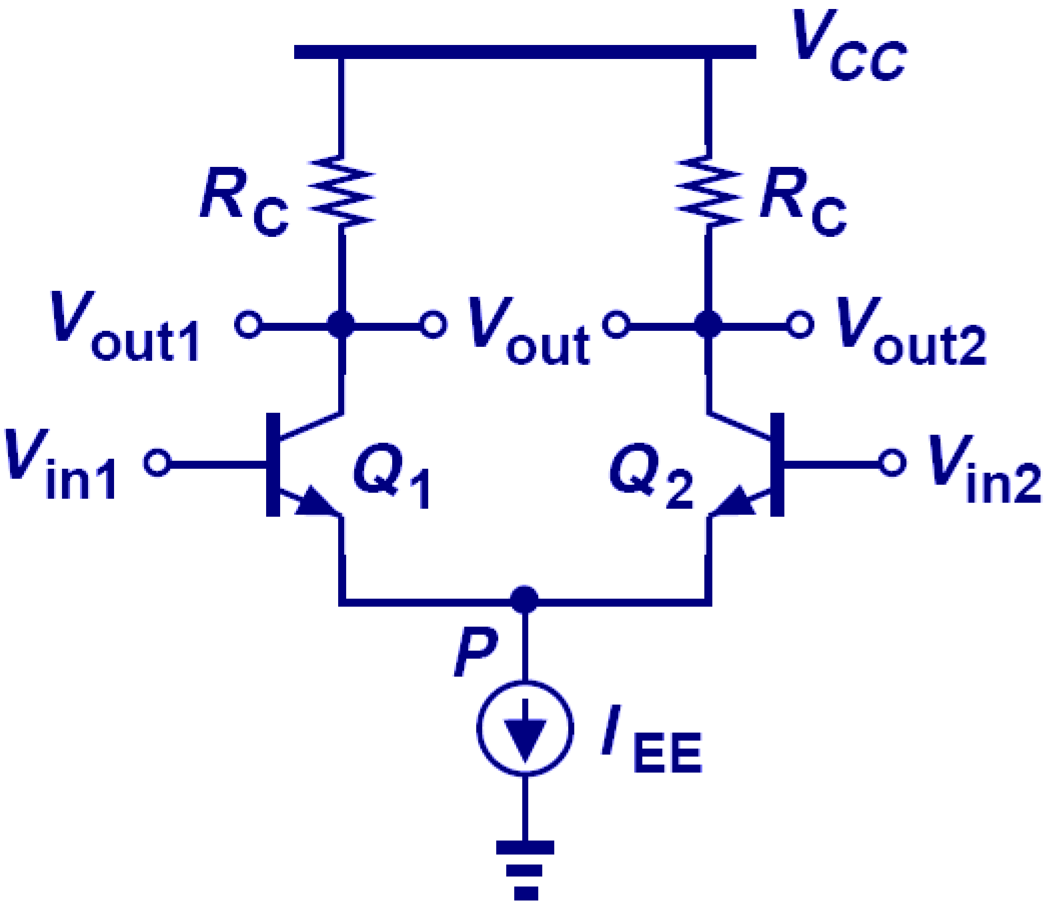
Small-Signal Differential Gain

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



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

Large-Signal Analysis



$$V_{in1} - V_{in2} = V_{BE1} - V_{BE2}$$

$$= V_T \ln\left(\frac{I_{C1}}{I_S}\right) - V_T \ln\left(\frac{I_{C2}}{I_S}\right)$$

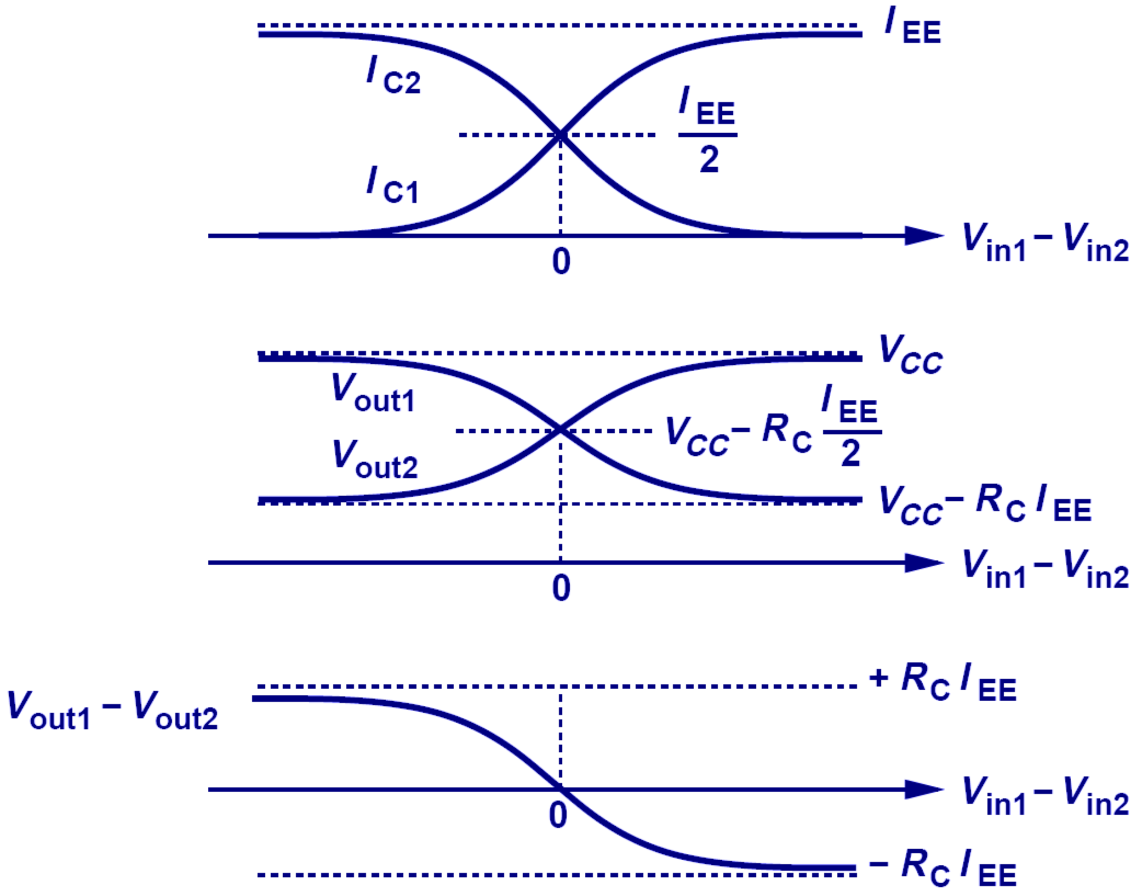
$$= V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right)$$

$$I_{C1} + I_{C2} = I_{EE}$$

$$I_{C1} = \frac{I_{EE} e^{\frac{V_{in1}-V_{in2}}{V_T}}}{1 + e^{\frac{V_{in1}-V_{in2}}{V_T}}}$$

$$I_{C2} = \frac{I_{EE}}{1 + e^{\frac{V_{in1}-V_{in2}}{V_T}}}$$

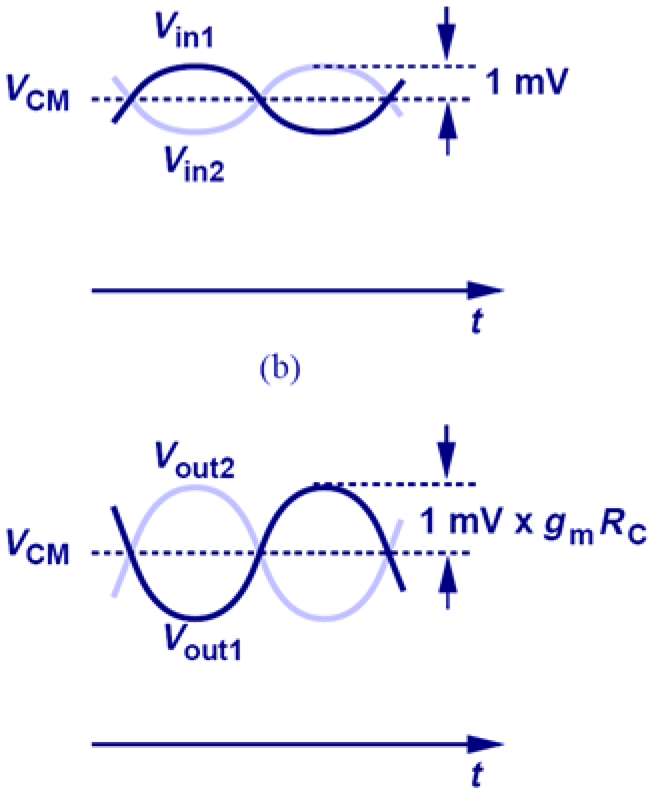
Input/Output Characteristics



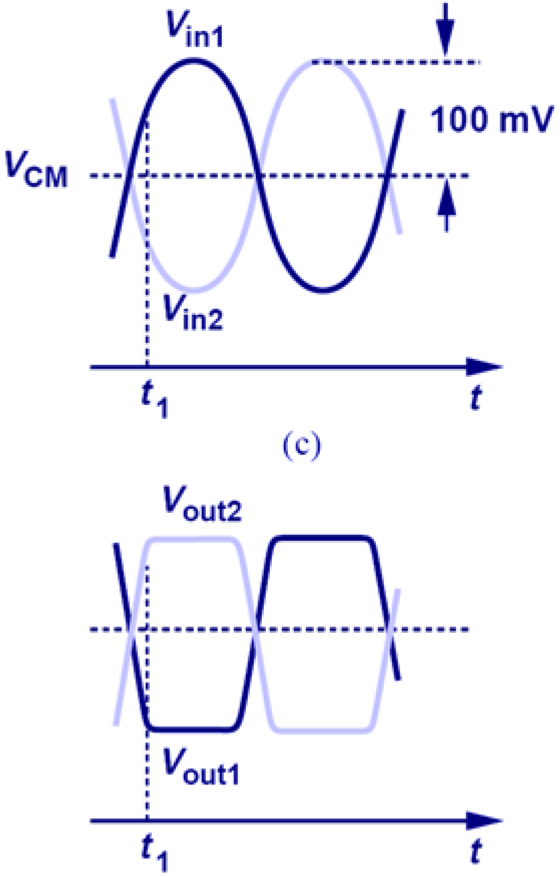
$$
\begin{aligned}
&V_{out1} - V_{out2} \\
&= (V_{CC} - I_{C1}R_C) \\
&\quad - (V_{CC} - I_{C2}R_C) \\
&= \left(I_{C2} - I_{C1}\right) R_C \\
&= -R_C I_{EE} \tanh\left(\frac{V_{in1} - V_{in2}}{2V_T}\right)
\end{aligned}
$$

Linear/Nonlinear Regions of Operation

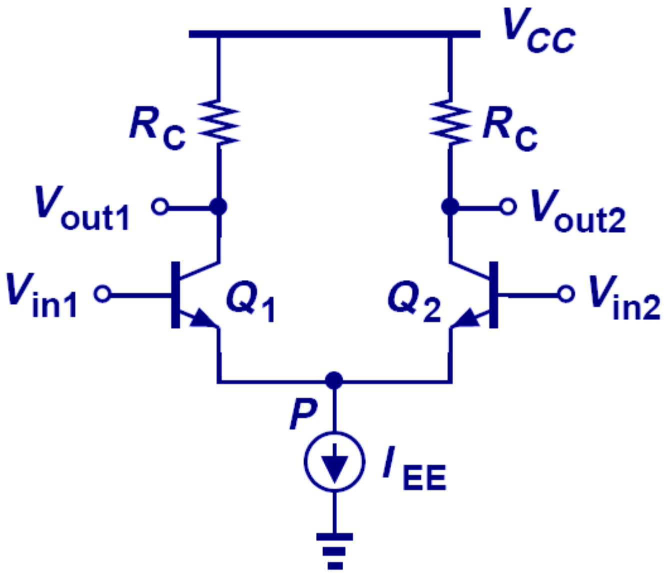
Amplifier operating in linear region

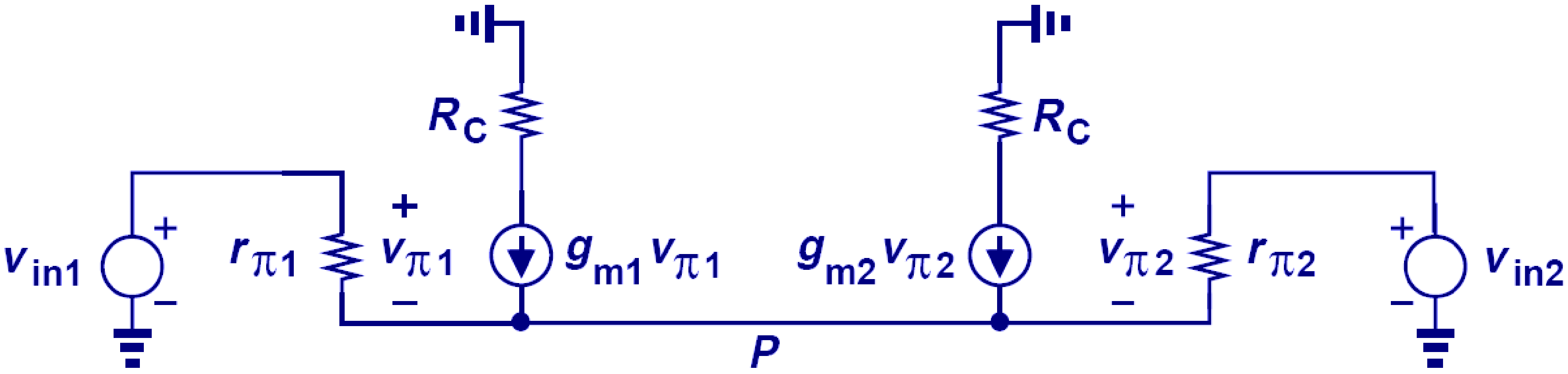


Amplifier operating in non-linear region



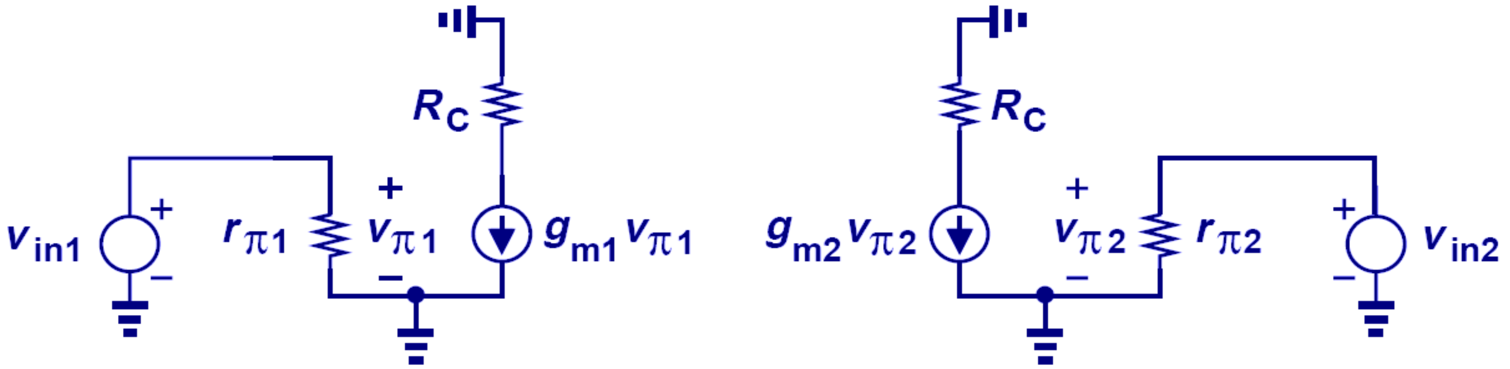
Small-Signal Analysis



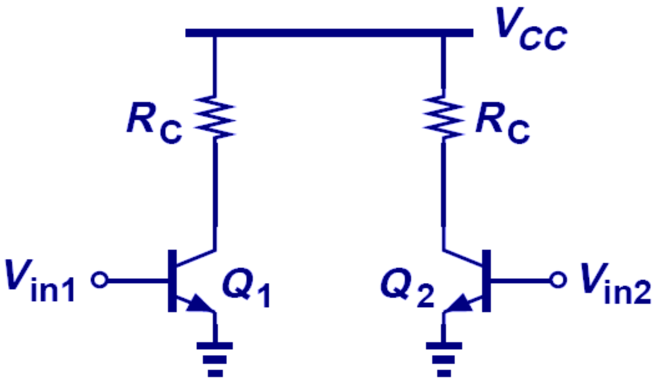


Half Circuits

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



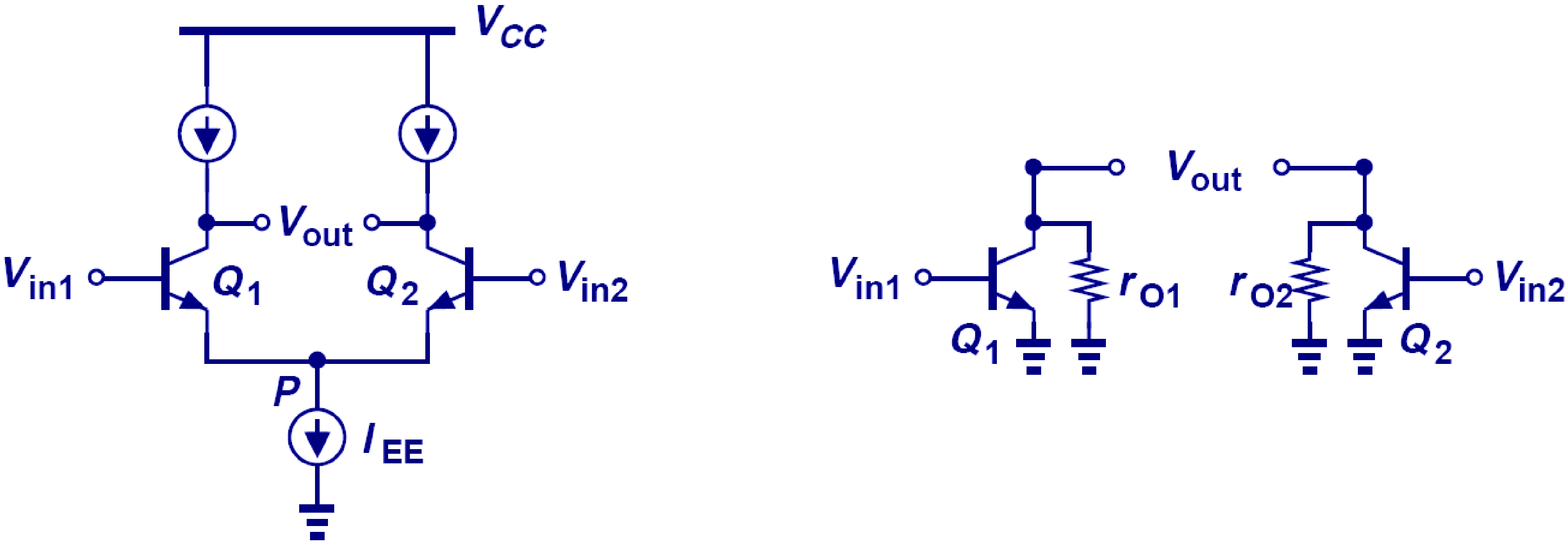
(b)



(c)

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

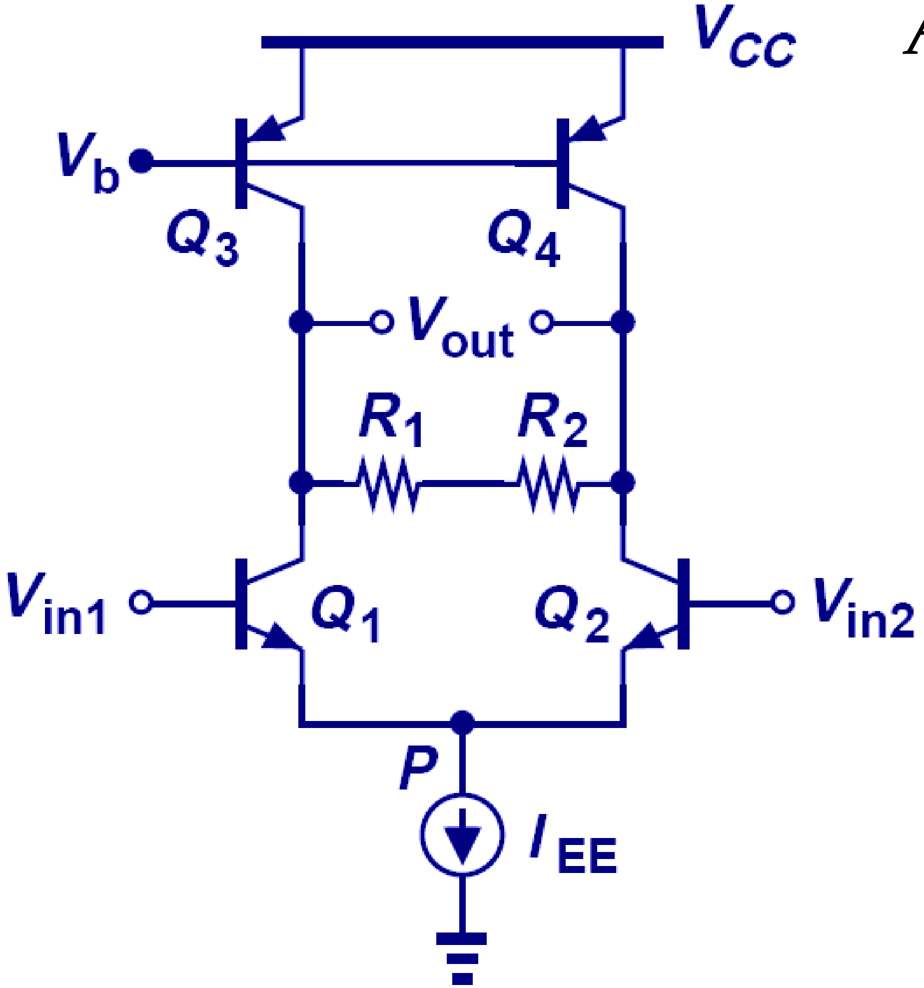
Half Circuit Example 1

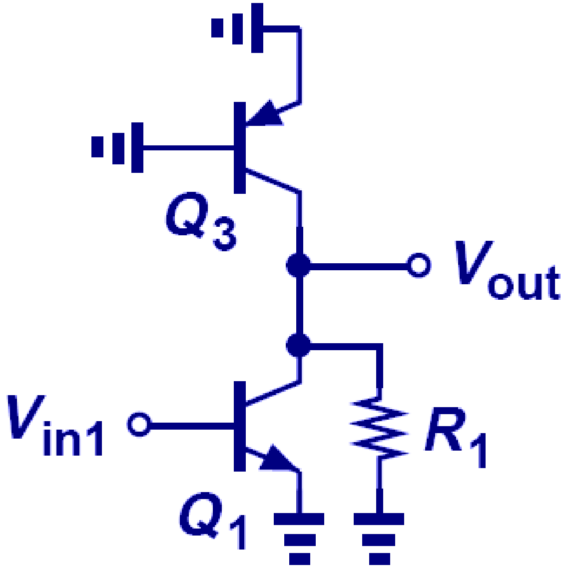


$$\frac{v_{out1} - v_{out2}}{v_{in1} - v_{in2}} = -g_m r_O$$

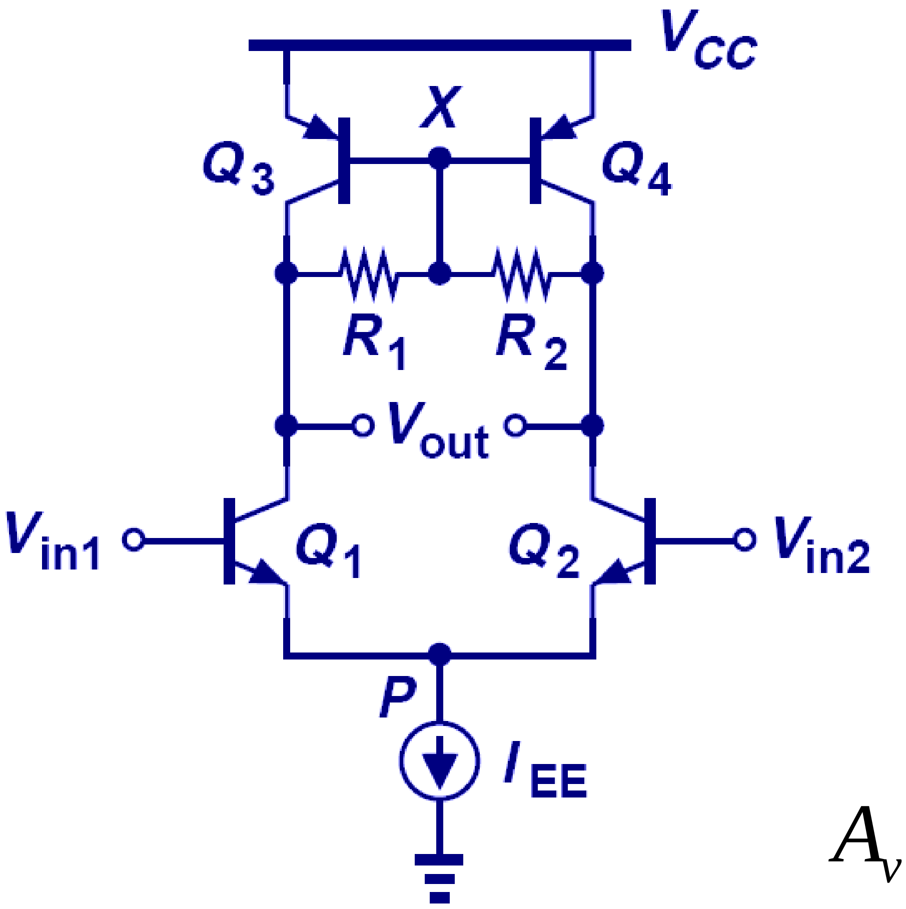
Half Circuit Example 2

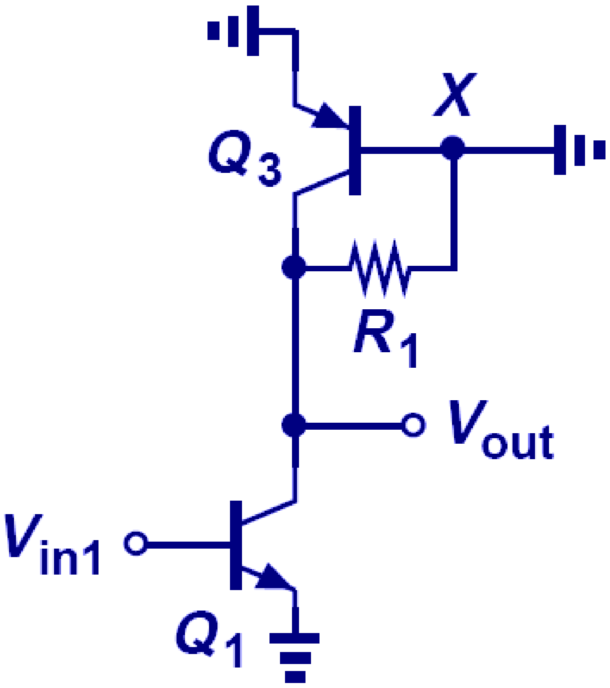
$$A_v = -g_{m1}\left(r_{O1} \parallel r_{O3} \parallel R_1\right)$$





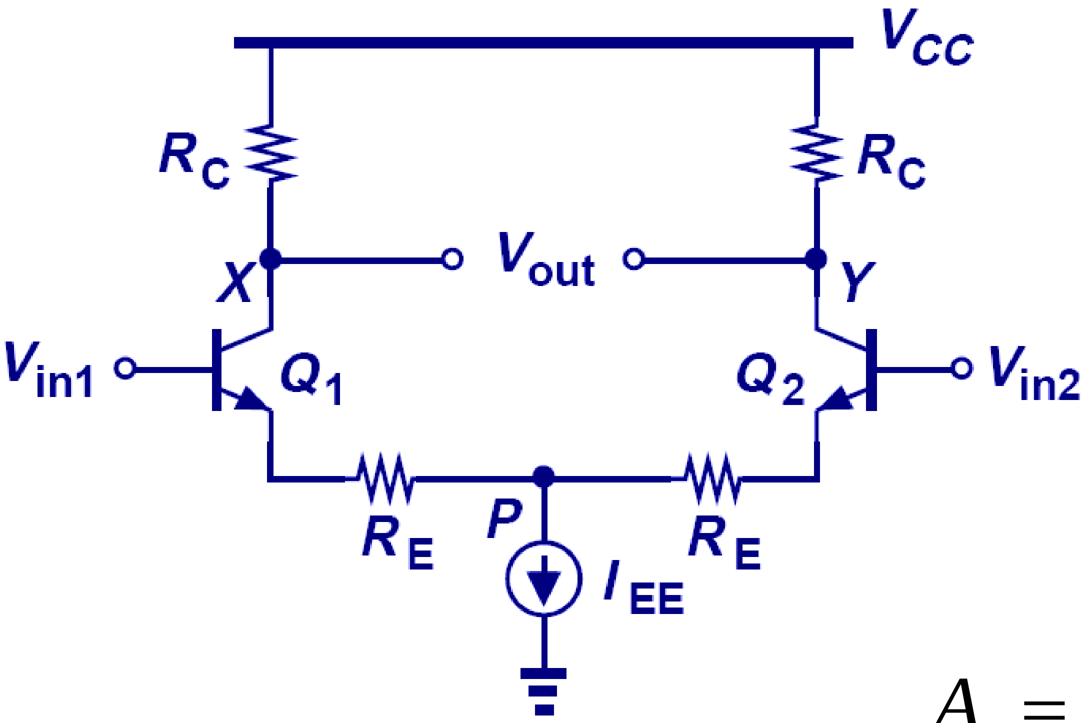
Half Circuit Example 3

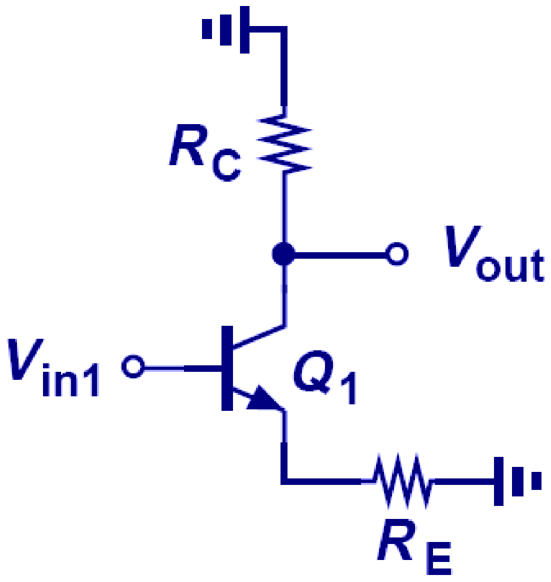




$$A_v = -g_{m1}\left(r_{O1} \parallel r_{O3} \parallel R_1\right)$$

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.