Lecture 30 (replaces previous lectures 28, 29 and 30)

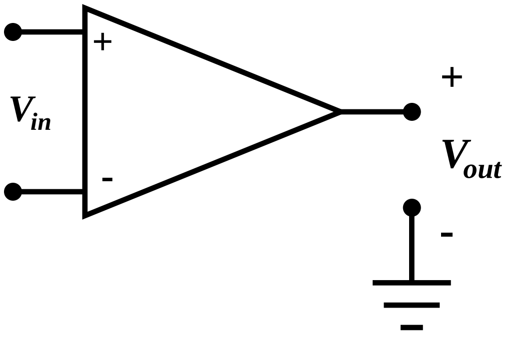
Feedback in Amplifiers and Differential Amplifiers

Reading: Jaeger 15.1-15.3 and Notes

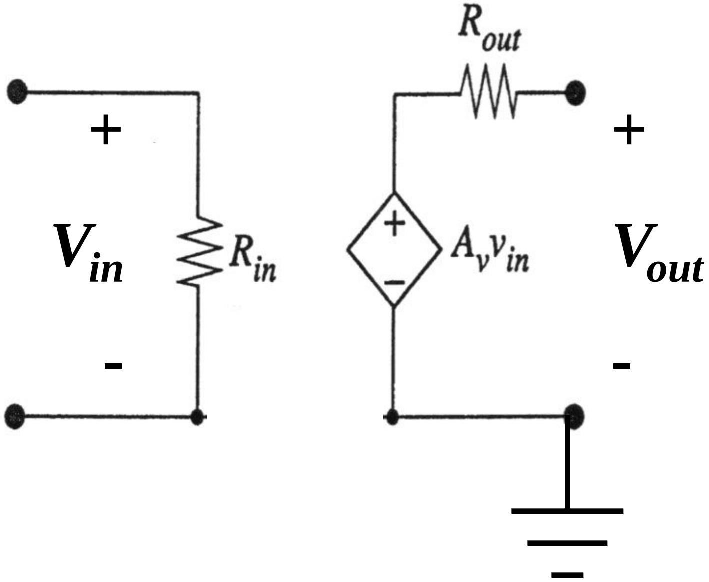
“System/Functional Level” Differential Amplifiers

- An operational Amplifier or “Op-Amp” is a multistage amplifier that is used for general electrical signal manipulation.
- The numbers of applications possible with Op-amps are two numerous to list.
- Most everyone agrees: “Op-Amp analysis is significantly easier than transistor analysis.”
- Though they are often internally complex and constructed of transistors and supporting components , their use in circuits most often simplifies the overall design.
- The circuit is modeled by an ideal voltage amplifier.

Circuit Symbol

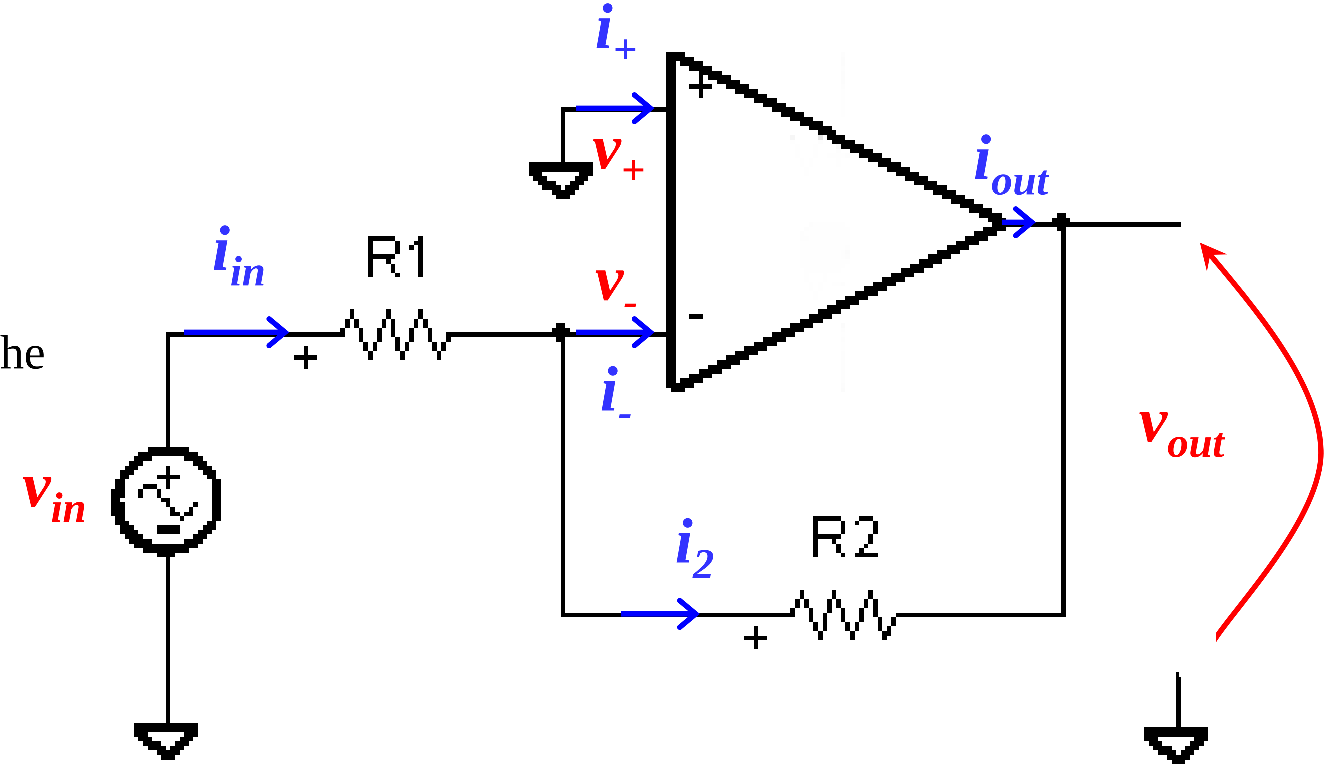


Model



Feedback's Role in Stabilizing an Operational Amplifier

- Large (or ideally infinite) gain means that the device is useless without adding "Feedback" to control the overall gain to a finite value.



- Consider the circuit to the right with v_{in}=0

$$v_{out} = A_v (v_+ - v_-)$$

If $A_v \to \infty$, the above equation is only satisfied for $(v_+ - v_-) = 0$

- Feedback forces the two input voltages to be equal! This is known as a "virtual ground".
- R1 and R2 form a "Feedback Network" with the amount of the output fed back to the input as β.
- β can be a function of frequency

Closed Loop Gain in Negative Feeback Amplifiers

- Real amplifiers do not have infinite “open loop” gain.
- By cascading stages, voltage gains are typically large but finite: ~10^4-10^6 V/V
- Finite gain causes a deviation from ideal amplifier behavior

$$v_{-} = v_{out}\frac{R_1}{R_1+R_2} = \beta v_{out}$$

$$\textit{where } \beta = \frac{R_1}{R_1+R_2} \text{ is known as the feedback factor}$$

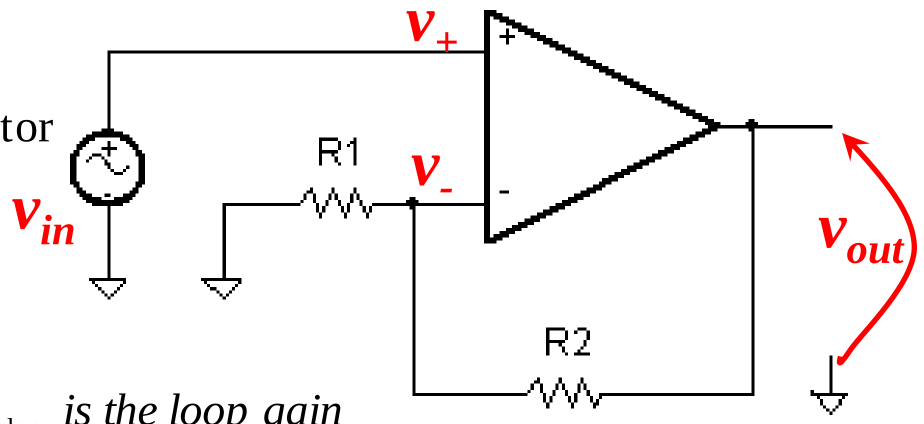
$$v_{out} = A_{openloop}\left(v_{+} - v_{-}\right) = A_{openloop}\left(v_{+} - \beta v_{out}\right)$$

$$\text{so since } v_{+} = v_{in},$$

$$A_{v,closedloop} = \frac{v_{out}}{v_{in}} = \frac{A_{openloop}}{1+\beta A_{openloop}}, \textit{ where } \beta A_{openloop} \textit{ is the loop gain}$$

$$\textit{If} \quad \beta A_{openloop} >> 1$$

$$A_{v,closedloop} = \frac{1}{\beta} = 1 + \frac{R_2}{R_1} \quad \Rightarrow \quad \text{approaches the infinite gain result}$$



Effects of Negative Feedback (Closed Loop Gain) in Amplifiers

- Closed-loop gain means the system Gain is reduced

$$\beta = \text{is known as the feedback factor}$$

$$A_{v,closedloop} = \frac{v_{out}}{v_{in}} = \frac{A_{openloop}}{1+\beta\, A_{openloop}},\ \textit{where } \beta\, A_{openloop} \textit{ is the loop gain}$$

Reduced Gain to a usable level

$$\textit{If} \quad \beta\, A_{openloop} >> 1$$

$$A_{v,closedloop} = \frac{1}{\beta} = 1 + \frac{R_2}{R_1} \quad \Rightarrow \quad \text{approaches the infinite gain result}$$

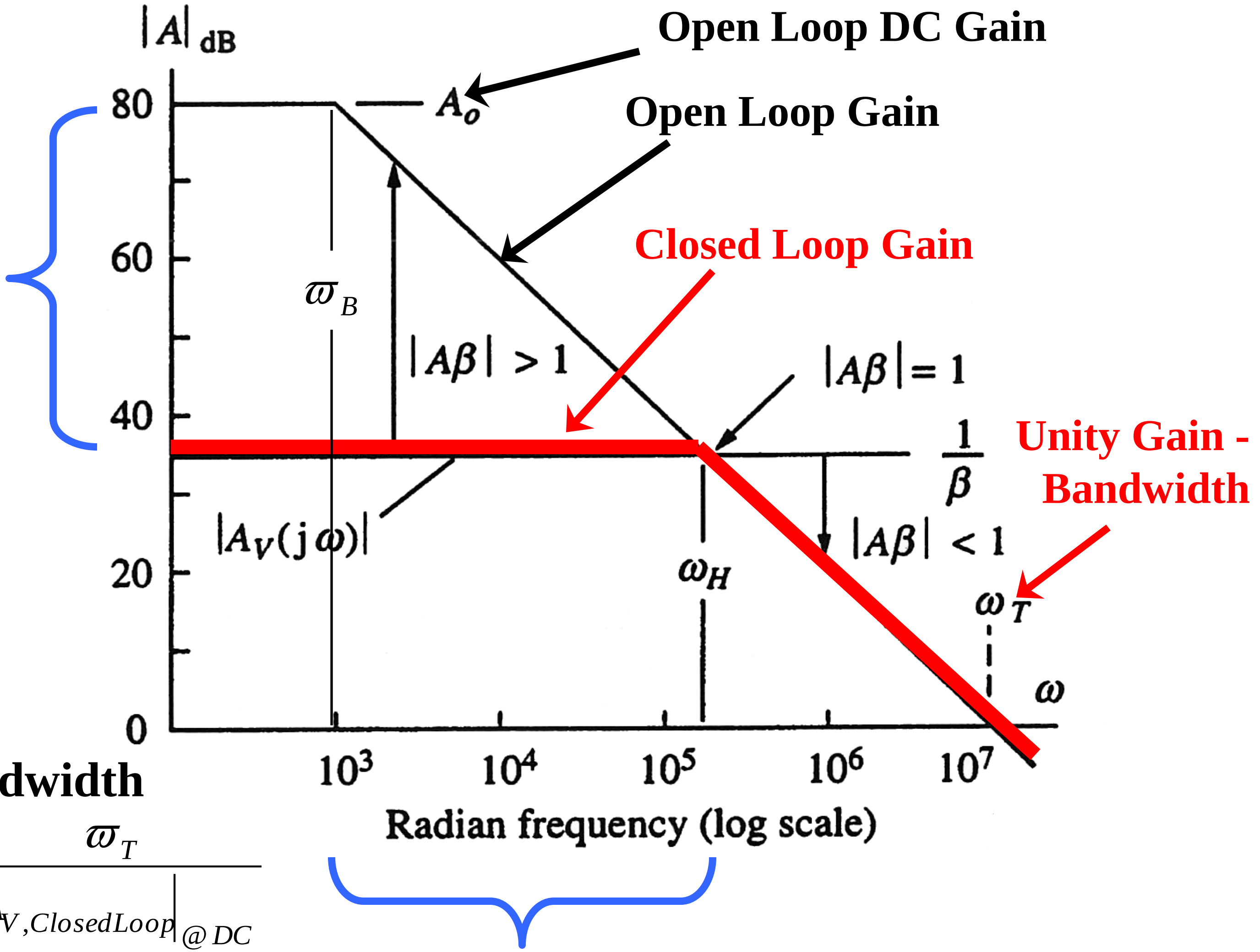
- Virtual Ground is not perfect!

$$v_+ - v_- = v_{in} - \beta v_{out} = v_{in} - \beta\left(\frac{A_{openloop}}{1+\beta\, A_{openloop}}\right)v_{in} = \frac{v_{in}}{1+\beta\, A_{openloop}}$$

Small but finite offset between + and - terminals

Feedback Amplifier Frequency Response

The closed Loop Amplifier has a lower gain than the Open Loop Amplifier



Open Loop DC Gain

Open Loop Gain

Closed Loop Gain

Unity Gain - Bandwidth

The closed Loop Amplifier has a higher bandwidth than the Open Loop Amplifier

Closed Loop Bandwidth

$$\varpi_H = \varpi_B\left(1+\beta A_O\right) = \frac{\varpi_T}{A_{V,ClosedLoop}\Big|_{@\,DC}}$$

Closed Loop DC Gain

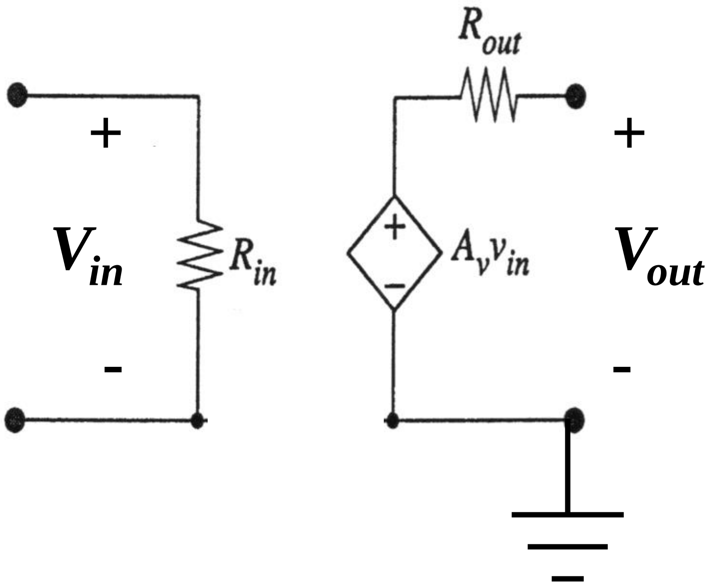
$$A_{V,ClosedLoop} = \frac{A_{OpenLoop}}{1+\beta\, A_{OpenLoop}}$$

Feedback Amplifier Input and Output Impedance

- Negative Feedback lowers the output impedance and raises the input impedance.

$$R_{outClosed} \cong \left(\frac{R_{outOpen}}{1 + A_{v,openloop}\beta} \right) \qquad R_{in\,Closed} \cong \left(1 + A_{v,openloop}\beta\right) R_{in\,Open}$$

Model



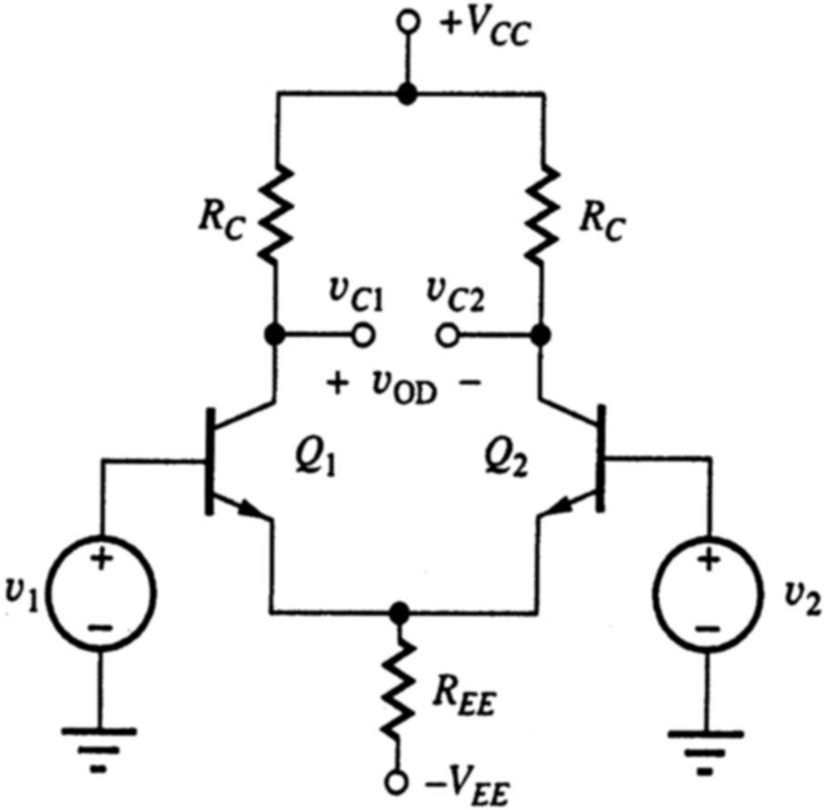
Negative Feedback is your Friend!

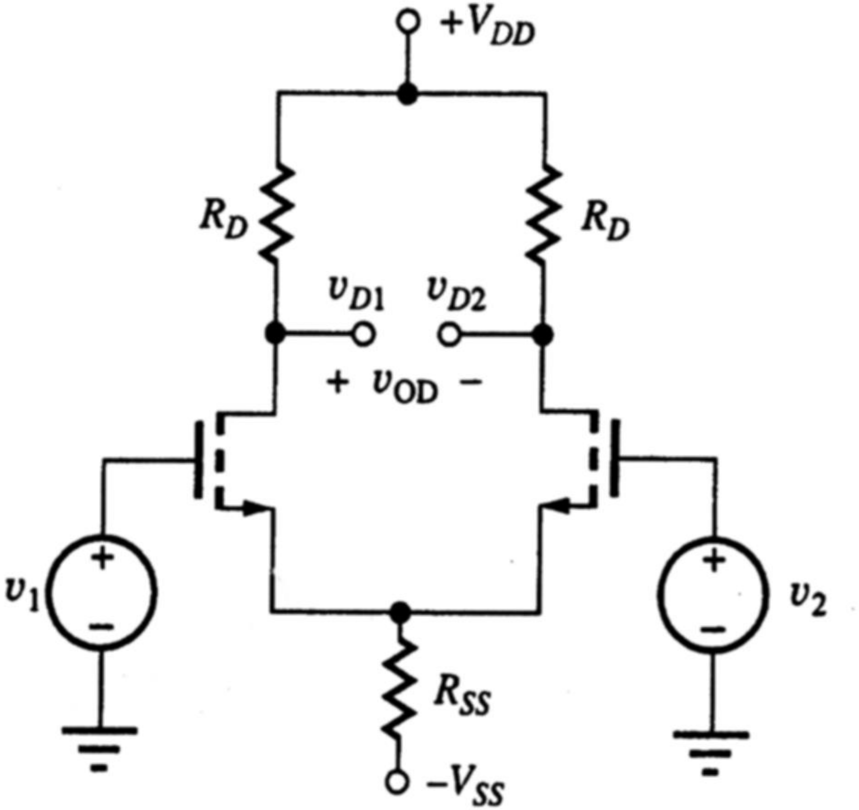
Differential Amplifiers

- To implement the operational amplifier, we need to have a circuit that can amplify the difference in two signals

- This can be used to remove unwanted signals common to both sources, such as:
  - Noise picked up on the input terminals.
    - Example: twisted pair telecom line: Both lines are exposed to the same noise sources. Thus, there is unwanted noise superimposed on the desired signal (voltage across the pair). We would like to amplify the desired “differential signal” while not amplifying the noise “common to both wires”.

Differential Amplifiers





The differential output voltage, v_{OD}, (difference in two collector/drain voltages) is the amplified difference of the two input signals

$$v_{OD}=A_{v\text{-}d}(v_1-v_2)$$

Differential Amplifiers

Q-Point: Assume "Matched Transistors" (identical parameters)

Set the time varying voltage sources to zero

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

From the Ebers-Moll model, $I_c=I_s e^{V_{BE}/V_T}$, $I_{C1}=I_{C2}=I_C$

$I_{E1}=I_{E2}=I_E$ and $I_{B1}=I_{B2}=I_B$

Thus,

$-V_{BE}=2I_E R_{EE}-V_{EE}$

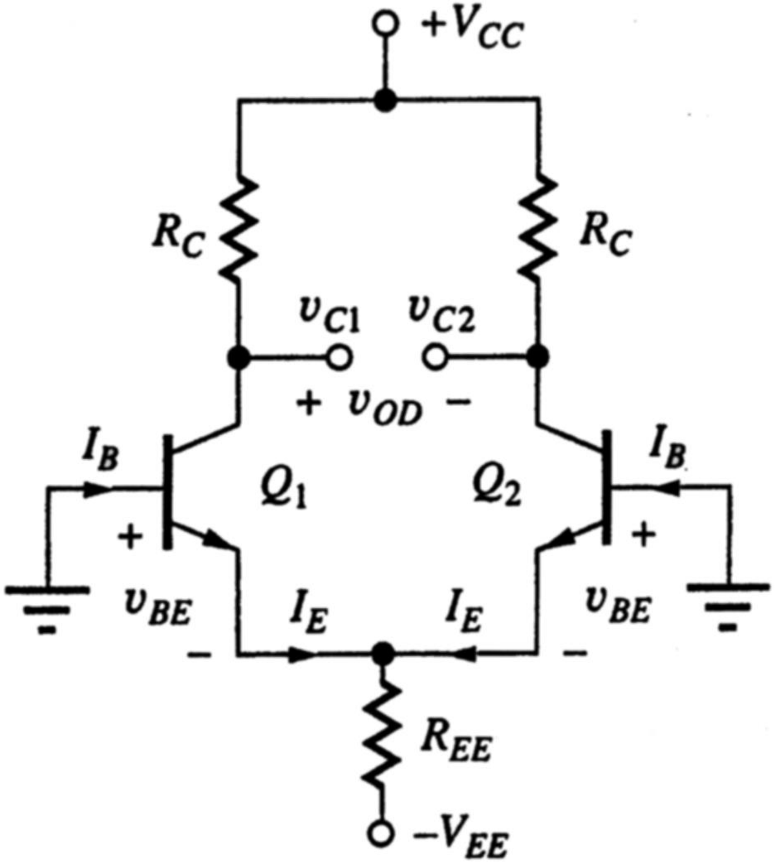
Or
$$I_E=\frac{V_{EE}-V_{BE}}{2R_{EE}}$$

$$I_C=\alpha\, I_E \quad and \quad I_B=\frac{I_C}{\beta}$$

$$and$$

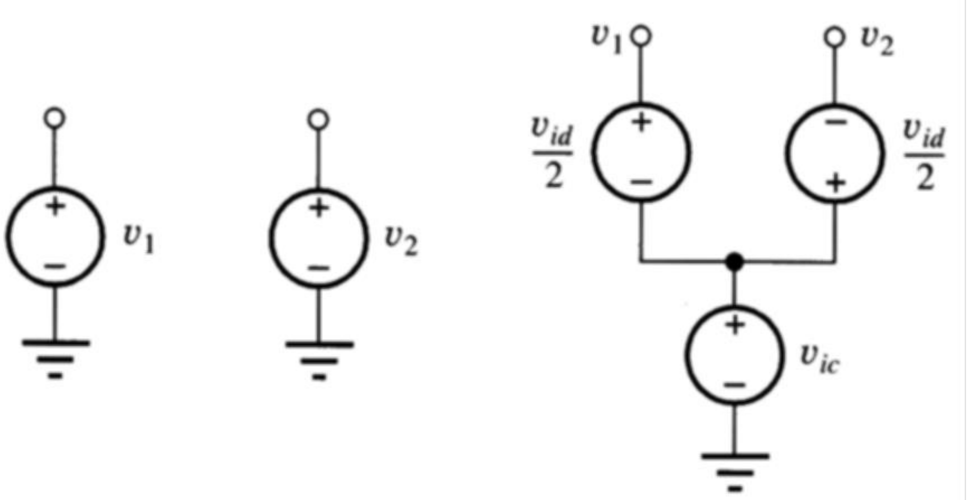
$$V_{C1}=V_{C2}=V_{CC}-I_C R_C$$

$$\Rightarrow V_{OD}=V_{C1}-V_{C2}=0V$$



See Jaeger Example 15.1 for a numerical example

Differential Amplifiers



For any arbitrary input voltage v_1 and v_2, we can construct an equivalent voltage consisting of:

Whatever voltage is common to both inputs, v_{ic}, =common mode voltage

$$v_{ic} = \frac{v_1 + v_2}{2}$$

A symmetric voltage $v_{id}/2$ = differential voltage as shown above.

$$v_{id} = v_1 - v_2$$

Example: v_1=10V, v_2=9V => v_{ic}=9.5V and v_{id}=1V (+/-v_{id}/2=+/-0.5V)

NOTE: In this example, the voltages are given as DC voltages but in general, they are time varying.

Differential Amplifiers

Use Superposition to solve for:

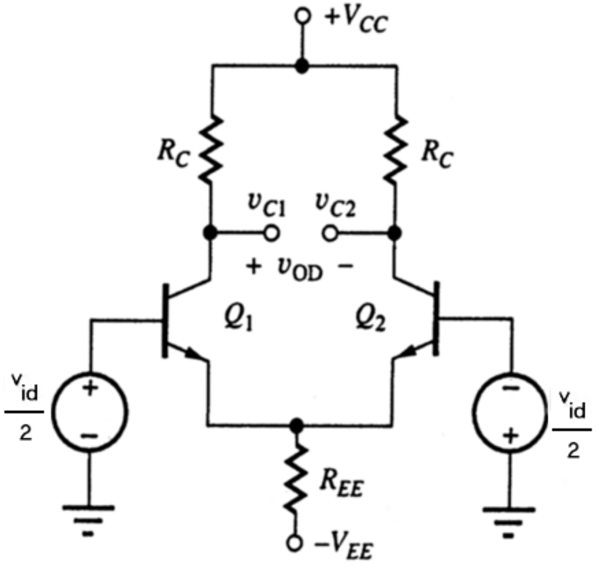
The Differential Mode Gain, $A_{dd}=v_{od}/v_{id}$

The Common Mode Gain, $A_{cc}=v_{oc}/v_{ic}$

Due to time constraints, we will only examine the behavior of this circuit and give the results but not solve these directly.

Differential Amplifiers

Differential Mode



How it works: If v_{id} increases from zero, i_{c1} and i_{e1} increase while i_{c2} and i_{e2} decrease by the same amount ($\Delta i_{c1}=-\Delta i_{c2}$). . Thus, the total current in R_{EE} remains constant making the emitter voltage v_e constant. The increase in i_{c1} lowers v_{c1} while the decrease in i_{c2} increases v_{c2} by the same amount ($\Delta v_{c1}=-\Delta v_{c2}$). Thus, the differential output voltage, $v_{OD}=v_{c1}-v_{c2}$ becomes negative (negative gain). We can define three useful gains (see Jaeger 15.3 for details).

$$A_{dd} = \left.\frac{v_{od}}{v_{id}}\right|_{v_{ic}=0} = -g_m R_C$$

Differential output: looks identical to a standard CE configuration

$$A_{dd1} = \left.\frac{v_{c1}}{v_{id}}\right|_{v_{ic}=0} = \frac{-g_m R_C}{2}$$

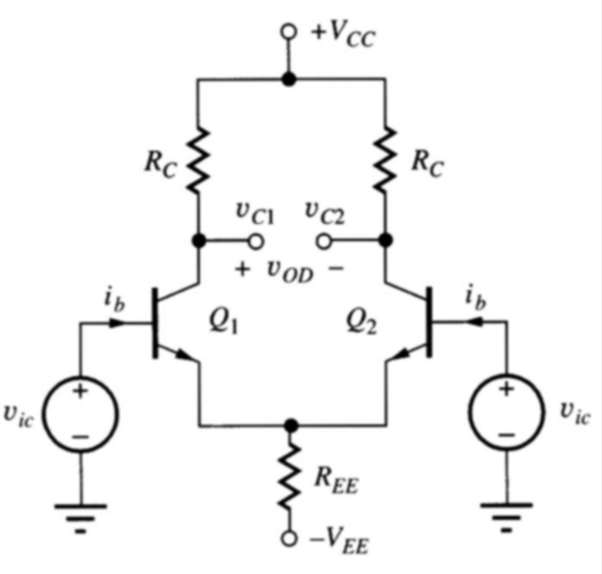
Single Ended Output off Q1: looks like a standard CE configuration divided by 2

$$A_{dd2} = \left.\frac{v_{c2}}{v_{id}}\right|_{v_{ic}=0} = \frac{g_m R_C}{2}$$

Single Ended Output off Q2: looks like a standard CE configuration divided by -2

Differential Amplifiers

Common Mode



How it works: If v_{ic} increases from zero, $i_{c1}$and i_{e1} increase as i_{c2} and i_{e2} increase by the same amount ($\Delta i_{c1}=\Delta i_{c2}$). . The increase in i_{c1} lowers v_{c1} while simultaneously the increase in i_{c2} lowers v_{c2} by the same amount ($\Delta v_{c1}=\Delta v_{c2}$). . Thus, the differential output voltage, $v_{OD}=v_{c1}-v_{c2}$ remains zero. We can define two useful gains (see Jaeger 15.3 for details).

$$\underbrace{A_{cd} = \left.\frac{v_{od}}{v_{ic}}\right|_{v_{id}=0} = 0}_{\text{Differential output: Rejects any “common” signal}} \qquad \underbrace{A_{cc} = \left.\frac{v_{c1}}{v_{ic}}\right|_{v_{id}=0} = \frac{-\beta R_C}{r_\pi + 2(\beta_O + 1)R_{EE}} \approx \frac{V_{CC}}{2V_{EE}} \rightarrow 0.5 \text{ for symmetric power supplies}}_{\text{Single Ended Output off Q1 or Q2: attenuates the common mode signal}}$$

Differential Amplifiers

Summary:

>>> Differential gain can be large while the common mode gain is small <<<

>>> Effectively amplifies only the difference of the two signals <<<

>>> Differential gain looks very similar to the Common Emitter Configuration <<<