Differential Inputs
- Offset
  - constant vs. time
  - Varying
    - Notes: rail-to-rail
  - DC coupled
  - Input bias
    - offset = drift

Practice makes ½ circuits
- Degeneration
  - Notes: extends input range
  - Notes: rail-to-rail (input)
- Equalizer
  - Summary

Single-ended output
- Take 1 side
- Mirror load
- Small signal Ro

Dynamics of differential
- Diff ½ ckt
- CM ½ ckt

Discussion/below rec... (1)

* From lab yesterday, need to review differential inputs

\[ V_{cm} \neq V_{dm} \text{ are unrelated to frequency} \]

\[ V_{in} = 2V \neq V_{in} = 1V \rightarrow V_{cm} = 1.5V \neq V_{dm} = 1V \]

\[ V_{dm} \text{ is often a large constant bias} \]

- \( V_{dm} \) is often small \( \rightarrow \) use small signal gain \( A_{in} \)

- Measure \( A_{cm} \) by injecting time varying common mode signal
  \[ V_{dm} = 0 \rightarrow V_{cm} = V_{cm} \sin(\omega t) \]
  \[ \Rightarrow V_{in} = V_{in} = V_{in} + V_{cm} \sin(\omega t) \]

- \( A_{cm} \) means \( V_{cm} \) peak will be \( A_{cm} \cdot V_{cm} \leftarrow V_{cm} = V_{cm} \sin(\omega t) \)
- Use time varying \( V_{cm} \) easier to see sinusoid \( \rightarrow \) output, but could measure just DC voltage \& multimeter

This is because it is DC coupled!

\[ \rightarrow \text{No coupling cap in amplifier} \rightarrow B_{in} = A_{cm} \frac{1}{\beta} \]

\[ \text{Limited input range \( \rightarrow \) too low cuts off B} \rightarrow \text{Oscillograph rails-to-rails} \]
Measure $A_{dm}$ w/ similar technique

$$V_{on} = \text{Amplitude}$$

$$V_{cn} = V_{b}$$

$$V_{cm} = V_{b} + \frac{V_{on}}{2} \sin (\omega t)$$

$$V_{cm} = V_{b} - \frac{V_{on}}{2} \sin (\omega t)$$

~ means $V_{on} \text{ pk-pk will be } A_{dm} \cdot V_{on}$

$$V_{ocm} = V_{ocm} + \frac{A_{dm}}{2} \cdot V_{on}$$

If transistors or resistors aren't identical then you get offset

**Mismatched $R$ (similar to mismatched $I_s$)**

In this case

$$V_{cn} = V_{b} + \frac{I_{heel} \Delta R}{4 \pi R}$$

$$V_{dm} = \frac{I_{heel} \Delta R}{2 \pi R}$$

- Add small constant
- Add input to balance output

Including $V_{os}$ (or $I_{os}$) in amp model

- Output referred offset voltage is $-I_{heel} \Delta R$
- $V_{cm} = V_{b}$
- $V_{dm} = 0$

**OR**

Nominally $I_{heel}$ constant

- But can vary as soon $V_{BE}$
- Can be balanced, so it almost
- Real output offset taken into account
We often want a differential input vs. a single-ended output
- e.g. op-amps

* easiest way

\[ V_{out} = \frac{1}{2} V_{in} + V_{in} \]

- but what we're doing anyway

= use current

\[ -9m \text{ generator of left side reflected to right} \]

- How do we make \( \frac{1}{2} \) circuit to analyze something symmetric

- \( G_{m3} + G_{m4} \) appear in parallel (in midpoint node

- \( R_{o3} = R_{o4} \) sort of in parallel (\( Y_0 \) for diff node)

- But \( R_o \) is a fundamentally single ended measurement!

- \( A_v \) can be still considered differentially

\[ A_v = \frac{V_{out}}{V_{in}} \]

\[ A_v = (G_{m3} + G_{m4}) \left( \frac{R_{o4}}{R_{o3}} \right) \]

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\[ A_v = \frac{V_{out}}{V_{in}} \]

- For \( A_v \):

\[ V_{in} = \frac{1}{2} R_{o3} \]

- For \( R_o \):

\[ \text{current ... my most disappointing moment in this class) NOT \( \frac{R_{o4}}{2} \), rather \( \frac{R_{o4}}{2} \)}

- see \( R_{o3} \) in \( \frac{1}{m4} \) rest

\[ Z_1 = \frac{1}{2} \text{ control } V_i, \text{ directly} \]

- \( L_0 \) all current flows in \( \frac{1}{m4} \) resister, so

\[ V_m = \frac{g_{m4}}{2} V_i + V_{in} \]

\[ Z_2 = R_{o4} + \frac{R_{o4}}{2} + \frac{g_{m4} R_{o4}}{2} \]

\[ L_0 \text{ is } V_i = \frac{V_{in}}{m4} = \frac{V_{in}}{2} \frac{g_{m4}}{2} \frac{R_{o4}}{2} \frac{1}{g_{m4}} \to V_m = \frac{V_{in}}{2} \frac{g_{m4}}{2} \frac{R_{o4}}{2} \]

\[ - \frac{V_{in}}{2} \frac{g_{m4}}{2} \frac{R_{o4}}{2} \frac{1}{g_{m4}} = \frac{V_{in}}{2} \frac{g_{m4}}{2} \frac{R_{o4}}{2} \]
More practice w/ V/2 circuits

- Draw an V/2 circuit & find Au

- Looks like CE V/degen
  \[ Au = \frac{-R_c}{R_E} \]

- Extends linear input range ... also true of single ended design
  - Ube remains \( \approx 0.7 \) even as current source left or right
  - Linear range \( \approx I_{sat} R_E \) \( \rightarrow \) voltage when all I source 1 way
    \( \leftarrow \) point @ which Ube starts changing

- Find \( d_m \approx C_h \frac{1}{2} C_k \). Assume Q1=Q2 identical

An equalizer, CE, experiences gain boost & we'll see why

- \( R_E \) & \( C_E \) shunt \( \frac{1}{2} C_k \)
  - tail nodes @ same voltage

- Differential ground in middle, \( R_E \) can't short
  - Double impedance \( \rightarrow \) \( \frac{R_E}{2}, 2C_E \)

Dynamics
- Different for dm signals & em signals \( \frac{1}{2} C_k \) they see different impedances
  - Use \( \frac{1}{2} C_k + 0.5 \times CT \) or old exact solutions