Opamps Are Utilized in a Wide Range of Applications

- Each application comes with different opamp requirements
  - How are the input common-mode range requirements different among the above applications?
  - How are the output range requirements different?
  - How are the bandwidth requirements different?

Integrated opamps are typically custom designed for their specific application
Single-Ended Versus Fully Differential Topologies

- Analog circuits are sensitive to noise from the power supply and other coupling mechanisms

- Fully differential topologies can offer rejection of common-mode noise (such as from supplies)
  - Information is encoded as the *difference* between two signals
  - More complex implementation than single-ended designs
Key Focus of Lecture

- Examine fully differential version of basic two stage opamp
- Examine more advanced opamp topologies and the advantages/disadvantages they present
We can separate this into differential and common mode circuits, similar to a single differential amplifier.

- Differential behavior same as the single-ended opamp
  - Note that we have twice the effective range in input/output swing due to the differential signaling
- Common mode setting needs to be dealt with
Maximum swing for fully differential signals requires
- Accurate setting of the common mode value
- Suppression of common mode noise
Common-Mode Gain From Input

- Analysis is same as for single-ended design
  - Can be simplified to common-mode “half-circuit”

\[ a_{vc} = \frac{r_{o4}}{1/gm2 + 2r_{o5}} g_{m6a} (r_{o6a} || r_{o7a}) \]

- Common-mode output is sensitive to common-mode input
Common mode “half circuit can still be used

\[ a_{v bias} \approx (g_{m4}r_{o4}) g_{m6a} (r_{o6a}||r_{o7a}) \]

- Common-mode output is extremely sensitive to \( V_{bias} \)!
Common Mode Feedback Biasing (CMFB)

- Use an auxiliary circuit to accurately set the common mode output value to a controlled value $V_{\text{ref}}$
  - Need to be careful not to load the outputs with the common mode sensing circuit ($R_{\text{large}}$ in this case)
  - Need to design CMFB to be stable
Parasitic Pole/Zero Pair of Current Mirrors

- Single-ended signal travels through current mirror
  - Introduces an extra parasitic pole/zero

\[ \omega_{p\_par} = \frac{g_{m3}}{C_{gs3} + C_{gs4}} \quad \omega_{z\_par} = 2\omega_{p\_par} \]

- Fully differential signal does not see this pole/zero pair
Note that signal at $V_2$ is composed of the sum of paths (a) and (b) shown above

$$\frac{i_{sc}(s)}{v_{id}(s)} = \frac{gm}{2} + \left(\frac{gm}{2}\right) \frac{1}{1 + \frac{s}{wp_{par}}}$$

$$= \left(\frac{gm}{2}\right) \frac{2 + \frac{s}{wp_{par}}}{1 + \frac{s}{wp_{par}}} = gm \frac{1 + \frac{s}{(2wp_{par})}}{1 + \frac{s}{wp_{par}}}$$
Advantages of fully differential topologies
- Improved CMRR and PSRR across a wide frequency range
- Twice the effective signal swing
- Removal of pole/zero pair due to current mirror
  - Potentially improved phase margin

Disadvantages of fully differential topologies
- Power and complexity

Most opamp topologies can be modified to support either single-ended or fully differential signaling
Telescopic Opamp (Fully Differential Version)

- Popular for high frequency applications
  - Single stage design
  - Limitation: input and output swing quite limited
Open Loop Response of Telescopic Opamp

- Determine $K$, $w_{dom}$, $w_0$, $w_p$

- Why is this topology good for high bandwidth applications?
Notice that parasitic pole is much higher than for two stage opamp, yielding higher potential unity gain BW
Telescopic Opamp (Single-Ended Version)

- Issue: parasitic pole lower than fully differential version

\[
wp_2 \approx \frac{g_{m7}}{C_{gs7} + C_{gs8} + C_{d3,d5}} < wp_1 \approx \frac{g_{m4}}{C_{gs4} + C_{s4,d2}}
\]

- Singled-ended version not as useful for wide bandwidth
Folded Cascode Opamp

- Modified version of telescopic opamp
  - Significantly improved input/output swing
  - High BW (better than two stage, worse than telescopic)
  - Single stage of gain (lower than telescopic)

Must set $I_{bias2} > I_{bias1/2}$
Open Loop Response of Folded Cascode Opamp

\[ K = g_{m2}R_{out} \quad w_{dom} = \frac{1}{(R_{out}C_L)} \]

\[ w_o = \frac{g_{m2}}{C_L} \quad w_p \approx \frac{g_{m8}}{C_{gs8} + C_{d2,d10,s8}} \]

where \( R_{out} = ((g_{m6}r_{o6})r_{o4})||((g_{m8}r_{o8})r_{o10}) \)

More capacitive loading than for telescopic due to higher drain current in M_{10}

\( R_{o10} \) is lower than for telescopic
Two Stage with Cascoded Output Stage

- Higher DC gain than with two stage or folded cascode
  - Two gain stages with boosted gain on the output stage
- Same output swing as folded cascode
  - Lower than for basic two stage
Open Loop Response Calculations

\[ K = g_{m2} (r_{o2} || r_{o4}) g_{m6} R_{out} \]

\[ w_{dom} = \frac{1}{((r_{o2} || r_{o4}) C_M)} \]

\[ w_o = \frac{g_{m2}}{C_c} \quad w_p \approx \frac{g_{m6}}{C_L} \]

where \( R_{out} = ((g_{m7} r_{o7}) r_{o6}) || ((g_{m8} r_{o8}) r_{o9}) \)

\[ C_M \approx (g_{m6} R_{out}) C_c \]
Two Stage with Cascoded Input Stage

- Compared to two stage with cascoded output
  - Similar DC gain
  - Improved output swing
  - Reduced input swing
Open Loop Response Calculations

\[ K = g_{m2}R_{out1}g_{m6}(r_{o6}||r_{o7}) \]

\[ w_{dom} = \frac{1}{(R_{out1}C_{M})} \quad w_{o} = \frac{g_{m2}}{C_{c}} \quad w_{p} \approx \frac{g_{m6}}{C_{L}} \]

where \( R_{out1} = ((g_{m12}r_{o12})r_{o2})||((g_{m10}r_{o10})r_{o4}) \)

\[ C_{M} \approx (g_{m6}(r_{o6}||r_{o7}))C_{c} \]
Summary

- Opamp topologies can be configured to process fully differential signals
  - Provides improved immunity to noise from common-mode perturbations such as power supply noise
  - Increases effective signal swing by a factor of two
  - Carries additional complexity for CMFB and increased power consumption

- Integrated opamps are often custom designed for a given application
  - Each application places different demands on DC gain, bandwidth, signal swing, etc.
  - Opamp topologies considered today include telescopic, folded cascode, and modified two stage
    - Each carries different tradeoffs on the above specifications