Analysis and Design of Analog Integrated Circuits
Lecture 19

Advanced Opamp Topologies

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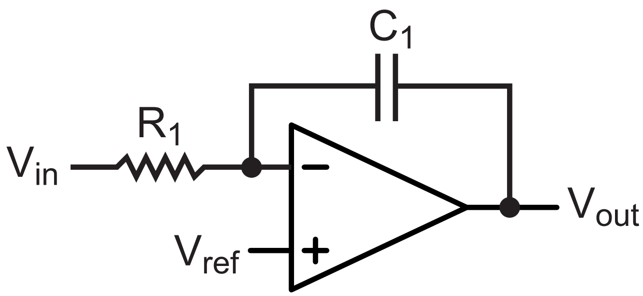
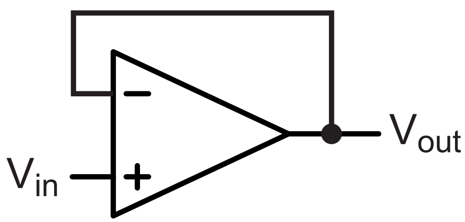
Opamps Are Utilized in a Wide Range of Applications

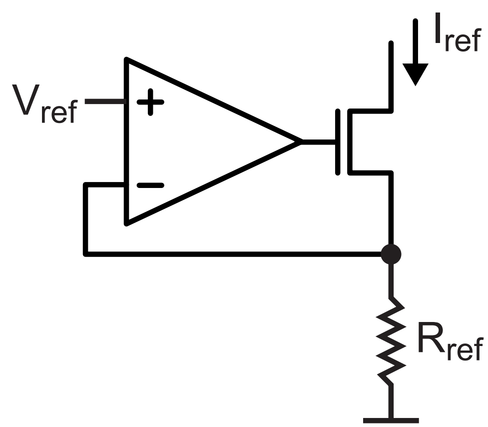
Analog Filters



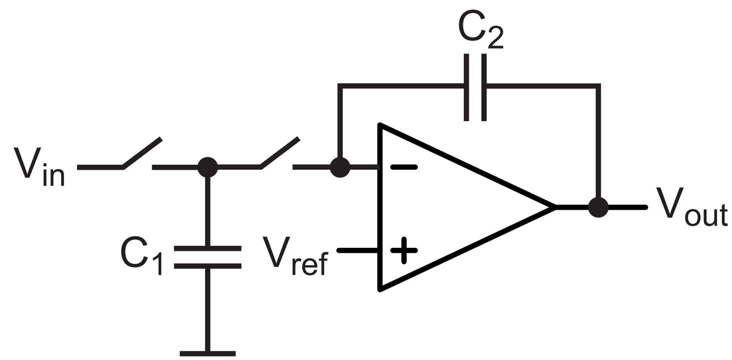
Analog Buffers



Current References



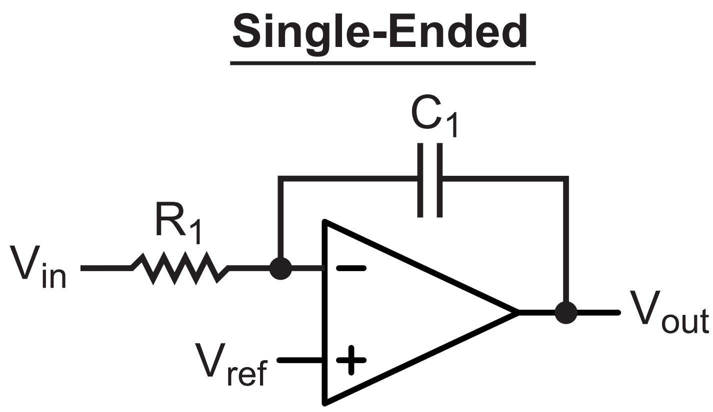
Switched Capacitor Circuits

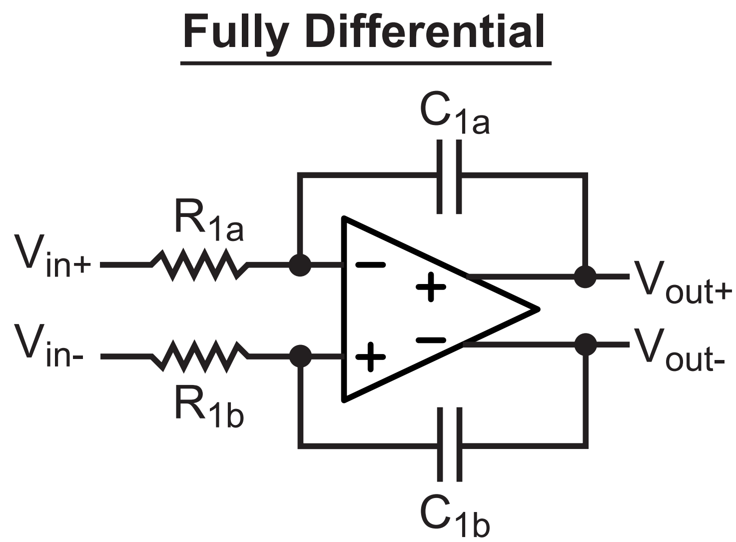


- **Each application comes with different opamp requirements**
  - **How are the input common-mode range requirements different among the above applications?**
  - **How are the output range requirements different?**
  - **How are the bandwidth requirements different?**

Integrated opamps are typically custom designed for their specific application

Single-Ended Versus Fully Differential Topologies



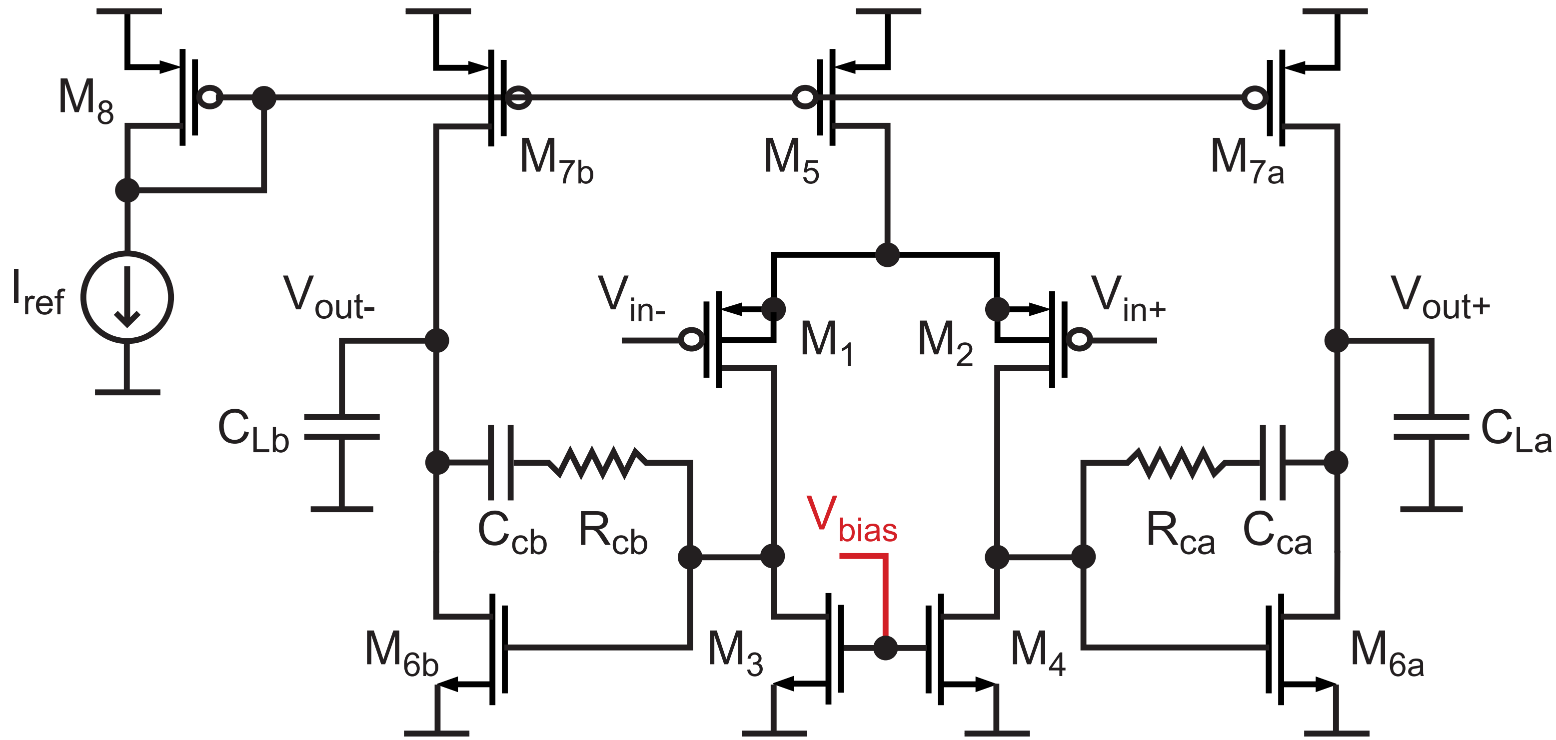


- Analog circuits are sensitive to noise from the power supply and other coupling mechanisms
- Fully differential topologies can offer rejection of common-mode noise (such as from supplies)
  - Information is encoded as the *difference* between two signals
  - More complex implementation than single-ended designs

Key Focus of Lecture

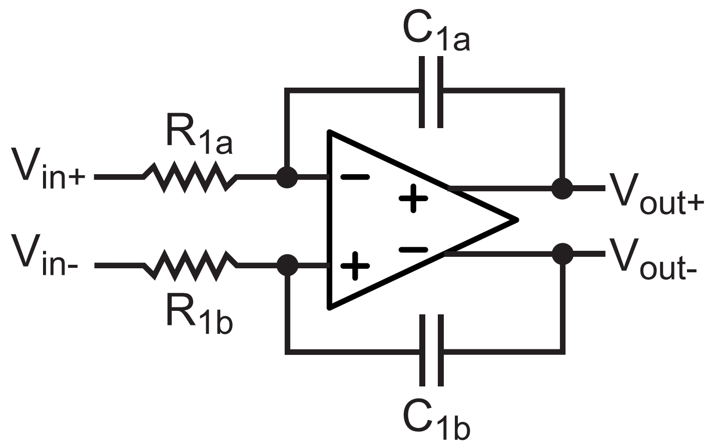
- **Examine fully differential version of basic two stage opamp**
- **Examine more advanced opamp topologies and the advantages/disadvantages they present**

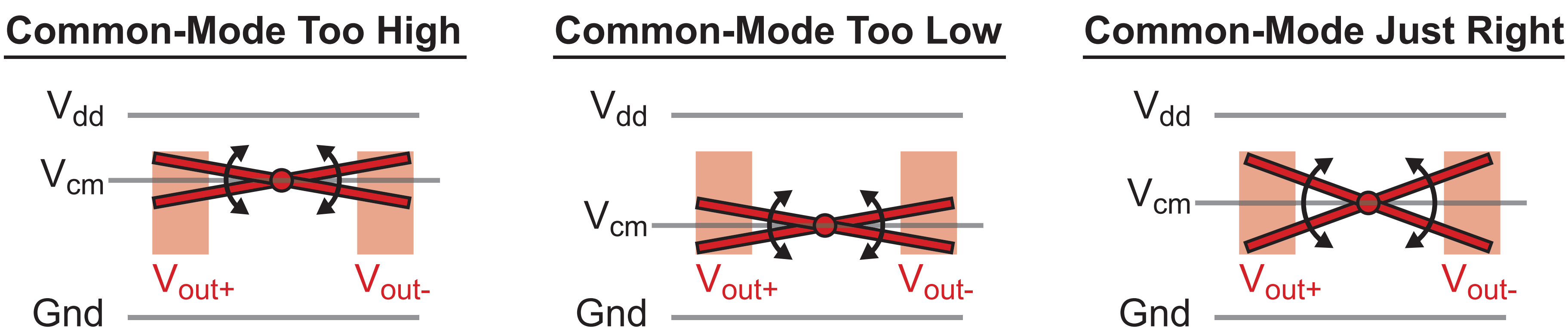
Fully Differential Version of Basic Two Stage Opamp



- **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**

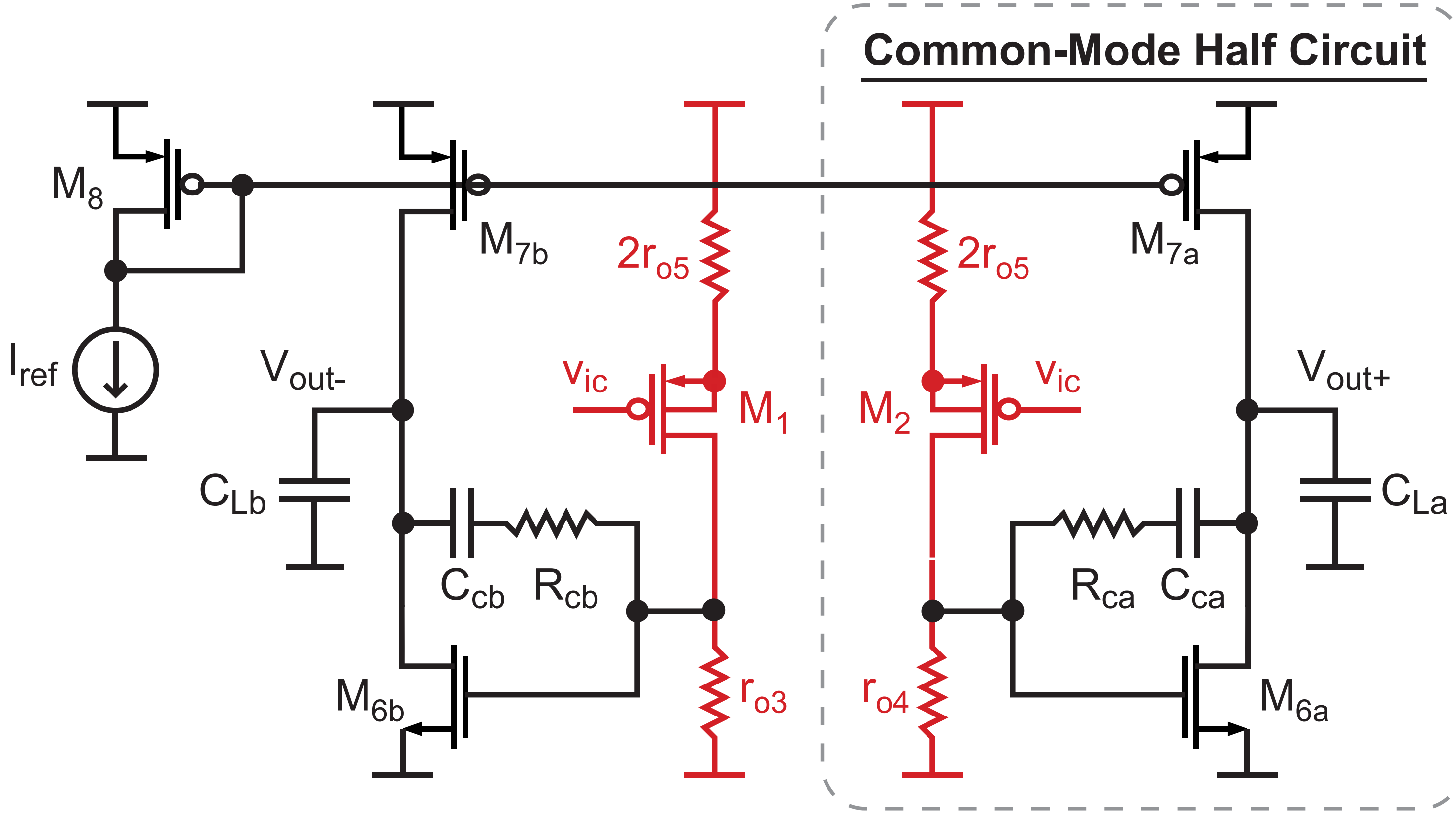
Illustration of Common Mode Influence





- **Maximum swing for fully differential signals requires**
  - **Accurate setting of the common mode value**
  - **Suppression of common mode noise**

Common-Mode Gain From Input

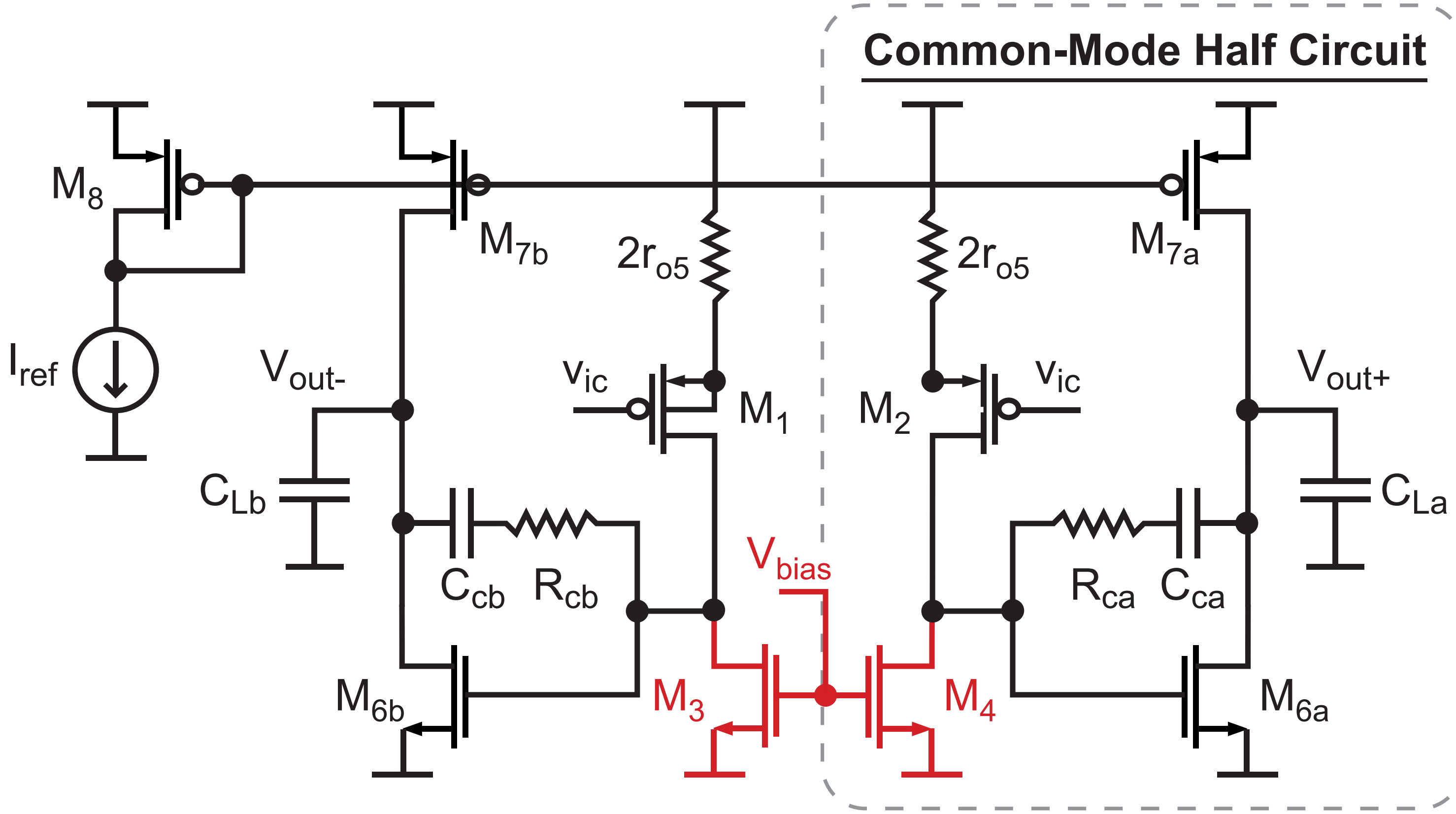


- Analysis is same as for single-ended design
  - Can be simplified to common-mode "half-circuit"

$$a_{vc} = \frac{r_{o4}}{1/g_{m2} + 2r_{o5}} g_{m6a} \left(r_{o6a} || r_{o7a} \right)$$

  - Common-mode output is sensitive to common-mode input

Common-Mode Gain From Input Bias

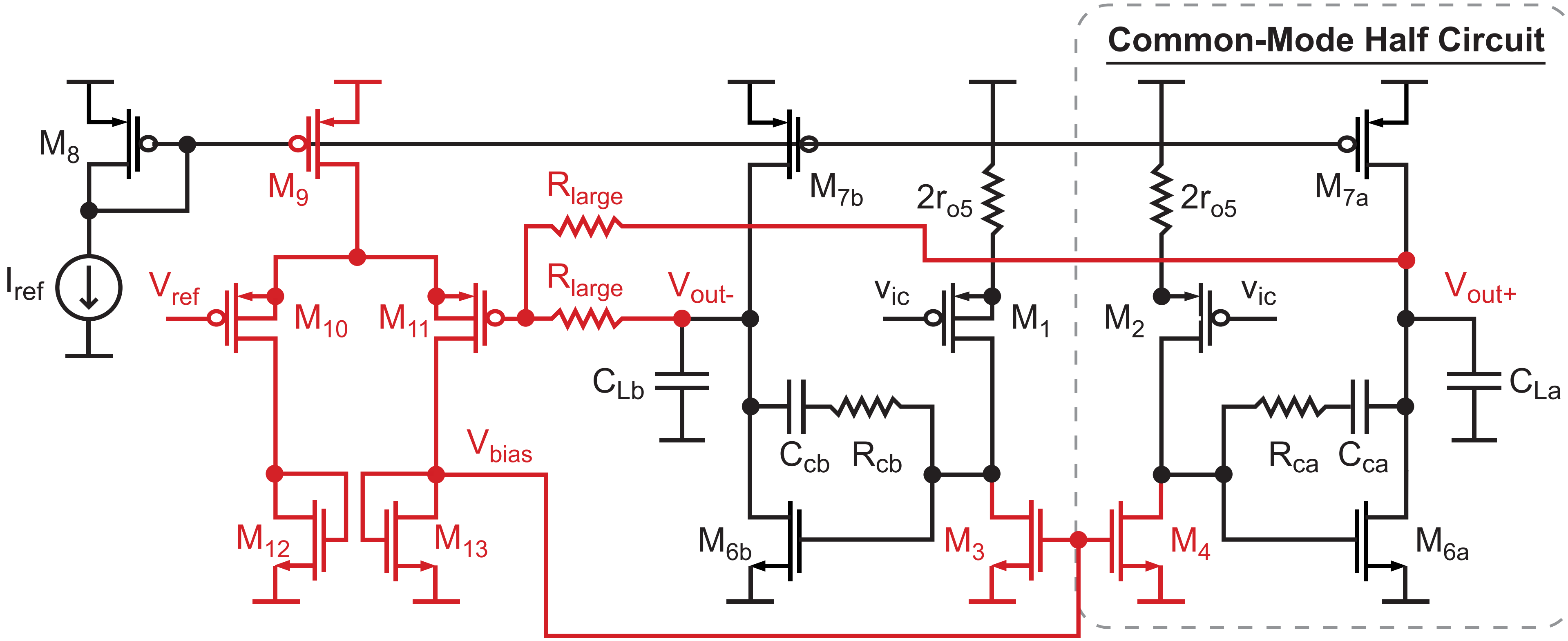


- Common mode “half circuit can still be used

$$a_{vbias} \approx (g_{m4} r_{o4})\, g_{m6a} (r_{o6a} || r_{o7a})$$

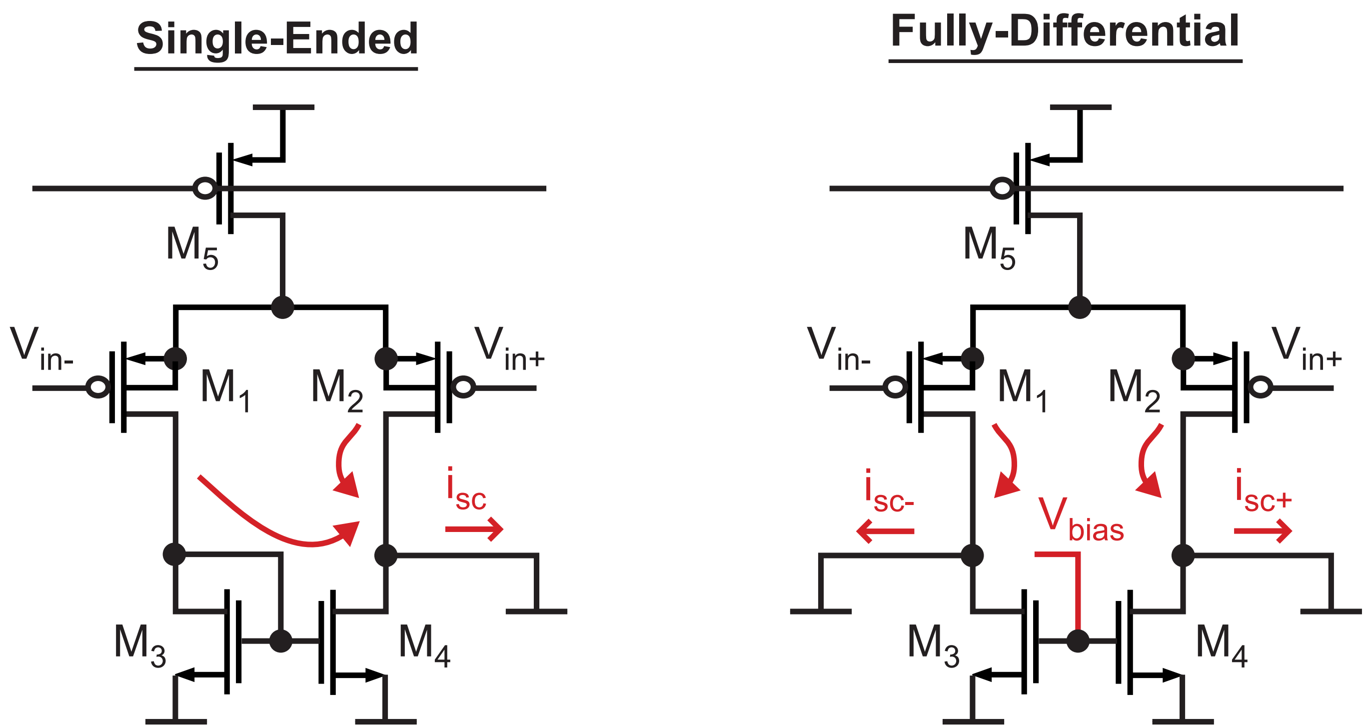
  - Common-mode output is extremely sensitive to V_{bias}!

Common Mode Feedback Biasing (CMFB)



- Use an auxiliary circuit to accurately set the common mode output value to a controlled value Vref
  - Need to be careful not to load the outputs with the common mode sensing circuit (R_{large} in this case)
  - Need to design CMFB to be stable

Parasitic Pole/Zero Pair of Current Mirrors

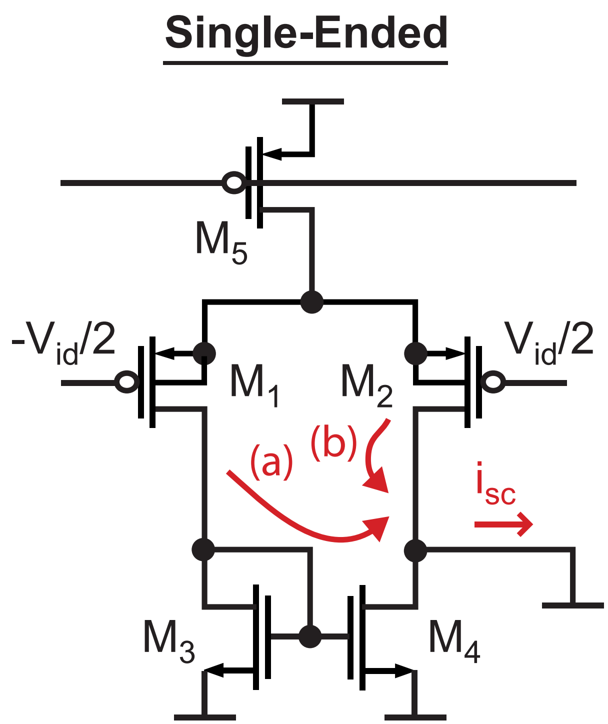


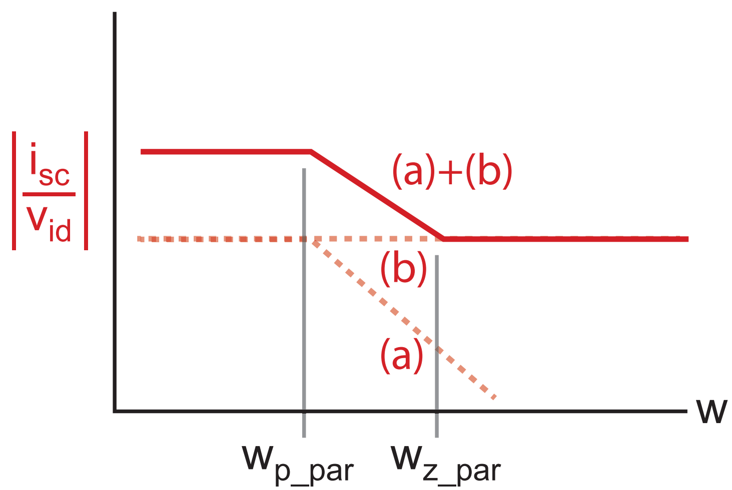
- **Single-ended signal travels through current mirror**
  - **Introduces an extra parasitic pole/zero**

$$w_{p\_par} = \frac{g_{m3}}{C_{gs3} + C_{gs4}} \qquad w_{z\_par} = 2w_{p\_par}$$

- **Fully differential signal does not see this pole/zero pair**

Closer Examination of Pole/Zero Relationship





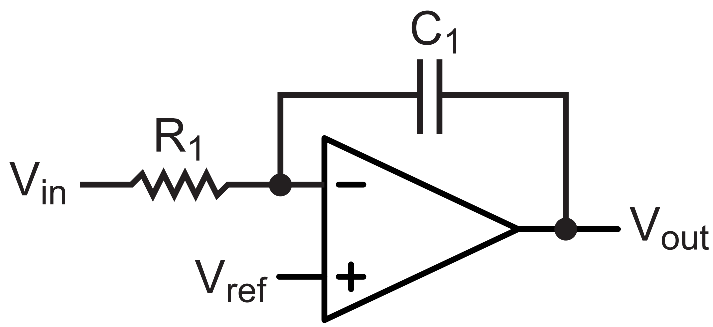
- Note that signal at V_2 is composed of the sum of paths (a) and (b) shown above

$$\frac{i_{sc}(s)}{v_{id}(s)} = \frac{g_m}{2} + \left(\frac{g_m}{2}\right)\frac{1}{1+s/w_{p\_par}}$$

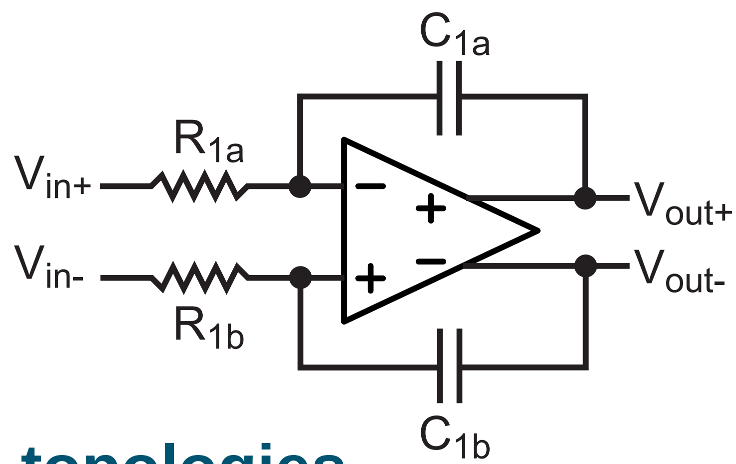
$$= \left(\frac{g_m}{2}\right)\frac{2+s/w_{p\_par}}{1+s/w_{p\_par}} = g_m\frac{1+s/(2w_{p\_par})}{1+s/w_{p\_par}}$$

Summary of Single-Ended Versus Fully Differential

Single-Ended



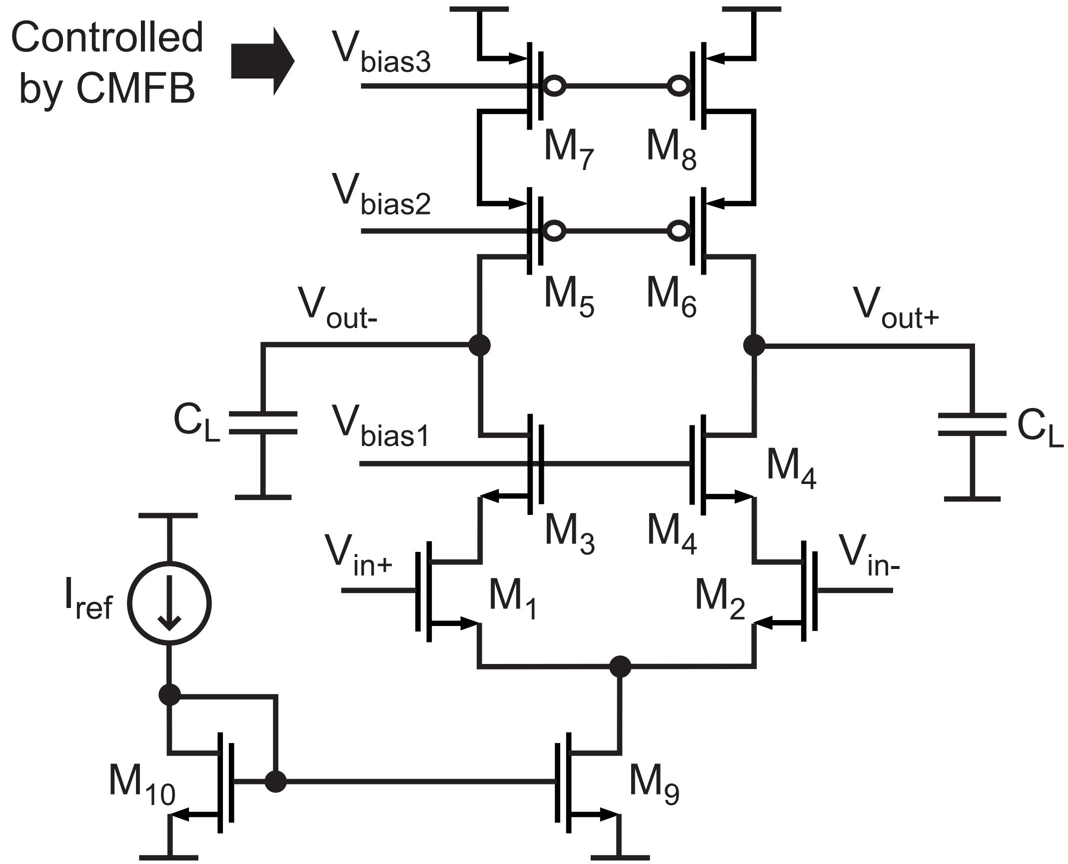
Fully Differential



- **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**

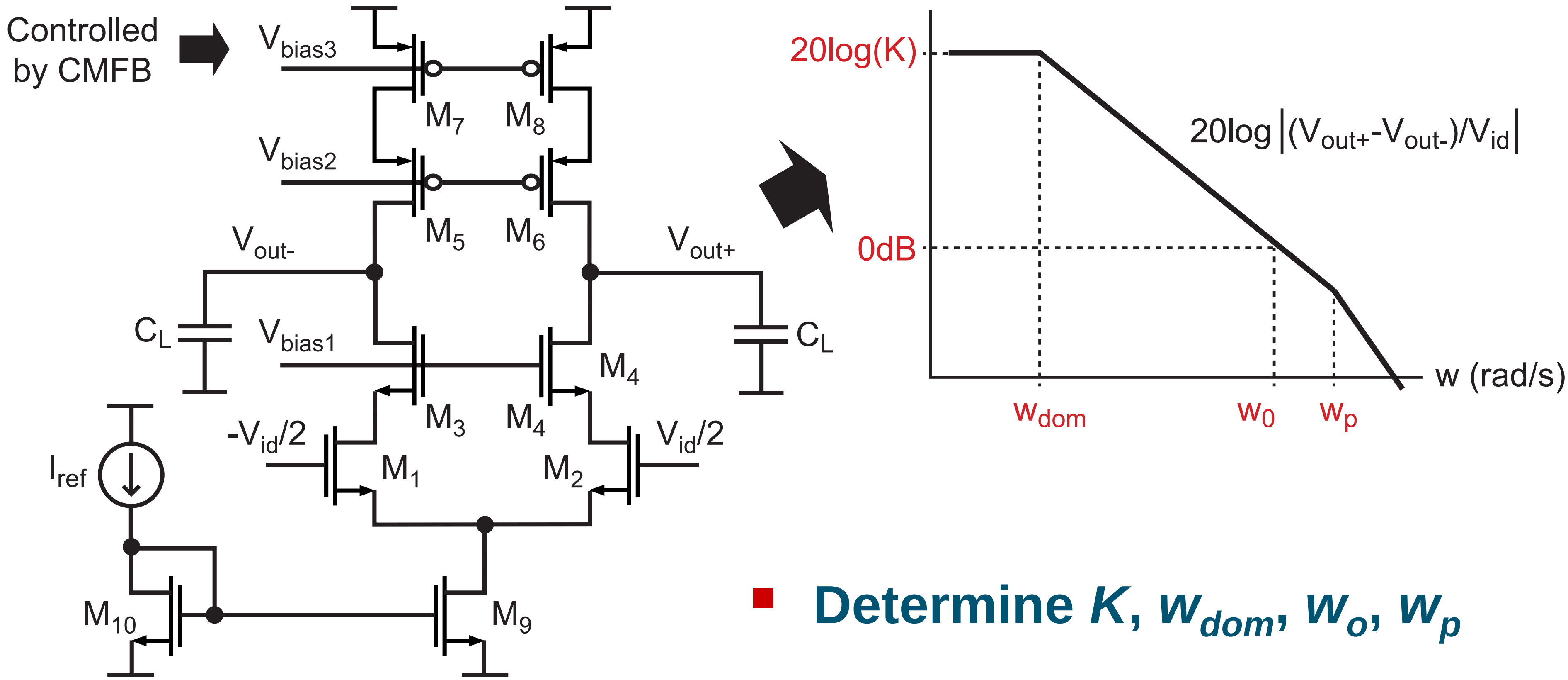
Most opamp topologies can be modified to support either single-ended or fully differential signaling

Telescopic Opamp (Fully Differential Version)



- **Popular for high frequency applications**
  - **Single stage design**
  - **Limitation: input and output swing quite limited**

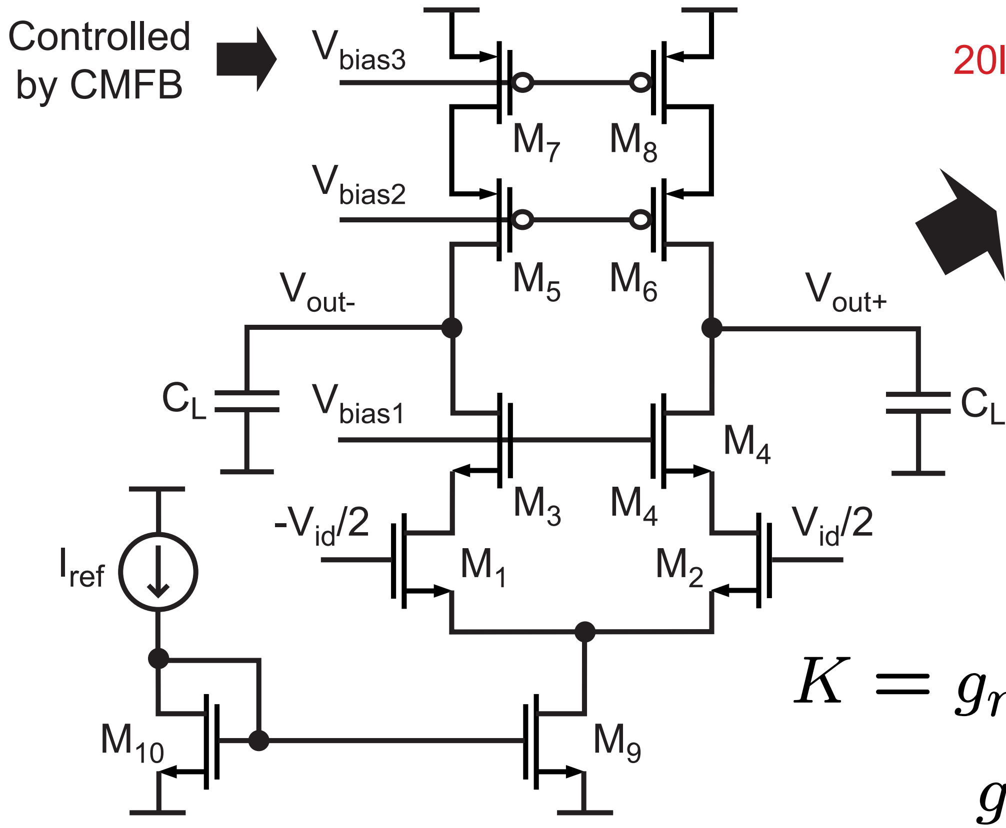
Open Loop Response of Telescopic Opamp

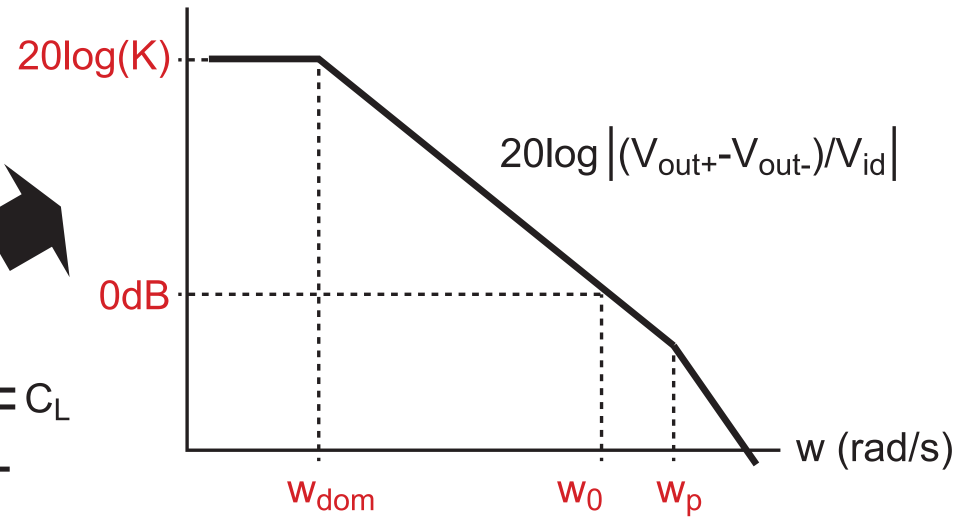


- **Determine K, w_{dom}, w_o, w_p**

- **Why is this topology good for high bandwidth applications?**

Open Loop Response of Telescopic Opamp





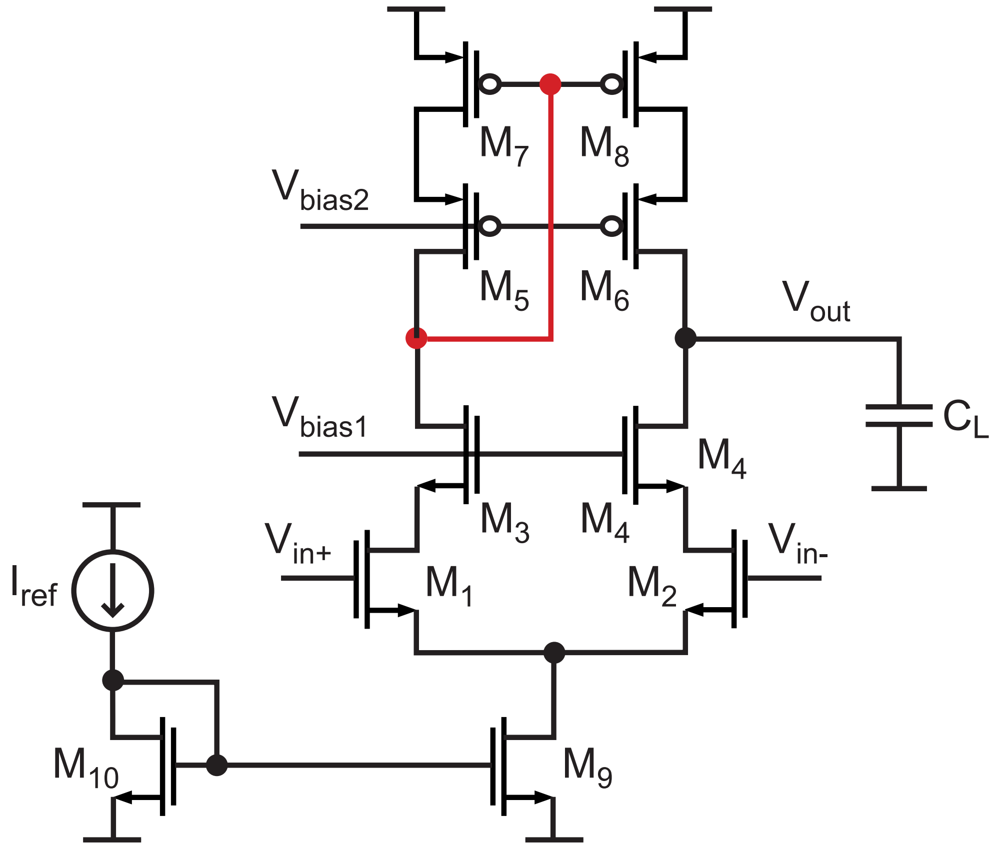
$$K = g_{m2}R_{out} \quad w_{dom} = 1/(R_{out}C_L)$$

$$w_o = \frac{g_{m2}}{C_L} \quad w_p \approx \frac{g_{m4}}{C_{gs4} + C_{s4,d2}}$$

where $R_{out} = ((g_{m4}r_{o4})r_{o2})||((g_{m6}r_{o6})r_{o8})$

- **Notice that parasitic pole is much higher than for two stage opamp, yielding higher potential unity gain BW**

Telescopic Opamp (Single-Ended Version)

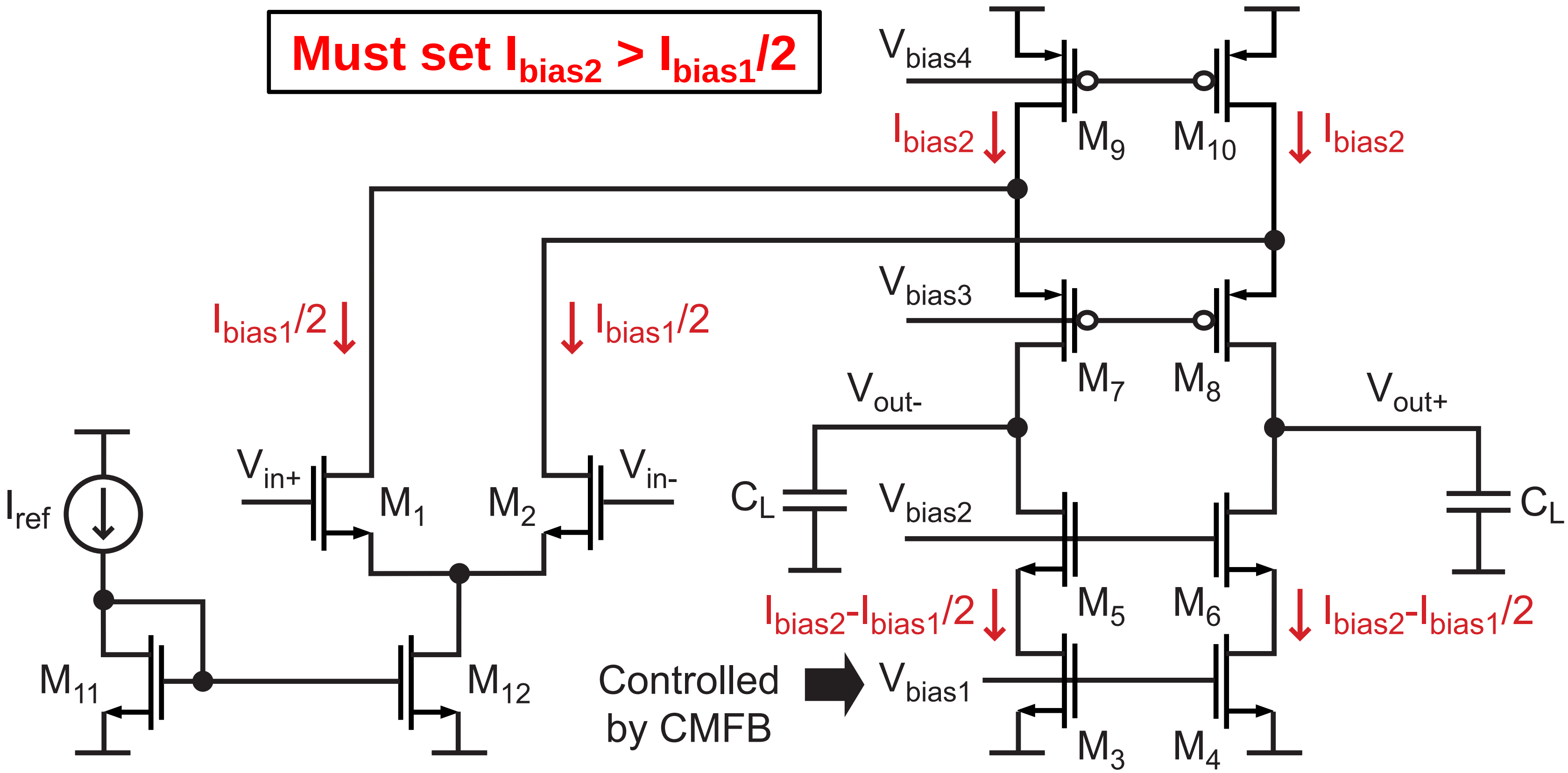


- **Issue: parasitic pole lower than fully differential version**

$$w_{p2} \approx \frac{g_{m7}}{C_{gs7} + C_{gs8} + C_{d3,d5}} < \; w_{p1} \approx \frac{g_{m4}}{C_{gs4} + C_{s4,d2}}$$

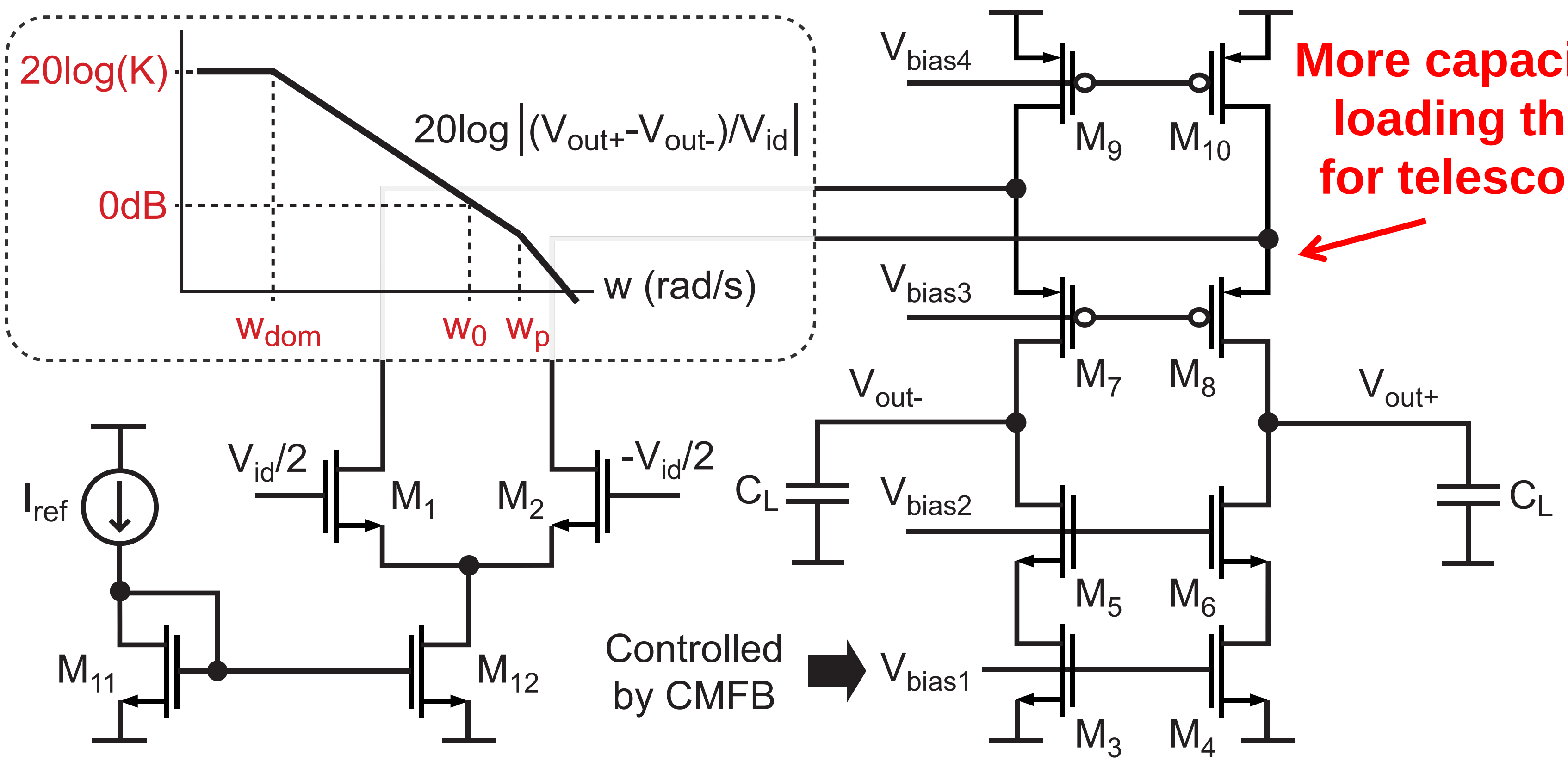
  - **Singled-ended version not as useful for wide bandwidth**

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)**

Open Loop Response of Folded Cascode Opamp



More capacitive loading than for telescopic

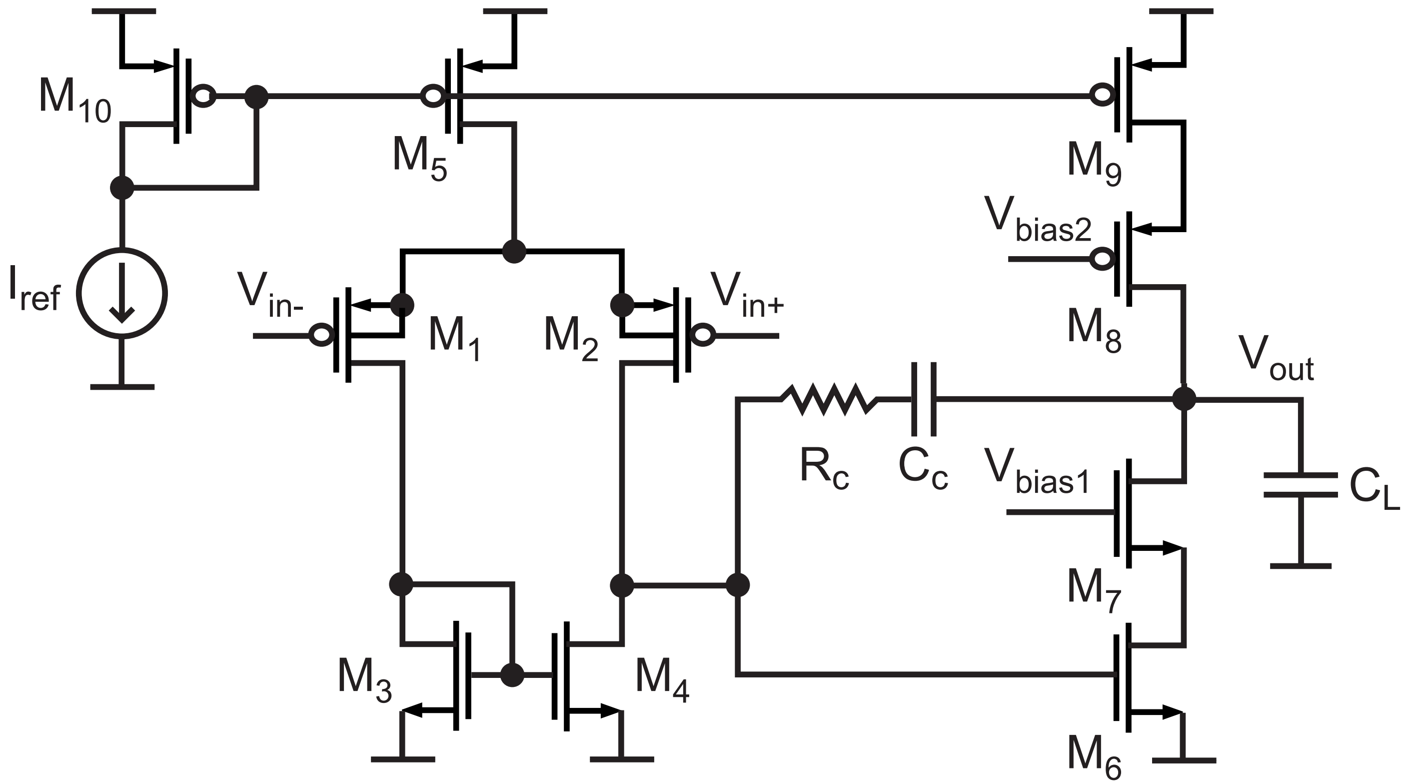
$$K = g_{m2}R_{out} \quad w_{dom} = 1/(R_{out}C_L)$$

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

R_{o10} is lower than for telescopic due to higher drain current in M_{10}

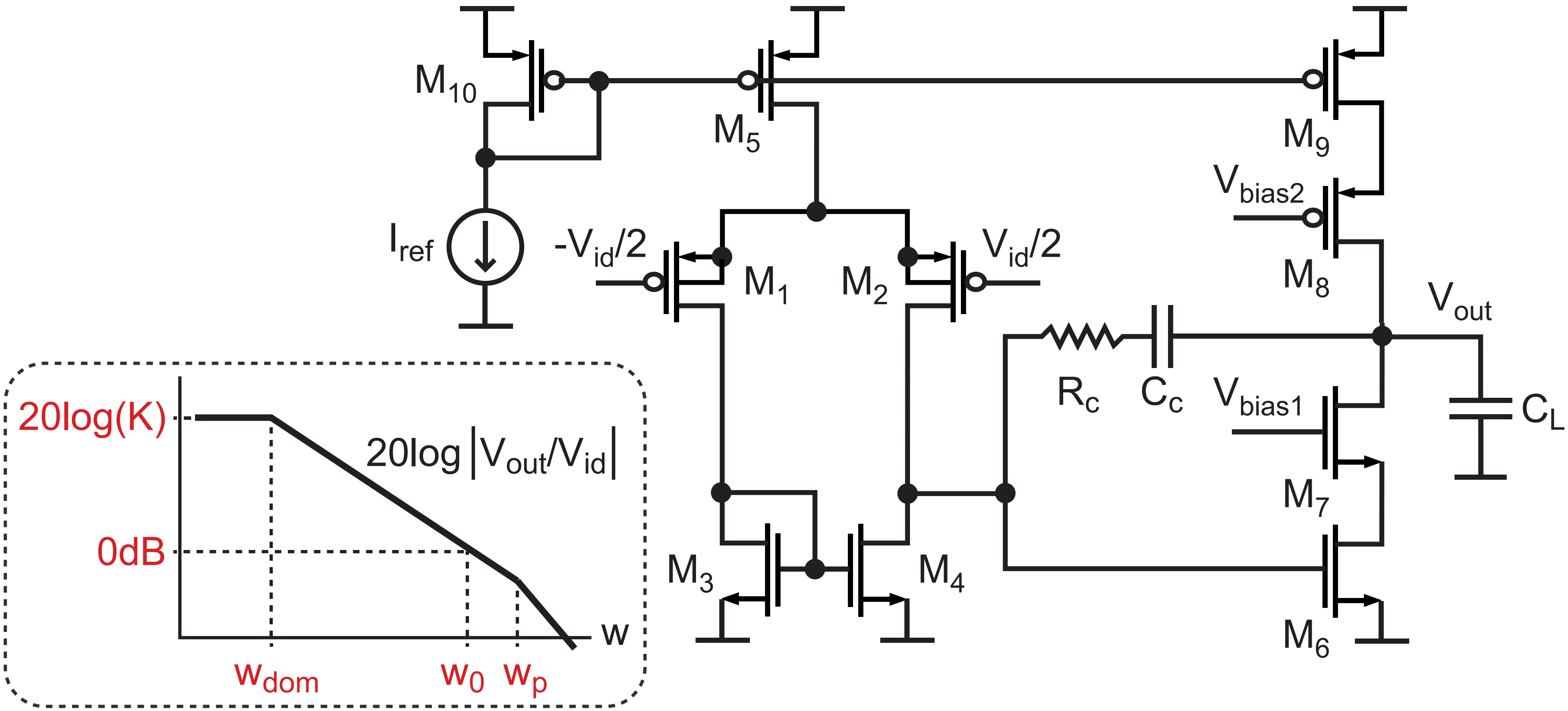
where $R_{out} = ((g_{m6}r_{o6})r_{o4})||((g_{m8}r_{o8})r_{o10})$

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



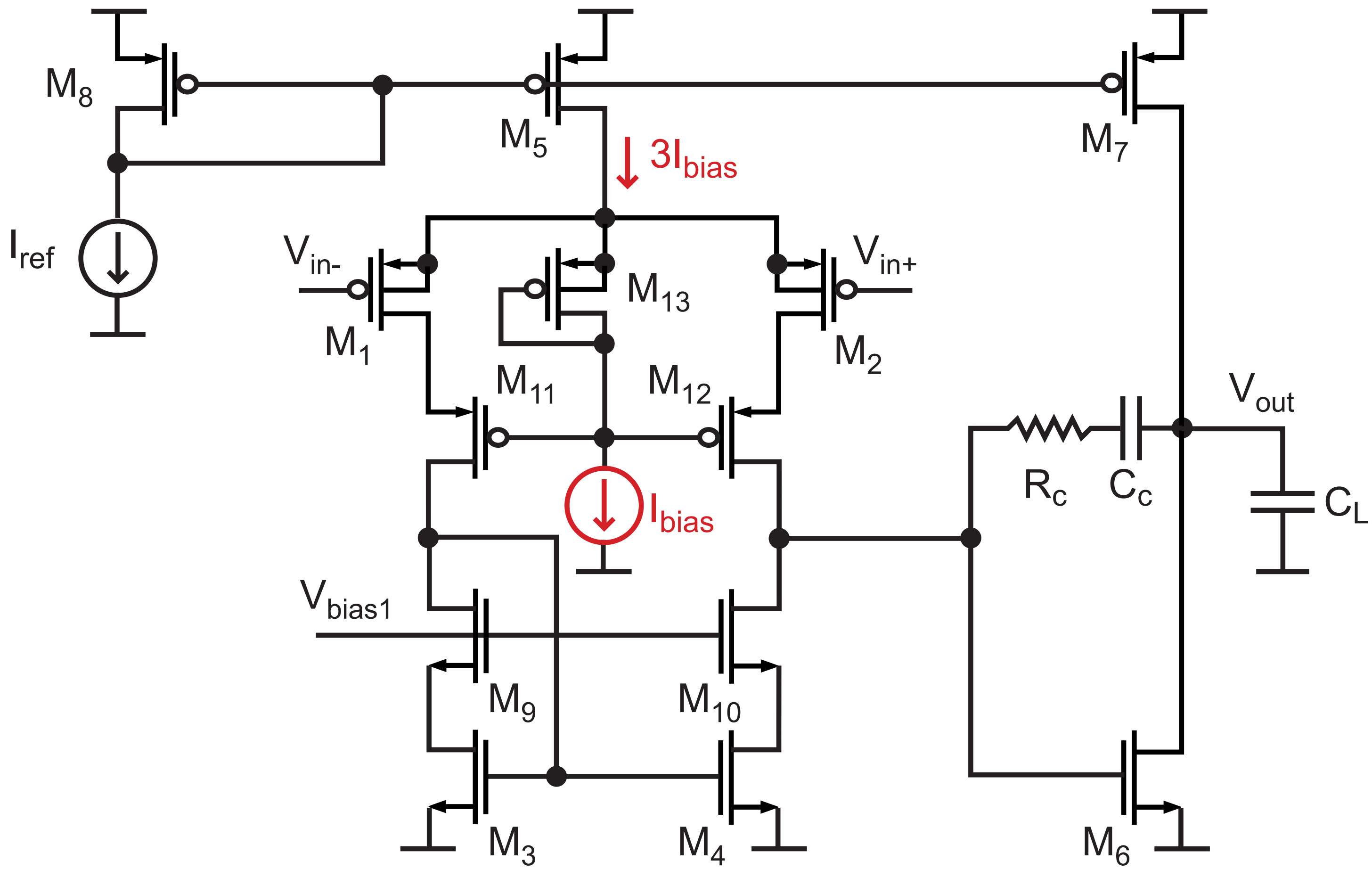
$$K = g_{m2}(r_{o2}||r_{o4})g_{m6}R_{out} \qquad w_{dom} = 1/((r_{o2}||r_{o4})C_M)$$

$$w_o = \frac{g_{m2}}{C_c} \qquad w_p \approx \frac{g_{m6}}{C_L}$$

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

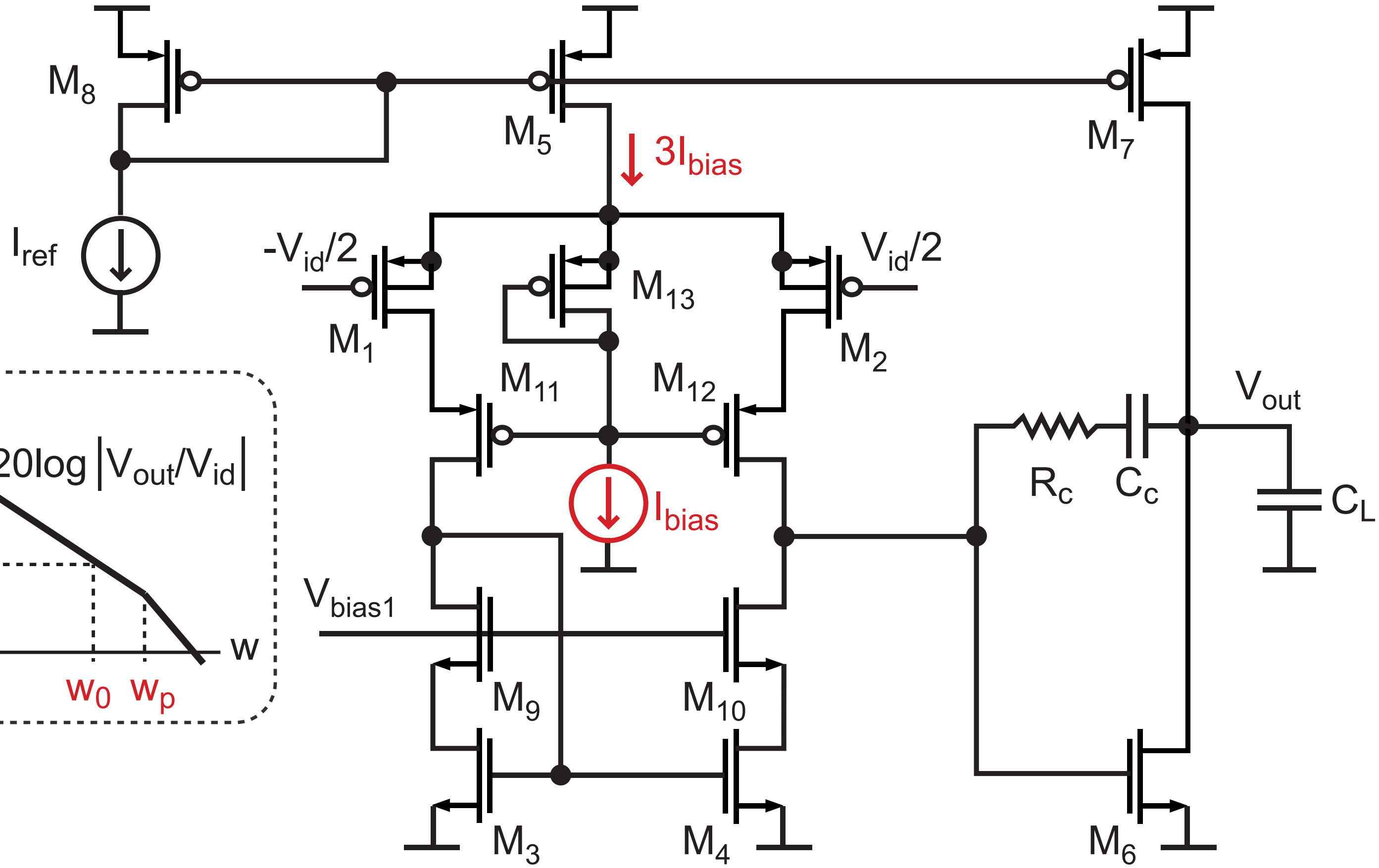
$$C_M \approx (g_{m6}R_{out})\,C_c$$

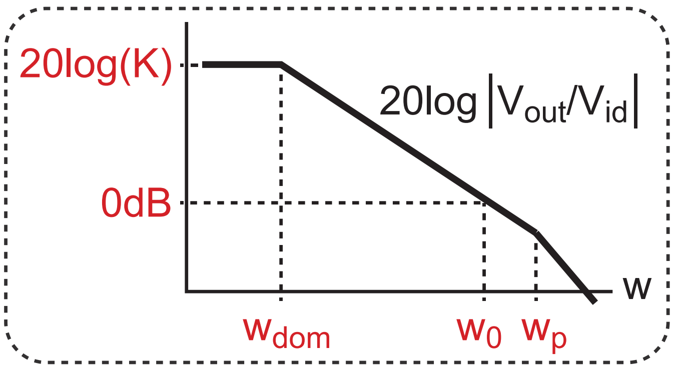
Two Stage with Cascoded Input Stage



- Compared to two stage with cascoded output
  - Similar DC gain
  - Improved output swing
  - Reduced input swing

Open Loop Response Calculations





$$K = g_{m2} R_{out1} g_{m6} (r_{o6} || r_{o7})$$

$$w_{dom} = 1/(R_{out1} C_M) \qquad w_o = \frac{g_{m2}}{C_c} \qquad w_p \approx \frac{g_{m6}}{C_L}$$

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