
Lecture 19:

CMOS Operational Amplifiers

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Overview

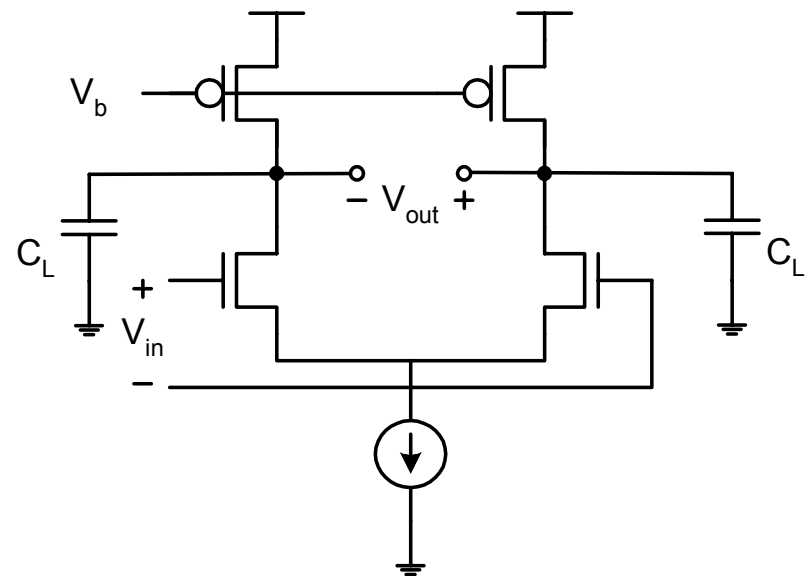
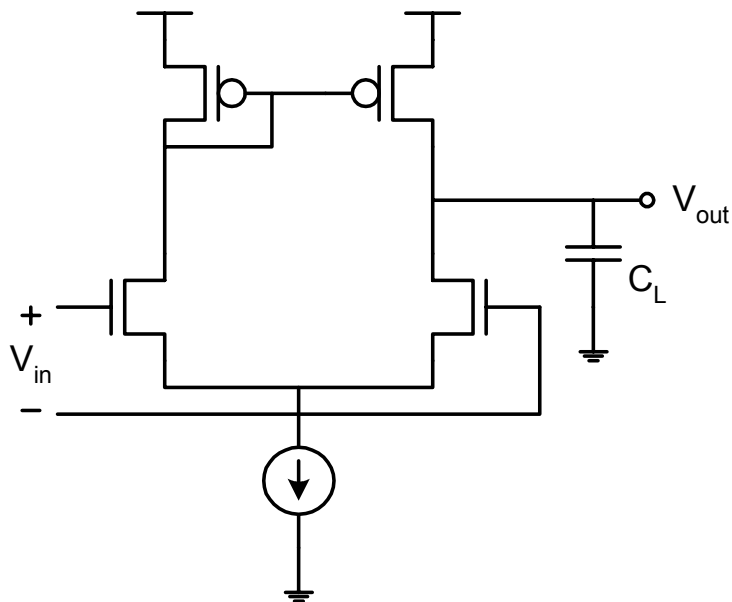
- **Reading**
 - S&S: Chapter 10.7 – 10.8
- **Background**
 - In the beginning of the semester, we built circuits that can perform interesting and useful operations with op amps. Now, we will take all that we have learned about circuits and devices to see how operational amplifiers themselves are built. In this lecture, we will focus on building CMOS op amps. S&S has much more detail in terms of building operational amplifiers with BJT and JFET devices. While these technologies are better suited for discrete op amp devices, because they offer the potential for higher bandwidths and output drive capabilities, CMOS op amp circuits find use in many integrated circuit systems. In CMOS implementations, extra output stages are used to provide the necessary off-chip drive. One can read more on this topic in Chapter 9 of S&S.

General Characteristics

- Op amps are an important component of modern CMOS IC's. They used to designed as general purpose amplifiers that can meet a variety of requirements. The main target was extremely high gain ($>1e5$), high input impedance and low output impedance (like an ideal amplifier). This was done (to some extent) at the expense of different aspects of performance (e.g., speed, output voltage range, power, etc.). Designs these days are much more tailored to have (good enough) performance w.r.t. the specific needs of particular applications. Within an IC, often use Operational Transconductance Amplifiers (OTA).
- Some performance parameters of op amps
 - Gain and Bandwidth
 - Want as large as possible
 - Output Swing
 - Maximize w.r.t. power supply (but supply shrinking in modern processes)
 - Linearity
 - Combat non-linearity with feedback
 - Noise and Offset
 - Can minimize by trading off other parameters
 - Supply Rejection
 - Strong dependence on current source output resistance

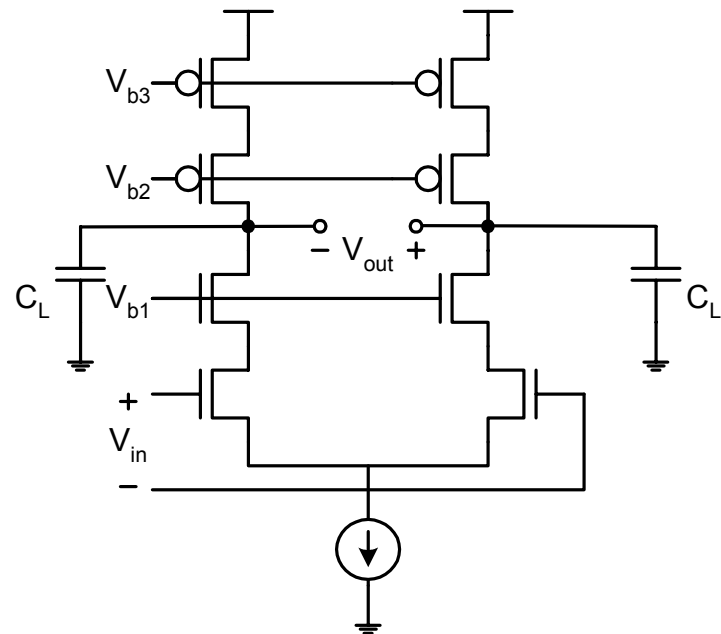
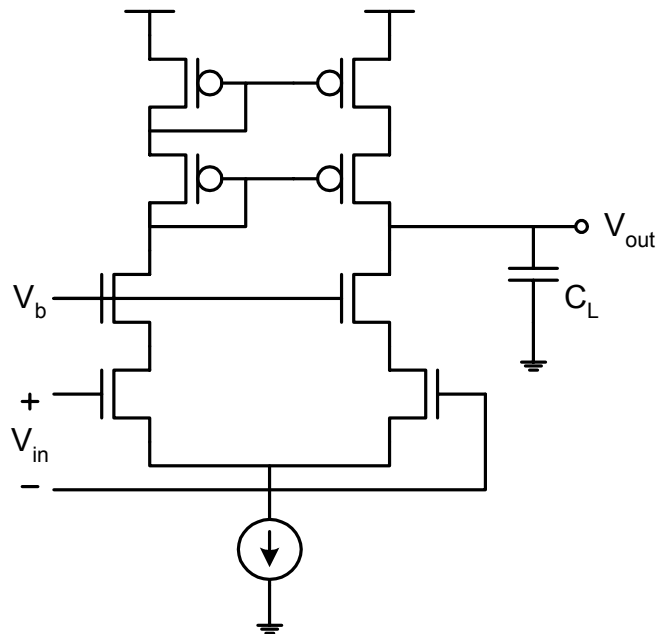
Simple One-Stage Op Amps

- Two differential pair amplifiers that we have already seen can be used as op amps. The low-frequency, small-signal gain of both is $g_{mN}(r_{oN}||r_{oP})$. The capacitive loads (C_L) usually determine their bandwidth.



Cascode Op Amps

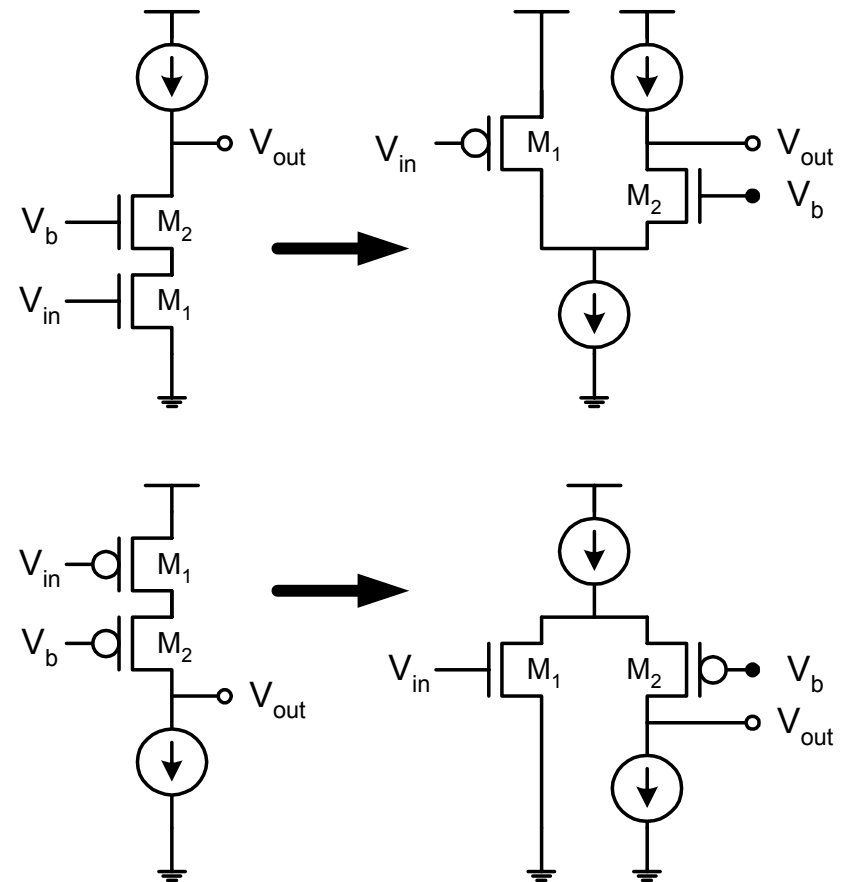
- In order to achieve higher gain, one can use cascoding. These amplifiers are often called 'telescopic' cascode amps. While gain increases, the output range of these devices are limited.



- Connecting the in unity-gain feedback configuration results in significant reduction of output range

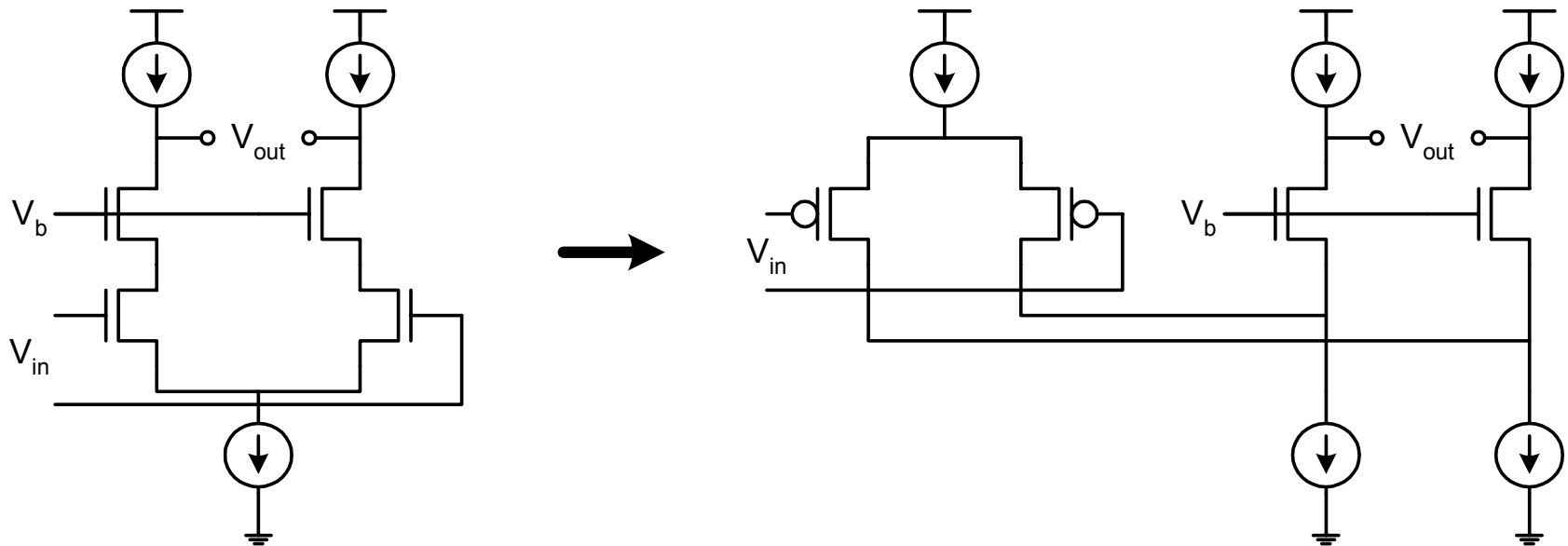
Folded Cascode Circuit

- In order to alleviate some of the drawbacks of telescopic op amps (limited output range), a “folded cascode” can be used (we analyzed this circuit in HW7)
 - M1 is common-source transconductance amp and M2 is common-gate transimpedance amp
 - Advantage is M₂ no longer stacks on top of M₁
 - Possible for either pMOS or nMOS cascodes
- The output resistance for cascode and folded cascode are roughly equivalent ($g_m r_o^2$)

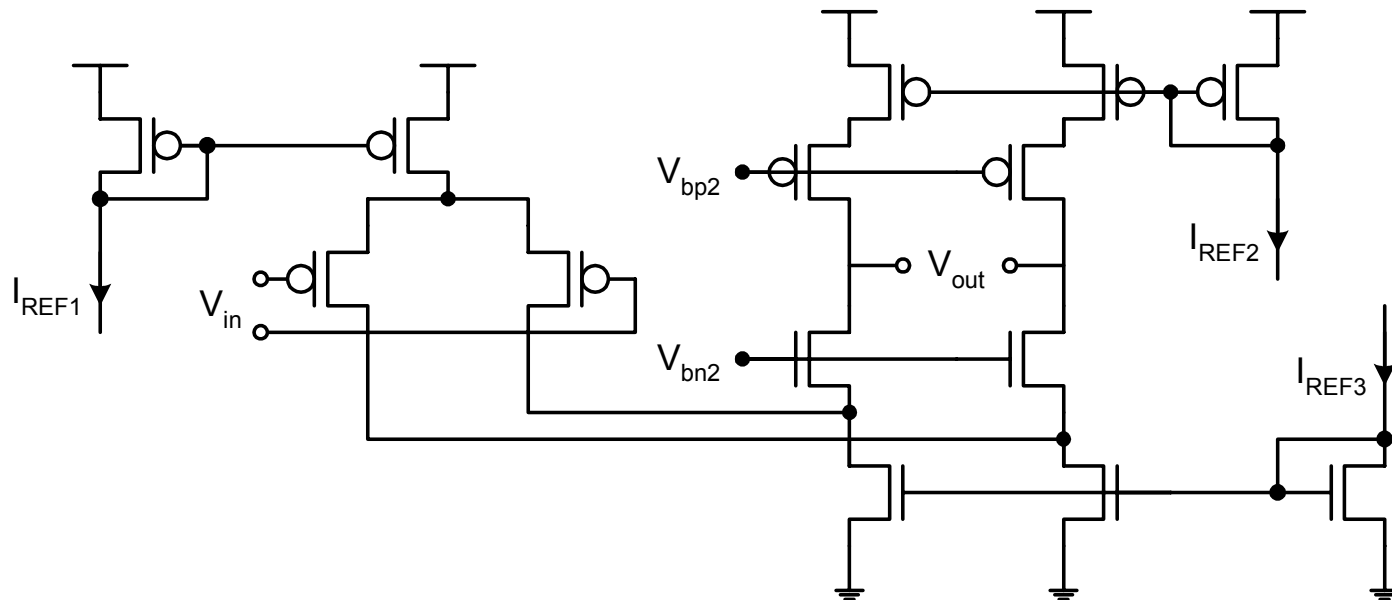


Folded Cascode Amplifier

- Turn a differential telescopic cascode amplifier into a folded cascode amplifier



Full circuit Implementation of Folded Cascode Amplifier



- Reference current sources are set: $I_{REF3} = I_{REF2} + I_{REF1}/2$
- A version with nMOS differential pair inputs also possible (flip upside down)
- What sets output common mode?
 - Depends on relative output resistances looking up and down
 - Can vary with process and reference current mismatches

Gain of a Folded-Cascode Amplifier

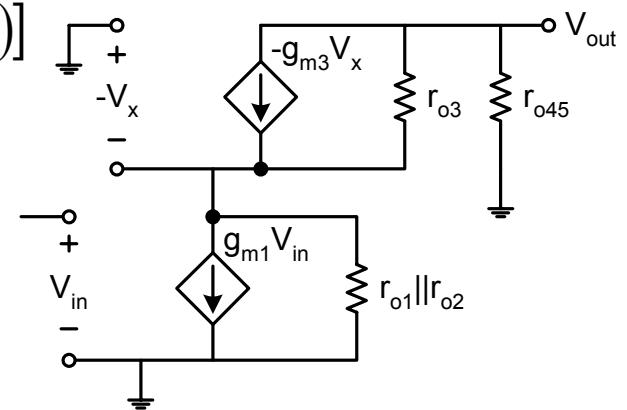
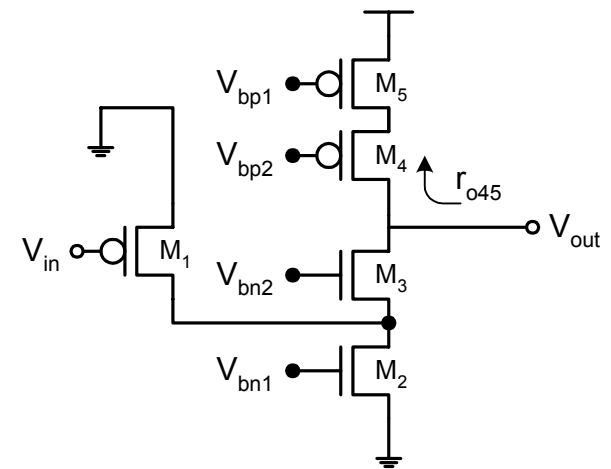
- Calculate gain using the differential half-circuit. Gain can be calculated as $G_m R_{out}$ where G_m is the short-circuit transconductance of the overall circuit and R_{out} is the output resistance.
 - Short out V_{out} to ground and solve for $I_{out}/V_{in} = G_m$
 - Solve for the output resistance

$$|A_v| = G_m R_{out}$$

$$G_m \cong g_{m1}$$

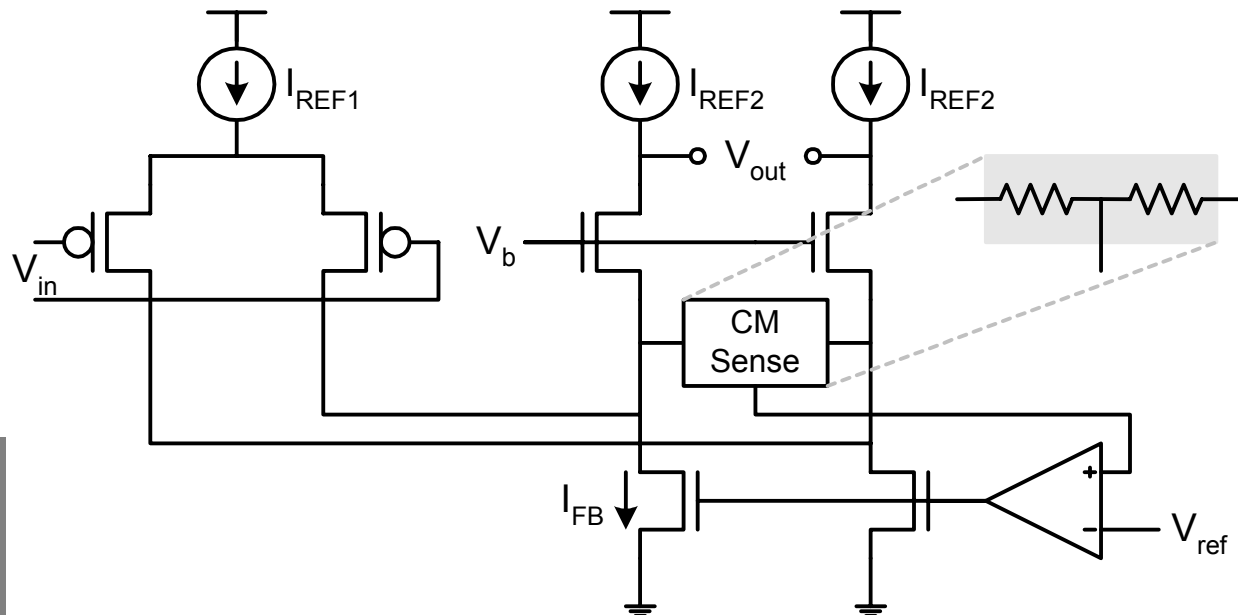
$$R_{out} = r_{o45} \parallel [g_{m3} r_{o3} (r_{o1} \parallel r_{o2})] = g_{m4} r_{o4} r_{o5} \parallel [g_{m3} r_{o3} (r_{o1} \parallel r_{o2})]$$

$$|A_v| \cong g_{m1} \{g_{m4} r_{o4} r_{o5} \parallel [g_{m3} r_{o3} (r_{o1} \parallel r_{o2})]\}$$



+Common-Mode Feedback

- Use feedback to set the output common mode of a folded cascode amplifier, called common-mode feedback
 - Sense the average (common-mode) voltage at the output, compare to a desired reference voltage (V_{ref}), and use it to set the current source

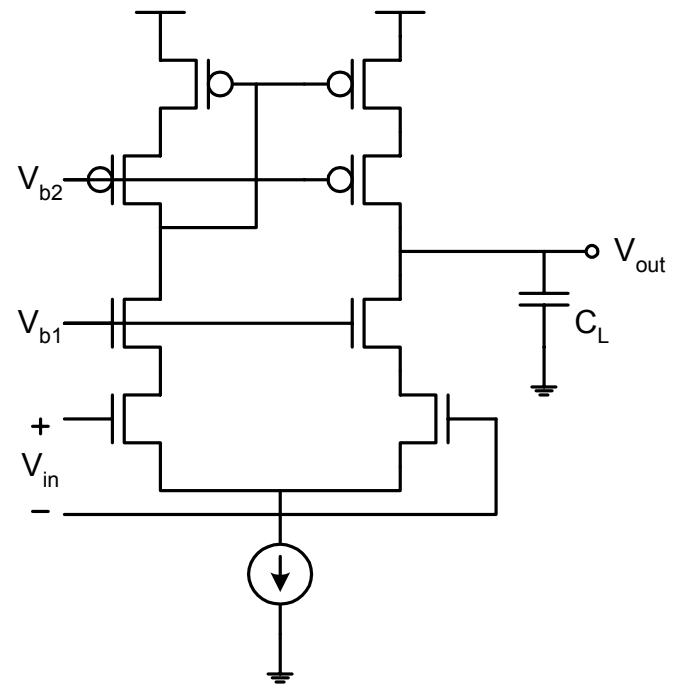
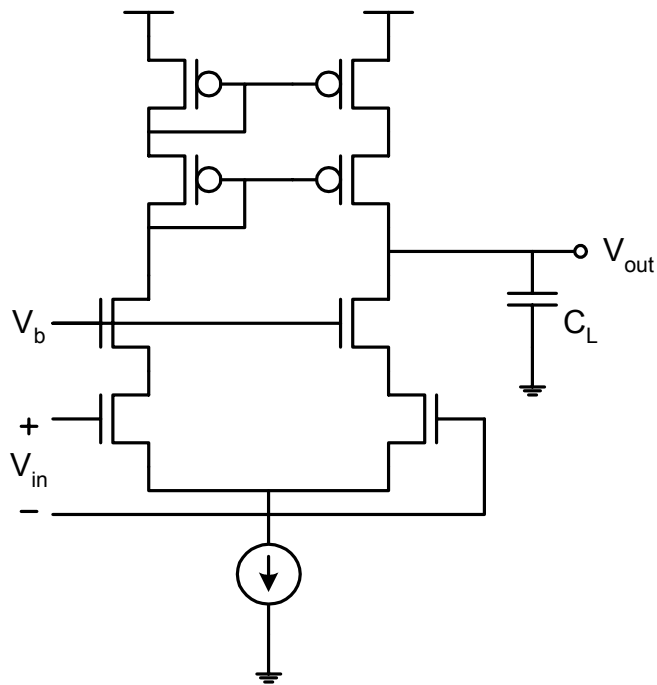


This is one of several methods for implementing CM feedback

- For $V_{in}=0$, feedback sets $I_{FB}=I_{REF2}+I_{REF1}/2$ and common-mode voltage = V_{ref}

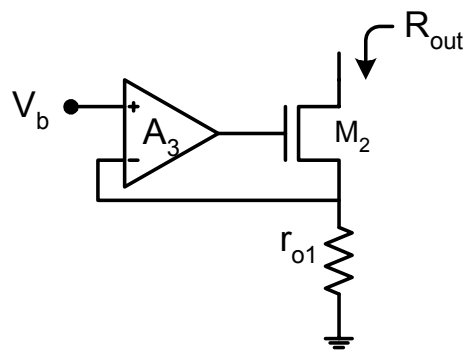
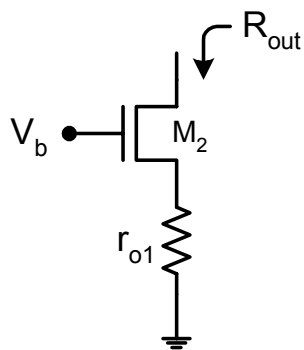
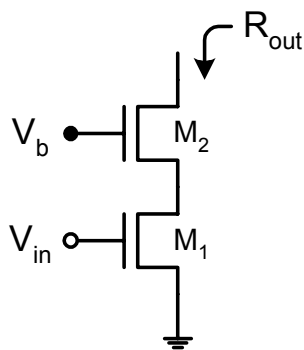
Using High-Swing Cascodes

- We can also use the high-swing cascode circuit as a load to achieve higher output range in a single-end telescopic amp

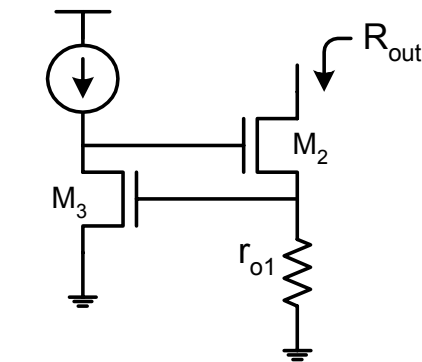


Gain Boosting

- Another method for increasing the output resistance of a cascode circuit is to use gain boosting



Gain Boosting Circuit



Regulated Cascode

- For the gain boosted cascode circuit...

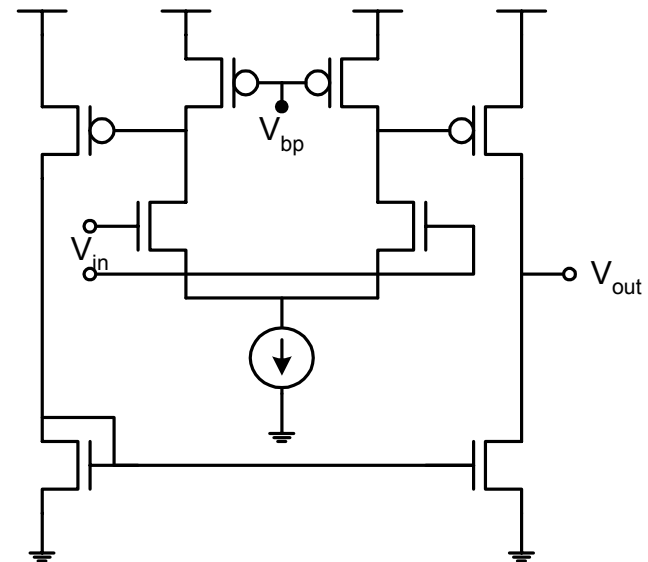
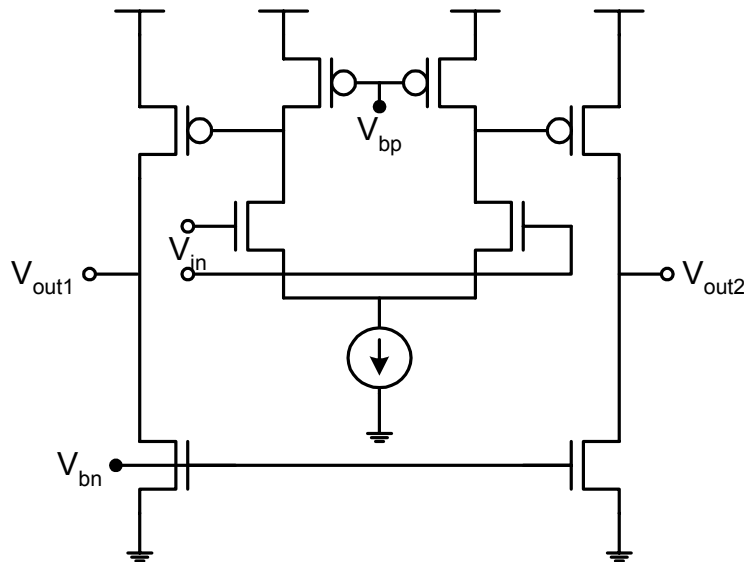
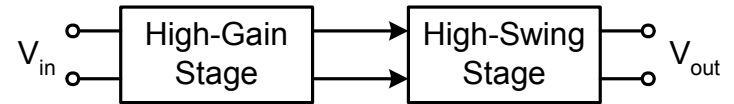
$$R_{out} \approx A_3 g_{m2} r_{o2} r_{o1}$$

- Similarly, with a regulated cascode

$$R_{out} \approx (g_{m3} r_{o3})(g_{m2} r_{o2} r_{o1})$$

Two-Stage Op Amps

- In order to implement amplifiers with high gain and high swing, we must resort to two-stage amplifier designs
 - First stage used to generate high gain
 - Second stage to generate high swing
- Use any high-gain first stage and high-swing second stage
 - two simple examples (differential and single-ended output amplifiers)



Next Time

- We will complete our discussion of Op amp design with a discussion of stability and frequency compensation. We first see how frequency analysis of the loop gain of a feedback circuit gives us the ability to determine whether the circuit will be stable or not. A loop gain transfer function with a single dominant pole can be shown to be stable. However, with multiple poles, stability can be compromised. To combat instability, frequency compensation can be used.