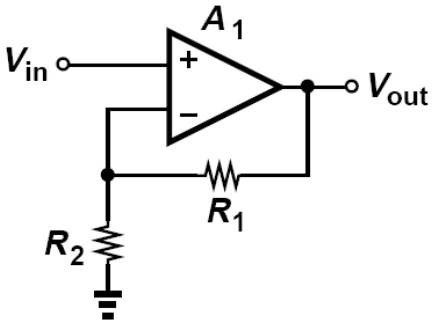
One-Stage Op Amps

Definition

We loosely define an op amp as "a high-gain differential amplifier." By "high," we mean a value that is adequate for the application. The gain could be anywhere from 10^1 to 10^5.

Op amps are usually used to realize a feedback system, i.e., when an operation must be performed precisely.



Old Op Amps

Two decades ago, op amps were designed to satisfy the requirements of many different applications, i.e., the design was to approach an ideal op amp:

$$A_V = \infty \ , \ R_{in} = \infty \ , \ R_{out} = 0$$

In doing so, many other aspects of the performance had to be sacrificed: power, output swing, speed.

Old op amp topology:

Modern Op Amps

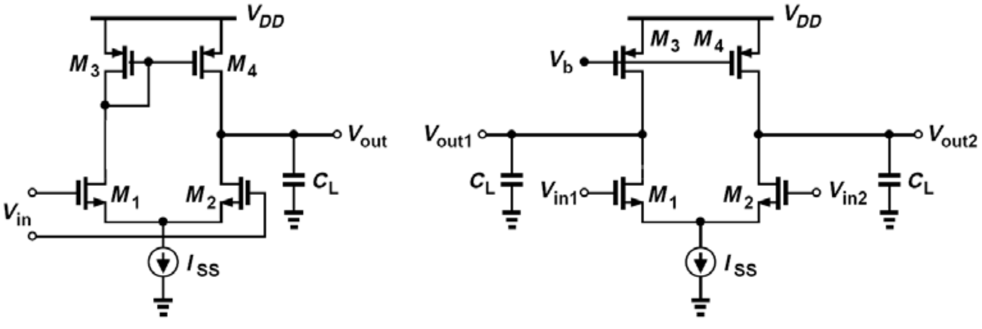
In modern op amps, we design for a specific application, often sacrificing unimportant aspects of the performance to improve the important ones.

For example, most of today's CMOS op amps have a high output impedance (in open loop). As such, they are called "transconductance amplifiers."

Performance Metrics:

- **Gain, Speed, Output Swing, Linearity, Power Dissipation**
- **Noise, Input CM Range, Supply Rejection**
- **Input Offset Voltage**

One-Stage Op Amps

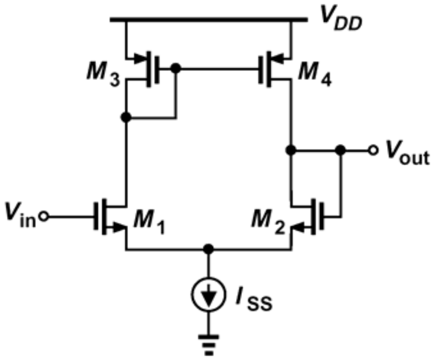


(a) (b)

- **Gain too low: $g_m(r_{on} \parallel r_{op})$**
- **Speed, output swing, power, noise: ok**
- **Mirror pole in single-ended circuit not good.**

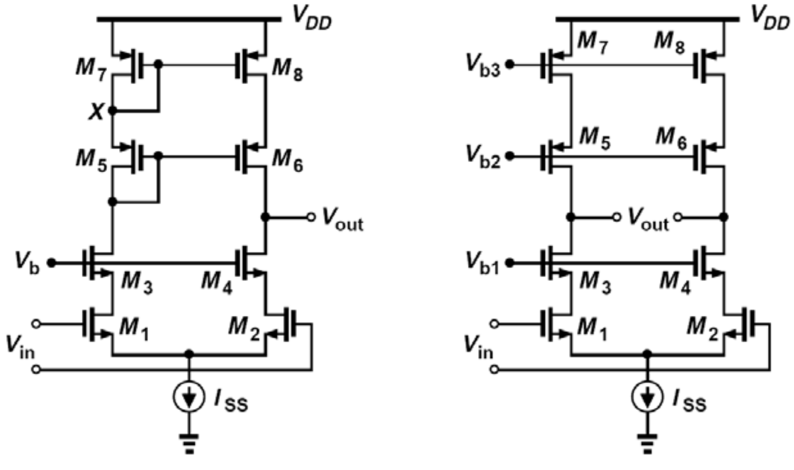
Example

Calculate the input CM range and output impedance of this buffer:



Telescopic Cascode Op Amp

Output Swing:

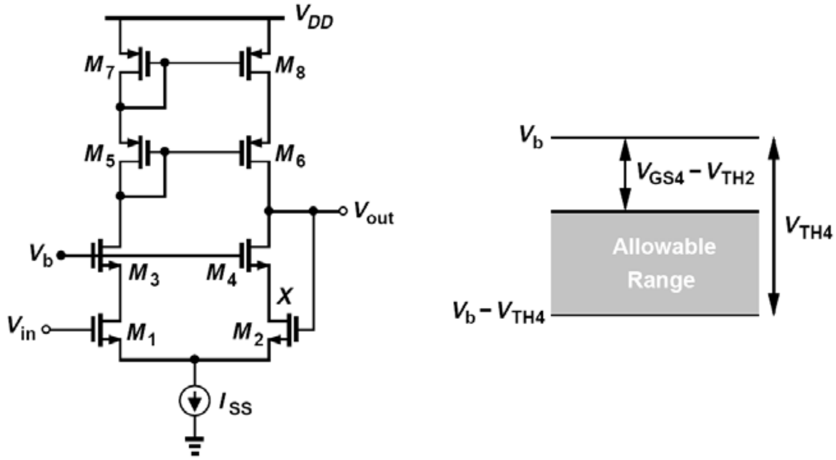


(a) (b)

- **Relatively high gain :**
- **Mirror pole in single-ended circuit not good.**

(Both output swing and mirror pole point to a differential circuit as the better choice.)

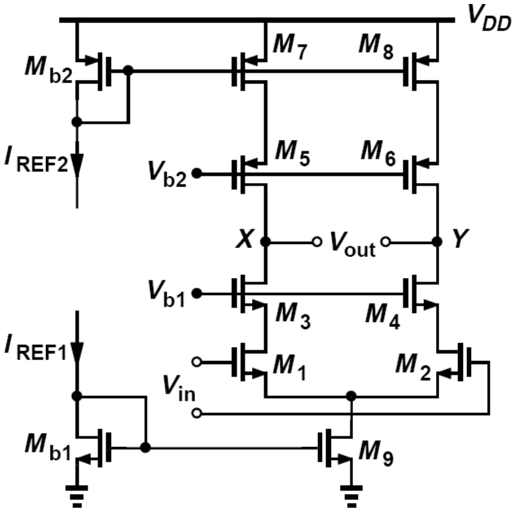
- **It is difficult to short the output to the input of a telescopic op amp:**



- **Speed: somewhat degraded with respect to simple op amp. (But less Miller effect.)**

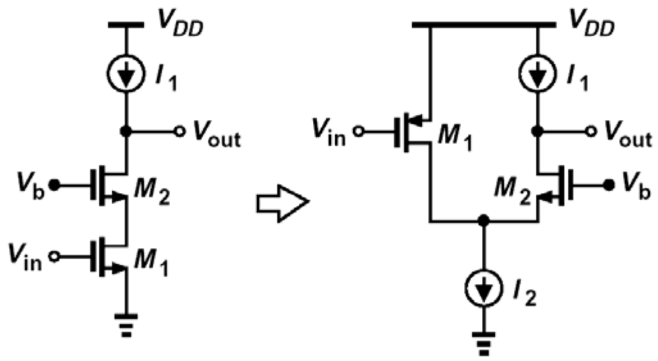
Summary: Telescopic op amp usually provides the best trade-off between gain, power dissipation, speed, and noise. But its output swing is limited and shorting the input and output is difficult.

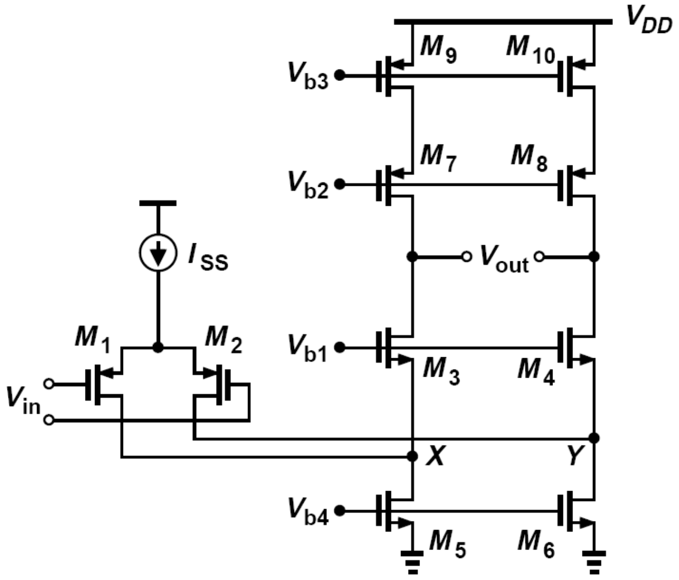
Design Example:



Folded Cascode Op Amp

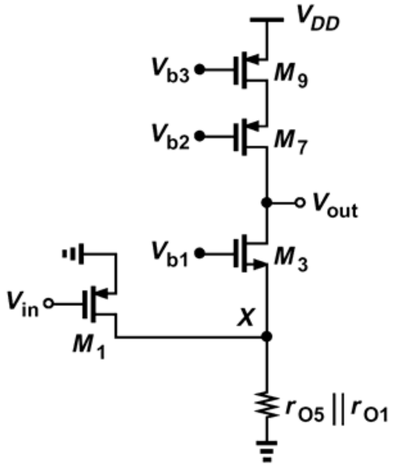
Recall that a cascode can be folded:



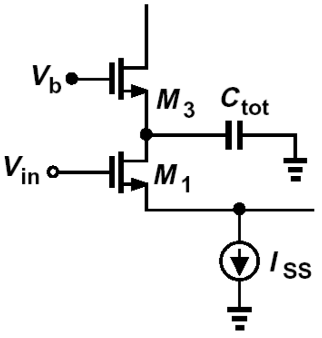


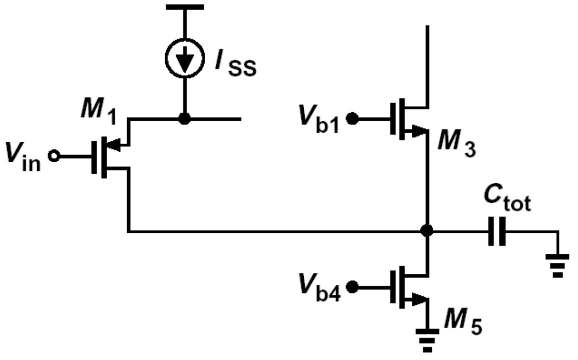
What is the output swing?

What is the voltage gain?

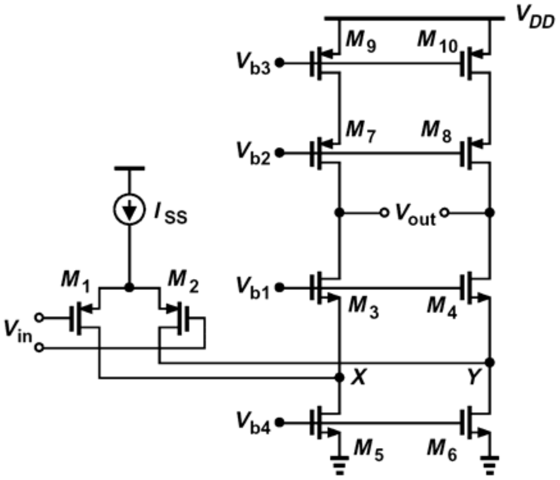


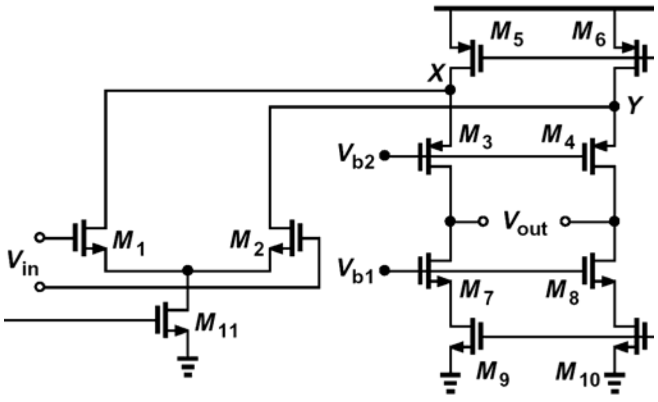
Effect of device cap on nondominant pole:



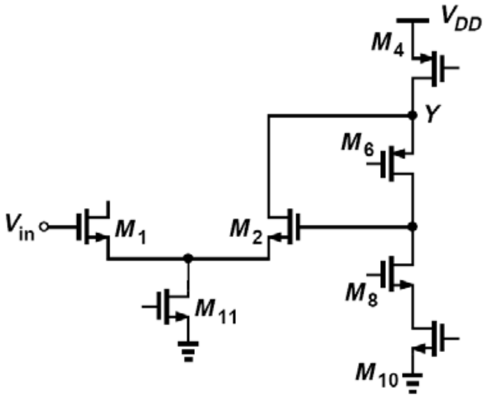


NMOS Input vs. PMOS Input:





Possibility of Shorting Input to Output:



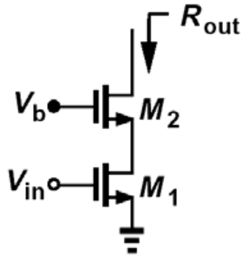
Comparison with telescopic op amp:

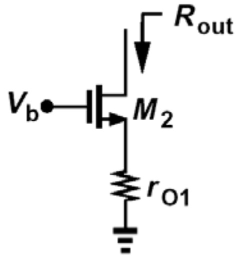
- **Power dissipation**
- **Voltage Gain**
- **Poles at X & Y**
- **Output Swing**
- **Possibility of Shorting I → O**
- **Noise**

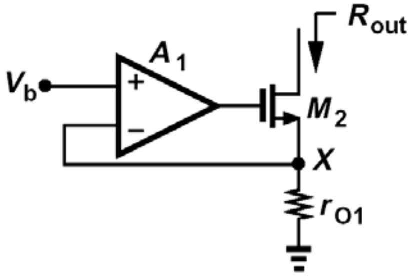
Other Op Amp Topologies

Gain Boosting

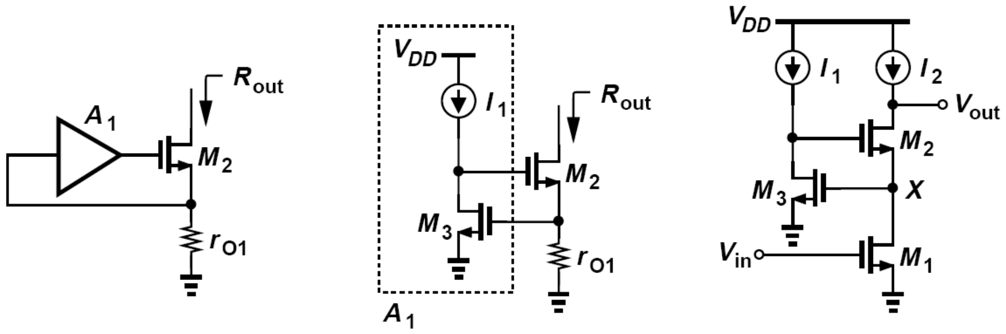
Observation: Feedback can raise the output impedance of a cascode stage:





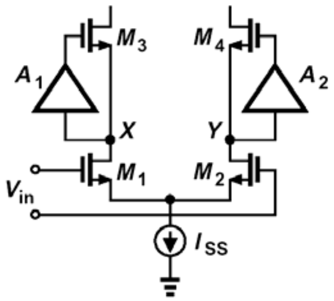


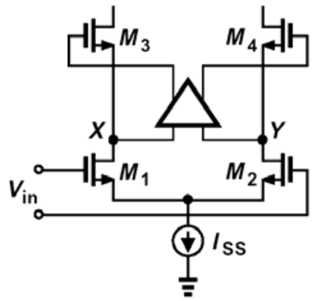
Implementation Example:

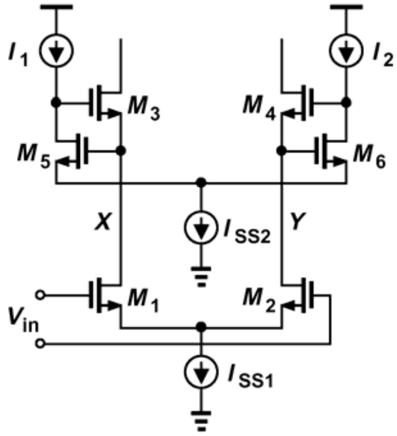


(a) (b) (c)

We can apply this to both PMOS and NMOS cascodes in an op amp:

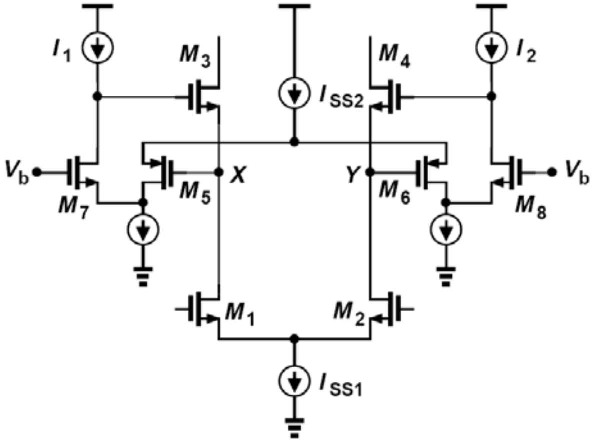






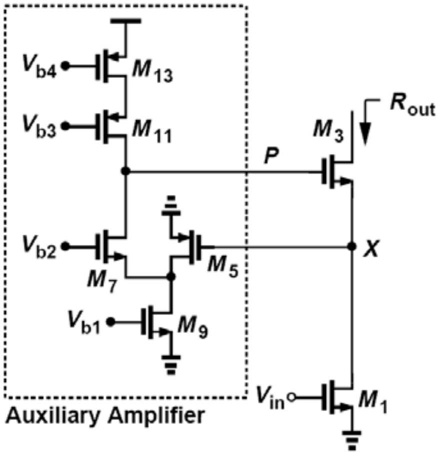
What is the output swing?

Folded-Cascode Auxiliary Amp:

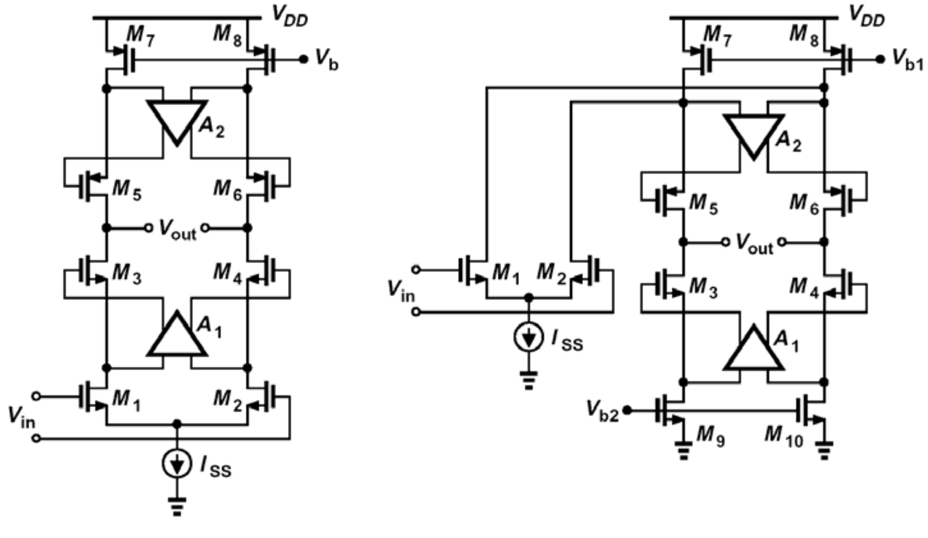


What is the output swing?

Example: Determine the output impedance.



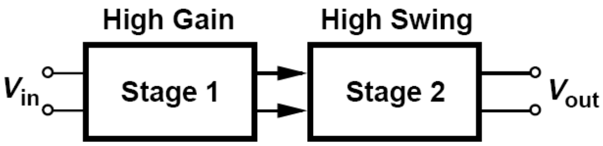
Gain Boosting in Signal Path and Loads:

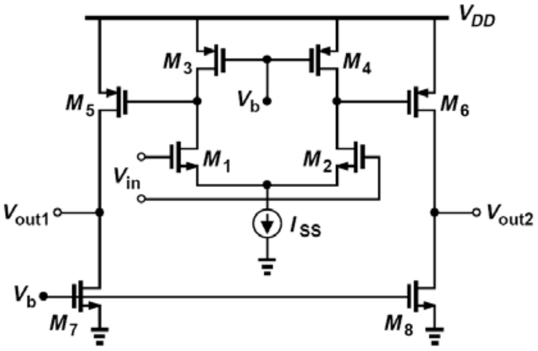


The additional poles in the auxiliary amplifiers somewhat degrade the closed-loop speed with respect to that of a simple folded-cascode op amp.

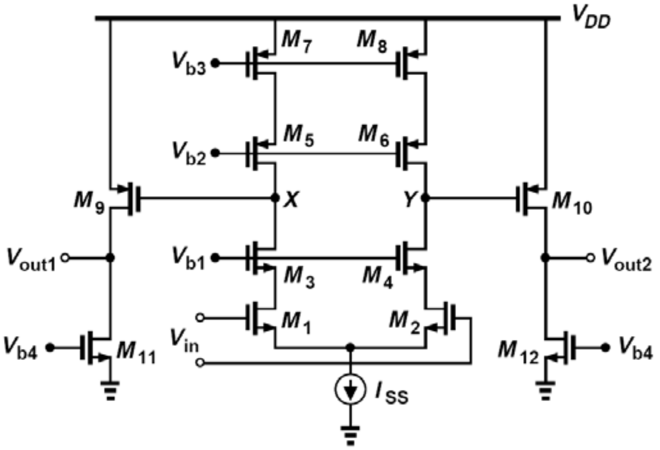
Two-Stage Op Amps

Voltage headroom of today's op amps is heavily constrained. For example, with a 1.2-V supply, losing 4x(overdrive) makes it very difficult to achieve any swing. Also, the lower gmro translates to a low gain in one-stage op amps. → two-stage op amp most common.





Calculate gain and output swings.



More practical design:

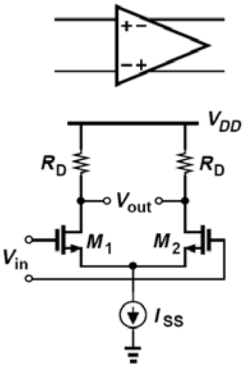
Calculate the gain and the output swings.

Can we cascade more stages to achieve a higher gain?

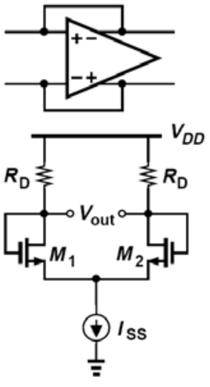
Comparison

	Gain	Output Swing	Speed	Power Dissipation	Noise
Telescopic	Medium	Medium	Highest	Low	Low
Folded−Cascode	Medium	Medium	High	Medium	Medium
Two−Stage	High	Highest	Low	Medium	Low
Gain−Boosted	High	Medium	Medium	High	Medium

Common-Mode Feedback

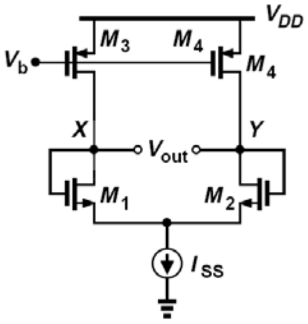


(a)

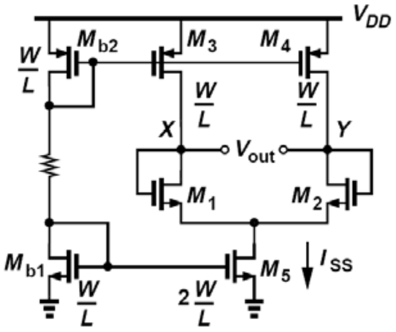


(b)

In fully-differential op amps, the output CM level is usually not well-defined.



(a)

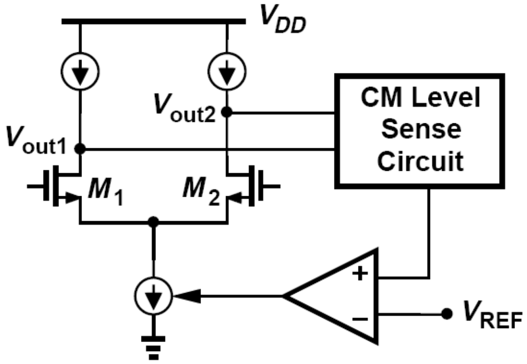


(b)

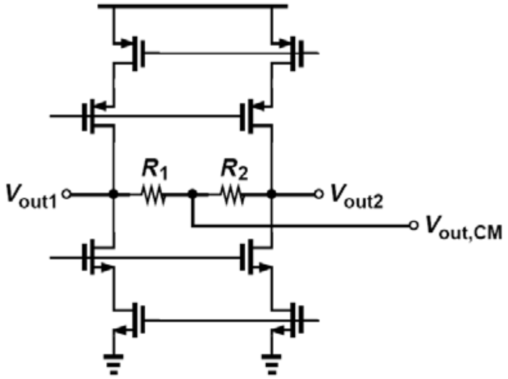
In this example, if the outputs are shorted to the inputs, the drain current of M_3 may not be exactly equal to $I_{ss}/2$.

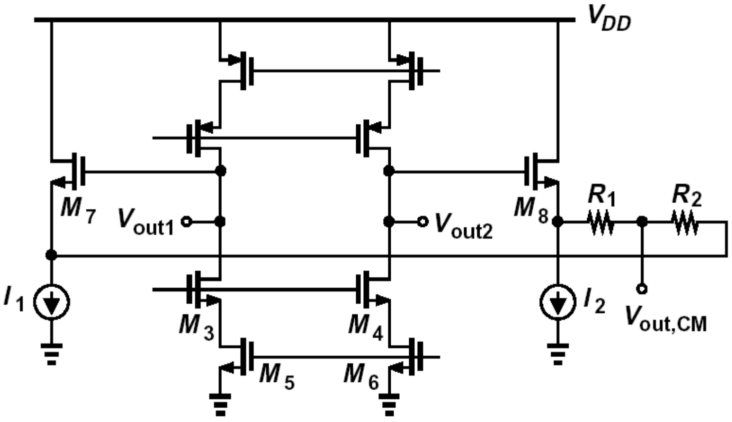
=> Need CM feedback:

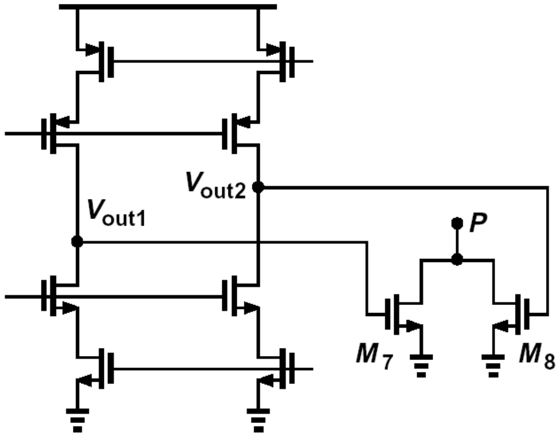
1. **Measure output CM level;**
2. **Compare with a reference;**
3. **Apply the error to correct the level.**



CM Sensing Techniques:

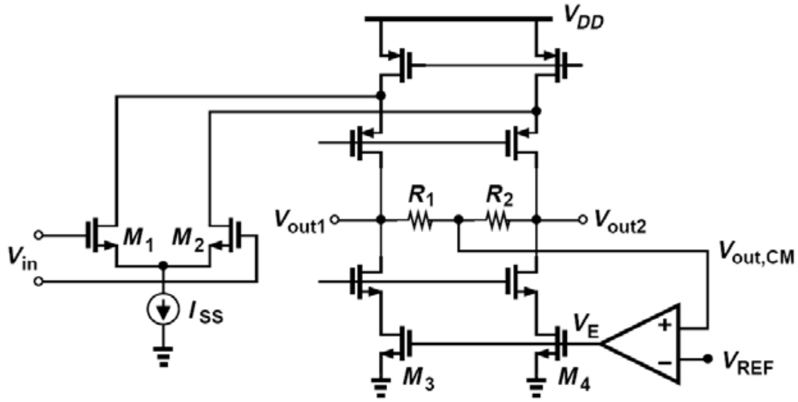






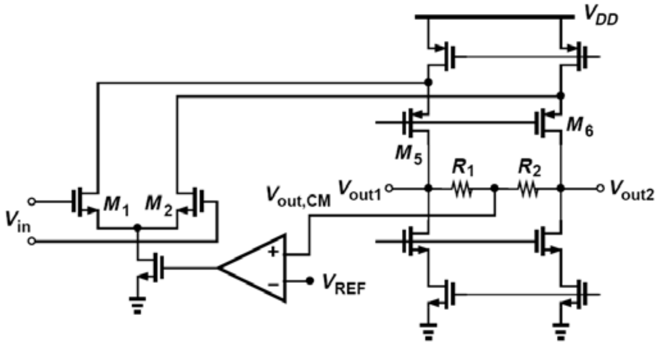
CM Feedback Techniques:

1. Control cascode current sources:

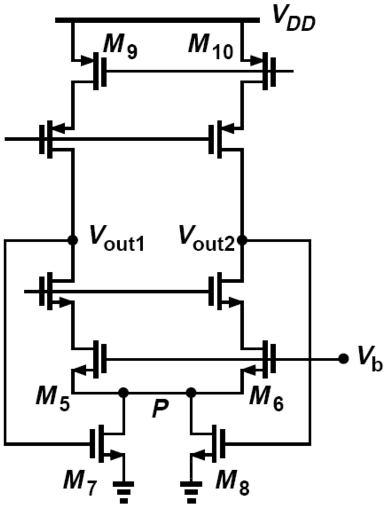


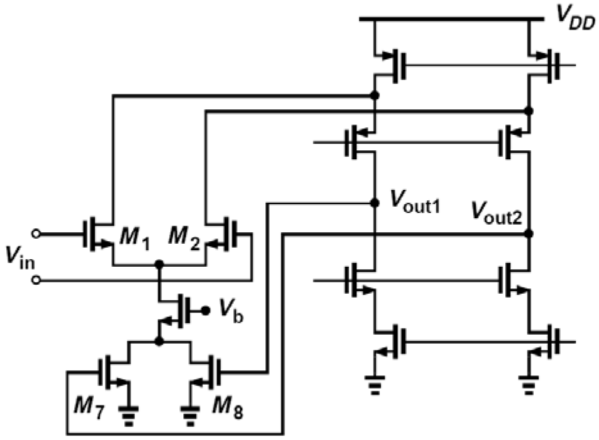
(Can also apply the feedback to the top current sources.)

2. Control tail current source:



Alternatives using transistors for CM sensing:





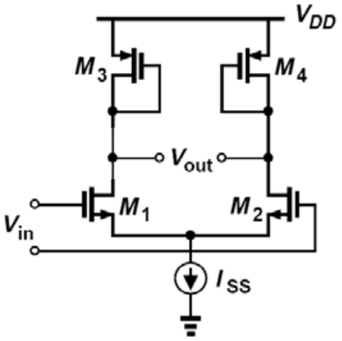
Calculate the output CM level:

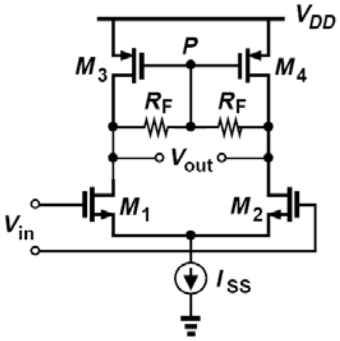
$$\frac{1}{\mu_n C_{ox}(\frac{W}{L})_{7,8}(V_{out2}+V_{out1}-2V_{TH})} = \frac{V_b - V_{GS5}}{2I_D}$$

The problem is that we don't exactly know what output CM we get. The magnitude of R_{tot} depends on process and temperature.

Another problem is that R_{tot} requires some voltage drop, decreasing the available output swing.

Simple CMFB

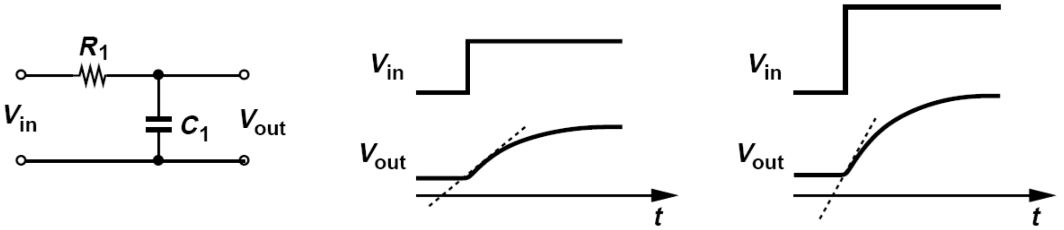




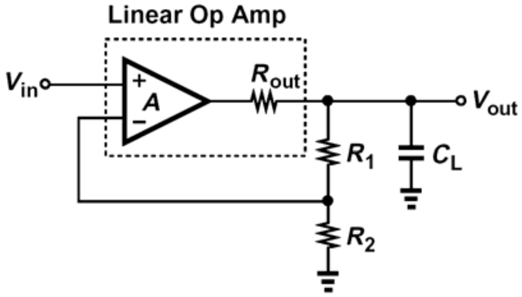
Slew Rate

Observation

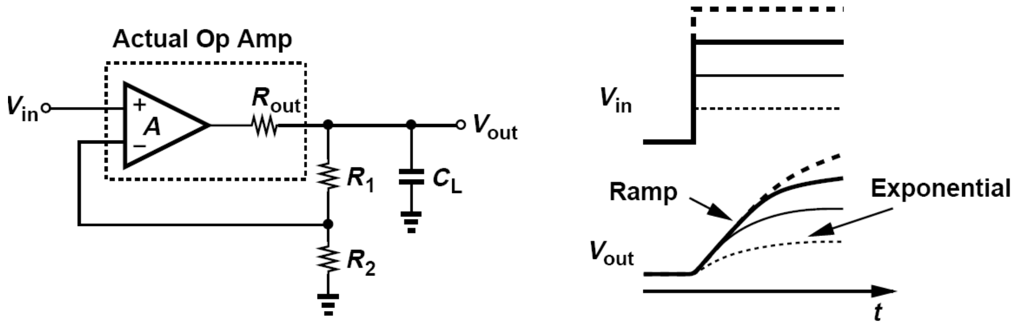
In a linear circuit, the slope of the step response depends on the final value:



In a linear feedback system, the same relationship exists:



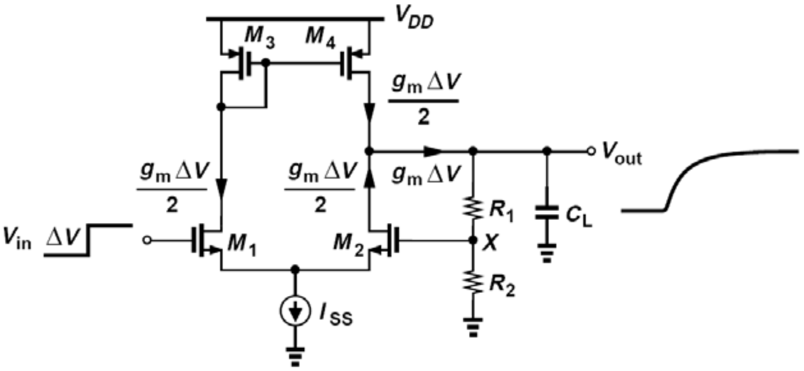
However, in a realistic case, an interesting effect occurs:

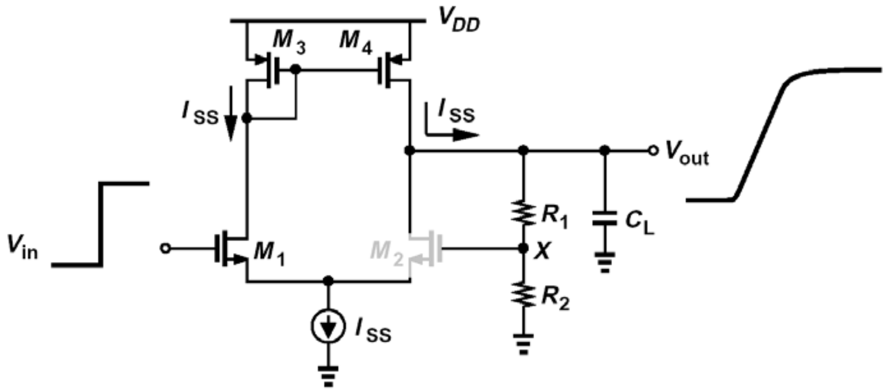


It seems that the maximum current available to charge the load capacitance is limited. This effect is called “slewing” and the slope of the transition is called the “slew rate.”

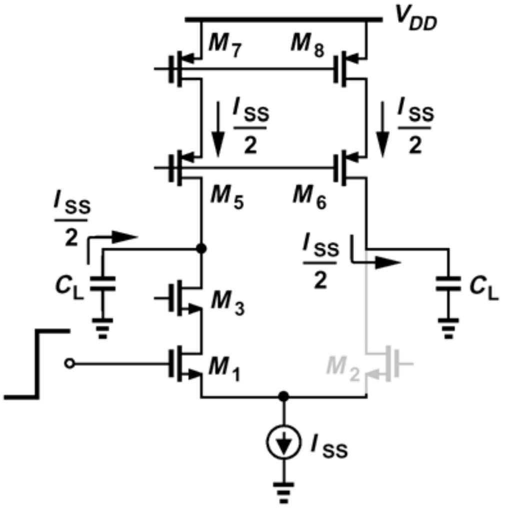
What causes slewing?

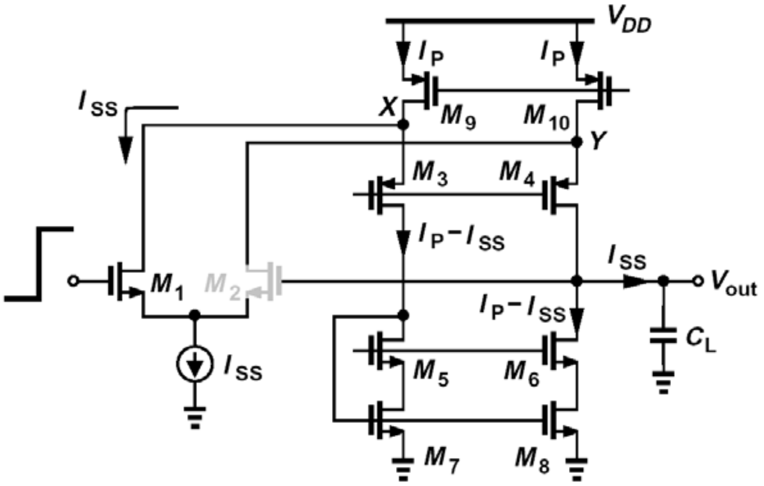
Example





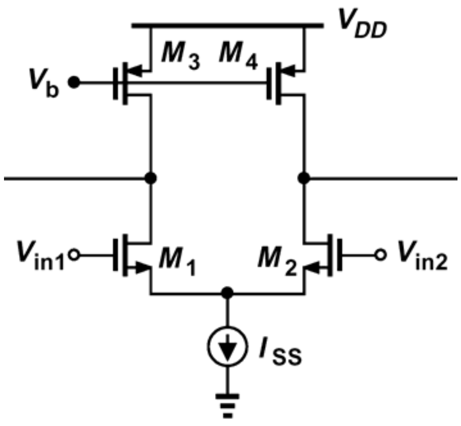
Slewing in Cascode Op Amps

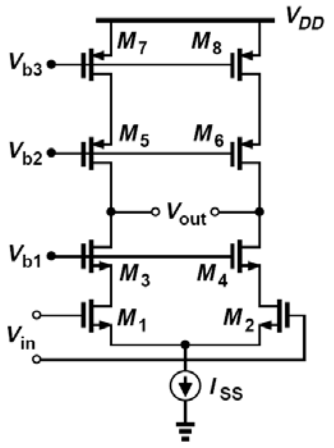


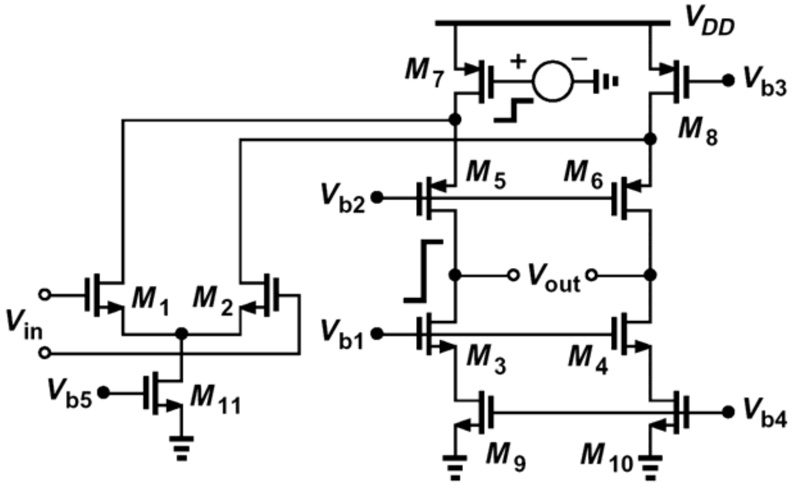


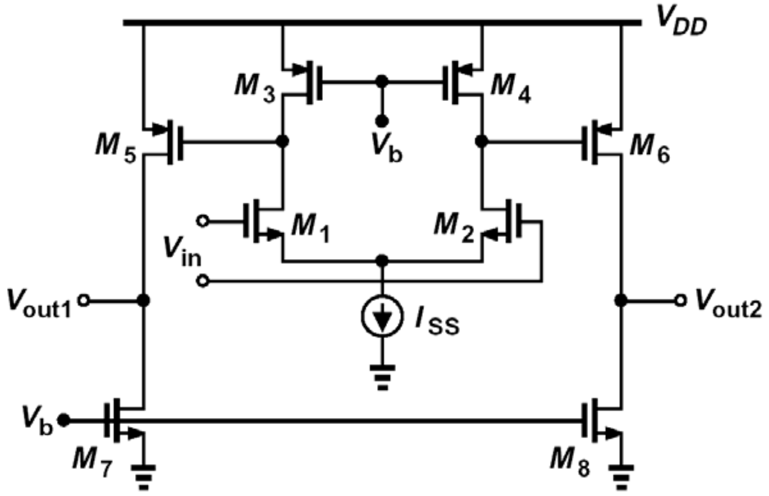
What is the optimum choice of $I_1 = I_2$ in terms of I_{ss}?

Noise in Op Amps






V_DD
M7
+
−
V_b3
M8
M5
M6
V_b2
V_out
M1
M2
V_in
V_b1
M3
M4
V_b5
M11
V_b4
M9
M10


V_DD
M3
M4
V_b
M5
M6
M1
M2
V_in
V_out1
V_out2
I_SS
V_b
M7
M8