Opamps Part 2

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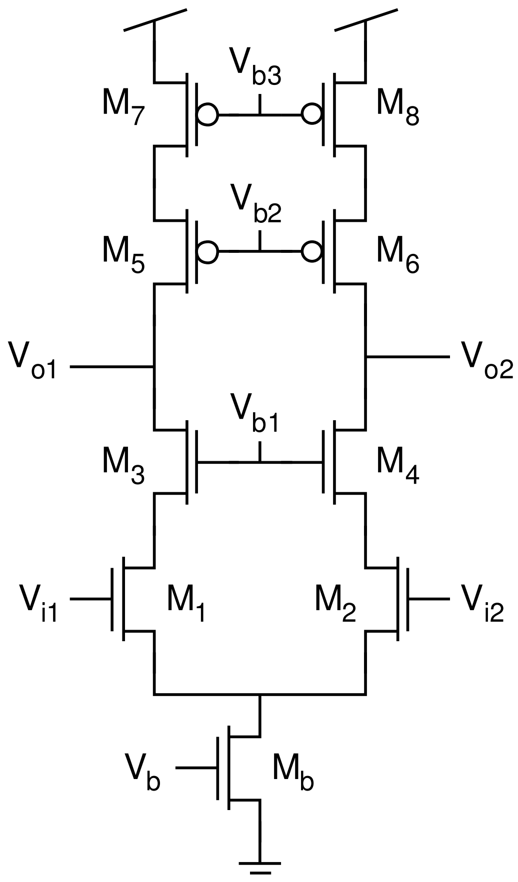
High Gain

- Goal of opamp design – High gain
- Previous opamps do not have very high gain
- Example – 5T Opamp
  - Gain = $-g_{m1}r_{o2}||r_{04}$
  - Subthreshold operation – |Gain| ≈ 650
  - Above threshold operation – |Gain| ≈ 50
- Need much higher gain
  - Casc<u>o</u>de structures provide high gain
  - Casc<u>a</u>de of multiple amplifiers

Telescopic Opamps



$$A_v = g_{m1}\left(r_{o2}g_{x4}r_{o4} \parallel r_{o8}g_{x6}r_{o6}\right)$$

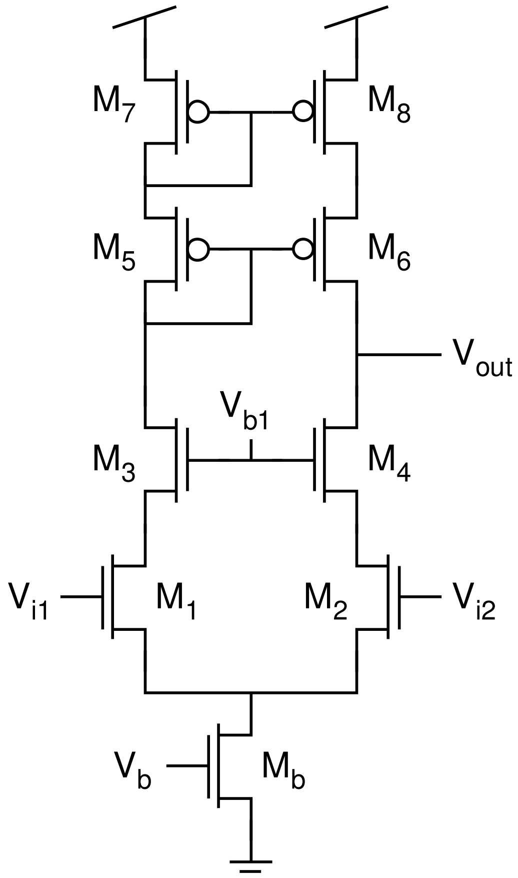
Approximately the square of the original gain

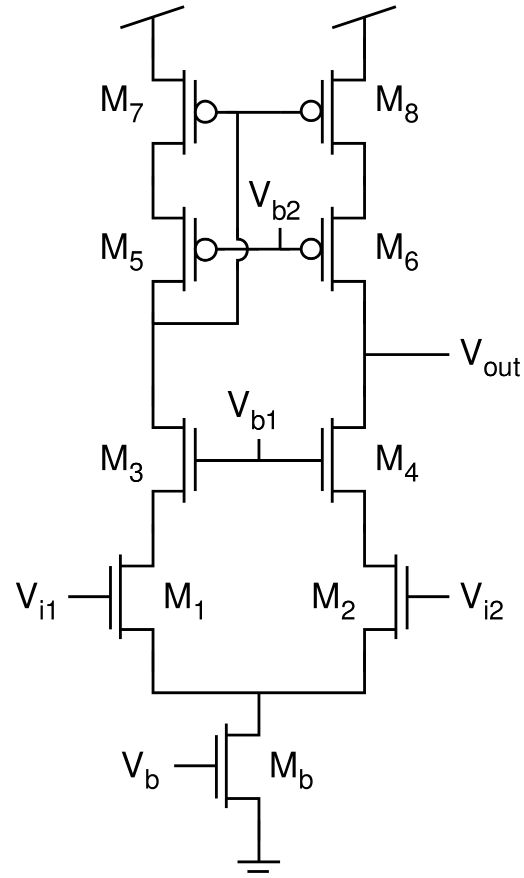
This is a high-speed opamp design

Major Drawback

- Very limited allowable signal swing
- Must ensure all transistors stay in saturation
- Limited signal swing at both the input and the output

Telescopic Opamps – Single-Ended Output

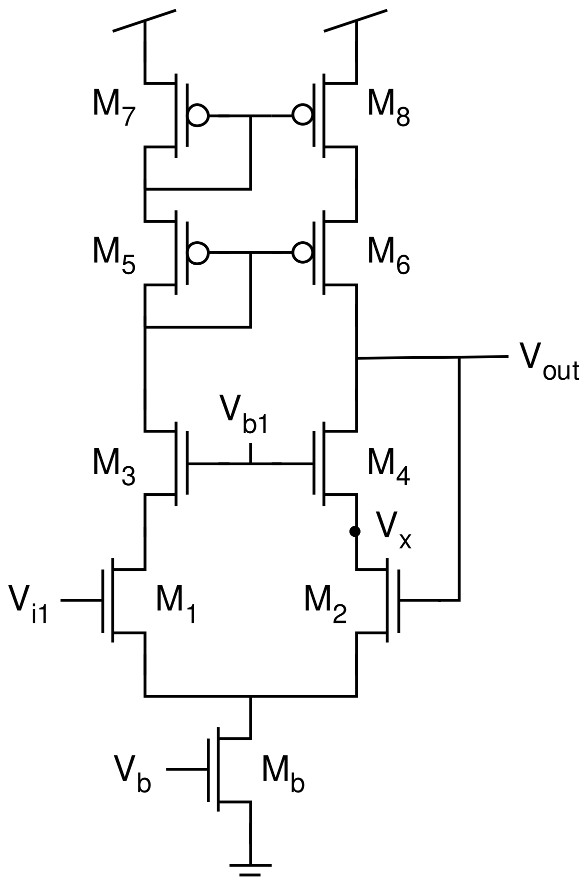




- Increased output signal swing
- Requires an additional bias

Unity-Gain Feedback Connection

- Another major drawback to the telescopic opamp is the very limited range for unity-feedback connections
- Therefore, this opamp is rarely used as a unity-gain buffer
- Often used in switched-capacitor circuits, where the output is fed back to the input only for short durations of time



For M_2 and M_4 to stay in saturation

$$V_{out} \le V_x + V_{T2} = V_{b1} - V_{gs4} + V_{T2} \quad \text{for } M_2$$

$$V_{out} \ge V_{b1} - V_{T4} \quad \text{for } M_4$$

$$V_{b1} - V_{T4} \le V_{out} \le V_{b1} - V_{gs4} + V_{T2}$$

Voltage range for V_{out}

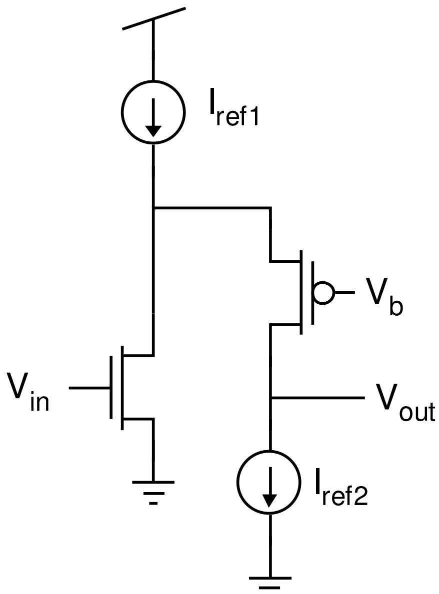
$$V_{max} - V_{min} = V_{T4} - V_{gs4} + V_{T2}$$

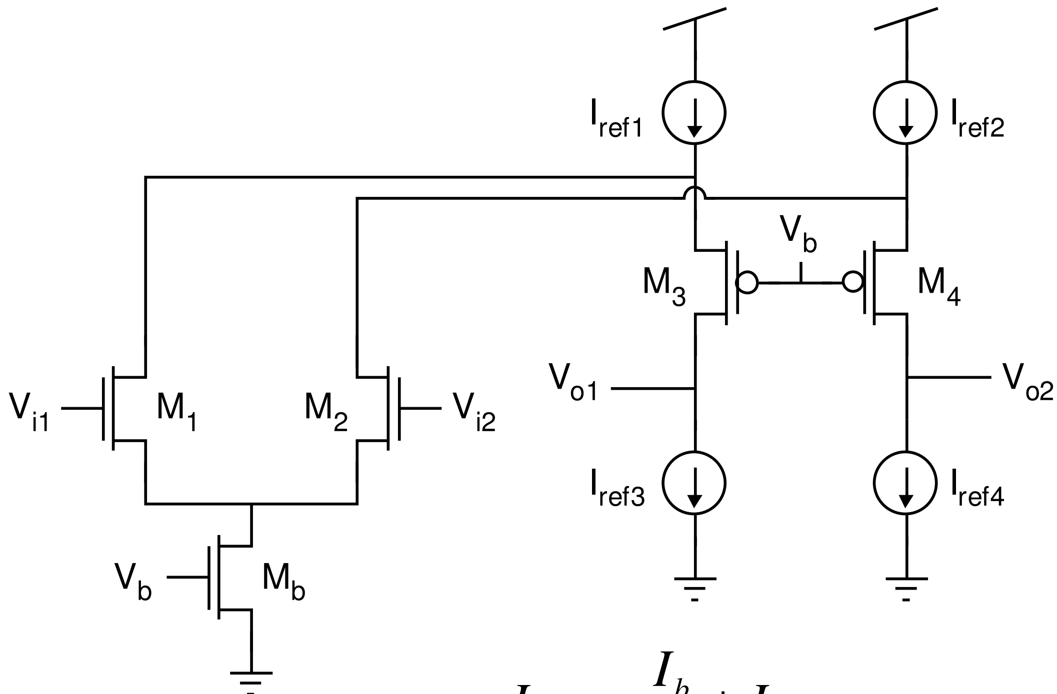
$$= V_{T2} - V_{ov4}$$

Always less than a threshold voltage

Folded Cascode Structure

Used in opamps to increase input/output voltage ranges

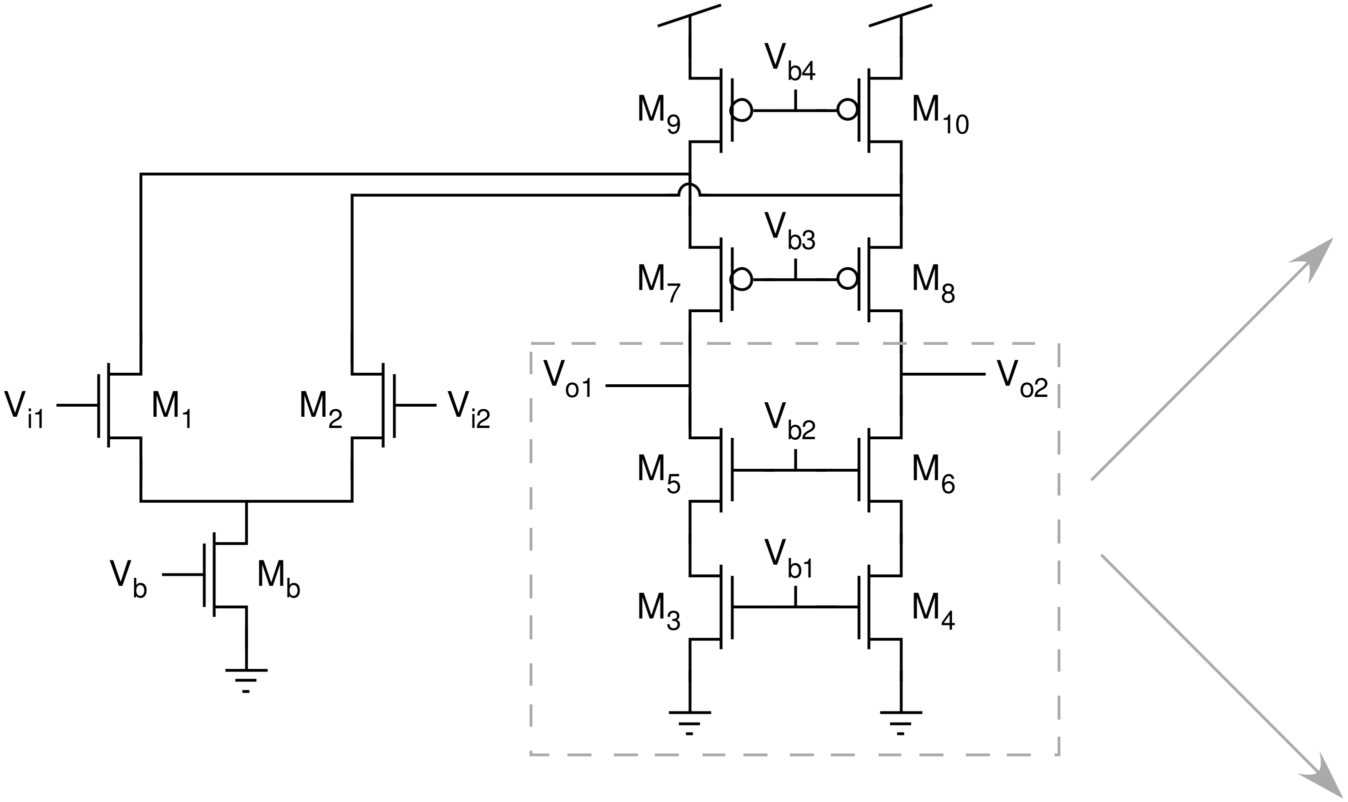


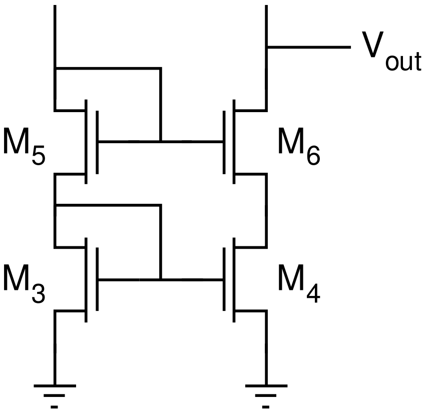


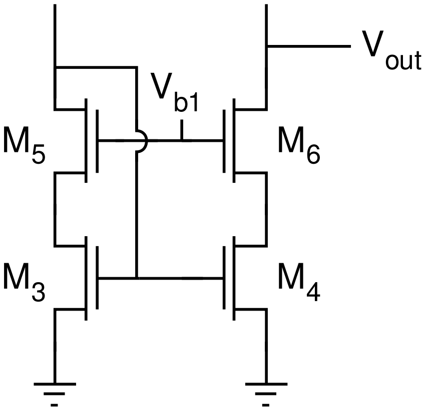
$$I_{ref3} = \frac{I_b}{2} + I_{ref1}$$

- I_{ref1} is typically greater than I_b to improve response after slewing
- Burns more power than the telescopic version

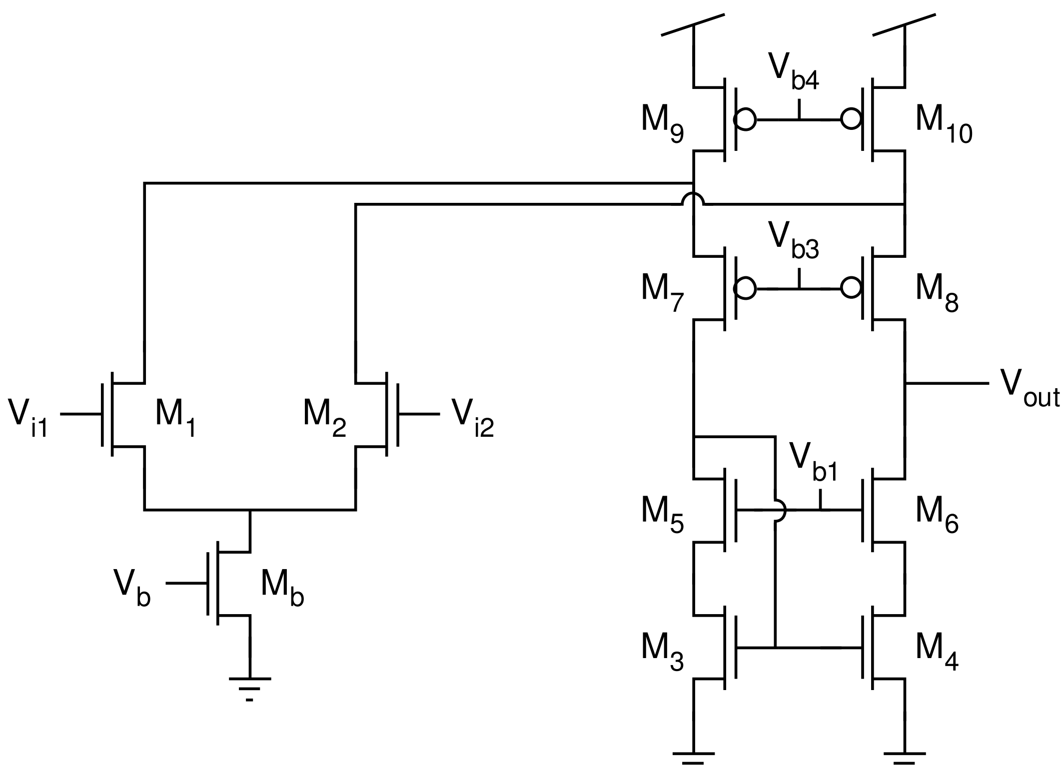
Folded Cascode Opamp







Differential Gain of the Folded Cascode Opamp



- Resistance looking into the source of M_7 is much less than $r_{o1}||r_{09}$
- Virtually all current flowing out of M_1 will flow into the source of M_7

$$A_v = g_{m1}\left[\left(r_{o8}g_{x8}\left(r_{o10} \parallel r_{o2}\right)\right) \parallel r_{o6}g_{x6}r_{o4}\right]$$

[Slightly] reduced gain from telescopic amplifier

ICMR

$$V_{gs1} + V_{sat,b} \text{ to } V_{dd} - V_{sat,9} - V_{sat,1} + V_{gs1}$$

$$= V_{dd} - V_{ov,9} + V_{T1}$$

Can use pFET inputs for operation to ground

Output range

$$2V_{sat} \text{ to } V_{dd} - 2V_{sat}$$

Folded Cascode Summary

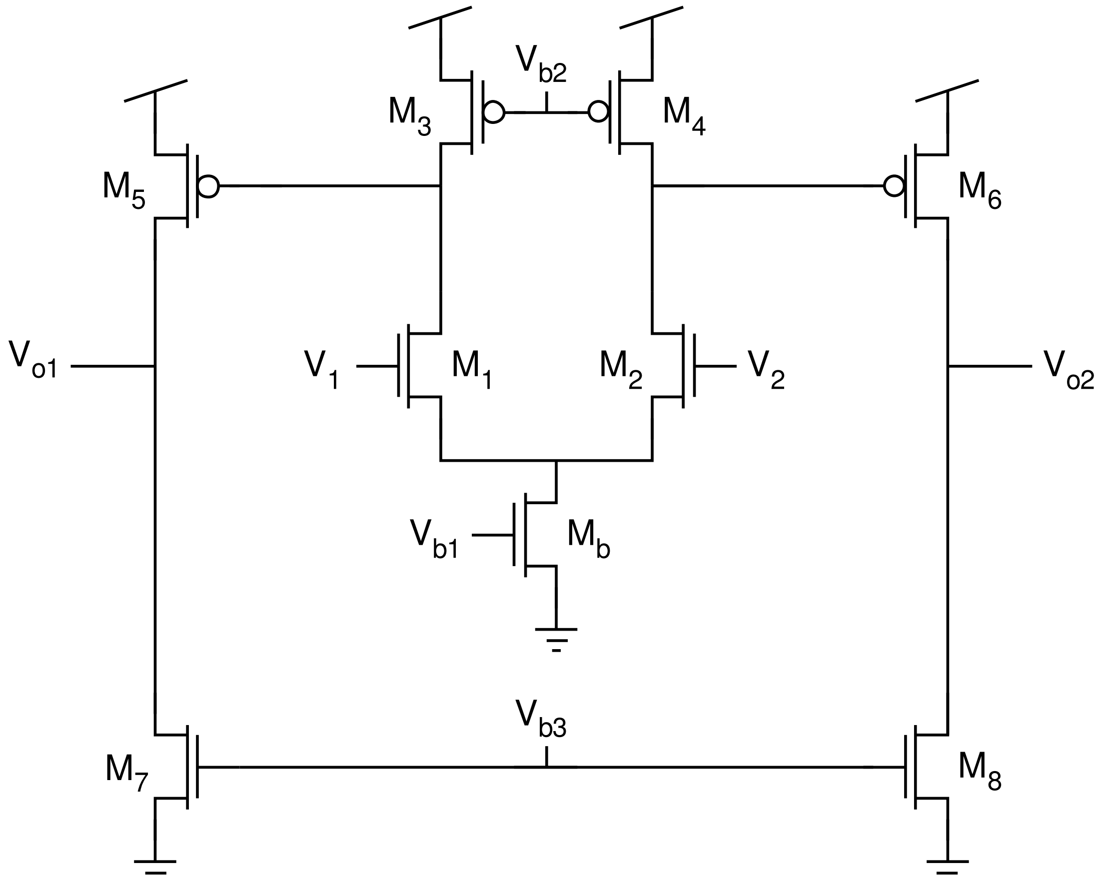
Comparison to Telescopic Opamp

- Larger input/output swings
- Can be used in unity-gain configuration
- One less voltage is *required* to be set
    - Do not need to worry about the CM voltage
- Decreased voltage gain
- Increased power consumption (plus, I_9 should be ~1.2-1.5 times I_b)
- Lower frequency of operation
- More noise

Overall, the folded cascode opamp is a good, widely used opamp

Two-Stage Opamp

- Cascade of two amplifier stages
  - First stage – Differential amplifier
  - Second stage – High-gain amplifier



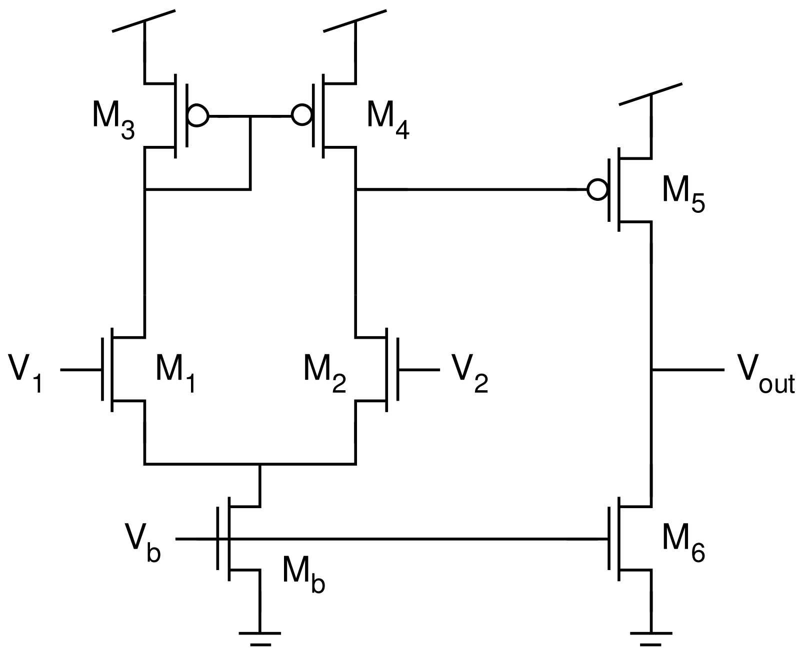
Two-Stage Opamp (Single-Ended Output)

- Cascade of two amplifier stages
  - First stage – Differential amplifier
  - Second stage – High-gain amplifier (CS Amp)

$$A_{v1} = -g_{m1} r_{o2} \parallel r_{o4}$$

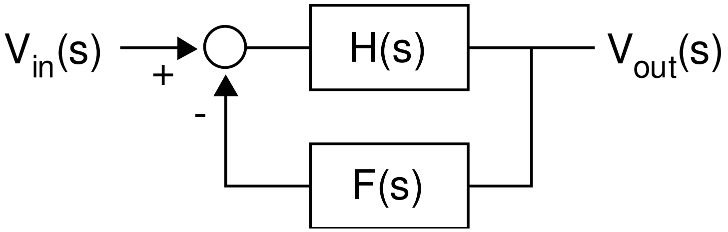
$$A_{v2} = -g_{m5} r_{o5} \parallel r_{o6}$$

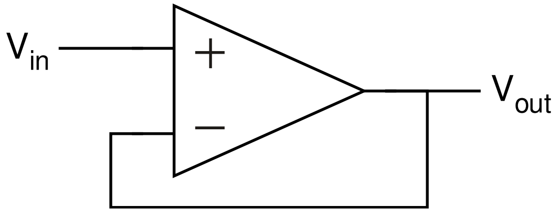
$$A_v = \left(g_{m1} r_{o2} \parallel r_{o4}\right)\left(g_{m5} r_{o5} \parallel r_{o6}\right)$$



- Large output swing ($V_{sat,6}$ to $V_{dd} - V_{sat,5}$)
- ICMR same as 5T opamp
- Unity-gain configuration sets a minimum voltage to V_{gs1}-$V_{sat,b}$
- Can include cascodes, as well
- Adding an amplifier stage adds a pole
- Typically requires compensation to remain stable

Feedback Systems

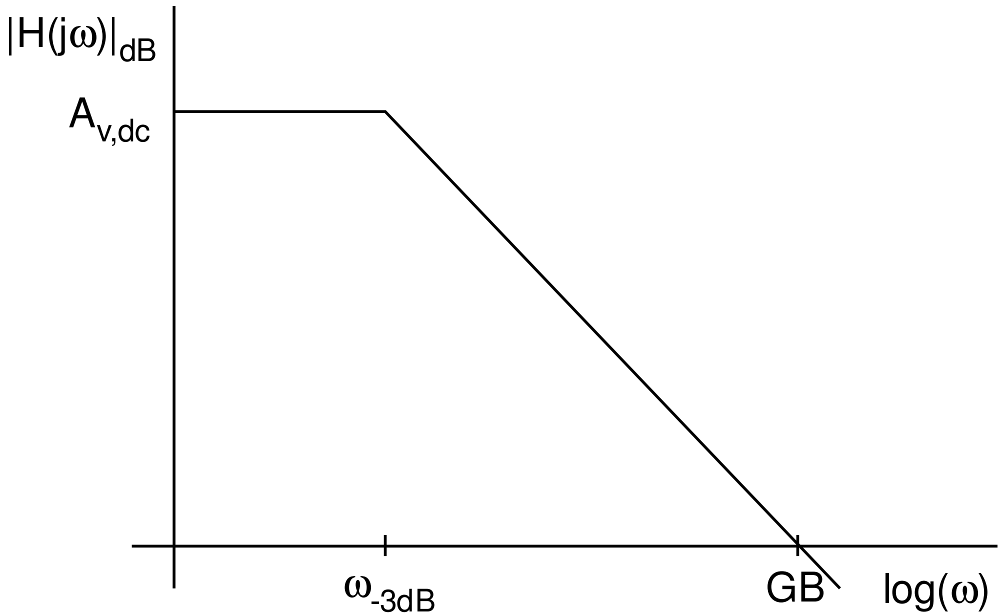




If F(s)=1, then unity gain feedback

Opamp Poles

- Several poles in an opamp
- Typically, one pole dominates
  - Dominant pole is closest to the origin (Re-Im Plot)
  - Dominant pole has the largest time constant
- Dominant pole is often associated with the output node in an unbuffered opamp
  - Large Rout and load capacitance



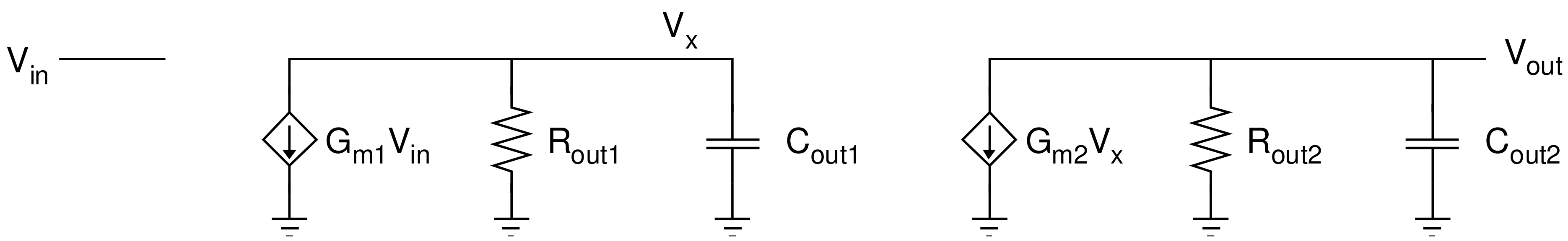
Gain Bandwidth, GB

$$GB = A_{v,dc}\omega_{-3dB}$$
$$= \left(-G_m R_{out}\right)\left(\frac{-1}{R_{out}C_{out}}\right)$$
$$= \frac{G_m}{C_{out}}$$

Multiple Poles

- For multi-pole systems, other poles may be close enough to the dominant pole to affect stability
- Typically two poles are of primary concern
- Typically, for a two-stage, unbuffered opamp
  - Pole at output of stage 1
  - Pole at output of stage 2
  - Dominant pole is usually associated with a large load capacitance (i.e. output node)

Multiple Poles

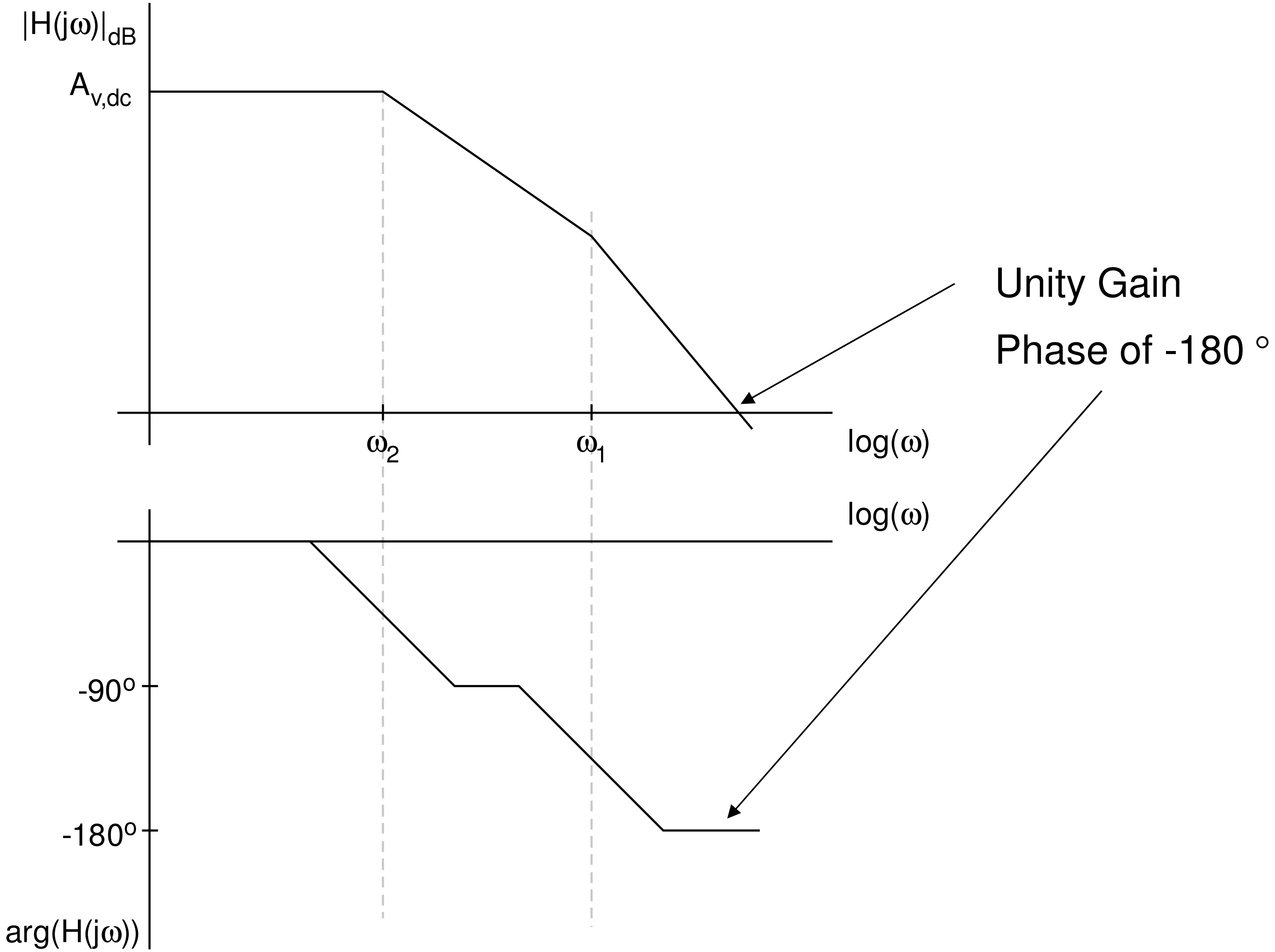


$$p_1 = \frac{-1}{R_1 C_1}$$

$$p_2 = \frac{-1}{R_2 C_2}$$

p_2 typically dominates because of the load capacitance

Multiple Poles



Negative Feedback

In negative feedback configuration, if

$$\left|H(j\omega)\right| \geq 1 \text{ and } \angle H(j\omega) = -180^\circ$$

Then, combined with subtraction (-180 °) at the input

- Results in -360 °phase shift
- This is addition (positive feedback)
  - Since the gain is > 1 at this frequency, the output will grow without bound
  - Therefore, this system is unstable at this frequency

- For stability, must ensure that

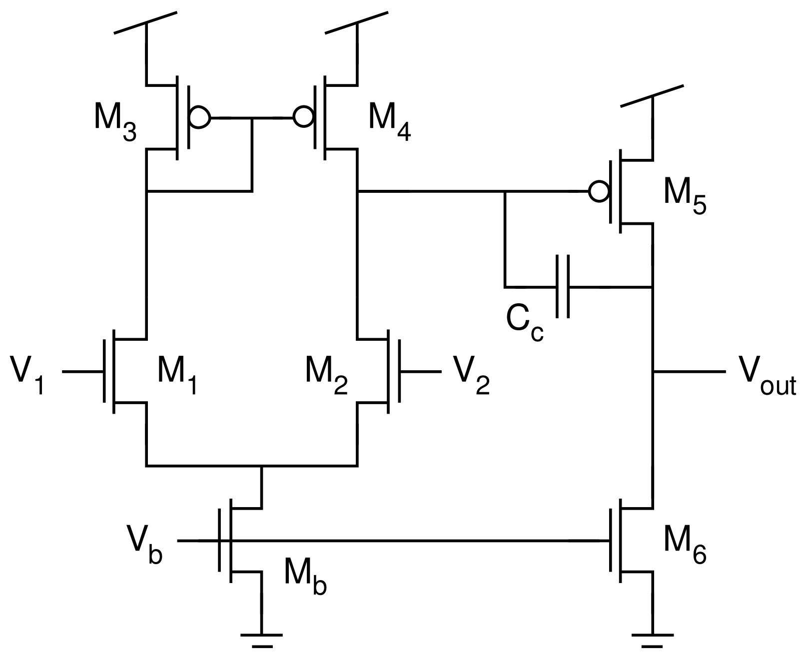
$$\left|H(j\omega)\right| < 1 \text{ for } \omega \text{ where } \angle H(j\omega) = -180^\circ$$

Phase Margin

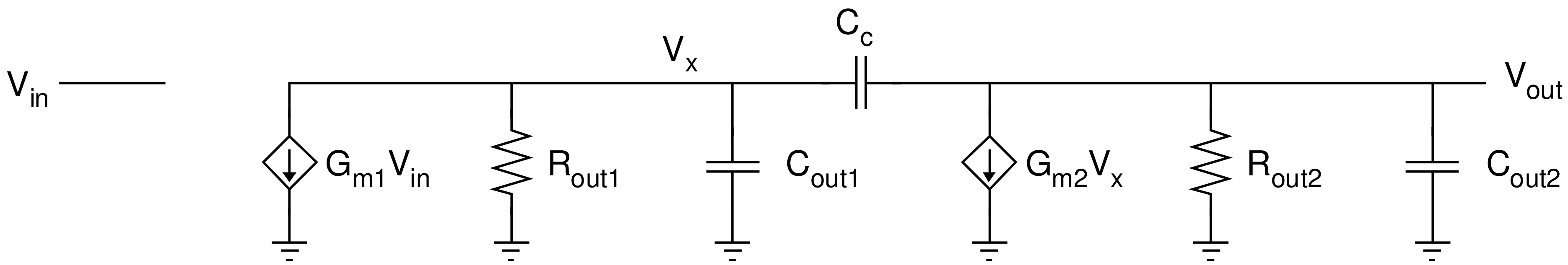
- Typically, we like to design to provide a margin of error
  - These conditions (magnitude and phase) can deviate from their designed values due to processes like noise and temperature drift
- Phase margin
  - A measure of how far away from a complete 360° phase shift
  - Phase margin = 180° - arg(H(jω))
  - Measure at ω where |H(jω)| = 1
- Typical designs call for Phase margins of greater than 45°
  - Often higher, e.g. 60° - 90°

Miller Compensation

- Need to spread the poles apart
- Add a capacitor from input to output of stage 2



Miller Compensation



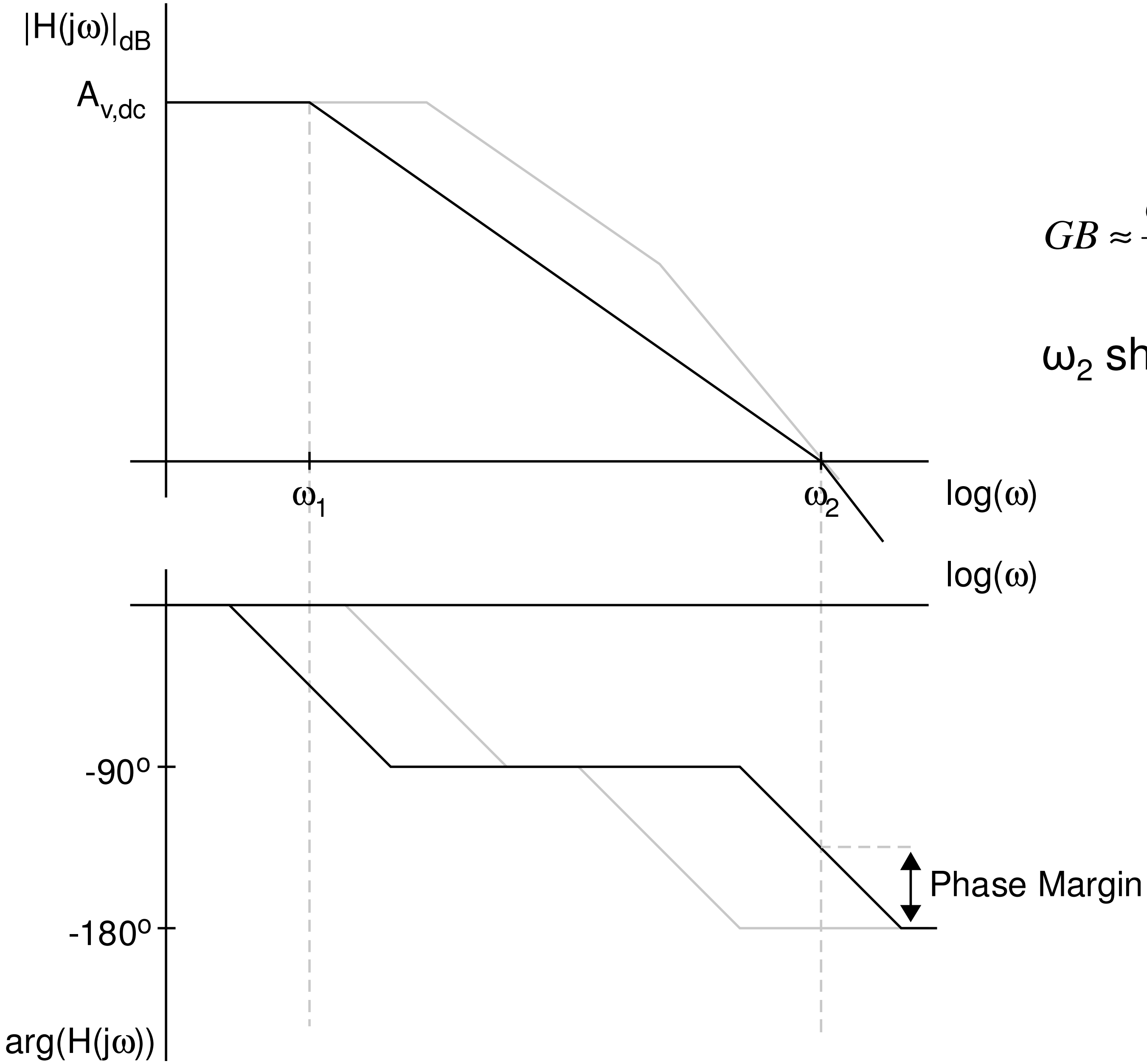
$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{G_{m1}G_{m2}R_1R_2\left(1 - sC_2/G_{m2}\right)}{s^2R_1R_2\left(C_1C_2 + C_cC_1 + C_cC_2\right) + s\left[R_1\left(C_1 + C_c\right) + R_2\left(C_2 + C_c\right) + G_{m2}R_1R_2C_c\right] + 1}$$

$$p_1 \approx \frac{-1}{G_{m2}R_1R_2C_c}$$

$$p_2 \approx \frac{-G_{m2}C_c}{C_1C_2 + C_2C_c + C_1C_c} \approx \frac{-G_{m2}}{C_2}$$

If $C_2 >> C_1$ and $C_c > C_1$

Miller Compensation



$$GB \approx \frac{G_{m1}}{C_c}$$

ω_2 should be ≥ GB

Opamp 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