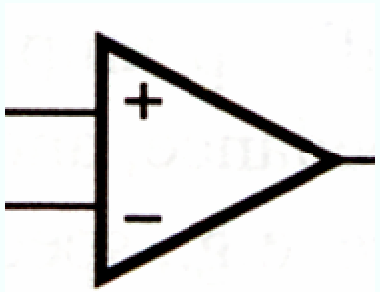
Ch 9 CMOS OP amp

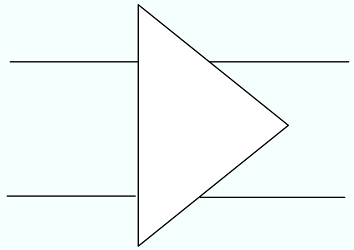
1. Introduction
2. 2-stage OP amp
3. Folded cascode OP amp
4. Design examples

1. Introduction

OP amp :

(1) Voltage amp : Vo = Avd * (Vi+ - Vi-)
(2) Differential input, single-ended output
(3) Fully differential OP amp: diff output





Ideal OP amp :

(1) Differential mode voltage gain: infinity
(2) Common mode voltage gain: 0
(3) Input resistance: infinity
(4) Output resistance: 0
(5) Bandwidth: inifinity

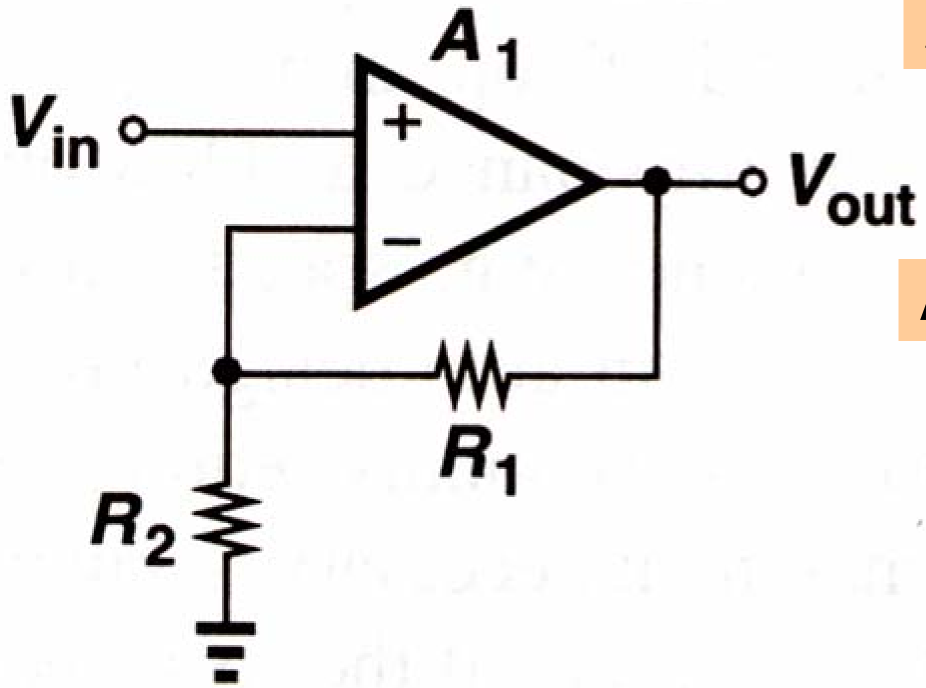
General purpose OP amp :

(1) example 741 OP amp
(2) small Rout to drive any load including R load
(3) needs output stage

CMOS OP amp :

(1) usually drive on-chip capacitive load only
(2) large Rout ➔ current output ➔ OTA (operational transconductance amplifier)
(3) does not need output stage

Gain error (1/2)



A1=infinity ➔ gain=1+(R1/R2)

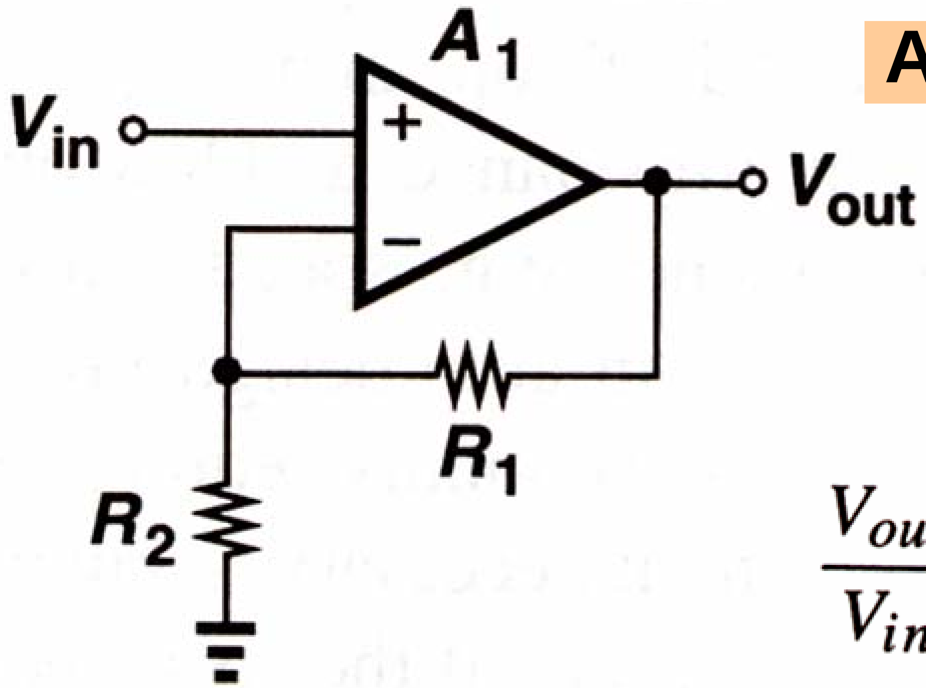
A1=? for gain error < 1%

$$V_{out} = A_1 \cdot (V_{in} - \frac{R_2}{R_1 + R_2} \cdot V_{out})$$

$$\frac{V_{out}}{V_{in}} = \frac{A_1}{1 + \frac{R_2}{R_1 + R_2} A_1}$$

$$= \frac{R_1 + R_2}{R_2} \frac{A_1}{\frac{R_1 + R_2}{R_2} + A_1}$$

Gain error (2/2)



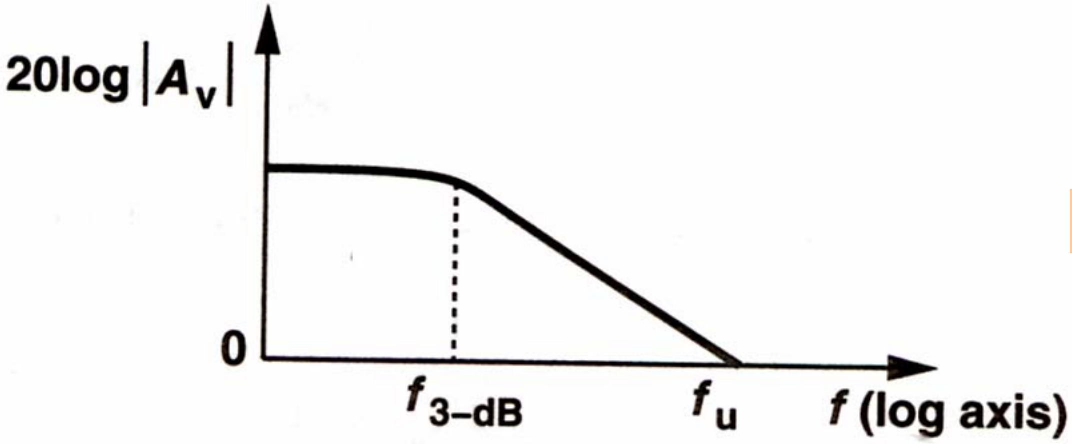
A1=? for gain error < 1%

$$\frac{V_{out}}{V_{in}} \approx \left(1 + \frac{R_1}{R_2}\right)\left(1 - \frac{R_1 + R_2}{R_2}\frac{1}{A_1}\right)$$

for gain error < 1%

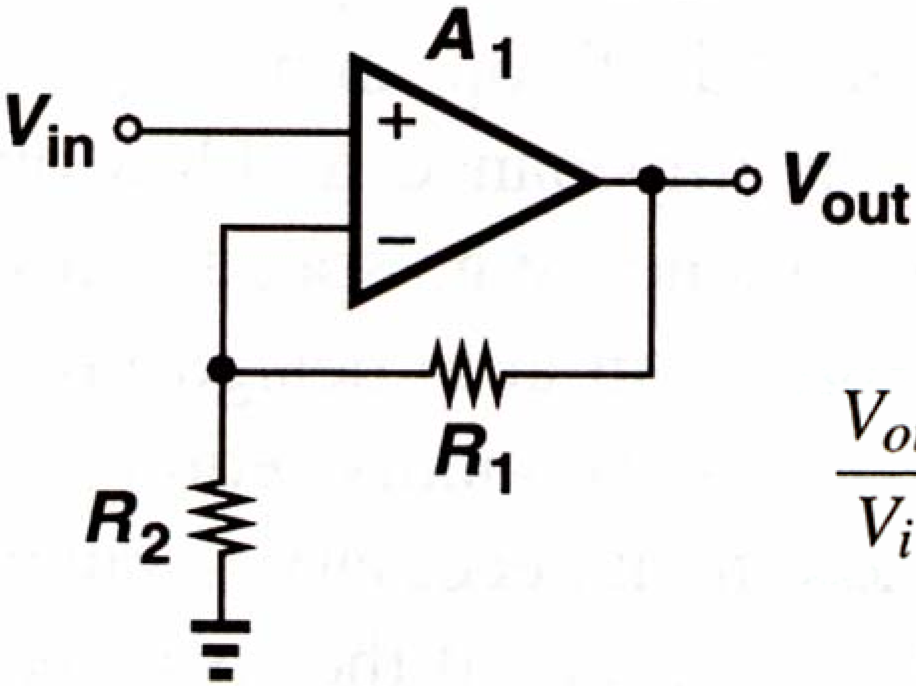
$$A_1 > 100 \cdot \frac{R_1 + R_2}{R_2}$$

Bandwidth (1/3)



$$A(s) = A_0/(1 + s/\omega_0)$$

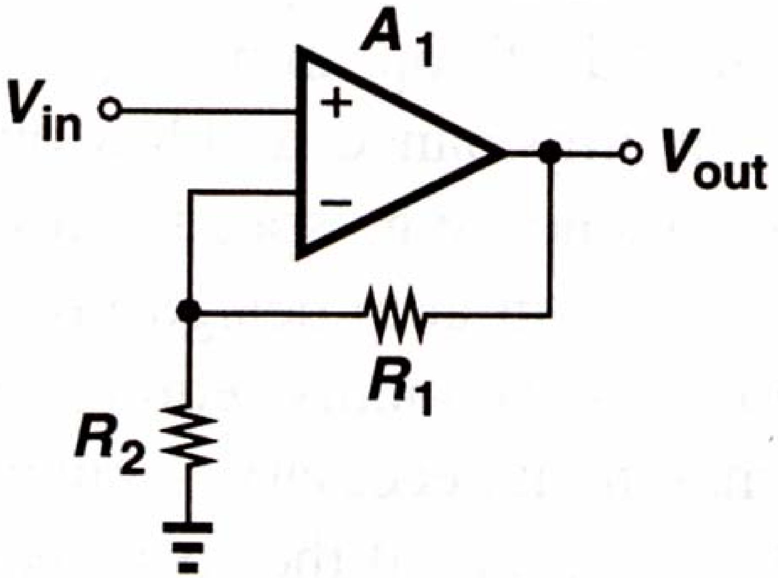
Single pole characteristic assumed



$$\left(V_{in} - V_{out}\frac{R_2}{R_1 + R_2}\right)A(s) = V_{out}$$

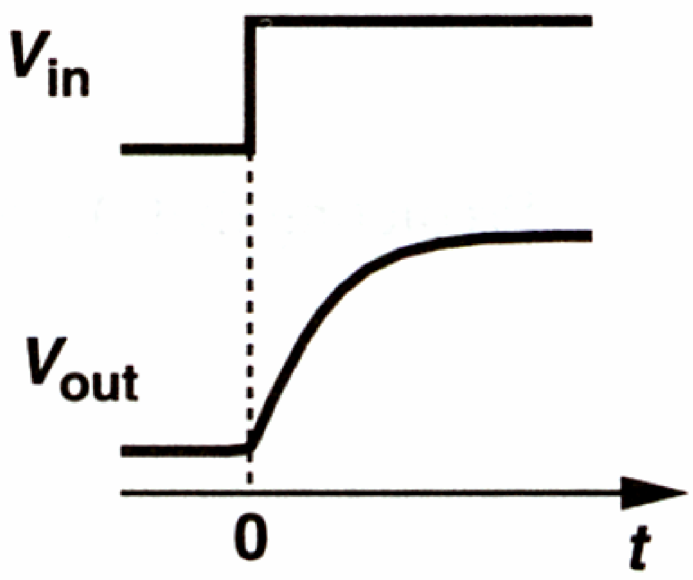
$$\frac{V_{out}}{V_{in}}(s) = \frac{\dfrac{A_0}{1 + \dfrac{R_2}{R_1 + R_2}A_0}}{1 + \dfrac{s}{\left(1 + \dfrac{R_2}{R_1 + R_2}A_0\right)\omega_0}}$$

Bandwidth (2/3)



$$\frac{V_{out}}{V_{in}}(s) = \frac{\dfrac{A_0}{1+\dfrac{R_2}{R_1+R_2}A_0}}{1+\dfrac{s}{\left(1+\dfrac{R_2}{R_1+R_2}A_0\right)\omega_0}}$$

Step response

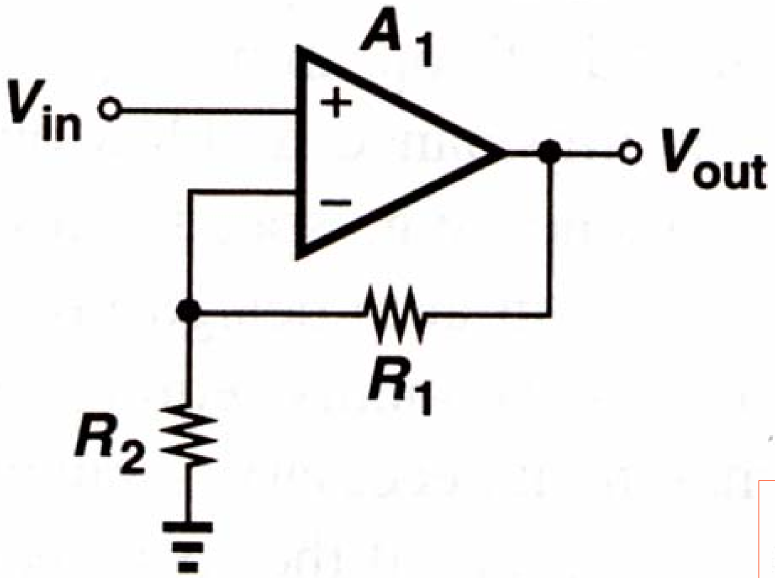


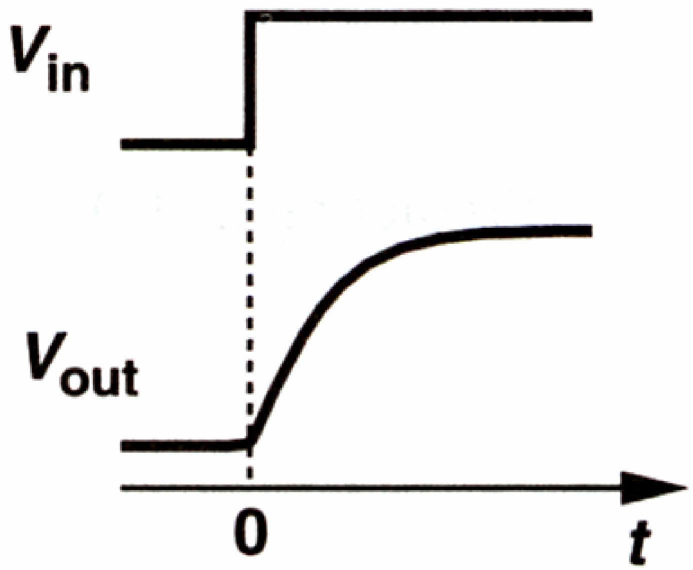
$$V_{in} = au(t)$$

$$V_{out}(t) \approx a\left(1+\frac{R_1}{R_2}\right)\left(1-\exp\frac{-t}{\tau}\right)u(t)$$

$$\tau = \frac{1}{\left(1+\dfrac{R_2}{R_1+R_2}A_0\right)\omega_0} \approx \left(1+\frac{R_1}{R_2}\right)\frac{1}{A_0\omega_0}$$

Bandwidth (3/3)





Step response

$$V_{in} = au(t)$$

$$V_{out}(t) \approx a\left(1+\frac{R_1}{R_2}\right)\left(1-\exp\frac{-t}{\tau}\right)u(t)$$

$$\tau = \frac{1}{\left(1+\frac{R_2}{R_1+R_2}A_0\right)\omega_0} \approx \left(1+\frac{R_1}{R_2}\right)\frac{1}{A_0\omega_0}$$

reduced by 1+(loop gain)

For 1% settling, $V_{out} = 0.99V_F$

$$t_{1\%} = \tau \ln 100 \approx 4.6\tau$$

Simple differential pair : voltage gain not enough

(< 20 for submicron devices)

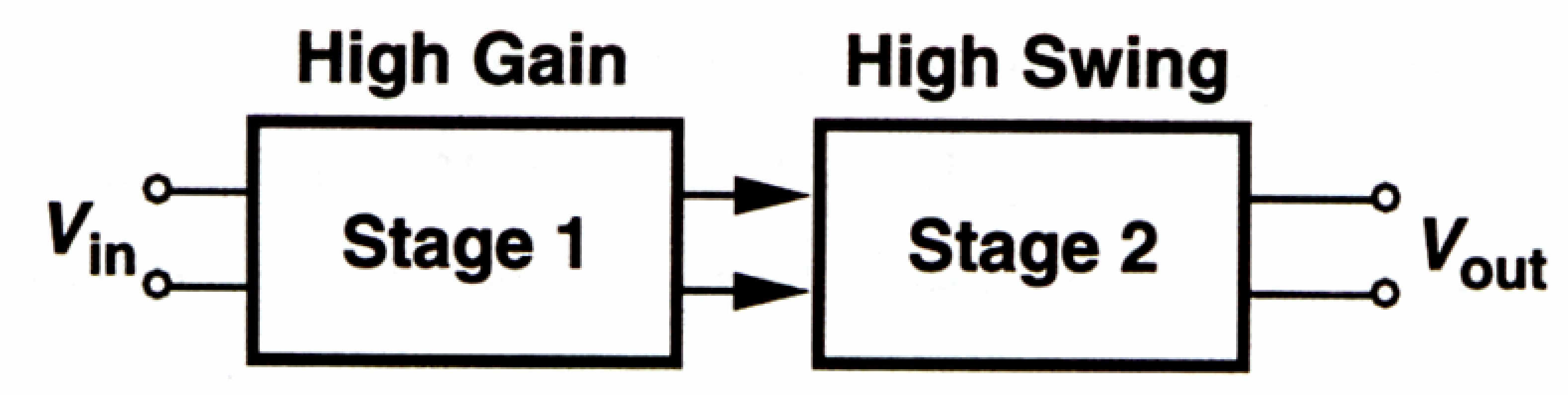
For high gain

➔ 1-stage cascode OP amp (gain boost optional)

(telescopic OP amp, folded cascode OP amp)

➔ reduced output swing

2-stage OP amp : pro → high gain + large output swing



2-stage OP amp :

con → requires frequency compensation (Miller pole-splitting frequency compensation)

2-stage OP amp

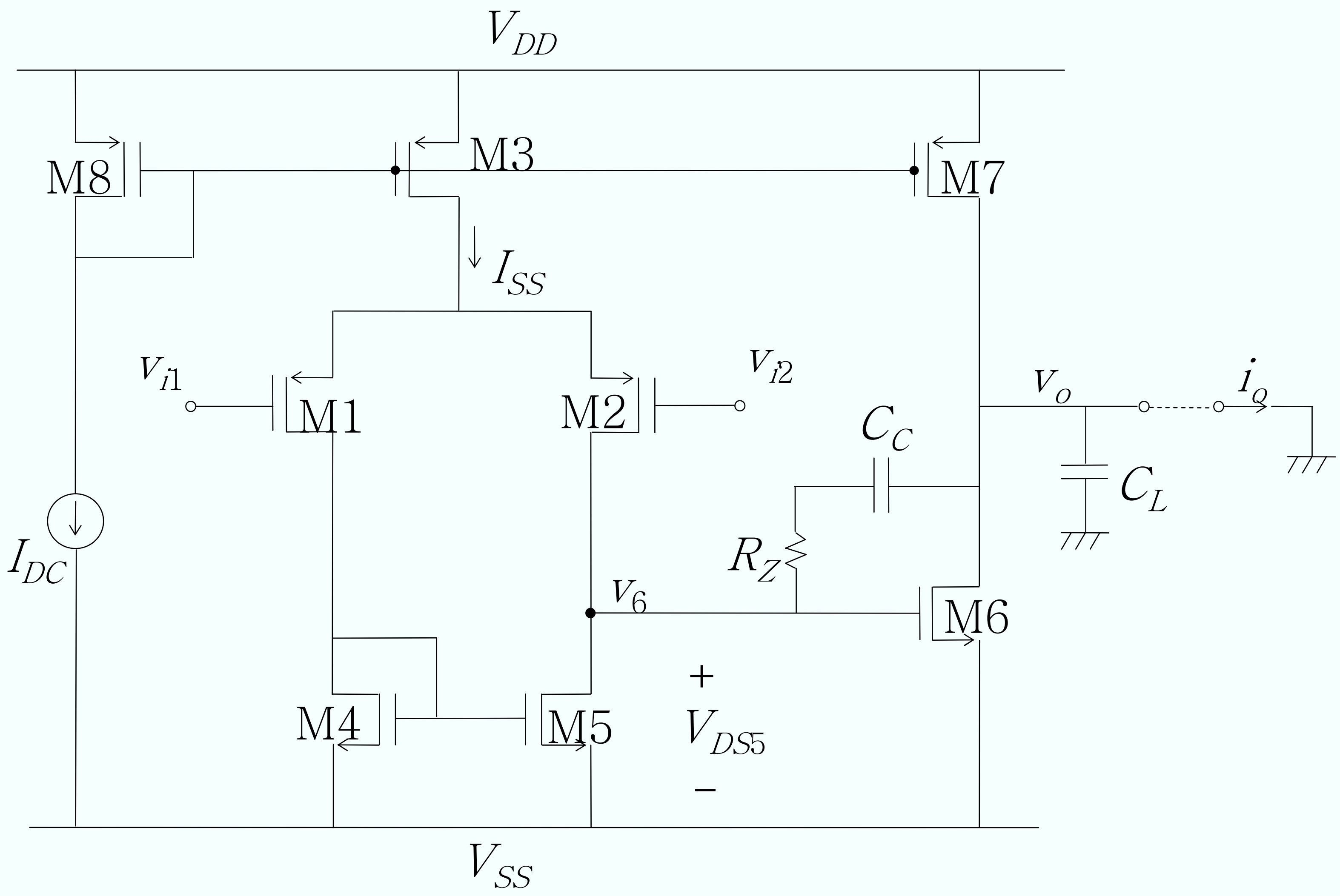
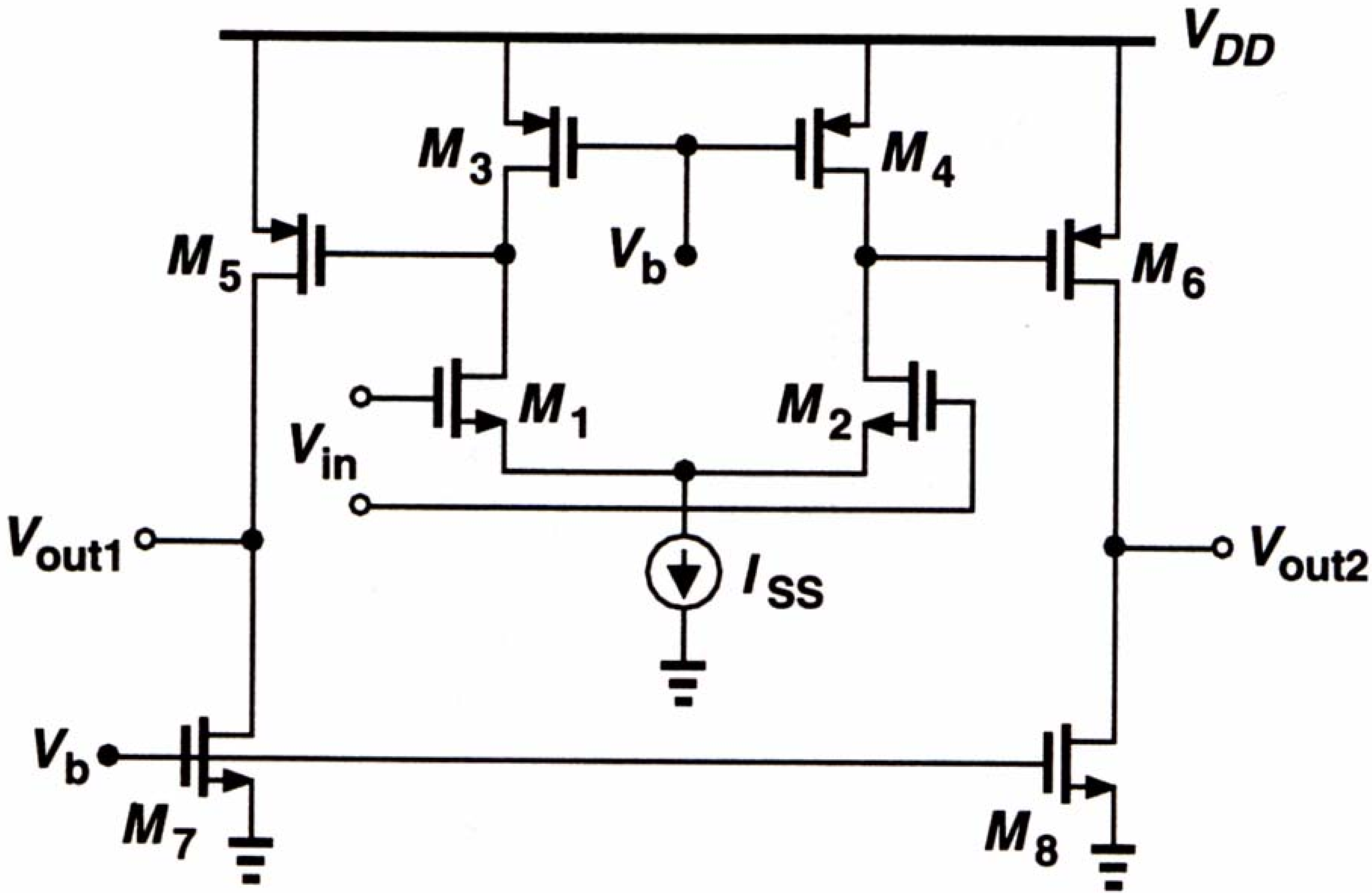


Fig 9.1.1 2-stage CMOS OP amp circuit

2-stage OP amp (fully differential)



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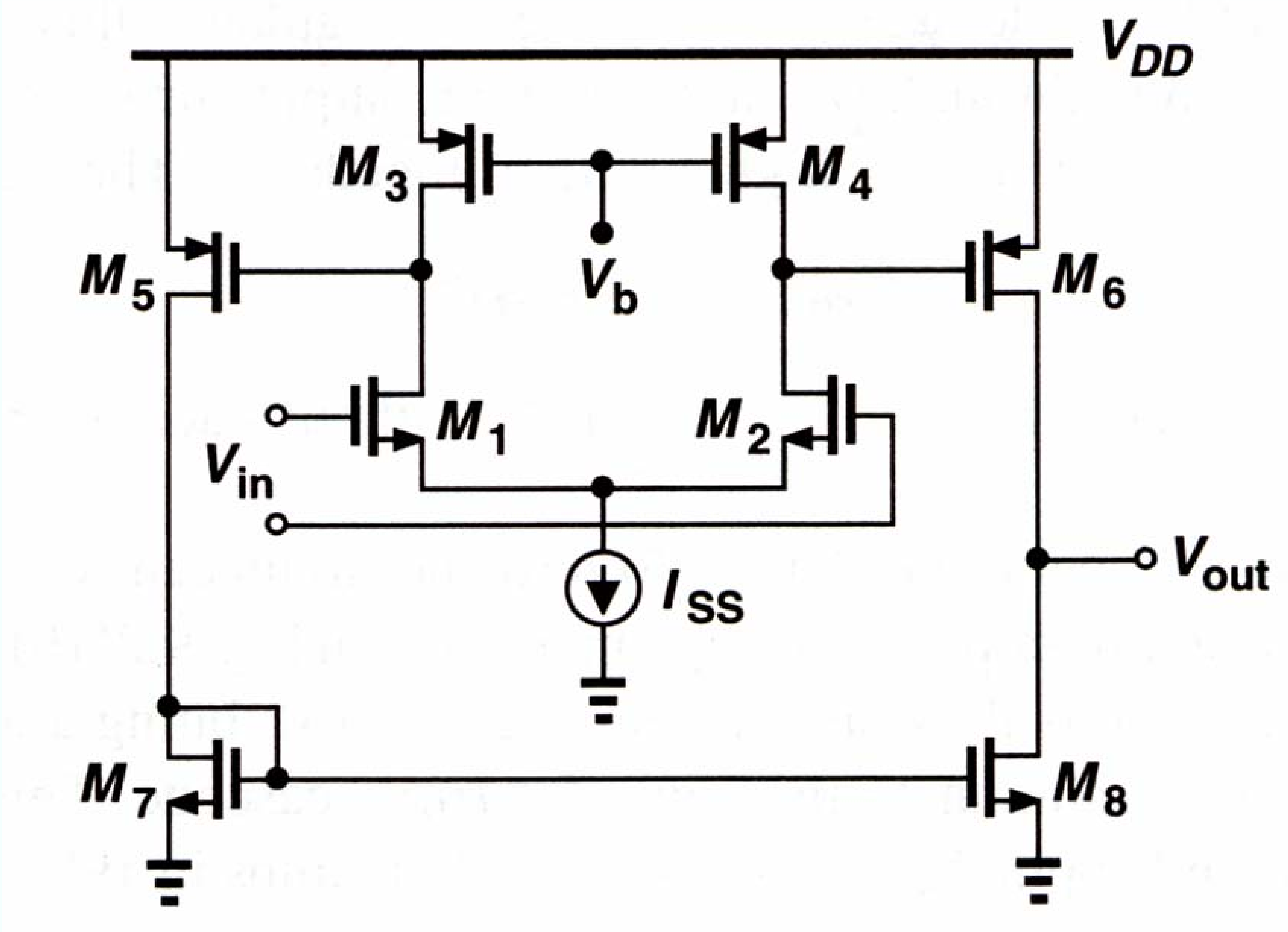
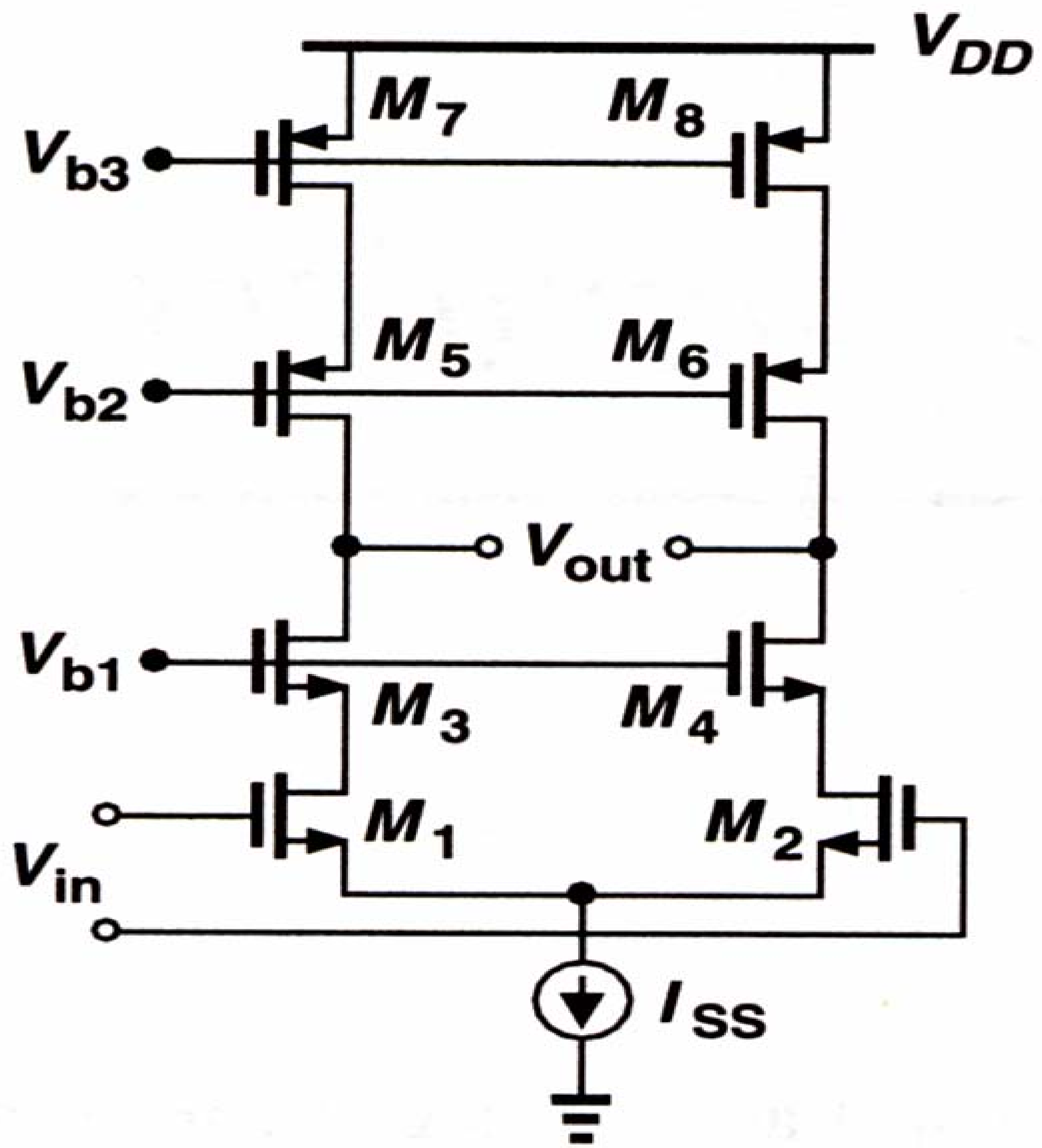
2-stage OP amp (single ended out)



Razavi

Cascode (Telescopic) OP amp



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2-stage OP amp (cascode 1st stage)

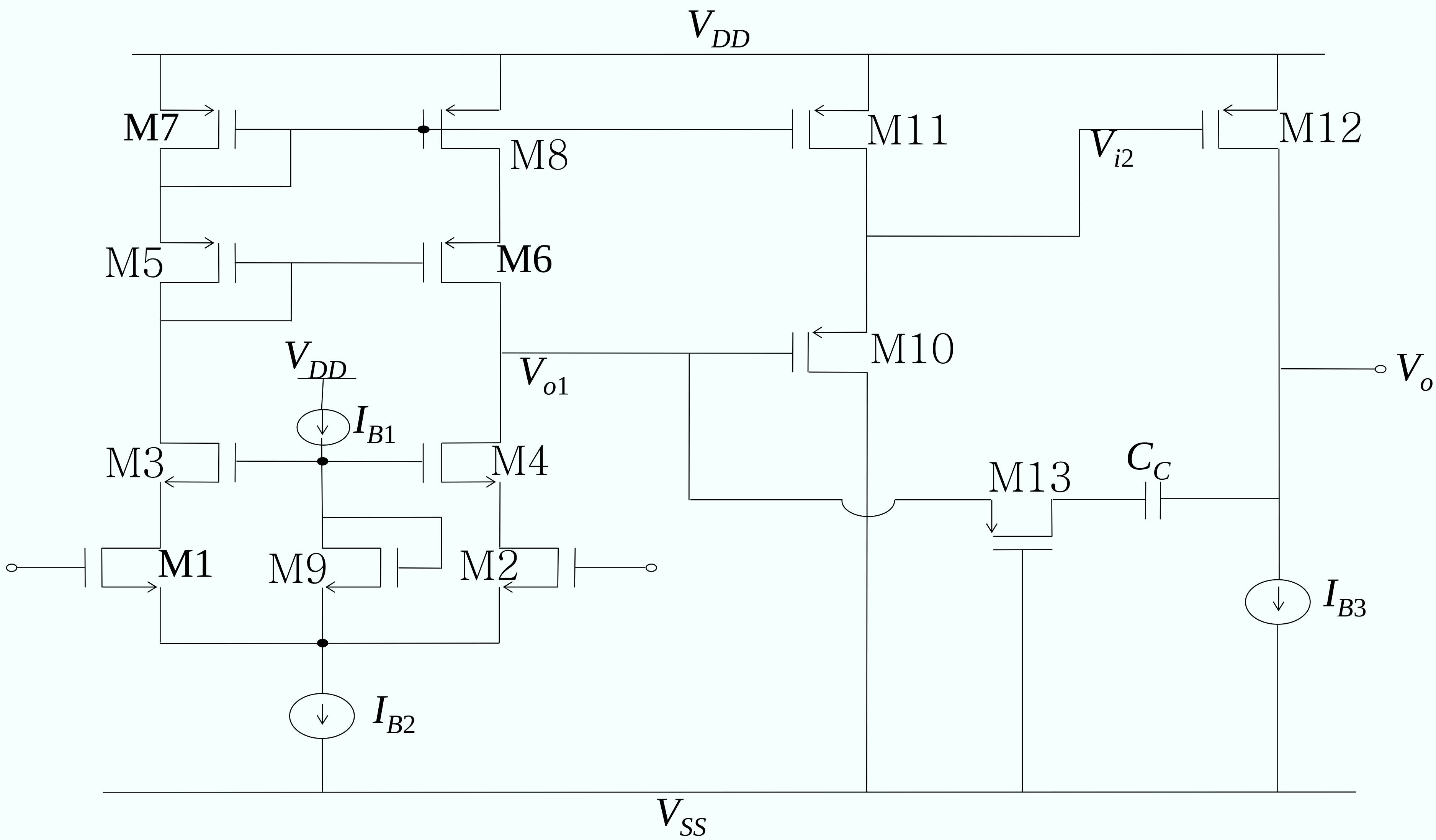
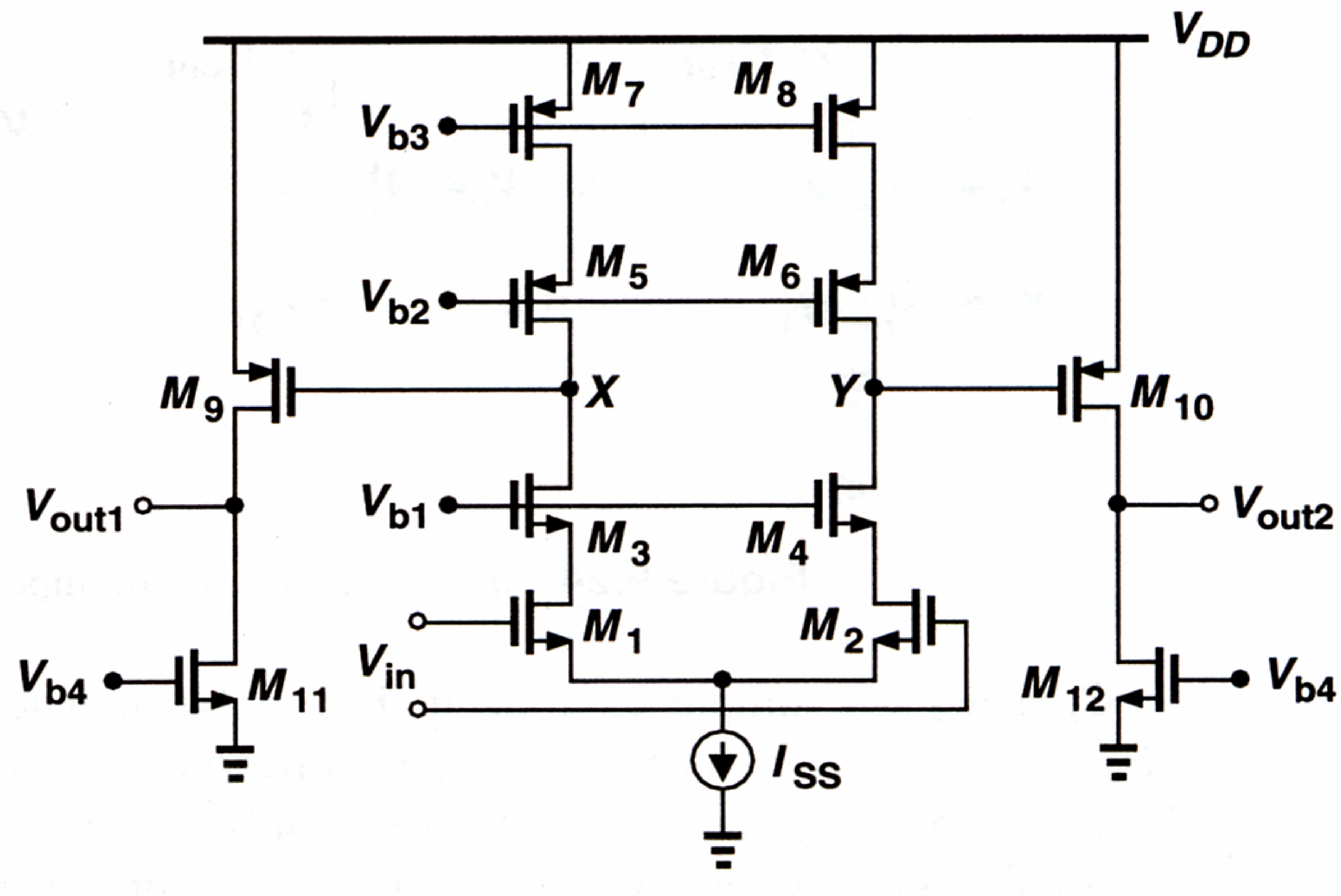


Fig 9.1.22 2-stage CMOS OP amp with a cascode 1st stage

M9 config. increases input common mode range

2-stage OP amp (fully differential)



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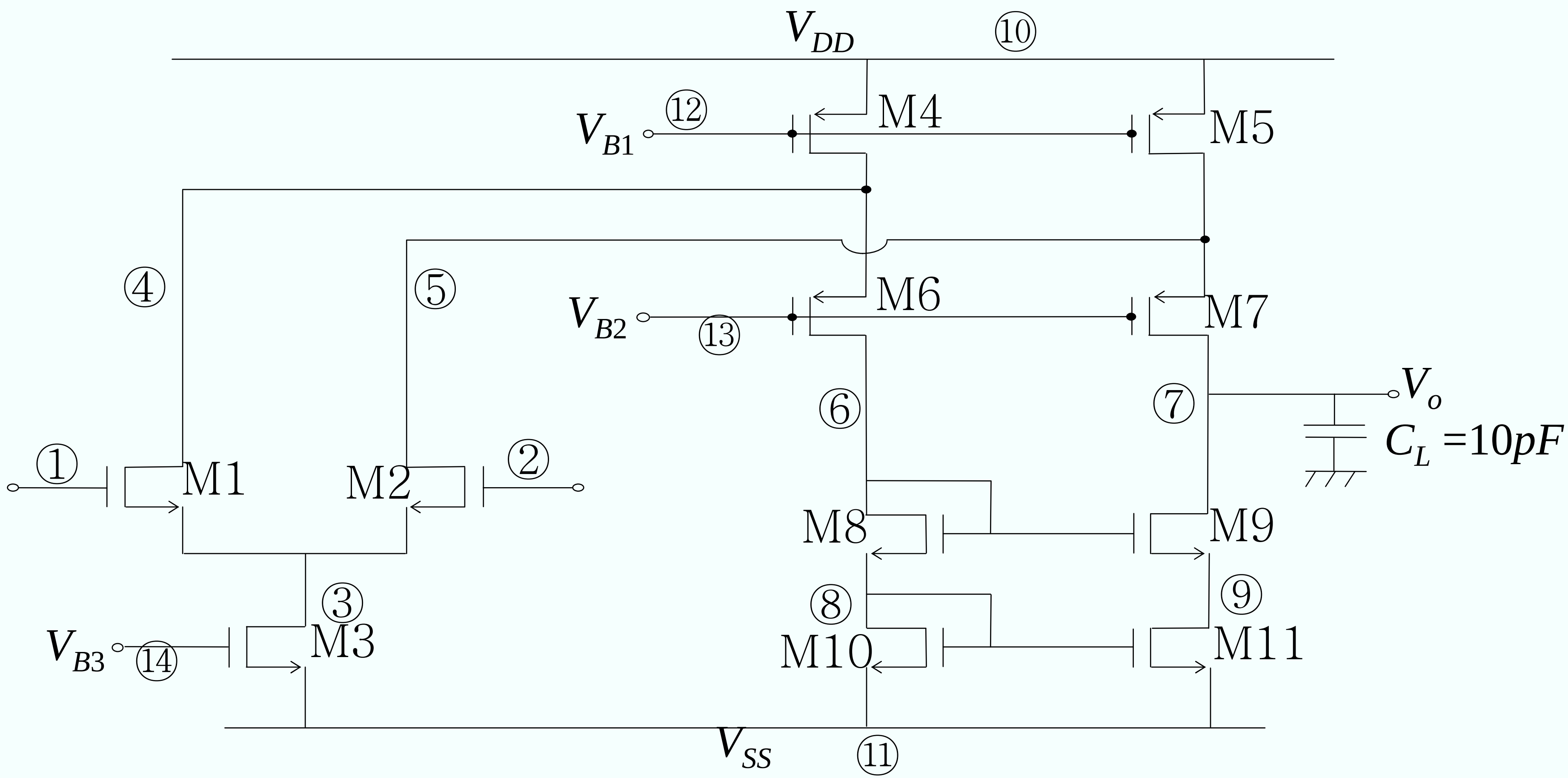
NMOS-input Folded cascode OP amp



(1) Input common mode range: extended up to VDD

(2) Output voltage range increased compared to telescopic

PMOS-input Folded cascode OP amp

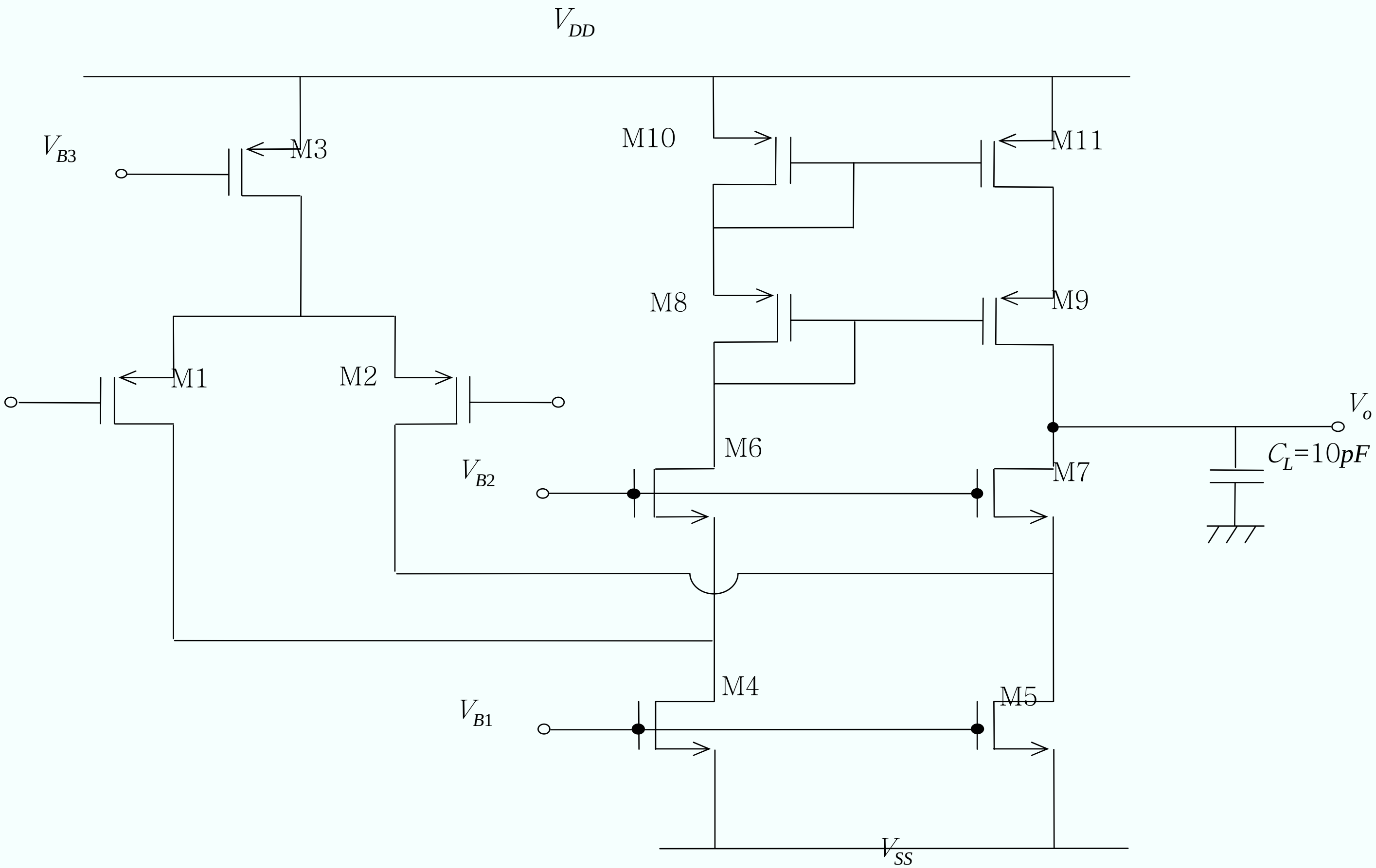
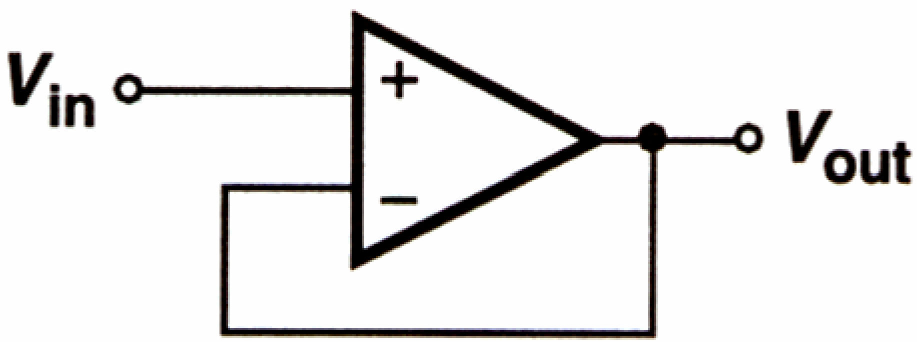


Fig 9.2.9 folded cascode CMOS OP amp with PMOS input transistors(M1, M2)

(1) Input common mode range: extended down to VSS

(2) Output voltage range increased compared to telescopic

Unity-gain buffer (1/6)

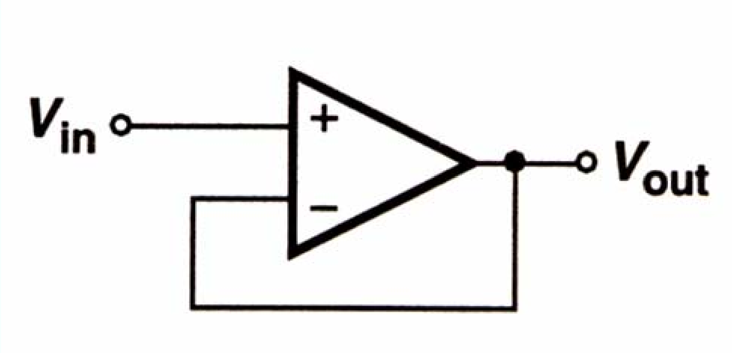


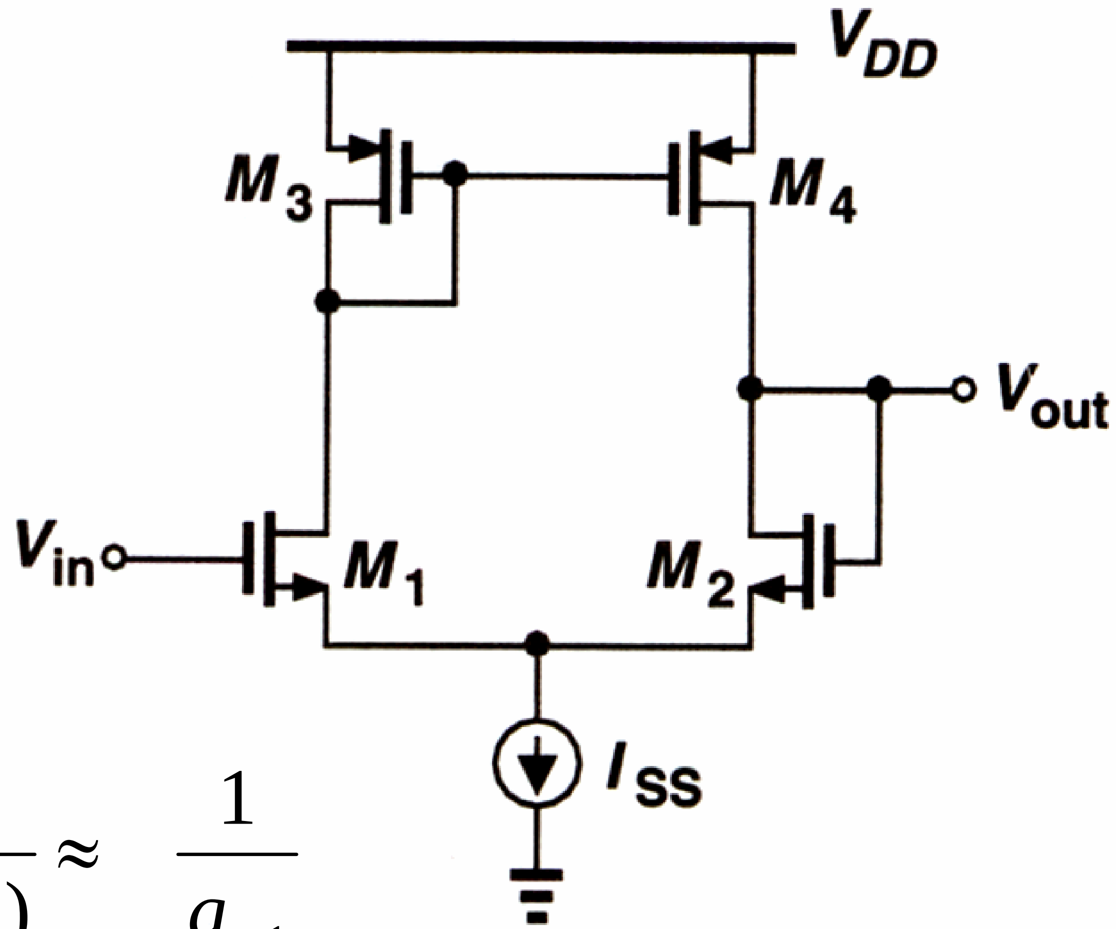
$$V_{out} \approx V_{in}$$

➔ **Must meet both <u>output swing requirement</u> and <u>input CM voltage range requirement</u> simultaneously**

Telescopic OP amp : narrow output swing and narrow input common mode range ➔ not suitable for unity-gain buffer application (folded cascode OK)

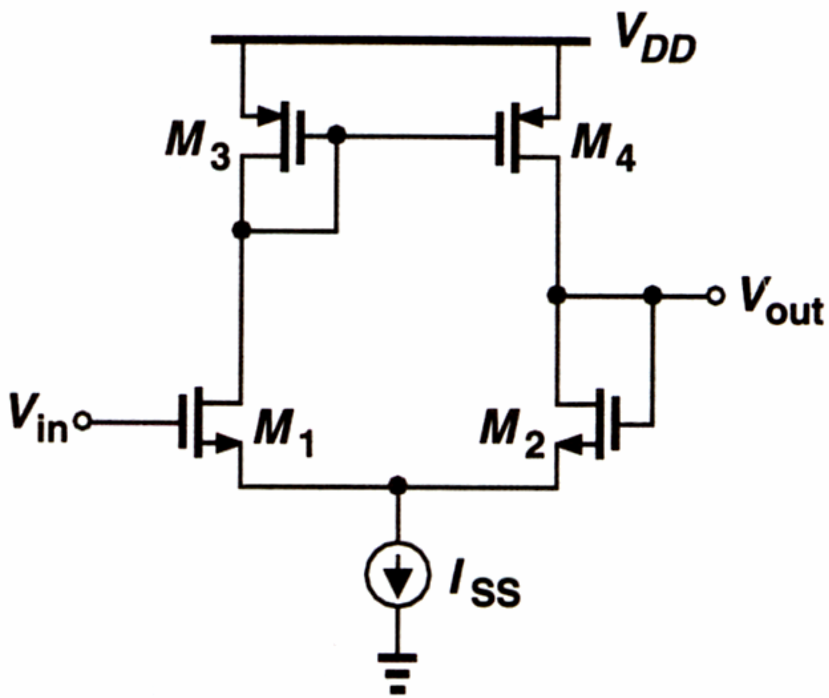
Unity gain buffer using simple diff pair





$$R_{out} = \frac{r_{o2} \parallel r_{o4}}{1 + g_{m1} \cdot (r_{o2} \parallel r_{o4})} \approx \frac{1}{g_{m1}}$$

Unity gain buffer using simple diff pair



Assume the same VDSAT

(For open loop)

Input CM min: 2 VDSAT + VTH

Input CM max: VDD – VDSAT

Output min: 2 VDSAT

Output max: VDD – VDSAT

(For unity-gain feedback)

Vout min: 2 VDSAT + VTH (limited by input CM)

Vout max: VDD – VDSAT

Vout swing: VDD – 3 VDSAT – VTH

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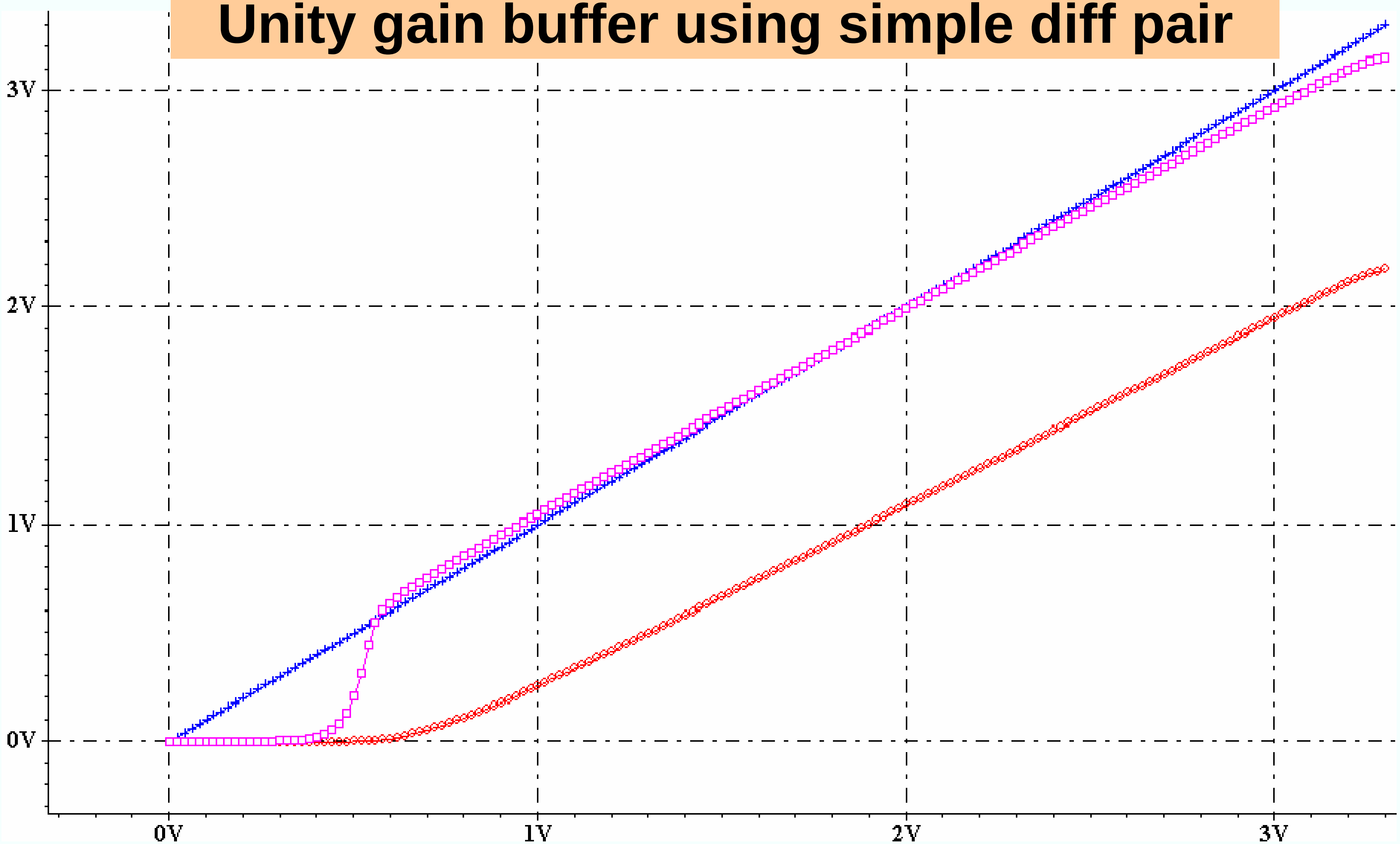
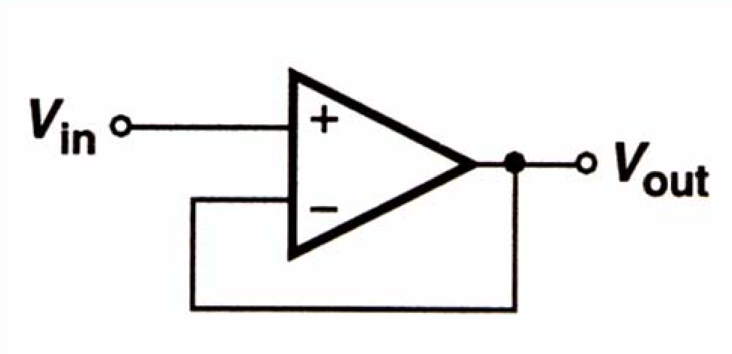
Unity-gain buffer (4/6)

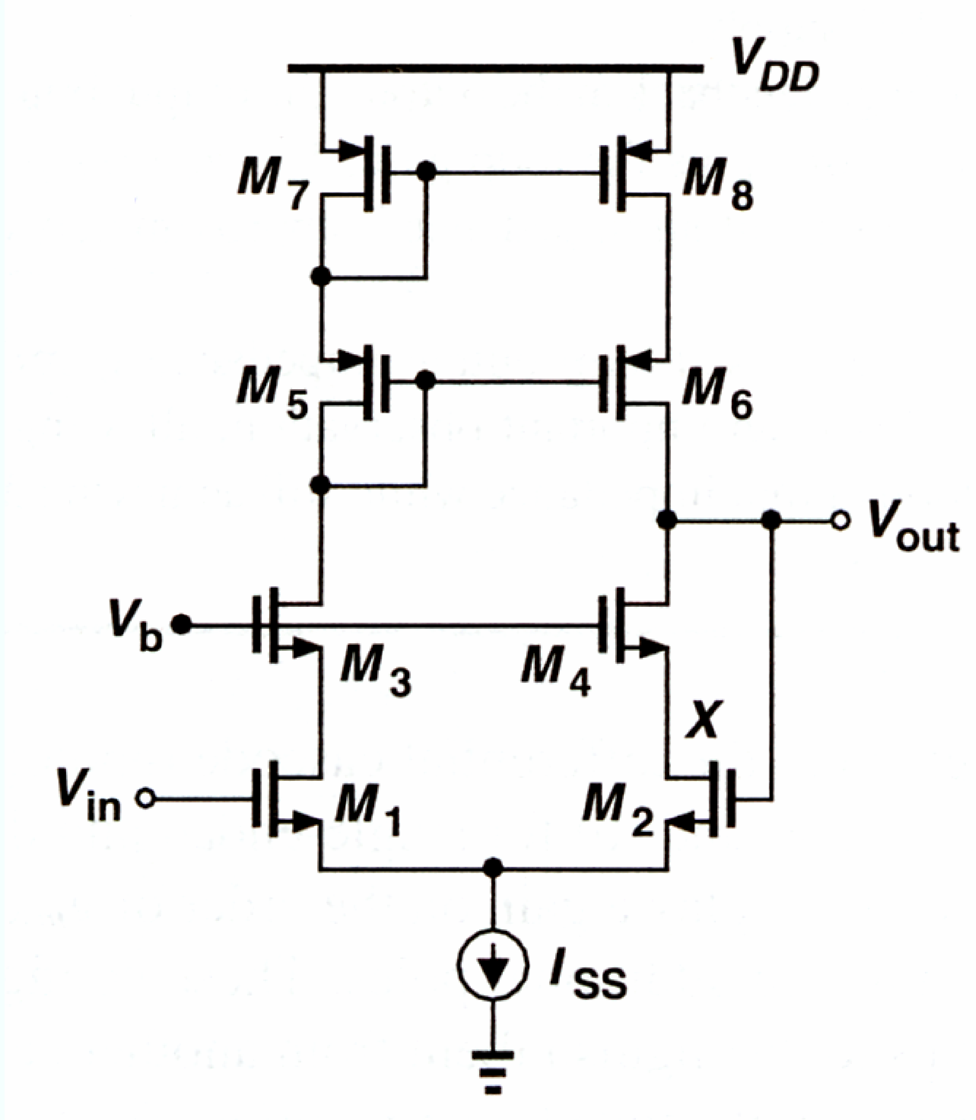
Unity gain buffer using simple diff pair



Unity-gain buffer (5/6)

Unity gain buffer using telescopic OP amp





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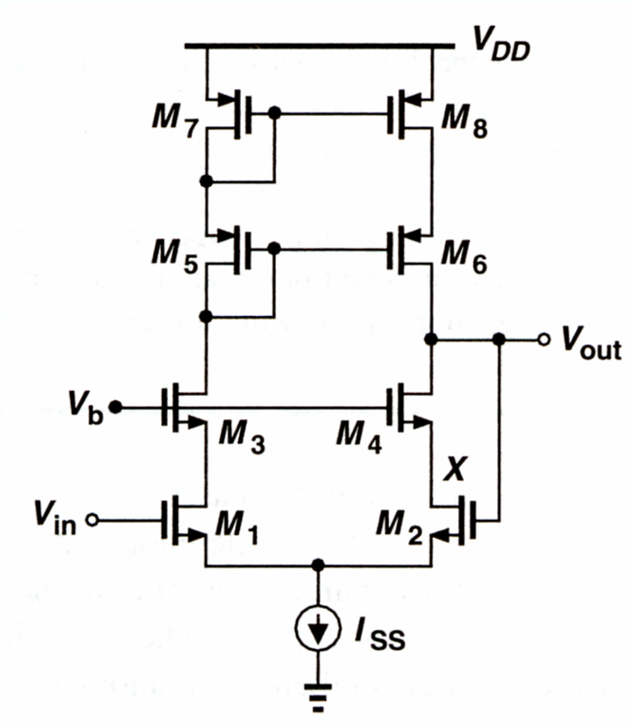
Unity gain buffer using telescopic OP amp



Assume the same VDSAT

(For open loop, optimum Vb)

Input CM min: 2 VDSAT + VTH

Input CM max: VDD – 3 VDSAT – VTH

Output min: 3 VDSAT

Output max: VDD – 2 VDSAT – VTH

(For unity-gain feedback , optimum Vb)

Vout min: 2 VDSAT + VTH (limited by input CM)

Vout max: VDD – 3 VDSAT – VTH (limited by input CM)

Vout swing: VDD – 5 VDSAT – 2 VTH (severely limited)

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