LECTURE 390 – OPEN-LOOP COMPARATORS
(READING: AH – 461-475)

Objective

The objective of this presentation is:

1.) Show other types of continuous-time, open-loop comparators

2.) Improve the performance of continuous-time, open-loop comparators

Outline

- Push-pull comparators
- Comparators that can drive large capacitors
- Autozeroing techniques
- Comparators using hysteresis
- Summary

Push-Pull Comparators

Clamped:

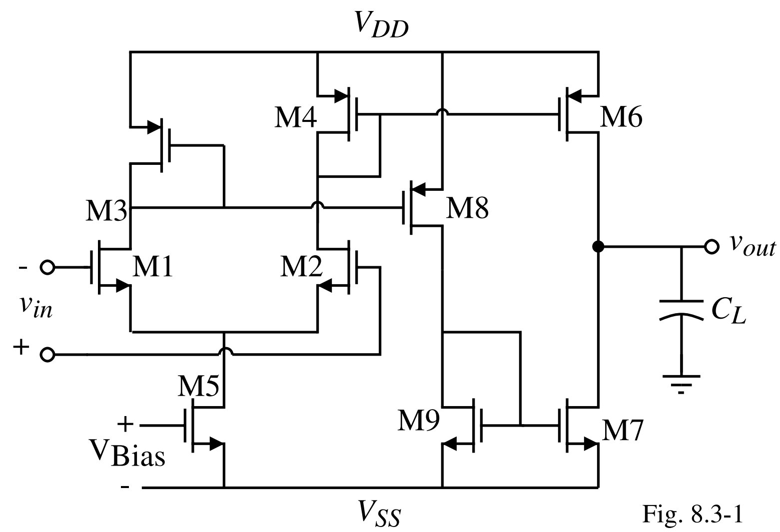

Fig. 8.3-1

Comments:

- Gain reduced → Larger input resolution
- Push-pull output → Higher slew rates

Push-Pull Comparators - Improved

Cascode output stage:

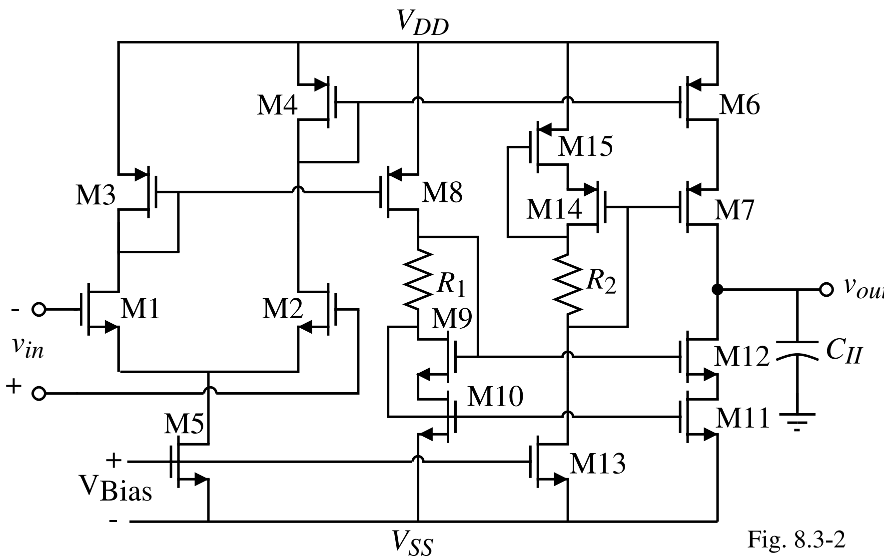

Fig. 8.3-2

Comments:

- Can also use the folded cascode architecture
- Cascode output stage result in a slow linear response (dominant pole is small)
- Poorer noise performance

Comparators that Can Drive Large Capacitive Loads

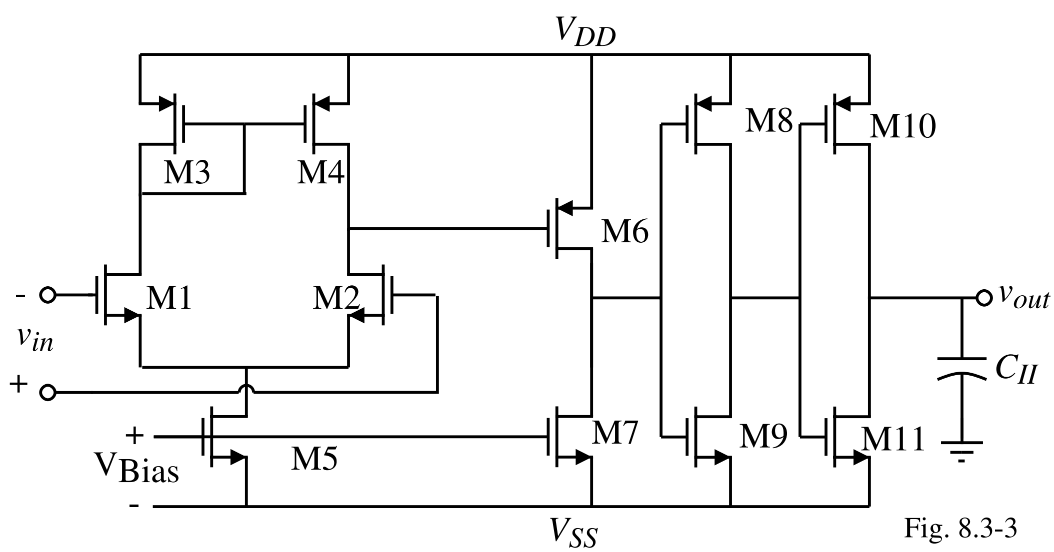

Fig. 8.3-3

Comments:

- Slew rate = 3V/μs into 50pF
- Linear rise/fall time = 100ns into 50pF
- Propagation delay time ≈ 1μs
- Loop gain ≈ 32,000 V/V

Self-Biased Differential Amplifier†

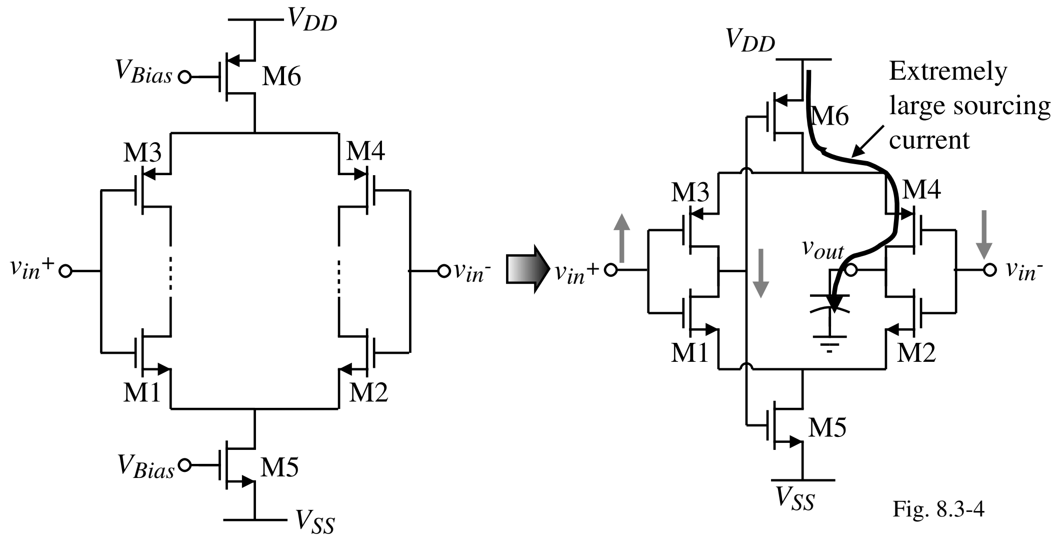

Fig. 8.3-4

Advantage:

Large sink or source current with out a large quiescent current.

Disadvantage:

Poor common mode range (v_{in}^+ slower than v_{in}^-)

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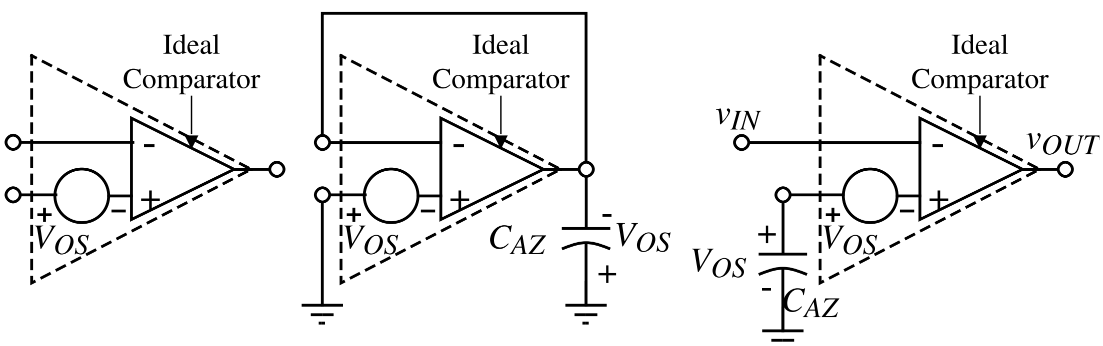
† M. Bazes, "Two Novel Full Complementary Self-Biased CMOS Differential Amplifiers," *IEEE Journal of Solid-State Circuits*, Vol. 26, No. 2, Feb. 1991, pp. 165-168.

Autozeroing Techniques

Use the comparator as an op amp to sample the dc input offset voltage and cancel the offset during operation.



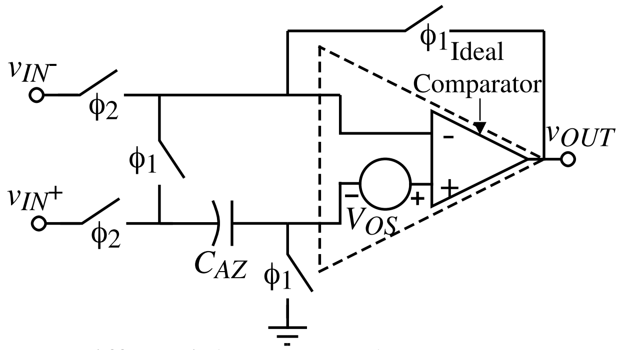
Model of Comparator. Autozero Cycle Comparison Cycle

Fig. 8.4-1

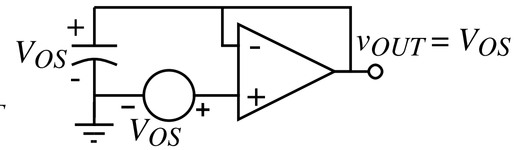
Comments:

- The comparator must be stable in the unity-gain mode (self-compensating comparators are good, the two-stage op comparator would require compensation to be switched in during the autozero cycle.)
- Complete offset cancellation is limited by charge injection

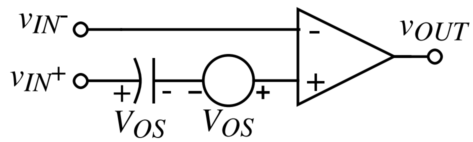
Differential Implementation of Autozeroed Comparators



Differential Autozeroed Comparator



Comparator during ϕ_1 phase



Comparator during ϕ_2 phase

Fig. 8.4-2

Single-Ended Autozeroed Comparators

Noninverting:

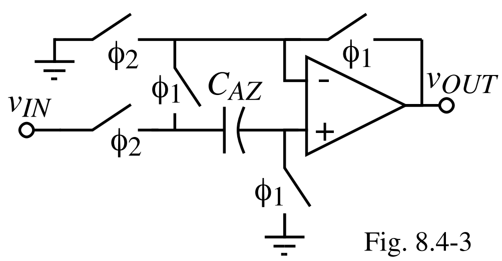


Fig. 8.4-3

Inverting:

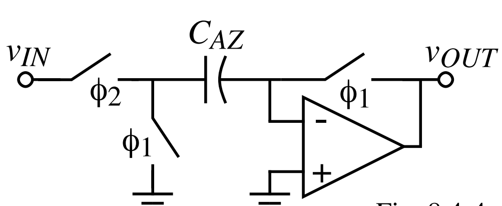


Fig. 8.4-4

Comment on autozeroing:

Need to be careful about noise that gets sampled onto the autozeroing capacitor and is present on the comparison phase of the process.

Influence of Input Noise on the Comparator

Comparator without hysteresis:

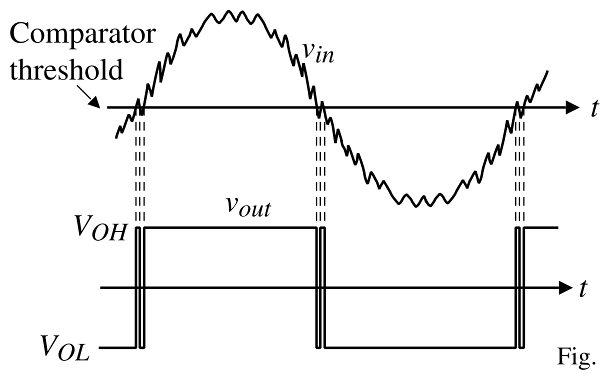


Fig. 8.4-6A

Comparator with hysteresis:

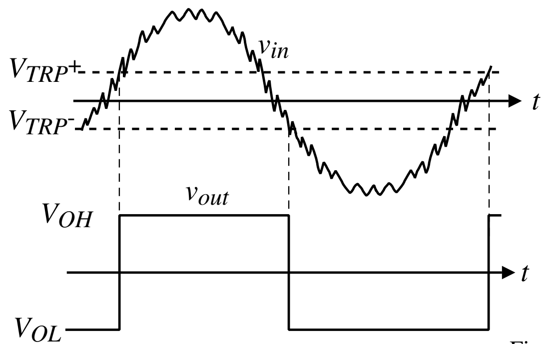


Fig. 8.4-6B

Use of Hysteresis for Comparators in a Noisy Environment

Transfer curve of a comparator with hysteresis:

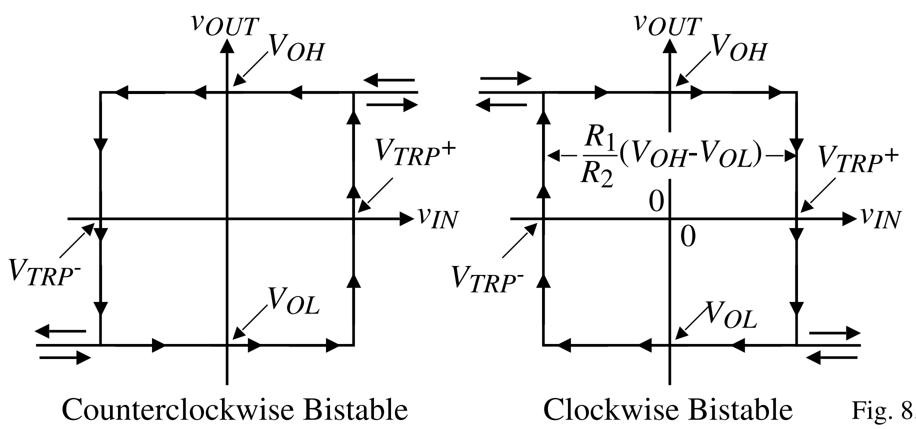


Fig. 8.4-5

Hysteresis is achieved by the use of positive feedback

- Externally
- Internally

Noninverting Comparator using External Positive Feedback

Circuit:

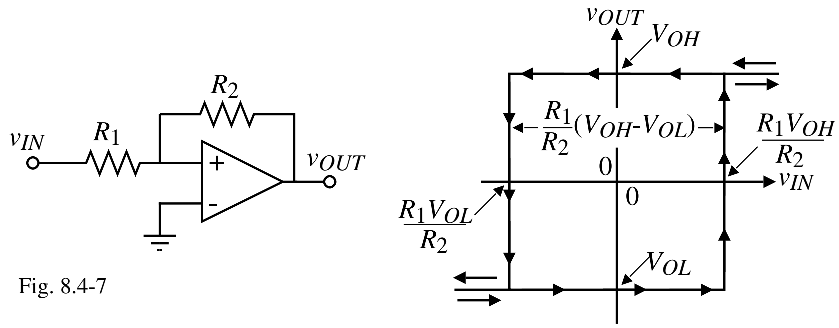


Fig. 8.4-7

Upper Trip Point:

Assume that $v_{OUT} = V_{OL}$, the upper trip point occurs when,

$$0 = \left(\frac{R_1}{R_1+R_2}\right)V_{OL} + \left(\frac{R_2}{R_1+R_2}\right)V_{TRP^+} \quad \rightarrow \quad V_{TRP^+} = -\frac{R_1}{R_2}V_{OL}$$

Lower Trip Point:

Assume that $v_{OUT} = V_{OH}$, the lower trip point occurs when,

$$0 = \left(\frac{R_1}{R_1+R_2}\right)V_{OH} + \left(\frac{R_2}{R_1+R_2}\right)V_{TRP^-} \quad \rightarrow \quad V_{TRP^-} = -\frac{R_1}{R_2}V_{OH}$$

Width of the bistable characteristic:

$$\Delta V_{in} = V_{TRP^+} - V_{TRP^-} = \left(\frac{R_1}{R_2}\right)(V_{OH} - V_{OL})$$

Inverting Comparator using External Positive Feedback

Circuit:

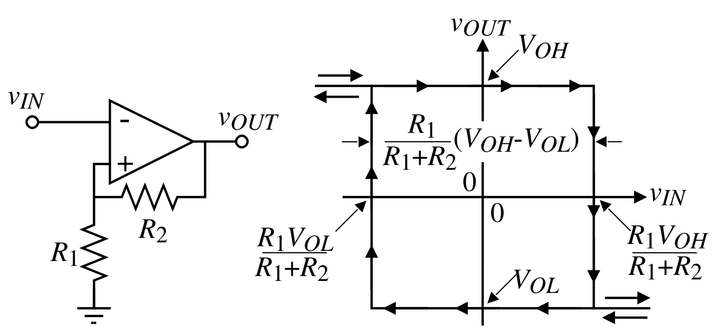


Fig. 8.4-8

Upper Trip Point:

$$v_{IN} = V_{TRP^+} = \left(\frac{R_1}{R_1+R_2}\right)V_{OH}$$

Lower Trip Point:

$$v_{IN} = V_{TRP^-} = \left(\frac{R_1}{R_1+R_2}\right)V_{OL}$$

Width of the bistable characteristic:

$$\Delta V_{in} = V_{TRP^+} - V_{TRP^-} = \left(\frac{R_1}{R_1+R_2}\right)(V_{OH} - V_{OL})$$

Horizontal Shifting of the CCW Bistable Characteristic

Circuit:

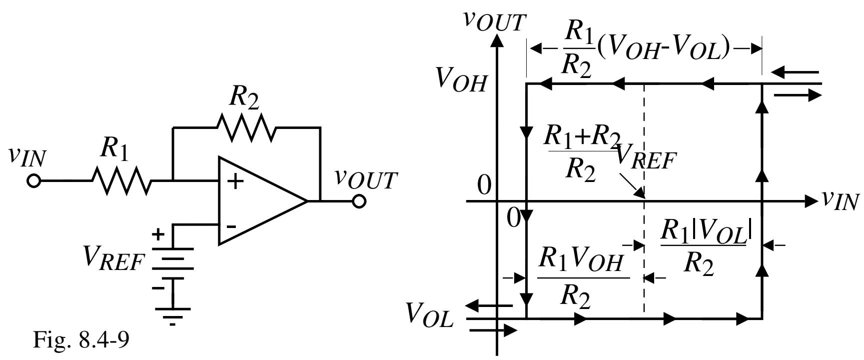


Fig. 8.4-9

Upper Trip Point:

$$V_{REF} = \left(\frac{R_1}{R_1+R_2}\right)V_{OL} + \left(\frac{R_2}{R_1+R_2}\right)V_{TRP^+} \quad \rightarrow \quad V_{TRP^+} = \left(\frac{R_1+R_2}{R_2}\right)V_{REF} - \frac{R_1}{R_2}V_{OL}$$

Lower Trip Point:

$$V_{REF} = \left(\frac{R_1}{R_1+R_2}\right)V_{OH} + \left(\frac{R_2}{R_1+R_2}\right)V_{TRP^-} \quad \rightarrow \quad V_{TRP^-} = \left(\frac{R_1+R_2}{R_2}\right)V_{REF} - \frac{R_1}{R_2}V_{OH}$$

Shifting Factor:

$$\left(\frac{R_1+R_2}{R_2}\right)V_{REF}$$

Horizontal Shifting of the CW Bistable Characteristic

Circuit:

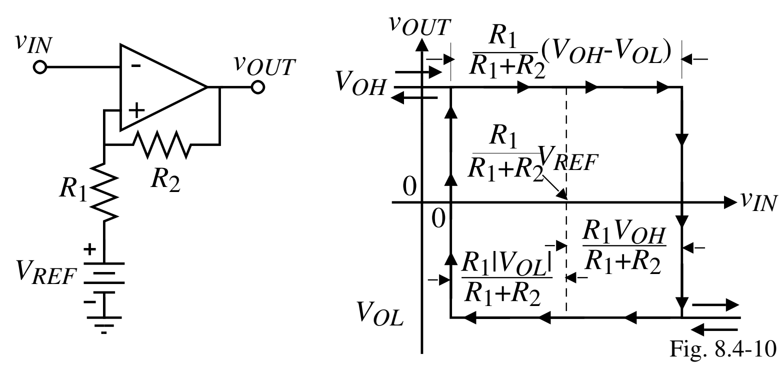


Fig. 8.4-10

Upper Trip Point:

$$v_{IN} = V_{TRP^+} = \left(\frac{R_1}{R_1+R_2}\right)V_{OH} + \left(\frac{R_1}{R_1+R_2}\right)V_{REF}$$

Lower Trip Point:

$$v_{IN} = V_{TRP^-} = \left(\frac{R_1}{R_1+R_2}\right)V_{OL} + \left(\frac{R_1}{R_1+R_2}\right)V_{REF}$$

Shifting Factor:

$$\left(\frac{R_1}{R_1+R_2}\right)V_{REF}$$

Example 8.4-1 Design of an Inverting Comparator with Hysteresis

Use the inverting bistable to design a high-gain, open-loop comparator having an upper trip point of 1V and a lower trip point of 0V if V_{OH} = 2V and V_{OL} = -2V.

Solution

Putting the values of this example into the above relationships gives

$$1 = \left(\frac{R_1}{R_1+R_2}\right) 2 + \left(\frac{R_1}{R_1+R_2}\right) V_{REF}$$

and

$$0 = \left(\frac{R_1}{R_1+R_2}\right) (-2) + \left(\frac{R_1}{R_1+R_2}\right) V_{REF}$$

Solving these two equations gives $3R_1 = R_2$ and V_{REF} = 2V.

Hysteresis using Internal Positive Feedback

Simple comparator with internal positive feedback:

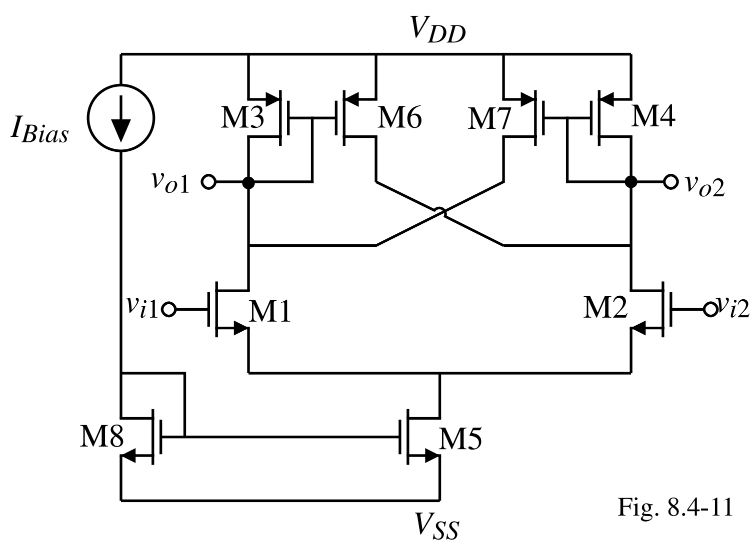


Fig. 8.4-11

Internal Positive Feedback - Upper Trip Point

Assume that the gate of M1 is on ground and the input to M2 is much smaller than zero. The resulting circuit is:

M1 on, M2 off → M3 and M6 on, M4 and M7 off.

$\therefore\quad v_{o2}$ is high.

M6 would like to source the current $i_6 = \dfrac{W_6/L_6}{W_3/L_3}\, i_1$

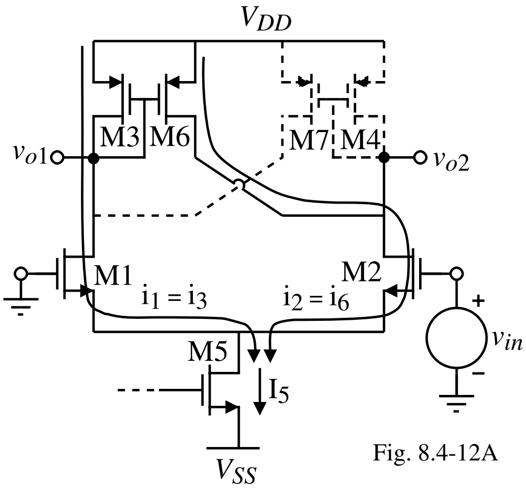


Fig. 8.4-12A

As v_{in} begins to increase towards the trip point, the current flow through M2 increases. When $i_2 = i_6$, the upper trip point will occur.

$$\therefore\quad i_5 = i_1 + i_2 = i_3 + i_6 = i_3 + \left(\frac{W_6/L_6}{W_3/L_3}\right) i_3 = i_3\left[1 + \frac{W_6/L_6}{W_3/L_3}\right] \rightarrow\ i_1 = i_3 = \frac{i_5}{1 + [(W_6/L_6)/(W_3/L_3)]}$$

Also, $i_2 = i_5 - i_1 = i_5 - i_3$

Knowing i_1 and i_2 allows the calculation of v_{GS1} and v_{GS2} which gives

$$V_{TRP^+} = v_{GS2} - v_{GS1} = \sqrt{\frac{2i_2}{\beta_2}} + V_{T2} - \sqrt{\frac{2i_1}{\beta_1}} - V_{T1}$$

Internal Positive Feedback - Lower Trip Point

Assume that the gate of M1 is on ground and the input to M2 is much greater than zero. The resulting circuit is:

M2 on, M1 off → M4 and M7 on, M3 and M6 off.

$\therefore\quad v_{o1}$ is high.

M7 would like to source the current $i_7 = \dfrac{W_7/L_7}{W_4/L_4}\, i_2$

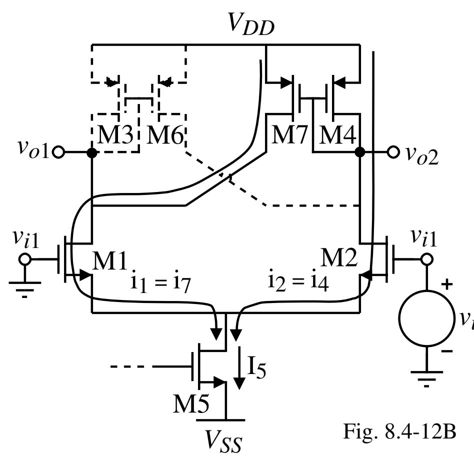


Fig. 8.4-12B

As v_{in} begins to decrease towards the trip point, the current flow through M1 increases. When $i_1 = i_7$, the lower trip point will occur.

$$\therefore\ i_5 = i_1 + i_2 = i_7 + i_4 = \left(\frac{W_7/L_7}{W_4/L_4}\right) i_4 + i_4 = i_4\left[1 + \frac{W_7/L_7}{W_4/L_4}\right]$$

$$\rightarrow i_2 = i_4 = \frac{i_5}{1 + [(W_7/L_7)/(W_4/L_4)]}$$

Also, $i_1 = i_5 - i_2 = i_5 - i_4$

Knowing i_1 and i_2 allows the calculation of v_{GS1} and v_{GS2} which gives

$$V_{TRP^-} = v_{GS2} - v_{GS1} = \sqrt{\frac{2i_2}{\beta_2}} + V_{T2} - \sqrt{\frac{2i_1}{\beta_1}} - V_{T1}$$

Example 8.4-2 - Calculation of Trip Voltages for a Comparator with Hysteresis

Consider the circuit shown. Using the transistor device parameters given in Table 3.1-2 calculate the positive and negative threshold points if the device lengths are all 1 μm and the widths are given as: $W_1 = W_2 = W_6 = W_7 = 10\ \mu$m and $W_3 = W_4 = 2\ \mu$m. The gate of M1 is tied to ground and the input is the gate of M2. The current, $i_5 = 20\ \mu$A

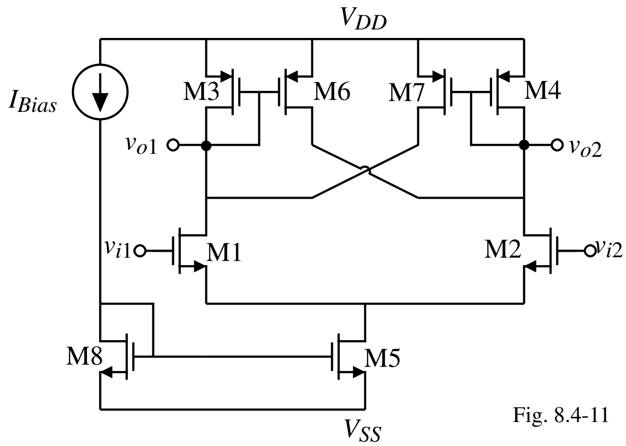


Fig. 8.4-11

Solution

To calculate the positive trip point, assume that the input has been negative and is heading positive.

$$i_6 = \frac{(W/L)_6}{(W/L)_3} i_3 = (5/1)(i_3) \quad\rightarrow\quad i_3 = \frac{i_5}{1 + [(W/L)_6/(W/L)_3]} = i_1 = \frac{20\ \mu\text{A}}{1+5} = 3.33\ \mu\text{A}$$

$$i_2 = i_5 - i_1 = 20 - 3.33 = 16.67\ \mu\text{A} \quad\rightarrow\quad v_{GS1} = \left(\frac{2i_1}{\beta_1}\right)^{1/2} + V_{T1} = \left(\frac{2\cdot 3.33}{(5)110}\right)^{1/2} + 0.7 = 0.81\text{V}$$

$$v_{GS2} = \left(\frac{2i_2}{\beta_2}\right)^{1/2} + V_{T2} = \left(\frac{2\cdot 16.67}{(5)110}\right)^{1/2} + 0.7 = 0.946\text{V}$$

$$\therefore \quad V_{TRP+} \cong v_{GS2} - v_{GS1} = 0.946 - 0.810 = 0.136\text{V}$$

Example 8.4-2 - Continued

Determining the negative trip point, similar analysis yields

$i_4 = 3.33\ \mu$A

$i_1 = 16.67\ \mu$A

$v_{GS2} = 0.81$V

$v_{GS1} = 0.946$V

$V_{TRP-} \cong v_{GS2} - v_{GS1} = 0.81 - 0.946 = -0.136$V

PSPICE simulation results of this circuit are shown below.

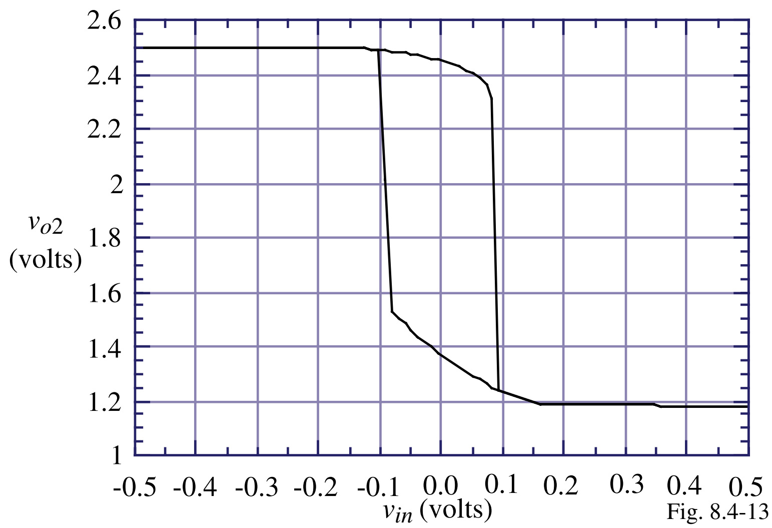


Fig. 8.4-13

Complete Comparator with Internal Hysteresis

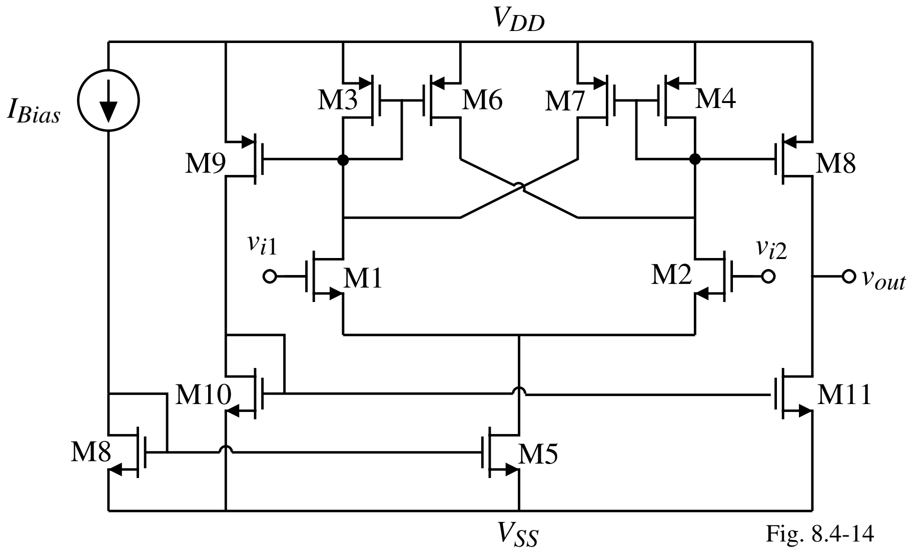


Fig. 8.4-14

Schmitt Trigger

The Schmitt trigger is a circuit that has better defined switching points.

Consider the following circuit:

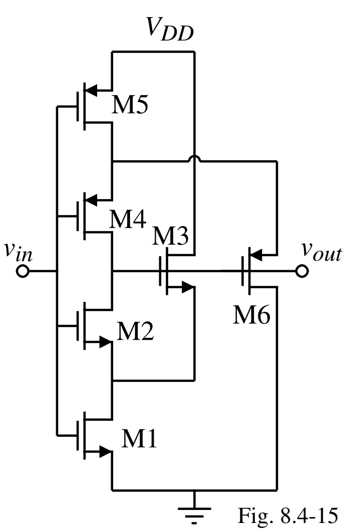


Fig. 8.4-15

How does this circuit work?

Assume the input voltage, v_{in}, is low and the output voltage, v_{out} , is high.

∴ M3, M4 and M5 are on and M1, M2 and M6 are off.

When v_{in} is increased from zero, M2 starts to turn on causing M3 to start turning off. Positive feedback causes M2 to turn on further and eventually both M1 and M2 are on and the output is at zero.

The upper switching point, $V_{TRP}+$ is found as follows:

When v_{in} is low, the voltage at the source of M2 (M3) is

$$v_{S2} = V_{DD}\text{-}V_{TN3}$$

$V_{TRP}+ = v_{in}$ when M2 turns on given as $V_{TRP}+ = V_{TN2} + v_{S2}$

$V_{TRP}+$ occurs when the input voltage causes the currents in M3 and M1 to be equal.

Schmitt Trigger – Continued

Thus, $i_{D1} = \beta_1(V_{TRP}^{+} - V_{TN1})^2 = \beta_3(V_{DD} - v_{S2}- V_{TN3})^2 = i_{D3}$

which can be written as, assuming that $V_{TN2} = V_{TN3}$,

$$\beta_1(V_{TRP}^{+} - V_{TN1})^2 = \beta_3(V_{DD} - V_{TRP}^{+})^2 \quad \Rightarrow \quad V_{TRP}^{+} = \frac{V_{TN1} + \sqrt{\beta_3/\beta_1}\, V_{DD}}{1 + \sqrt{\beta_3/\beta_1}}$$

The switching point, V_{TRP}^{-} is found in a similar manner and is:

$$\beta_5(V_{DD} - V_{TRP}^{-} - V_{TP5})^2 = \beta_6(V_{TRP}^{-})^2 \Rightarrow V_{TRP}^{-} = \frac{\sqrt{\beta_5/\beta_6}\,(V_{DD} - V_{TP5})}{1 + \sqrt{\beta_5/\beta_6}}$$

The bistable characteristic is,

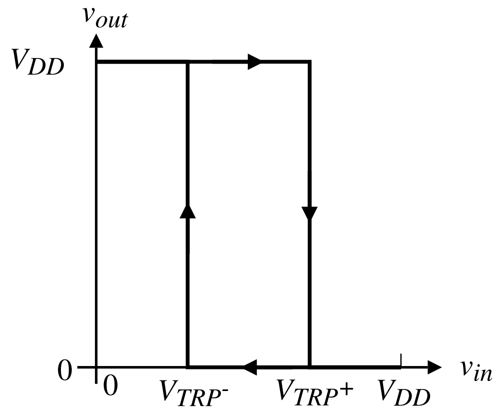


Fig. 8.4-16

SUMMARY

- Open-loop, continuous-time comparators can be improved in the areas of:
  - Current sinking and sourcing
  - Removal of offset voltages
  - Removal of the influence of a noisy signal through hysteresis
- Comparators with hysteresis (positive feedback)
  - External
  - Internal