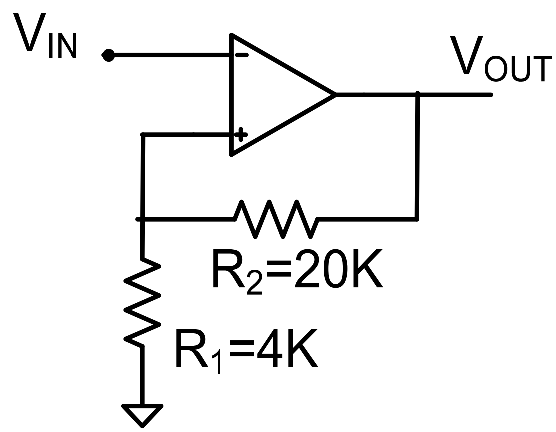
EE 230
Lecture 22

Nonlinear Op Amp Applications

– Waveform Generators

Quiz 16

Plot the transfer charactristics of the following circuit. Assume the op amp has V_{SATH}=12V and V_{SATL}=-12V.



And the number is ?

1 3 8

5 4

?

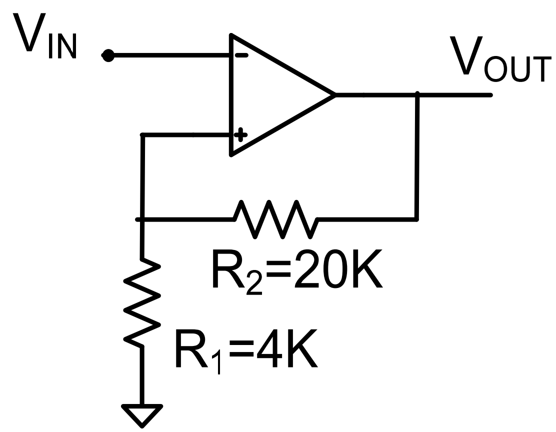
2 6

9

7

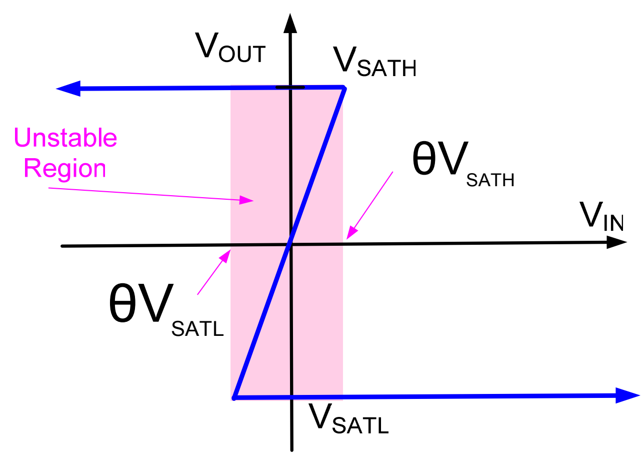
Quiz 16

Plot the transfer charactristics of the following circuit. Assume the op amp has V_{SATH}=12V and V_{SATL}=-12V.



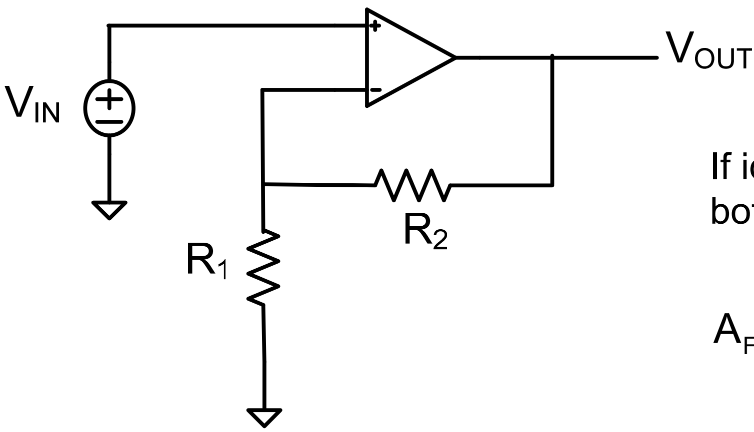
Solution

Define $\theta = \dfrac{R_1}{R_1+R_2}$



Review from Last Lecture

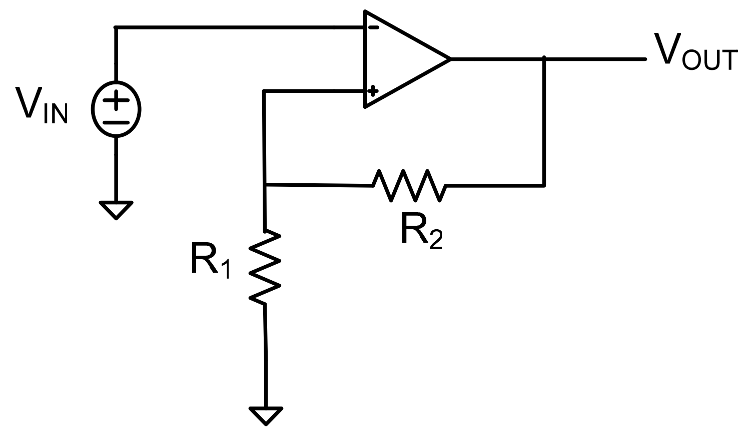
Before trashing the “bad” circuit which we saw was unstable, lets see if it has any useful properties!



Usually the good circuit

If ideal op amps both have gain

$$A_{FB}=1+\frac{R_2}{R_1}$$

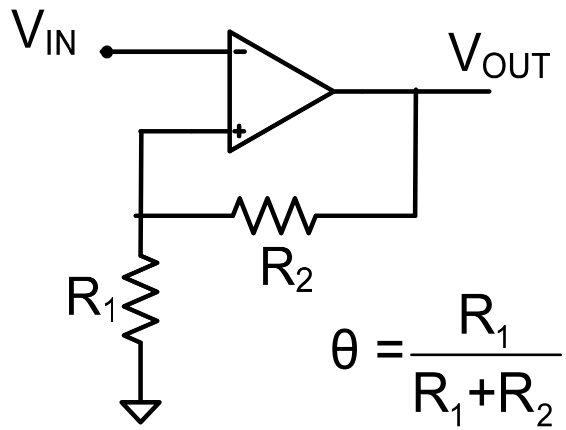


Usually the bad circuit

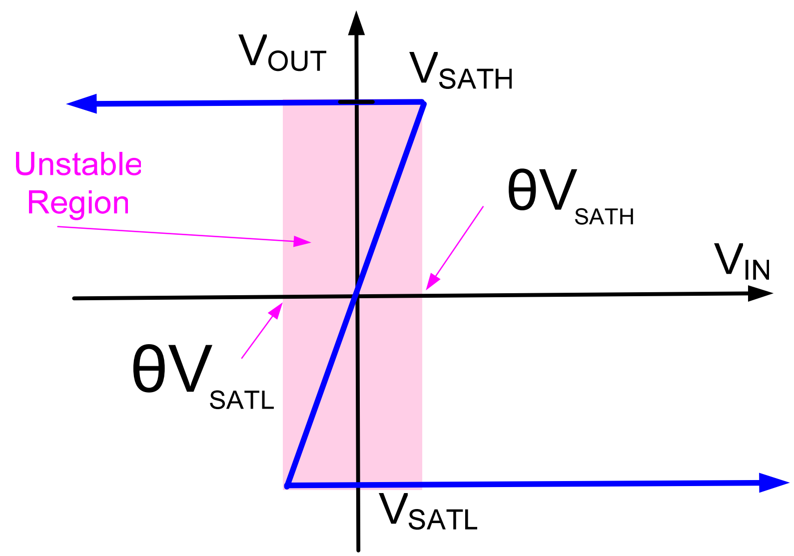
This circuit is unstable !

Review from Last Lecture

Comparator with Hysteresis

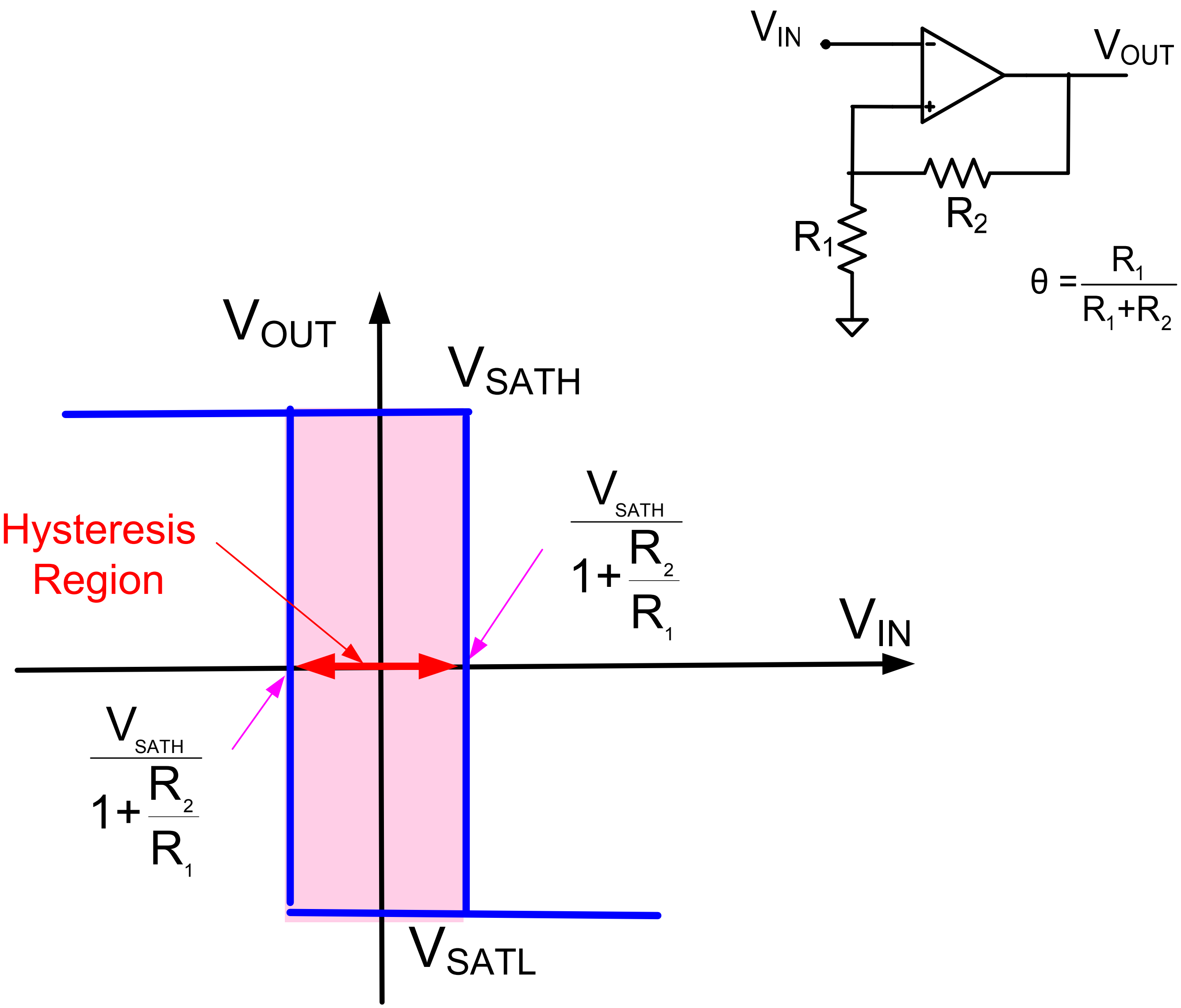


$$\theta = \frac{R_1}{R_1 + R_2}$$

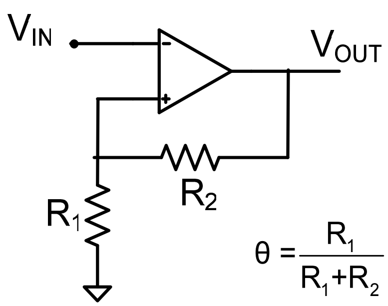


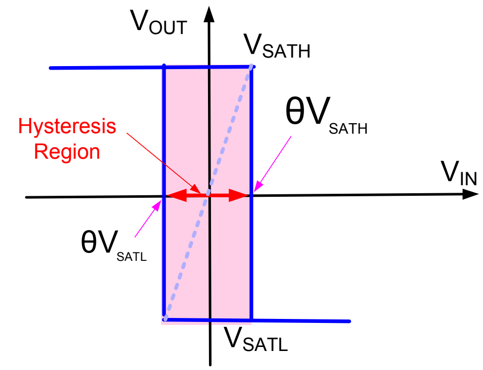
Review from Last Lecture

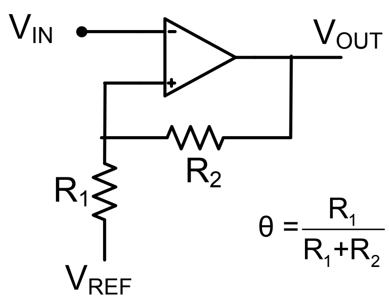
Comparator with Hysteresis

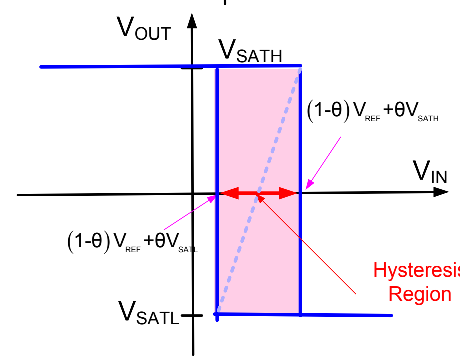


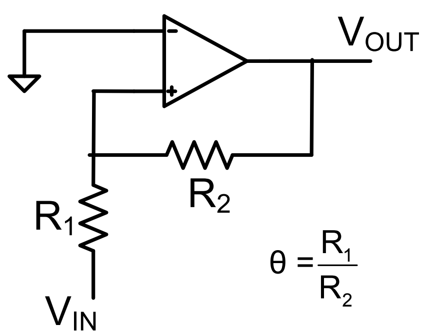
Modifications of Comparator with Hysteresis



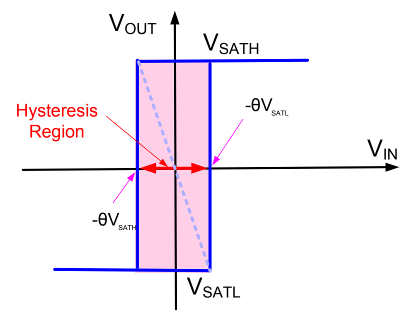




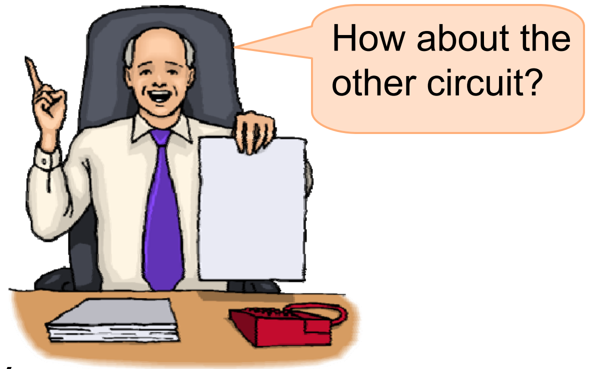


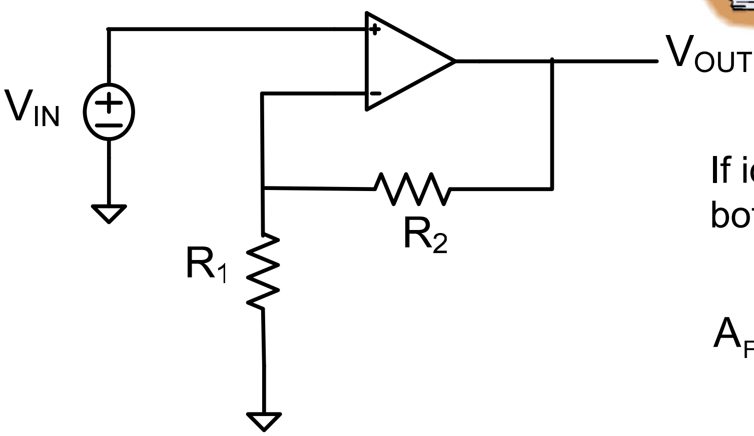


Note this is the basic inverting amplifier with op amp terminals interchanged



Many other ways to control position and size of hysteresis window

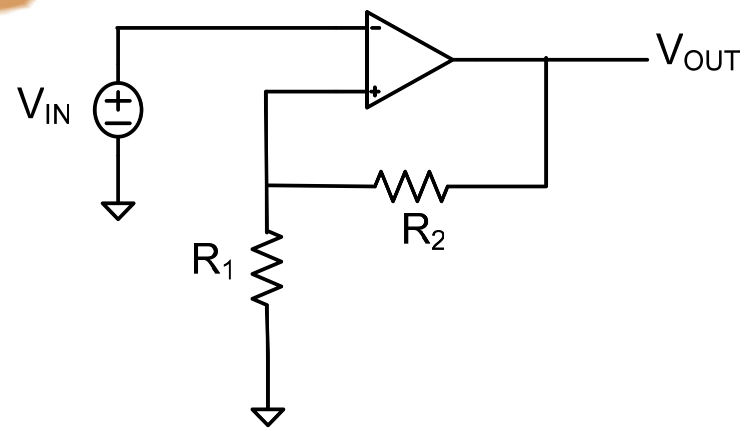




Usually the good circuit

If ideal op amps both have gain

$$A_{FB}=1+\frac{R_2}{R_1}$$

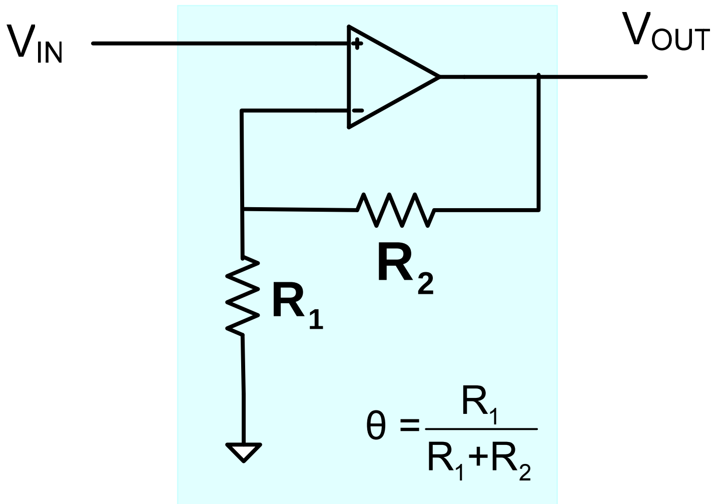


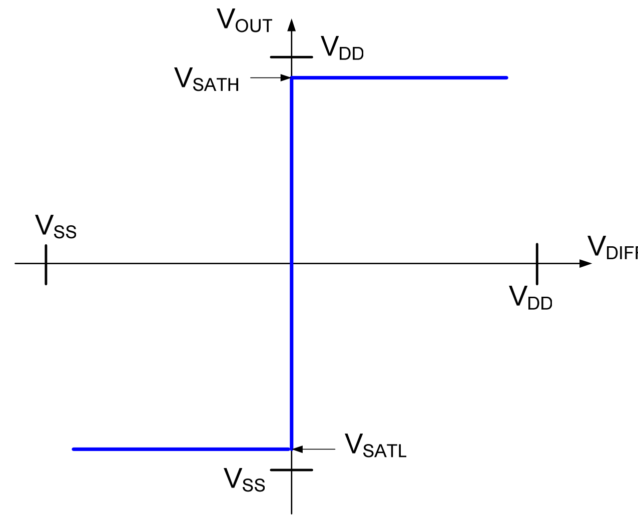
Usually the bad circuit

This circuit is unstable !

Will now analyze the “usually good” circuit using nonlinear analysis methods

Consider this circuit





$$V_{OUT} = \begin{cases} V_{SATH} & V_{DIFF} > V_{SATH}/A_0 \\ A_0 V_{IN} & V_{SATL}/A_0 < V_{DIFF} < V_{SATH}/A_0 \\ V_{SATL} & V_{DIFF} < V_{SATL}/A_0 \end{cases}$$

Region 1

Region 2

Region 3

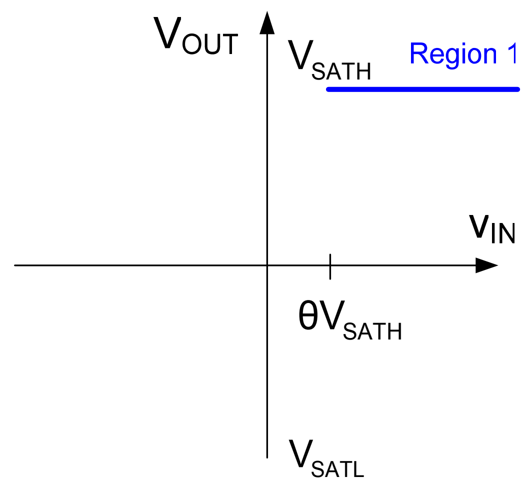
Assume in Region 1 (must verify)

$$V_{OUT} = V_{SATH}$$

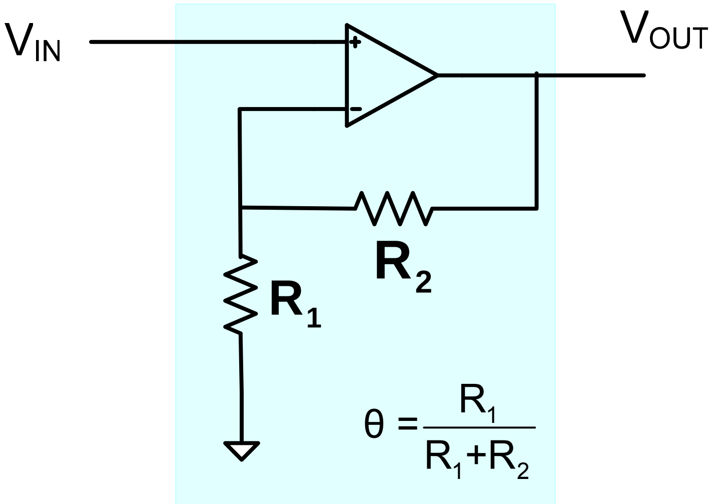
Valid for

$$V_{IN} - \theta V_{SATH} > \frac{V_{SATH}}{A_0}$$

$$\theta V_{SATH} < V_{IN}$$



Consider this circuit



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

$$V_{OUT} = \begin{cases} V_{SATH} & V_{DIFF} > V_{SATH}/A_0 & \text{Region 1} \\ A_0 V_{IN} & V_{SATL}/A_0 < V_{DIFF} < V_{SATH}/A_0 & \text{Region 2} \\ V_{SATL} & V_{DIFF} < V_{SATL}/A_0 & \text{Region 3} \end{cases}$$

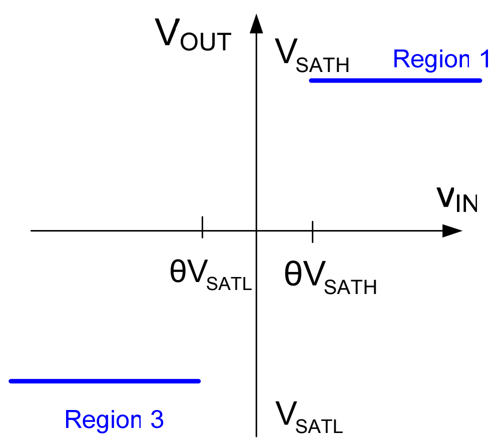
Assume in Region 3 (must verify)

$$V_{OUT} = V_{SATL}$$

Valid for

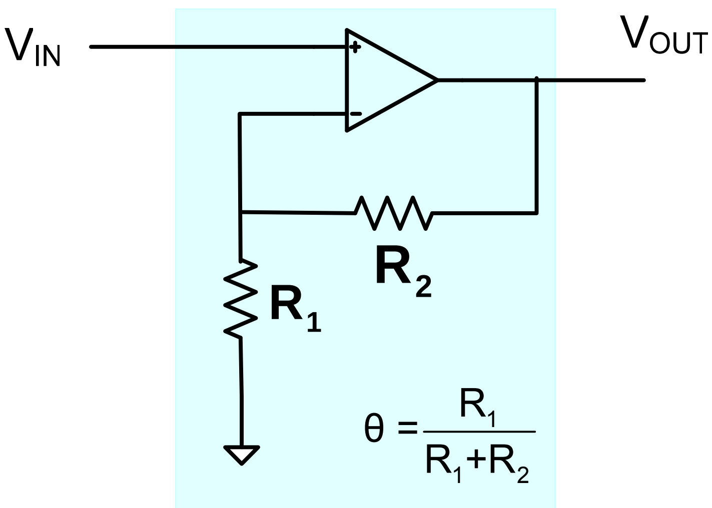
$$V_{IN} - \theta V_{OUT} < \frac{V_{SATL}}{A_0}$$

$$\theta V_{SATL} > V_{IN}$$



Note this is now single-valued for the range considered so far

Consider this circuit



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

$$V_{OUT} = \begin{cases} V_{SATH} & V_{DIFF} > V_{SATH}/A_0 \\ A_0 V_{IN} & V_{SATL}/A_0 < V_{DIFF} < V_{SATH}/A_0 \\ V_{SATL} & V_{DIFF} < V_{SATL}/A_0 \end{cases}$$

Region 1

Region 2

Region 3

Assume in Region 2 (must verify)

$$V_{DIFF} = V_{IN} - \theta V_{OUT}$$

$$V_{OUT} = A_0 V_{DIFF}$$

$$V_{OUT} = \left(\frac{1}{\theta + A_0^{-1}}\right) V_{IN}$$

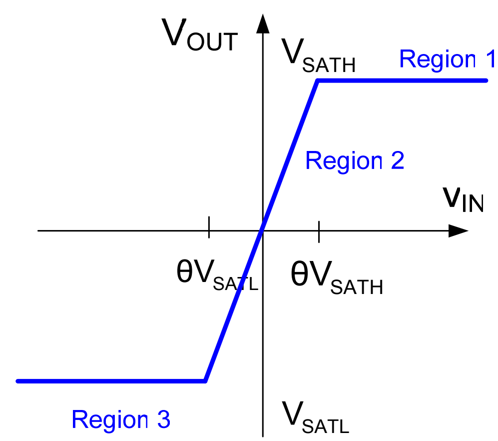
$$V_{OUT} = \left(\frac{1}{\theta}\right) V_{IN}$$

Valid for

$$\frac{V_{SATL}}{A_0} < V_{IN} - \theta V_{OUT} < \frac{V_{SATH}}{A_0}$$

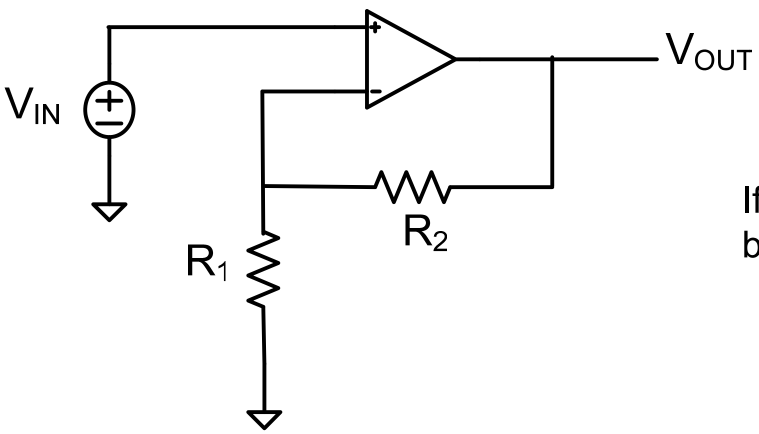
(must use exact value for V_{OUT} to avoid degenerate conditions)

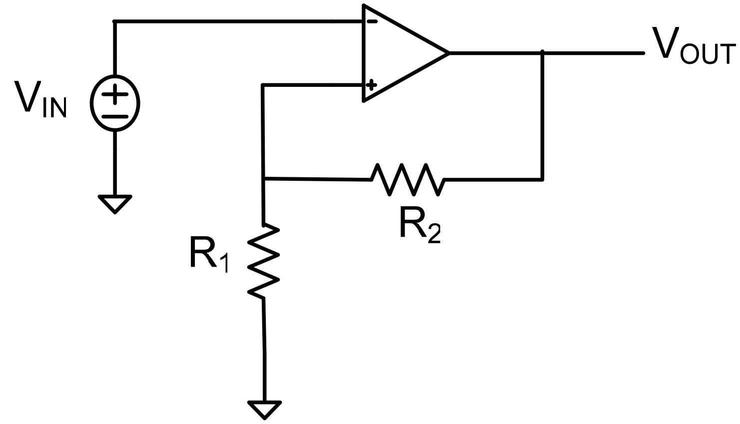
$$\theta V_{SATL} < V_{IN} < \theta V_{SATH}$$



- Note this circuit does not have a hysteresis loop
- Simply serves as a noninverting amplifier that saturates at extreme inputs

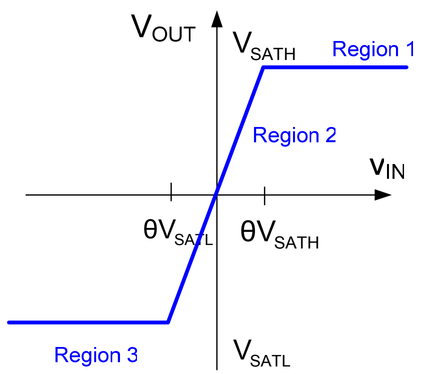
Comparison of basic noninverting amplifier structures

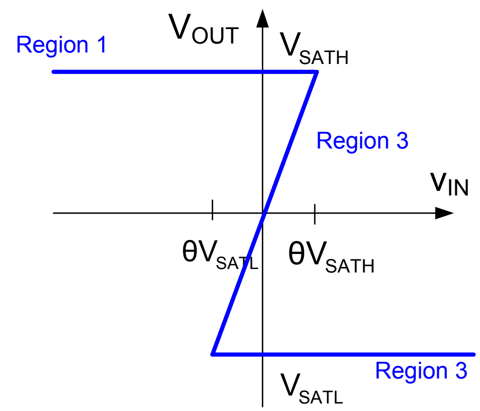




If ideal op amps both have gain

$$A_{FB}=1+\frac{R_2}{R_1}$$

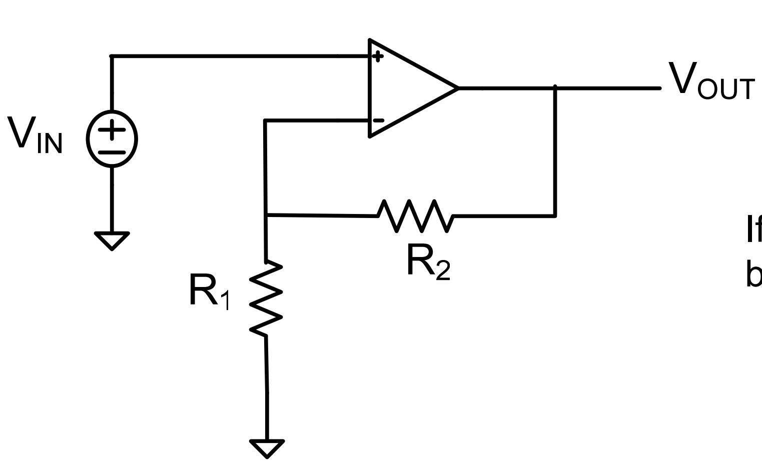




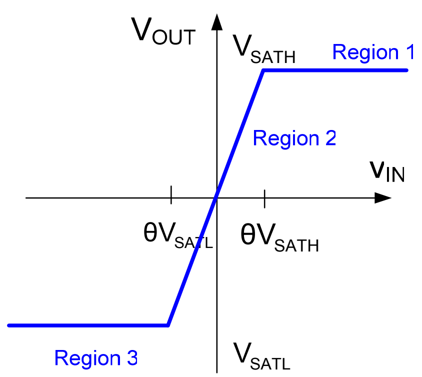
- Serves as an amplifier <u>directly</u>
- Stable
- No hysteresis loop

- Not useful as an amplifier <u>directly</u>
- Unstable
- Serves as comparator with hysteresis

Comparison of basic noninverting amplifier structures



Usually a good amplifier



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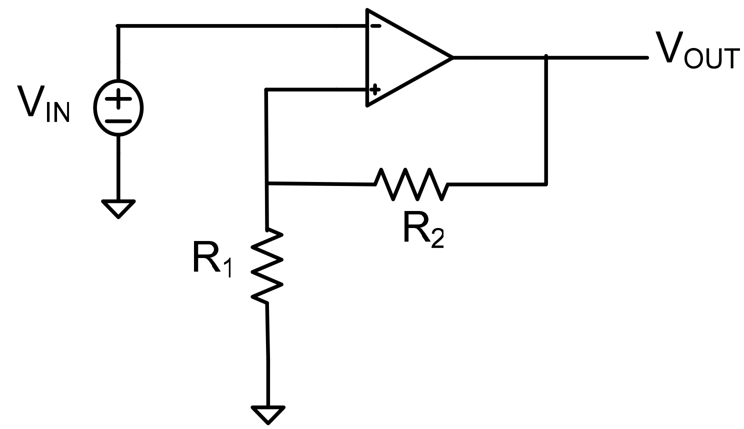
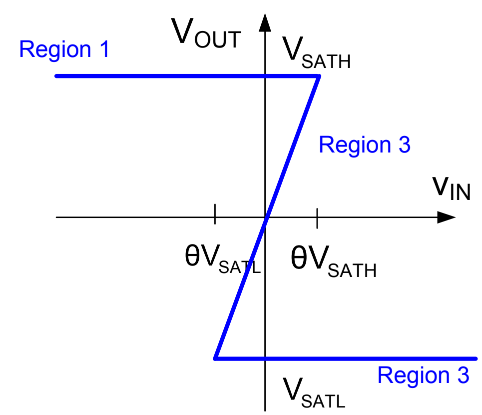
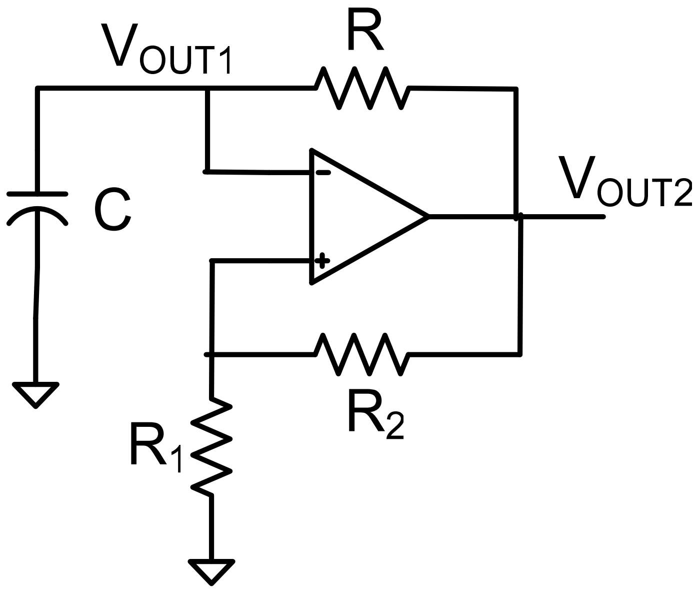


Usually not a good amplifier



Give examples where the circuit the left serves as an amplifier and that on the right does not

Waveform Generator



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

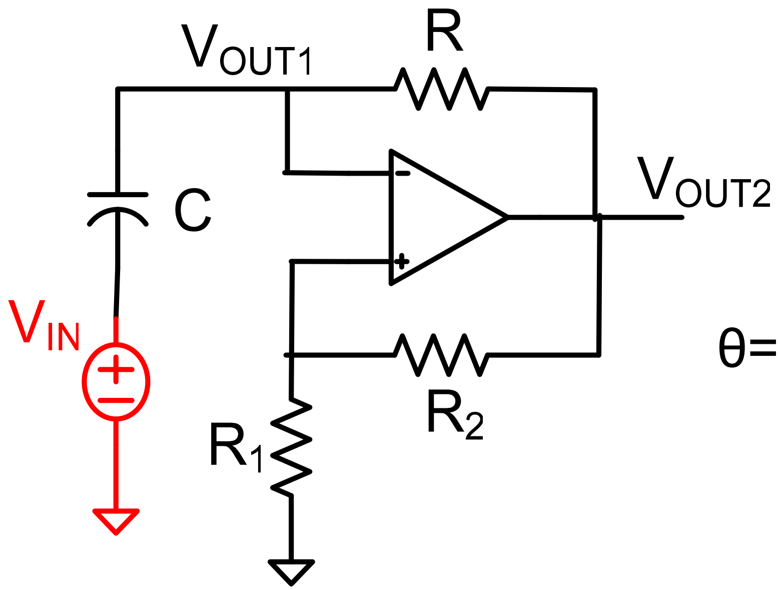
Lets first check stability

Will add an excitation that does not change the “dead” network to obtain a transfer function

The roots of the denominator are the poles of the circuit

Actually can check stability without adding input but will not go into details at this time

Waveform Generator



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

Lets first check stability

$$V_{OUT2} = \frac{GB}{s}\left(\theta V_{OUT2} - V_{OUT1}\right)$$

$$V_{OUT1}\left(sC + G\right) = GV_{OUT2} + sCV_{IN}$$

$$T(s) = \frac{V_{OUT2}}{V_{IN}} = \frac{sC}{s^2\left(\frac{C}{GB}\right) + s\left(\frac{G}{GB} - \theta C\right) + G(1-\theta)}$$

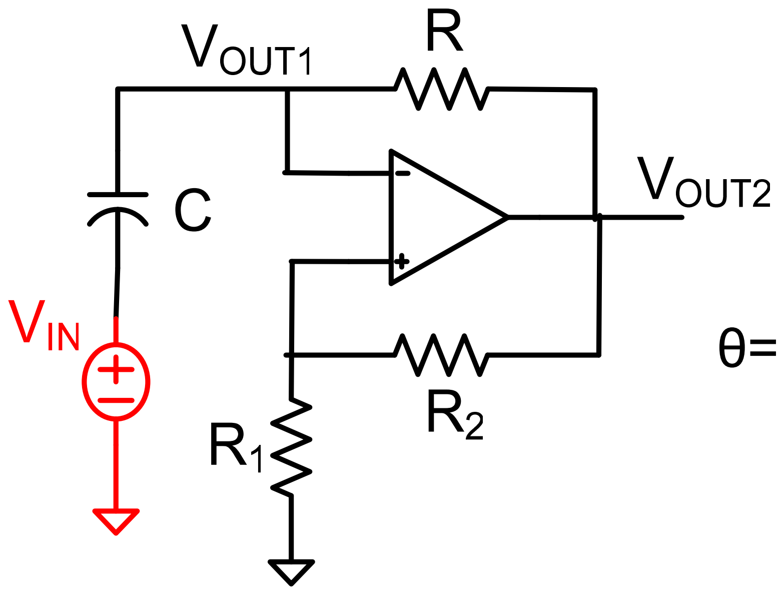
$$T(s) \simeq \frac{sC}{s^2\left(\frac{C}{GB}\right) + s(-\theta C) + G(1-\theta)}$$

It follows that there is a pole on the positive real axis !

Thus the circuit is unstable and will operate nonlinearly !

Can find the RHP pole of THIS circuit even if op amp is ideal!

Waveform Generator



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

Can also check stability for this with ideal op amp

$$V_{OUT1} = \theta V_{OUT2}$$

$$V_{OUT1}(sC+G) = GV_{OUT2} + sCV_{IN}$$

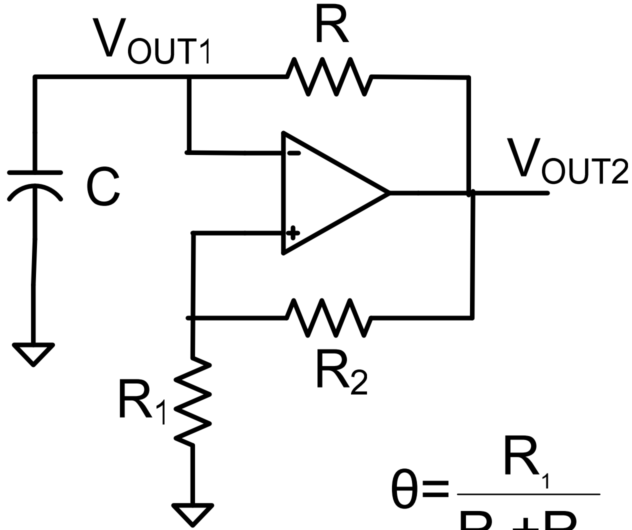
$$T(s) \simeq \frac{sC}{s(-\theta C) + G(1-\theta)}$$

Pole at $$p = \frac{G(1-\theta)}{\theta C}$$

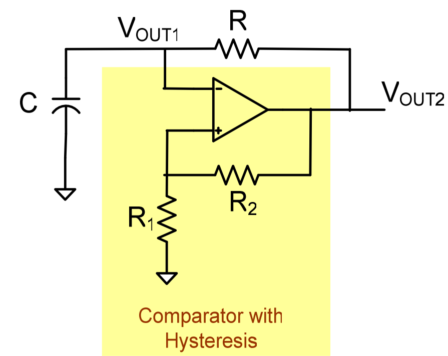
Observe the pole is on the positive real axis !

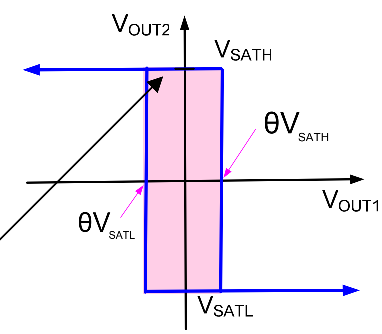
Thus the circuit is unstable and will operate nonlinearly !

Waveform Generator



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





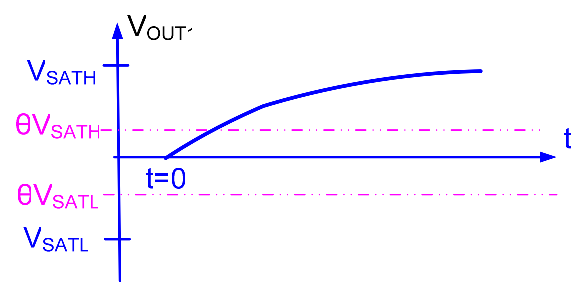
Assume V_{OUT2} is in either the high or low state at any time t

w.l.o.g. assume that $V_{OUT1}=0$ at t=0 and $V_{OUT2}=V_{SATH}$

$$V_{OUT1} = F + (I - F)e^{-\frac{t}{RC}}$$

$F=V_{SATH}$, $I=0$

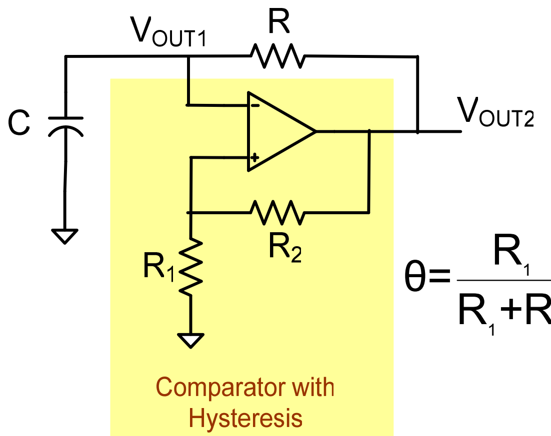
$$V_{OUT1} = V_{SATH}\left(1 - e^{-\frac{t}{RC}}\right)$$



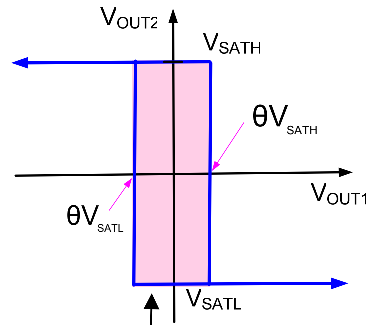
while in this state, V_{OUT1} is increasing, however, this is valid only for $V_{OUT1} < \theta V_{SATH}$

As soon as $V_{OUT1} = \theta V_{SATH}$, comparator output will switch to V_{SATL}

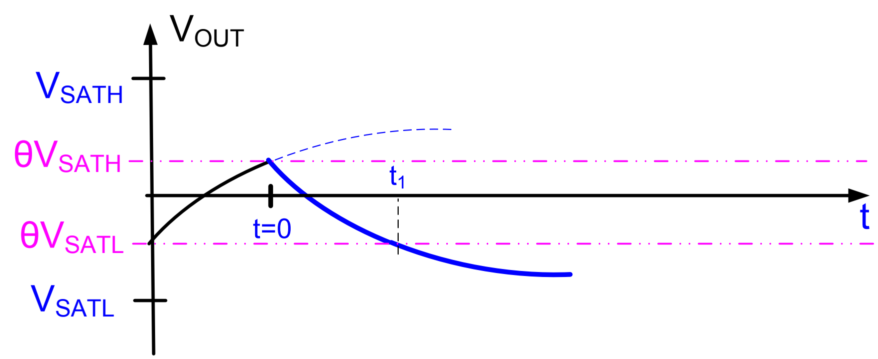
Waveform Generator



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



For convenience reset the time axis as shown



now, for t>0 have

$$V_{OUT1}=F+\left(I-F\right)e^{-\frac{t}{RC}} \qquad F=V_{SATL},\ I=\theta V_{SATH}$$

$$V_{OUT1}=V_{SATL}\left(1-e^{-\frac{t}{RC}}\right)+\theta V_{SATH}e^{-\frac{t}{RC}}$$

while in this state, V_{OUT1} is decreasing, however, this is valid only for $V_{OUT1}>\theta V_{SATL}$

As soon as $V_{OUT1}=\theta V_{SATL}$, comparator output will switch to V_{SATH}

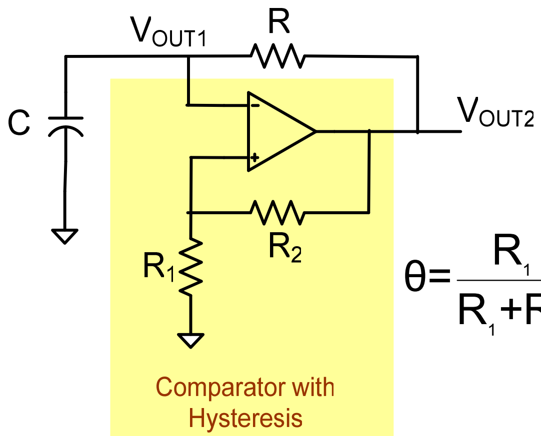
If we define t_1 to be the time where this switch occurs, it follows that

$$\theta V_{SATL}=V_{SATL}\left(1-e^{-\frac{t_1}{RC}}\right)+\theta V_{SATH}e^{-\frac{t_1}{RC}}$$

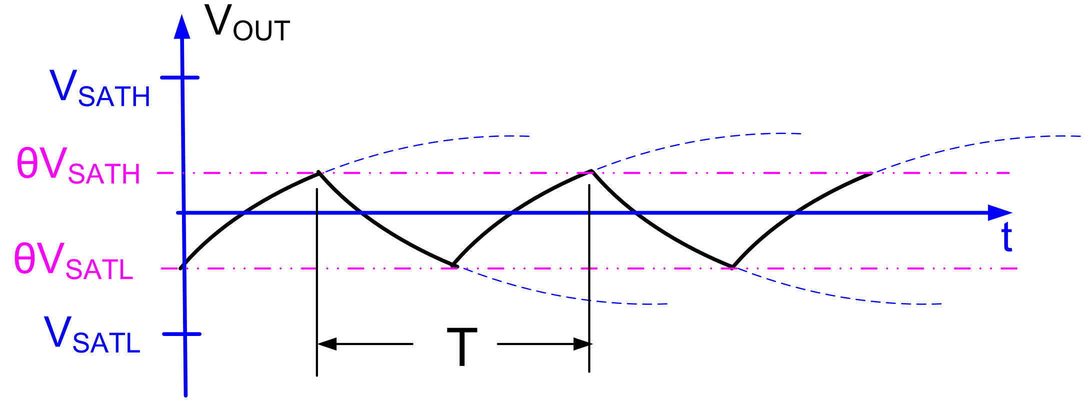
Solving for t_1, obtain

$$t_1=-RC\ln\left(\frac{V_{SATL}(\theta-1)}{\theta V_{SATH}-V_{SATL}}\right)$$

Waveform Generator



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



$$t_1 = -RC \ln\left(\frac{V_{SATL}(\theta - 1)}{\theta V_{SATH} - V_{SATL}}\right)$$

this process repeats itself

the rise time and the fall times are identical

the period of the nearly triangular waveform is thus $2t_1$

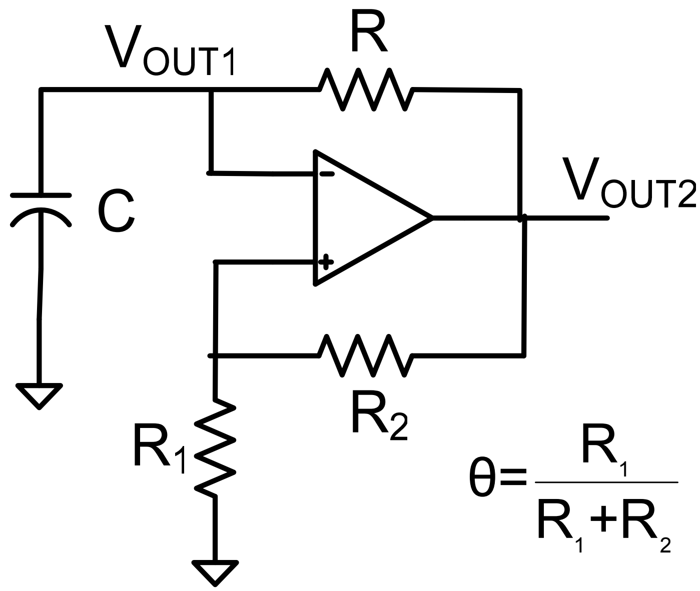
$$T = 2t_1 = -2RC \ln\left(\frac{V_{SATL}(\theta - 1)}{\theta V_{SATH} - V_{SATL}}\right)$$

$$f = \frac{1}{T} = \frac{1}{2RC} \frac{1}{\ln\left(\frac{\theta V_{SATH} - V_{SATL}}{V_{SATL}(\theta - 1)}\right)}$$

If $V_{SATL} = -V_{SATH}$, this simplifies to

$$f = \frac{1}{2RC} \frac{1}{\ln\left(\frac{1+\theta}{1-\theta}\right)}$$

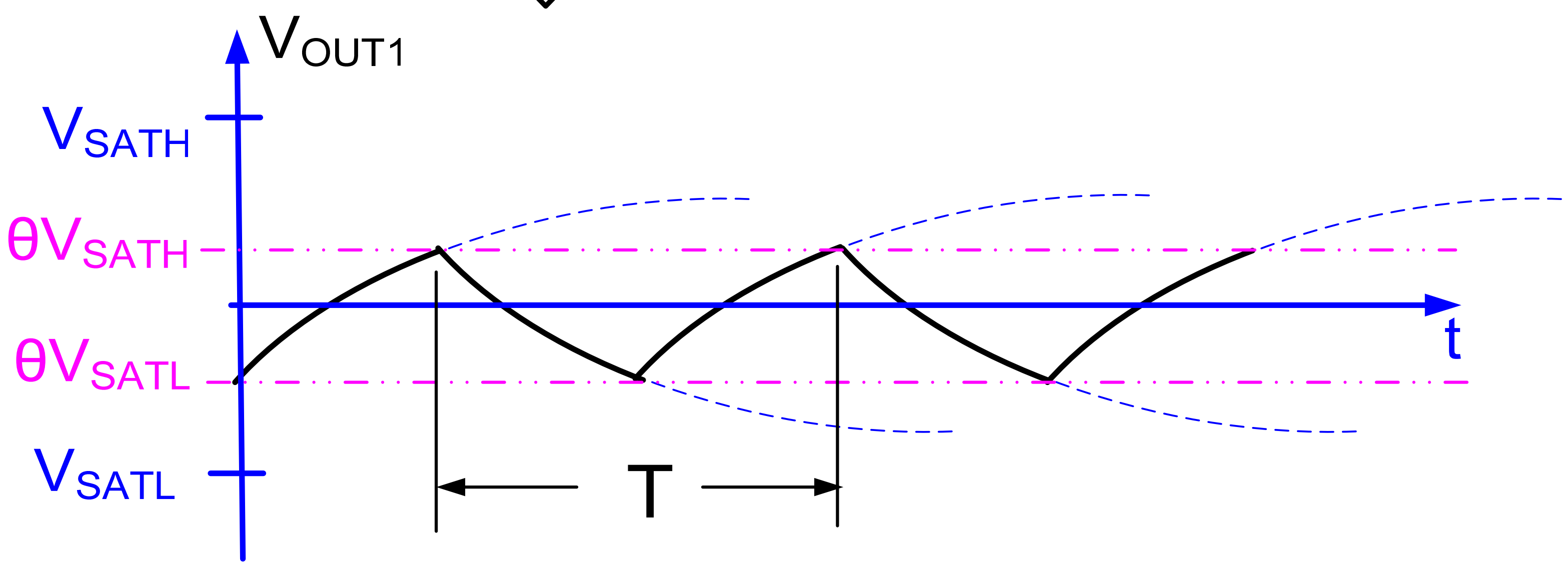
Waveform Generator

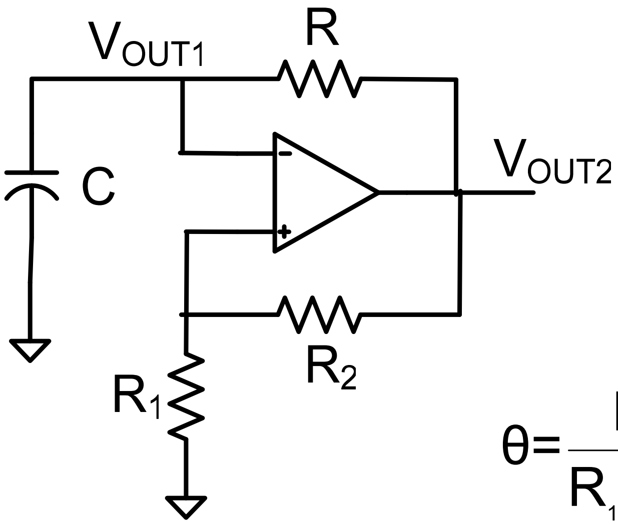


$$\theta = \frac{R_1}{R_1 + R_2}$$

for $V_{SATL} = -V_{SATH}$

$$T = 2RC\ln\left(\frac{1+\theta}{1-\theta}\right)$$

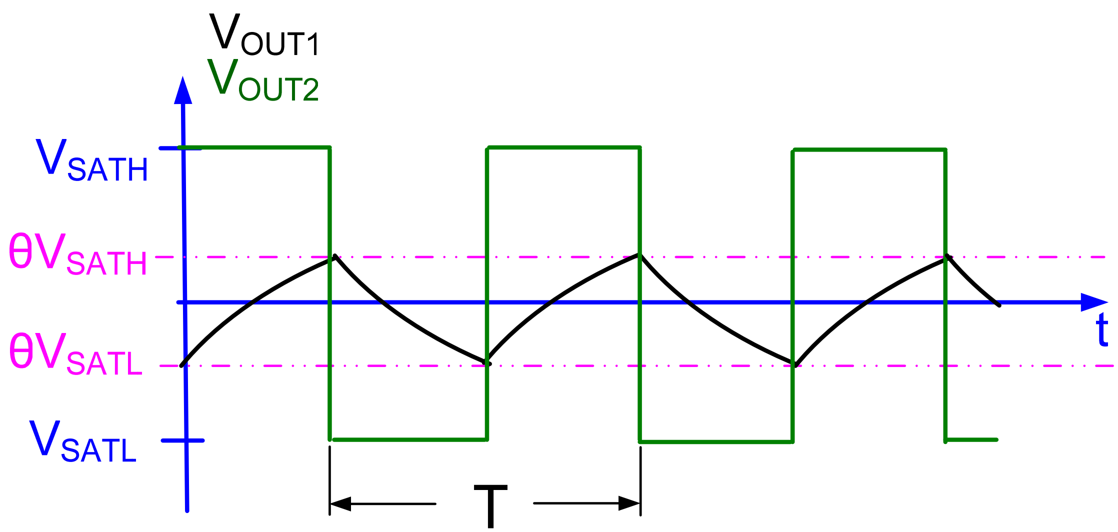




for $V_{SATL} = -V_{SATH}$

$$f = \frac{1}{2RC} \frac{1}{\ln\left(\frac{1+\theta}{1-\theta}\right)}$$

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



Square and distorted triangular output waveforms
Slope of square wave is determined by SR of Op Amp

End of Lecture 22