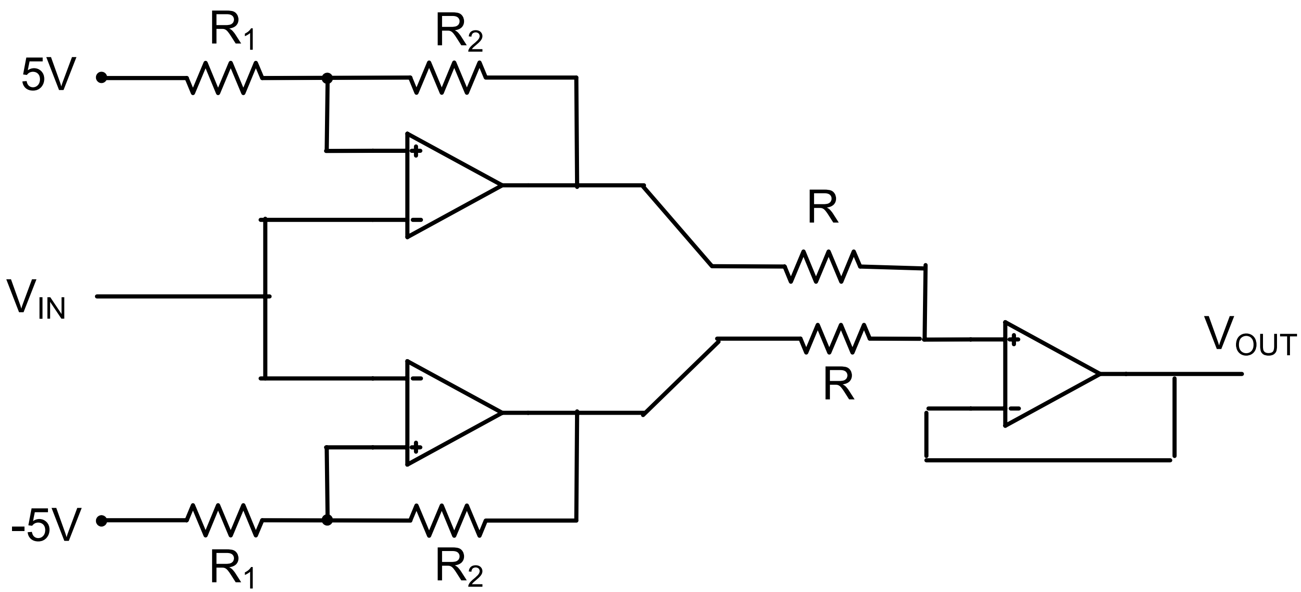
EE 230
Lecture 23

Nonlinear Op Amp Applications

- waveform generators

Quiz 16

Obtain an expression for and plot the transfer characteristics of the following circuit. Assume R_1=2K, R_2=8K, R=10K, V_{DD}+15V, V_{SS}=-15V



And the number is ?

1 3 8

5 4

2 6

9 7

And the number is ?

1 3 8

5 4

3

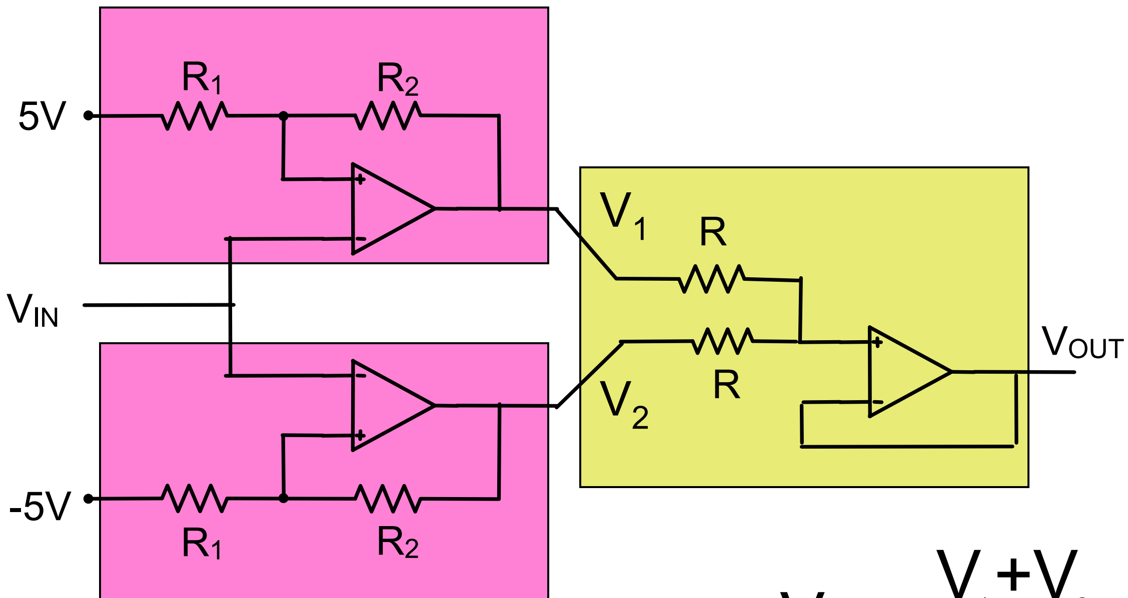
2 6

9 7

Quiz 16

Solution:

Obtain an expression for and plot the transfer characteristics of the following circuit. Assume R_1=2K, R_2=8K, R=10K, V_{DD}+15V, V_{SS}=-15V



$$V_{OUT}=\frac{V_1+V_2}{2}$$

$$V_{HYH}=\theta V_{SATH}+\left(1\text{-}\theta\right)V_R$$

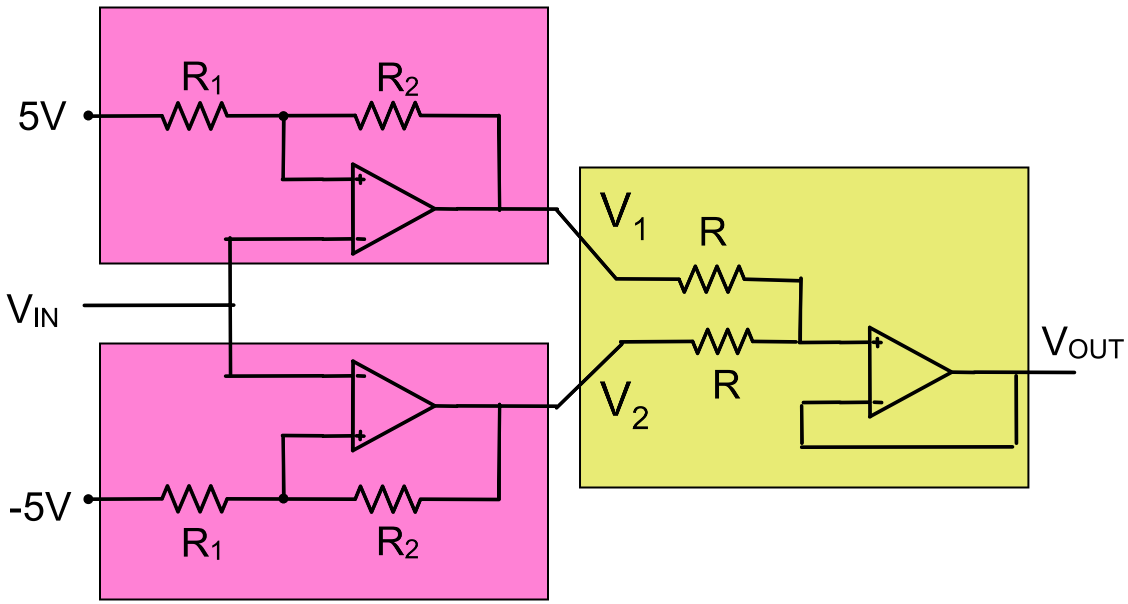
$$V_{HYL}=\theta V_{SATL}+\left(1\text{-}\theta\right)V_R$$

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

Quiz 16

Solution:

Obtain an expression for and plot the transfer characteristics of the following circuit. Assume R_1=2K, R_2=8K, R=10K, V_{DD}+15V, V_{SS}=-15V



$$\theta = \frac{R_1}{R_1+R_2} = 0.2$$

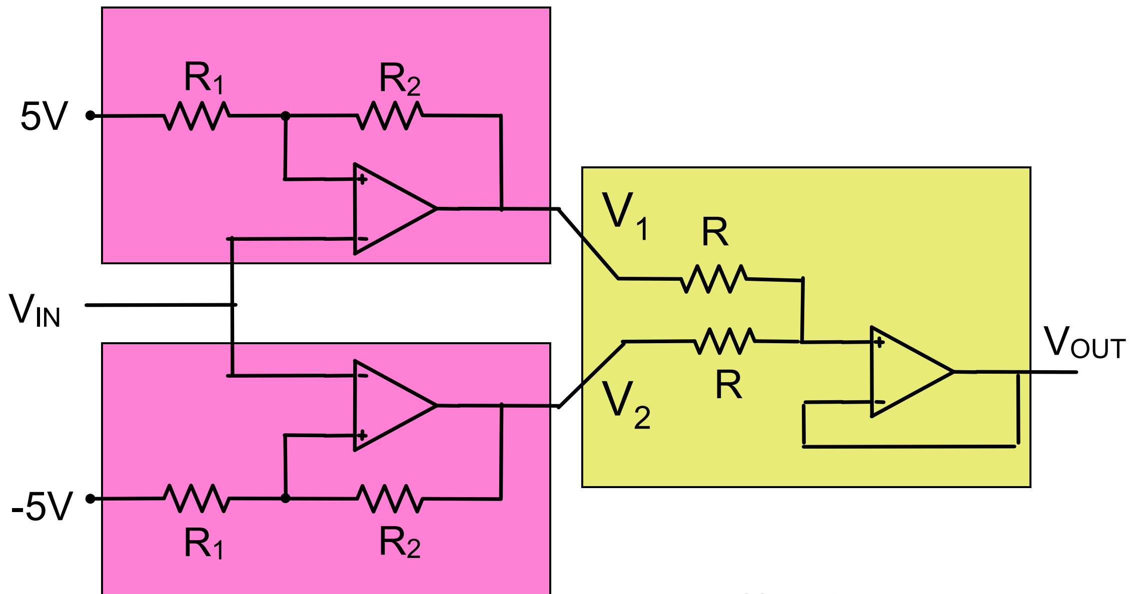
$$V_{HYH} = \theta V_{SATH} + (1-\theta) V_R = 3V+4V=7V \qquad V_{HYH} = \theta V_{SATH} + (1-\theta) V_R = 3V-4V= -1V$$

$$V_{HYL} = \theta V_{SATL} + (1-\theta) V_R = -3V+4V=1V \qquad V_{HYL} = \theta V_{SATL} + (1-\theta) V_R = -3V-4V= -7V$$

Quiz 16

Solution:

Obtain an expression for and plot the transfer characteristics of the following circuit. Assume R_1=2K, R_2=8K, R=10K, V_{DD}+15V, V_{SS}=-15V



$$V_{HYH} = \theta V_{SATH} + (1\text{-}\theta) V_R = 3V\text{-}4V = \text{-}1V$$

$$V_{HYL} = \theta V_{SATL} + (1\text{-}\theta) V_R = \text{-}3V\text{-}4V = \text{-}7V$$

$$V_{HYH} = \theta V_{SATH} + (1\text{-}\theta) V_R = 3V+4V = 7V$$

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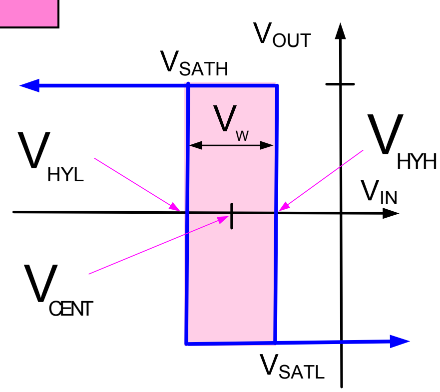
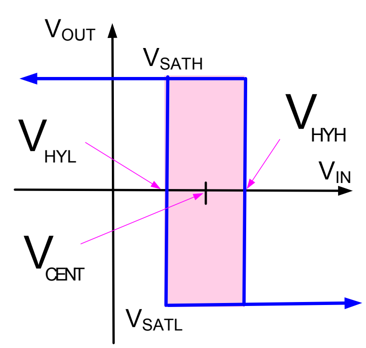




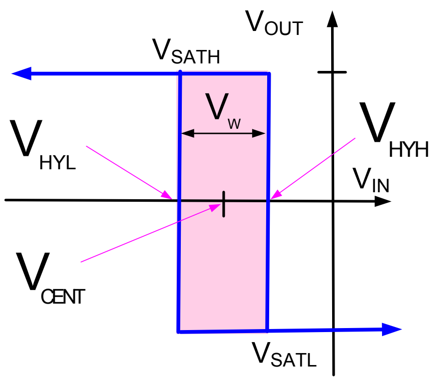
Quiz 16

Solution:

Obtain an expression for and plot the transfer characteristics of the following circuit. Assume R_1=2K, R_2=8K, R=10K, V_{DD}+15V, V_{SS}=-15V

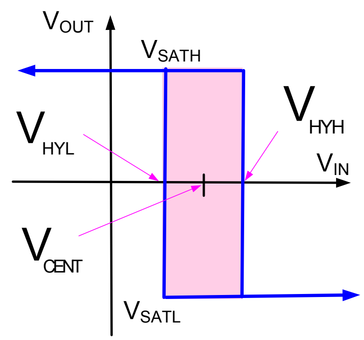
$$V_{HYH} = \theta V_{SATH} + (1\text{-}\theta)V_R = 3V - 4V = -1V$$

$$V_{HYL} = \theta V_{SATL} + (1\text{-}\theta)V_R = -3V - 4V = -7V$$

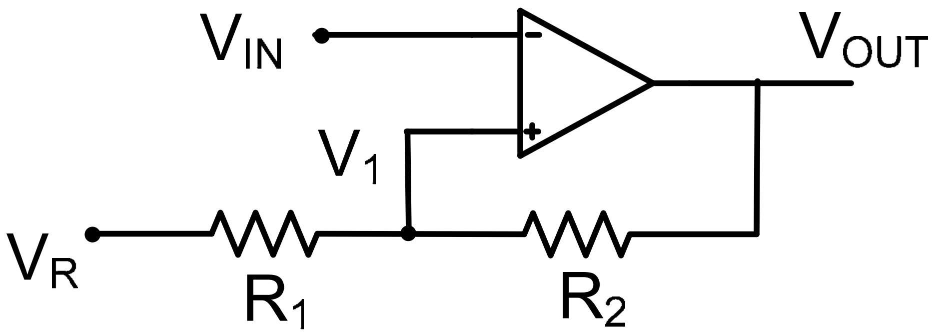


$$V_{HYH} = \theta V_{SATH} + (1\text{-}\theta)V_R = 3V + 4V = 7V$$

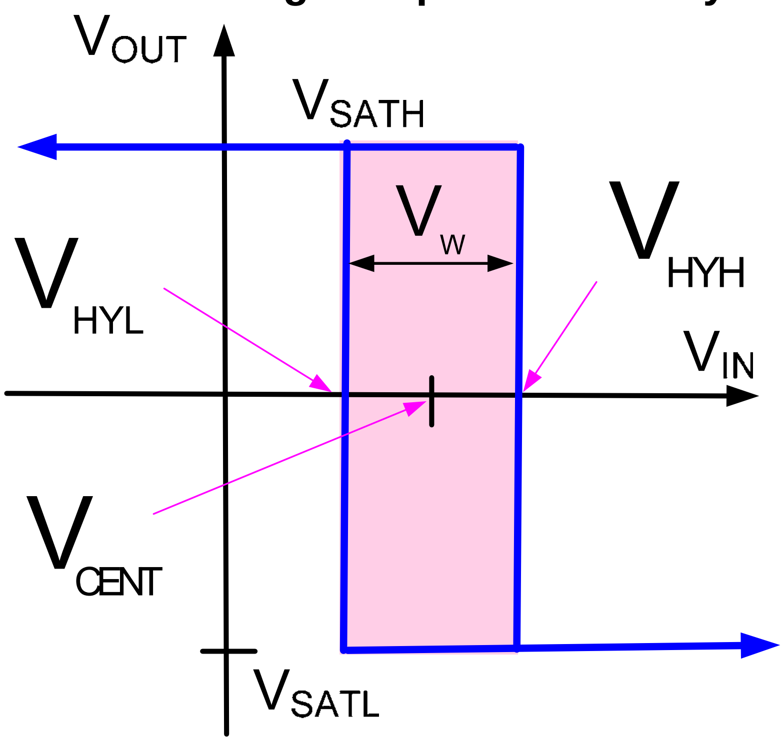
$$V_{HYL} = \theta V_{SATL} + (1\text{-}\theta)V_R = -3V + 4V = 1V$$



Review from Last Time:



Shifted Inverting Comparator with Hysteresis



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

$$V_W=\theta\left(V_{SATH}-V_{SATL}\right)$$

$$V_{CENT}=\left(\frac{\theta\left(V_{SATH}+V_{SATL}\right)}{2}\right)+\left(1-\theta\right)V_R$$

If $V_{SATH}=V_{DD}$, $V_{STAL}=V_{SS}=-V_{DD}$

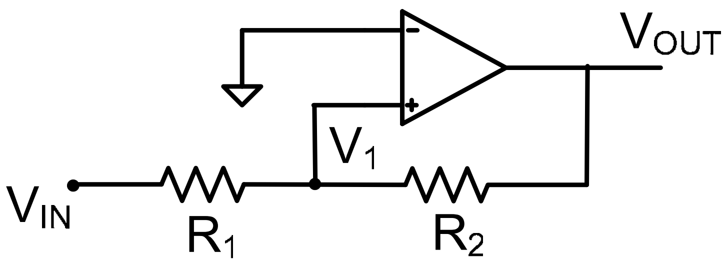
$$V_W=2\theta V_{DD}$$

$$V_{CENT}=\left(1-\theta\right)V_R$$

Shift can be to left or right depending upon sign of V_R

Review from Last Time:

Inversion of Hysteresis Loop



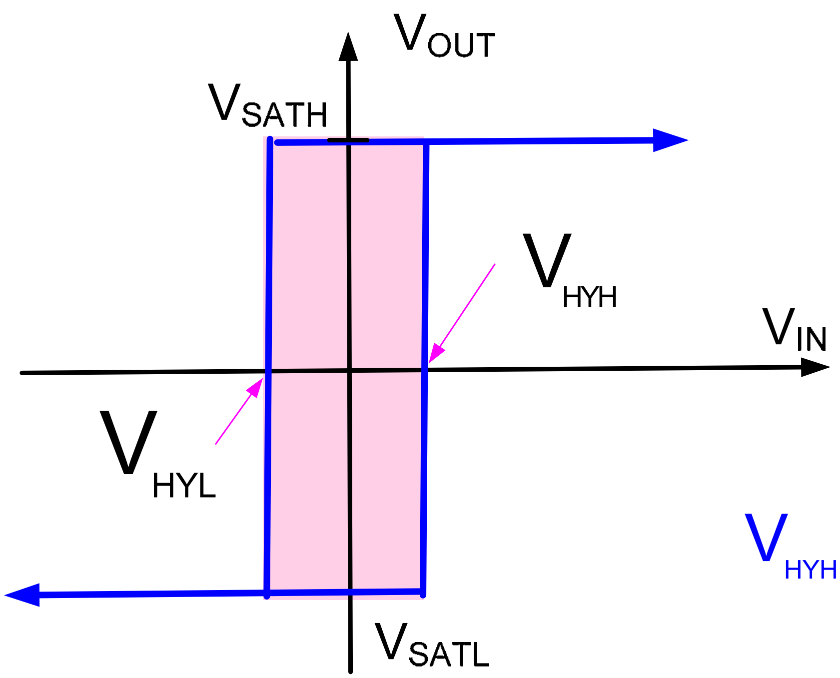
Noninverting Comparator with Hysteresis

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

$$V_{SATH}\cong V_{DD} \qquad V_{SATL}\cong V_{SS}$$

$$V_{HYH}=\frac{\theta}{\theta-1}V_{SATL}$$

$$V_{HYL}=\frac{\theta}{\theta-1}V_{SATH}$$

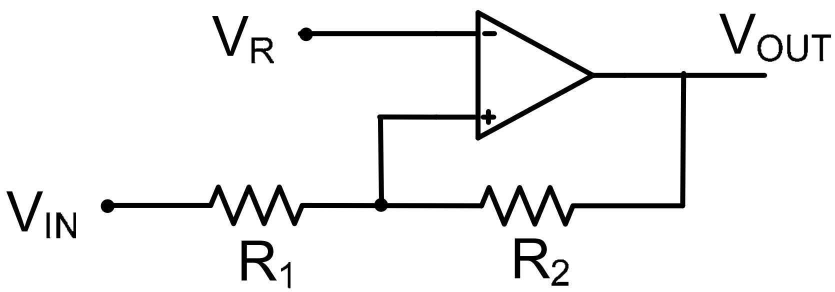


If $V_{SATH}=V_{DD}$, $V_{STAL}=V_{SS}=-V_{DD}$

$$V_{HYH}=\frac{\theta}{1-\theta}V_{DD} \qquad V_{HYL}=\frac{-\theta}{1-\theta}V_{DD}$$

Review from Last Time:

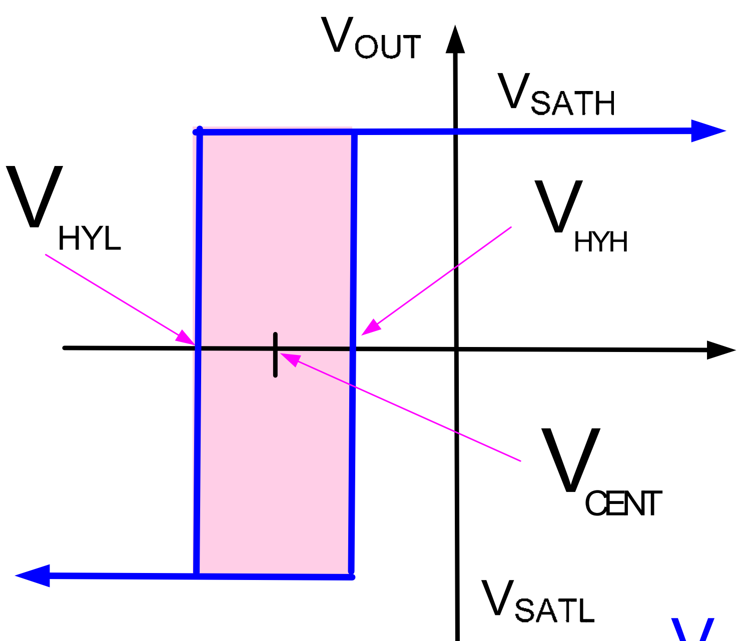
Shifted Inverted Hysteresis Loop



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

$$V_{SATH} \cong V_{DD} \qquad V_{SATL} \cong V_{SS}$$

Shifted Noninverting Comparator with Hysteresis



$$V_{HYH} = \frac{V_R}{1-\theta} + \frac{\theta}{\theta-1} V_{SATL}$$

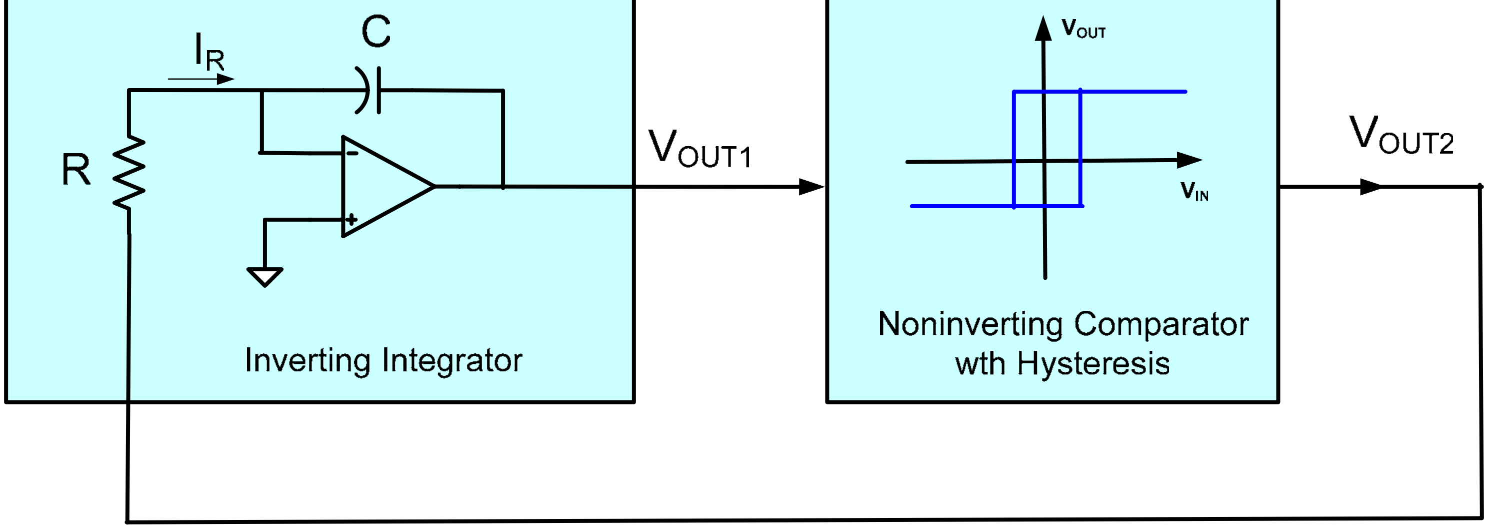
$$V_{HYL} = \frac{V_R}{1-\theta} + \frac{\theta}{\theta-1} V_{SATH}$$

$$V_{CENT} = \frac{V_R}{1-\theta} + \frac{\theta}{\theta-1}\left(\frac{V_{SATH} - V_{SATL}}{2}\right)$$

If $V_{SATH}=V_{DD}$, $\quad V_{STAL}=V_{SS}=-V_{DD}$

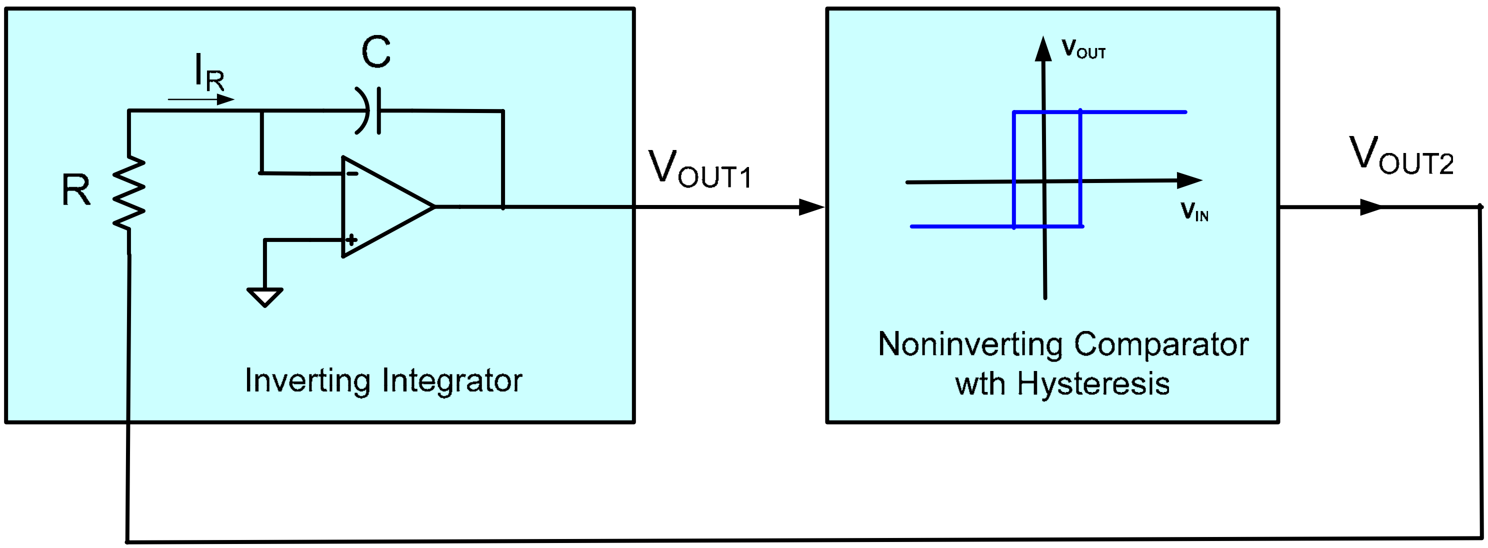
$$V_{HYH} = \frac{V_R}{1-\theta} + \frac{\theta}{1-\theta} V_{DD} \qquad V_{HYL} = \frac{V_R}{1-\theta} + \frac{-\theta}{1-\theta} V_{DD}$$

Waveform Generator with Linear Triangle Waveform



Goal: Determine how this circuit operates, the output waveforms, and the frequency of the output

Waveform Generator with Linear Triangle Waveform



Since the comparator will be in one of two states, the current in the resistor will be constant when $V_{OUT2}=V_{SATH}$ and will be constant when $V_{OUT2}=V_{SATL}$

Analysis strategy: Guess state of the V_{OUT2}, solve circuit, and show where valid

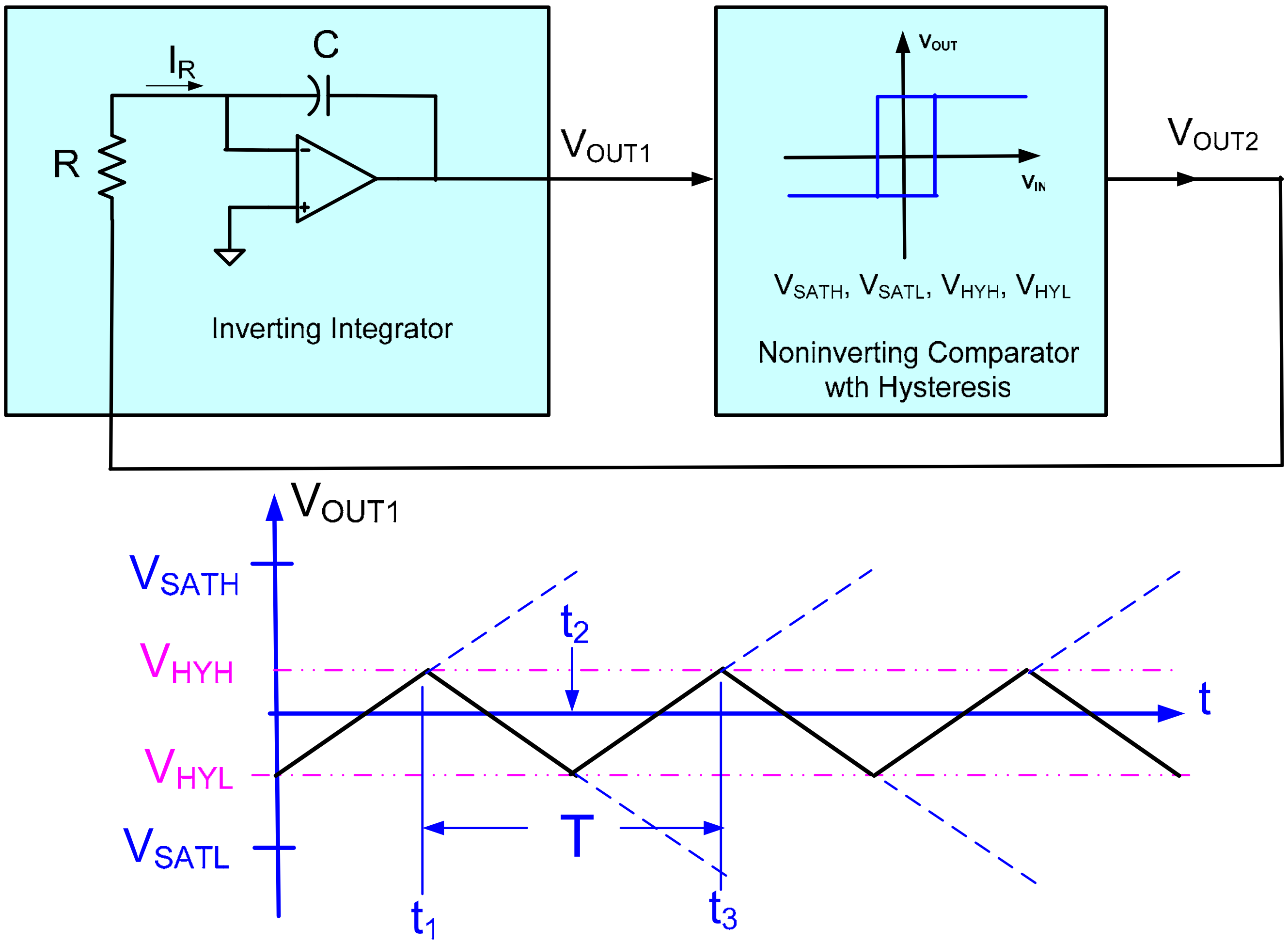
when $V_{OUT2}=V_{SATH}$, I_R will be positive and V_{OUT1} will be decreasing linearly

when $V_{OUT2}=V_{SATH}$, I_R will be positive and V_{OUT1} will be increasing linearly

Waveform Generator with Linear Triangle Waveform

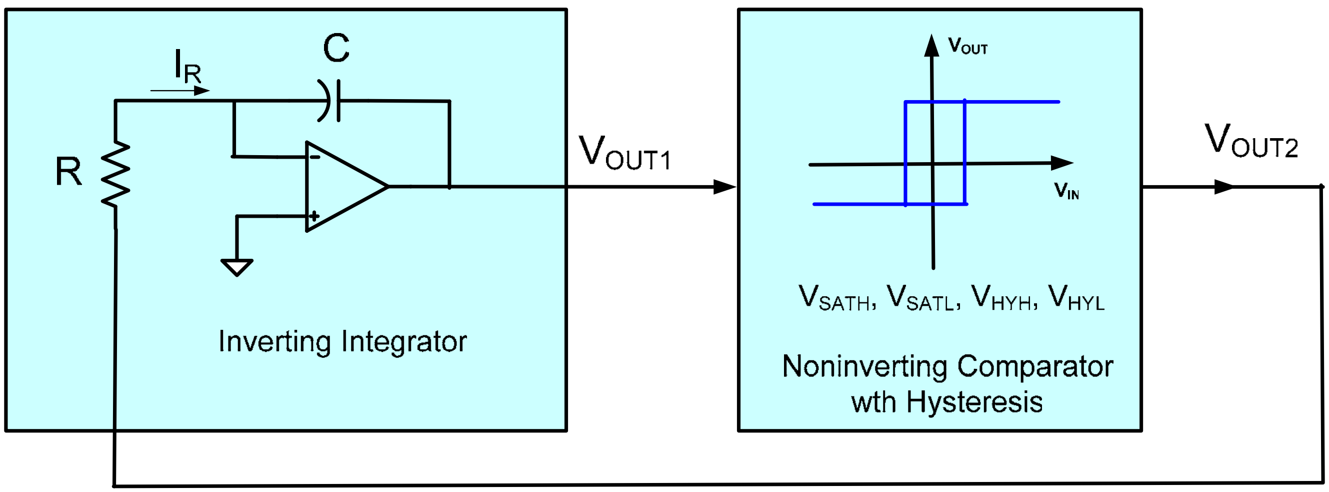
$V_{SATH} \cong V_{DD}$

$V_{SATL} \cong V_{SS}$



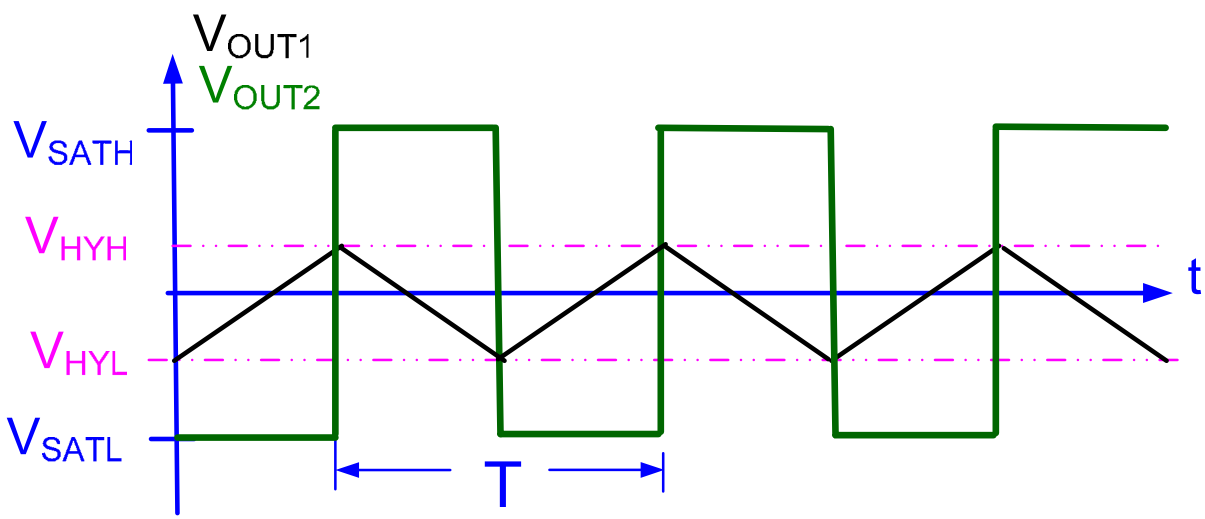
Observe $T = t_3 - t_1 = (t_2 - t_1) + (t_3 - t_2)$

Waveform Generator with Linear Triangle Waveform

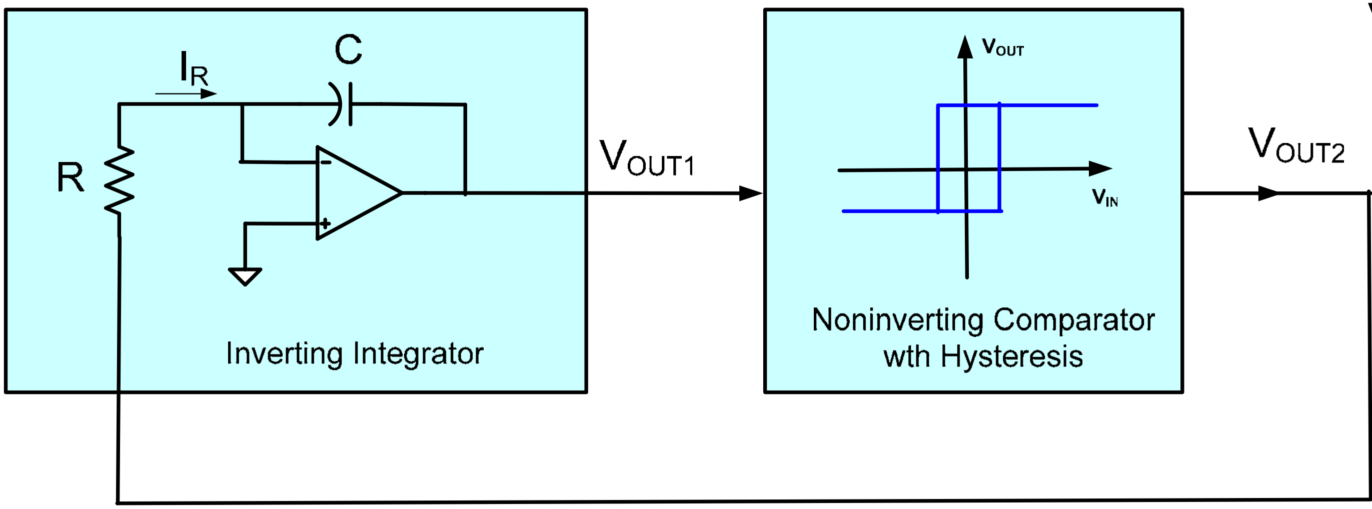


$$V_{SATH} \cong V_{DD}$$

$$V_{SATL} \cong V_{SS}$$



Waveform Generator with Linear Triangle Waveform



$$V_{SATH} \cong V_{DD}$$

$$V_{SATL} \cong V_{SS}$$

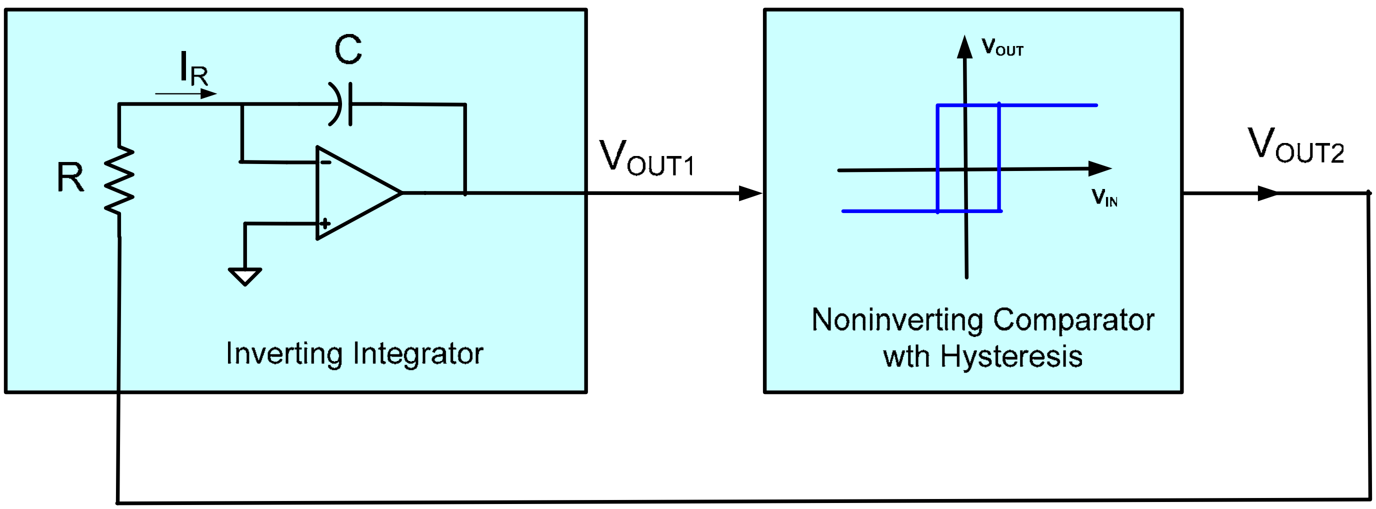
Guess $V_{OUT2}=V_{SATH}$ will obtain t_2-t_1

$$V_{OUT1} = -\frac{1}{RC}\int_{t_1}^{t} V_{SATH}\,d\tau + V_{OUT1}(t_1)$$

$$V_{OUT1}(t_1) = V_{HYH}$$

valid for $t_1 < t < t_2$

Waveform Generator with Linear Triangle Waveform



$$V_{SATH} \cong V_{DD}$$

$$V_{SATL} \cong V_{SS}$$

Guess $V_{OUT2}=V_{SATH}$ valid for $t_1 < t < t_2$

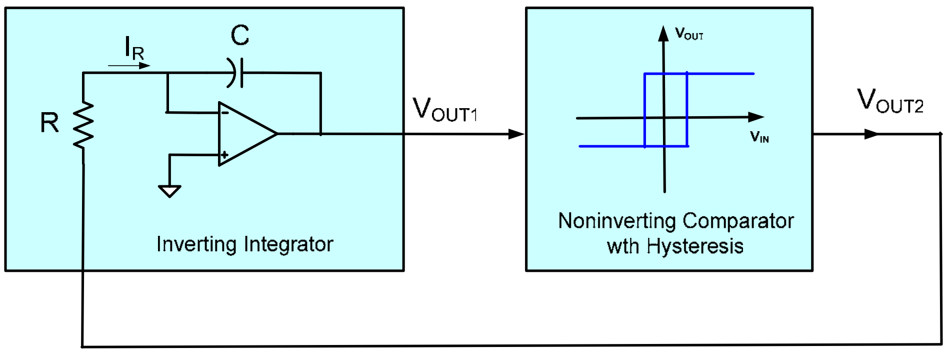
$$V_{OUT1}= -\frac{1}{RC}\int_{t_1}^{t} V_{SATH}\,d\tau+V_{OUT1}\left(t_1\right) \qquad V_{OUT1}\left(t_1\right)=V_{HYH}$$

at $t=t_2$, V_{OUT1} will become V_{SATL}

Substituting into integral expression for V_{OUT1} we obtain

$$V_{HYL}= -\frac{1}{RC}\int_{t_1}^{t} V_{SATH}\,d\tau+V_{HYH}$$

Waveform Generator with Linear Triangle Waveform



$$V_{SATH} \cong V_{DD}$$

$$V_{SATL} \cong V_{SS}$$

Guess $V_{OUT2}=V_{SATH}$ valid for $t_1 < t < t_2$

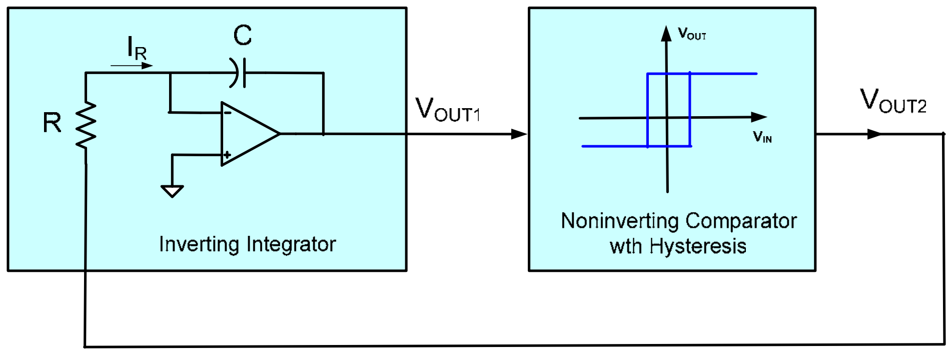
$$V_{HYL} = -\frac{1}{RC}\int_{t_1}^{t} V_{SATH}\,d\tau + V_{HYH}$$

$$V_{HYL} = -\frac{1}{RC}V_{SATH}\int_{t_1}^{t_2} 1\,d\tau + V_{HYH}$$

$$V_{HYL} = -\frac{1}{RC}V_{SATH}\left(\tau\Big|_{t_1}^{t_2}\right) + V_{HYH}$$

$$V_{HYL} = -\frac{1}{RC}V_{SATH}\left(t_2 - t_1\right) + V_{HYH}$$

Waveform Generator with Linear Triangle Waveform



$$V_{SATH} \cong V_{DD}$$

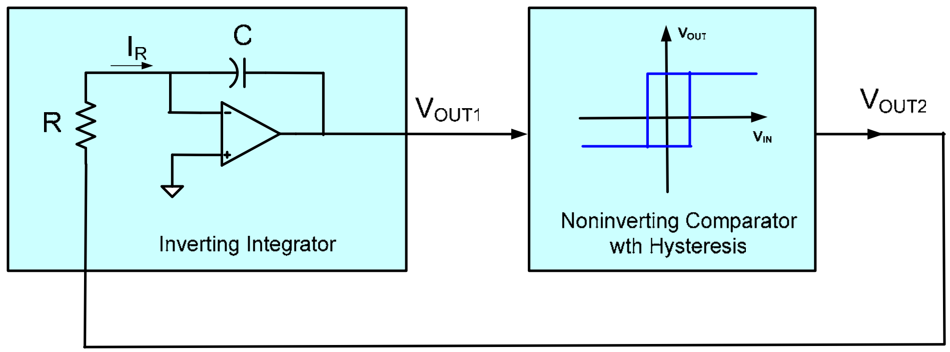
$$V_{SATL} \cong V_{SS}$$

Guess $V_{OUT2}=V_{SATH}$ valid for $t_1 < t < t_2$

$$V_{HYL} = -\frac{1}{RC} V_{SATH}\left(t_2 - t_1\right) + V_{HYH}$$

$$t_2 - t_1 = RC\frac{\left(V_{HYH} - V_{HYL}\right)}{V_{SATH}}$$

Waveform Generator with Linear Triangle Waveform



$$V_{SATH} \cong V_{DD}$$

$$V_{SATL} \cong V_{SS}$$

Guess $V_{OUT2}=V_{SATL}$ will obtain t_3-t_2 valid for $t_2 < t < t_3$

Following the same approach observe

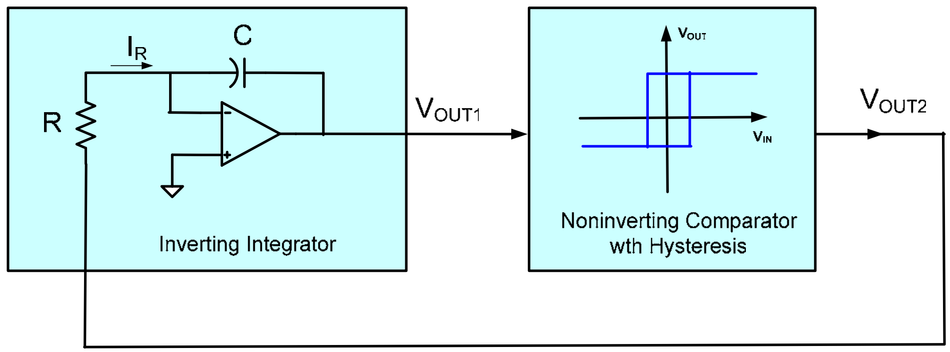
$$V_{OUT1}= -\frac{1}{RC}\int_{t_2}^{t} V_{SATL}\,d\tau+V_{OUT1}(t_2)$$

$$V_{OUT1}(t_2)=V_{HYL}$$

It thus follows that

$$V_{HYH}= -\frac{1}{RC}V_{SATL}(t_3-t_2)+V_{HYL} \qquad t_3-t_2=RC\frac{(V_{HYL}-V_{HYH})}{V_{SATL}}$$

Waveform Generator with Linear Triangle Waveform



$$V_{SATH} \cong V_{DD}$$

$$V_{SATL} \cong V_{SS}$$

$$T = (t_2 - t_1) + (t_3 - t_2)$$

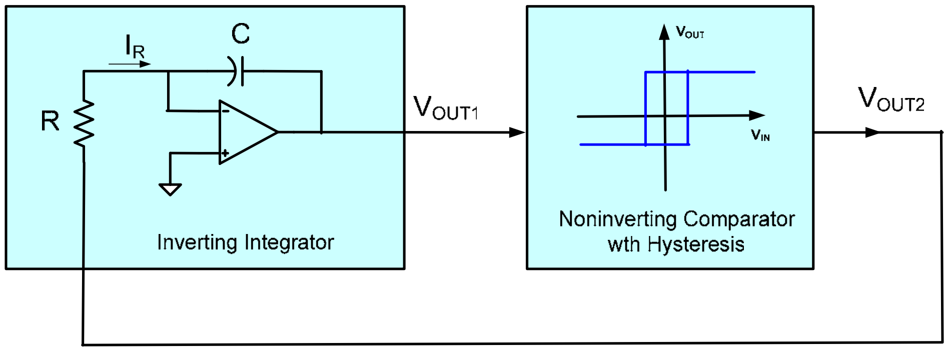
$$t_2 - t_1 = RC\frac{(V_{HYH} - V_{HYL})}{V_{SATH}}$$

$$t_3 - t_2 = RC\frac{(V_{HYL} - V_{HYH})}{V_{SATL}}$$

$$T = RC(V_{HYH} - V_{HYL})\left(\frac{1}{V_{SATH}} - \frac{1}{V_{SATL}}\right)$$

$$f = \frac{1}{t} = \frac{1}{RC}\frac{V_{SATL}V_{SATH}}{(V_{HYH} - V_{HYL})(V_{SATL} - V_{SATH})}$$

Waveform Generator with Linear Triangle Waveform



$$f=\frac{1}{RC}\frac{V_{SATL}V_{SATH}}{(V_{HYH}-V_{HYL})(V_{SATL}-V_{SATH})}$$

If we use the noninverting comparator with hysteresis circuit developed previously and if

If $V_{SATH}=V_{DD}$, $\quad V_{STAL}=V_{SS}=-V_{DD}$ $\quad \theta=\frac{R_1}{R_1+R_2}$

then

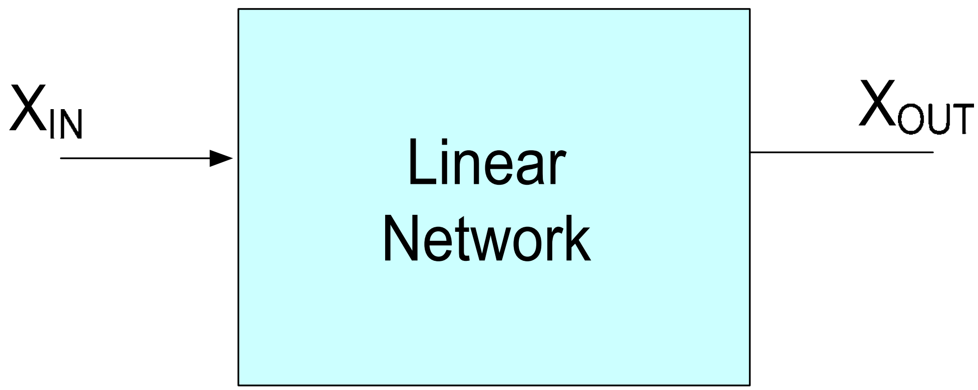
$$V_{HYH}=\frac{\theta}{1-\theta}V_{DD} \qquad V_{HYL}=\frac{-\theta}{1-\theta}V_{DD}$$

$$f=\frac{1}{2RC}\frac{1-\theta}{\theta}$$

Stability and Waveform Generation

- Waveform generators provide an output with no excitation
- Waveform circuits are circuits that, when operated in quiescent linear condition, have one or more poles in the right half-plane
- Will now investigate the pole locations of waveform generators
  - Conditions for oscillation
  - Triangle/Square/Sinusoidal Oscillations

Poles of a Network



$$T(s) = \frac{X_{OUT}(s)}{X_{IN}(s)}$$

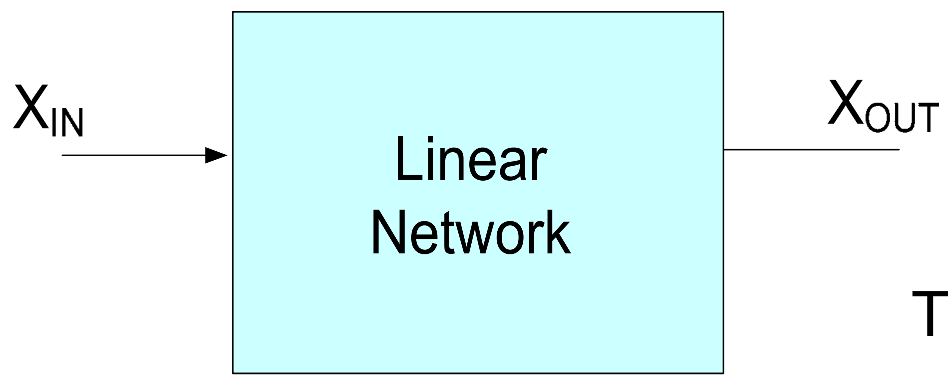
T(s) can be expressed as

$$T(s) = \frac{N(s)}{D(s)}$$

where N(s) and D(s) are polynomials in s

- D(s) is termed the characteristic equation or the characteristic polynomial of the network
- Roots of D(s) are the poles of the network

Poles of a Network

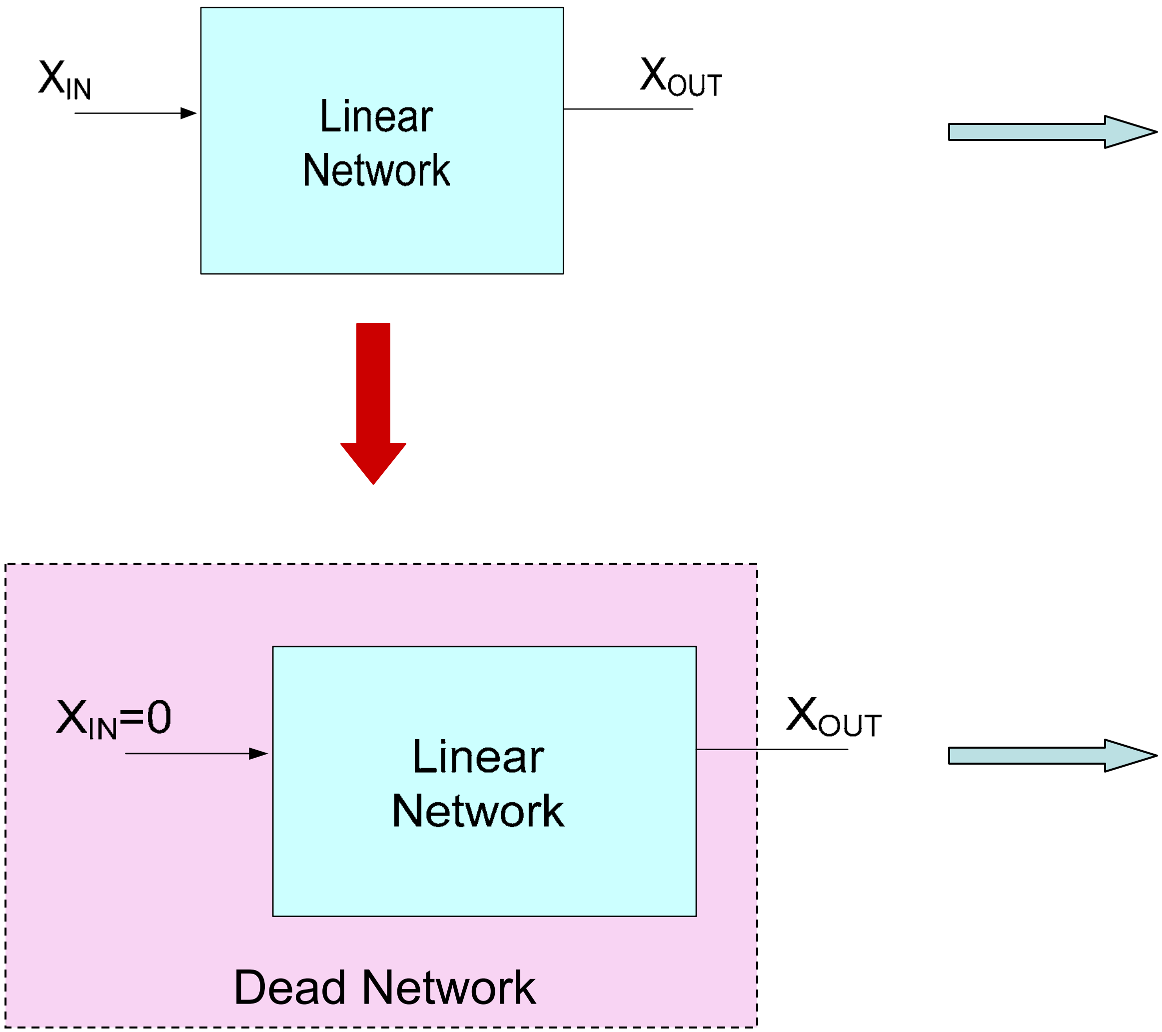


$$T(s) = \frac{N(s)}{D(s)}$$

Theorem: The poles of any transfer function of a linear system are independent of where the excitation is applied and where the response is taken provided the dead networks are the same

Equivalently, the characteristic equation, D(s), is characteristic of a network (or the corresponding dead network) and is independent of where the excitation is applied and where the response is taken.

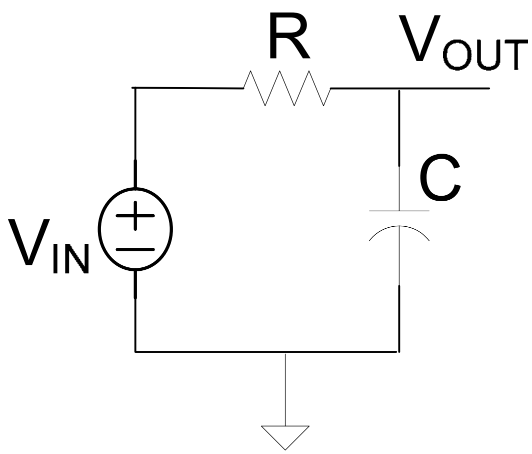
Poles of a Network



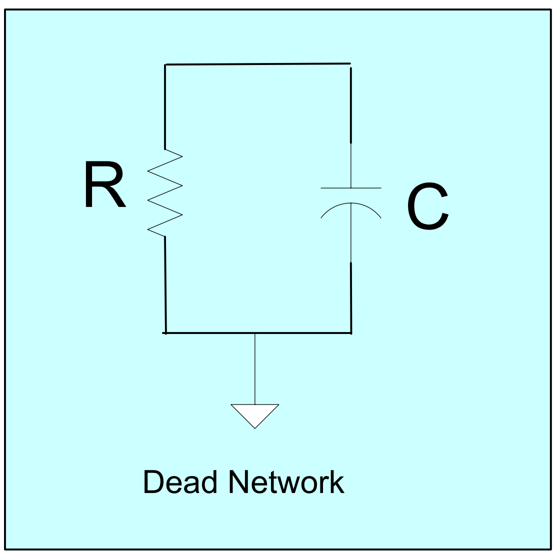
$$T(s)=\frac{N(s)}{D(s)}$$

$$D(s)$$

Poles of Networks – some examples

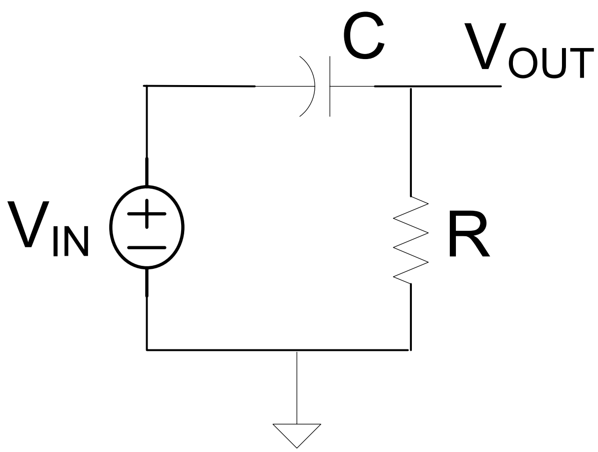


$$T(s)=\frac{V_{OUT}}{V_{IN}}=\frac{1}{1+RCs}$$

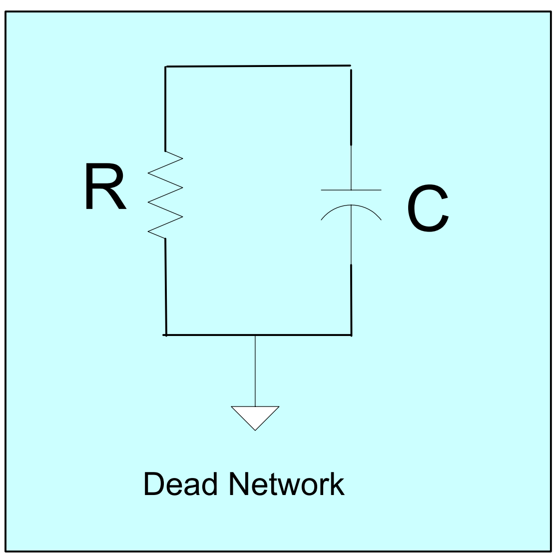


$$D(s)=1+RCs$$

Poles of Networks – some examples

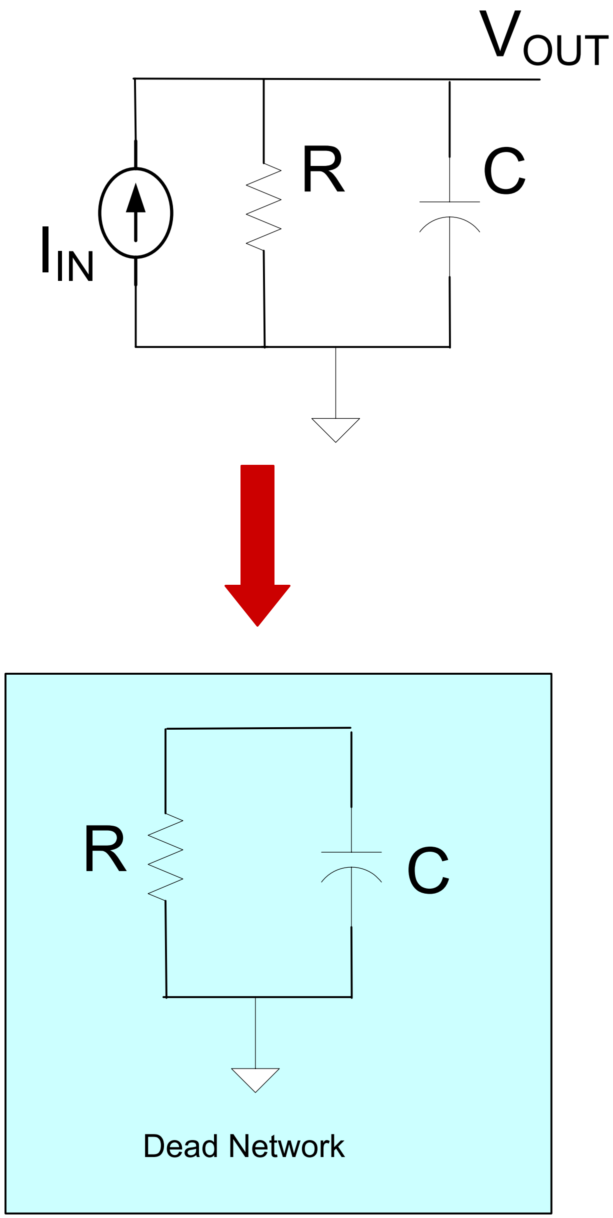


$$T(s) = \frac{V_{OUT}}{V_{IN}} = \frac{RCs}{1+RCs}$$



$$D(s) = 1 + RCs$$

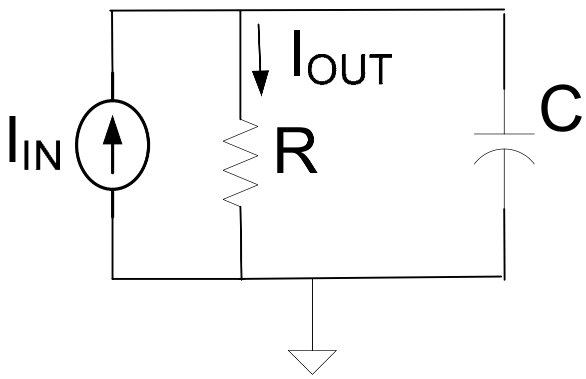
Poles of Networks – some examples



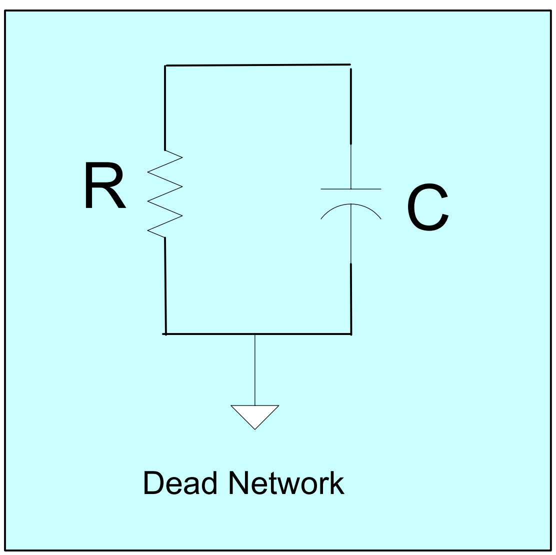
$$T(s) = \frac{V_{OUT}}{I_{IN}} = \frac{R}{1+RCs}$$

$$D(s) = 1 + RCs$$

Poles of Networks – some examples

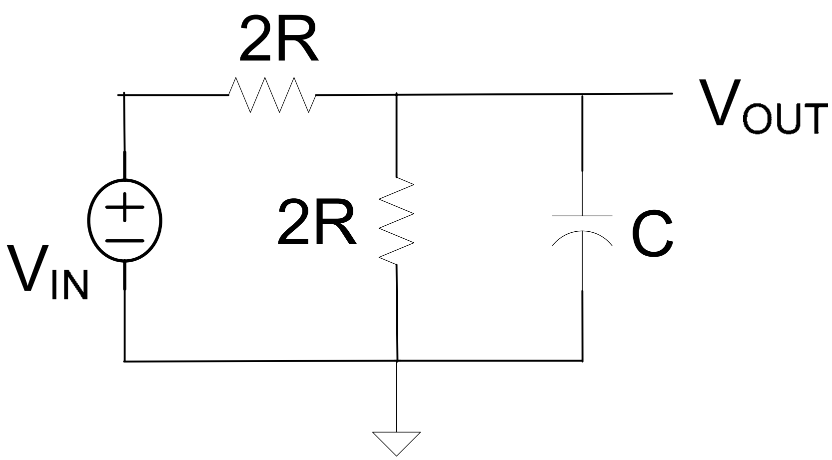


$$T(s) = \frac{I_{OUT}}{I_{IN}} = \frac{1}{1+RCs}$$

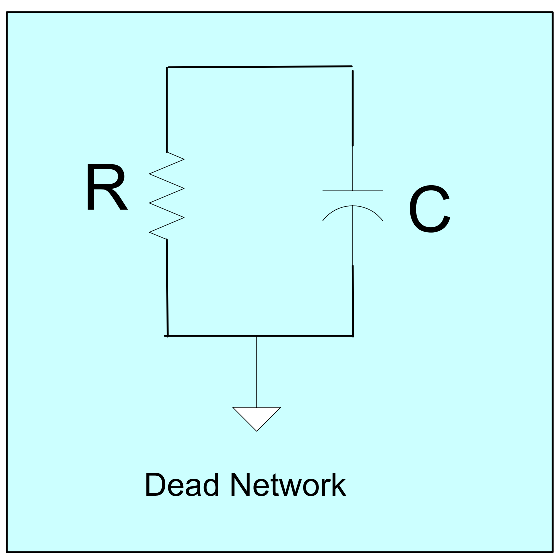


$$D(s) = 1 + RCs$$

Poles of Networks – some examples

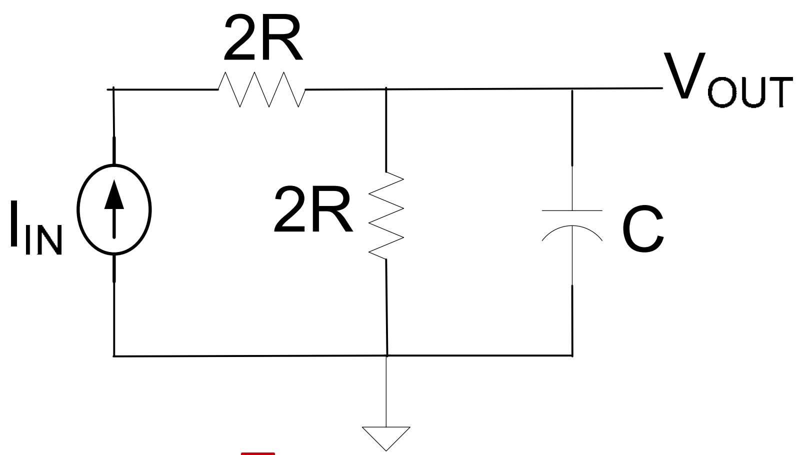


$$T(s) = \frac{V_{OUT}}{V_{IN}} = \frac{\frac{1}{2}}{1+RCs}$$

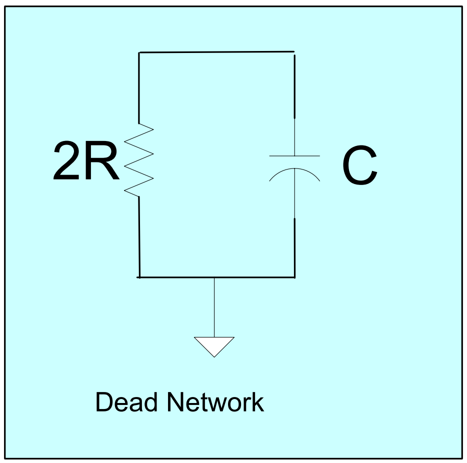


$$D(s) = 1 + RCs$$

Poles of Networks – some examples



$$T(s) = \frac{V_{OUT}}{I_{IN}} = \frac{2R}{1+2RCs}$$



$$D(s) = 1 + 2RCs$$

Note dead network has changed as has D(s) and thus the pole