



BLM3620 Digital Signal Processing

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$$y[n] = \sum_{k=0}^N a_k x[n-k] \quad \text{FIR}$$

$$y[n] = \sum_{k=1}^M b_k y[n-k] + \sum_{m=0}^L a_m x[n-m] \quad \text{IIR}$$

$M \rightarrow$ IIR filter order

$$x[n] \xrightarrow{z^t} X(z)$$

$$y[n] \xrightarrow{z^t} Y(z)$$

$$h[n] \xrightarrow{z^t} H(z)$$

$$= \frac{Y(z)}{X(z)}$$

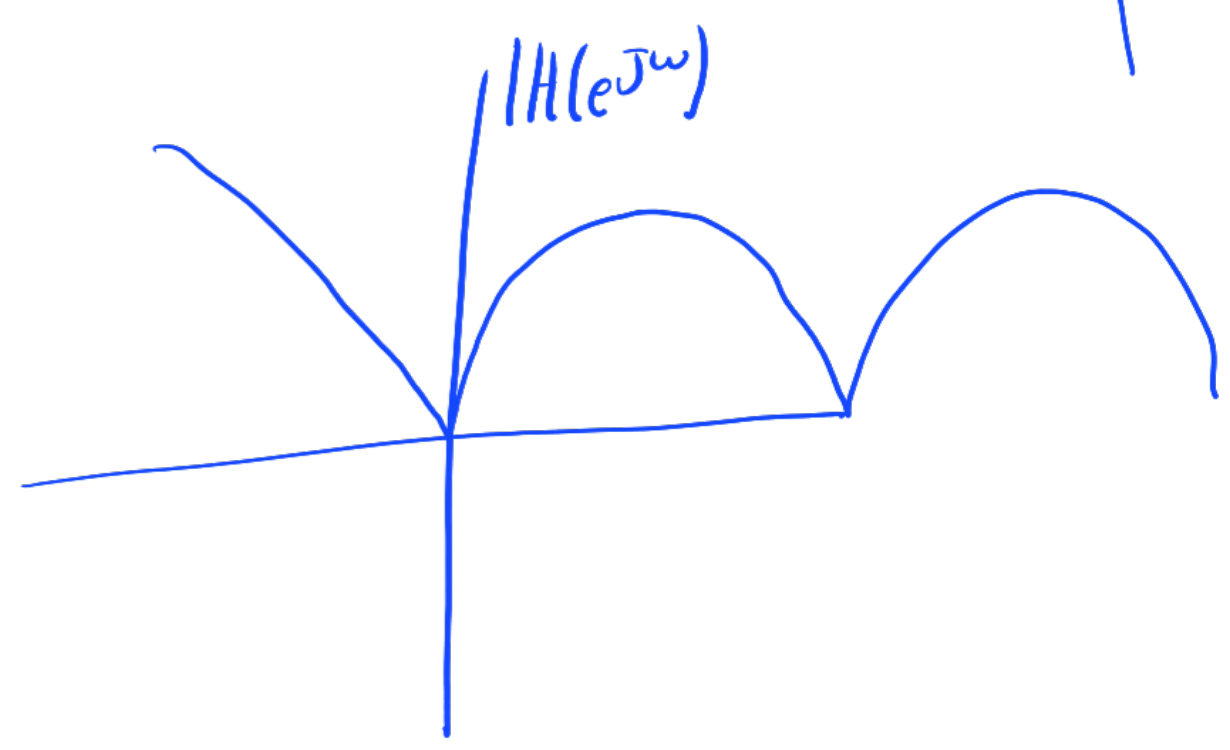
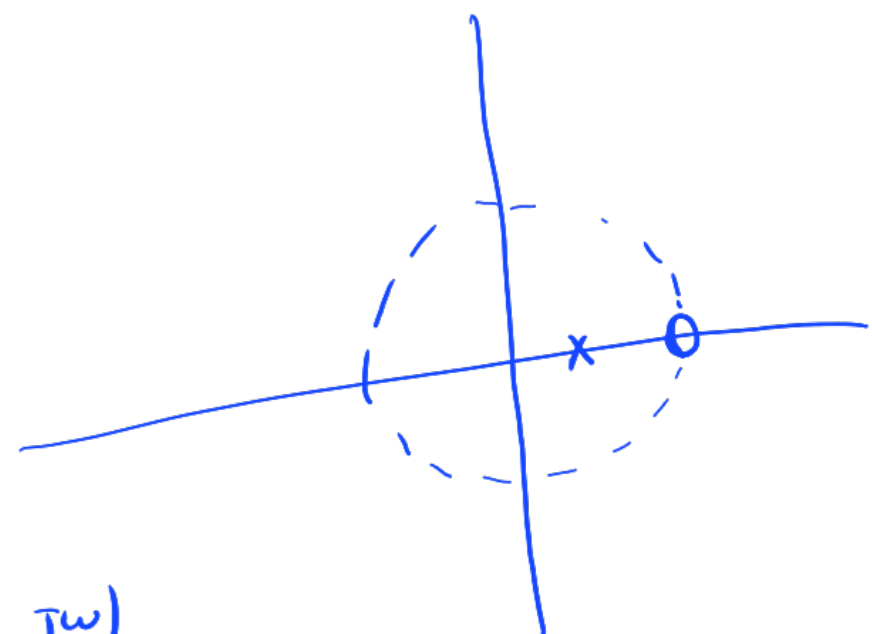
$$y[n] = 0.2 y[n-1] + x[n] - x[n-1]$$

$$Y(z) = 0.2 z^{-1} Y(z) + X(z) - z^{-1} X(z)$$

$$X(z) (1 - 0.2 z^{-1}) = X(z) (1 - z^{-1})$$

$$H(z) = \frac{1 - z^{-1}}{1 - 0.2 z^{-1}}$$

1, 0.2



Lecture #14 – Filter Design Basics

- Relation of z-Transform and DTFT
- Examples
- Filter Design Using z-Plane
- MATLAB Example

Important Materials:

- James H. McClellan, R. W. Schafer, M. A. Yoder, *DSP First Second Edition*, Pearson, 2015.
- Lizhe Tan, Jean Jiang, *Digital Signal Processing: Fundamentals and Applications*, Third Edition, Academic Press, 2019.

Auxiliary Materials:

- Prof. Sarp Ertürk, *Sayısal İşaret İşleme*, Birsen Yayınevi.
- Prof. Nizamettin Aydın, DSP Lecture Notes.
- J. G. Proakis, D. K. Manolakis, *Digital Signal Processing Fourth Edition*, Pearson, 2014.
- J. K. Perin, *Digital Signal Processing, Lecture Notes*, Stanford University, 2018.

Syllabus



Week	Lectures
1	Introduction to DSP and MATLAB
2	Sinuzoids and Complex Exponentials
3	Spectrum Representation
4	Sampling and Aliasing
5	Discrete Time Signal Properties and Convolution
6	Convolution and FIR Filters
7	Frequency Response of FIR Filters
8	Midterm Exam
9	Discrete Time Fourier Transform and Properties
10	Discrete Fourier Transform and Properties
11	Fast Fourier Transform and Windowing
12	-
13	z- Transforms
14	FIR Filter Design and Applications

For more details -> Bologna page: <http://www.bologna.yildiz.edu.tr/index.php?r=course/view&id=5730&aid=3>

Z-Transform EXAMPLE



- ANY SIGNAL has a z-Transform:

$$X(z) = \sum_n x[n]z^{-n}$$

$$H(z) = \sum_n h[n]z^{-n}$$

Example 7.1

n	$n < -1$	-1	0	1	2	3	4	5	$n > 5$
$x[n]$	0	0	2	4	6	4	2	0	0

$$X(z) = ?$$

$$X(z) = 2 + 4z^{-1} + 6z^{-2} + 4z^{-3} + 2z^{-4}$$

FREQUENCY RESPONSE ?



- Same Form:

$\hat{\omega}$ – Domain

$$H(e^{j\hat{\omega}}) = \sum_{k=0}^M b_k e^{-j\hat{\omega}k}$$
$$H(e^{j\hat{\omega}}) = \sum_{k=0}^M b_k (e^{j\hat{\omega}})^{-k}$$

$$z = e^{j\hat{\omega}}$$

z – Domain

$$H(z) = \sum_{k=0}^M b_k z^{-k}$$

SAME COEFFICIENTS

If we have single complex exponential signal....

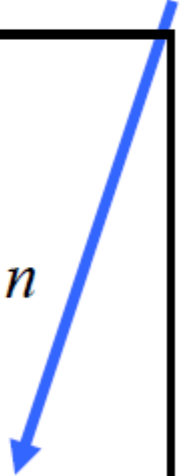


SINUSOIDAL RESPONSE

- $x[n] = \text{SINUSOID} \Rightarrow y[n]$ is SINUSOID
- Get MAGNITUDE & PHASE from $H(z)$

$$\text{if } x[n] = e^{j\hat{\omega}n}$$

$$\text{then } y[n] = H(e^{j\hat{\omega}}) e^{j\hat{\omega}n}$$

$$\text{where } H(e^{j\hat{\omega}}) = H(z) \Big|_{z=e^{j\hat{\omega}}}$$
A blue arrow originates from the boxed equation and points towards the text 'Get MAGNITUDE & PHASE from H(z)' in the list above, indicating that the boxed equation is the mathematical basis for that step.

POP QUIZ

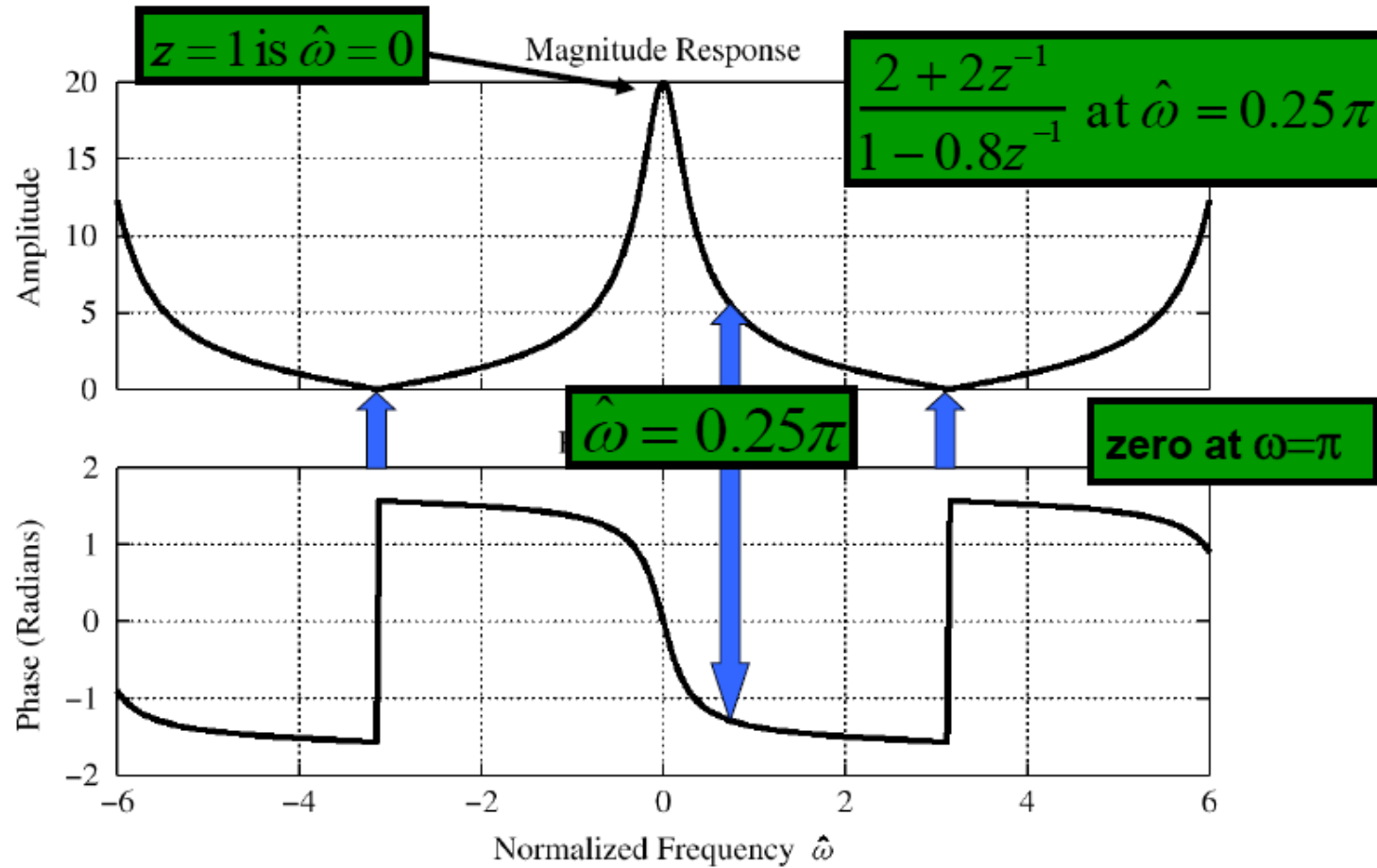
- Given: $H(z) = \frac{2 + 2z^{-1}}{1 - 0.8z^{-1}}$
- Find the **Impulse Response**, $h[n]$
- Find the output, $y[n]$
 - When

$$x[n] = \cos(0.25\pi n)$$

Exercise-1



Evaluate FREQ. RESPONSE



POP QUIZ: Eval Freq. Resp.

- Given:

$$H(z) = \frac{2 + 2z^{-1}}{1 - 0.8z^{-1}}$$

- Find output, $y[n]$, when

– Evaluate at

$$x[n] = \cos(0.25\pi n)$$

$$z = e^{j0.25\pi}$$

$$H(z) = \frac{2 + 2(\frac{\sqrt{2}}{2} - j\frac{\sqrt{2}}{2})}{1 - 0.8e^{-j0.25\pi}} = 5.182e^{-j1.309}$$

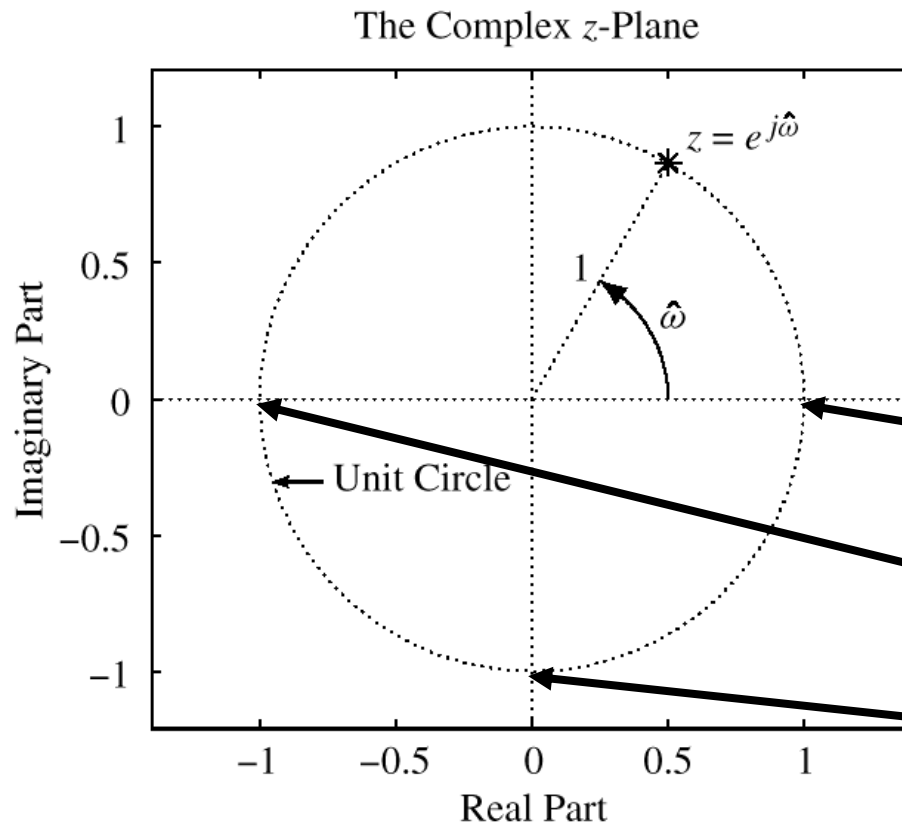
$$y[n] = 5.182 \cos(0.25\pi n - 0.417\pi)$$

UNIT CIRCLE: RECAP



- MAPPING BETWEEN

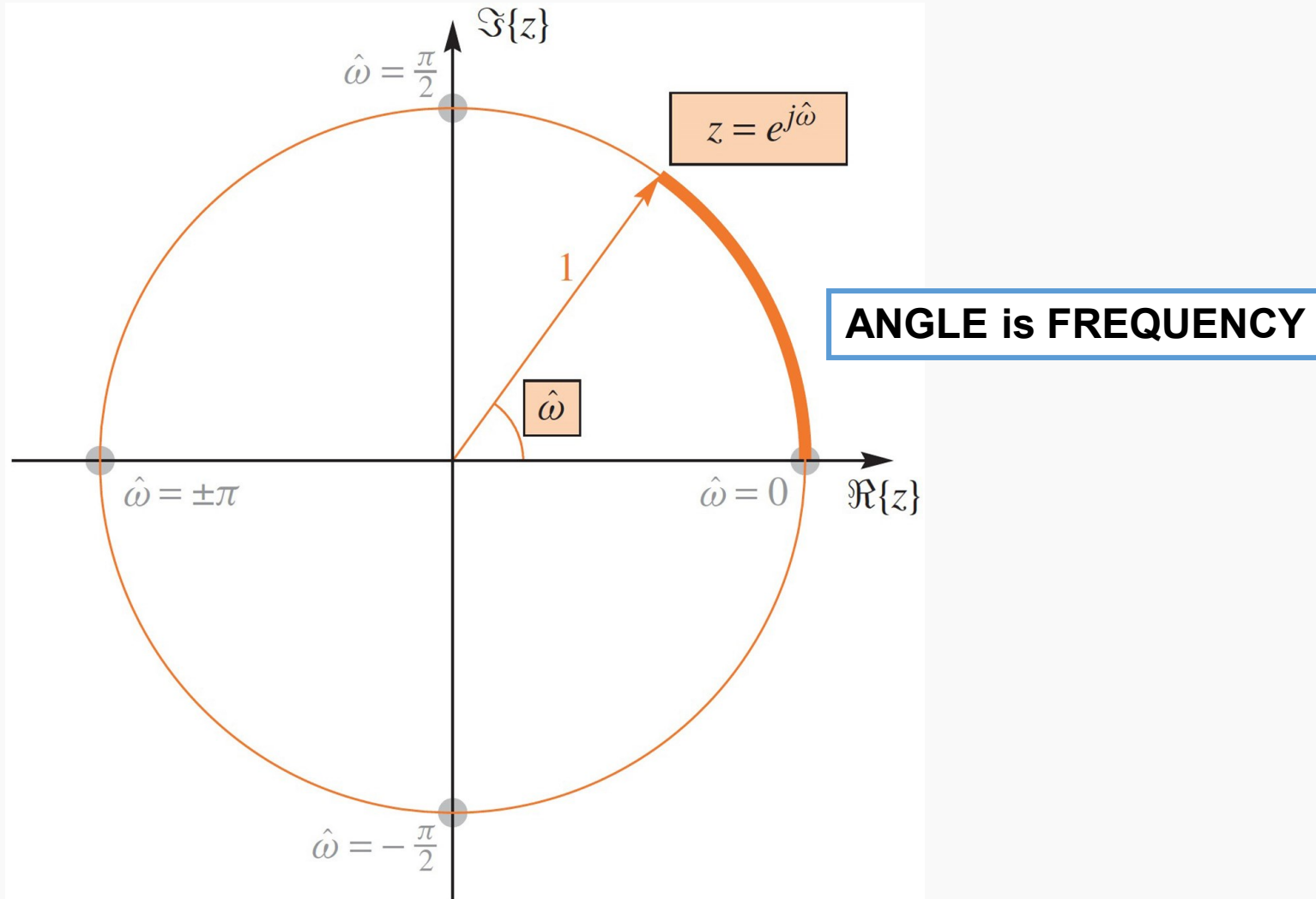
z and $\hat{\omega}$



$$z = e^{j\hat{\omega}}$$

$$\begin{aligned} z = 1 &\leftrightarrow \hat{\omega} = 0 \\ z = -1 &\leftrightarrow \hat{\omega} = \pm \pi \\ z = \pm j &\leftrightarrow \hat{\omega} = \pm \frac{1}{2} \pi \end{aligned}$$

$$H(e^{j\hat{\omega}}) = H(z) \Big|_{z=e^{j\hat{\omega}}}$$



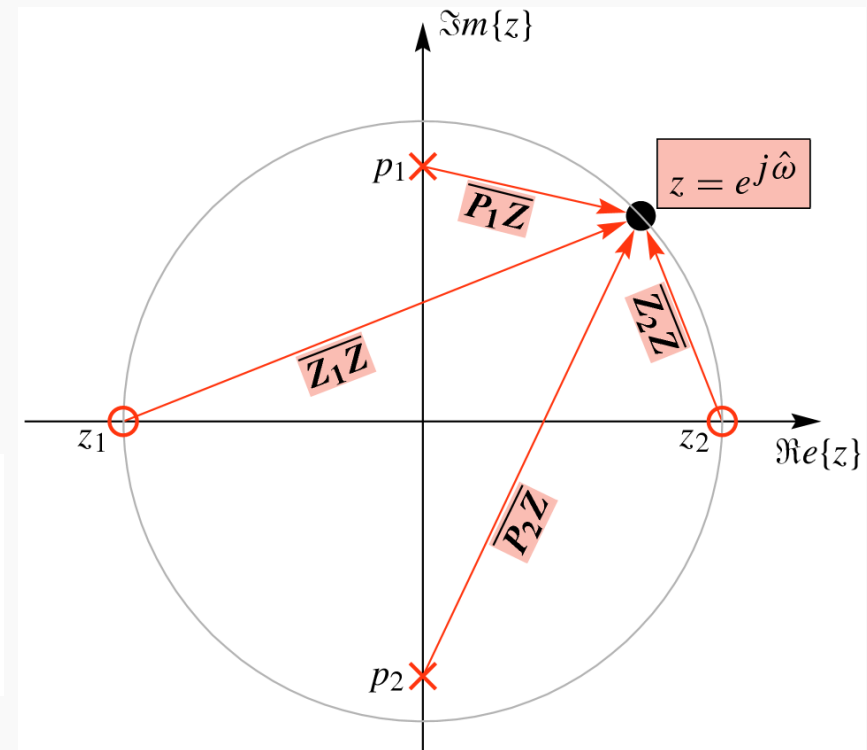
Frequency Response from poles and zeros



$$|H(e^{j\hat{\omega}})| = G \frac{|e^{j\hat{\omega}} - z_1| |e^{j\hat{\omega}} - z_2|}{|e^{j\hat{\omega}} - p_1| |e^{j\hat{\omega}} - p_2|}$$

$$|H(e^{j\hat{\omega}})| = G \frac{\overline{z_1 z} \cdot \overline{z_2 z}}{\overline{p_1 z} \cdot \overline{p_2 z}}$$

$$H(z) = G \frac{(z - z_1)(z - z_2)}{(z - p_1)(z - p_2)}$$

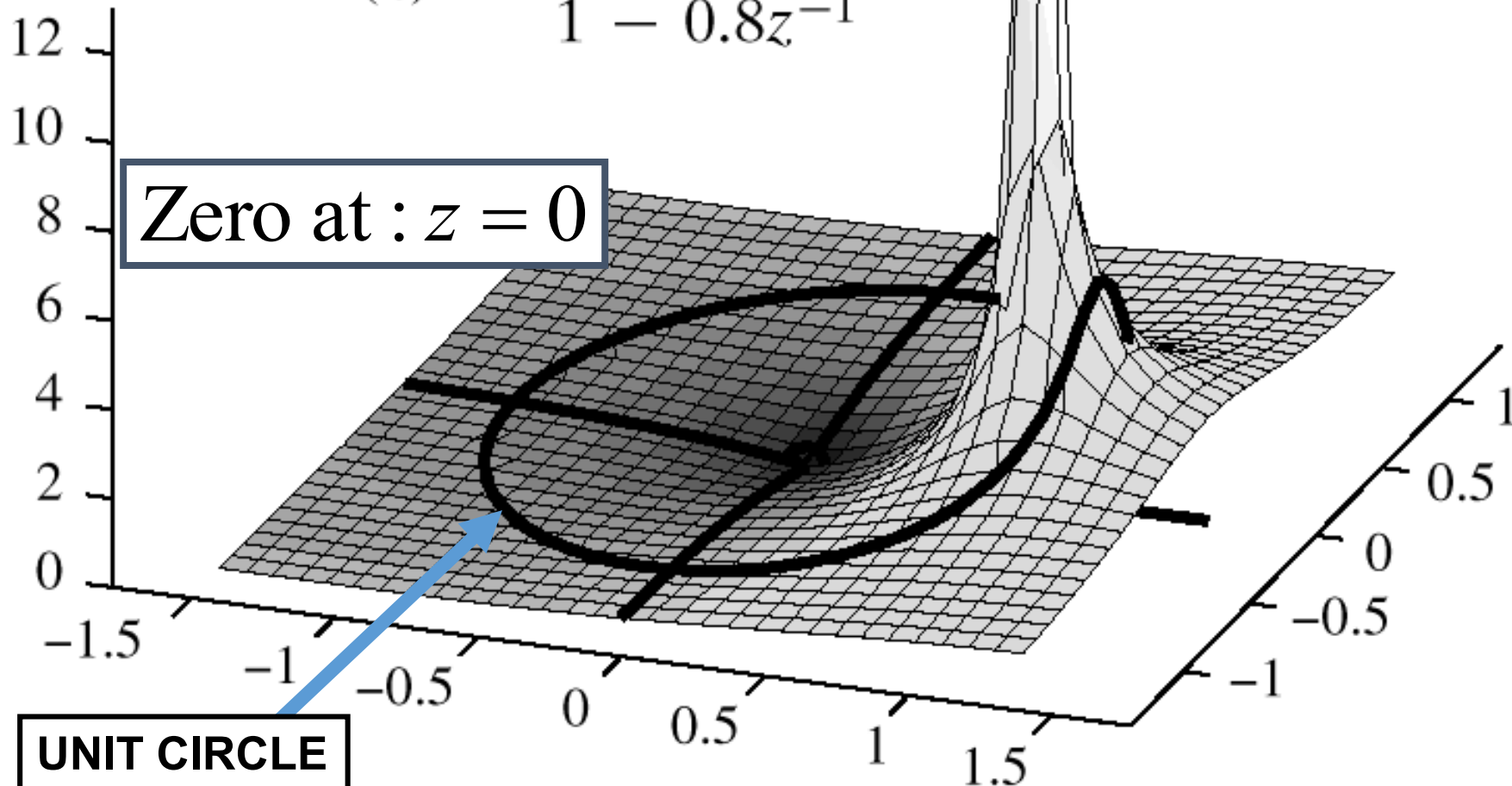


3-D VIEWPOINT: EVALUATE $H(z)$ EVERYWHERE

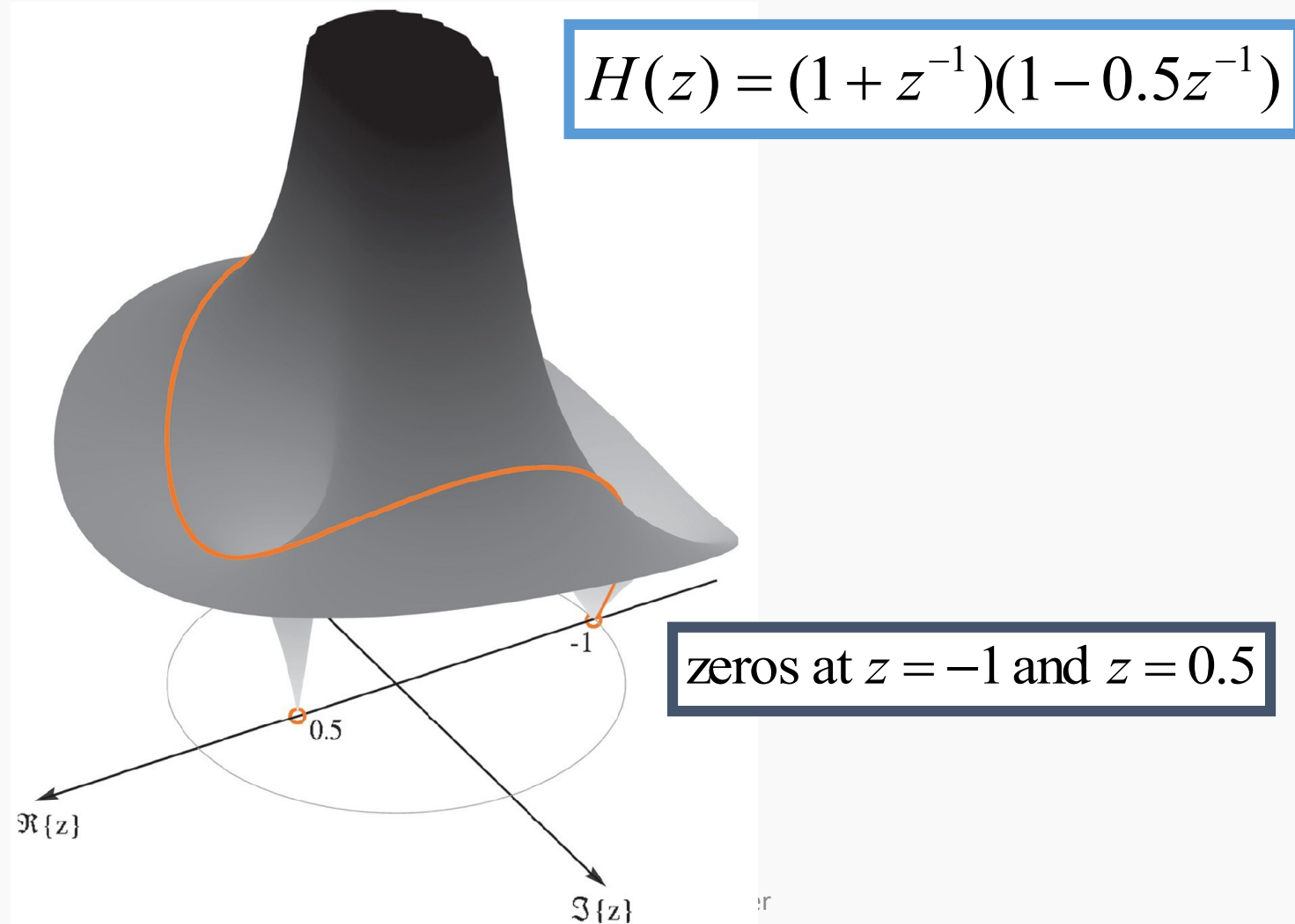
Pole at : $z = 0.8$

$$H(z) = \frac{1}{1 - 0.8z^{-1}}$$

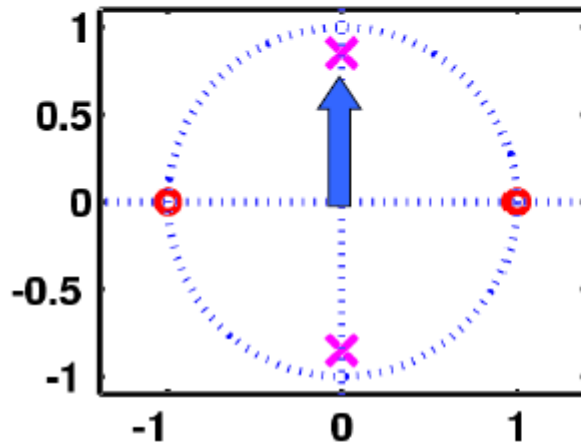
Zero at : $z = 0$



Evaluate $H(z)$ on Unit Circle

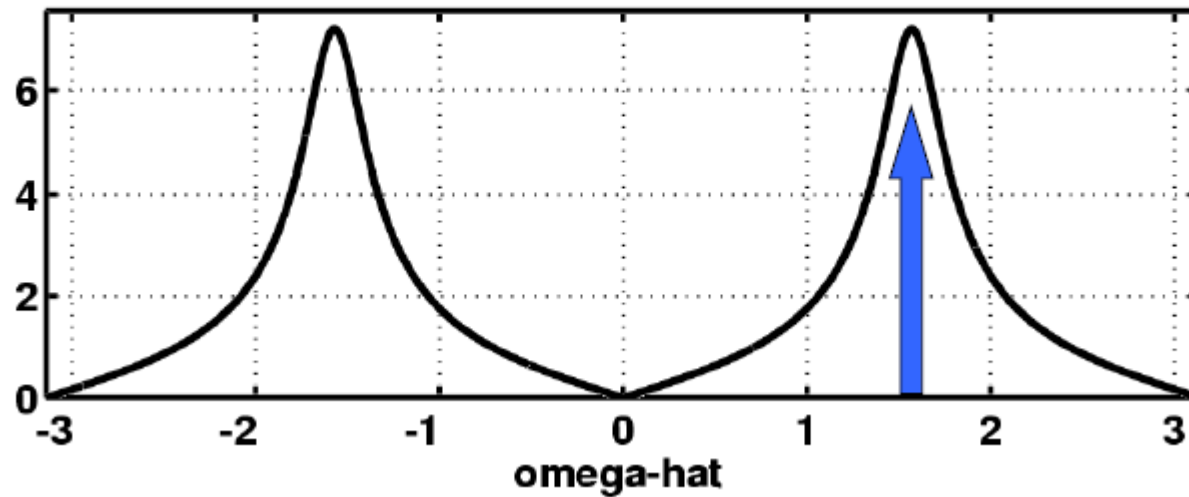


FREQUENCY RESPONSE from POLE-ZERO PLOT



$$H(e^{j\hat{\omega}}) = \frac{1 - e^{-j2\hat{\omega}}}{1 + 0.7225e^{-j2\hat{\omega}}}$$

Magnitude Response



ZEROS of $H(z)$ – example 2



- Find z , where $H(z)=0$
 - Interesting when z is ON the unit circle.

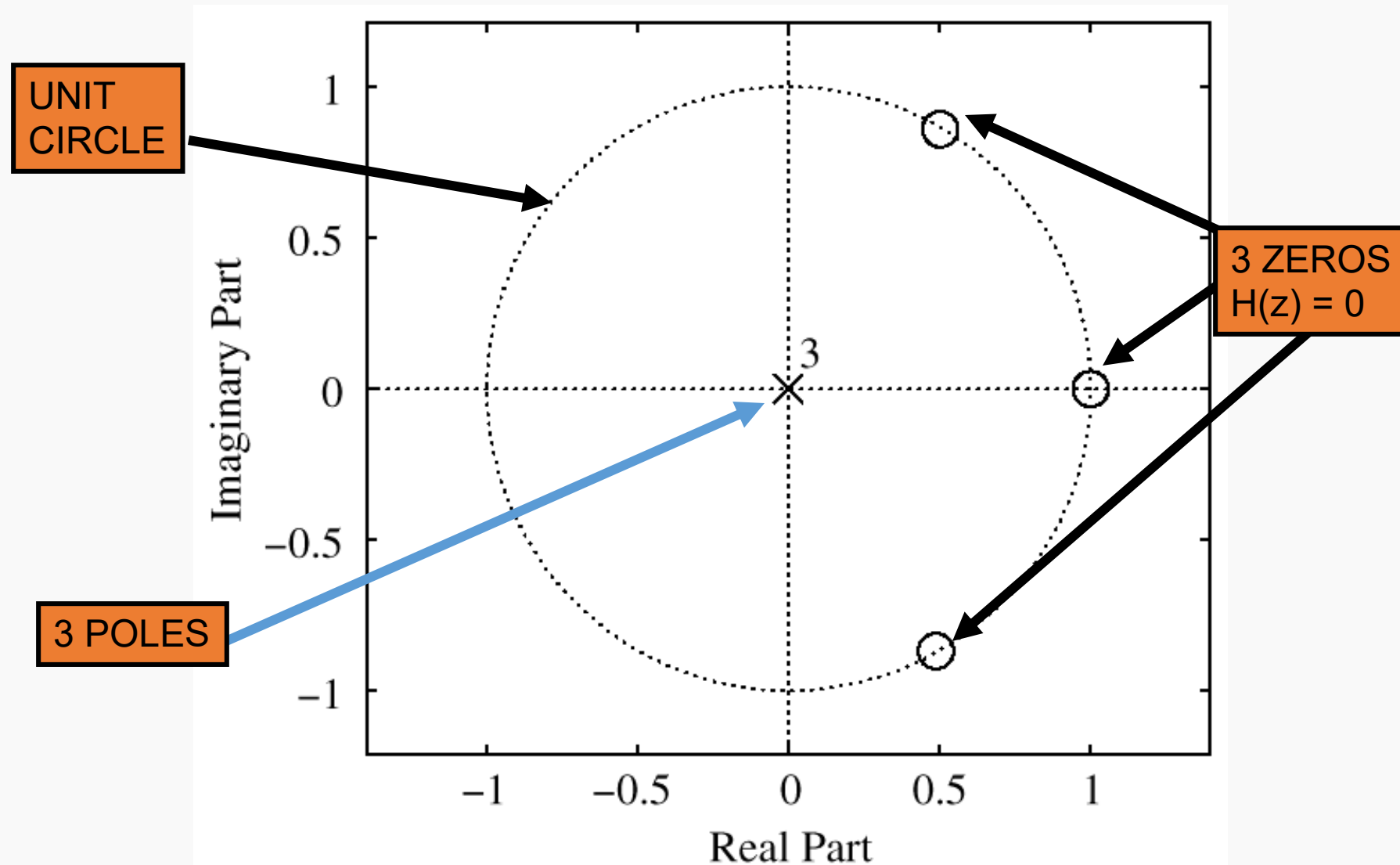
$$H(z) = 1 - 2z^{-1} + 2z^{-2} - z^{-3}$$

$$H(z) = (1 - z^{-1})(1 - z^{-1} + z^{-2})$$

Roots : $z = 1, \frac{1}{2} \pm j \frac{\sqrt{3}}{2}$ $\rightarrow e^{\pm j\pi/3}$

Recall: Roots occur in Conjugate pairs when coefficients are real

PLOT ZEROS in z-DOMAIN



POLES of $H(z)$



- Find z , where
 - FIR only has poles at $z=0$

$$H(z) \rightarrow \infty$$

$$H(z) = 1 - 2z^{-1} + 2z^{-2} - z^{-3}$$

$$H(z) = \frac{z^3 - 2z^2 + 2z - 1}{z^3}$$

Three Poles at : $z = 0$

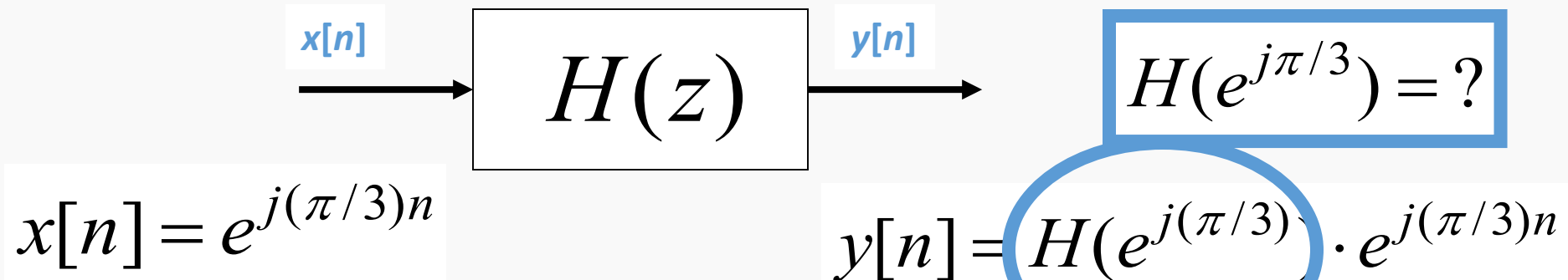
NULLING PROPERTY of $H(z)$



- When $H(z)=0$ on the unit circle.
 - Find inputs $x[n]$ that give zero output

$$H(z) = 1 - 2z^{-1} + 2z^{-2} - z^{-3}$$

$$H(e^{j\hat{\omega}}) = 1 - 2e^{-j\hat{\omega}} + 2e^{-j2\hat{\omega}} - e^{-j3\hat{\omega}}$$



NULLING PROPERTY of $H(z)$



- Evaluate $H(z)$ at the input “frequency”

$$H(e^{j\hat{\omega}}) = 1 - 2e^{-j\hat{\omega}} + 2e^{-j2\hat{\omega}} - e^{-j3\hat{\omega}}$$

$$y[n] = H(e^{j\pi/3}) \cdot e^{j(\pi/3)n}$$

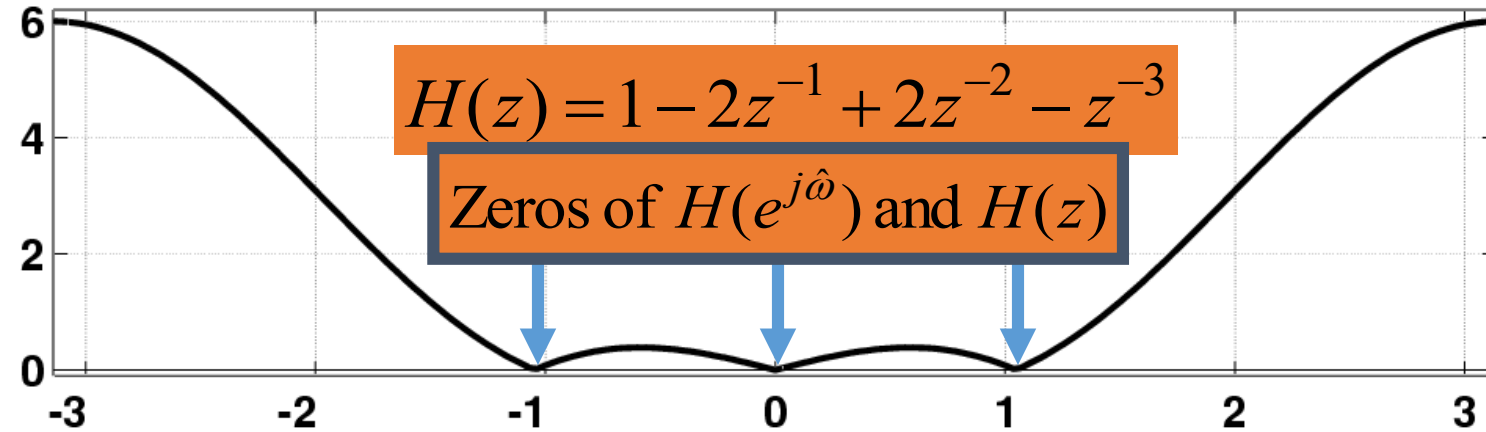
$$y[n] = (1 - 2e^{-j\pi/3} + 2e^{-j2\pi/3} - e^{-j3\pi/3}) \cdot e^{j(\pi/3)n}$$

$$(1 - 2(\frac{1}{2} - j\frac{\sqrt{3}}{2}) + 2(-\frac{1}{2} - j\frac{\sqrt{3}}{2}) - (-1))$$

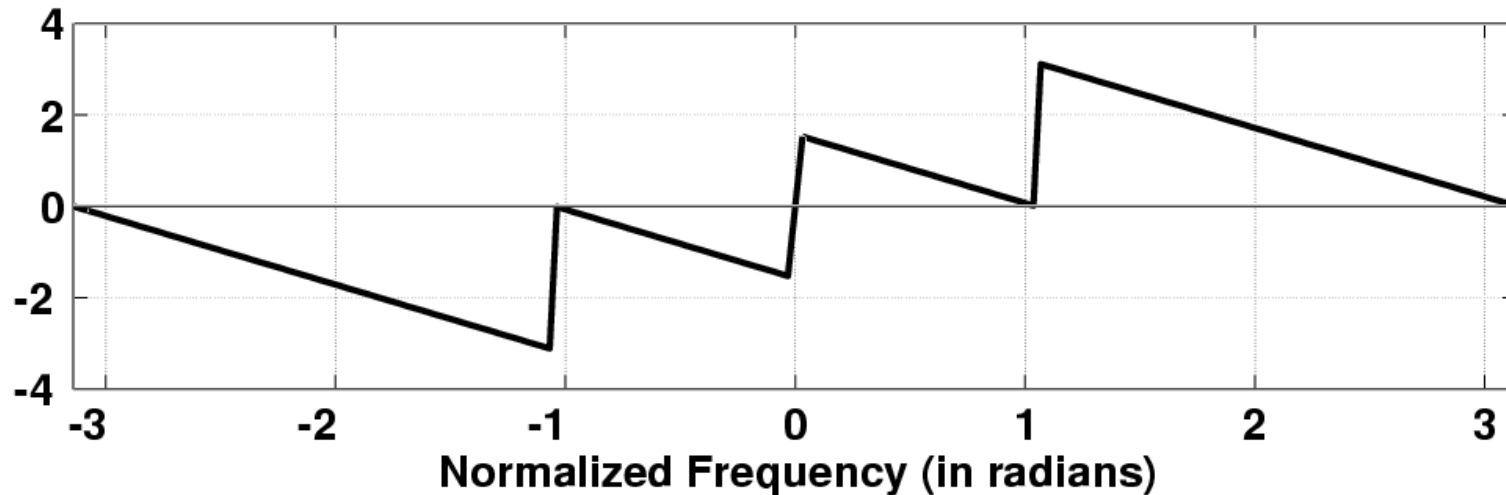
$$y[n] = (1 - 1 + j\sqrt{3} - 1 - j\sqrt{3} + 1) \cdot e^{j(\pi/3)n} = 0$$

FIR Frequency Response

Magnitude of Frequency Response for $h[n] = 1, -2, 2, -1$

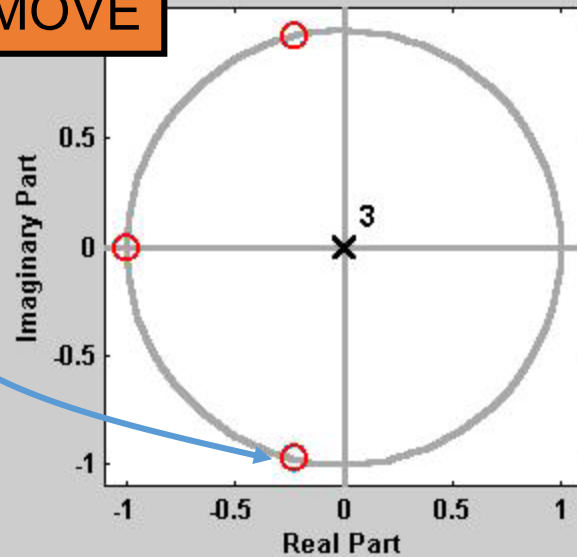


Phase Angle of Frequency Response for $h[n] = 1, -2, 2, -1$



3 DOMAINS MOVIE: FIR

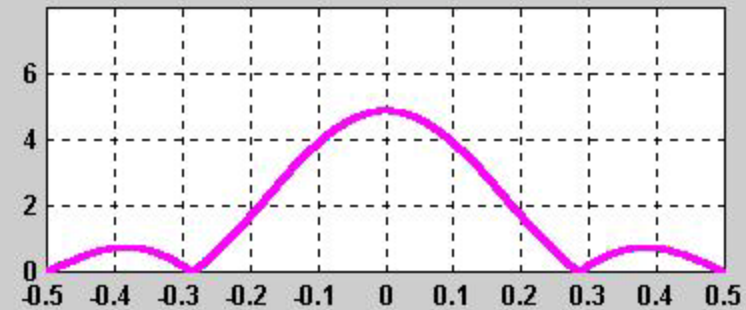
ZEROS MOVE



$$1 + 1.45z^{-1} + 1.45z^{-2} + z^{-3}$$

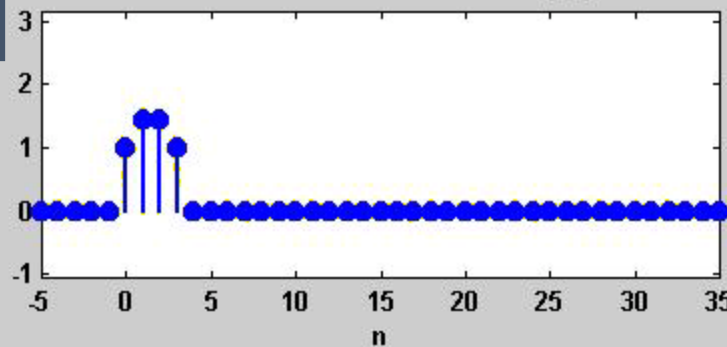
$H(z)$

DTFT: MAGNITUDE RESPONSE

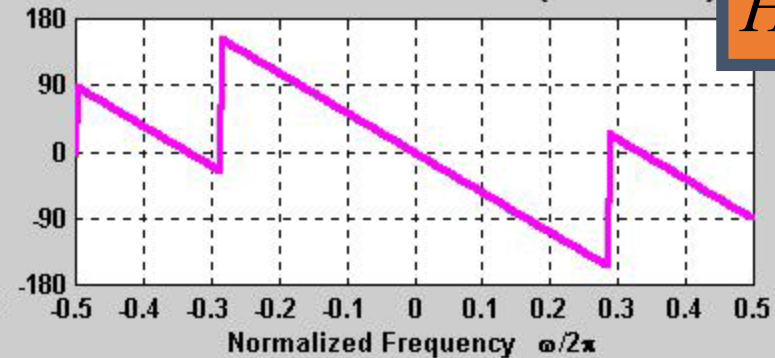


$h[n]$

IMPULSE RESPONSE: $h[n]$



DTFT: PHASE RESPONSE (DEGREES)



$H(e^{j\hat{\omega}})$

4 MOVIES @ WEBSITE



- http://dspfirst.gatech.edu/chapters/07ztrans/demos/3_domain/index.html
- 3 DOMAINS MOVIES: FIR Filters
 - Two zeros moving around UC and inside
 - Three zeros; one held fixed at $z=-1$
 - Ten zeros; 9 equally spaced around UC; one moving
 - Ten zeros; 8 equally spaced around UC; two moving

DESIGN PROBLEM



- Example:
 - Design a Lowpass FIR filter (Find b_k)
 - Reject completely 0.7π , 0.8π , and 0.9π
 - Estimate the filter length needed to accomplish this task. How many b_k ?
- Z POLYNOMIALS provide the TOOLS

NULLING FILTER DESIGN



- PLACE ZEROS to make $y[n] = 0$

Need 6 ZEROS
where $H(z) = 0$

$$H(z_k) = 0, \quad \text{for } z_k = e^{\pm j0.7\pi}, e^{\pm j0.8\pi}, e^{\pm j0.9\pi}$$

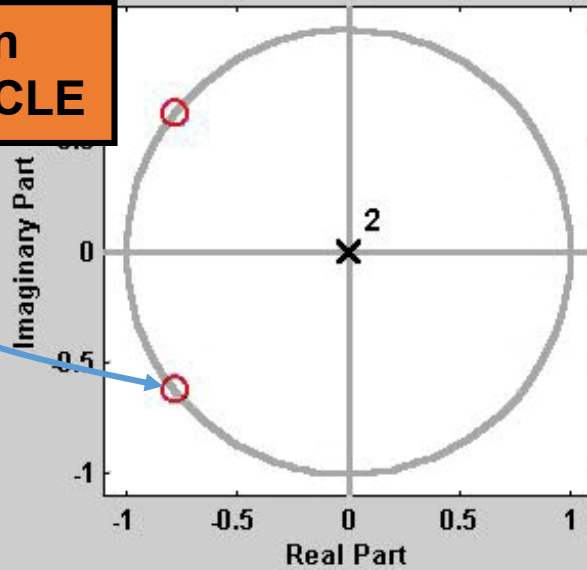
- 6th order FIR has 7 filter coefficients

$$x[n] = e^{j0.8\pi n} \Rightarrow y[n] = H(e^{j0.8\pi})e^{j0.8\pi n}$$

$$H(z) = b_0 + b_1z^{-1} + b_2z^{-2} + b_3z^{-3} + b_4z^{-4} + b_5z^{-5} + b_6z^{-6}$$

3 DOMAINS MOVIE: FIR

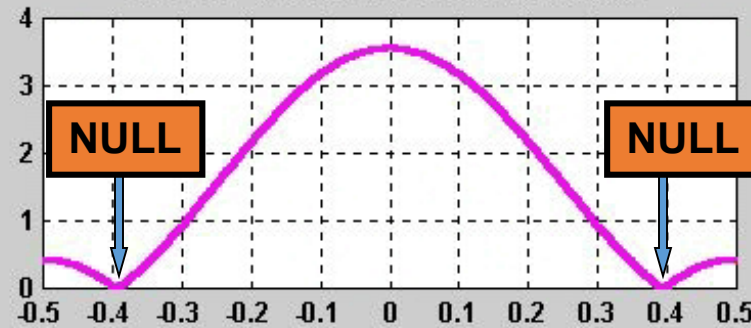
ZEROS on
UNIT-CIRCLE



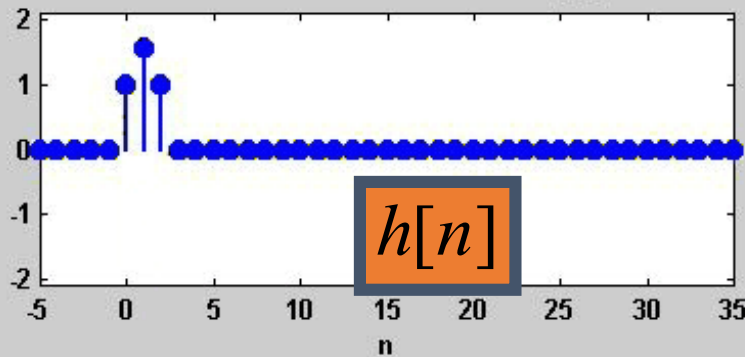
$$1 + 1.56z^{-1} + z^{-2}$$

$$H(z)$$

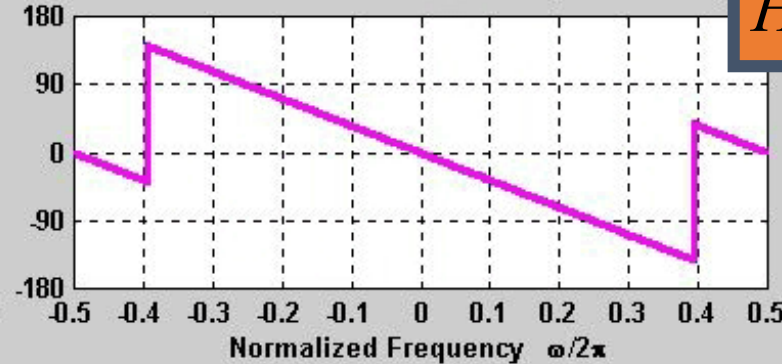
DTFT: MAGNITUDE RESPONSE



IMPULSE RESPONSE: $h[n]$

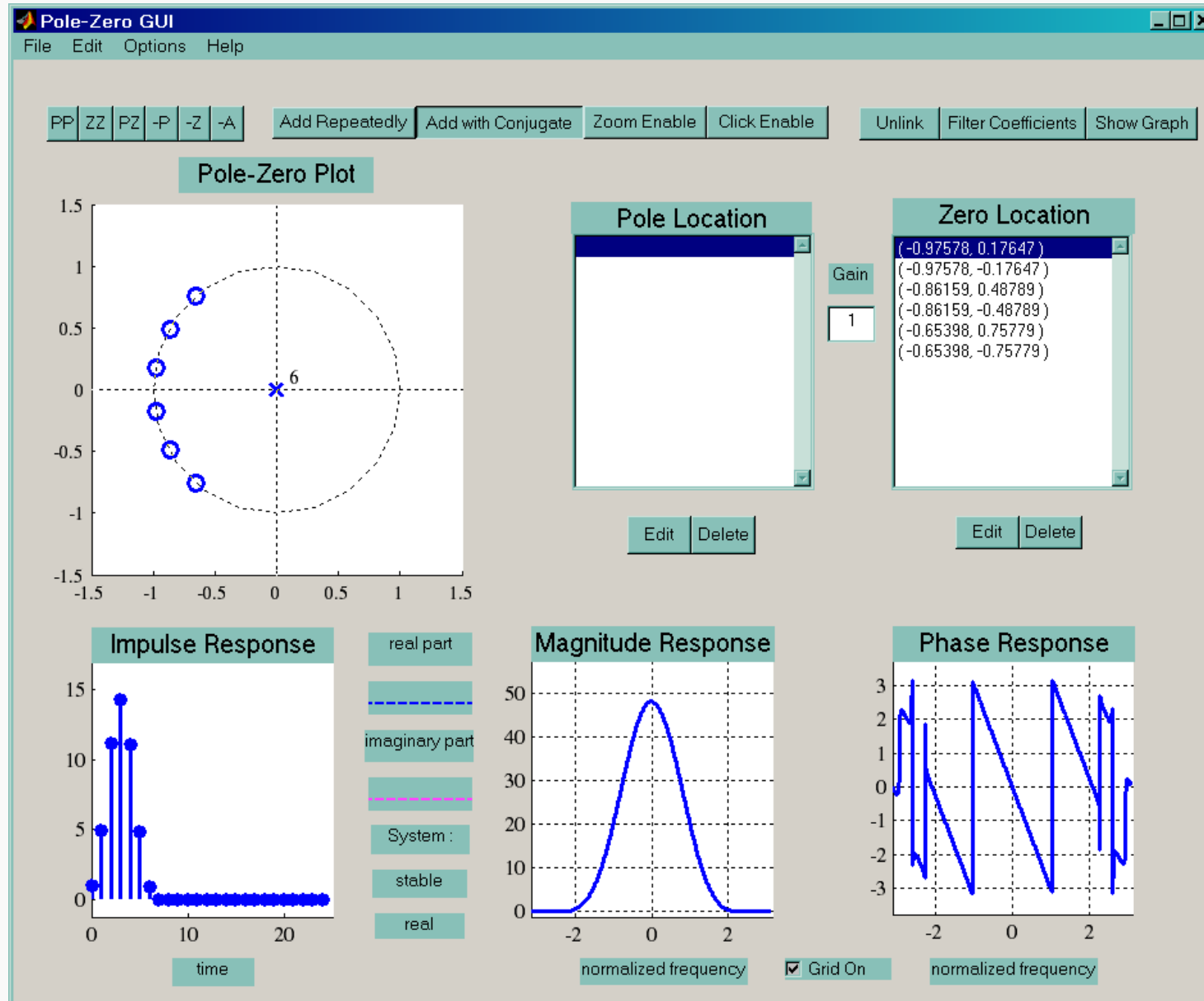


DTFT: PHASE RESPONSE (DEGREES)



$$H(e^{j\hat{\omega}})$$

PeZ Demo: Zero Placing



One zero, two zeros, ...

We usually want filters with real coefficients

$$H(z) = 1 - az^{-1} \Rightarrow H(z) = 0 \text{ @ } z = a$$

If we want to block sinusoid with $\hat{\omega} = \pm 0.8\pi$

$$\begin{aligned} H(z_k) &= 0 \quad \text{for } z_k = e^{\pm j0.8\pi} \\ \Rightarrow H(z) &= z^{-2}(z - e^{j0.8\pi})(z - e^{-j0.8\pi}) \\ &= z^{-2}(z^2 - z(e^{j0.8\pi} + e^{-j0.8\pi}) + 1) \\ &= 1 - 2(\cos 0.8\pi)z^{-1} + z^{-2} = 1 + 1.618z^{-1} + z^{-2} \end{aligned}$$

z^{-2} needed for causality

$$h[0] = 1, \quad h[1] = 1.618, \quad h[2] = 1$$

Block Multiple Frequencies



Want to totally block: $\hat{\omega}_1, \hat{\omega}_2, \dots, \hat{\omega}_m$

$H(z)$ must have zeros at: $z = e^{\pm j\hat{\omega}_1}, e^{\pm j\hat{\omega}_2}, \dots, e^{\pm j\hat{\omega}_m}$

To block $\hat{\omega} = 0$ or π must have zero at $z = 1$ or -1

So, the general form becomes:

$$H(z) = (1 - z^{-1})(1 + z^{-1}) \prod_{n=1}^m (1 - e^{j\hat{\omega}_n} z^{-1})(1 - e^{-j\hat{\omega}_n} z^{-1})$$

to block DC  to block $f_s/2$ 

On the other hand: Not much control over other frequencies

L-pt RUNNING SUM $H(z)$

$$H(z) = \sum_{k=0}^{L-1} z^{-k} = \frac{1 - z^{-L}}{1 - z^{-1}} = \frac{z^L - 1}{z^{L-1}(z - 1)}$$

$$z^L - 1 = 0 \Rightarrow z^L = 1 = e^{j2\pi k}$$

$$z = e^{j(2\pi/L)k} \quad \text{for } k = 1, 2, \dots, L-1$$

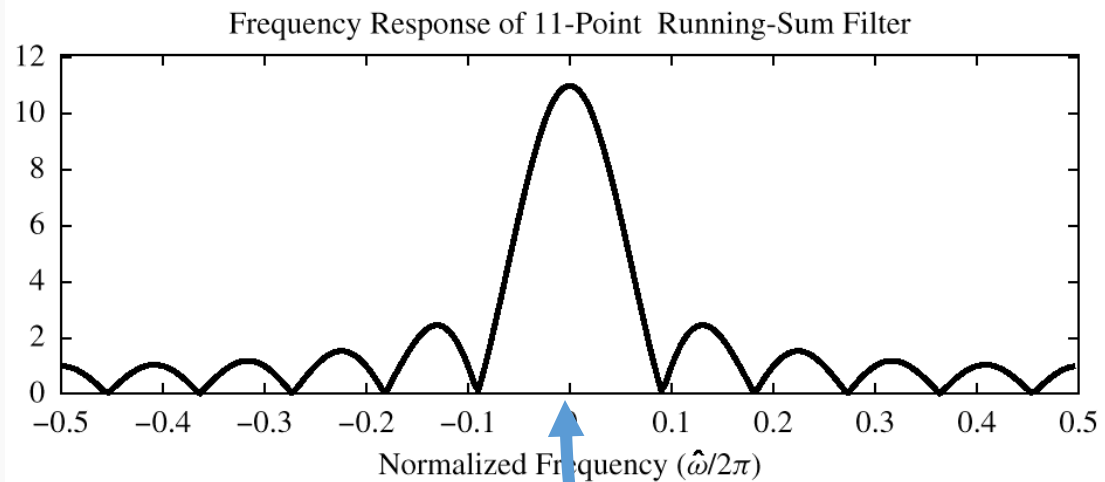
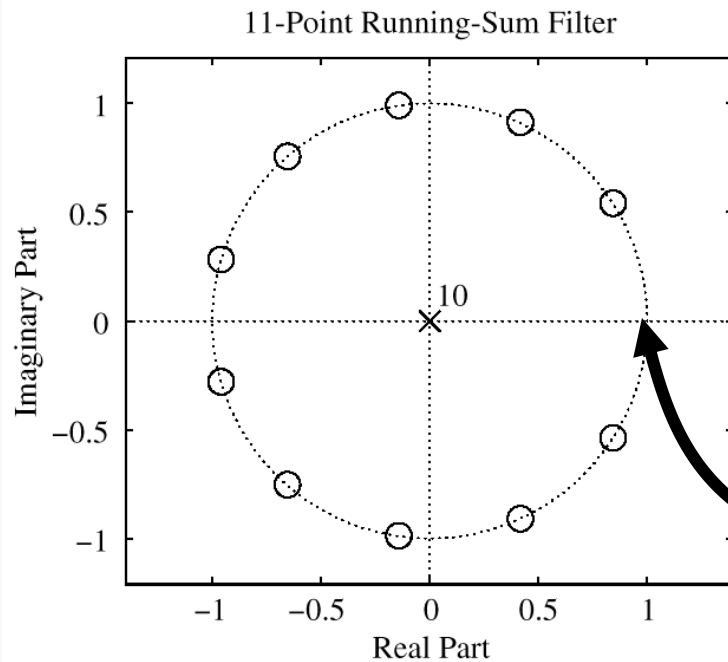
ZEROS on
UNIT CIRCLE

(z-1) in
denominator
cancels k=0 term

11-pt RUNNING SUM $H(z)$

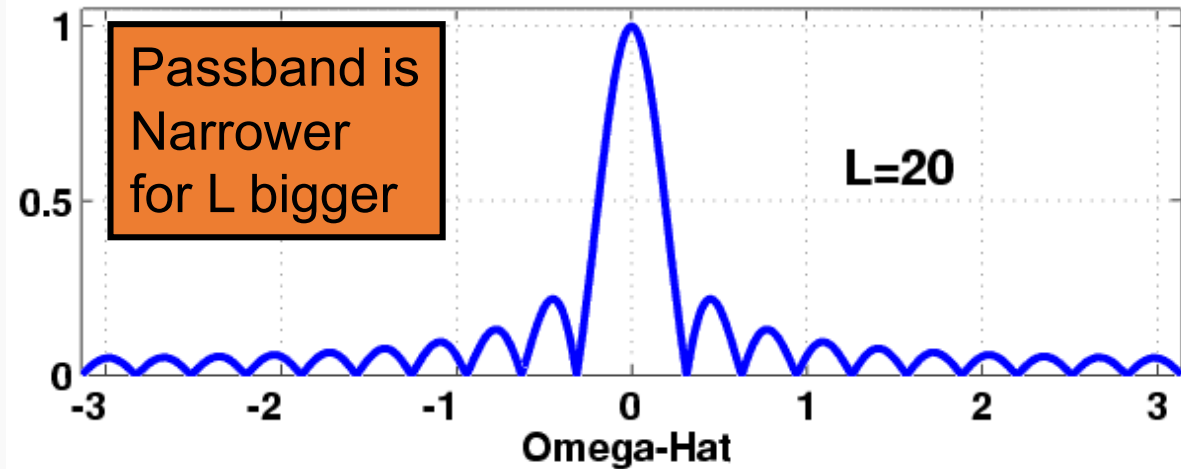
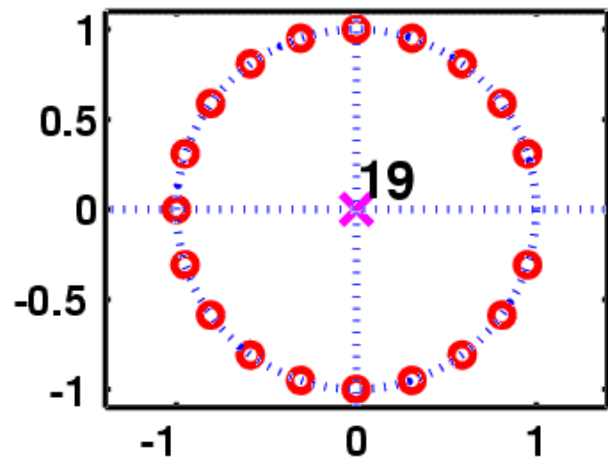
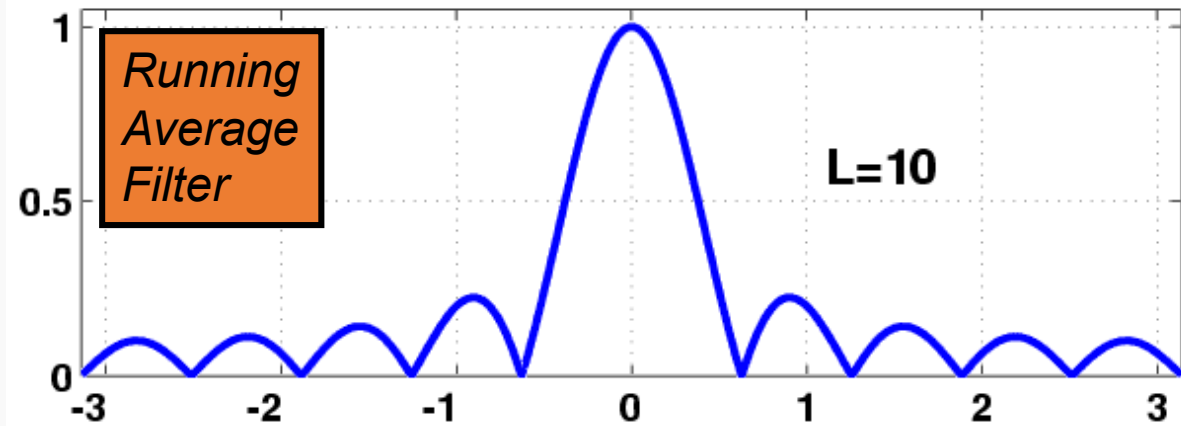
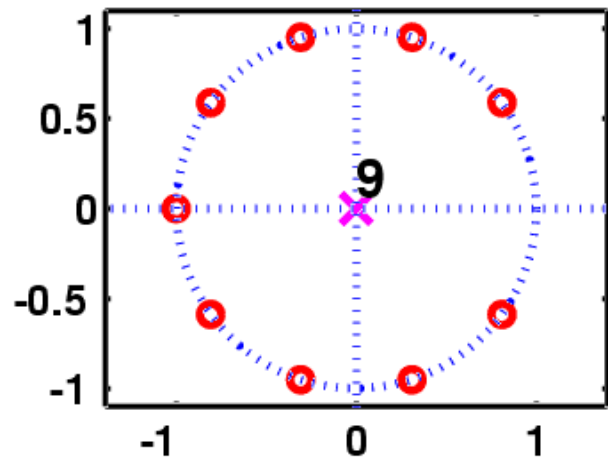
$$H(z) = \sum_{k=0}^{10} z^{-k}$$

$$H(z) = (1 - e^{j2\pi/11}z^{-1})(1 - e^{j4\pi/11}z^{-1}) \cdots (1 - e^{j20\pi/11}z^{-1})$$



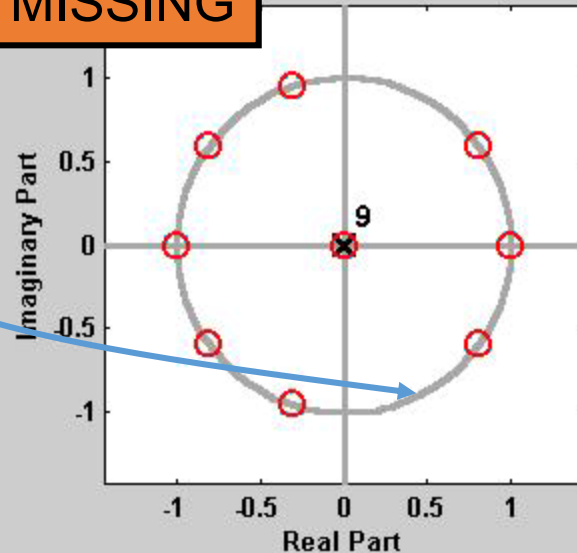
NO zero at $z=1$

FILTER DESIGN: CHANGE L

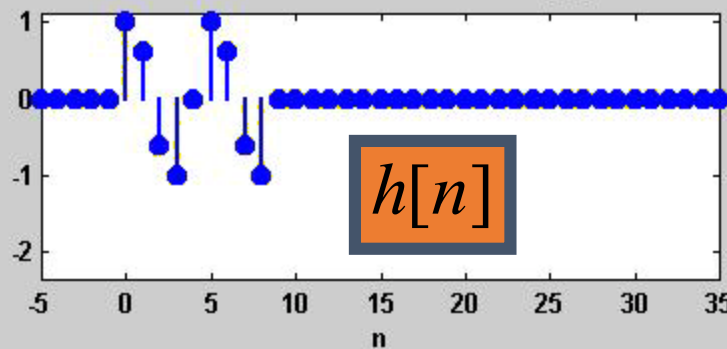


3 DOMAINS MOVIE: FIR BPF

ZEROS MISSING



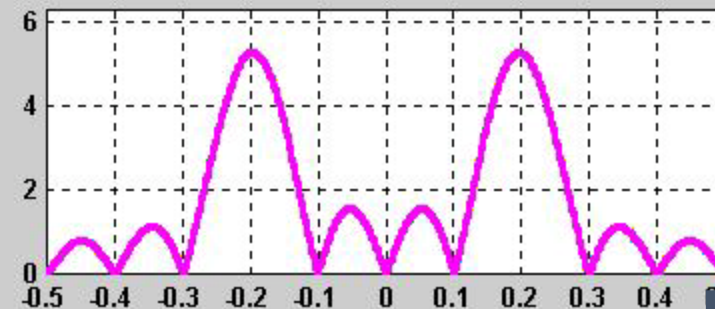
IMPULSE RESPONSE: $h[n]$



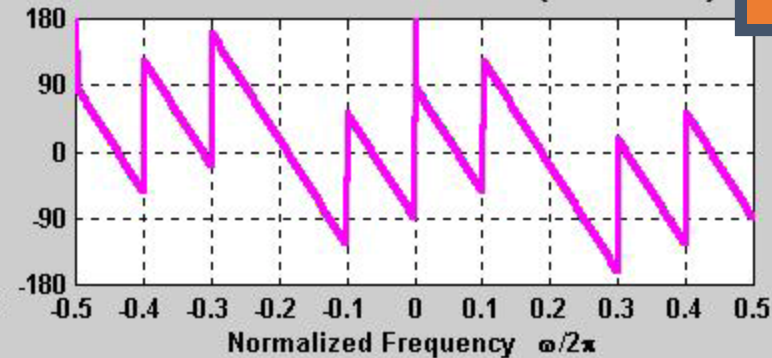
$$1 + 0.618z^{-1} - 0.618z^{-2} - z^{-3} + z^{-5} + 0.618z^{-6} - 0.618z^{-7} - z^{-8}$$

$H(z)$

DTFT: MAGNITUDE RESPONSE



DTFT: PHASE RESPONSE (DEGREES)



$H(e^{j\hat{\omega}})$

Check Website & MATLAB Code



https://dspfirst.gatech.edu/chapters/07ztrans/demos/3_domain/index.html

```
%% load piano sounds
load labtest.mat;
sound(xx,fs);
figure(1); spectrogram(xx);

%% If I want to pass  $w = 0.2\pi$ 
load filter2.mat;
yy = filter( z_values, p_values, xx);
[h,w] = freqz( z_values, p_values, 'whole',120);
plot((w)/pi,abs(h));

sound(yy,fs);
figure(2); spectrogram(yy);
```