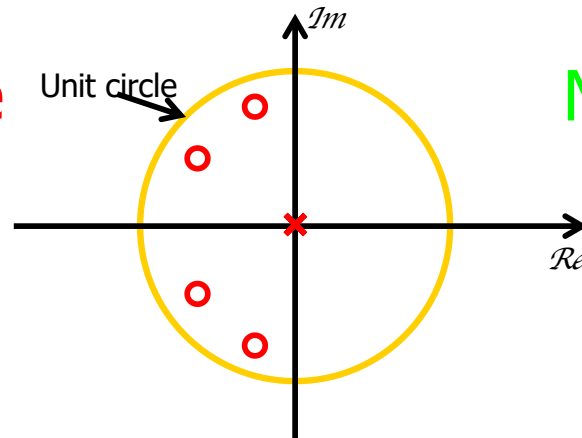


ESE 531: Digital Signal Processing

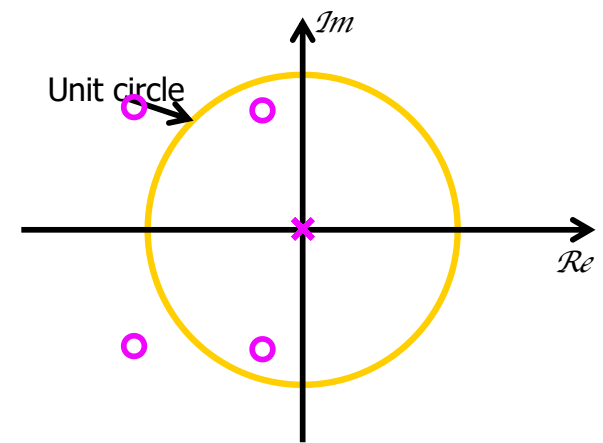
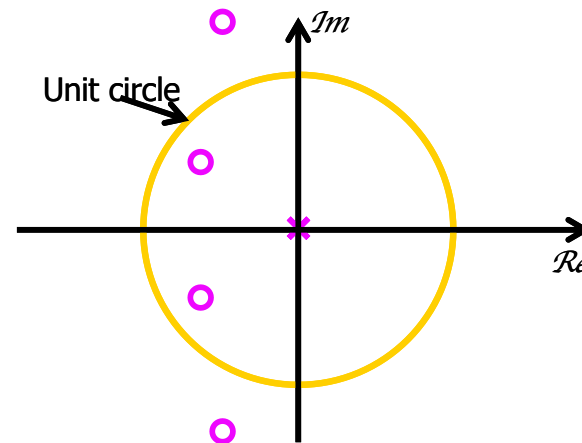
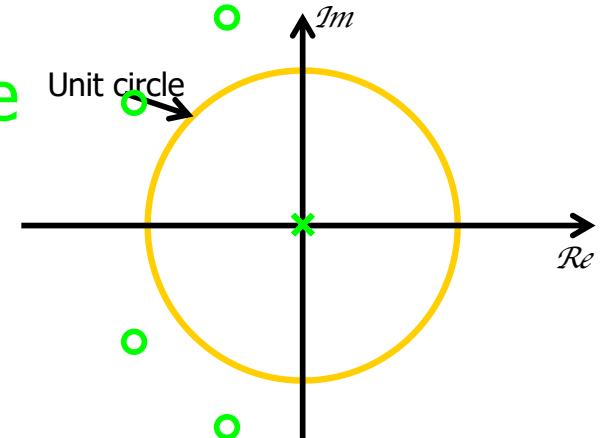
Lecture 15: March 3, 2022
Generalized Linear Phase Systems

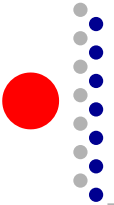
Minimum Phase

Min phase



Max phase





Minimum Phase Lag Property

- All pass properties
 - $\arg[H_{ap}(e^{j\omega})] \leq 0$
 - $\text{grd}[H_{ap}(e^{j\omega})] > 0$

Minimum Phase Lag Property

□ All pass properties

■ $\arg[H_{ap}(e^{j\omega})] \leq 0$

■ $\text{grd}[H_{ap}(e^{j\omega})] > 0$

□
$$\begin{aligned}\arg[H_{\max}(e^{j\omega})] &= \arg[H_{\min}(e^{j\omega}) * H_{ap}(e^{j\omega})] \\ &= \arg[H_{\min}(e^{j\omega})] + \arg[H_{ap}(e^{j\omega})] \\ &= \arg[H_{\min}(e^{j\omega})] + \leq 0\end{aligned}$$

Minimum Group Delay Property

□ All pass properties

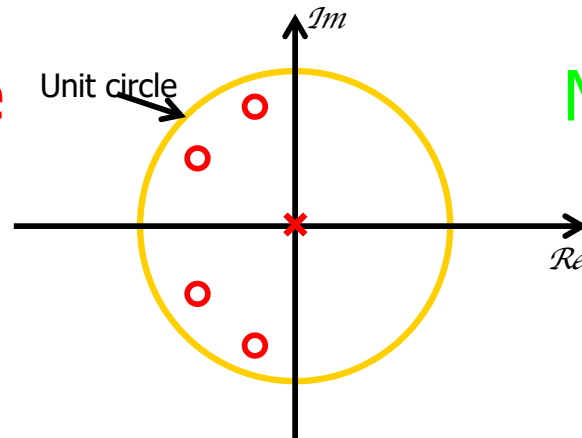
■ $\arg[H_{ap}(e^{j\omega})] \leq 0$

■ $\text{grd}[H_{ap}(e^{j\omega})] > 0$

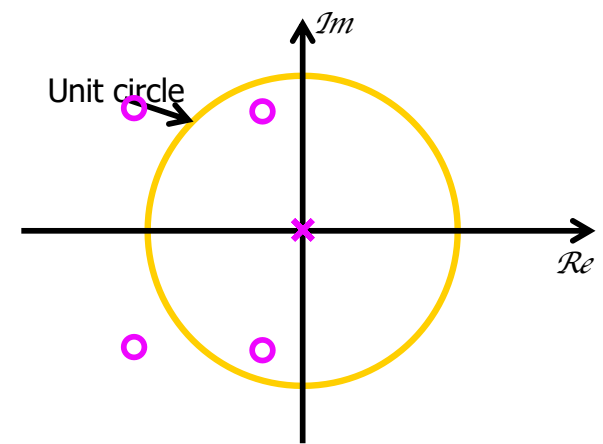
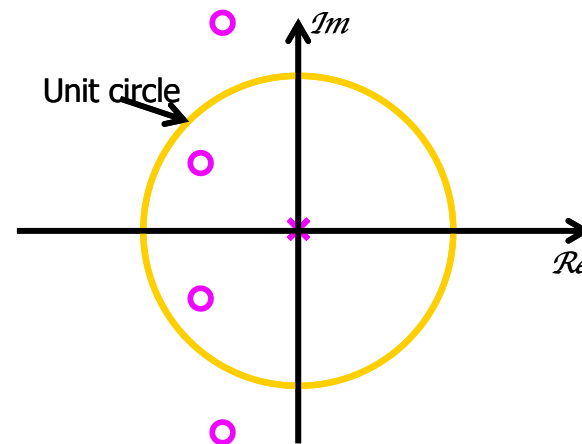
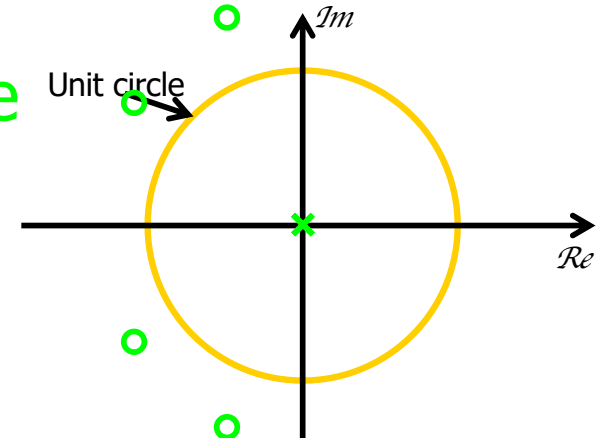
□
$$\begin{aligned}\text{grd}[H_{\max}(e^{j\omega})] &= \text{grd}[H_{\min}(e^{j\omega}) * H_{ap}(e^{j\omega})] \\ &= \text{grd}[H_{\min}(e^{j\omega})] + \text{grd}[H_{ap}(e^{j\omega})] \\ &= \text{grd}[H_{\min}(e^{j\omega})] + \geq 0\end{aligned}$$

Minimum Phase

Min phase



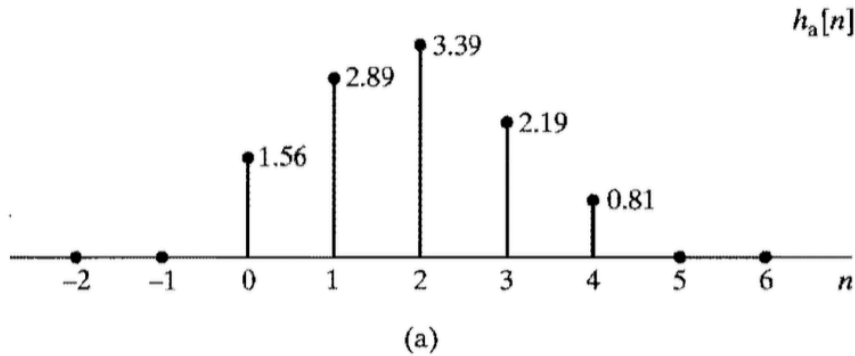
Max phase



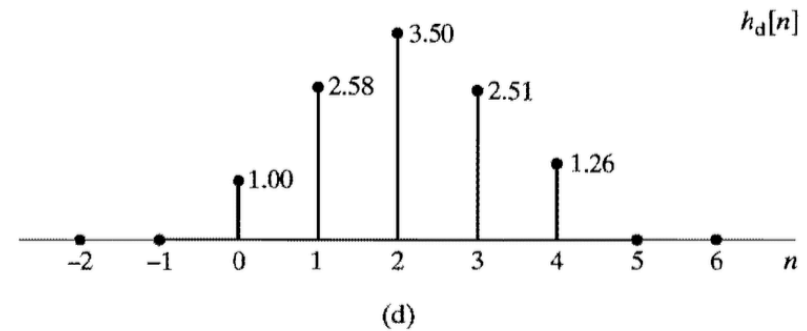
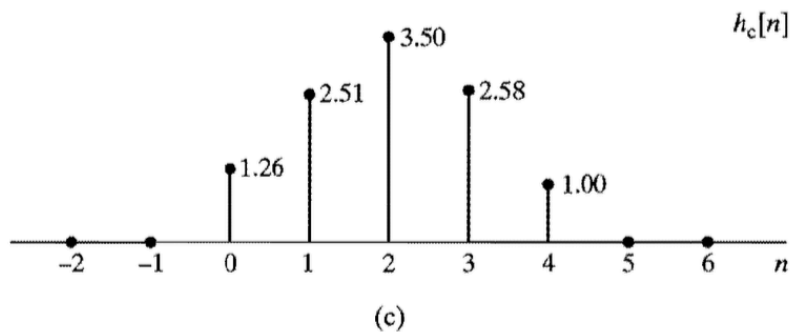
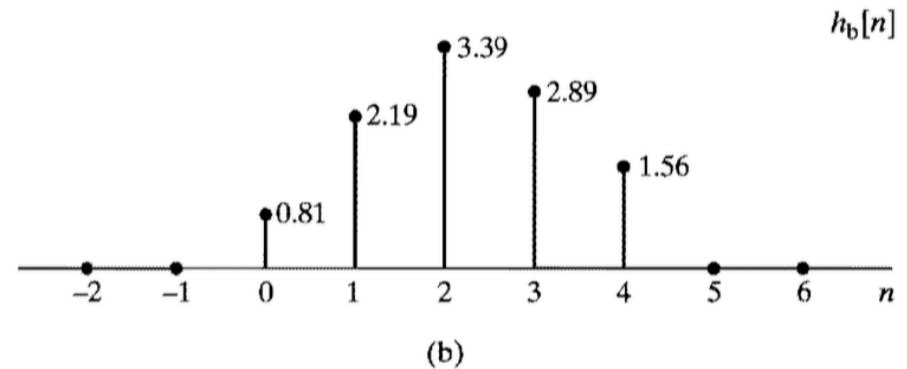
What kind of filter is this?

Minimum Energy-Delay Property

Min phase



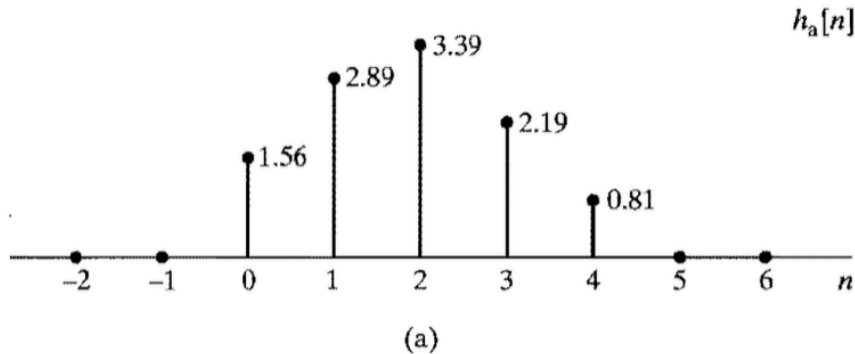
Max phase



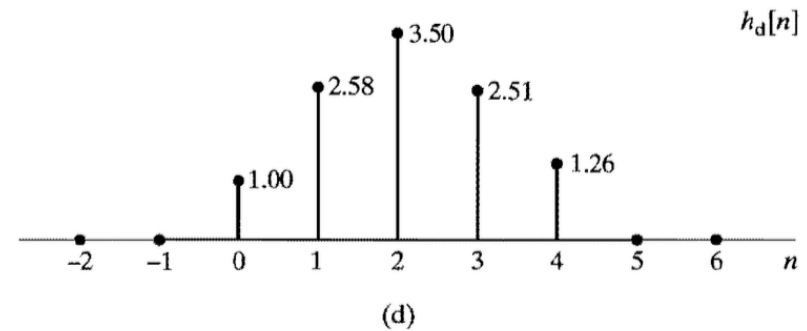
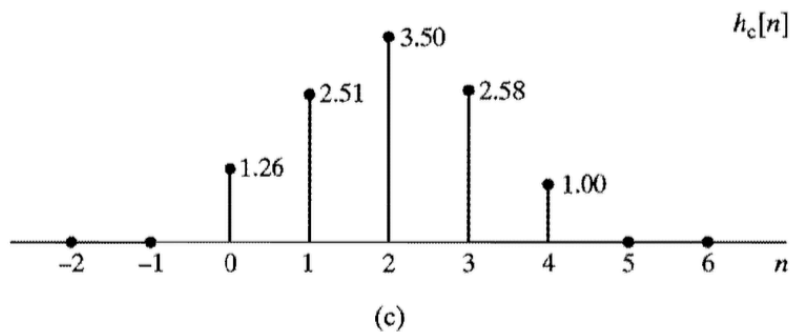
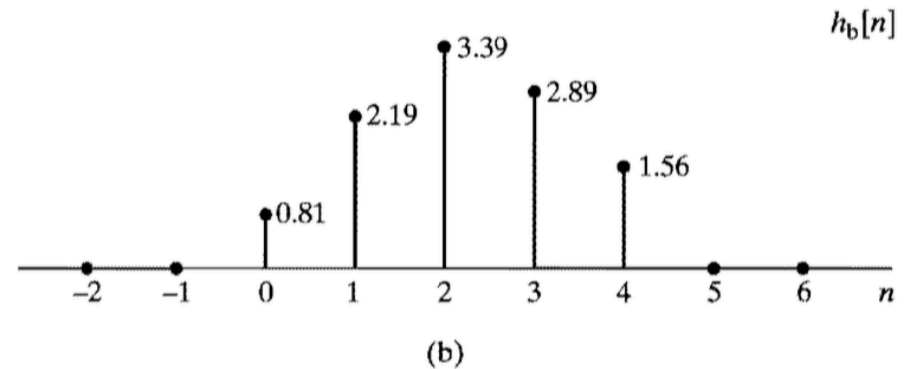
Total energy: $E = \sum_{n=0}^{\infty} |h[n]|^2$

Minimum Energy-Delay Property

Min phase

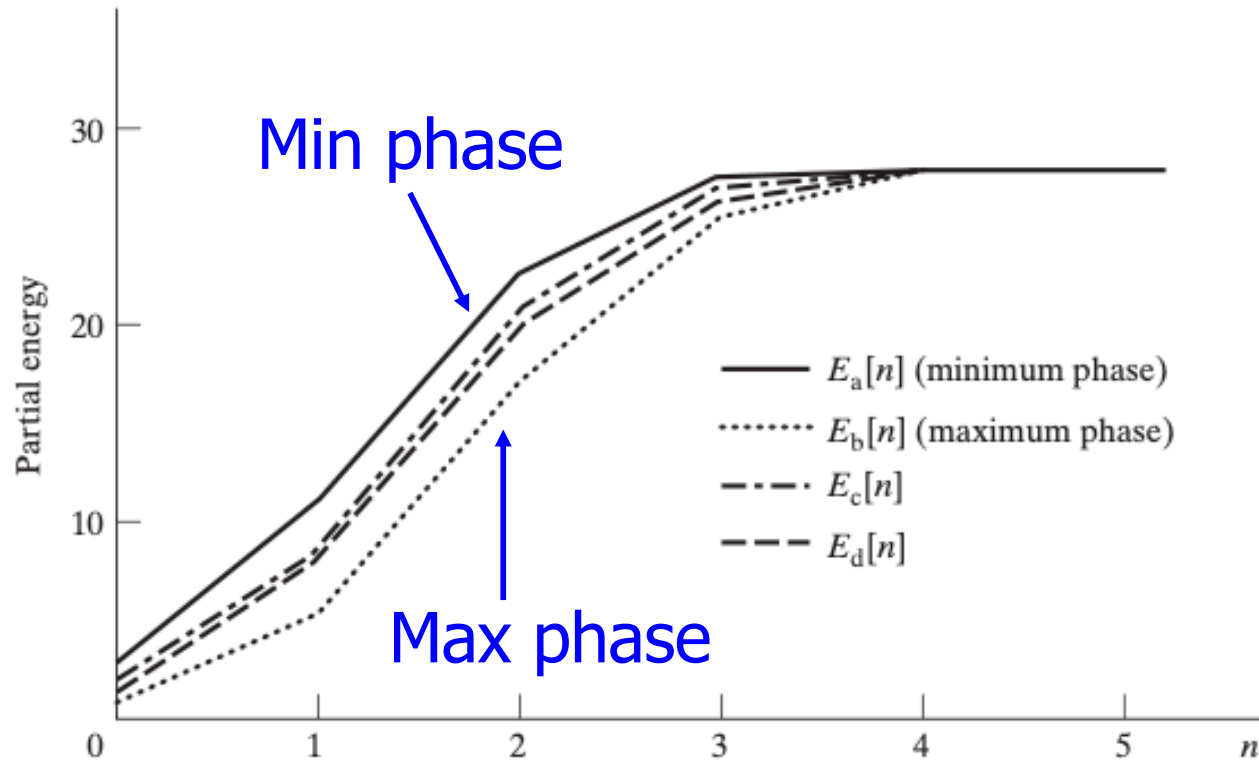


Max phase



Partial energy: $E[n] = \sum_{m=0}^n |h[m]|^2$

Minimum Energy-Delay Property

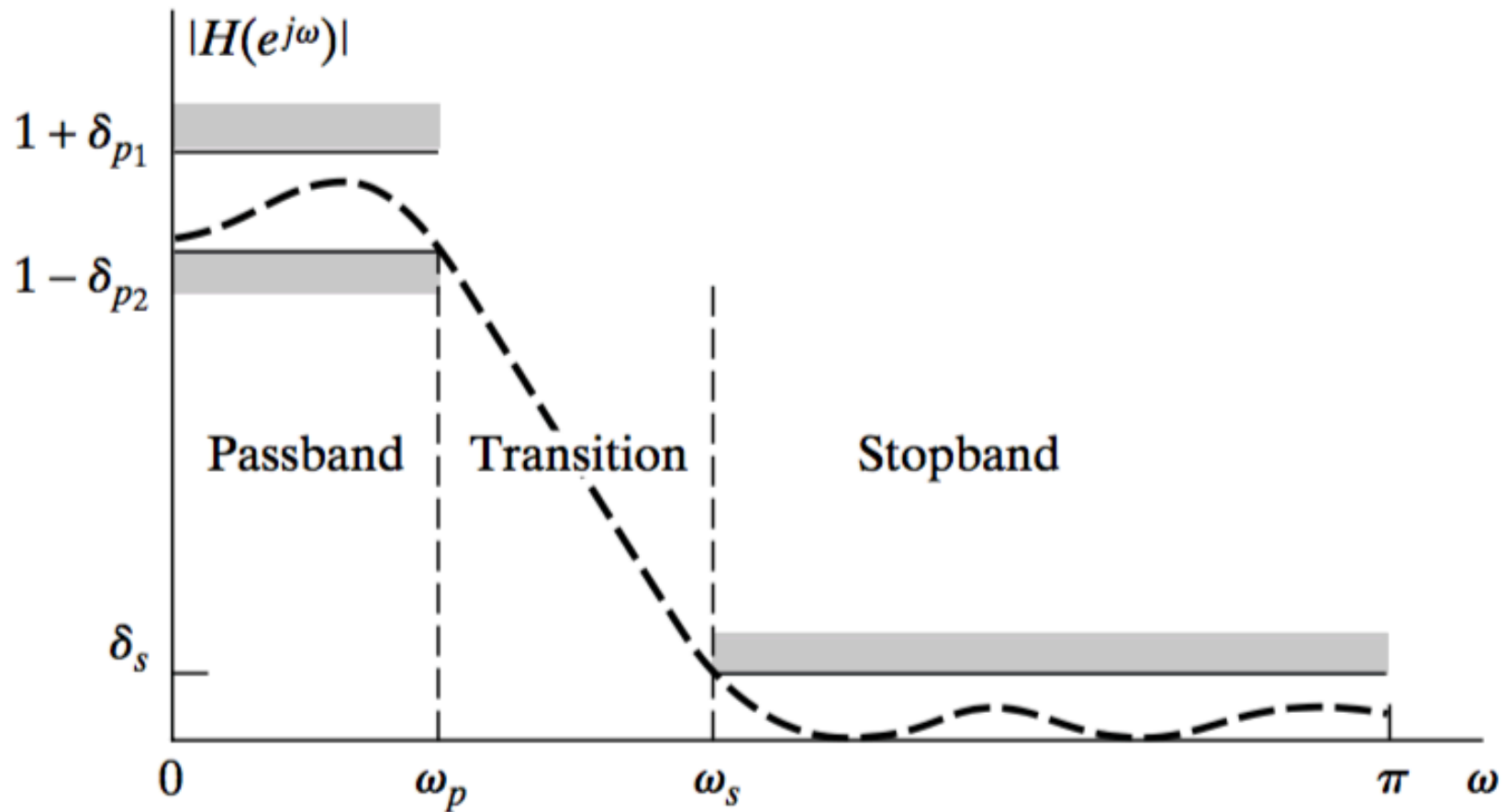


Partial energy: $E[n] = \sum_{m=0}^n |h[m]|^2$



Generalized Linear Phase Systems

Filter Specifications



Generalized Linear Phase

- An LTI system has generalized linear phase if frequency response $H(e^{j\omega})$ can be expressed as:

$$H(e^{j\omega}) = A(\omega)e^{-j\omega\alpha+j\beta}, \quad |\omega| < \pi$$

- Where $A(\omega)$ is a real function.

Generalized Linear Phase

- An LTI system has generalized linear phase if frequency response $H(e^{j\omega})$ can be expressed as:

$$H(e^{j\omega}) = A(\omega)e^{-j\omega\alpha+j\beta}, \quad |\omega| < \pi$$

- Where $A(\omega)$ is a real function.
- What is the group delay?



Causal FIR Systems

$$y[n] = b_0x[n] + b_1x[n-1] + \dots + b_Mx[n-M], \quad \text{all } n$$

$$H(z) = b_0 + b_1z^{-1} + \dots + b_Mz^{-M} = b_0 \prod_{k=1}^M (1 - c_k z^{-1})$$

$$h[n] = \begin{cases} b_n, & n = 0, 1, \dots, M \\ 0, & \text{otherwise} \end{cases}$$

Causal FIR Systems

- Causal FIR systems have generalized linear phase if they have impulse response length $(M+1)$ and some symmetry
- It can be shown if

$$h[n] = \begin{cases} h[M - n], & 0 \leq n \leq M, \\ 0, & \text{otherwise,} \end{cases}$$

- then

$$H(e^{j\omega}) = A_e(e^{j\omega})e^{-j\omega M/2},$$

Example: Moving Average

□ Moving Average Filter

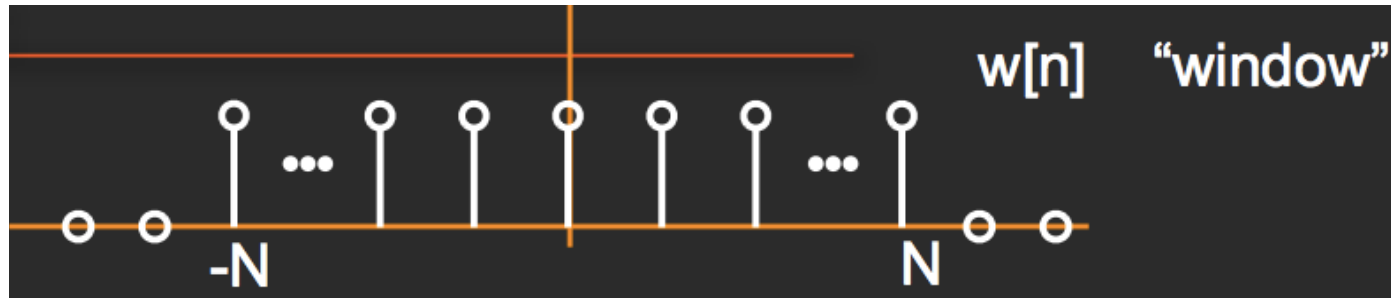
- Causal: $M_1=0$, $M_2=M$

$$y[n] = \frac{x[n-M] + \dots + x[n]}{M+1}$$

Impulse
response

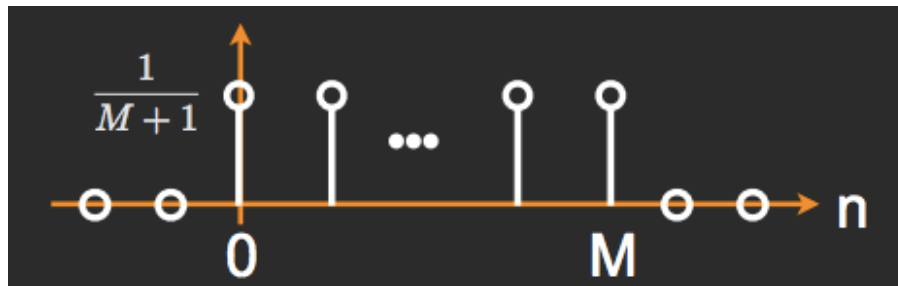


Example: Moving Average



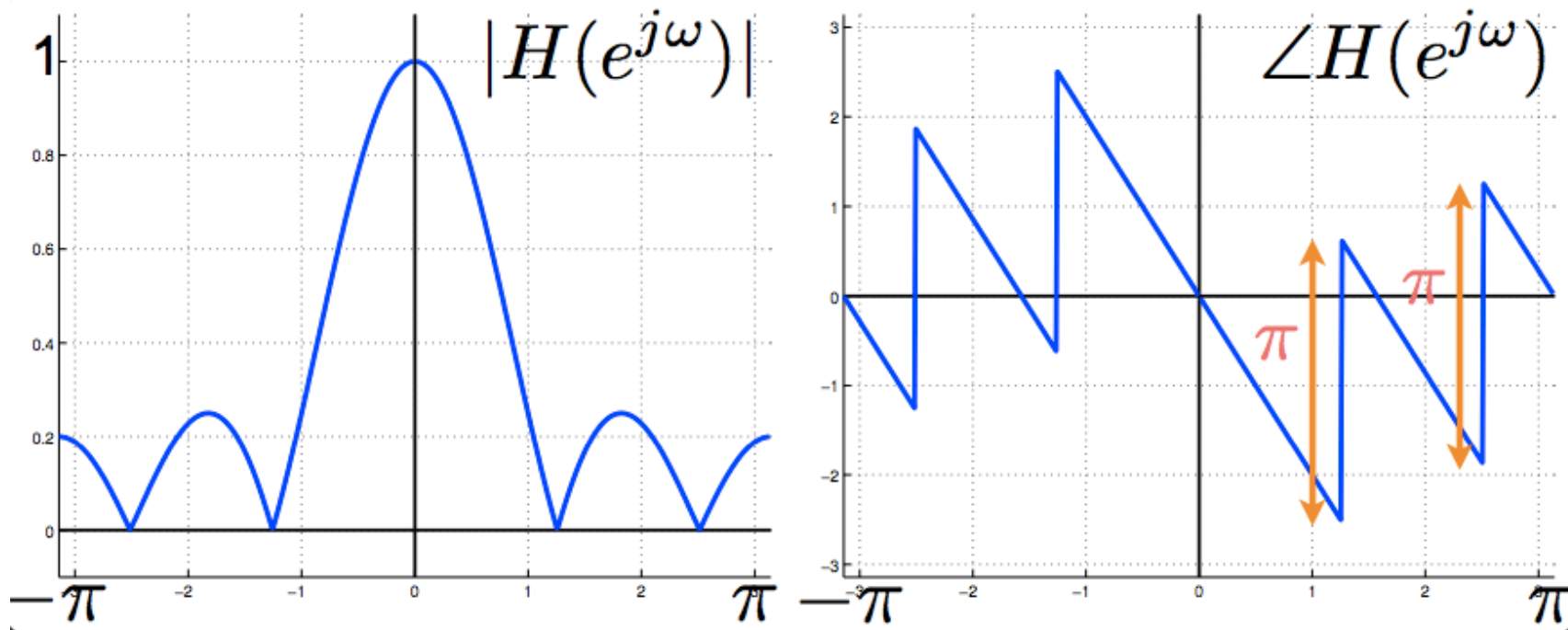
$$w[n] \leftrightarrow W(e^{j\omega}) = \frac{\sin((N + 1/2)\omega)}{\sin(\omega/2)}$$

Scaled & Time
Shifted window



$$\frac{1}{M+1} w[n - M/2] \leftrightarrow W(e^{j\omega}) = \frac{e^{-j\omega M/2}}{M+1} \frac{\sin((M/2 + 1/2)\omega)}{\sin(\omega/2)}$$

Example: Moving Average



Causal FIR Systems

- Causal FIR systems have generalized linear phase if they have impulse response length $(M+1)$
- It can be shown if

$$h[n] = \begin{cases} h[M - n], & 0 \leq n \leq M, \\ 0, & \text{otherwise,} \end{cases}$$

- Then

$$H(e^{j\omega}) = A_e(e^{j\omega})e^{-j\omega M/2},$$

- Sufficient conditions to guarantee GLP, not necessary
 - Causal IIR can also have GLP



FIR GLP Systems

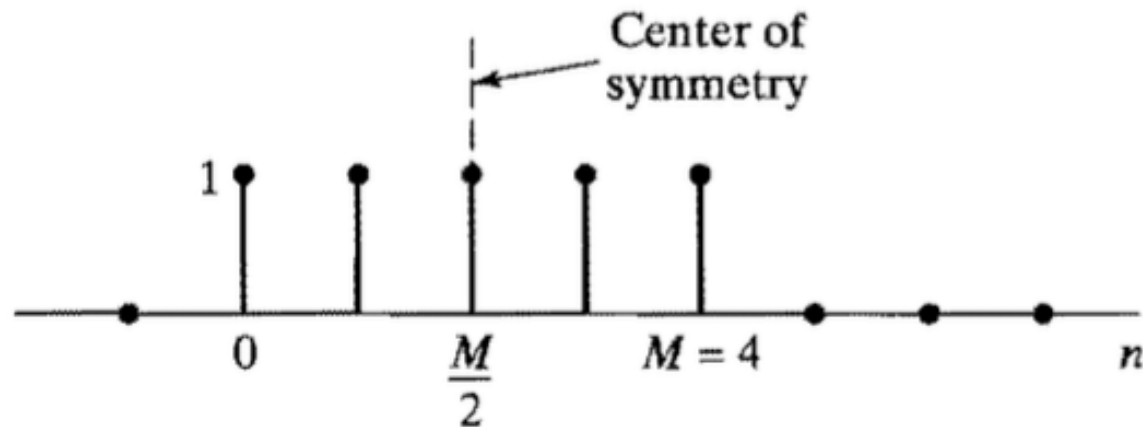
- Four types of FIR GLP
 - Type I
 - Even Symmetry, M even
 - Type II
 - Even Symmetry, M odd
 - Type III
 - Odd Symmetry, M even
 - Type IV
 - Odd Symmetry, M odd



FIR GLP: Type I

Type I Even Symmetry, M even

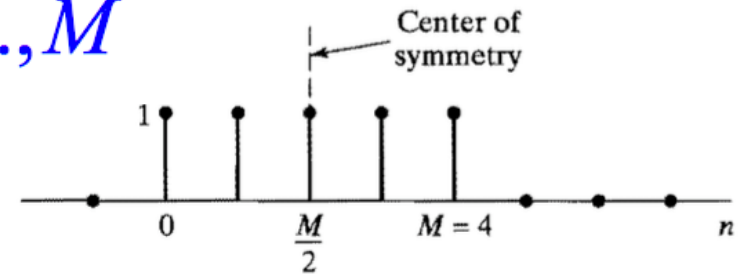
$$h[n] = h[M - n], \quad n = 0, 1, \dots, M$$



FIR GLP: Type I

Type I Even Symmetry, M even

$$h[n] = h[M - n], \quad n = 0, 1, \dots, M$$



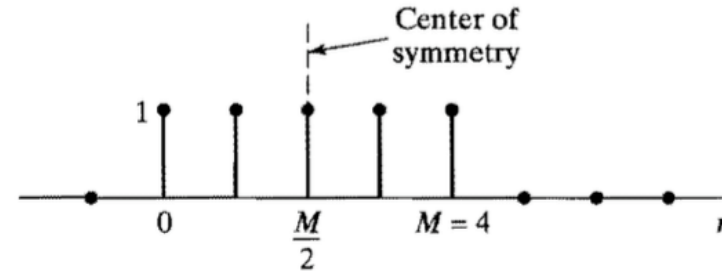
$$\text{Then } H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Even}} e^{-j\omega M/2}$$

← integer delay

FIR GLP: Type I – Example, $M=4$

Type I Even Symmetry, M even

$$h[n] = h[M - n], \quad n = 0, 1, \dots, M$$



$$\text{Then } H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Even}} e^{-j\omega M/2}$$

integer delay

FIR GLP: Type I – Example, $M=4$

Type I Even Symmetry, M even

$$h[n] = h[M - n], \quad n = 0, 1, \dots, M$$

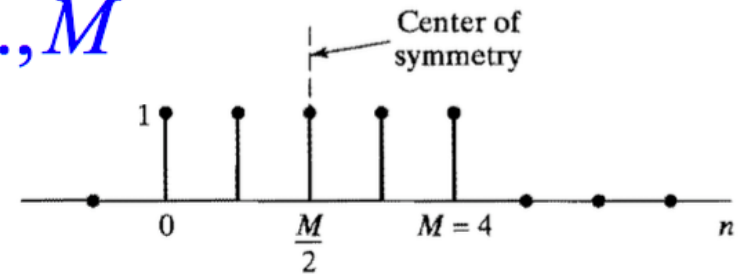
$$\text{Then } H(e^{j\omega}) = \sum_{n=0}^M h[n]e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Even}} e^{-j\omega M/2} \quad \leftarrow \text{integer delay}$$

$$\begin{aligned} H(e^{j\omega}) &= h[0] + h[1]e^{-j\omega} + h[2]e^{-j2\omega} + h[3]e^{-j3\omega} + h[4]e^{-j4\omega} \\ &= e^{-j2\omega} \left[h[0]e^{j2\omega} + h[1]e^{j\omega} + h[2] + h[1]e^{-j\omega} + h[0]e^{-j2\omega} \right] \\ &= \underbrace{\left[2h[0]\cos(2\omega) + 2h[1]\cos(\omega) + h[2] \right]}_{A(\omega) \text{ (even)}} e^{-j2\omega} \end{aligned}$$

FIR GLP: Type I

Type I Even Symmetry, M even

$$h[n] = h[M - n], \quad n = 0, 1, \dots, M$$



$$\text{Then } H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Even}} e^{-j\omega M/2}$$

integer delay

$$H(e^{j\omega}) = e^{-j\omega M/2} \left(\sum_{k=0}^{M/2} a[k] \cos \omega k \right)$$

$$a[0] = h[M/2],$$

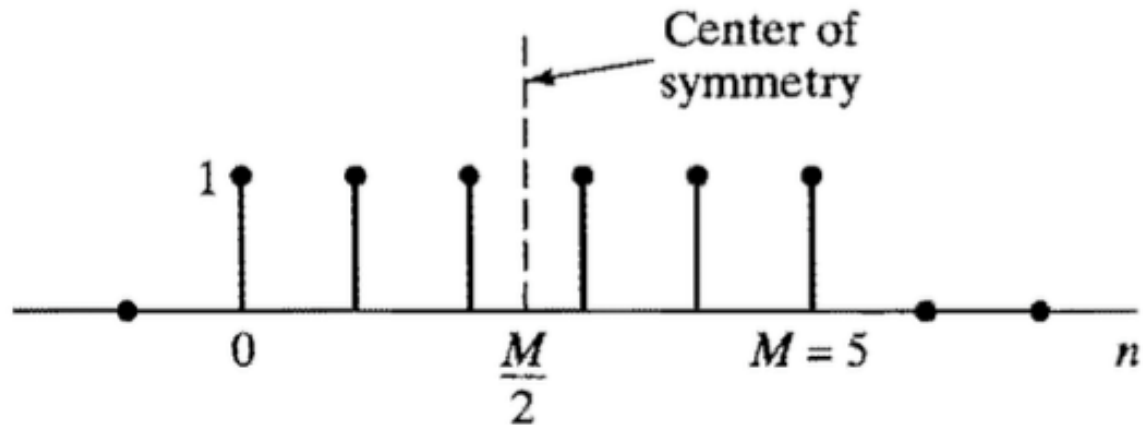
$$a[k] = 2h[(M/2) - k], \quad k = 1, 2, \dots, M/2.$$



FIR GLP: Type II

Type II Even Symmetry, M odd

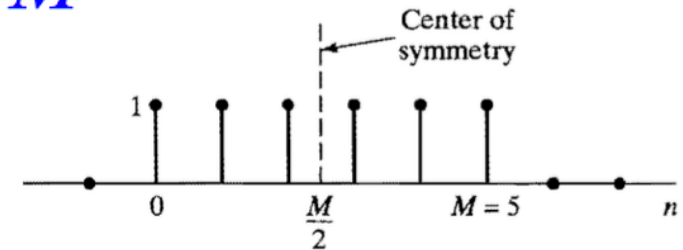
$$h[n] = h[M - n], \quad n = 0, 1, \dots, M$$



FIR GLP: Type II

Type II Even Symmetry, M odd

$$h[n] = h[M - n], \quad n = 0, 1, \dots, M$$



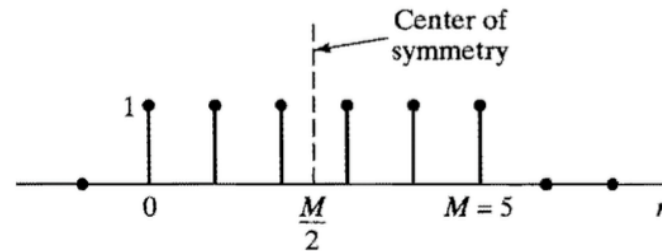
$$\text{Then } H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Even}} e^{-j\omega M/2}$$

integer delay

FIR GLP: Type II – Example, $M=3$

Type II Even Symmetry, M odd

$$h[n] = h[M - n], \quad n = 0, 1, \dots, M$$



$$\text{Then } H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Even}} e^{-j\omega M/2}$$

integer delay

FIR GLP: Type II – Example, $M=3$

Type II Even Symmetry, M odd

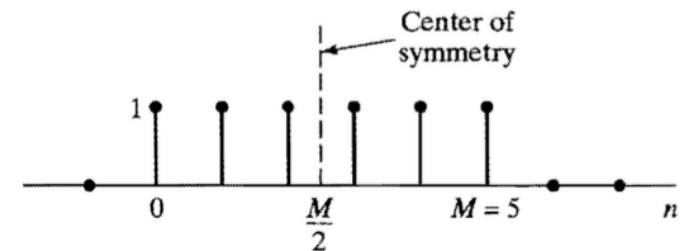
$$\text{Then } H(e^{j\omega}) = \sum_{n=0}^M h[n]e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Even}} e^{-j\omega M/2} \quad \leftarrow \text{integer delay}$$

$$H(e^{j\omega}) = h[0] + h[1]e^{-j\omega} + h[2]e^{-j2\omega} + h[3]e^{-j3\omega}$$

$$H(e^{j\omega}) = \underbrace{\left[2h[0]\cos(3\omega / 2) + 2h[1]\cos(\omega / 2) \right]}_{A(\omega)} e^{-j3\omega/2}$$

FIR GLP: Type II

Type II Even Symmetry, M odd



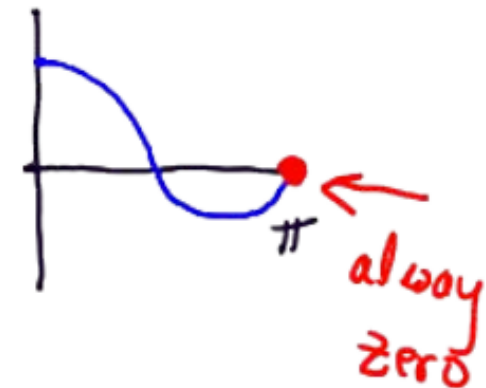
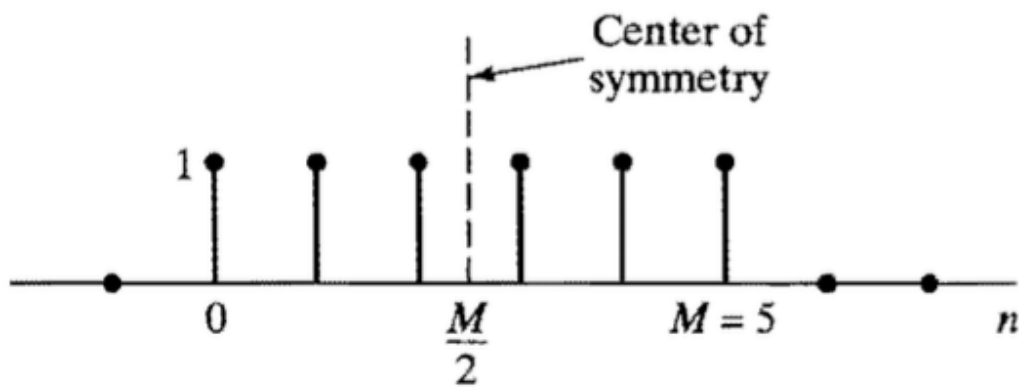
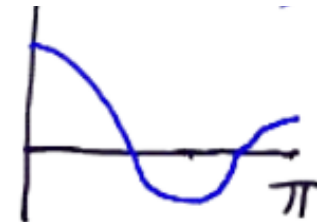
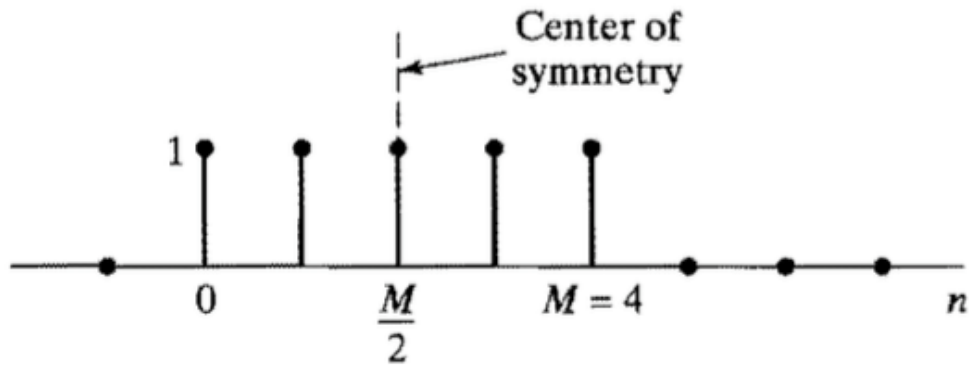
$$\text{Then } H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Even}} e^{-j\omega M/2}$$

← integer delay

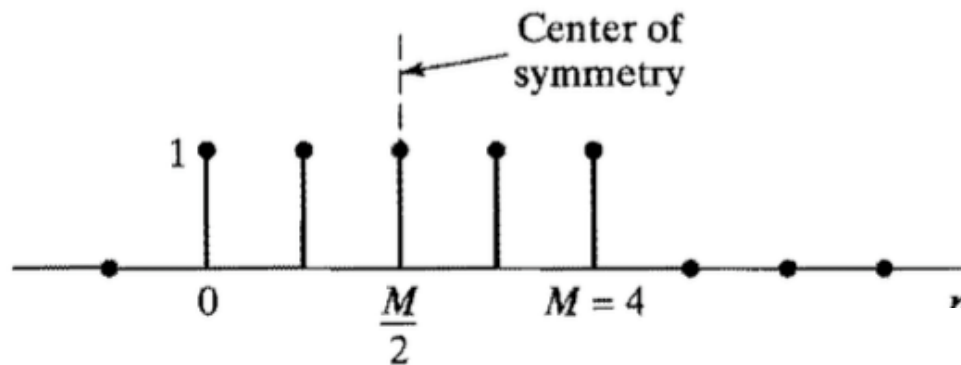
$$H(e^{j\omega}) = e^{-j\omega M/2} \left\{ \sum_{k=1}^{(M+1)/2} b[k] \cos \left[\omega \left(k - \frac{1}{2} \right) \right] \right\}$$

$$b[k] = 2h[(M+1)/2 - k], \quad k = 1, 2, \dots, (M+1)/2.$$

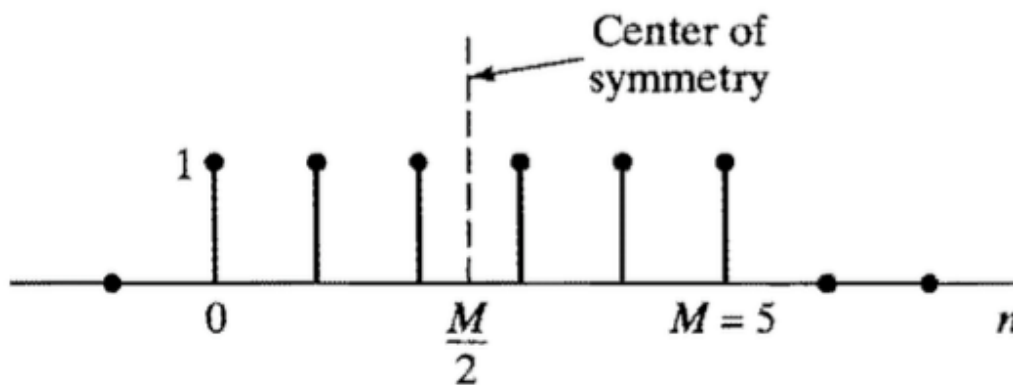
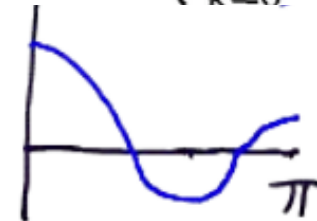
FIR GLP: Type I and II



FIR GLP: Type I and II



$$H(e^{j\omega}) = e^{-j\omega M/2} \left(\sum_{k=0}^{M/2} a[k] \cos \omega k \right)$$

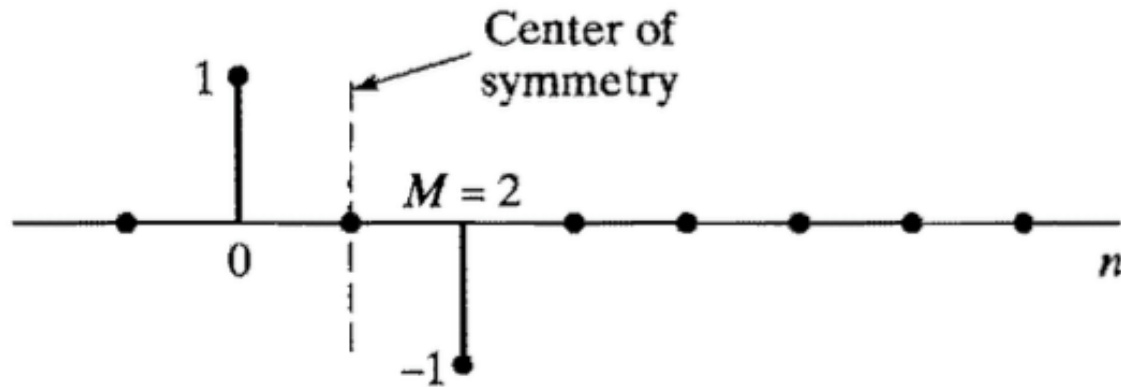


$$H(e^{j\omega}) = e^{-j\omega M/2} \left\{ \sum_{k=1}^{(M+1)/2} b[k] \cos \left[\omega \left(k - \frac{1}{2} \right) \right] \right\}$$



Type III Odd Symmetry, M even

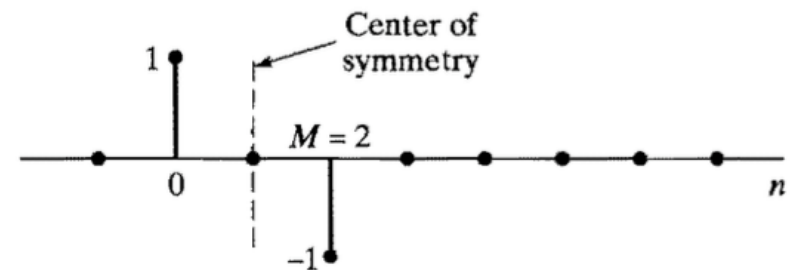
$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (\text{note } h[M/2] = 0)$$



FIR GLP: Type III

Type III Odd Symmetry, M even

$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (\text{note } h[M/2] = 0)$$

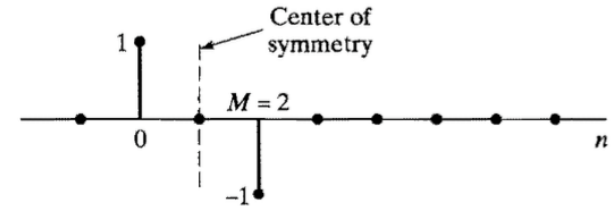


$$H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Odd}} e^{-j\omega M/2 + j\pi/2}$$

FIR GLP: Type III – Example, $M=4$

Type III Odd Symmetry, M even

$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (\text{note } h[M/2] = 0)$$



$$H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Odd}} e^{-j\omega M/2 + j\pi/2}$$

FIR GLP: Type III – Example, M=4

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$$H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Odd}} e^{-j\omega M/2 + j\pi/2}$$

$$\begin{aligned} H(e^{j\omega}) &= h[0] + h[1]e^{-j\omega} + h[2]e^{-j2\omega} + h[3]e^{-j3\omega} + h[4]e^{-j4\omega} \\ &= e^{-j2\omega} \left[h[0]e^{j2\omega} + h[1]e^{j\omega} - h[1]e^{-j\omega} - h[0]e^{-j2\omega} \right] \\ &= \underbrace{\left[2h[0]\sin(2\omega) + 2h[1]\sin(\omega) \right]}_{A(\omega) \text{ (odd)}} j e^{-j2\omega} \end{aligned}$$

FIR GLP: Type III

Type III Odd Symmetry, M even

$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (\text{note } h[M/2] = 0)$$

$$H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Odd}} e^{-j\omega M/2 + j\pi/2}$$

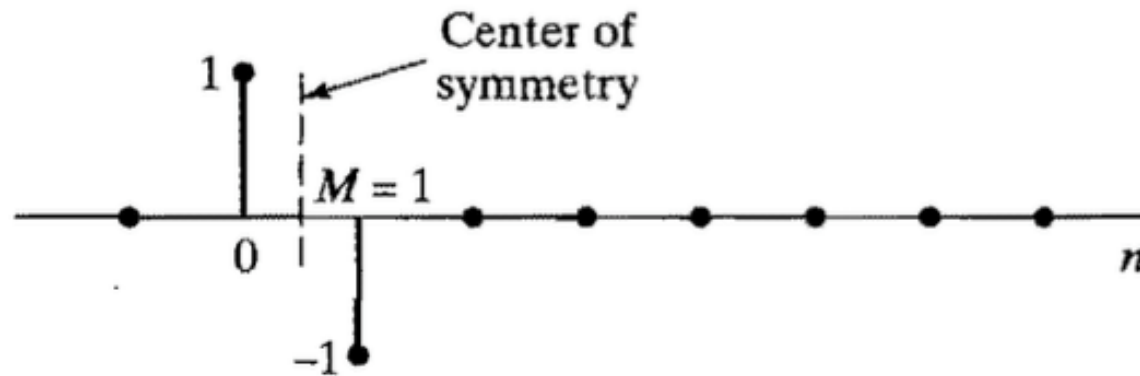
$$H(e^{j\omega}) = j e^{-j\omega M/2} \left[\sum_{k=1}^{M/2} c[k] \sin \omega k \right]$$

$$c[k] = 2h[(M/2) - k], \quad k = 1, 2, \dots, M/2.$$

FIR GLP: Type IV

Type IV Odd Symmetry, M Odd

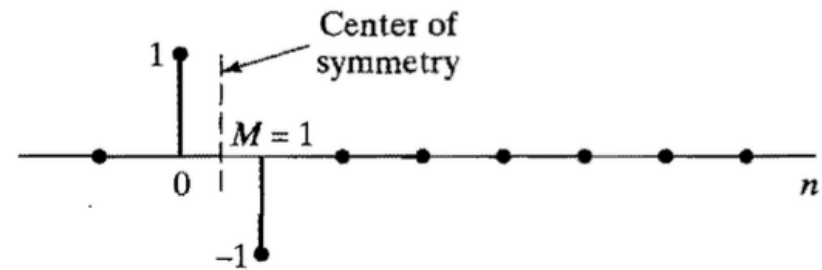
$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (M / 2 \text{ not an integer})$$



FIR GLP: Type IV

Type IV Odd Symmetry, M Odd

$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (M / 2 \text{ not an integer})$$



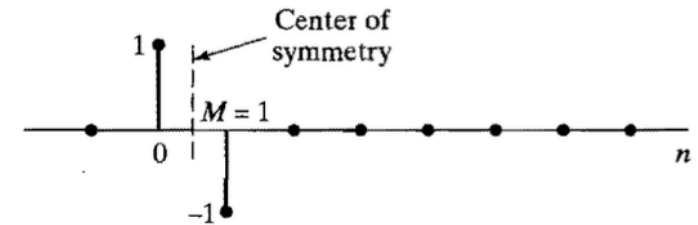
$$H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Odd}} e^{-j\omega M/2 + j\pi/2}$$

fractional delay

FIR GLP: Type IV – Example, $M=3$

Type IV Odd Symmetry, M Odd

$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (M/2 \text{ not an integer})$$



$$H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Odd}} e^{-j\omega M/2 + j\pi/2}$$

fractional delay

FIR GLP: Type IV – Example, $M=3$

Type IV Odd Symmetry, M Odd

$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (M / 2 \text{ not an integer})$$

$$H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Odd}} e^{-j\omega M/2 + j\pi/2}$$

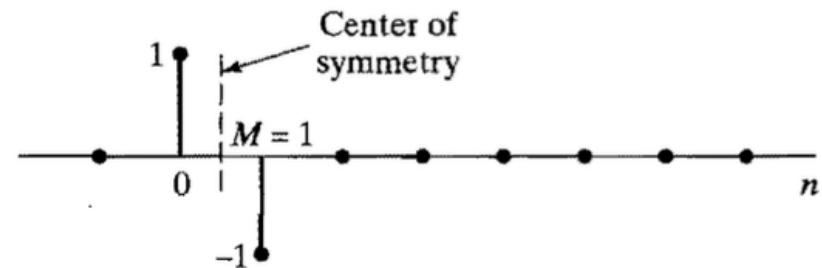
fractional delay

$$H(e^{j\omega}) = \underbrace{[2h[0]\sin(3\omega / 2) + 2h[1]\sin(\omega / 2)]}_{A(\omega)} j e^{-j3\omega/2}$$

FIR GLP: Type IV

Type IV Odd Symmetry, M Odd

$$h[n] = -h[M - n], \quad n = 0, 1, \dots, M \quad (M / 2 \text{ not an integer})$$



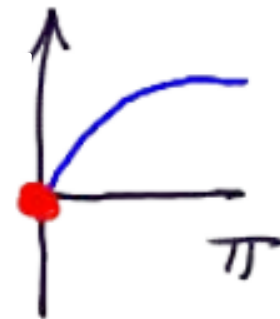
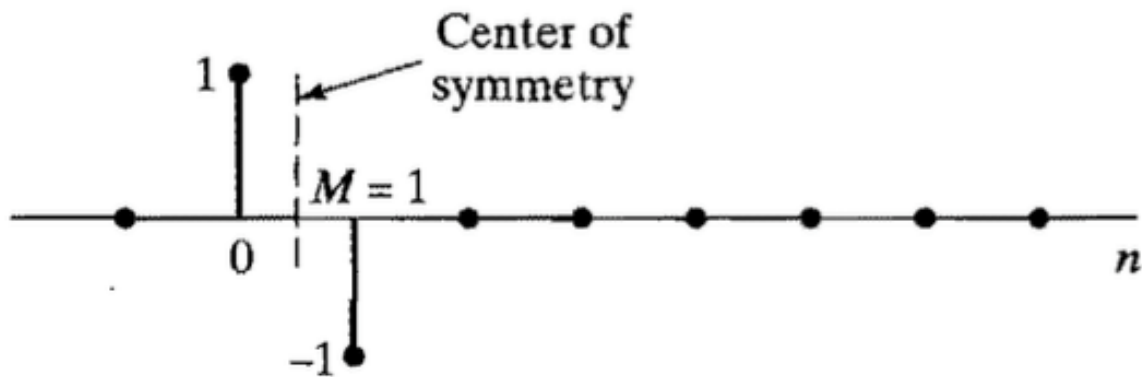
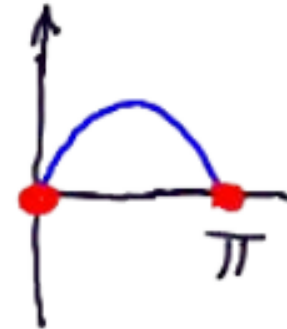
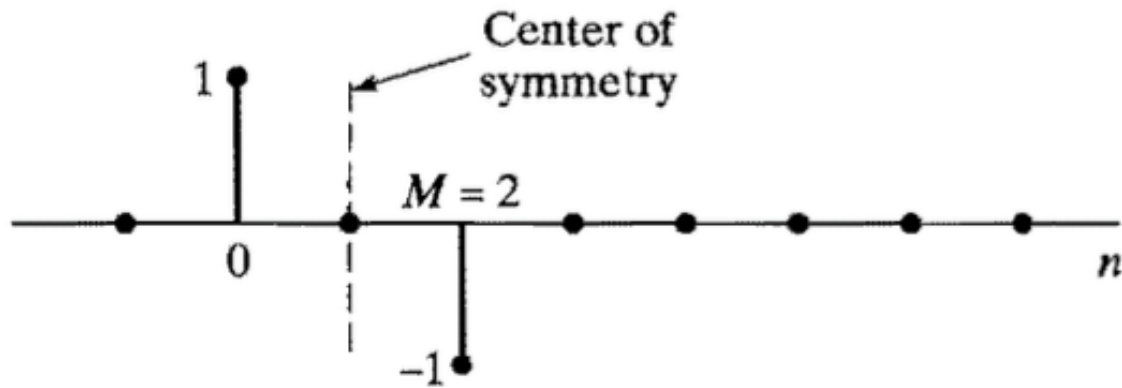
$$H(e^{j\omega}) = \sum_{n=0}^M h[n] e^{-j\omega n} = \underbrace{A(\omega)}_{\text{Real, Odd}} e^{-j\omega M/2 + j\pi/2}$$

fractional delay

$$H(e^{j\omega}) = j e^{-j\omega M/2} \left[\sum_{k=1}^{(M+1)/2} d[k] \sin \left[\omega \left(k - \frac{1}{2} \right) \right] \right]$$

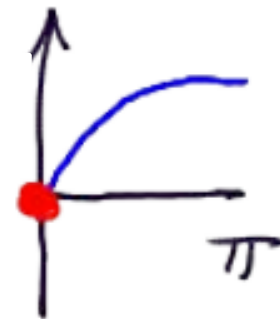
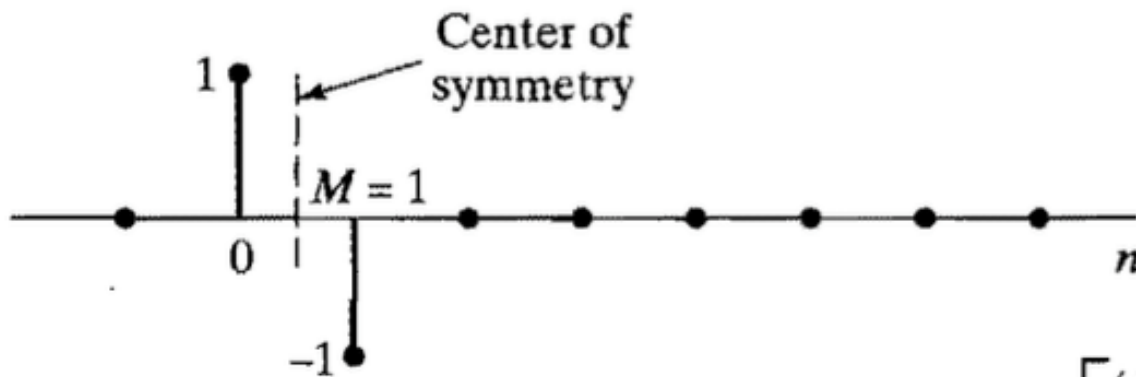
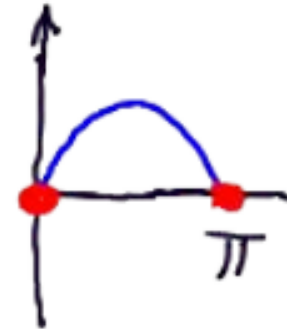
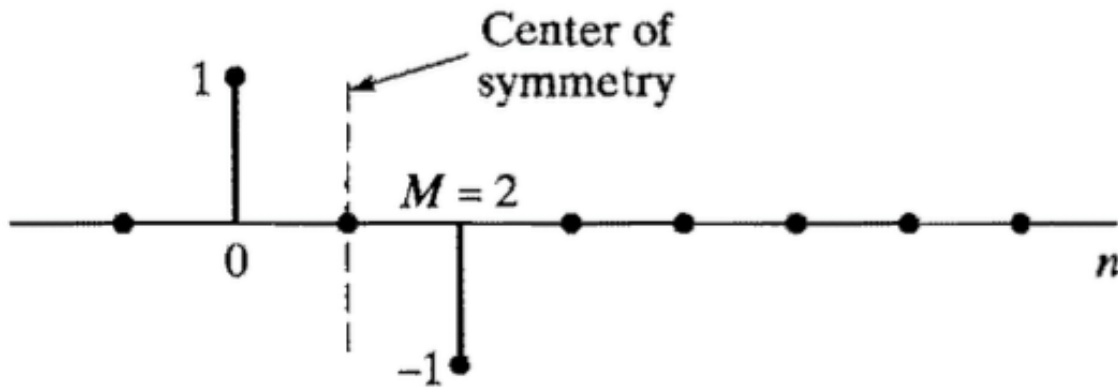
$$d[k] = 2h[(M+1)/2 - k], \quad k = 1, 2, \dots, (M+1)/2.$$

FIR GLP: Type III and IV



FIR GLP: Type III

$$H(e^{j\omega}) = je^{-j\omega M/2} \left[\sum_{k=1}^{M/2} c[k] \sin \omega k \right]$$



$$H(e^{j\omega}) = je^{-j\omega M/2} \left[\sum_{k=1}^{(M+1)/2} d[k] \sin \left[\omega \left(k - \frac{1}{2} \right) \right] \right]$$



Zeros of GLP System – Type I and II

□ FIR GLP System Function

$$H(z) = \sum_{n=0}^M h[n]z^{-n}$$

Zeros of GLP System – Type I and II

□ FIR GLP System Function

$$H(z) = \sum_{n=0}^M h[n]z^{-n}$$

$$\begin{aligned} H(z) &= \sum_{n=0}^M h[M-n]z^{-n} = \sum_{k=M}^0 h[k]z^k z^{-M} \\ &= z^{-M} H(z^{-1}). \end{aligned}$$

If z_0 is a zero then z_0^{-1} is also a zero.



Zeros of GLP System – Type I and II

- FIR GLP System Function

$$H(z) = \sum_{n=0}^M h[n]z^{-n}$$

- If $h[n]$ is real,

Zeros of GLP System – Type I and II

□ FIR GLP System Function

$$H(z) = \sum_{n=0}^M h[n]z^{-n}$$

If z_0 is a zero then z_0^{-1} is also a zero.

□ If $h[n]$ is real,

If z_0 is a zero then z_0^* is also a zero.

Zeros of GLP System – Type I and II

□ FIR GLP System Function

$$H(z) = \sum_{n=0}^M h[n]z^{-n}$$

Real system → zeros occur in conjugate-reciprocal groups of 4

$$(1 - \underbrace{re^{j\theta} z^{-1}}_{z_0})(1 - \underbrace{re^{-j\theta} z^{-1}}_{(z_0)^*})(1 - \underbrace{r^{-1}e^{j\theta} z^{-1}}_{(z_0^{-1})^*})(1 - \underbrace{r^{-1}e^{-j\theta} z^{-1}}_{z_0^{-1}})$$

Zeros of GLP System – Type I and II

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□ If zero is on unit circle ($r=1$)

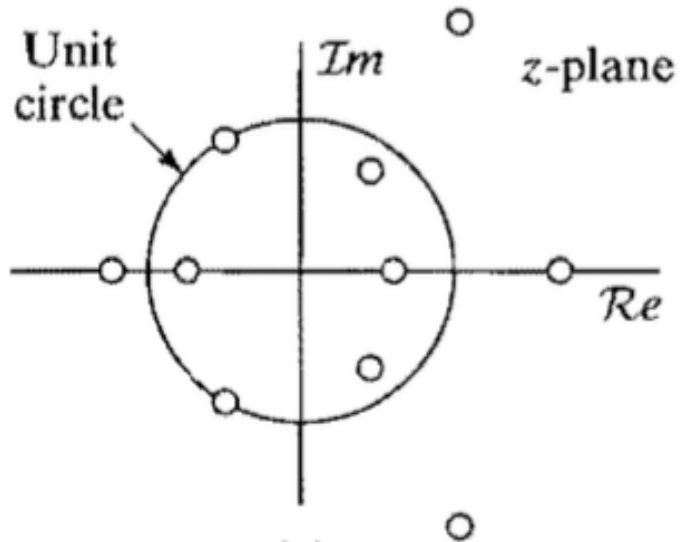
$$(1 - e^{j\theta}z^{-1})(1 - e^{-j\theta}z^{-1}).$$

□ If zero is real and not on unit circle ($\theta=0$)

$$(1 \pm rz^{-1})(1 \pm r^{-1}z^{-1}).$$

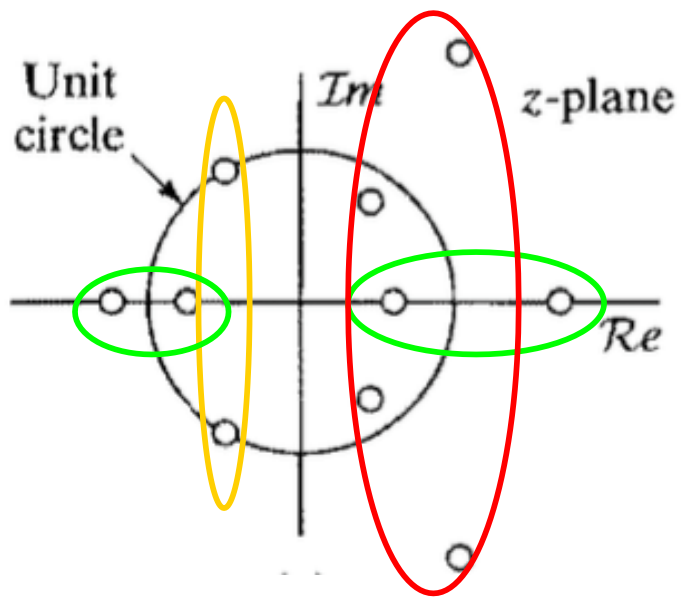
Zeros of GLP System – Type I

Type I



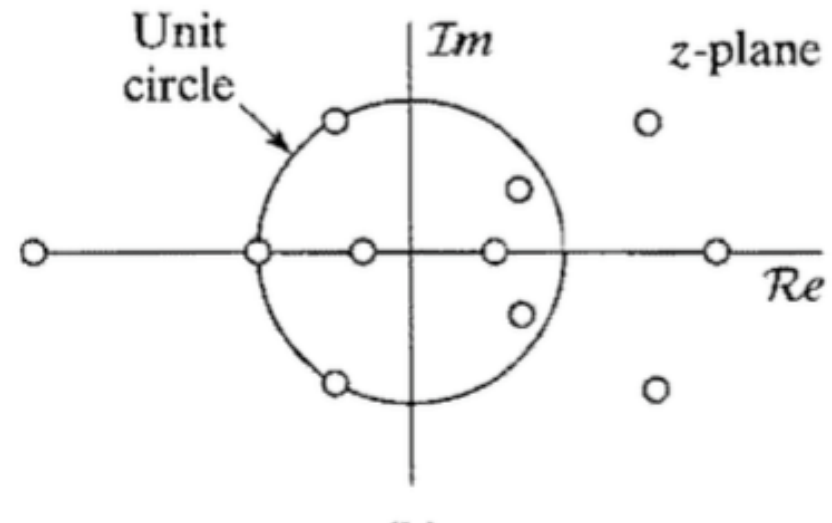
Zeros of GLP System – Type I

Type I



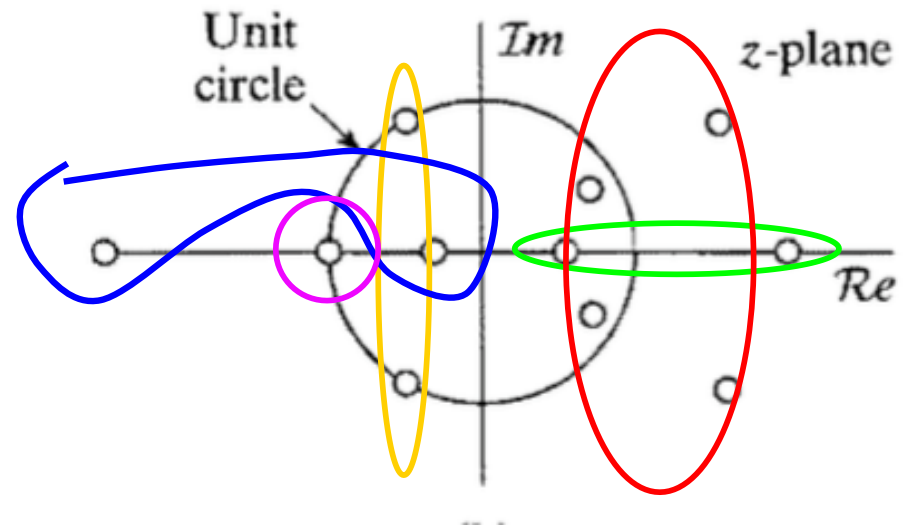
Zeros of GLP System – Type II

Type II



Zeros of GLP System – Type II

Type II



Zeros of GLP System – Type II

□ FIR GLP System Function

$$\begin{aligned} H(z) &= \sum_{n=0}^M h[M-n]z^{-n} = \sum_{k=M}^0 h[k]z^k z^{-M} \\ &= z^{-M} H(z^{-1}). \end{aligned}$$

Consider $z = -1$:

Zeros of GLP System – Type II

□ FIR GLP System Function

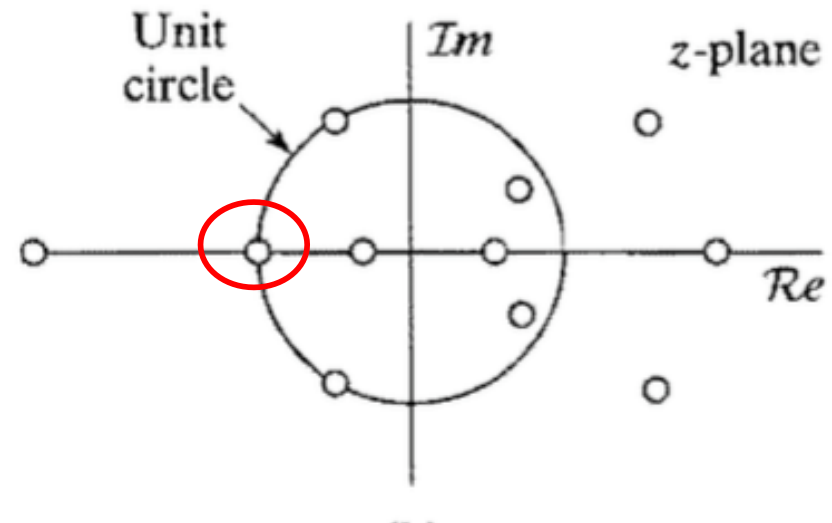
$$\begin{aligned} H(z) &= \sum_{n=0}^M h[M-n]z^{-n} = \sum_{k=M}^0 h[k]z^k z^{-M} \\ &= z^{-M} H(z^{-1}). \end{aligned}$$

Consider $z = -1$: $H(-1) = (-1)^{-M} H(-1)$

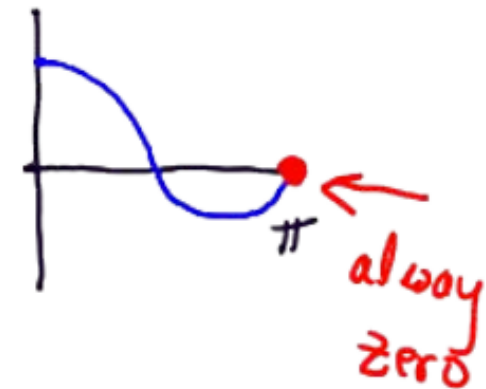
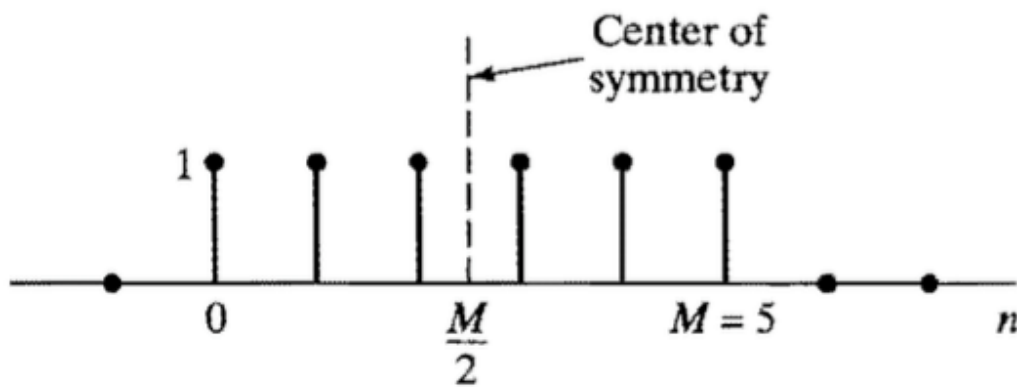
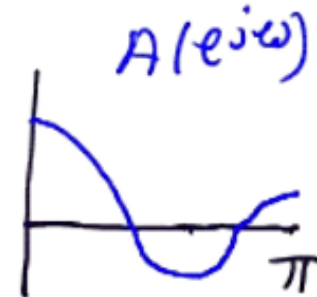
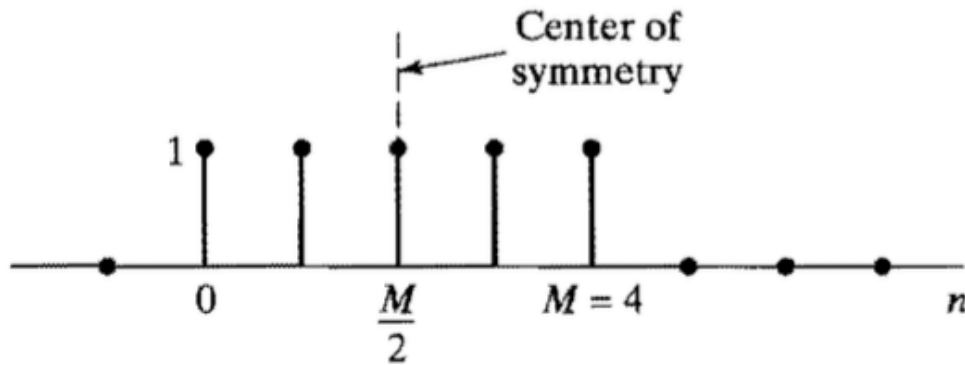
$\Rightarrow$ for M odd, $z = -1$ must be a zero (Type II)

Zeros of GLP System – Type II

Type II



FIR GLP: Type I and II





Zeros of GLP System – Type III and IV

□ FIR GLP System Function

$$H(z) = \sum_{n=0}^M h[n]z^{-n}$$

Zeros of GLP System – Type III and IV

□ FIR GLP System Function

$$H(z) = \sum_{n=0}^M h[n]z^{-n}$$

$$H(z) = -z^{-M} H(z^{-1}).$$

Zeros of GLP System – Type III and IV

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$$H(z) = -z^{-M} H(z^{-1}).$$

If z_0 is a zero then z_0^{-1} is also a zero.

Zeros of GLP System – Type III and IV

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$$H(z) = \sum_{n=0}^M h[n]z^{-n}$$

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$$(1 - re^{j\theta}z^{-1})(1 - re^{-j\theta}z^{-1})(1 - r^{-1}e^{j\theta}z^{-1})(1 - r^{-1}e^{-j\theta}z^{-1})$$

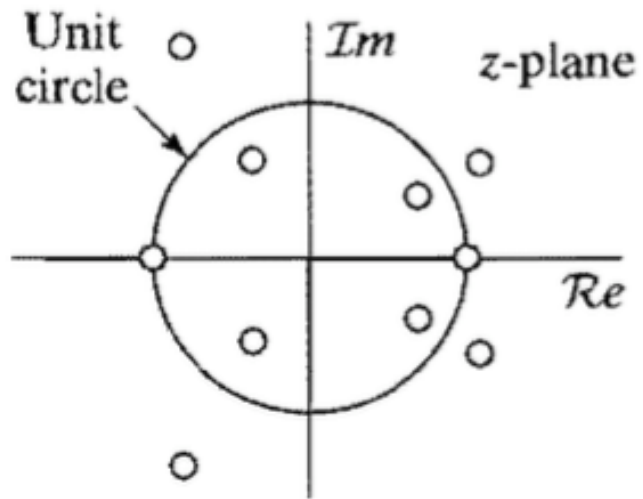
□ If zero is on unit circle ($r=1$)

$$(1 - e^{j\theta}z^{-1})(1 - e^{-j\theta}z^{-1}).$$

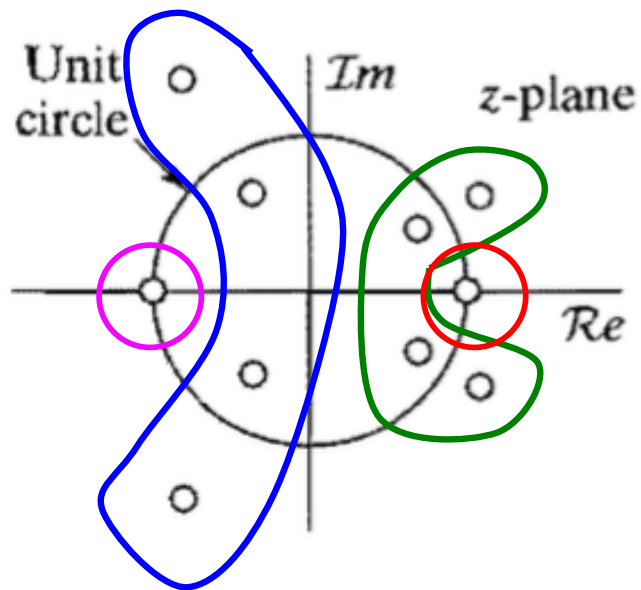
□ If zero is real and not on unit circle ($\theta=0$)

$$(1 \pm rz^{-1})(1 \pm r^{-1}z^{-1}).$$

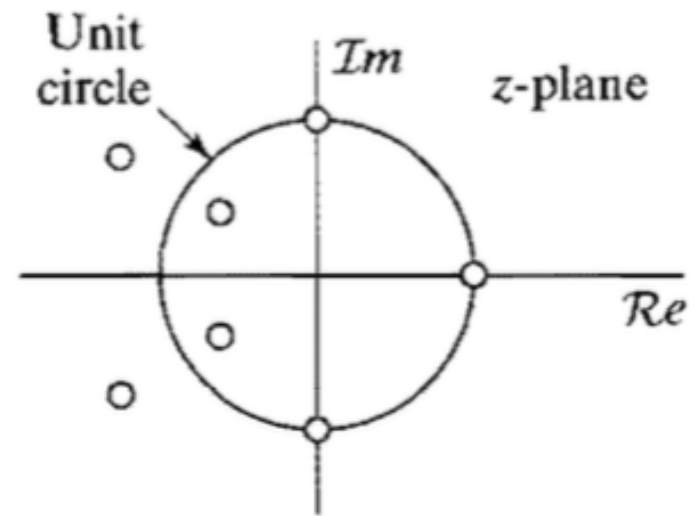
Zeros of GLP System – Type III



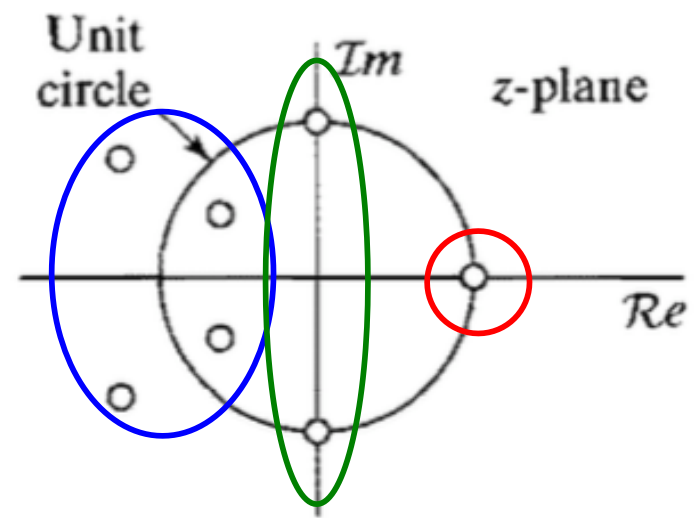
Zeros of GLP System – Type III



Zeros of GLP System – Type IV

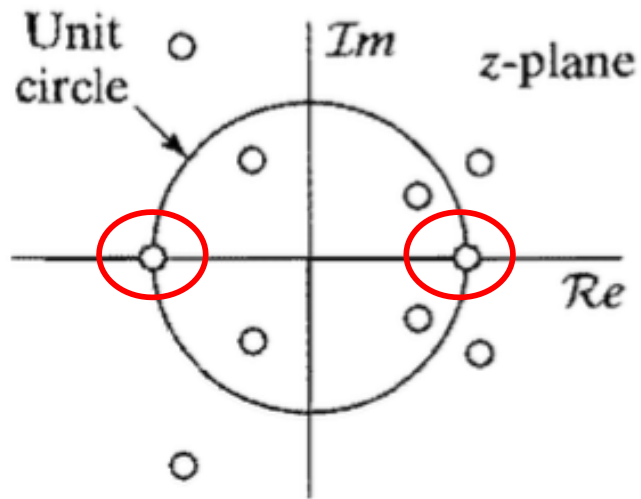


Zeros of GLP System – Type IV

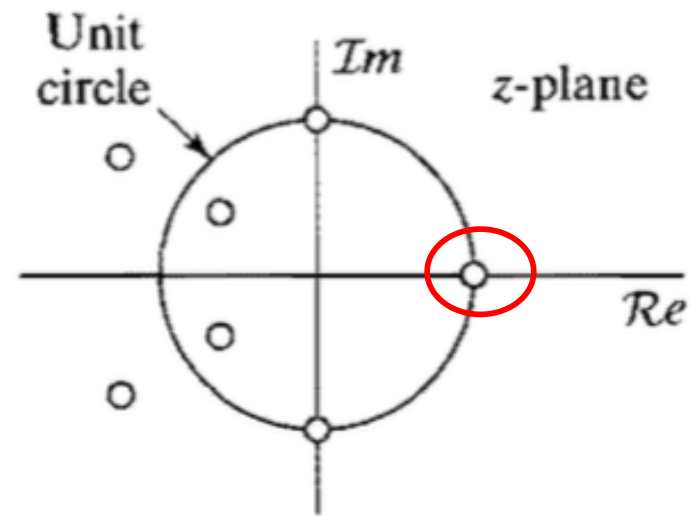


Zeros of GLP System – Type III and IV

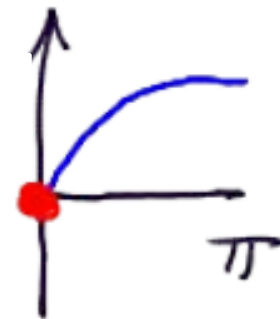
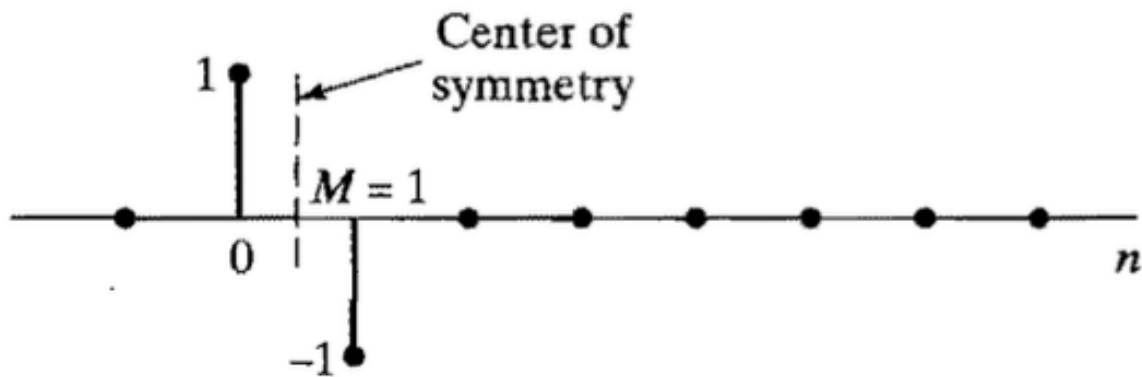
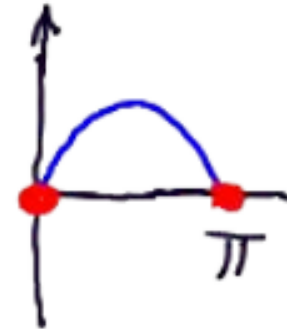
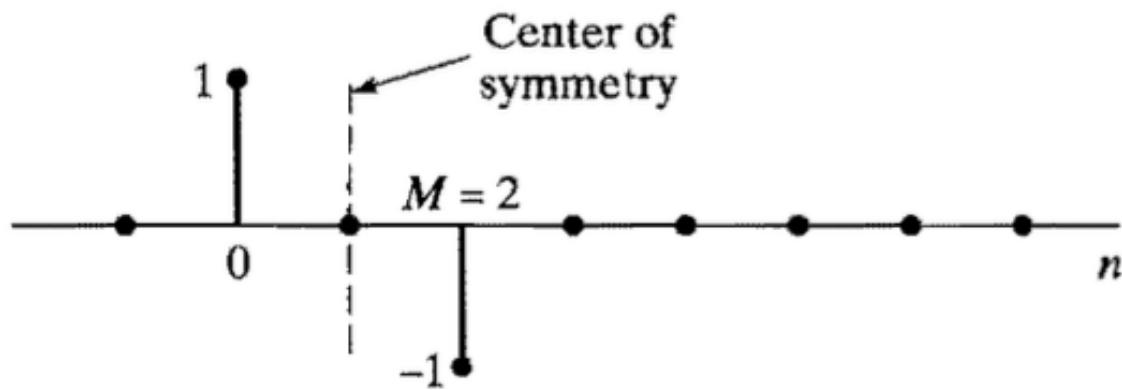
Type III



Type IV



FIR GLP: Type III and IV





GLP and Min Phase Systems

- Any FIR linear-phase system can be decomposed into:

$$H(z) = H_{\min}(z)H_{uc}(z)H_{\max}(z)$$

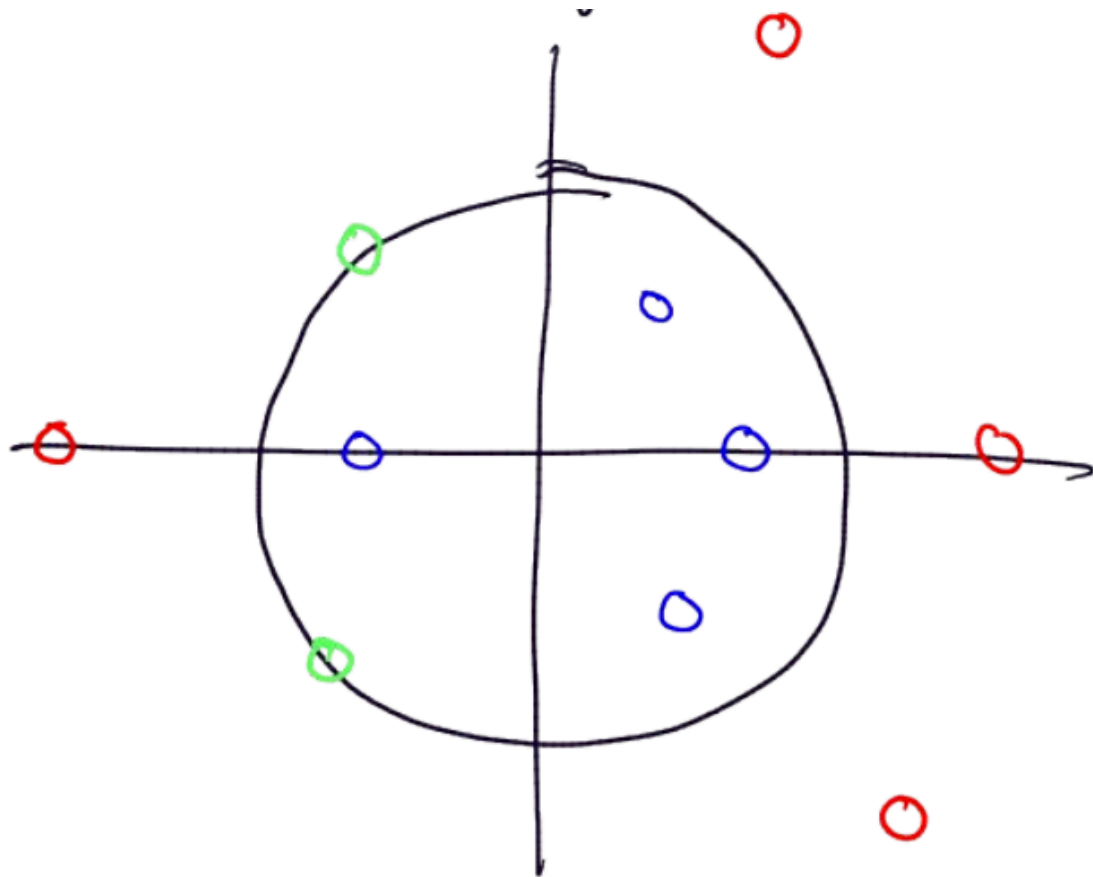
- A min phase system, system containing only zeros on unit circle, and max phase system

GLP and Min Phase Systems

- Any FIR linear-phase system can be decomposed into:

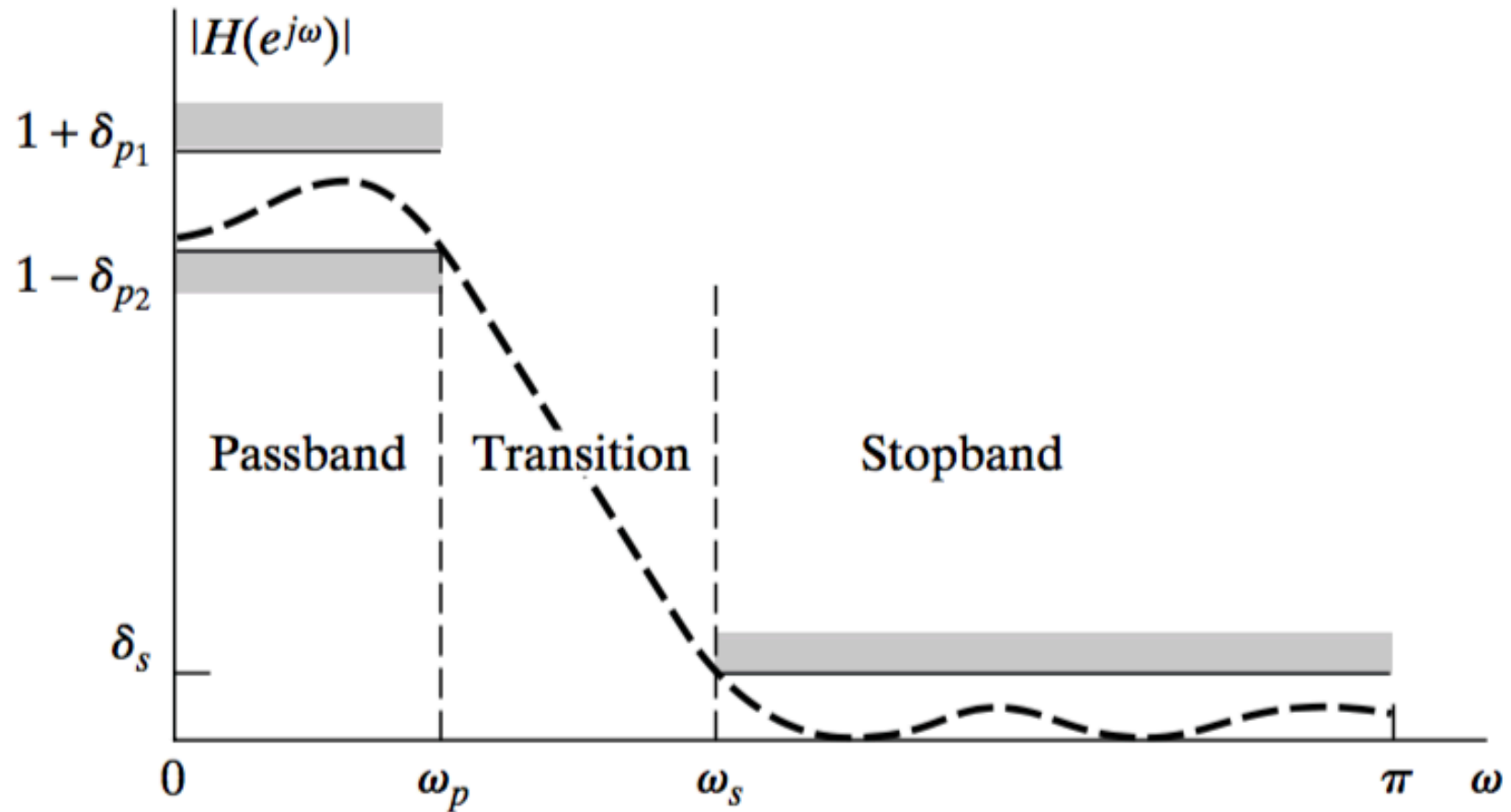
$$H(z) =$$

- A min phase system with all poles inside the unit circle, and zeros on unit circle, and





Filter Specifications

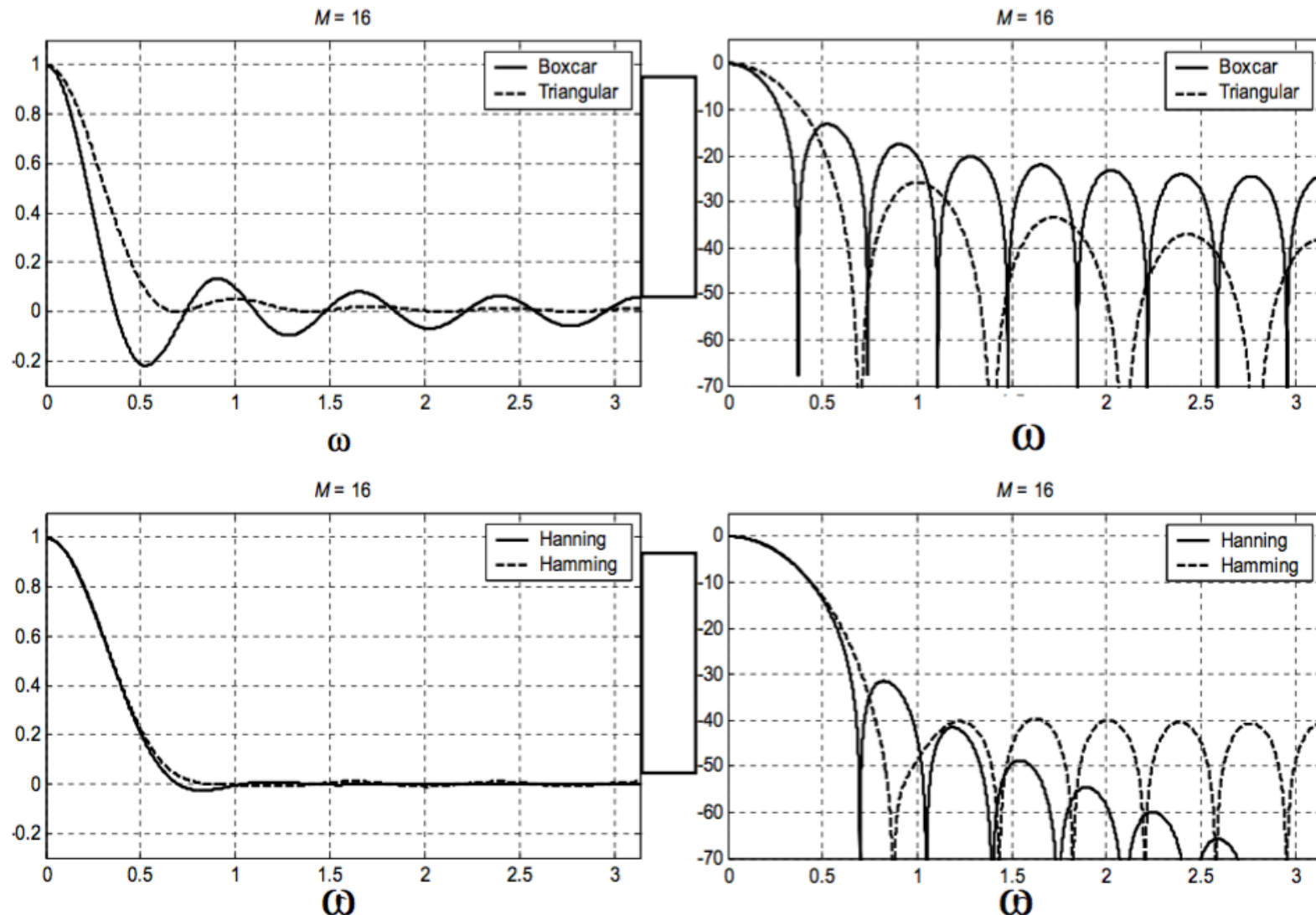




Tapered Windows

Name(s)	Definition	MATLAB Command	Graph ($M = 8$)
Hann	$w[n] = \begin{cases} \frac{1}{2} \left[1 + \cos\left(\frac{\pi n}{M/2}\right) \right] & n \leq M/2 \\ 0 & n > M/2 \end{cases}$	<code>hann(M+1)</code>	hann(M+1), M = 8
Hanning	$w[n] = \begin{cases} \frac{1}{2} \left[1 + \cos\left(\frac{\pi n}{M/2 + 1}\right) \right] & n \leq M/2 \\ 0 & n > M/2 \end{cases}$	<code>hanning(M+1)</code>	hanning(M+1), M = 8
Hamming	$w[n] = \begin{cases} 0.54 + 0.46 \cos\left(\frac{\pi n}{M/2}\right) & n \leq M/2 \\ 0 & n > M/2 \end{cases}$	<code>hamming(M+1)</code>	hamming(M+1), M = 8

Tradeoff – Ripple vs. Transition Width





Big Ideas

- Generalized Linear Phase Systems
 - Useful for design of causal FIR filters



Admin

- ❑ HW 6 (UPDATED)
 - Due Sunday 3/13
- ❑ All office hours will continue during spring break
- ❑ Midterm
 - Thursday 3/17 in person during class in DRLB A1
 - Covers lectures 1-14
 - Doesn't cover data converters and noise shaping
 - Old exams online
 - Disclaimer: 2020/2021 had different exam coverage
 - Virtual TA Review session Monday 3/14 (π -day!)
 - See Piazza for more information coming
 - Closed book/notes
 - Can bring 1 8"x11" cheat sheet and non-cell phone calculator