ESE 531: Digital Signal Processing

Lec 14: February 28th, 2017

All-Pass Systems and Min Phase Decomposition

Penn ESE 531 Spring 2017 – Khanna
Adapted from M. Lustig, EECS Berkeley

Lecture Outline

- Frequency Response of LTI Systems
  - Magnitude Response, Phase Response, Group Delay
  - Examples:
    - Zero on Real Axis
    - 2^{nd} order IIR
    - 3^{rd} order Low Pass
- Stability and Causality
- All Pass Systems
- Minimum Phase Systems

Frequency Response of LTI System

$$Y\left(e^{j\omega}\right) = H\left(e^{j\omega}\right) X\left(e^{j\omega}\right)$$

- We can define a magnitude response

$$\left|Y\left(e^{j\omega}\right)\right| = \left|H\left(e^{j\omega}\right)\right|\left|X\left(e^{j\omega}\right)\right|$$

- And a phase response

$$\angle Y\left(e^{j\omega}\right) = \angle H\left(e^{j\omega}\right) + \angle X\left(e^{j\omega}\right)$$

Group Delay

- General phase response at a given frequency can be characterized with group delay, which is related to phase

$$\mathrm{grd}[H(e^{j\omega})] = -\frac{d}{d\omega}\{\arg[H(e^{j\omega})]\}$$

- More later…

Linear Difference Equations

$$\sum_{k=0}^{N} a_k y[n-k] = \sum_{k=0}^{M} b_k x[n-k]$$

Example: $y[n] = x[n] + 0.1y[n-1]$

$$H(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_M z^{-M}}{a_0 + a_1 z^{-1} + \ldots + a_N z^{-N}} = \frac{b_0}{a_0} \frac{\prod_{k=1}^{M}(1 - c_k z^{-1})}{\prod_{k=1}^{N}(1 - d_k z^{-1})}$$

Group Delay Math

$$H(z) = \frac{b_0}{a_0} \frac{\prod_{k=1}^{M} (1 - c_k z^{-1})}{\prod_{k=1}^{N} (1 - d_k z^{-1})}$$

$$H(e^{j\omega}) = \frac{b_0}{a_0} \frac{\prod_{k=1}^{M} (1 - c_k e^{-j\omega})}{\prod_{k=1}^{N} (1 - d_k e^{-j\omega})}$$

Group Delay Math

$$H(z) = \frac{b_0}{a_0} \frac{\prod_{k=1}^{M}(1 - c_k z^{-1})}{\prod_{k=1}^{N}(1 - d_k z^{-1})} \qquad H(e^{j\omega}) = \frac{b_0}{a_0} \frac{\prod_{k=1}^{M}(1 - c_k e^{-j\omega})}{\prod_{k=1}^{N}(1 - d_k e^{-j\omega})}$$

arg of products is sum of args

$$\arg[H(e^{j\omega})] = \sum_{k=1}^{M} \arg[1 - c_k e^{-j\omega}] - \sum_{k=1}^{N} \arg[1 - d_k e^{-j\omega}]$$

$$\mathrm{grd}[H(e^{j\omega})] = \sum_{k=1}^{M} \mathrm{grd}[1 - c_k e^{-j\omega}] - \sum_{k=1}^{N} \mathrm{grd}[1 - d_k e^{-j\omega}]$$

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- Look at each factor:

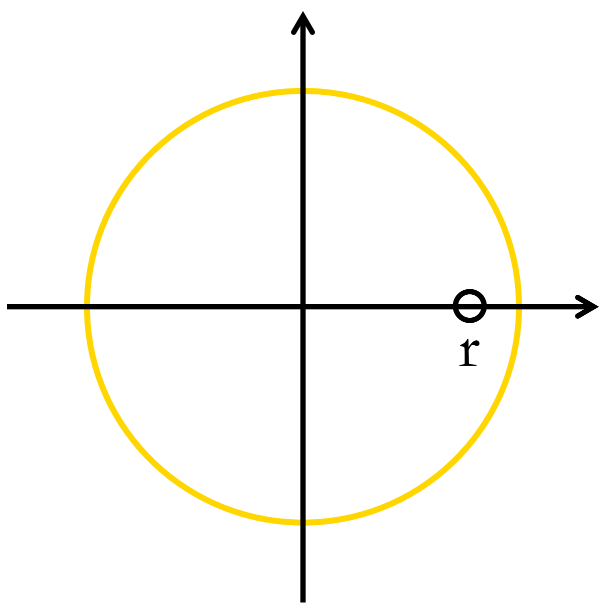
$$\arg[1 - re^{j\theta}e^{-j\omega}] = \tan^{-1}\left(\frac{r\sin(\omega - \theta)}{1 - r\cos(\omega - \theta)}\right)$$

$$\text{grd}[1 - re^{j\theta}e^{-j\omega}] = \frac{r^2 - r\cos(\omega - \theta)}{\left|1 - re^{j\theta}e^{-j\omega}\right|^2}$$

Example: Zero on Real Axis

- Geometric Interpretation for ($\theta = 0$)

$$\arg[1 - re^{-j\omega}]$$



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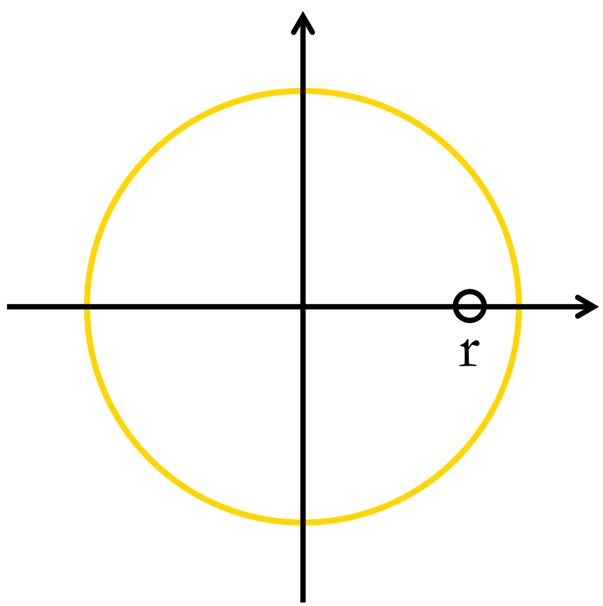
$$\arg[1 - re^{-j\omega}] = \arg[(e^{j\omega} - r)e^{-j\omega}] = \underbrace{\arg[e^{j\omega} - r]}_{\varphi} - \underbrace{\arg[e^{j\omega}]}_{\omega}$$



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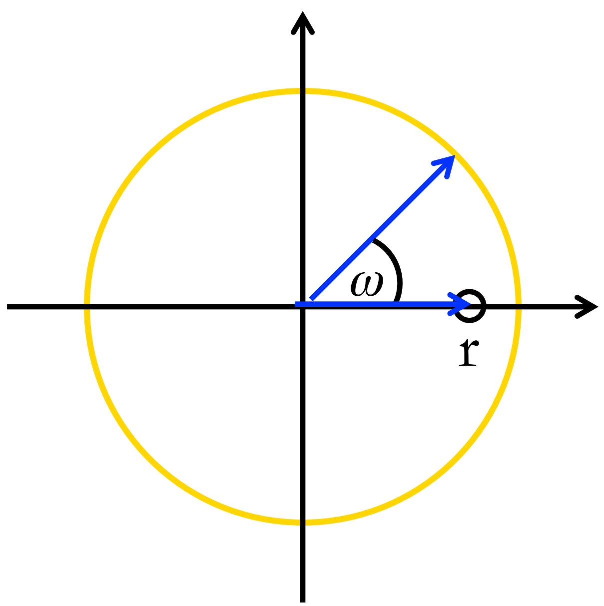

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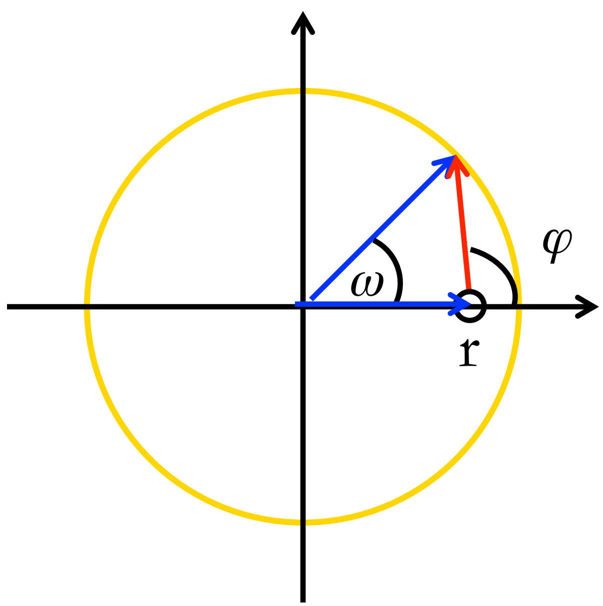

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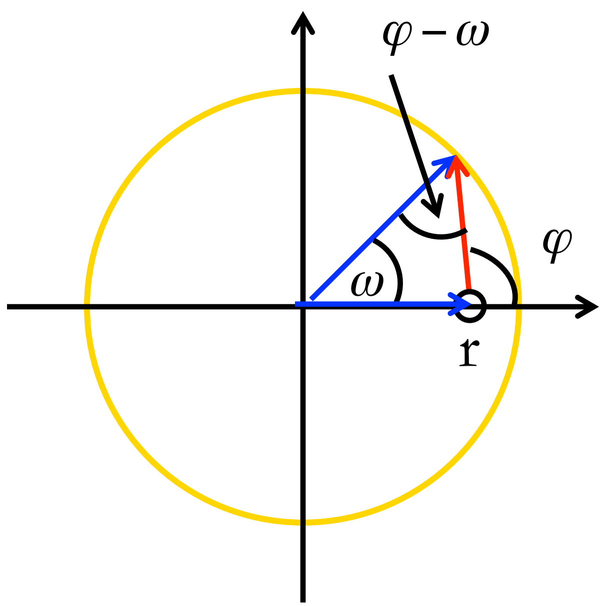

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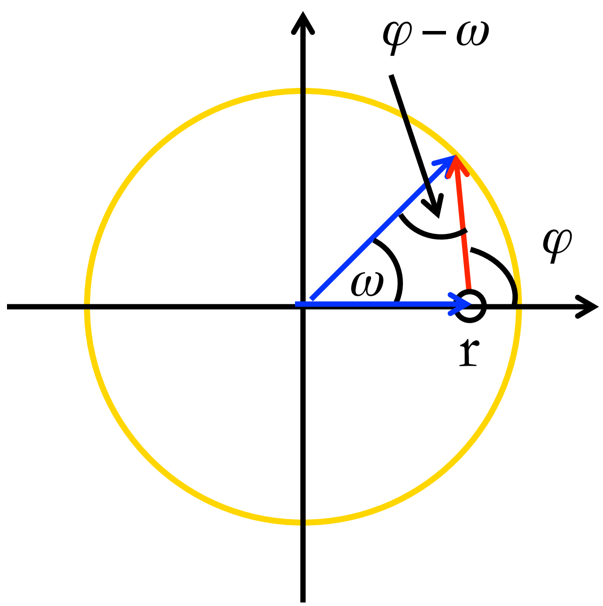

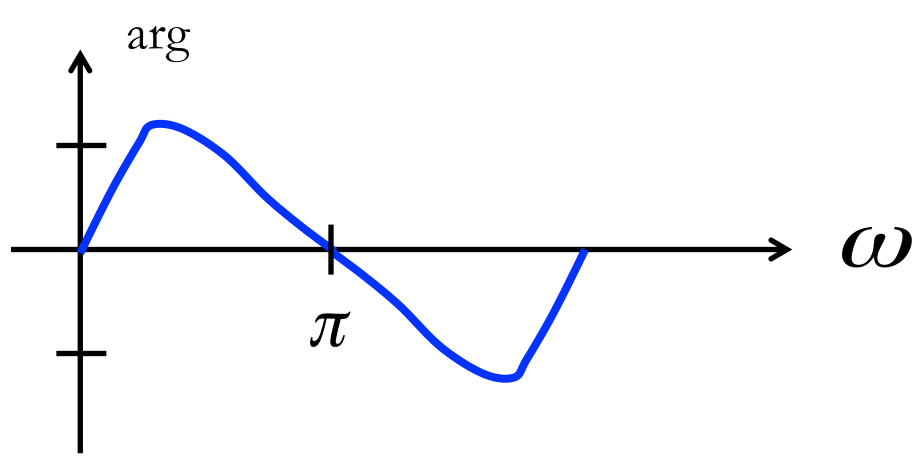

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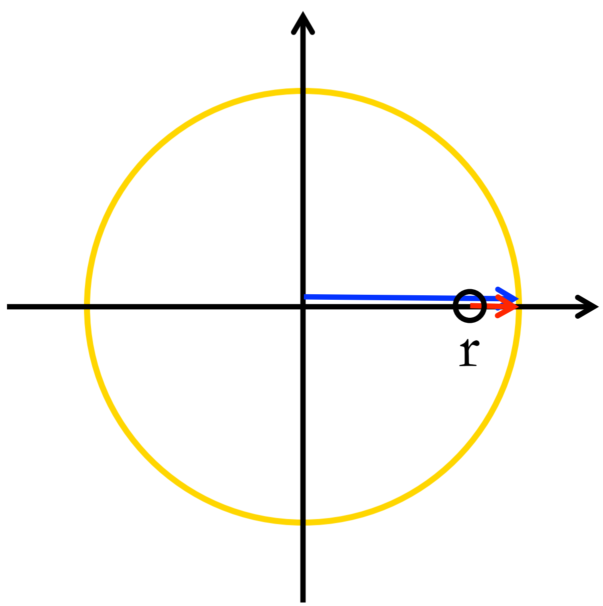
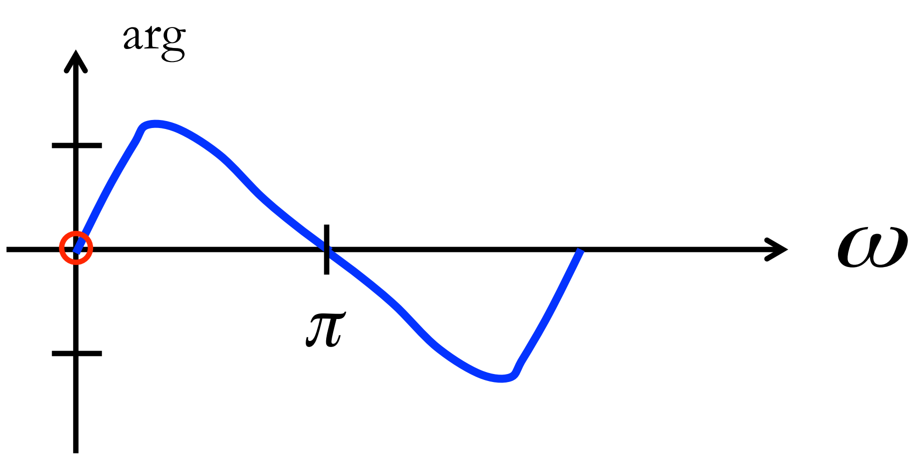
$\omega = 0$





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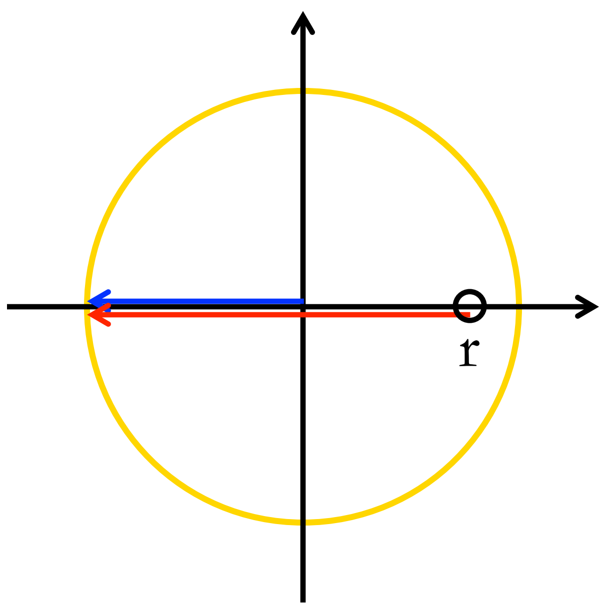
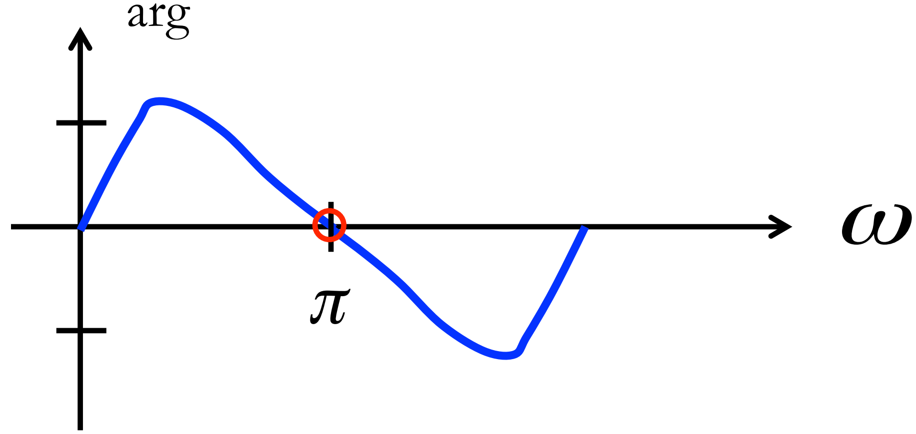
$\omega = \pi$





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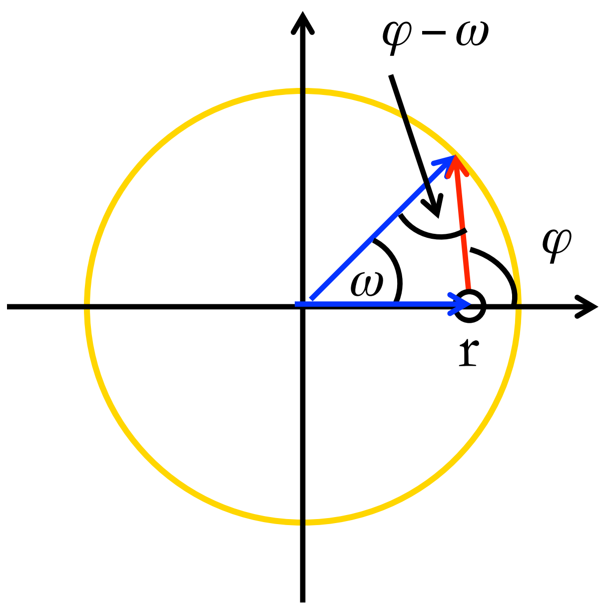

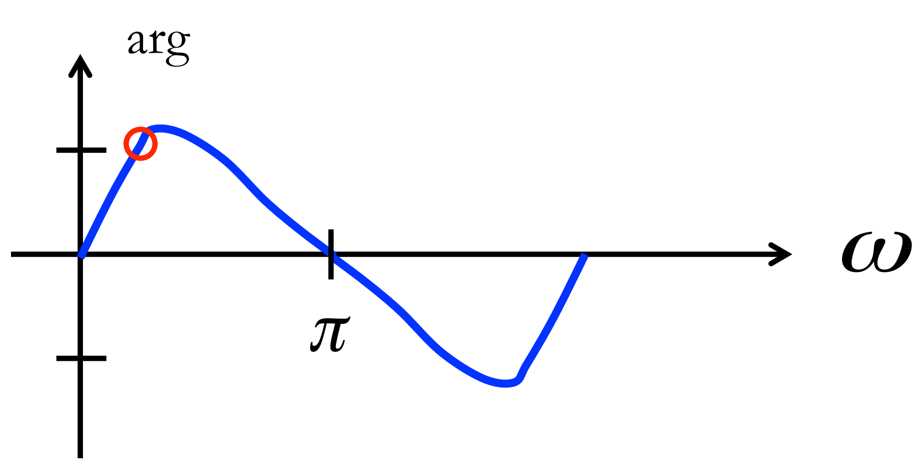

Example: Zero on Real Axis

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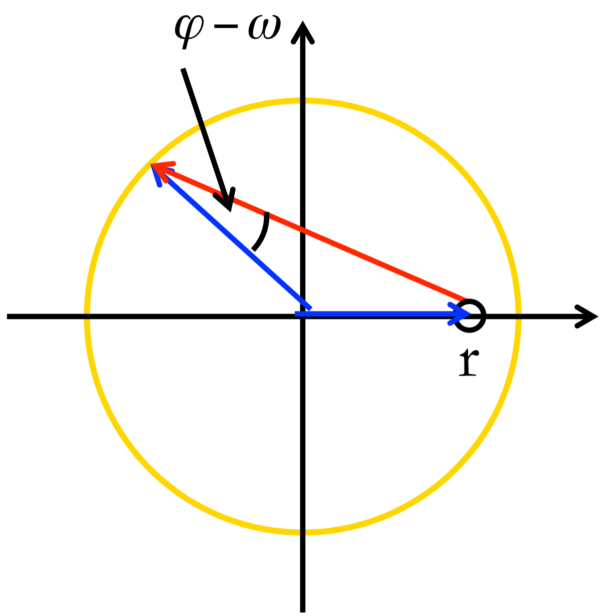

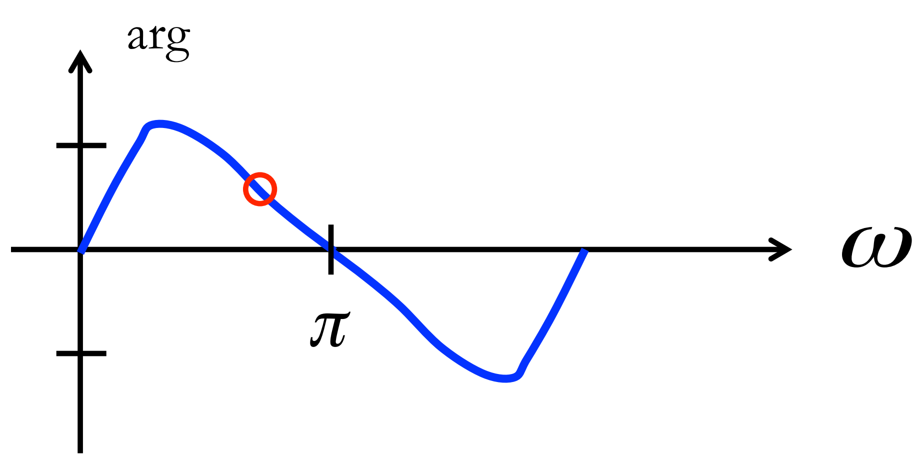

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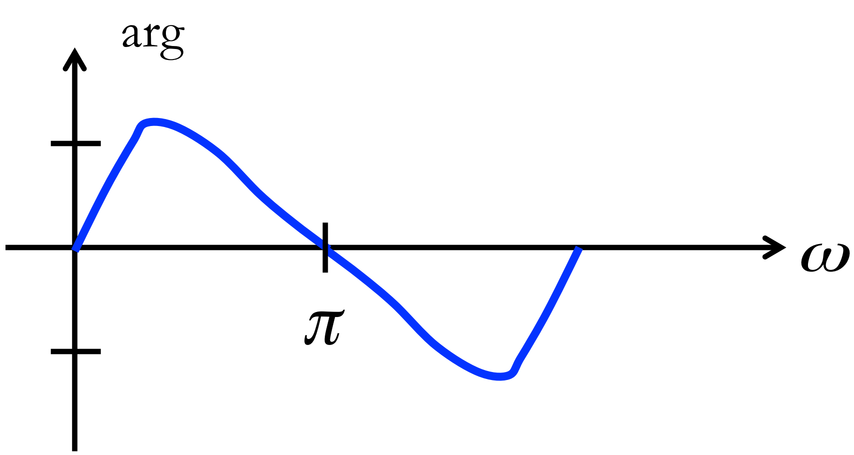

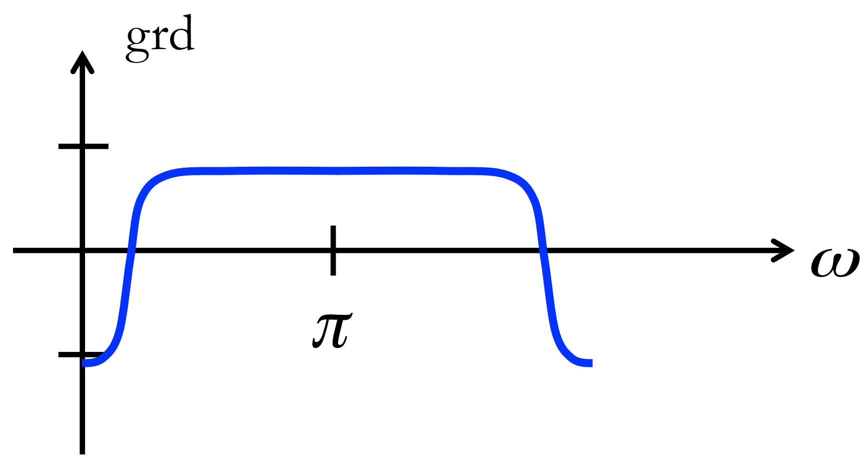

Group Delay Math

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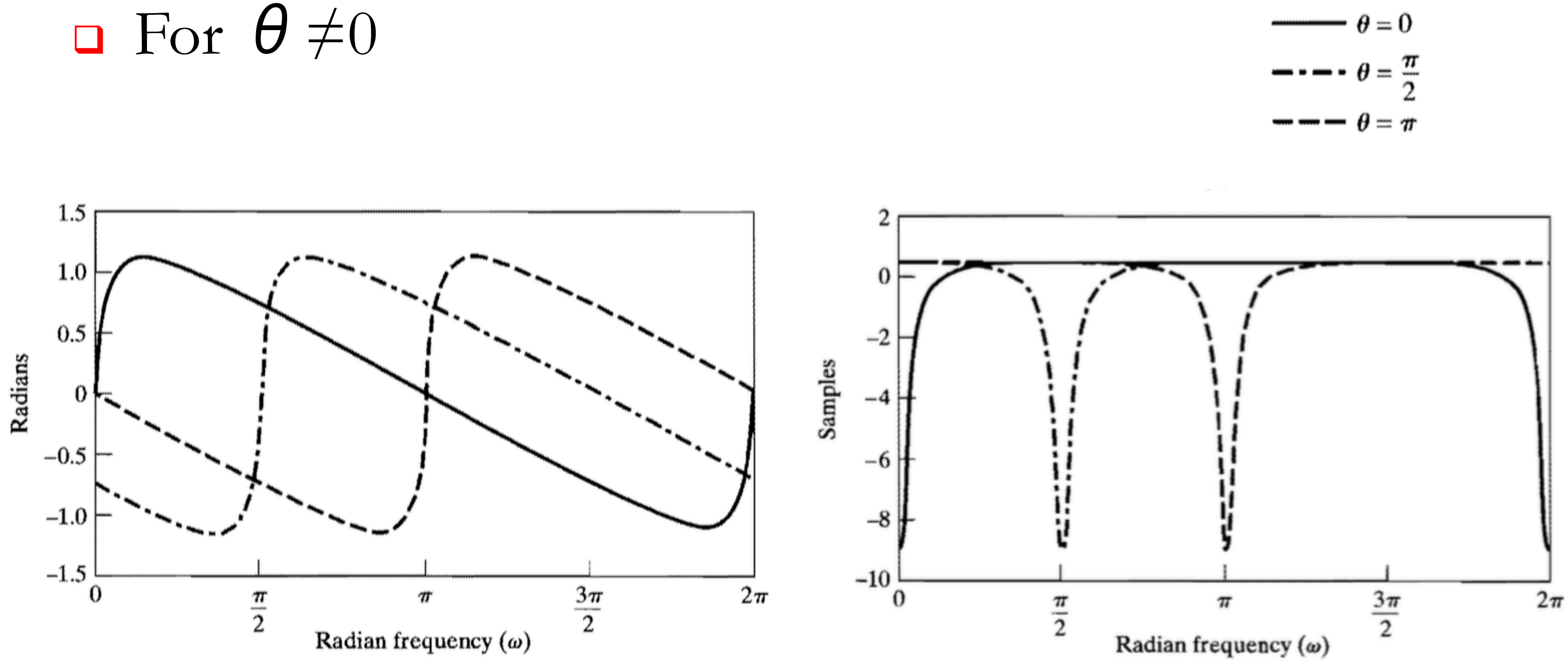
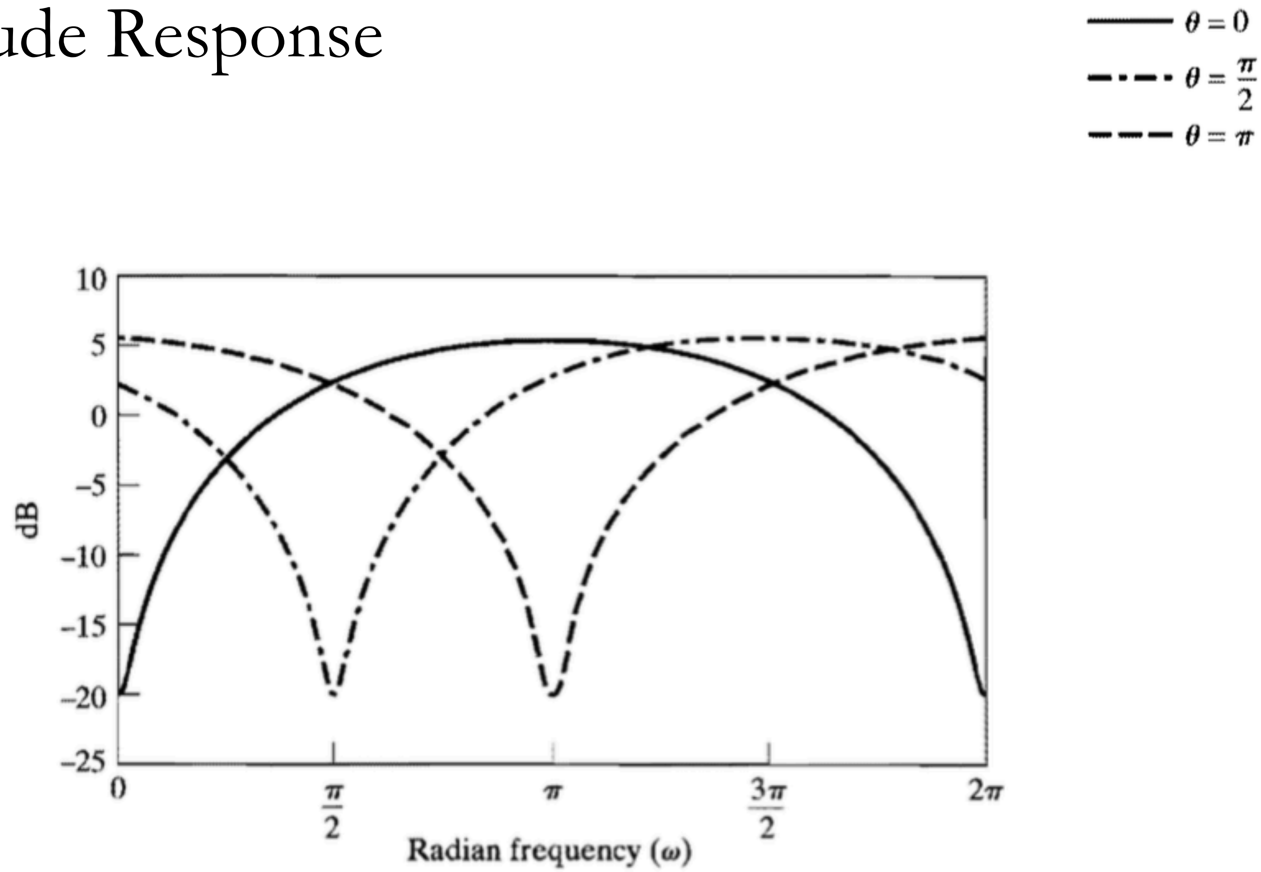
Example: Zero on Real Axis

- For $\theta \neq 0$



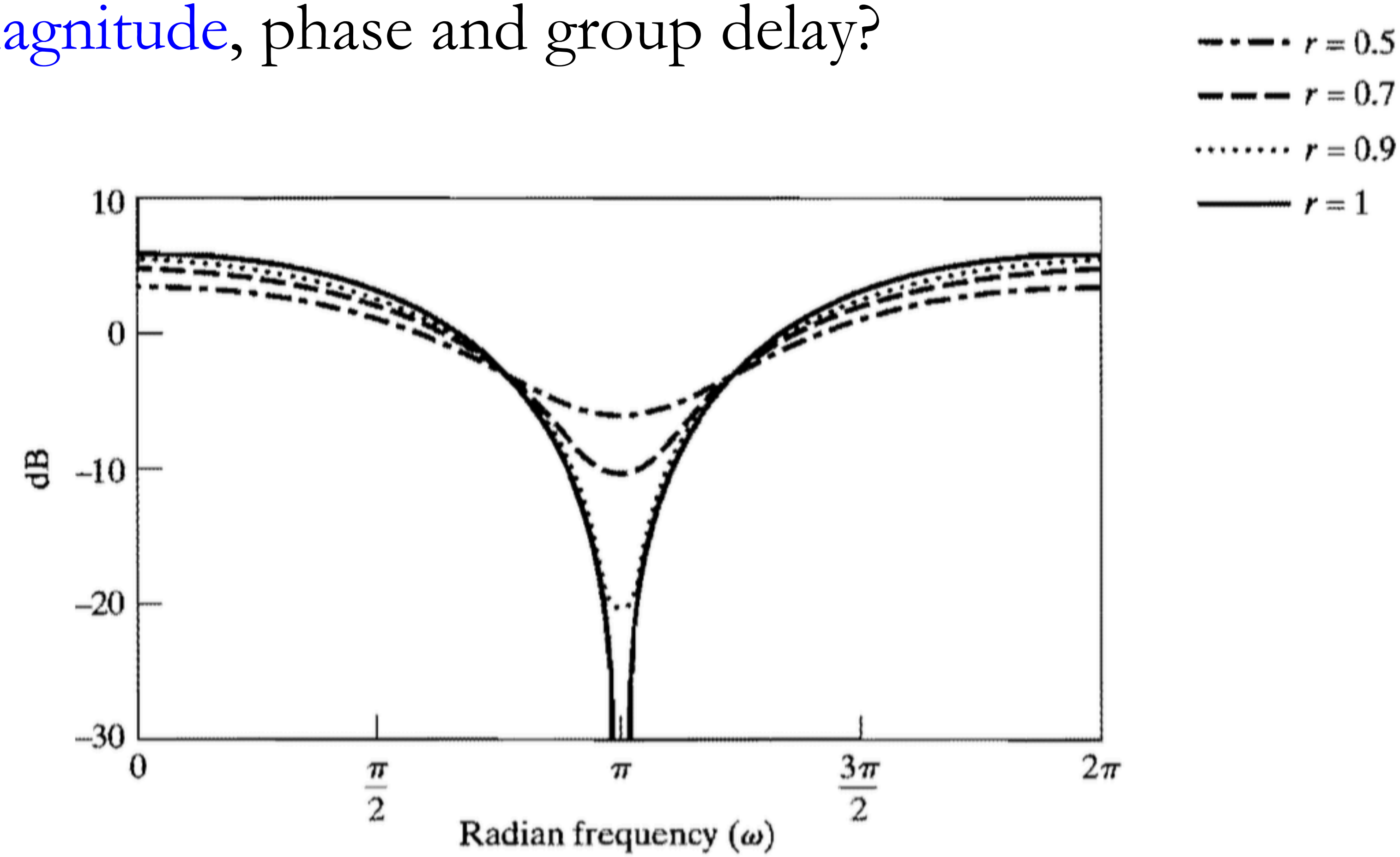
Example: Zero on Real Axis

- Magnitude Response



Example: Zero on Real Axis

- For $\theta = \pi$, how does zero location effect magnitude, phase and group delay?



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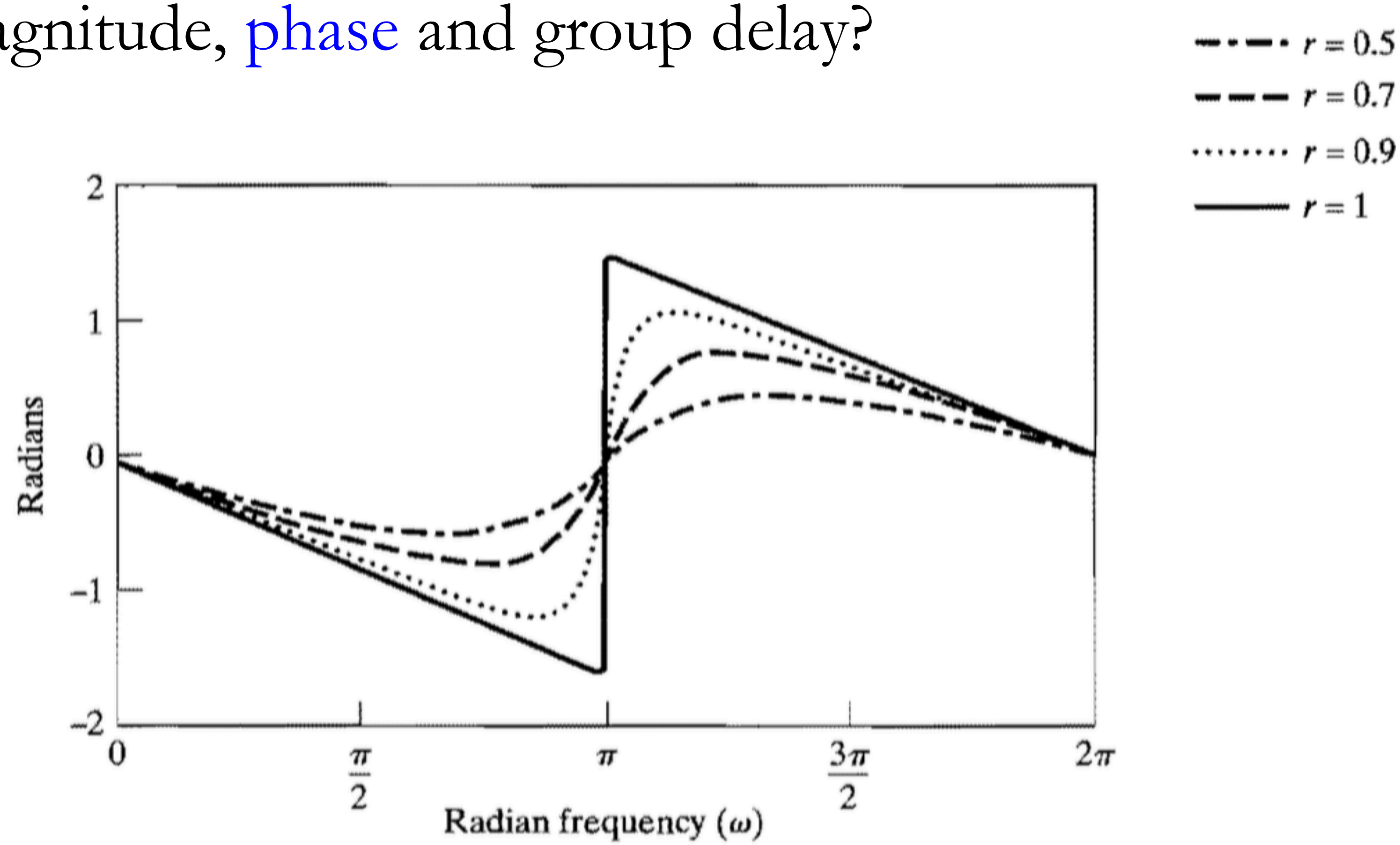

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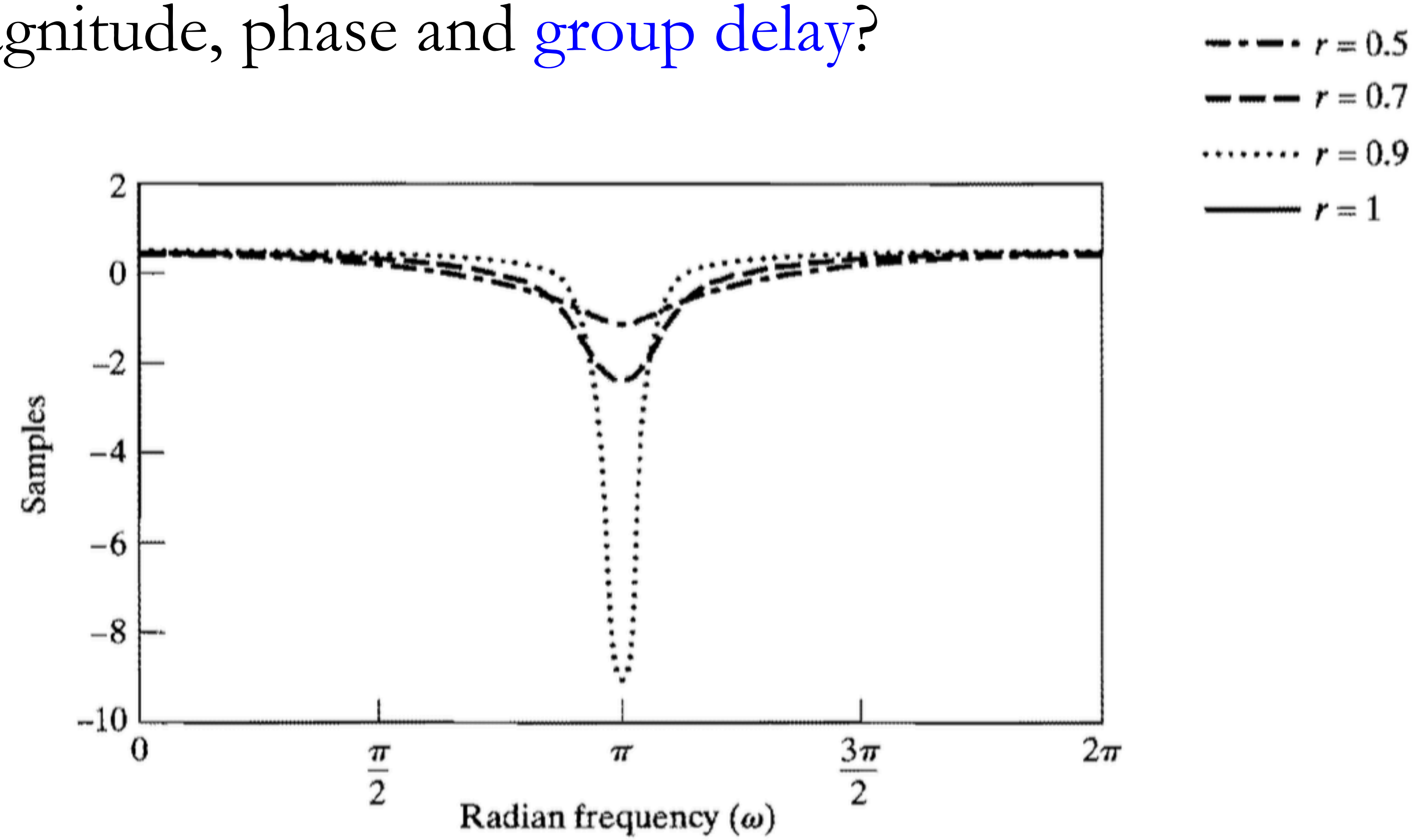
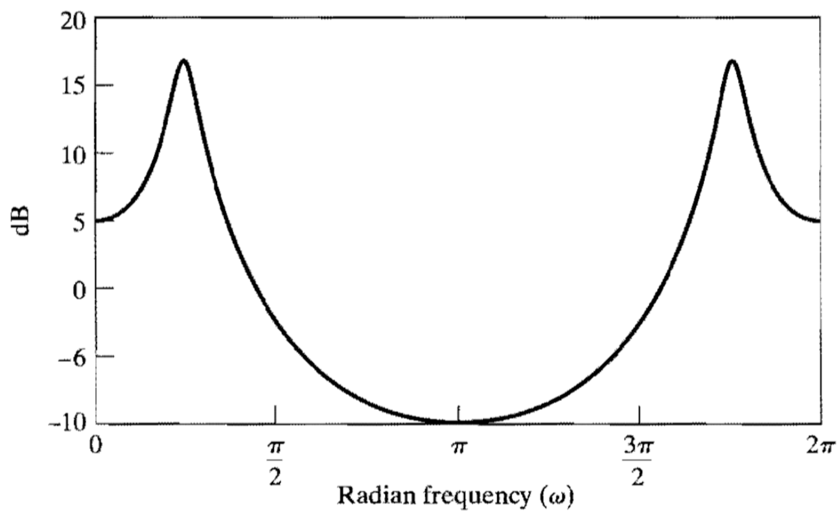


2nd Order IIR with Complex Poles

$$H(z) = \frac{1}{(1 - re^{j\theta}z^{-1})(1 - re^{-j\theta}z^{-1})}$$

$r=0.9,\ \theta = \pi/4$

magnitude



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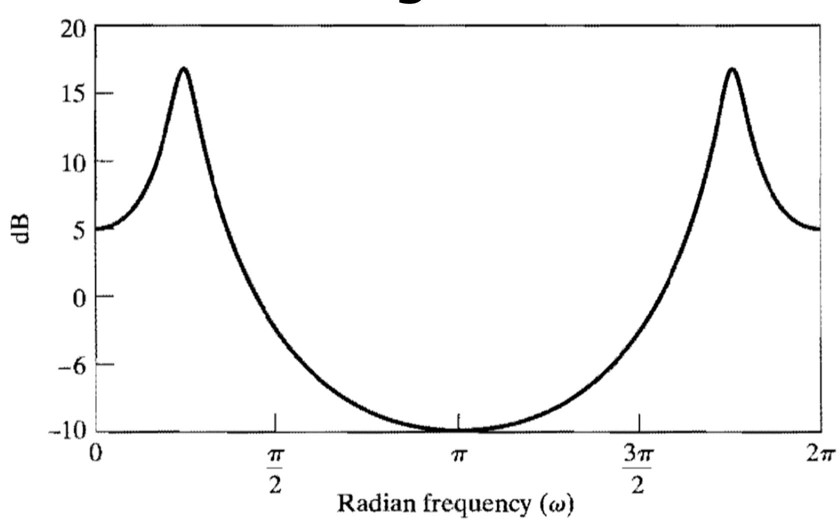
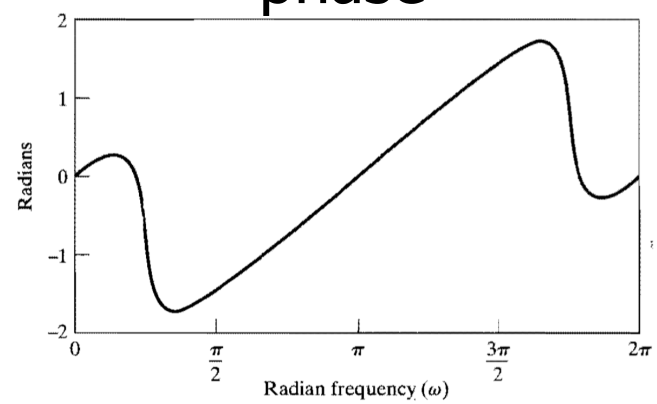
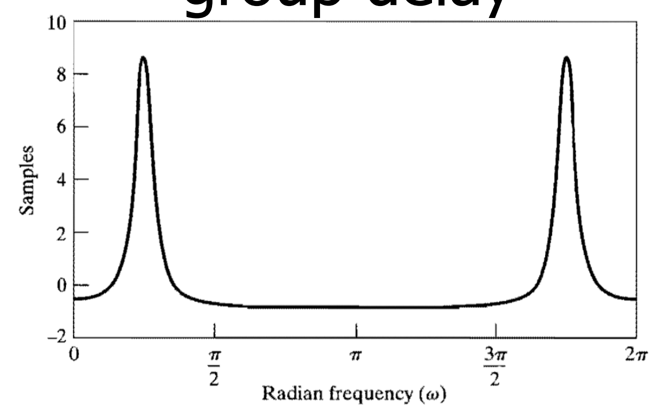


phase

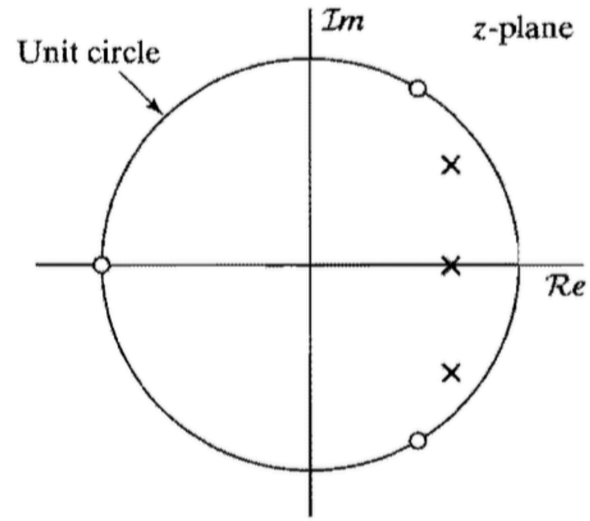


group delay



3rd Order IIR Example

$$H(z) = \frac{0.05634(1 + z^{-1})(1 - 1.0166z^{-1} + z^{-2})}{(1 - 0.683z^{-1})(1 - 1.4461z^{-1} + 0.7957z^{-2})}$$



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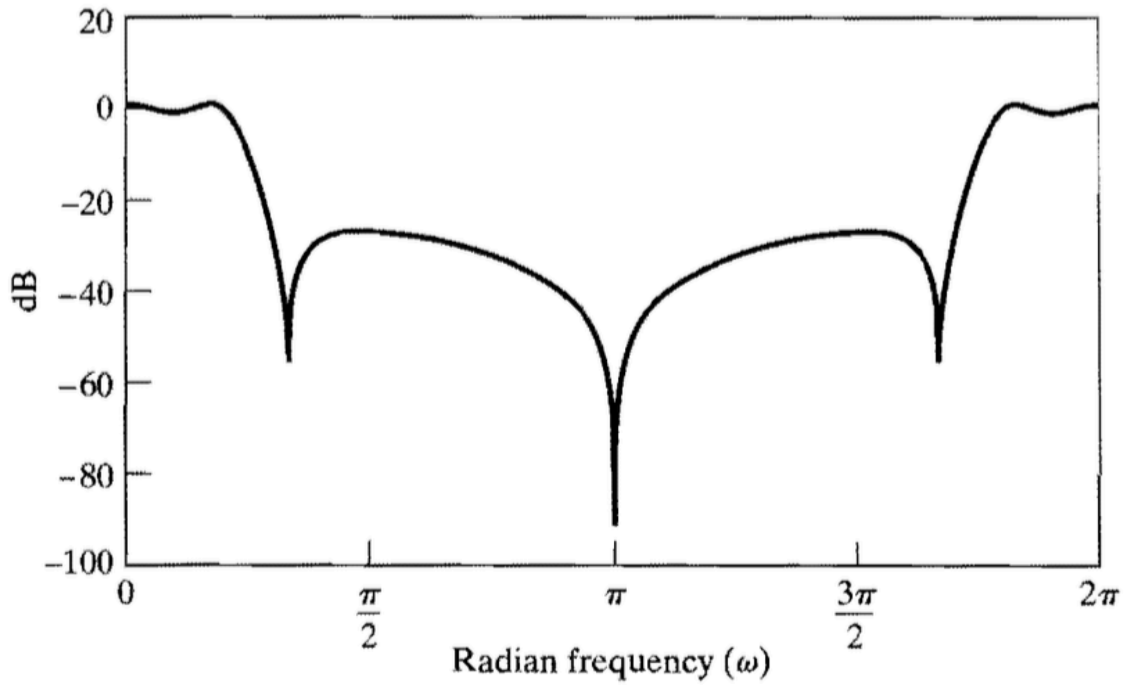

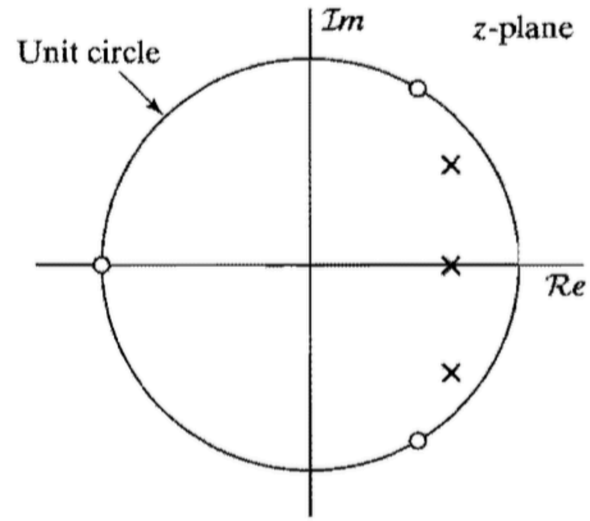

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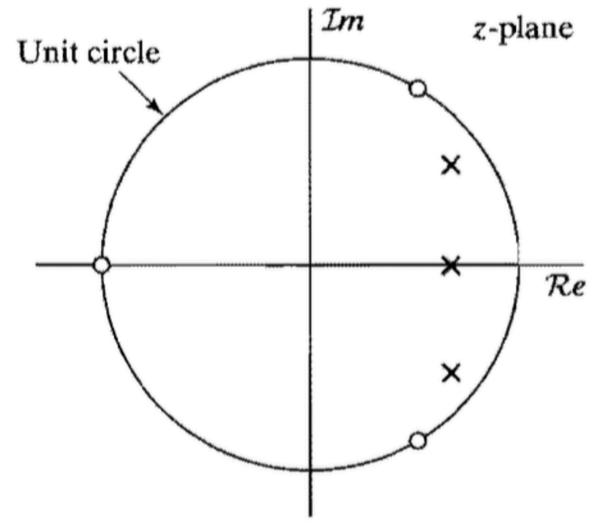

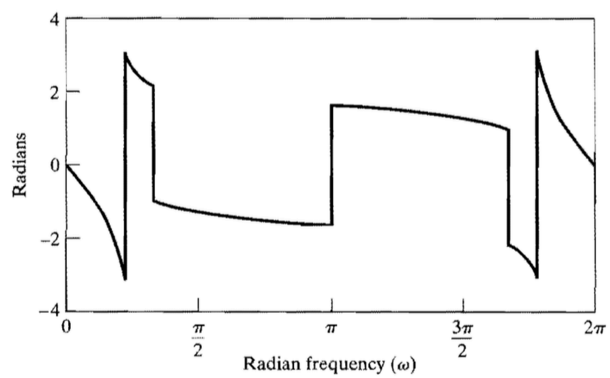

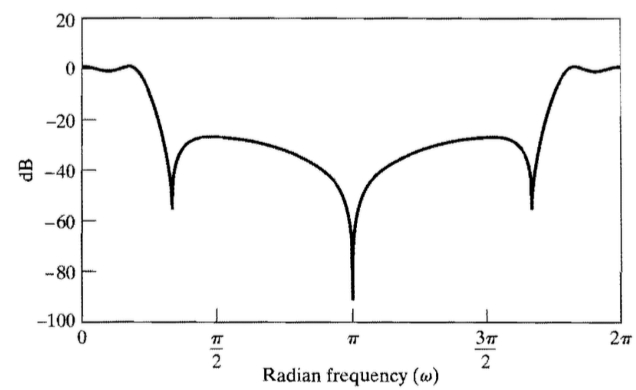

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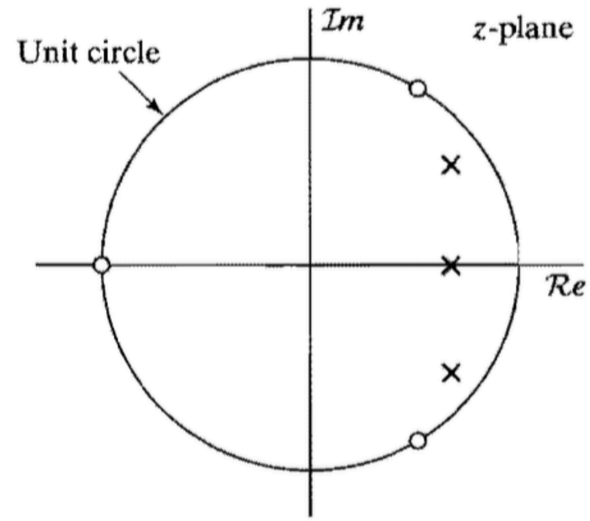
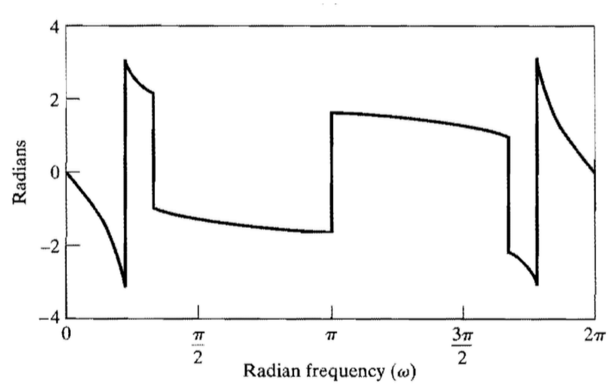
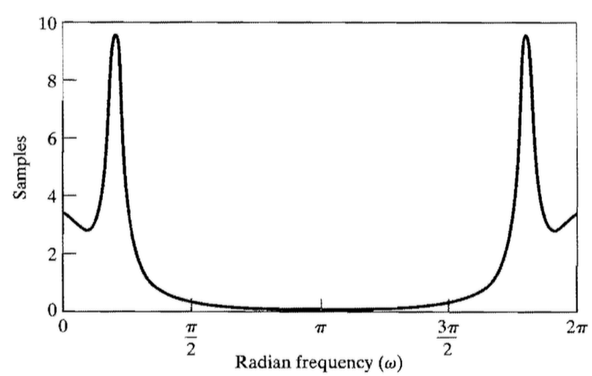
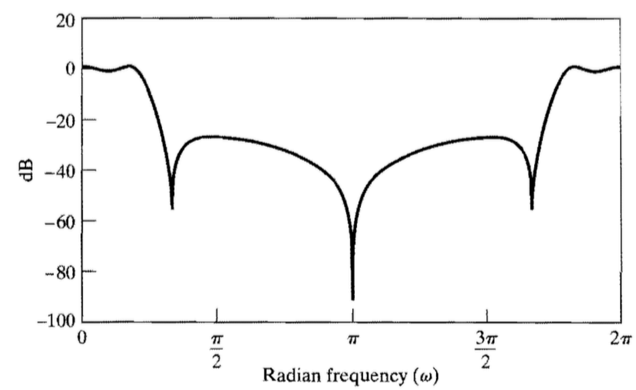








Stability and Causality

LTI System

$$\sum_{k=0}^{N} a_k y[n-k] = \sum_{k=0}^{M} b_k x[n-k]$$

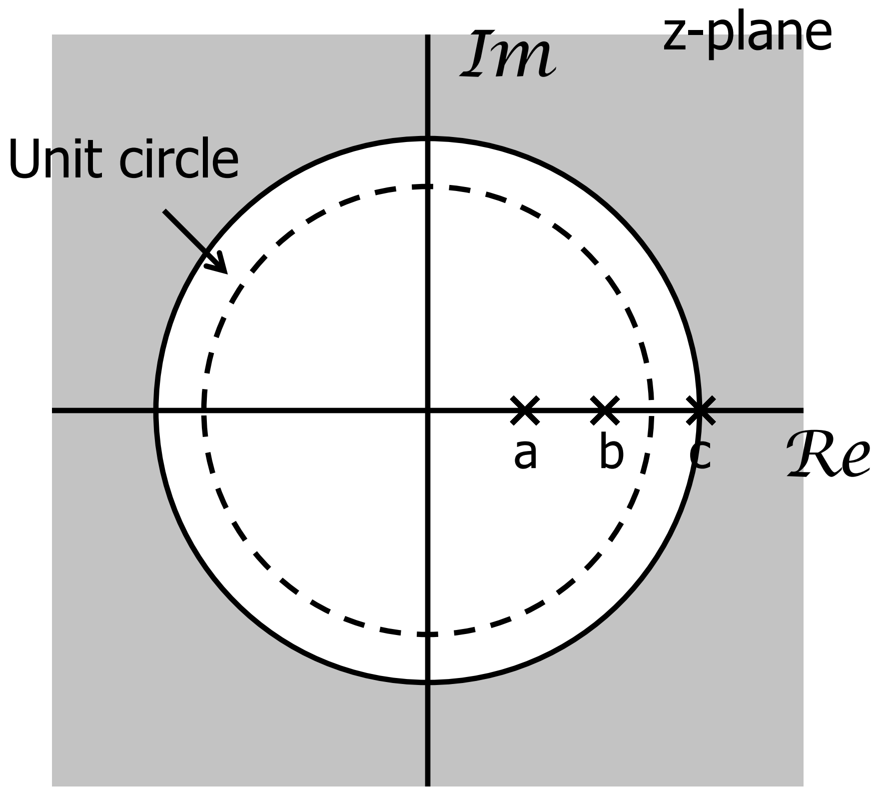
Example: $y[n] = x[n] + 0.1y[n-1]$

$$H(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_M z^{-M}}{a_0 + a_1 z^{-1} + \ldots + a_N z^{-N}} = \frac{b_0}{a_0} \frac{\prod_{k=1}^{M}(1 - c_k z^{-1})}{\prod_{k=1}^{N}(1 - d_k z^{-1})}$$

- Transfer function is not unique without ROC
  - If diff. eq represents LTI and causal system, ROC is region outside all singularities
  - If diff. eq represents LTI and stable system, ROC includes unit circle in z-plane

Example: ROC from Pole-Zero Plot

ROC 1: right-sided



LTI System

$$\sum_{k=0}^{N} a_k y[n-k] = \sum_{k=0}^{M} b_k x[n-k]$$

Example: $y[n] = x[n] + 0.1y[n-1]$

Stable and causal if all poles inside unit circle

$$H(z) = \frac{b_0 + b_1 z^{-1} + \ldots + b_M z^{-M}}{a_0 + a_1 z^{-1} + \ldots + a_N z^{-N}} = \frac{b_0}{a_0} \frac{\prod_{k=1}^{M}(1 - c_k z^{-1})}{\prod_{k=1}^{N}(1 - d_k z^{-1})}$$

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All-Pass Systems

All-Pass Filters

- A system is an all-pass system if

$$\left|H(e^{j\omega})\right| = 1, \ \ \text{all } \omega$$

- Its phase response $\theta(\omega)$ may be non-trivial

All-Pass Filter

$$H(z) = \frac{z^{-1} - a^*}{1 - az^{-1}}$$

$$a = re^{j\omega}$$

$$a^* = re^{-j\omega}$$

First Order All-Pass Filter

$$H(z) = \frac{z^{-1} - a^*}{1 - az^{-1}}$$

$$a = re^{j\omega}$$
$$a^* = re^{-j\omega}$$

$$\left|H(e^{j\omega})\right| = \frac{\left|e^{-j\omega} - a^*\right|}{\left|1 - ae^{-j\omega}\right|}$$

$$= \frac{\left|e^{-j\omega}(1 - a^* e^{j\omega})\right|}{\left|1 - ae^{-j\omega}\right|} = \frac{\left|1 - a^* e^{j\omega}\right|}{\left|1 - ae^{-j\omega}\right|}$$

$$= \frac{\left|1 - a^* e^{j\omega}\right|}{\left|1 - ae^{-j\omega}\right|} = 1$$

General All-Pass Filter

- d_k=real pole, e_k=complex poles paired w/ conjugate, e_k^*

$$H_{\mathrm{ap}}(z) = A \prod_{k=1}^{M_r} \frac{z^{-1} - d_k}{1 - d_k z^{-1}} \prod_{k=1}^{M_c} \frac{(z^{-1} - e_k^*)(z^{-1} - e_k)}{(1 - e_k z^{-1})(1 - e_k^* z^{-1})}$$

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- Example:

$$d_k = -\frac{3}{4}$$

$$e_k = 0.8 e^{j\pi/4}$$

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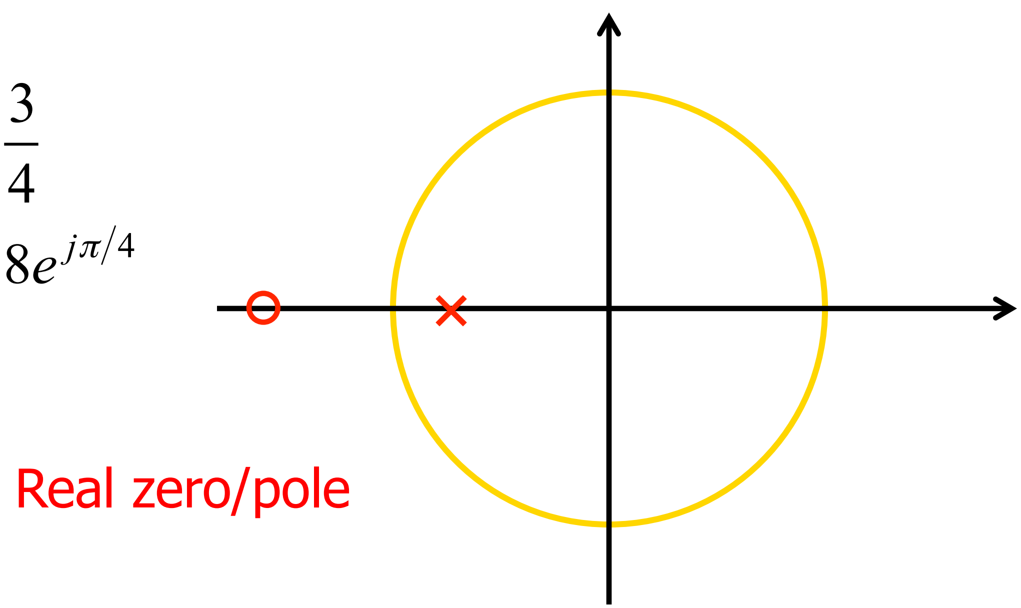

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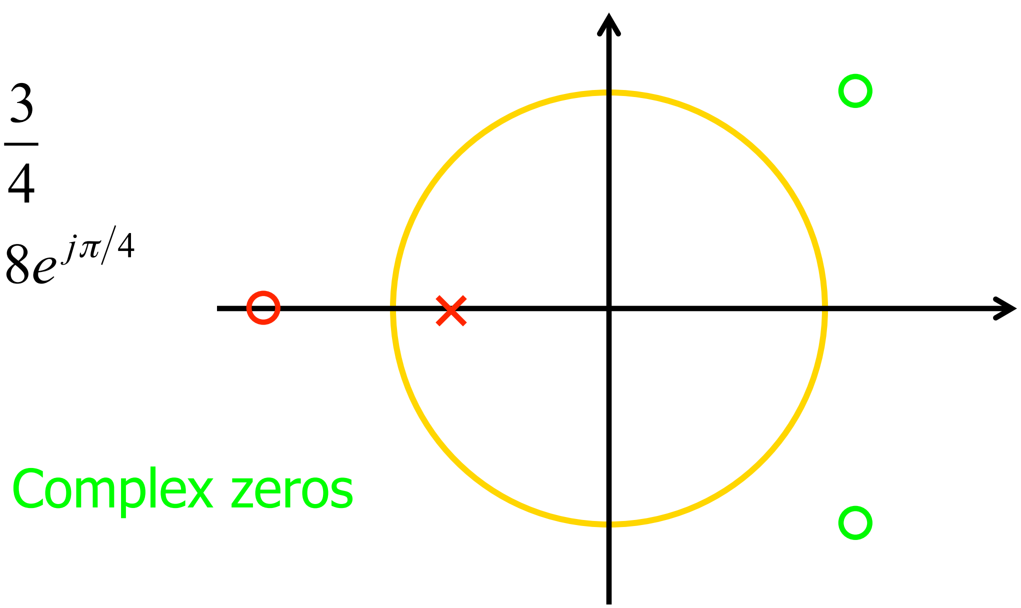
$$H_{ap}(z) = A \prod_{k=1}^{M_r} \frac{z^{-1} - d_k}{1 - d_k z^{-1}} \prod_{k=1}^{M_c} \frac{(z^{-1} - e_k^*)(z^{-1} - e_k)}{(1 - e_k z^{-1})(1 - e_k^* z^{-1})}$$

- Example:

$$d_k = -\frac{3}{4}$$

$$e_k = 0.8e^{j\pi/4}$$



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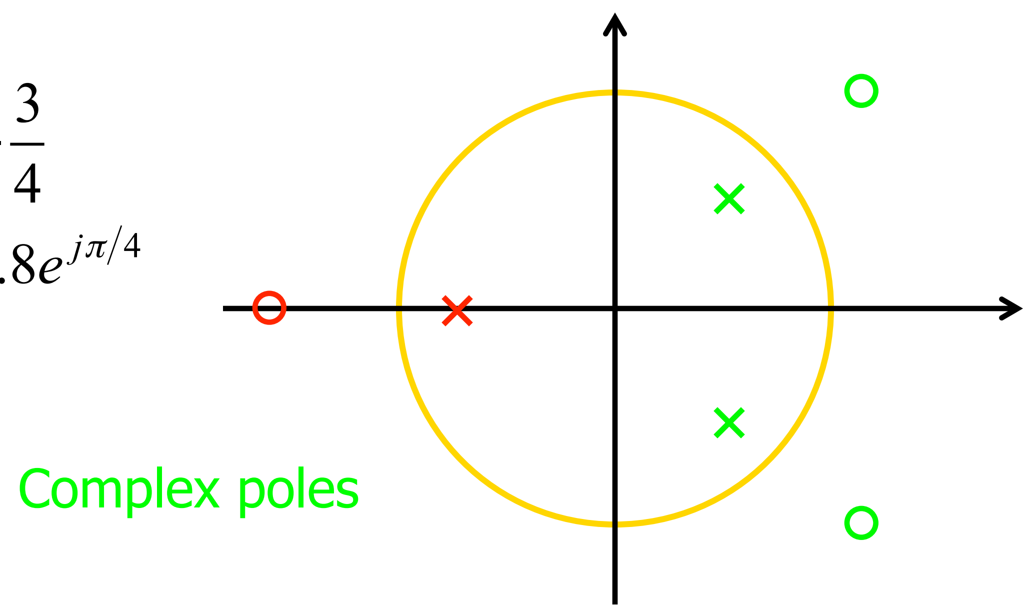

All Pass Filter Phase Response

- First order system
$$H(e^{j\omega}) = \frac{e^{-j\omega} - a^*}{1 - ae^{-j\omega}}$$
$$= \frac{e^{-j\omega} - re^{-j\theta}}{1 - re^{j\theta}e^{-j\omega}}$$

- phase

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$$= \arg\left(\frac{e^{-j\omega}(1 - re^{-j\theta}e^{j\omega})}{1 - re^{j\theta}e^{-j\omega}}\right)$$

$$= \arg(e^{-j\omega}) + \arg(1 - re^{-j\theta}e^{j\omega}) - \arg(1 - re^{j\theta}e^{-j\omega})$$

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$$= \arg(e^{-j\omega}) + \arg(1 - re^{-j\theta}e^{j\omega}) - \arg(1 - re^{j\theta}e^{-j\omega})$$

$$= -\omega - \arg(1 - re^{j\theta}e^{-j\omega}) - \arg(1 - re^{j\theta}e^{-j\omega})$$

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$$= -\omega - \arg(1 - re^{j\theta}e^{-j\omega}) - \arg(1 - re^{j\theta}e^{-j\omega})$$
$$= -\omega - 2\arg(1 - re^{j\theta}e^{-j\omega})$$

Group Delay Math

$$\text{grd}[H(e^{j\omega})] = \sum_{k=1}^{M} \text{grd}[1 - c_k e^{-j\omega}] - \sum_{k=1}^{N} \text{grd}[1 - d_k e^{-j\omega}]$$

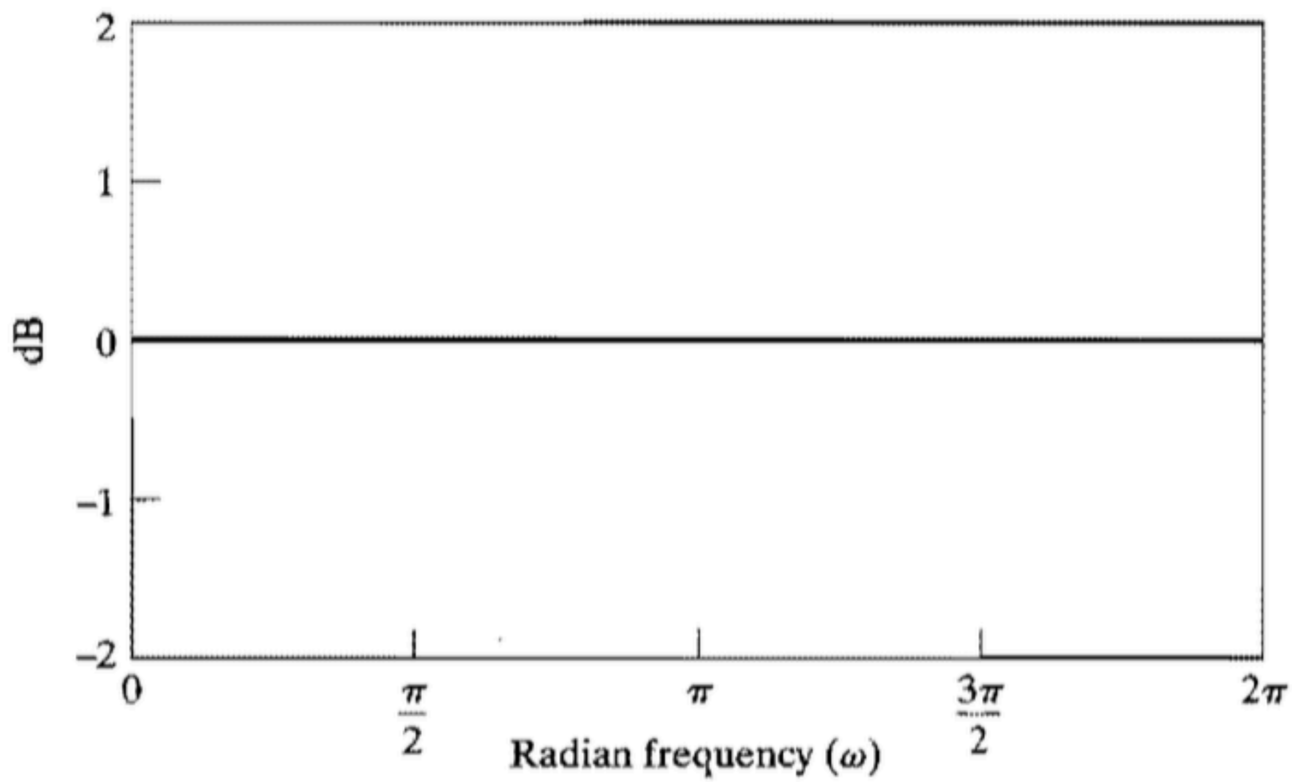
- Look at each factor:

$$\arg[1 - re^{j\theta}e^{-j\omega}] = \tan^{-1}\left(\frac{r\sin(\omega-\theta)}{1 - r\cos(\omega-\theta)}\right)$$

$$\text{grd}[1 - re^{j\theta}e^{-j\omega}] = \frac{r^2 - r\cos(\omega-\theta)}{\left|1 - re^{j\theta}e^{-j\omega}\right|^2}$$

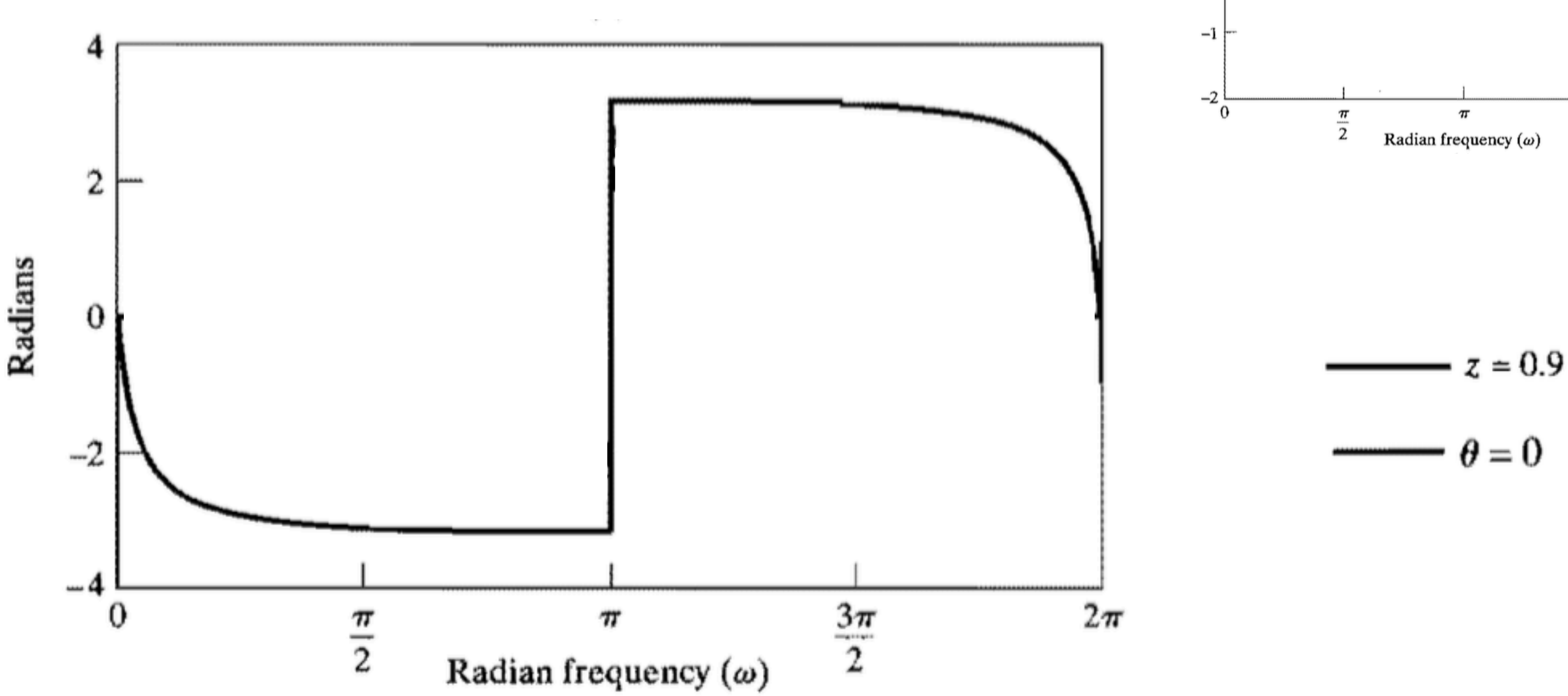
First Order Example

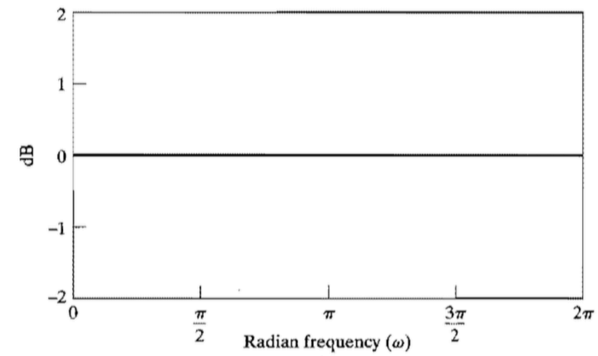
- Magnitude:



First Order Example

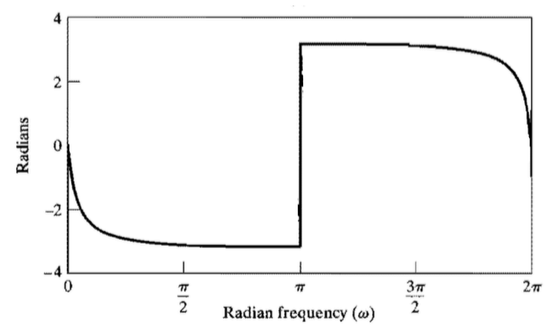
- Phase:

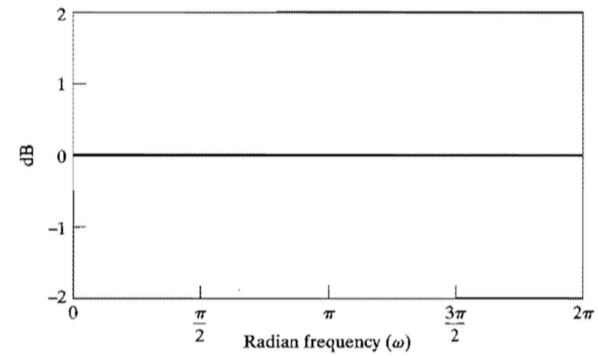


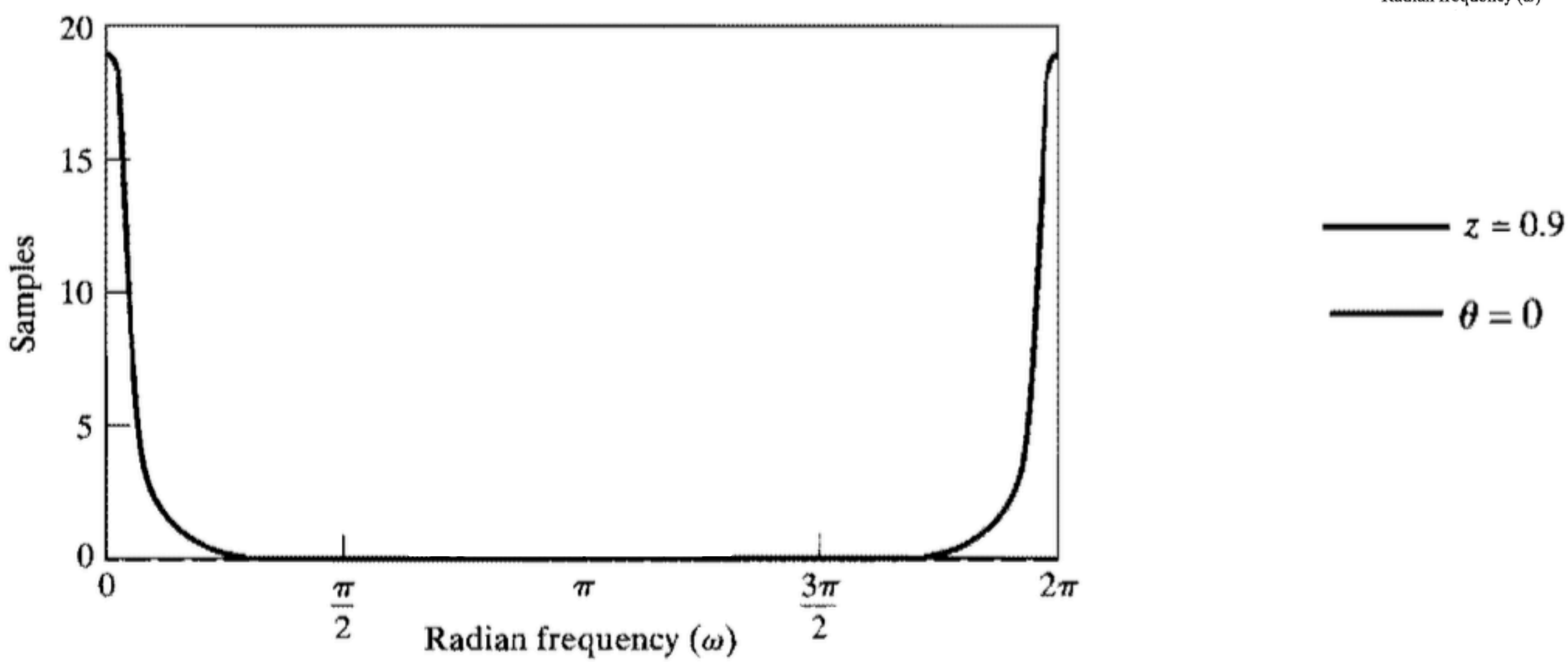


First Order Example

- Group Delay:







All Pass Filter Phase Response

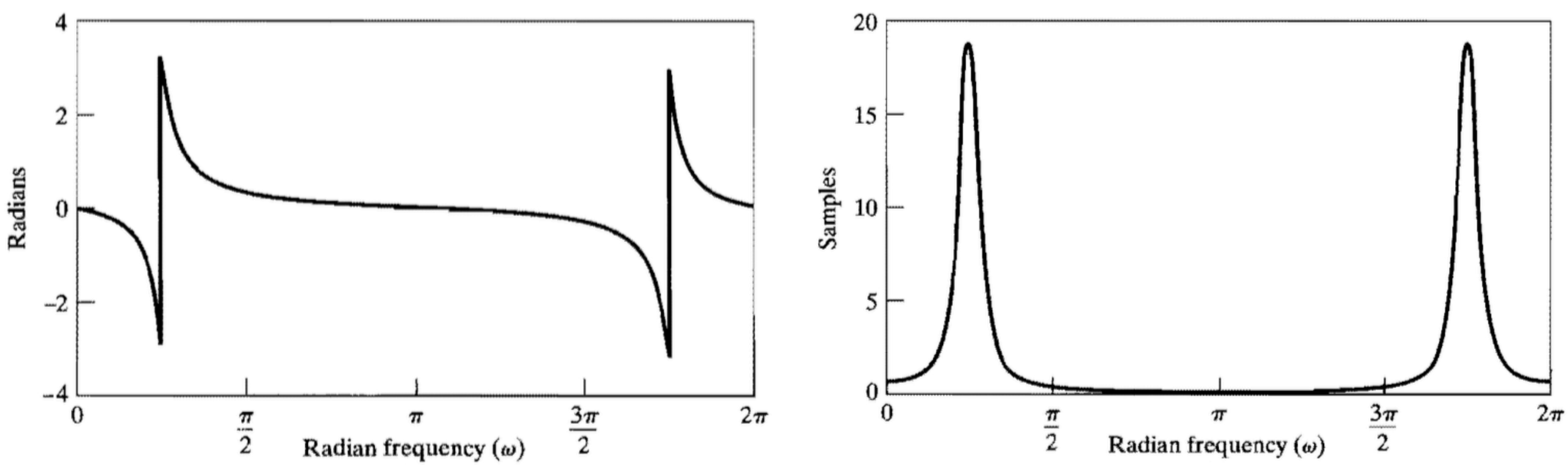
- Second order system with poles at $z = re^{j\theta}, re^{-j\theta}$

$$\angle\left[\frac{(e^{-j\omega} - re^{-j\theta})(e^{-j\omega} - re^{j\theta})}{(1 - re^{j\theta}e^{-j\omega})(1 - re^{-j\theta}e^{-j\omega})}\right] = -2\omega - 2\arctan\left[\frac{r\sin(\omega-\theta)}{1 - r\cos(\omega-\theta)}\right]$$

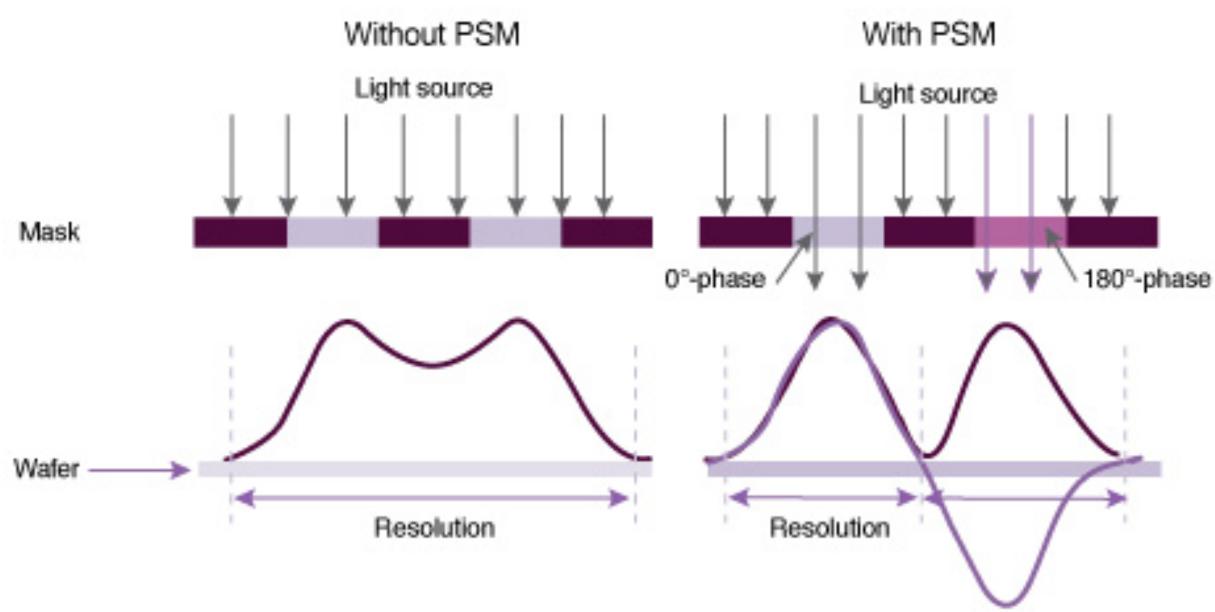
$$-2\arctan\left[\frac{r\sin(\omega+\theta)}{1 - r\cos(\omega+\theta)}\right].$$

Second Order Example

- Poles at $z = 0.9e^{\pm j\pi/4}$ (zeros at conjugates)



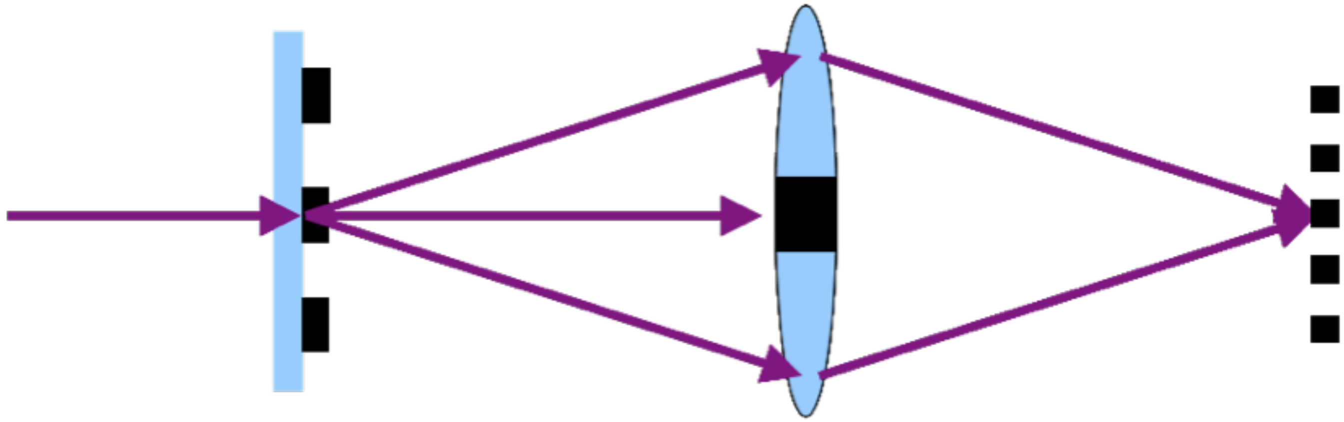
Phase Shift Masking

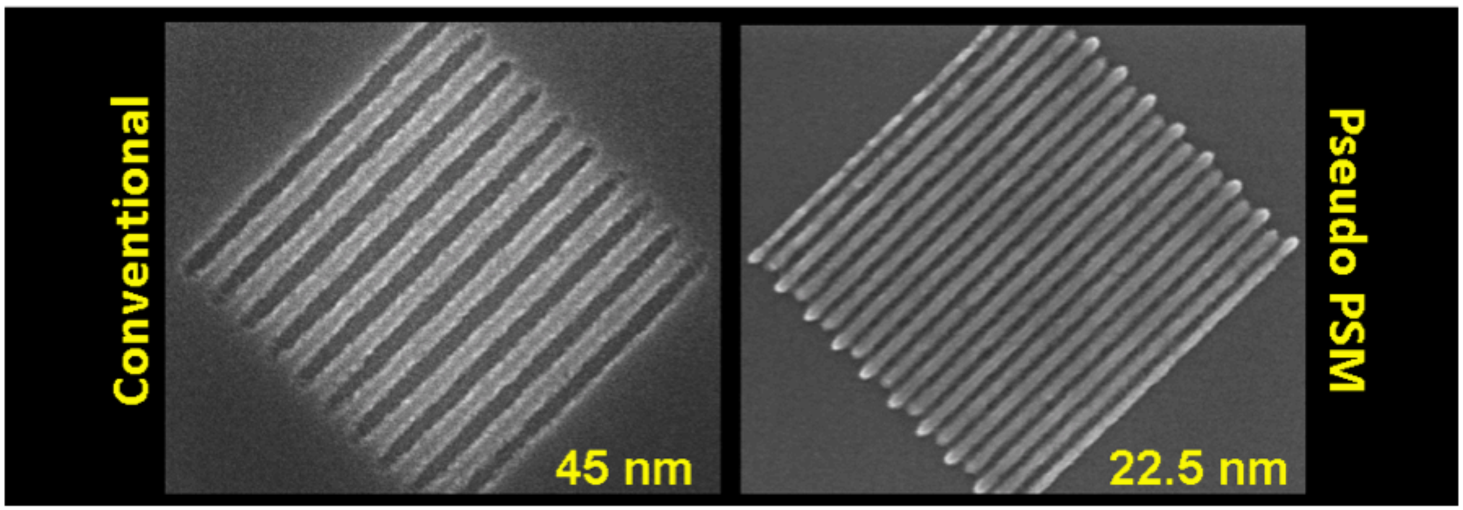


Today's chips use λ=193nm

Source
http://www.synopsys.com/Tools/Manufacturing/MaskSynthesis/PSMCreate/Pages/default.aspx

Phase Shift Masking





Patrick Naulleau, et al., "The SEMATECH Berkeley MET pushing EUV development beyond 22nm half pitch", Proc. SPIE 7636, Extreme Ultraviolet (EUV) Lithography, 76361J (March 22, 2010)

All-Pass Properties

- Claim: For a stable all-pass system:
  - $\arg[H_{ap}(e^{j\omega})] \leq 0$
    - Unwrapped phase always non-positive and decreasing
  - $\text{grd}[H_{ap}(e^{j\omega})] > 0$
    - Group delay always positive
  - Intuition
    - delay is positive → system is causal
    - Phase negative → phase lag

Minimum-Phase Systems

Minimum-Phase Systems

- Definition: A stable and causal system H(z) (i.e. poles inside unit circle) whose inverse 1/H(z) is also stable and causal (i.e. zeros inside unit circle)
  - All poles and zeros inside unit circle

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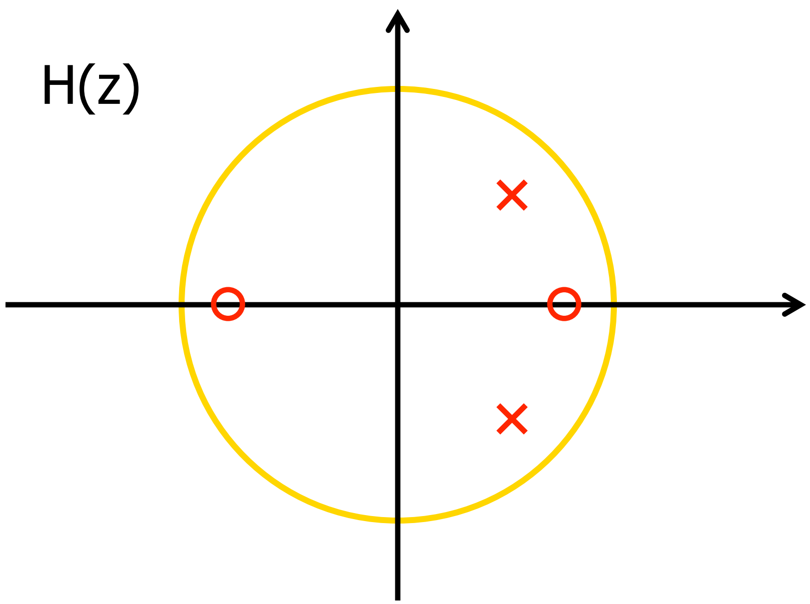
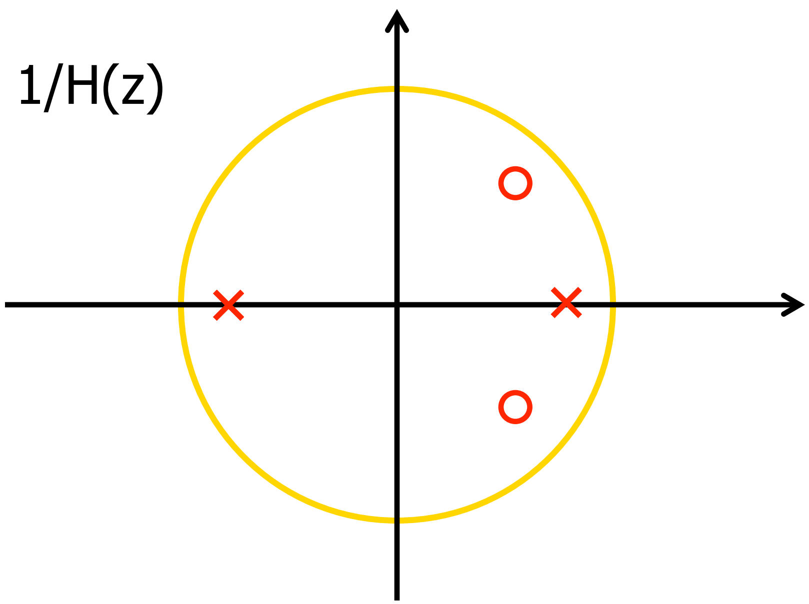




All-Pass Min-Phase Decomposition

- Any stable, causal system can be decomposed to:

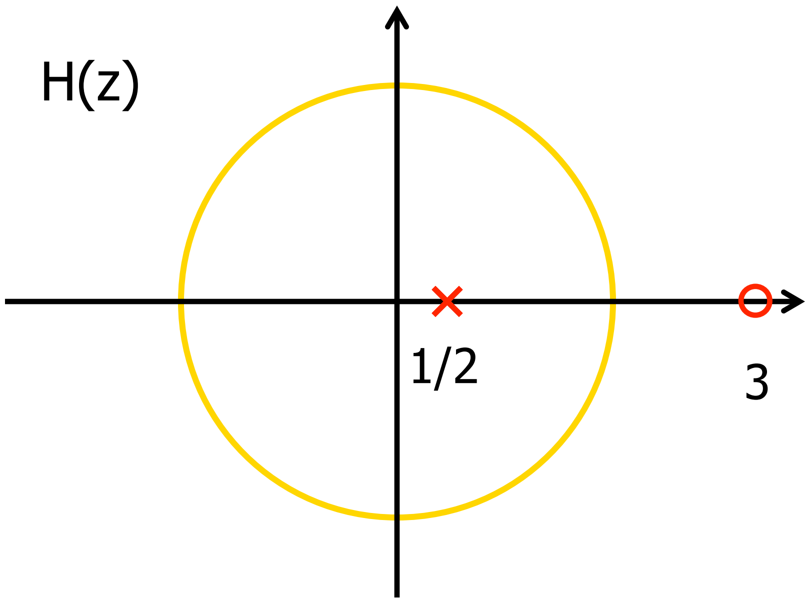
$$H(z) = H_{\min}(z) \cdot H_{ap}(z)$$

- Approach:
  - (1) First construct H_{ap} with all zeros outside unit circle
  - (2) Compute

$$H_{\min}(z) = \frac{H(z)}{H_{ap}(z)}$$

Min-Phase Decomposition Example

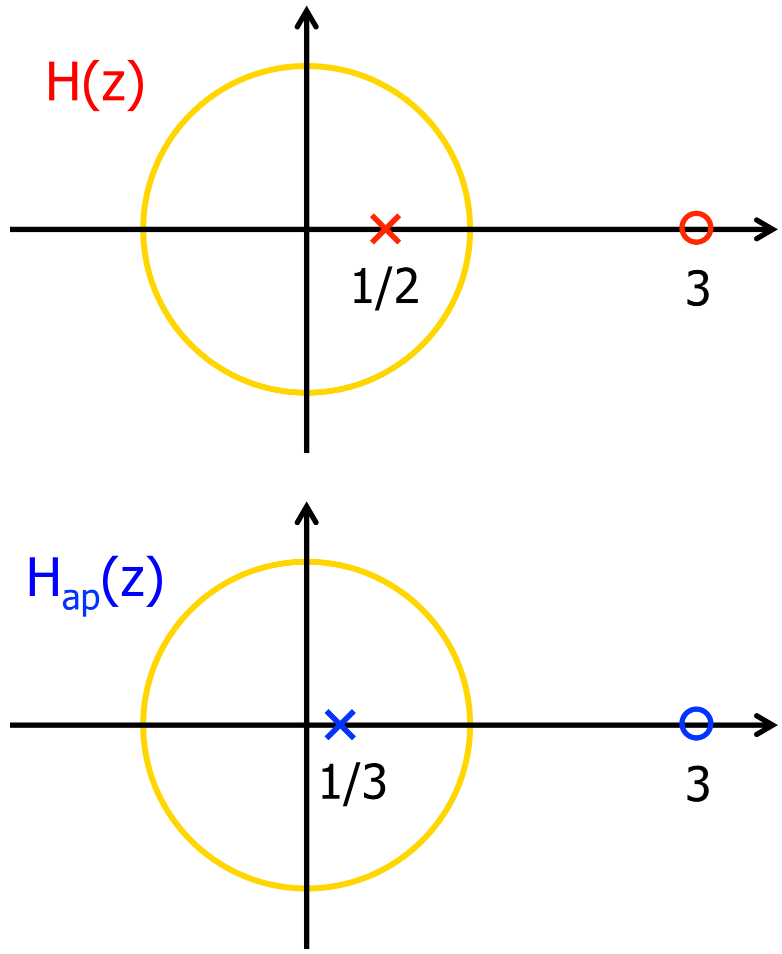
$$H(z) = \frac{1 - 3z^{-1}}{1 - \frac{1}{2}z^{-1}}$$



Min-Phase Decomposition Example

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

- Set $H_{ap}(z) = \dfrac{z^{-1}-\frac{1}{3}}{1-\frac{1}{3}z^{-1}}$



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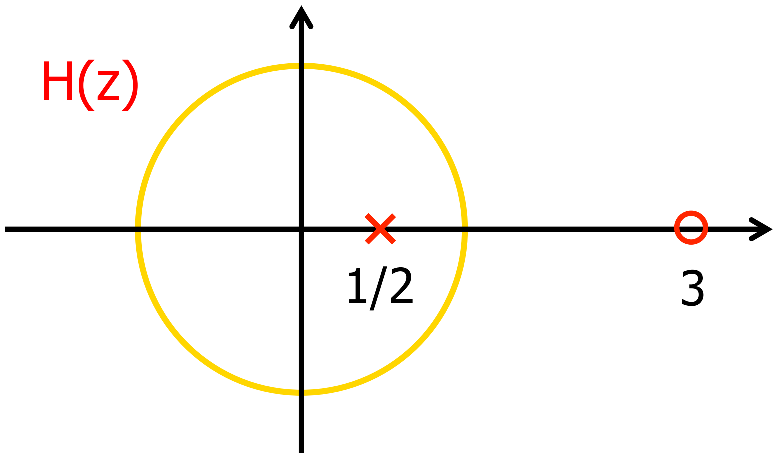

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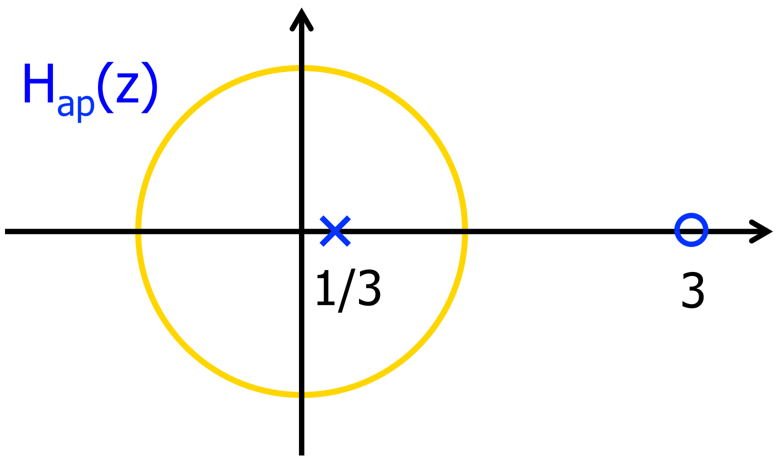


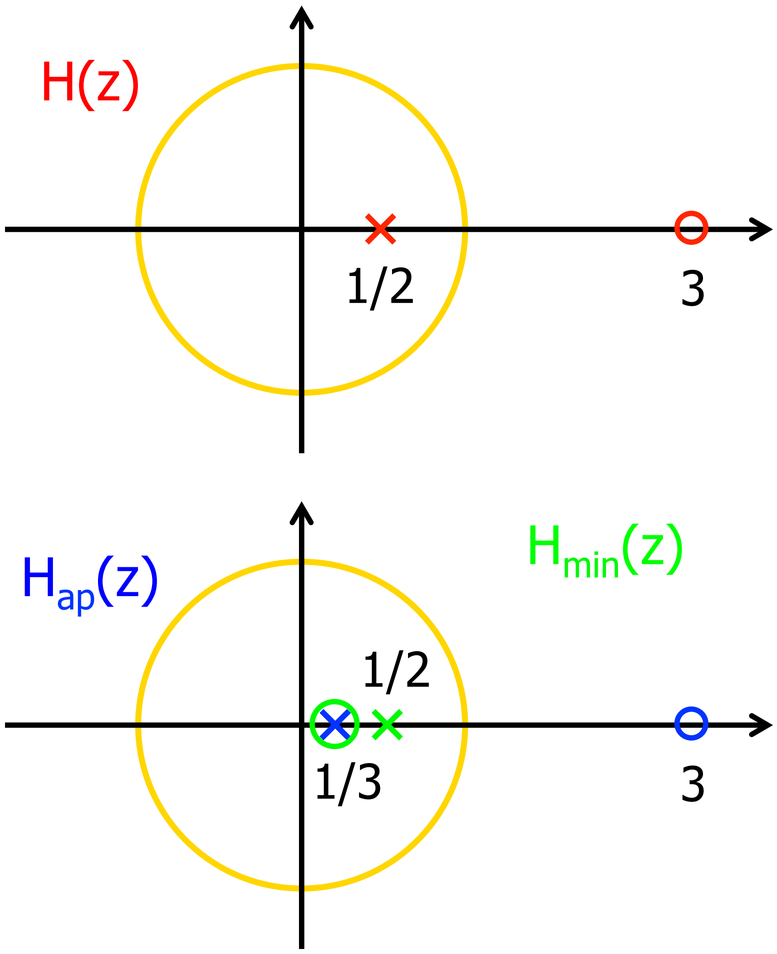
$$H_{\min}(z) = \frac{1 - 3z^{-1}}{1 - \frac{1}{2}z^{-1}} \left(\frac{z^{-1} - \frac{1}{3}}{1 - \frac{1}{3}z^{-1}} \right)^{-1}$$

Min-Phase Decomposition Example

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

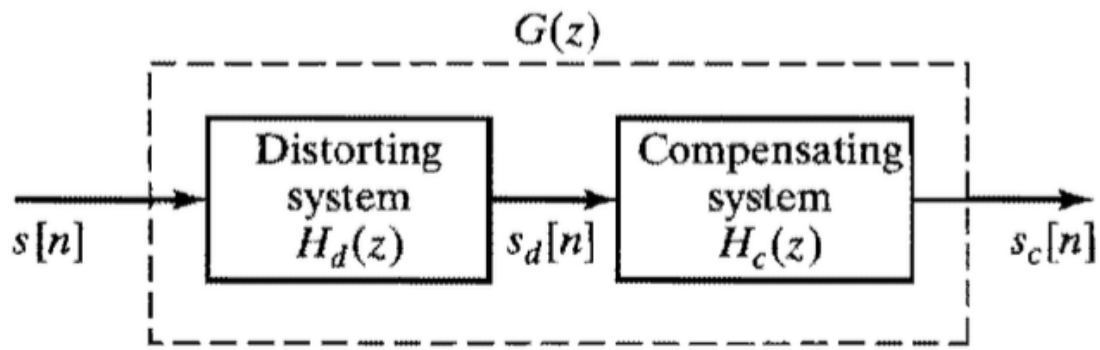
- Set $H_{ap}(z) = \dfrac{z^{-1}-\frac{1}{3}}{1-\frac{1}{3}z^{-1}}$

$$H_{\min}(z) = -3\frac{1-\frac{1}{3}z^{-1}}{1-\frac{1}{2}z^{-1}}$$



Min-Phase Decomposition Purpose

- Have some distortion that we want to compensate for:



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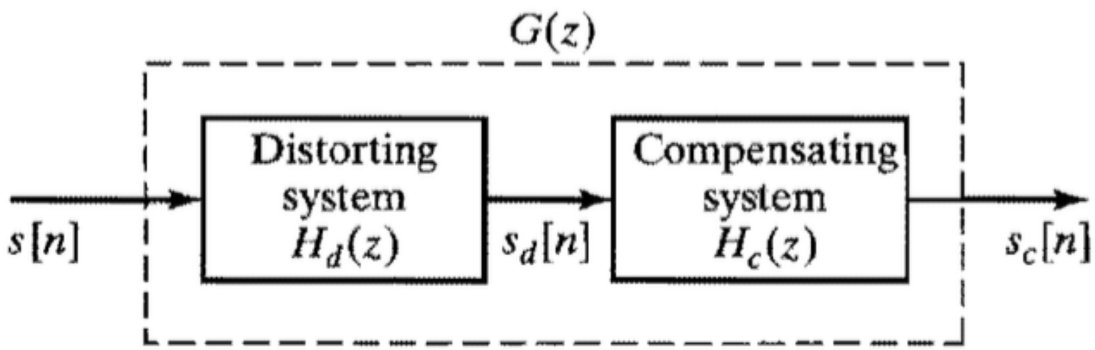

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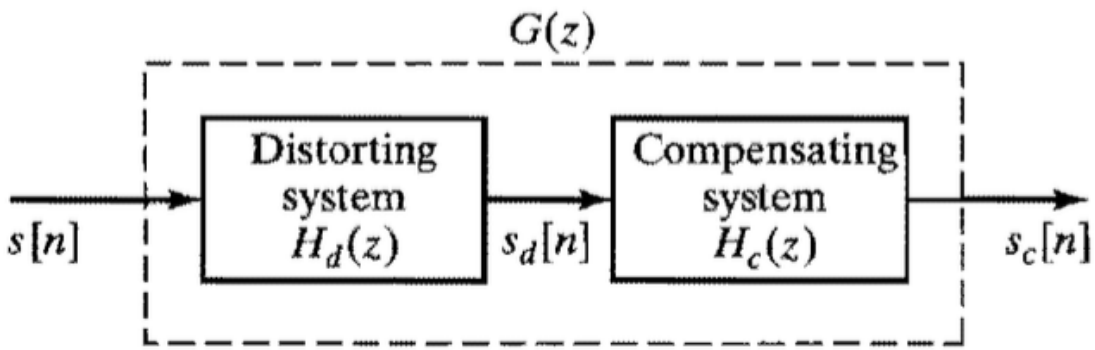
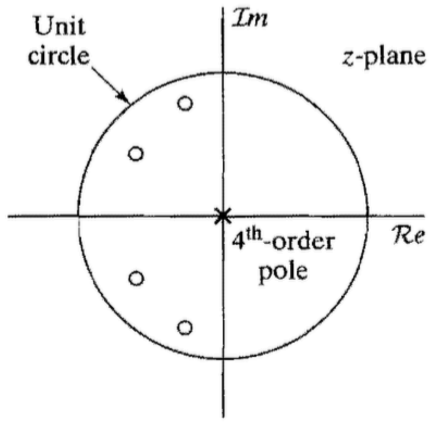


- If $H_d(z)$ is min phase, easy:
  - $H_c(z)=1/H_d(z)$ ← also stable and causal
- Else, decompose $H_d(z)=H_{d,min}(z)\ H_{d,ap}(z)$
  - $H_c(z)=1/H_{d,min}(z) \rightarrow H_d(z)H_c(z)=H_{d,ap}(z)$
    - Compensate for magnitude distortion

Minimum Energy-Delay Property

Min phase

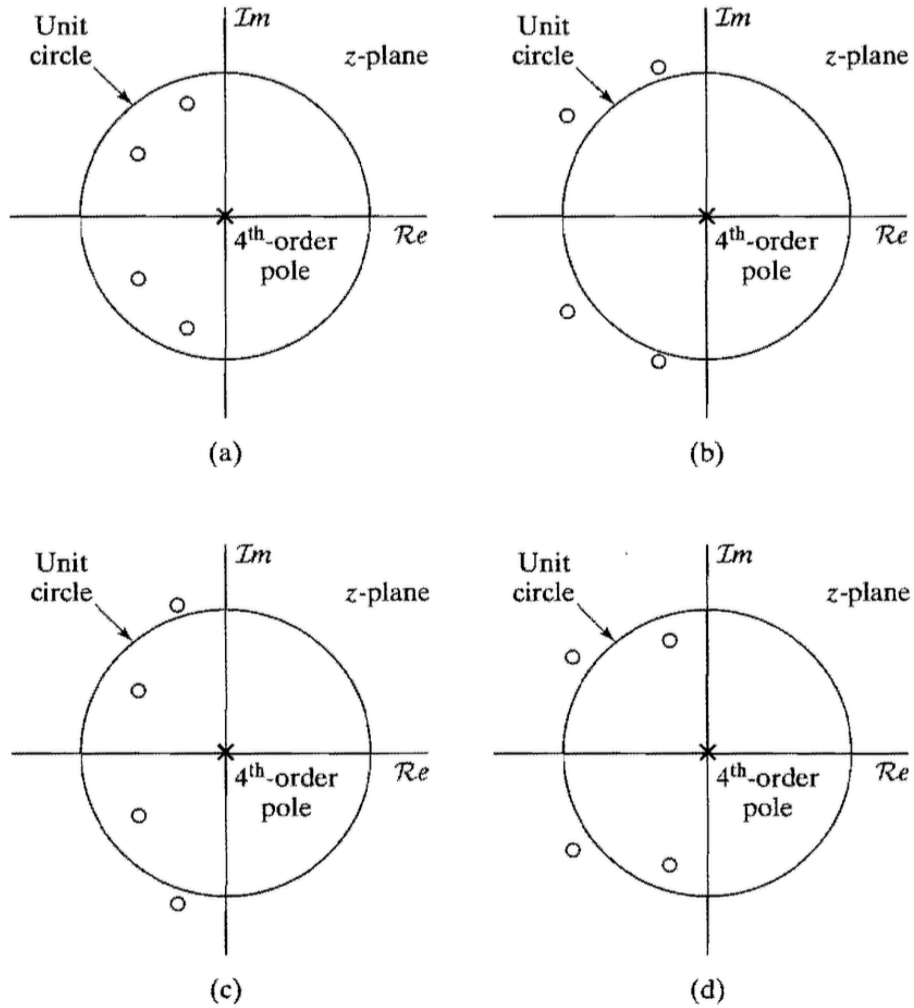


(a)

Minimum Energy-Delay Property

Min phase

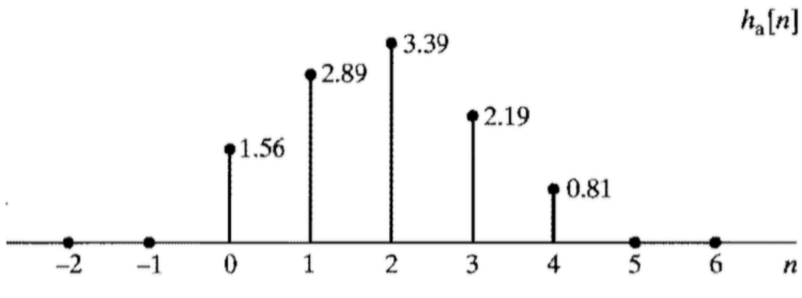
Max phase



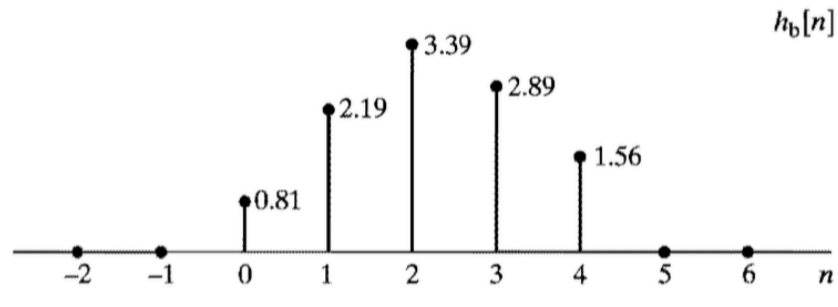
Minimum Energy-Delay Property

Min phase

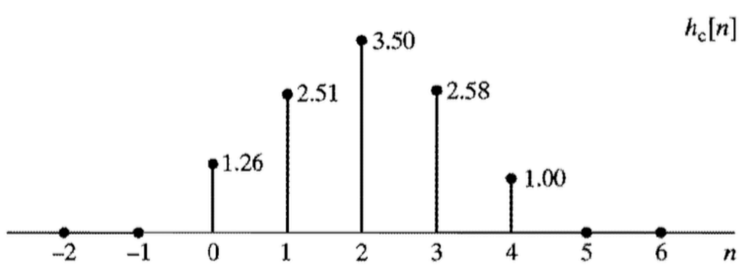
Max phase



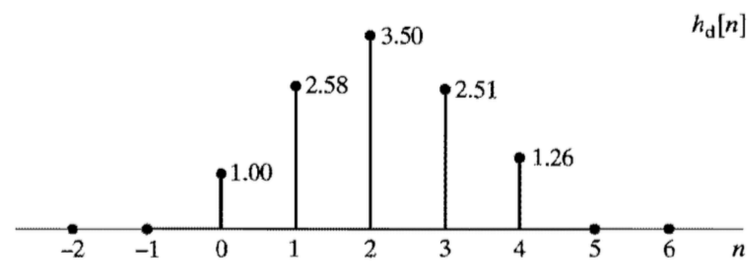
(a)



(b)



(c)



(d)

Big Ideas

- Frequency Response of LTI Systems
  - Magnitude Response, Phase Response, Group Delay
- LTI Stability and Causality
  - If all poles inside unit circle
- All Pass Systems
  - Used for delay compensation
- Minimum Phase Systems
  - Can compensate for magnitude distortion
  - Minimum energy-delay property

Midterm Exam

- Midterm – 3/14
  - In class
    - Starts at exactly 4:30pm, ends at exactly 5:50pm (80 minutes)
  - Location Towne 303
  - Old exam posted on website
  - Covers Lec 1- 13
  - Closed book, one page cheat sheet allowed
  - Calculators allowed, no smart phones
  - Review Session by Shlesh on Sunday 3/12 - time and location TBD
  - Extra office hours on Monday (3/13) (time and location TBD)

Admin

- HW 5
  - Due Friday 3/3

- Homework solutions to be posted after class