ESE 531: Digital Signal Processing

Lec 14: March 3, 2020

All-Pass Systems and Min Phase Decomposition

Lecture Outline

- Frequency Response of LTI Systems
  - Examples:
    - Zero on Real Axis
    - 2^{nd} order IIR
    - 3^{rd} order Low Pass
- Stability and Causality
- All Pass Systems
- Minimum Phase Systems (If time)

Review: Frequency Response of LTI System

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

- We can define a magnitude response…

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

- a phase response…

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

- and group delay

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

Group Delay

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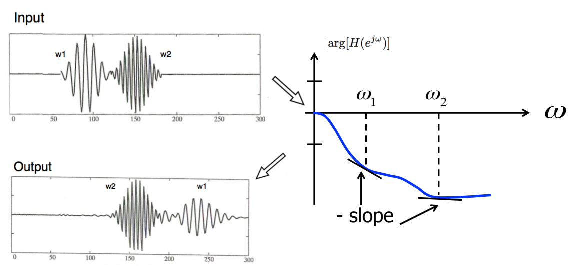

Group Delay Math

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

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arg of products is sum of args

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

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

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

- Look at each factor:

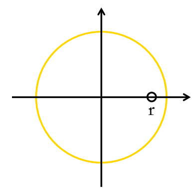
$$\arg[1 - re^{j\theta}e^{-j\omega}] = \tan^{-1}\left(\frac{r\sin(\omega-\theta)}{1 - r\cos(\omega-\theta)}\right)$$

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

Example: Zero on Real Axis

- Geometric Interpretation for (θ =0)

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



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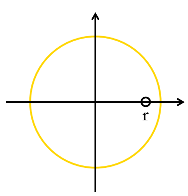

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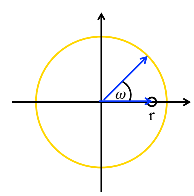

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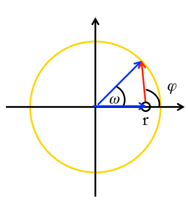

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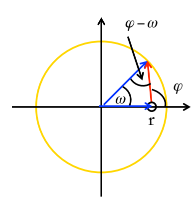

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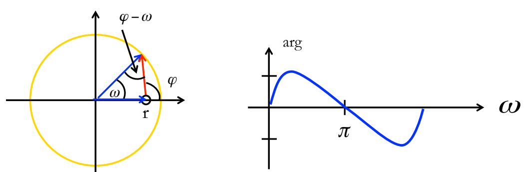

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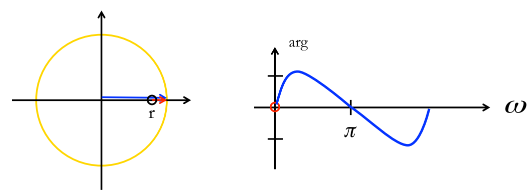
$\omega = 0$



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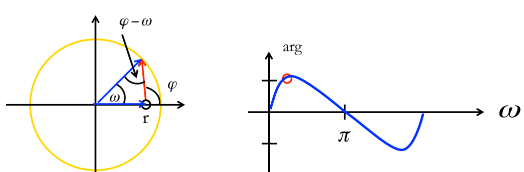

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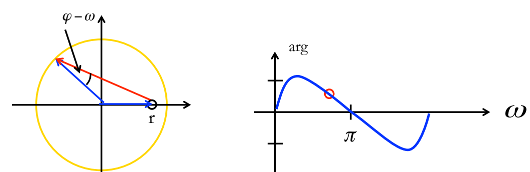

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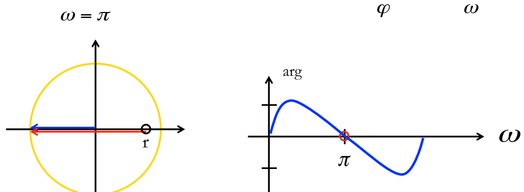
$\omega = \pi$



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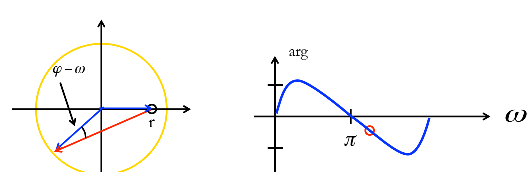

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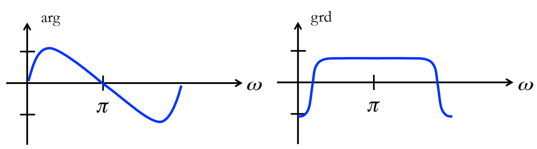
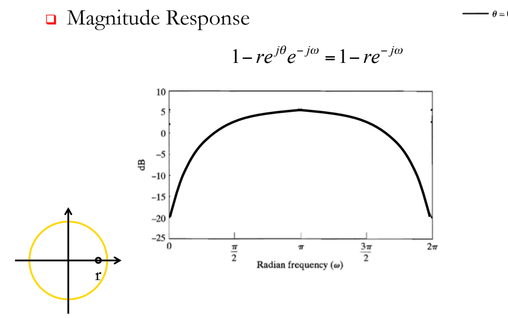


Example: Zero on Real Axis

- Magnitude Response

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



Group Delay Math

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- Look at each factor:

θ≠0?

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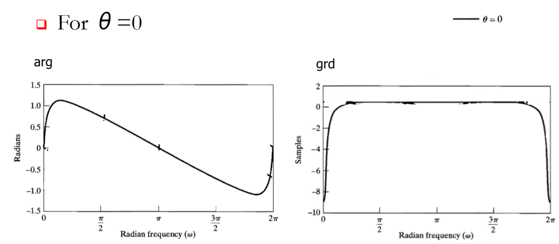
Example: Zero on Real Axis

- For $\theta=0$



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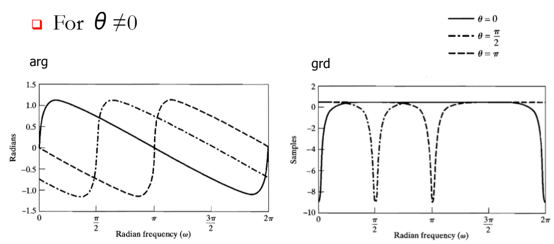
Example: Zero on Real Axis

- For $\theta\neq0$



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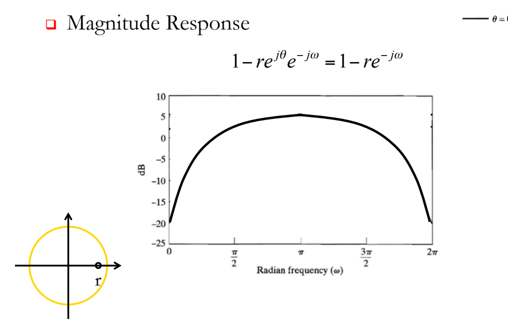
Example: Zero on Real Axis

- Magnitude Response

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

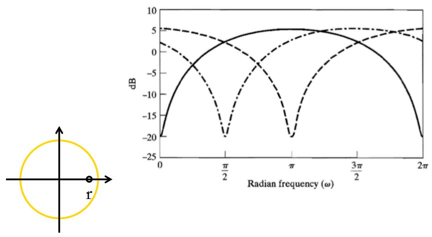


Example: Zero on Real Axis

- Magnitude Response

$$1-re^{j\theta}e^{-j\omega}$$

— $\theta = 0$
-·-· $\theta = \frac{\pi}{2}$
--- $\theta = \pi$

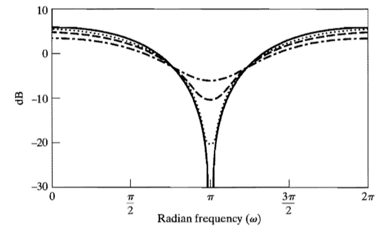


Example: Zero on Real Axis

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

$$1-re^{j\theta}e^{-j\omega}$$

-·-· $r = 0.5$
--- $r = 0.7$
····· $r = 0.9$
— $r = 1$



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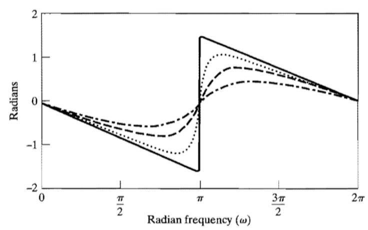

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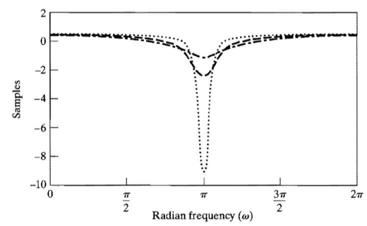
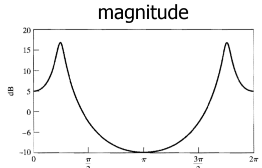


2nd Order IIR with Complex Poles

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

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

magnitude



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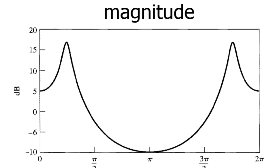
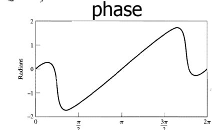
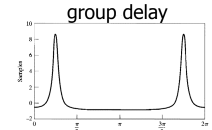


phase

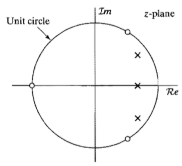


group delay



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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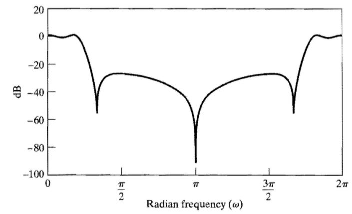

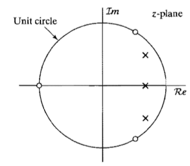

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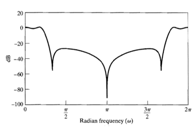

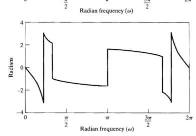

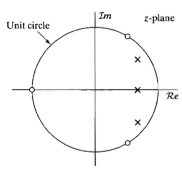

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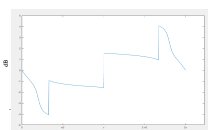

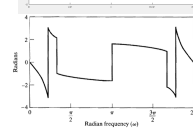

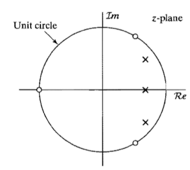

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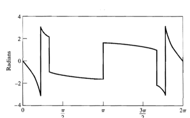
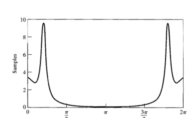
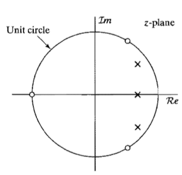
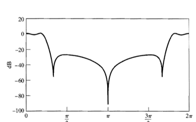








Stability and Causality

LTI System

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

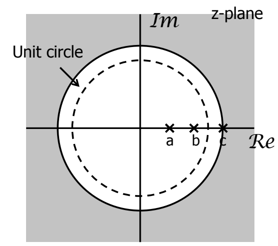
Example: $y[n] = x[n] + 0.1y[n-1]$

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

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

If stable and causal, all poles inside unit circle

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

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All-Pass Systems

All-Pass Filters

- A system is an all-pass system if

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

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

First Order All-Pass Filter (a real)

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

First Order All-Pass Filter (*a* real)

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

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

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

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

General All-Pass Filter

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

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

General All-Pass Filter

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

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- Example:

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

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

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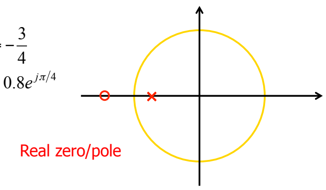

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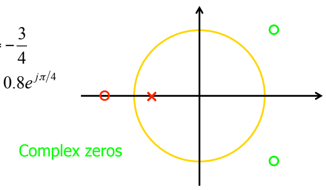

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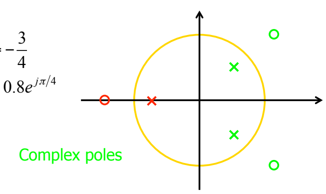


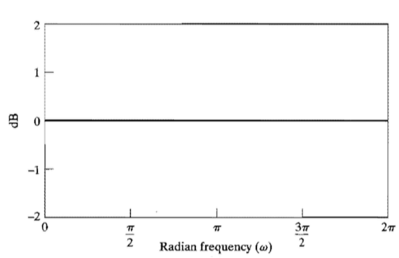
All Pass Filter Phase Response

- First order system

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

First Order Example

- Magnitude:



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

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

Group Delay Math

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

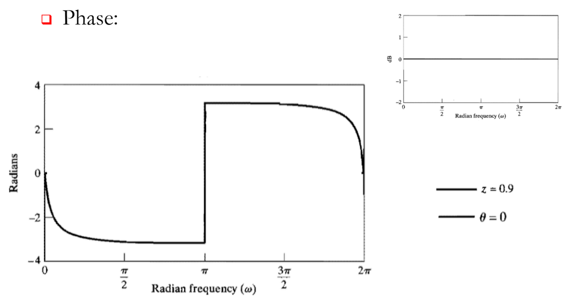
- Look at each factor:

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

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

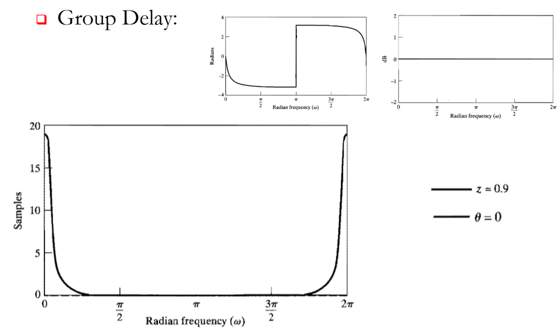
First Order Example

- Phase:



First Order Example

- Group Delay:



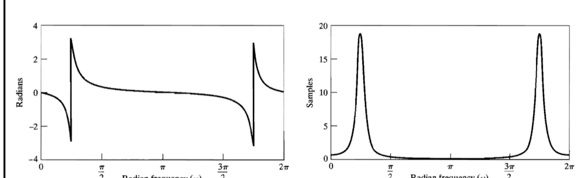
All Pass Filter Phase Response

- 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)



All-Pass Properties

- Claim: For a stable, causal ($r < 1$) all-pass system:
  - $\arg[H_{ap}(e^{j\omega})] \leq 0$
    - Unwrapped phase always non-positive and decreasing
  - $\mathrm{grd}[H_{ap}(e^{j\omega})] > 0$
    - Group delay always positive

Pg 309 in text book

- Intuition
  - delay is positive → system is causal
  - Phase negative → phase lag

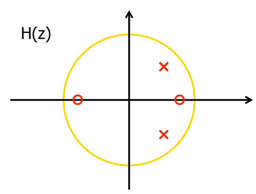
Minimum-Phase Systems

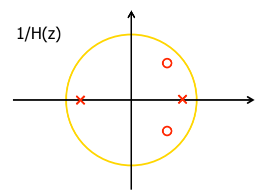
Minimum-Phase Systems

- 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)

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





All-Pass Min-Phase Decomposition

- Any stable, causal system can be decomposed to:

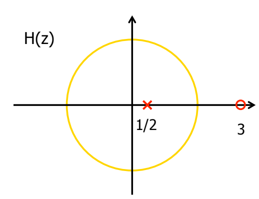
$$H(z) = H_{\min}(z) \cdot H_{ap}(z)$$

- 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

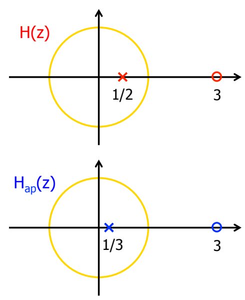
$$H(z) = \frac{1 - 3z^{-1}}{1 - \frac{1}{2}z^{-1}}$$



Min-Phase Decomposition Example

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

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

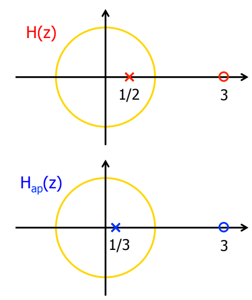


Min-Phase Decomposition Example

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

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

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

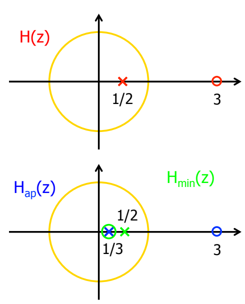


Min-Phase Decomposition Example

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

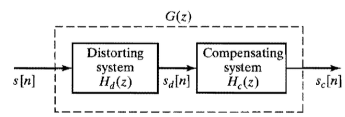
- Set $H_{ap}(z)=\dfrac{z^{-1}-\frac{1}{3}}{1-\frac{1}{3}z^{-1}}$

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



Min-Phase Decomposition Purpose

- Have some distortion that we want to compensate for:



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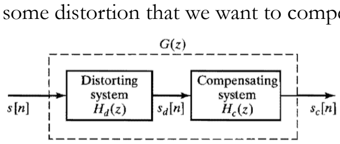

- If $H_d(z)$ is min phase, easy:
  - $H_c(z)=1/H_d(z)$ ← also stable and causal

Min-Phase Decomposition Purpose

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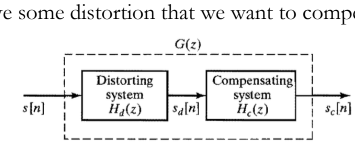
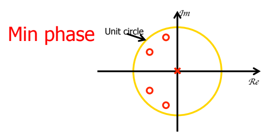
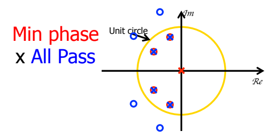


- If $H_d(z)$ is min phase, easy:
  - $H_c(z)=1/H_d(z)$ ← also stable and causal
- Else, decompose $H_d(z)=H_{d,min}(z)\,H_{d,ap}(z)$
  - $H_c(z)=1/H_{d,min}(z)$ → $H_d(z)H_c(z)=H_{d,ap}(z)$
    - Compensate for magnitude distortion

Minimum Phase to Max Phase



Minimum Phase to Max Phase



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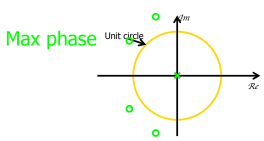
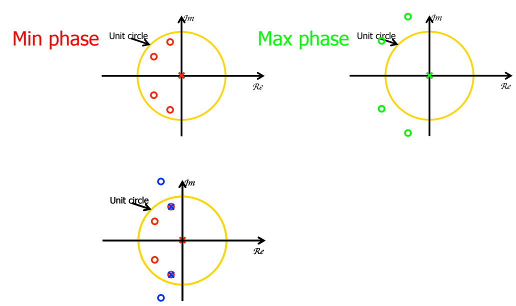


Minimum Phase



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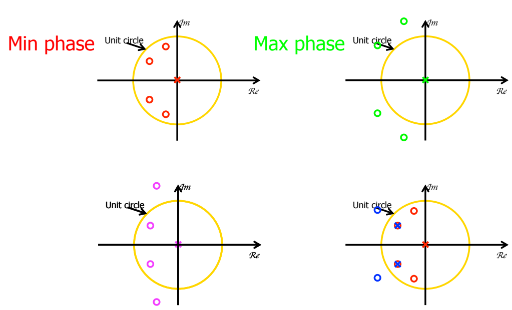

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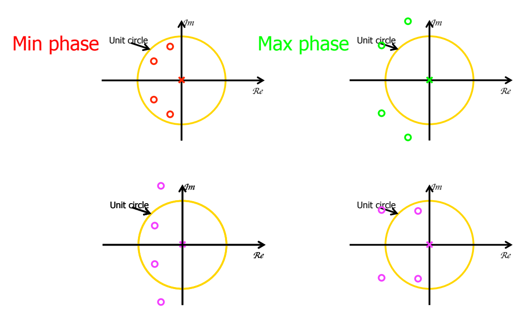


Minimum Phase Lag Property

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

- $\arg[H_{max}(e^{j\omega})] = \arg[H_{min}(e^{j\omega}) * H_{ap}(e^{j\omega})]$

$$= \arg[H_{min}(e^{j\omega})] + \arg[H_{ap}(e^{j\omega})]$$

$$= \quad \leq 0 \quad + \quad \leq 0$$

Minimum Group Delay Property

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

- $\mathrm{grd}[H_{max}(e^{j\omega})] = \mathrm{grd}[H_{min}(e^{j\omega}) * H_{ap}(e^{j\omega})]$

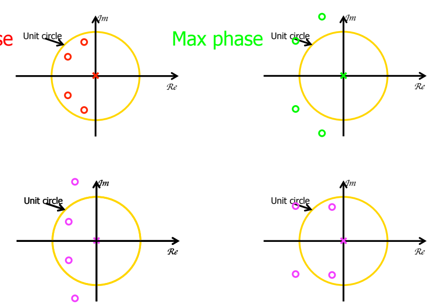
$$= \mathrm{grd}[H_{min}(e^{j\omega})] + \mathrm{grd}[H_{ap}(e^{j\omega})]$$

$$= \quad \geq 0 \quad + \quad \geq 0$$

Minimum Phase

Min phase

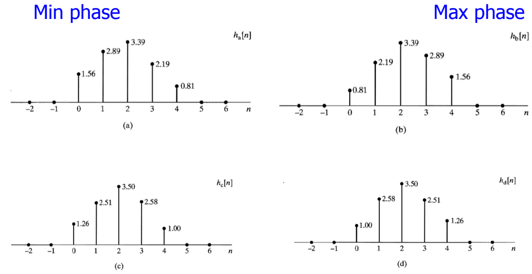
Max phase



Minimum Energy-Delay Property

Min phase

Max phase



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

Admin

- Dhaval extra now
  - See Piazza for time and location
  - Dhaval TH/F OH cancelled
- Yinghao OH W will be exam review session
- No office hours during spring break
- HW 6 posted after midterm

Admin - Midterm

- Midterm Thursday 3/5
  - During class
    - Starts at **exactly 4:30pm**, ends at exactly 5:50pm (80 minutes)
  - Location DRLB A2
  - Old exams posted on previous years' website
    - Disclaimer: old exams before 2019 covered more material
  - Covers Lec 1 - 11
  - Closed book, one page (8.5x11) cheat sheet allowed
  - Calculators allowed, no smart phones