

Signal Processing - 1 by One

Sibi Raj B. Pillai
Dept of Electrical Engineering
IIT Bombay



- Digital-Analog-Digital
- Fourier Analysis, Series and Transform
- Previous Weeks: DTFT, DFT, FFT, Circular Convolutions
- Previous Class: Practical Example of 4G
- Today: Filter Design, Z-Transform



- Digital-Analog-Digital
- Fourier Analysis, Series and Transform
- Previous Weeks: DTFT, DFT, FFT, Circular Convolutions
- Previous Class: Practical Example of 4G
- Today: Filter Design, Z-Transform



- Digital-Analog-Digital
- Fourier Analysis, Series and Transform
- Previous Weeks: DTFT, DFT, FFT, Circular Convolutions
- Previous Class: Practical Example of 4G
- Today: Filter Design, Z-Transform



Z-Transform

$$H(z) = \sum_{n \in \mathbb{Z}} h[n]z^{-n}. \quad (1)$$

Polynomial in z , which takes complex values.



Z-Transform

$$H(z) = \sum_{n \in \mathbb{Z}} h[n]z^{-n}. \quad (1)$$

Polynomial in z , which takes complex values.

Example: $(h_0, h_1, h_2) = (2, 7, \alpha)$:

$$H(z) = 2 + 7z^{-1} + \alpha z^{-2}.$$



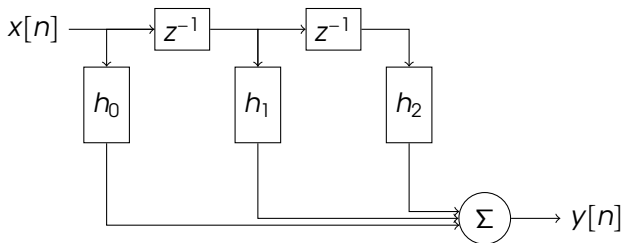
Z-Transform

$$H(z) = \sum_{n \in \mathbb{Z}} h[n] z^{-n}. \quad (1)$$

Polynomial in z , which takes complex values.

Example: $(h_0, h_1, h_2) = (2, 7, \alpha)$:

$$H(z) = 2 + 7z^{-1} + \alpha z^{-2}.$$



ROC: Region of Convergence

$$h[n] = a^n u[n], a \in \mathbb{C}.$$



ROC: Region of Convergence

$$h[n] = a^n u[n], a \in \mathbb{C}.$$

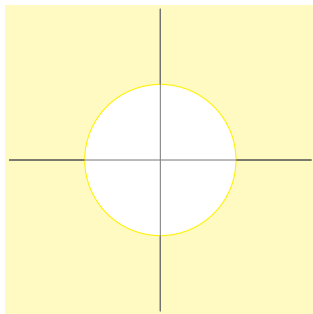
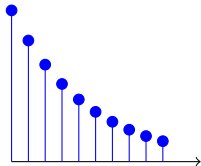
$$H(z) = \frac{1}{1 - az^{-1}} \text{ for } |z| > |a|.$$



ROC: Region of Convergence

$$h[n] = a^n u[n], a \in \mathbb{C}.$$

$$H(z) = \frac{1}{1 - az^{-1}} \text{ for } |z| > |a|.$$



Convolution-Multiplication

$$y[n] = x[n] * h[n] \Rightarrow Y(z) = X(z)H(z)$$



Convolution-Multiplication

$$y[n] = x[n] * h[n] \Rightarrow Y(z) = X(z)H(z)$$

Proof: Polynomial product \equiv Carry-less Multiplication of coeffs.



Convolution-Multiplication

$$y[n] = x[n] * h[n] \Rightarrow Y(z) = X(z)H(z)$$

Proof: Polynomial product \equiv Carry-less Multiplication of coeffs.

$$H(z) = \frac{Y(z)}{X(z)} : \text{Impulse Response of System}$$



Convolution-Multiplication

$$y[n] = x[n] * h[n] \Rightarrow Y(z) = X(z)H(z)$$

Proof: Polynomial product \equiv Carry-less Multiplication of coeffs.

$$H(z) = \frac{Y(z)}{X(z)} : \text{Impulse Response of System}$$

Example: LTI System with

$$Y(z) = X(z) + 3z^{-1}X(z) + 7z^{-3}X(z).$$



Convolution-Multiplication

$$y[n] = x[n] * h[n] \Rightarrow Y(z) = X(z)H(z)$$

Proof: Polynomial product \equiv Carry-less Multiplication of coeffs.

$$H(z) = \frac{Y(z)}{X(z)} : \text{Impulse Response of System}$$

Example: LTI System with

$$Y(z) = X(z) + 3z^{-1}X(z) + 7z^{-3}X(z).$$

$$h[n] = (1, 3, 0, 7).$$



Feedback IIR Implementation

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



Feedback IIR Implementation

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

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



Feedback IIR Implementation

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

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

$$y[n] - ay[n-1] = x[n]$$



Feedback IIR Implementation

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

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

$$y[n] - ay[n-1] = x[n]$$

$$y[n] = x[n] + ay[n-1] \Rightarrow \text{Causal Weighted Average}$$



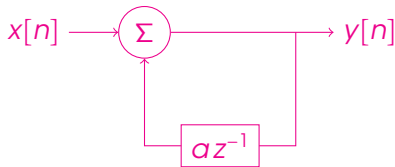
Feedback IIR Implementation

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

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

$$y[n] - ay[n-1] = x[n]$$

$$y[n] = x[n] + ay[n-1] \Rightarrow \text{Causal Weighted Average}$$



IIR Filters

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-3}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}}.$$



$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}}.$$

Stability: Poles inside the unit circle.

