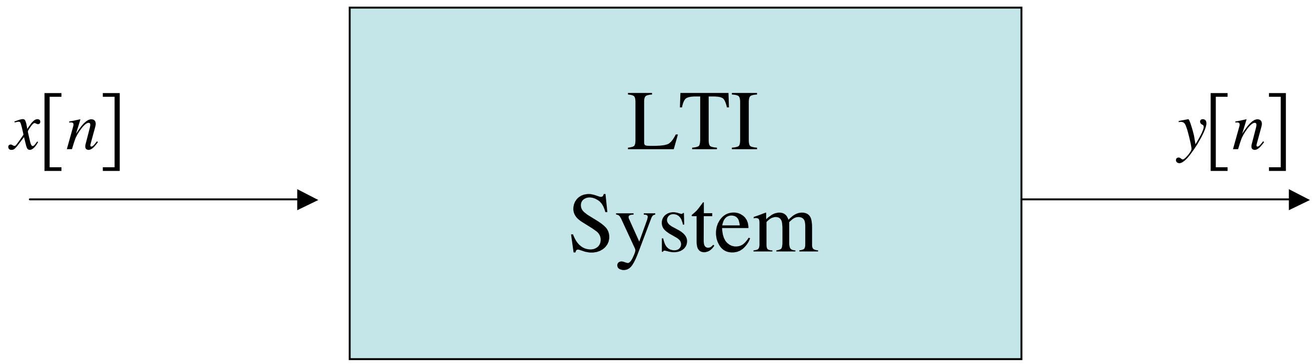


$x[n]$
LTI
System
$y[n]$

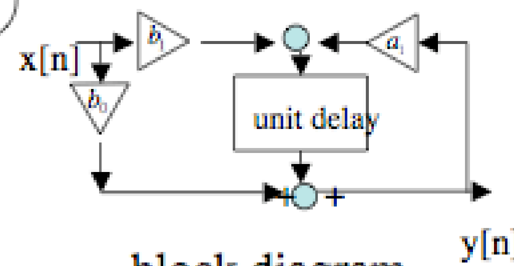
Equivalent ways to represent the system

(1)

$$y[n] = \sum_{l=1}^{N} a_l y[n-l] + \sum_{k=0}^{M} b_k x[n-k] \Leftrightarrow$$

difference equation

(2)



block diagram

$x[n]=\delta[n]$ $\Updownarrow$

$\Updownarrow$ inspection

(3)

$$h[n] = y[n]\Big|_{x[n]=\delta[n]} \overset{z}{\Leftrightarrow} H(z) = \frac{\sum_{k=0}^{M} b_k z^{-k}}{1-\sum_{k=1}^{N} a_k z^{-k}} = \frac{\prod_{i=0}^{M}\left(z-z_{zi}\right)}{\prod_{i=0}^{N}\left(z-z_{pi}\right)}$$

impulse response sequence

(4) system function polynomial

pole-zero locations (5)

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

(6)

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

frequency response

All poles must be inside unit circle for $\mathcal{H}(\omega)$ to converge and the system to be stable.
(FIR filter always stable)

Causal FIR filter

Q: What is the definition of an FIR filter?

A: The output y at each sample n is a weighted sum of the present input, x[n], and past inputs, x[n-1], x[n-2],…, x[n-M].

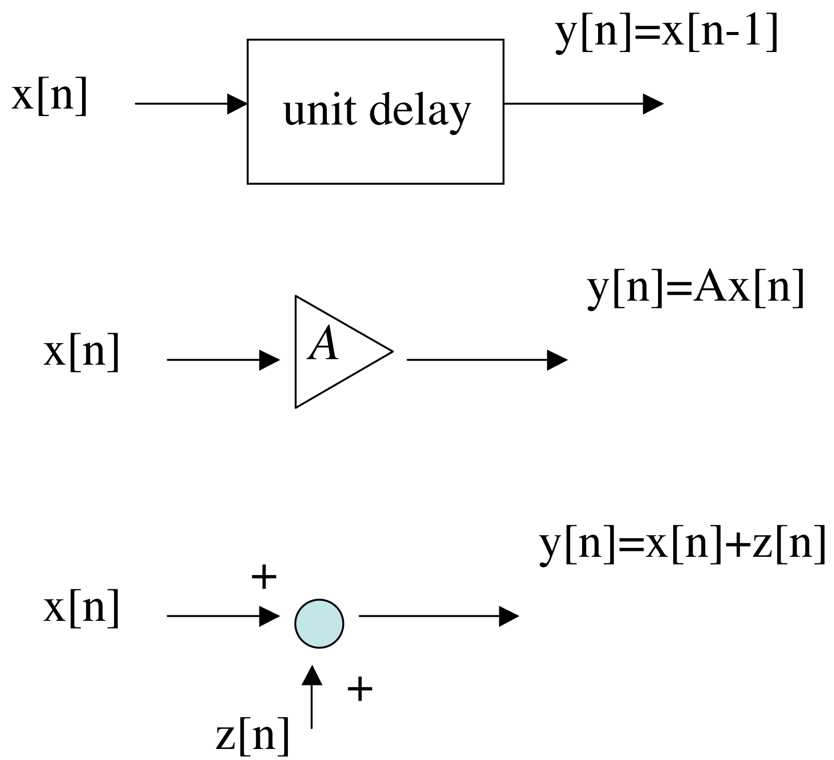
Causal FIR filter

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

$$y[n] = b_0 x[n] + b_1 x[n-1] + \ldots + b_M x[n-M]$$

The output y at each sample n is a weighted sum of the present input, x[n], and past inputs, x[n-1], x[n-2],…, x[n-M].

Block Diagrams



Block Diagrams: Direct Form

$$x[n] = \delta[n] = \{0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0\}$$

$$n = -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4$$

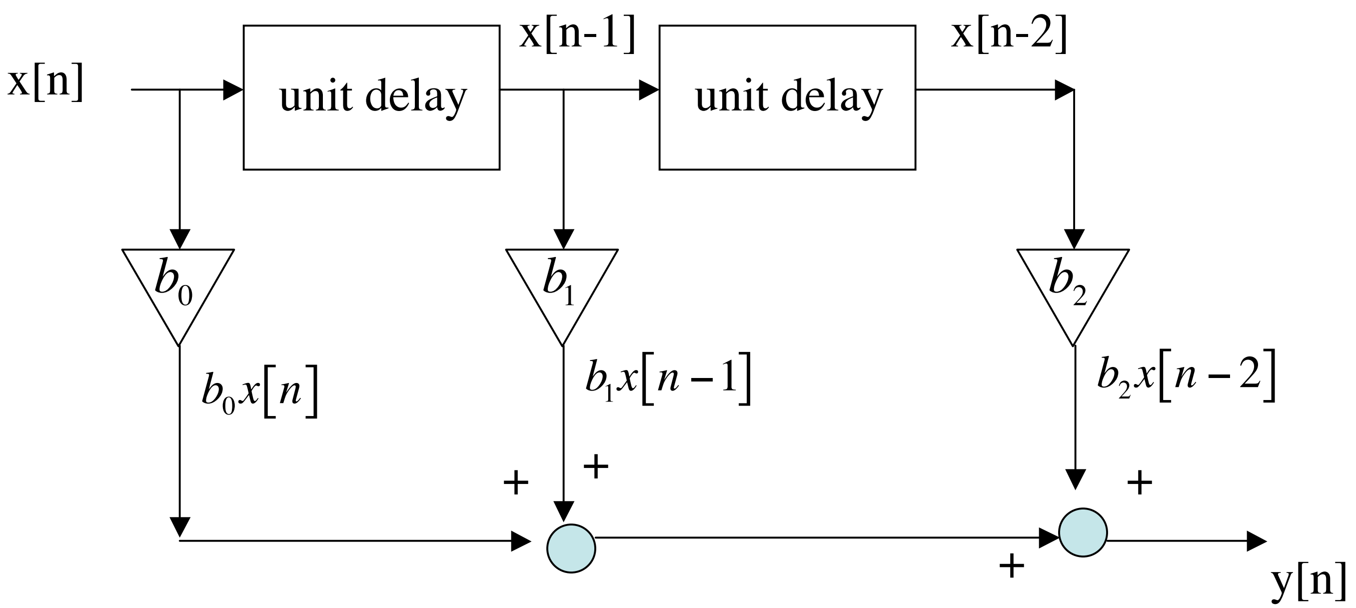
$$y[n] = \sum_{k=0}^{M} b_k x[n-k]$$

$$\{b_0, b_1, b_2\} = \left\{\tfrac{4}{8}, \tfrac{2}{8}, \tfrac{1}{8}\right\}$$

L=3, M=L-1=2

$$h[n] = y[n]\Big|_{x[n]=\delta[n]} = \left\{0 \quad 0 \quad \tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8} \quad 0 \quad 0\right\} = \{0 \quad 0 \quad b_0 \quad b_1 \quad b_2 \quad 0 \quad 0\}$$

$$y[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2]$$



Block Diagrams: Transpose Form

$$x[n] = \delta[n]$$

$$= \{0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0\}$$

$$n = -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4$$

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

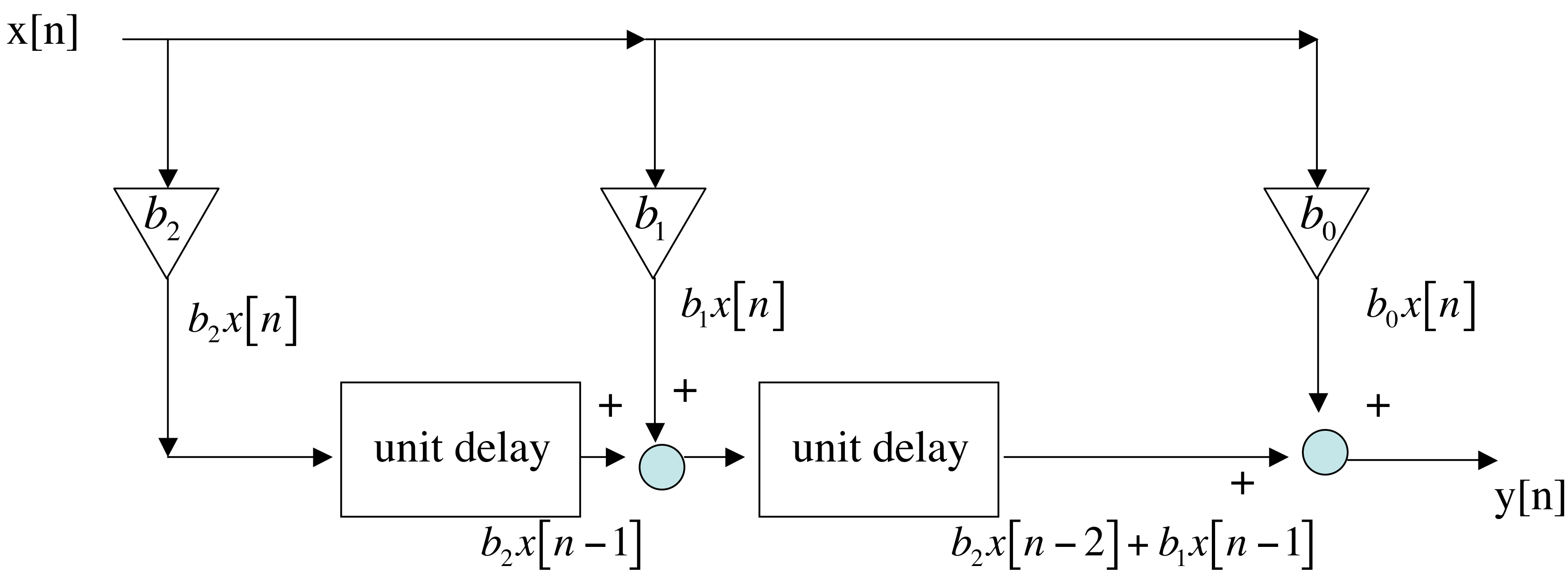
$$\{b_0, b_1, b_2\} = \{\tfrac{4}{8}, \tfrac{2}{8}, \tfrac{1}{8}\}$$

$$h[n] = y[n]\big|_{x[n]=\delta[n]}$$

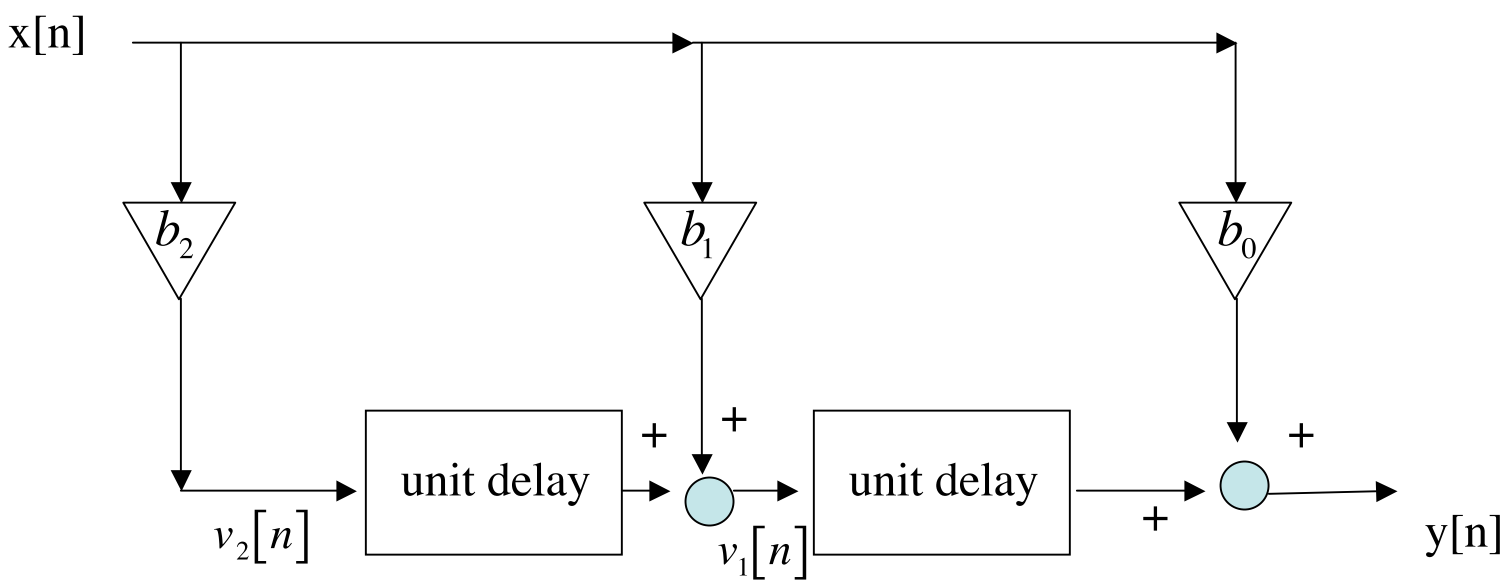
$$= \{0 \quad 0 \quad \tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8} \quad 0 \quad 0\}$$

$$= \{0 \quad 0 \quad b_0 \quad b_1 \quad b_2 \quad 0 \quad 0\}$$

$$y[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2]$$



Block Diagrams to Difference Equations



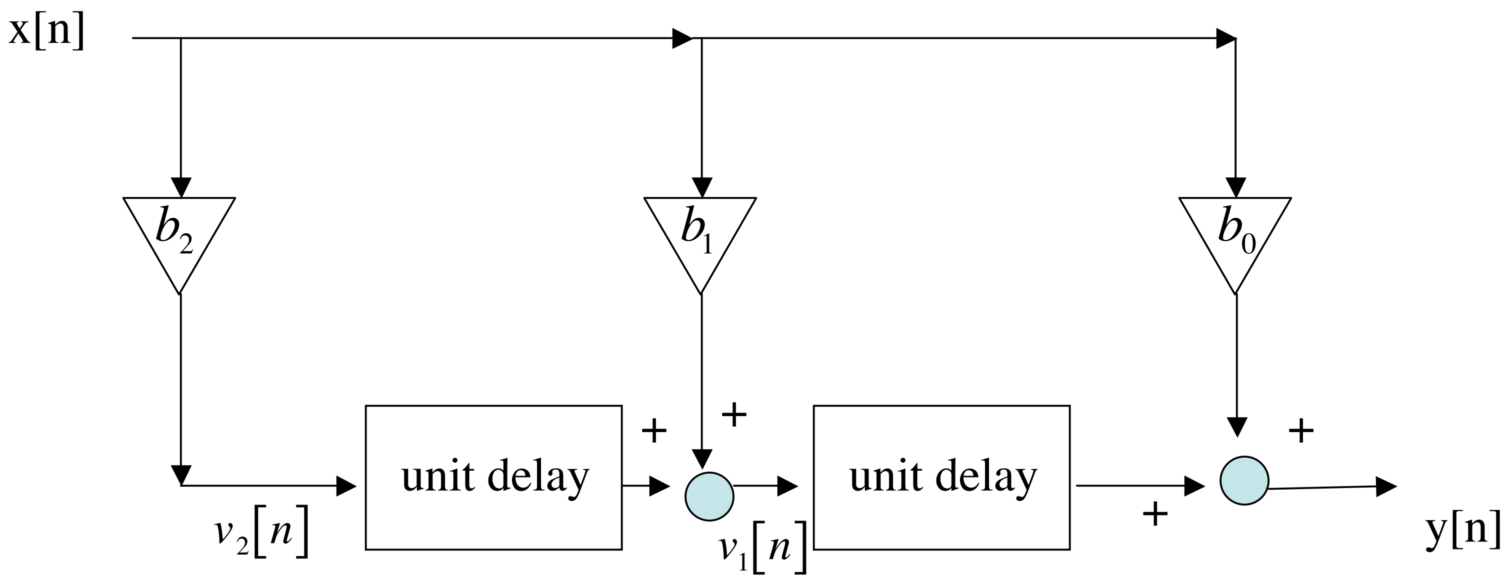
$v_2[n] = b_2 x[n]$ $\quad$ $v_1[n] = b_1 x[n] + v_2[n-1]$ $\quad$ $y[n] = b_0 x[n] + v_1[n-1]$

$$y[n] = b_0 x[n] + v_1[n-1]$$

$$v_1[n] = b_1 x[n] + v_2[n-1]$$

$$v_2[n] = b_2 x[n]$$

Block Diagrams to Difference Equations



$v_2[n] = b_2 x[n]$

$v_1[n] = b_1 x[n] + v_2[n-1]$

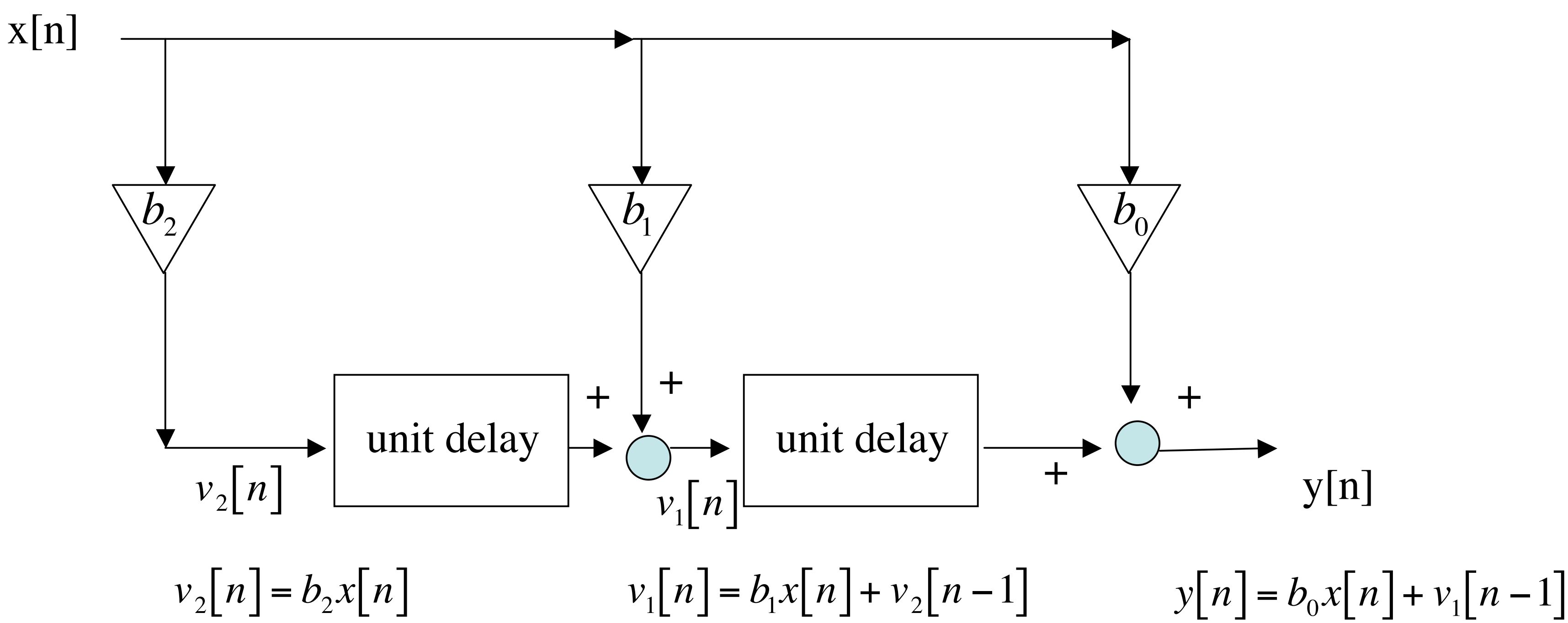
$y[n] = b_0 x[n] + v_1[n-1]$

$$y[n] = b_0 x[n] + v_1[n-1]$$

$$v_1[n-1] = b_1 x[n-1] + v_2[n-2]$$

$$v_2[n-2] = b_2 x[n-2]$$

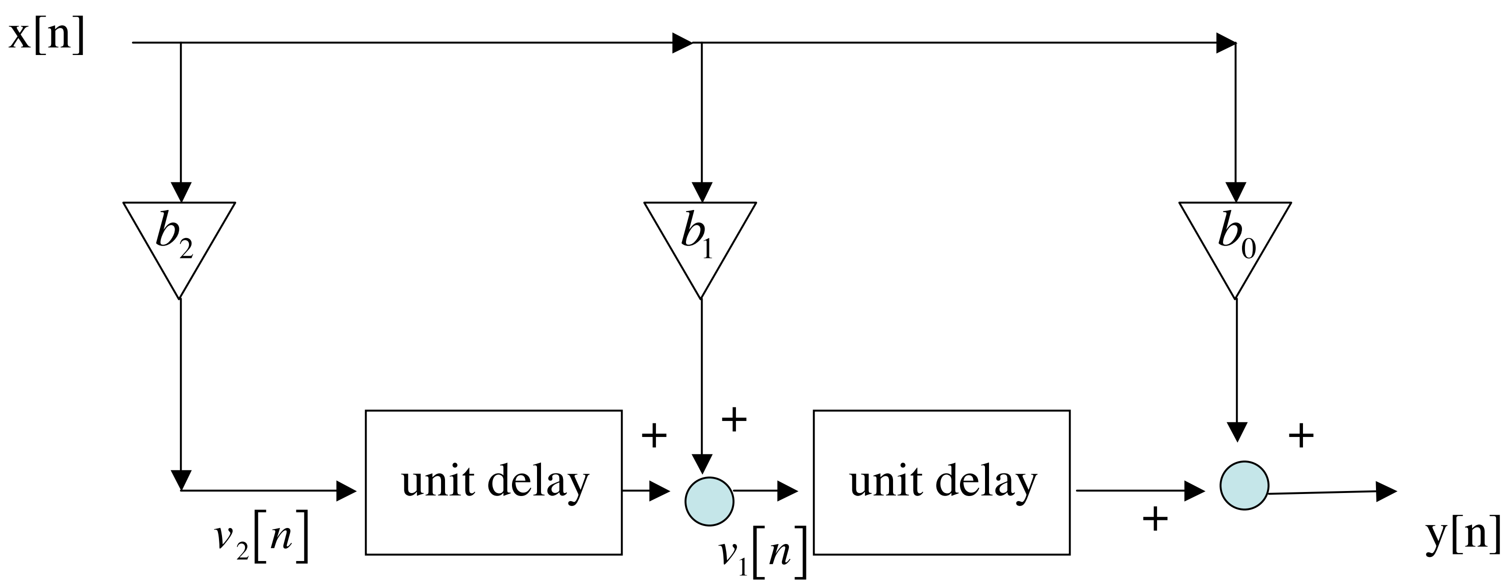
Block Diagrams to Difference Equations



$$y[n] = b_0 x[n] + v_1[n-1]$$

$$v_1[n-1] = b_1 x[n-1] + b_2 x[n-2]$$

Block Diagrams to Difference Equations



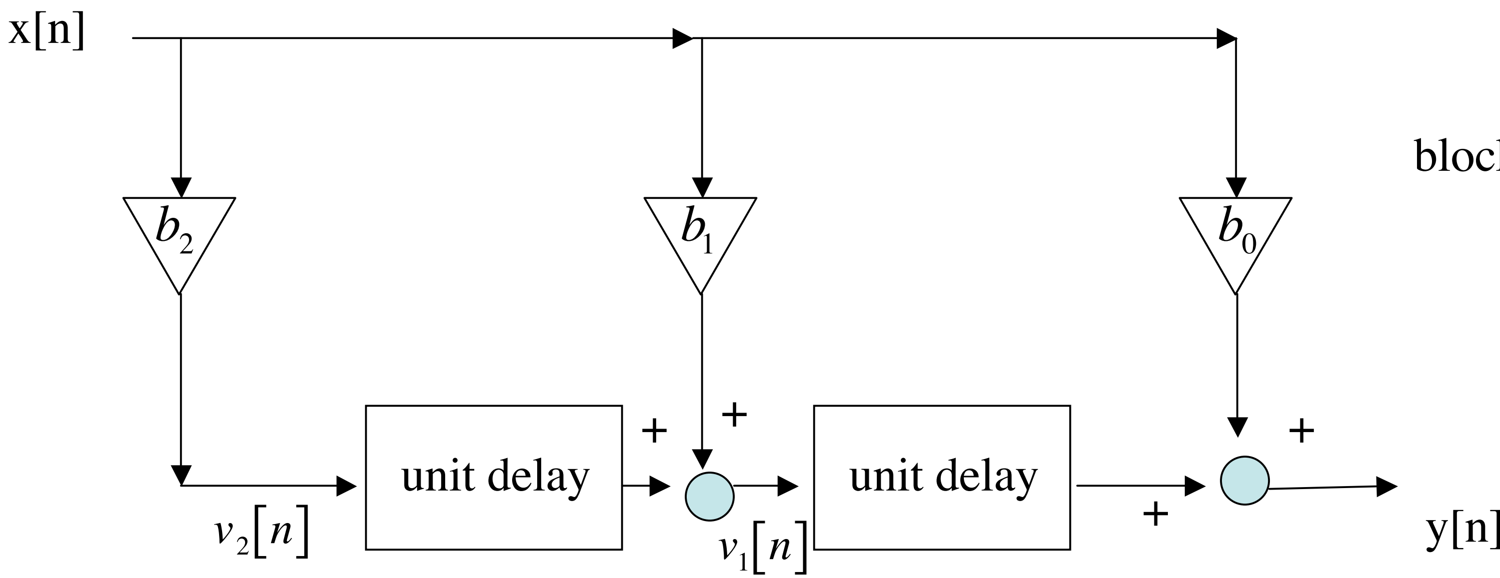
$v_2[n] = b_2 x[n]$

$v_1[n] = b_1 x[n] + v_2[n-1]$

$y[n] = b_0 x[n] + v_1[n-1]$

$$y[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2]$$

Block Diagrams to Difference Equations



block diagram

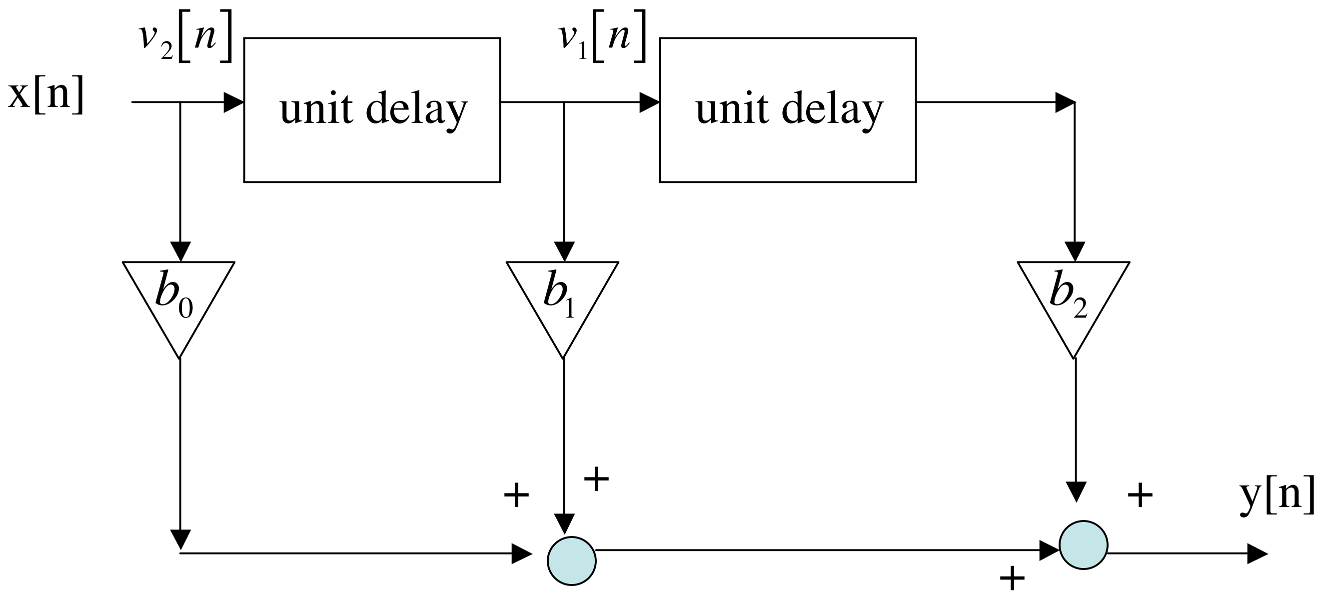
$$v_2[n] = b_2 x[n] \qquad v_1[n] = b_1 x[n] + v_2[n-1] \qquad y[n] = b_0 x[n] + v_1[n-1]$$

$$y[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2]$$ difference equation

$$h[n] = b_0 \delta[n] + b_1 \delta[n-1] + b_2 \delta[n-2]$$ impulse response

equivalent ways
of describing system

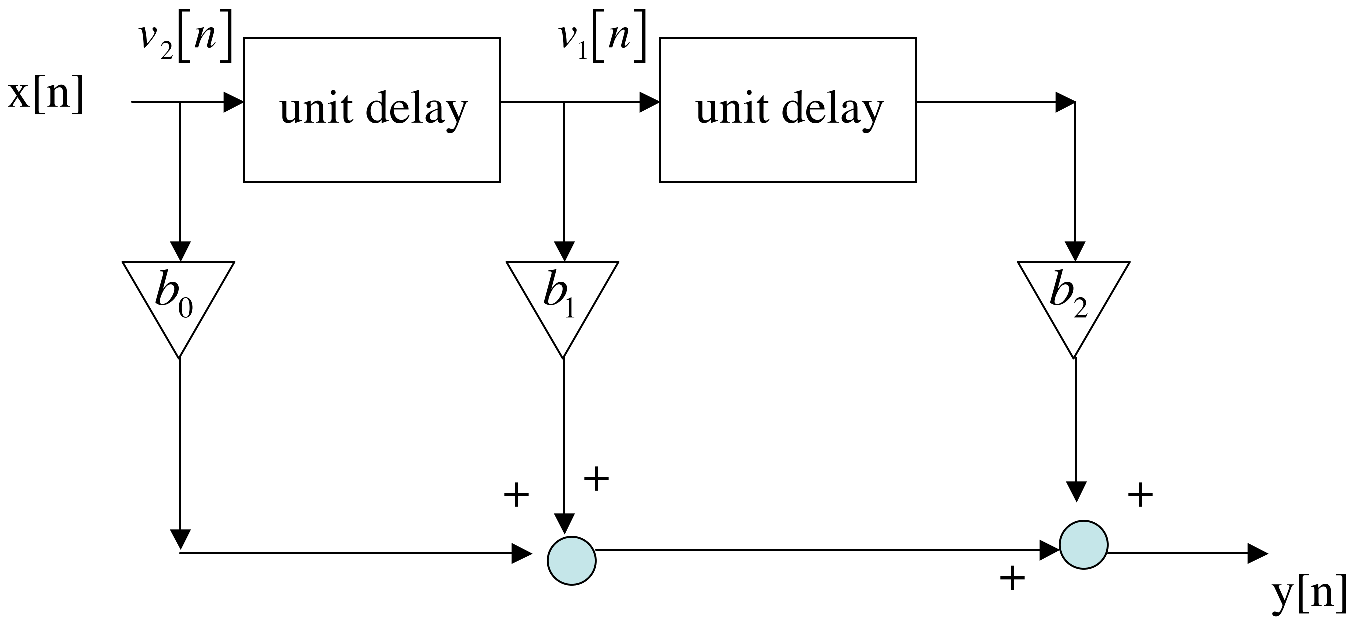
Block Diagrams to Difference Equations



$v_2[n] = x[n]$ $\quad$ $v_1[n] = v_2[n-1]$ $\quad$ $y[n] = b_0 v_2[n] + b_1 v_1[n] + b_2 v_1[n-1]$

$$y[n] = b_0 v_2[n] + b_1 v_1[n] + b_2 v_1[n-1]$$
$$v_1[n] = v_2[n-1]$$
$$v_2[n] = x[n]$$

Block Diagrams to Difference Equations



$v_2[n] = x[n]$

$v_1[n] = v_2[n-1]$

$y[n] = b_0 v_2[n] + b_1 v_1[n] + b_2 v_1[n-1]$

$$y[n] = b_0 v_2[n] + b_1 v_1[n] + b_2 v_1[n-1]$$

$$v_2[n] = x[n]$$

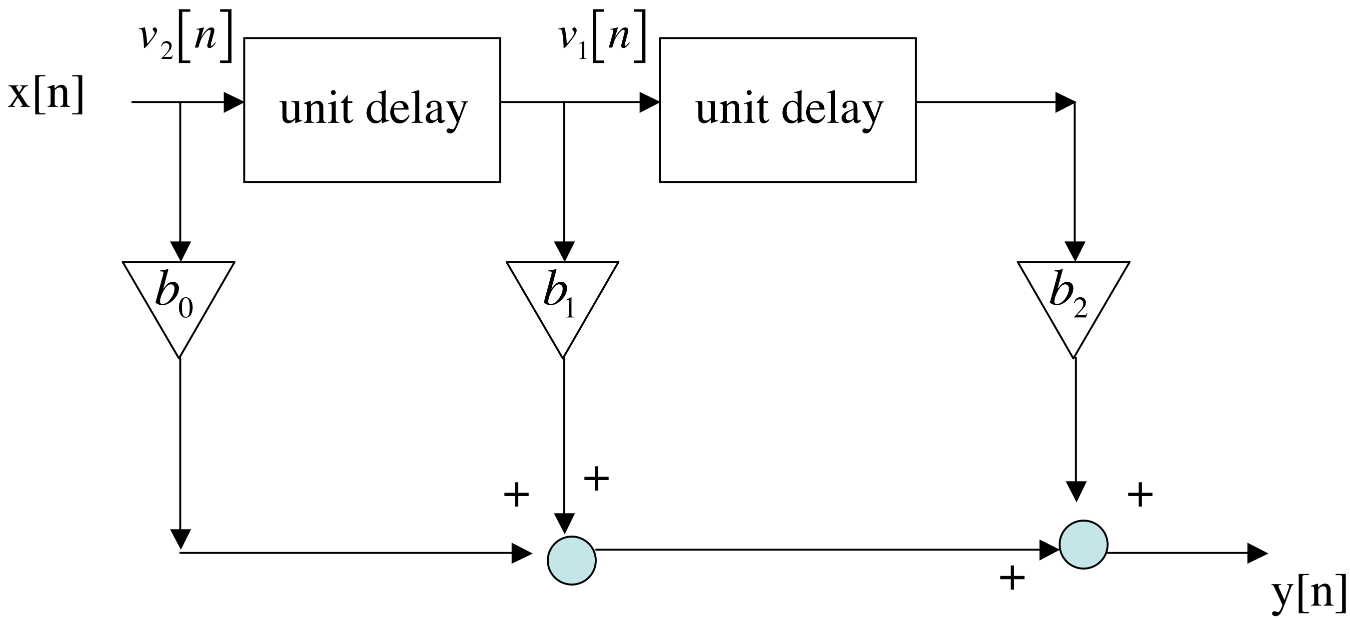
$$v_1[n-1] = v_2[n-2]$$

$$v_2[n-2] = x[n-2]$$

$$v_1[n] = v_2[n-1]$$

$$v_2[n-1] = x[n-1]$$

Block Diagrams to Difference Equations



$v_2[n] = x[n]$

$v_1[n] = v_2[n-1]$

$y[n] = b_0 v_2[n] + b_1 v_1[n] + b_2 v_1[n-1]$

$$y[n] = b_0 x[n] + b_1 x[n-1] + b_2 x[n-2]$$

Impulse response

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

$$x[n] = \delta[n] = \begin{cases} 1 & n = 0 \\ 0 & otherwise \end{cases}$$ Delta function

↓

$$y[n] = h[n] = \sum_{k=0}^{M} b_k \delta[n-k] \qquad \delta[n-k] = \begin{cases} 1 & n = k \\ 0 & otherwise \end{cases}$$

impulse response

Coefficients from impulse response

$$x[n] = \delta[n]$$
$$= \{0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0\}$$
$$n = -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4$$

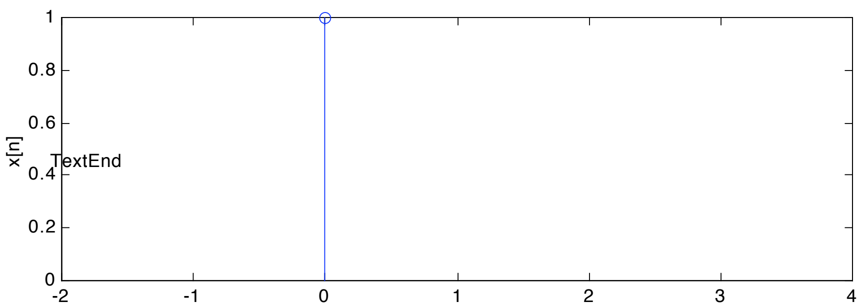
$\longrightarrow$

$$y[n] = \sum_{k=0}^{M} b_k x[n-k]$$
$$\{b_0, b_1, b_2\} = \left\{\tfrac{4}{8}, \tfrac{2}{8}, \tfrac{1}{8}\right\}$$

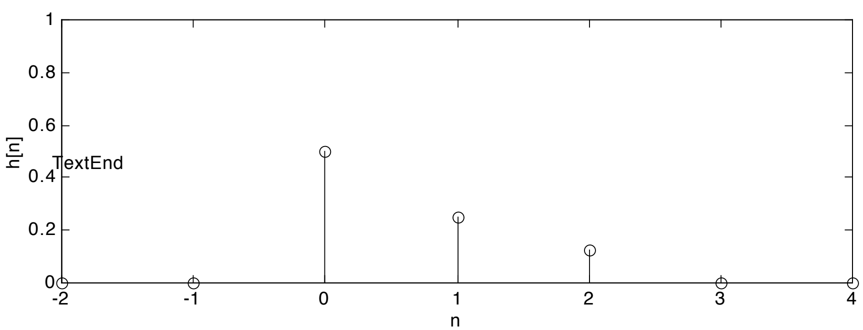
$\longrightarrow$

$$h[n] = y[n]\Big|_{x[n]=\delta[n]}$$
$$= \left\{0 \quad 0 \quad \tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8} \quad 0 \quad 0\right\}$$
$$= \{0 \quad 0 \quad b_0 \quad b_1 \quad b_2 \quad 0 \quad 0\}$$

x[n]



h[n]



Response from 2 impulses

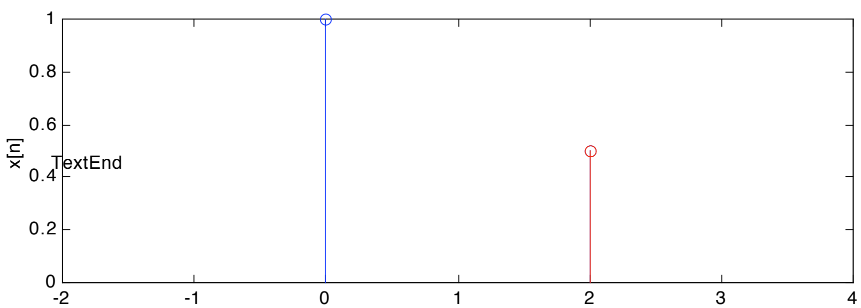
$$x[n] = \delta[n]$$
$$= \{0 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0\}$$
$$n = -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4$$

$$y[n] = \sum_{k=0}^{M} b_k x[n-k]$$
$$\{b_0, b_1, b_2\} = \{\tfrac{4}{8}, \tfrac{2}{8}, \tfrac{1}{8}\}$$

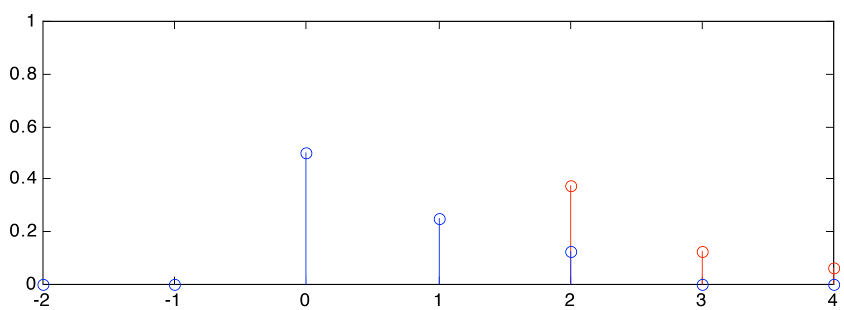
$$y[n] = \{0 \quad 0 \quad \tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8} + \tfrac{4}{16} \quad \tfrac{2}{8} \quad \tfrac{1}{16}\}$$

$$y[n] = \{0 \quad 0 \quad h[0]x[0] \quad h[1]x[0] \quad h[2]x[0] + h[0]x[2] \quad h[1]x[2] \quad h[2]x[2]\}$$

x[n]



y[n]



Sum the responses of each impulse

Response from 2 impulses

$$x[n] = \delta[n]$$

$$= \{0 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0\}$$

$$n = -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4$$

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

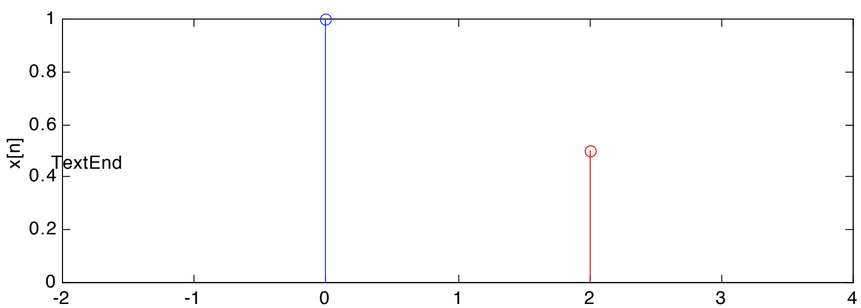
$$h[n] = \{b_0, b_1, b_2\} = \{\tfrac{4}{8}, \tfrac{2}{8}, \tfrac{1}{8}\}$$

$$y[n] =$$

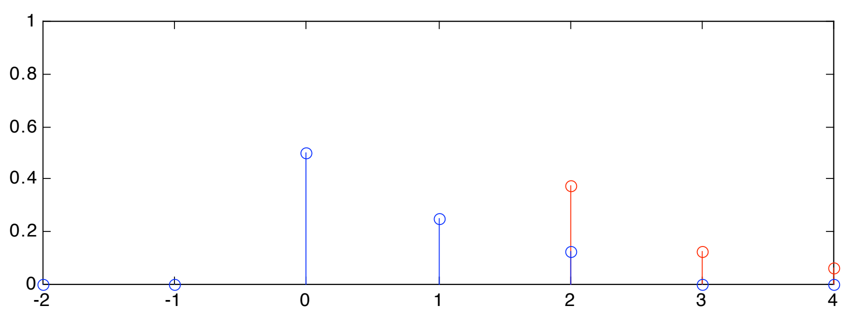
$$\{0 \quad 0 \quad \tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8} + \tfrac{4}{16} \quad \tfrac{2}{8} \quad \tfrac{1}{16}\}$$

$$y[n] = \{0 \quad 0 \quad h[0]x[0] \quad h[1]x[0] \quad h[2]x[0] + h[0]x[2] \quad h[1]x[2] \quad h[2]x[2]\}$$

x[n]



y[n]



$$y[2] = h[0]x[2-0] + h[1]x[2-1] + h[2]x[2-2]$$

$$y[n] = \sum_{k=0}^{3} h[k]x[n-k]$$

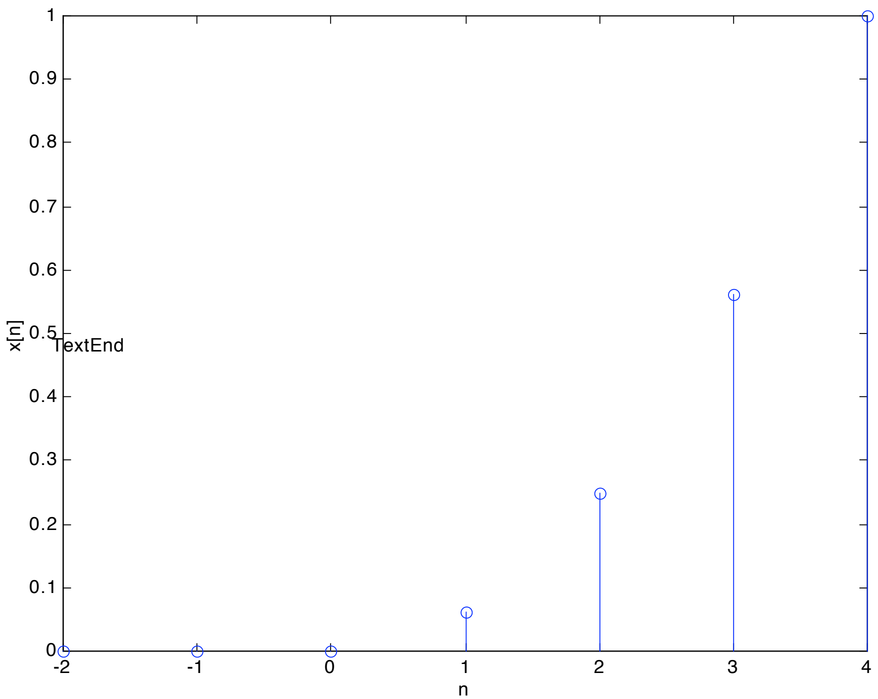
Convolution sum

$$x[n] = \frac{n^2}{16} \cdot u[n]$$

$$u[n] = \begin{cases} 1 & n \ge 0 \\ 0 & n < 0 \end{cases}$$

$$x[n] = \{0 \quad 0 \quad 0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16}\}$$

$$n = -2 \quad -1 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4$$



$$x[n] = 0 \cdot \delta[n] + \tfrac{1}{16} \cdot \delta[n-1] + \tfrac{4}{16} \cdot \delta[n-2] + \tfrac{9}{16} \cdot \delta[n-3] + \tfrac{16}{16} \cdot \delta[n-4]$$

Any discrete signal be thought of a weighted sum of delayed impulses

Convolution

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

$$h[n] = y[n]\Big|_{x[n]=\delta[n]} = \begin{cases} b_n & n = 0,1\ldots M \\ 0 & otherwise \end{cases}$$

↓

$$y[n] = \sum_{k=0}^{M} h[k]x[n-k]$$ convolution sum

or

$$y[n] = h * x$$

The output y[n] is equal to the input x[n] convolved with the unit impulse response h[n].

$$x[n] = \{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\}$$
$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n] = \{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\}$$

L=3, M=L-1=2

$$x[n] = 0 \cdot \delta[n] + \tfrac{1}{16} \cdot \delta[n-1] + \tfrac{4}{16} \cdot \delta[n-2] + \tfrac{9}{16} \cdot \delta[n-3] + \tfrac{16}{16} \cdot \delta[n-4]$$

$$h[n] = \tfrac{4}{8} \cdot \delta[n] + \tfrac{2}{8} \cdot \delta[n-1] + \tfrac{1}{8} \cdot \delta[n-2]$$

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

convolution sum

$$y[0] = h[0]x[0-0] + h[1]x[0-1] + h[2]x[0-2] = \tfrac{4}{8} \cdot 0 + \tfrac{2}{8} \cdot 0 + \tfrac{1}{8} \cdot 0 = 0$$

$$y[1] = h[0]x[1-0] + h[1]x[1-1] + h[2]x[1-2] = \tfrac{4}{8} \cdot \tfrac{1}{16} + \tfrac{2}{8} \cdot 0 + \tfrac{1}{8} \cdot 0 = \tfrac{4}{128}$$

$$x[n] = \{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\}$$
$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n] = \{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\}$$ L=3, M=L-1=2

$$x[n] = 0 \cdot \delta[n] + \tfrac{1}{16} \cdot \delta[n-1] + \tfrac{4}{16} \cdot \delta[n-2] + \tfrac{9}{16} \cdot \delta[n-3] + \tfrac{16}{16} \cdot \delta[n-4]$$
$$h[n] = \tfrac{4}{8} \cdot \delta[n] + \tfrac{2}{8} \cdot \delta[n-1] + \tfrac{1}{8} \cdot \delta[n-2]$$

$$y[n] = \sum_{k=0}^{M} h[k]x[n-k]$$ convolution sum

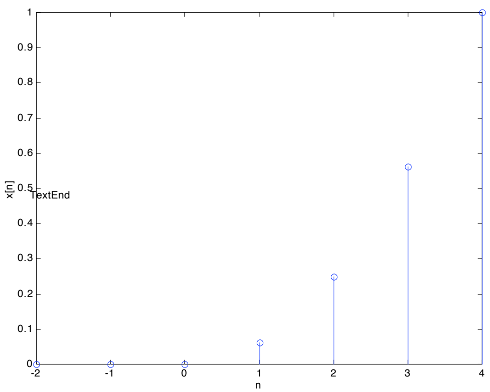
$$y[0] = h[0]x[0-0] + h[1]x[0-1] + h[2]x[0-2] = \tfrac{4}{8} \cdot 0 + \tfrac{2}{8} \cdot 0 + \tfrac{1}{8} \cdot 0 = 0$$
$$y[1] = h[0]x[1-0] + h[1]x[1-1] + h[2]x[1-2] = \tfrac{4}{8} \cdot \tfrac{1}{16} + \tfrac{2}{8} \cdot 0 + \tfrac{1}{8} \cdot 0 = \tfrac{4}{128}$$
$$y[2] = h[0]x[2-0] + h[1]x[2-1] + h[2]x[2-2] = \tfrac{4}{8} \cdot \tfrac{4}{16} + \tfrac{2}{8} \cdot \tfrac{1}{16} + \tfrac{1}{8} \cdot 0 = \tfrac{18}{16}$$
$$y[3] = h[0]x[3-0] + h[1]x[3-1] + h[2]x[3-2] = \tfrac{4}{8} \cdot \tfrac{9}{16} + \tfrac{2}{8} \cdot \tfrac{4}{16} + \tfrac{1}{8} \cdot \tfrac{1}{16} = \tfrac{45}{16}$$
$$y[4] = h[0]x[4-0] + h[1]x[4-1] + h[2]x[4-2] = \tfrac{4}{8} \cdot \tfrac{16}{16} + \tfrac{2}{8} \cdot \tfrac{9}{16} + \tfrac{1}{8} \cdot \tfrac{4}{16} = \tfrac{86}{16}$$
$$y[5] = h[0]x[5-0] + h[1]x[5-1] + h[2]x[5-2] = \tfrac{4}{8} \cdot 0 + \tfrac{2}{8} \cdot \tfrac{16}{16} + \tfrac{1}{8} \cdot \tfrac{9}{16} = \tfrac{41}{16}$$
$$y[6] = h[0]x[6-0] + h[1]x[6-1] + h[2]x[6-2] = \tfrac{4}{8} \cdot 0 + \tfrac{2}{8} \cdot 0 + \tfrac{1}{8} \cdot \tfrac{16}{16} = \tfrac{16}{128}$$

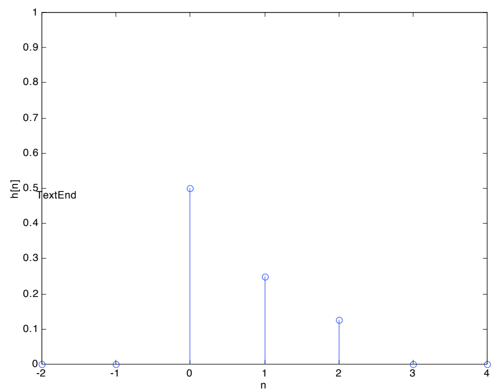
$$x[n] = \frac{n^2}{16} \cdot u[n] \longrightarrow \boxed{y[n] = \sum_{k=0}^{M} h[k]x[n-k]} \longrightarrow y[n]$$

$$x[n] = \{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\}$$

$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n] = \left\{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\right\}$$

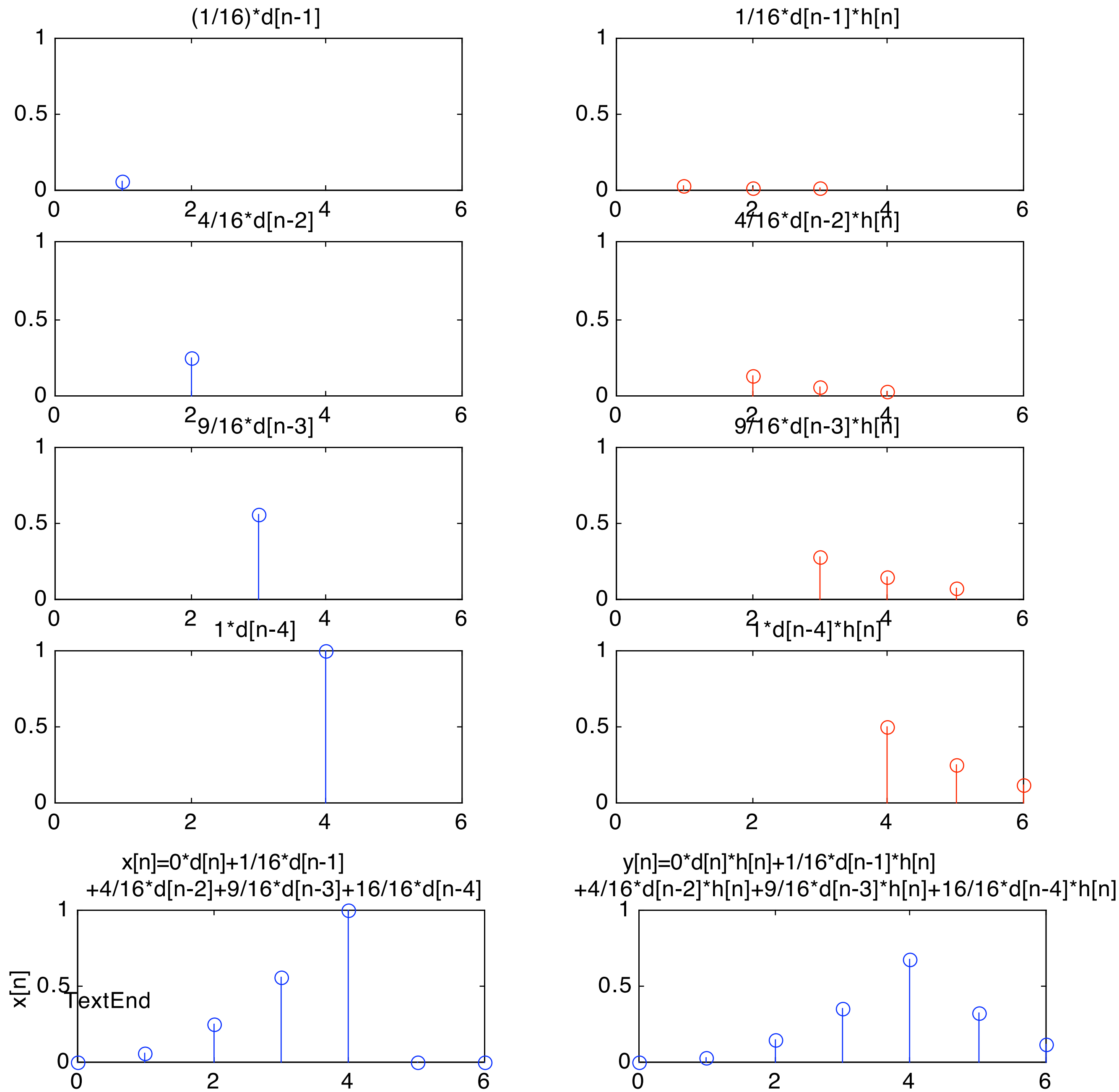




$$x[n] \quad * \quad h[n] \quad = \quad y[n]$$

$$x[n]=\left\{0 \quad \frac{1}{16} \quad \frac{4}{16} \quad \frac{9}{16} \quad \frac{16}{16} \quad 0 \quad 0\right\}$$

$$h[n]=\left\{\frac{4}{8} \quad \frac{2}{8} \quad \frac{1}{8}\right\}$$



$$x[n] = \{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\}$$
$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n] = \{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\}$$

x[n]	0	1/16	4/16	9/16	16/16	0	0
h[n]	4/8	2/8	1/8				

==

	0	0	0

==

$$x[n] = \{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\}$$
$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n] = \{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\}$$

x[n]	0	1/16	4/16	9/16	16/16	0	0
h[n]		4/8	2/8	1/8			

==

0	0	0	
	4/128	2/128	1/128

==

$$x[n] = \left\{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\right\}$$
$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n] = \left\{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\right\}$$

x[n]	0	1/16	4/16	9/16	16/16	0	0
h[n]			4/8	2/8	1/8		

==

0	0	0		
	4/128	2/128	1/128	
		16/128	8/128	4/128

==

$$x[n] = \left\{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\right\}$$
$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n] = \left\{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\right\}$$

x[n]	0	1/16	4/16	9/16	16/16	0	0
h[n]				4/8	2/8	1/8	

======================================

0	0	0				
	4/128	2/128	1/128			
		16/128	8/128	4/128		
			36/128	18/128	9/128	

======================================

$$x[n] = \left\{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\right\}$$

$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

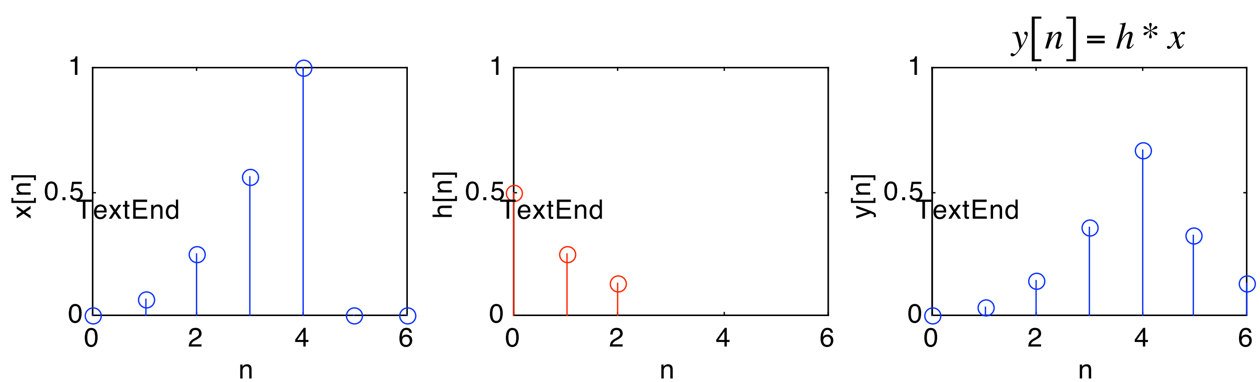
$$h[n] = \left\{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\right\}$$

x[n]	0	1/16	4/16	9/16	16/16	0	0
h[n]					4/8	2/8	1/8
	0	0	0				
		4/128	2/128	1/128			
			16/128	8/128	4/128		
				36/128	18/128	9/128	
					64/128	32/128	16/128
	0	4/128	18/128	45/128	86/128	41/128	16/128

$$x[n]=\{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\}$$
$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n]=\{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\}$$

x[n]	0	1/16	4/16	9/16	16/16	0	0
h[n]	4/8	2/8	1/8				
	0	0	0				
		4/128	2/128	1/128			
			16/128	8/128	4/128		
				36/128	18/128	9/128	
					64/128	32/128	16/128
	0	4/128	18/128	45/128	86/128	41/128	16/128



$$x[n] = \{0 \quad \tfrac{1}{16} \quad \tfrac{4}{16} \quad \tfrac{9}{16} \quad \tfrac{16}{16} \quad 0 \quad 0\}$$
$$n = 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6$$

$$h[n] = \{\tfrac{4}{8} \quad \tfrac{2}{8} \quad \tfrac{1}{8}\}$$

x[n]	0	1/16	4/16	9/16	16/16	0	0
h[n]	4/8	2/8	1/8				

===================================

x[n]*h[n]	0	4/128	18/128	45/128	86/128	41/128	16/128
	0	0.3125	0.1406	0.3516	0.6719	0.3203	0.125

MATLAB

```
»conv([4/8, 2/8, 1/8], [0, 1/16, 4/16, 9/16, 16/16])
ans =
     0    0.0312    0.1406    0.3516    0.6719    0.3203    0.1250
```

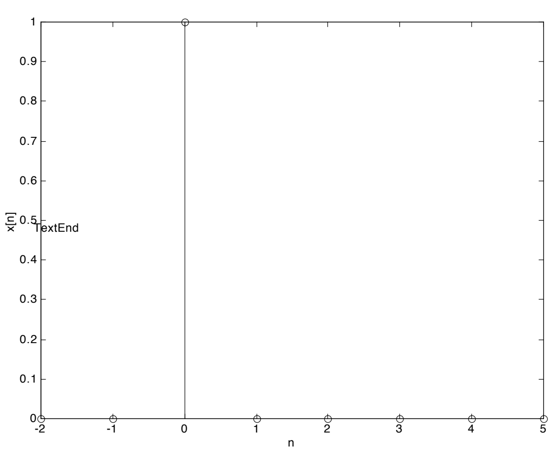
$$\begin{bmatrix} n & x[n] \\ -2 & 0 \\ -1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 2 & 0 \\ 3 & 0 \end{bmatrix}$$

$x[n] = \delta[n]$ → **Causal FIR filter** ($b_0 = 1, b_1 = 3, b_2 = 1$) → $y[n] = ?$

$y[n] = ?$

$h[n] = ?$

$y[1] = ?$



n	$x[n]$
-2	0
-1	0
0	1
1	0
2	0
3	0

$x[n]=\delta[n]$ → **Causal FIR filter** $b_0=1, b_1=3, b_2=1$ → $h[n]=y[n]\big|_{x[n]=\delta[n]}$

	$y[n]$
	0
	0
b_0	1
b_1	3
b_2	1
	0

$$y[n]=1x[n]+3x[n-1]+1x[n-2]$$

$$h[n]=y[n]=1\delta[n]+3\delta[n-1]+1\delta[n-2]$$

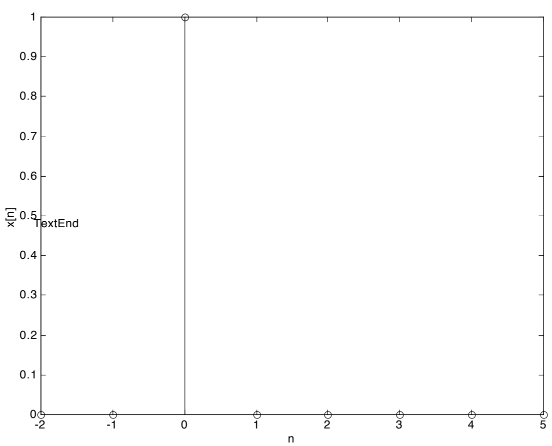
$$h[n]=b_n$$

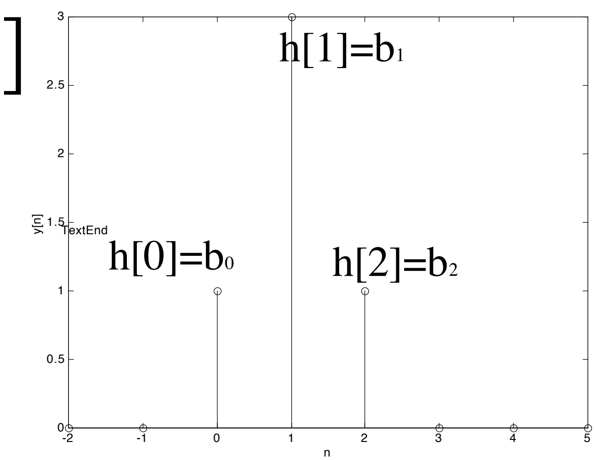
$$h[1]=1\delta[1]+3\delta[1-1]+1\delta[1-2]$$

$$h[1]=1\delta[1]+3\delta[0]+1\delta[-1]$$

$$h[1]=1(0)+3(1)+1(0)$$

$$h[1]=3$$





$$\begin{bmatrix} n & x[n] \\ 0 & 0 \\ 1 & 0.88 \\ 2 & -0.84 \\ 3 & -0.06 \\ 4 & 0.90 \\ 5 & -0.81 \end{bmatrix}$$

$x[n] = \sin(2\pi \cdot 0.33n)u[n]$ →

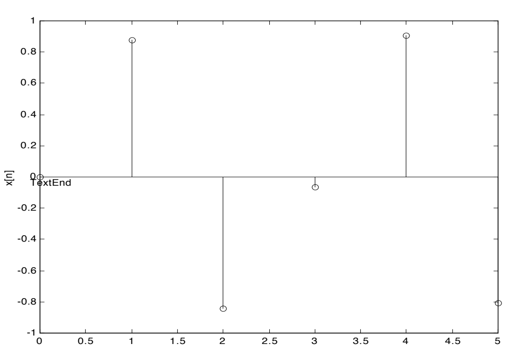
Causal FIR filter

$b_0 = 1, b_1 = 3, b_2 = 1$

$h[n] = [1, 3, 1]$

→ $y[n] = ?$

$y[3] = ?$



$$\begin{bmatrix} n & x[n] \\ 0 & 0 \\ 1 & 0.88 \\ 2 & -0.84 \\ 3 & -0.06 \\ 4 & 0.90 \\ 5 & -0.81 \end{bmatrix} \xrightarrow{x[n] = \sin(2\pi \cdot 0.33n)u[n]}$$

Causal FIR filter

$$b_0 = 1, b_1 = 3, b_2 = 1$$

$$h[n] = [1, 3, 1]$$

$$\longrightarrow \begin{bmatrix} n & y[n] \\ 0 & 0 \\ 1 & 0.88 \\ 2 & 1.78 \\ 3 & -1.72 \\ 4 & -0.13 \\ 5 & 1.84 \end{bmatrix}$$

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

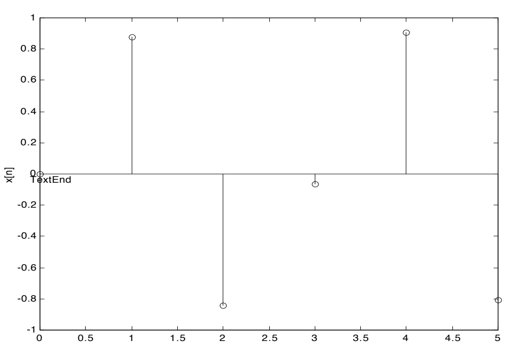
$$y[n] = 1x[n] + 3x[n-1] + 1x[n-2]$$

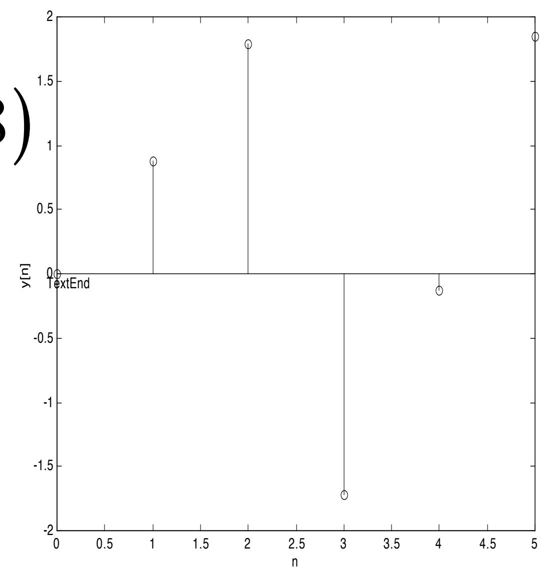
$$y[3] = 1x[3] + 3x[3-1] + 1x[3-2]$$

$$y[3] = 1x[3] + 3x[2] + 1x[1]$$

$$y[3] = 1(-0.06) + 3(-0.84) + 1(0.88)$$

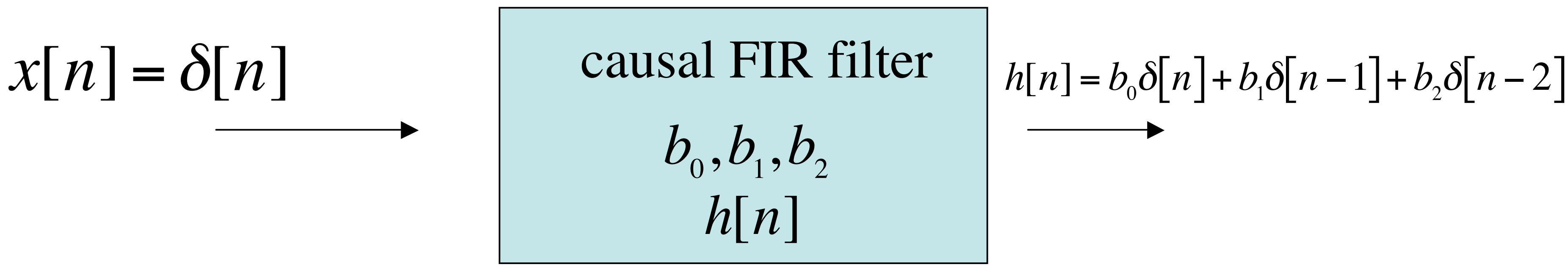
$$y[3] = -1.72$$

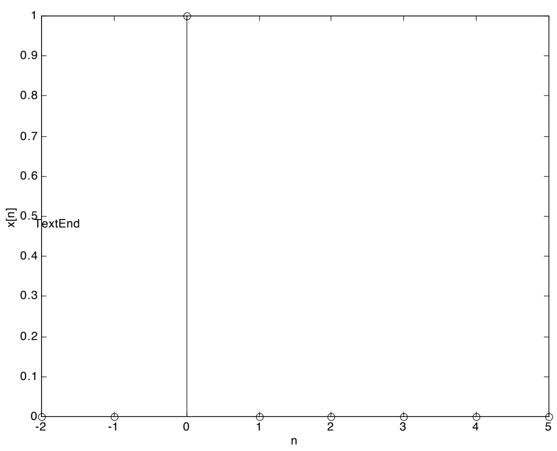


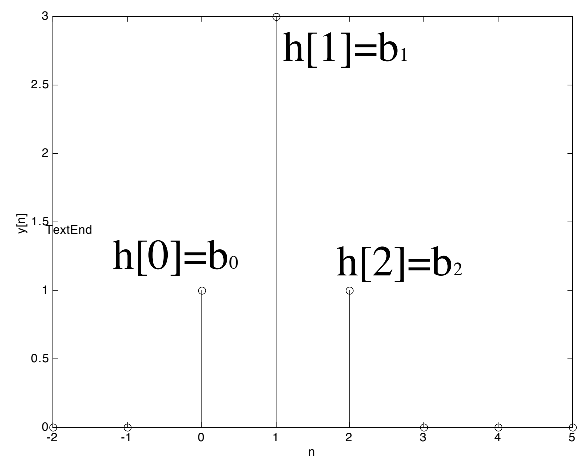


Graphical convolution by decomposition

1. Remember impulse response





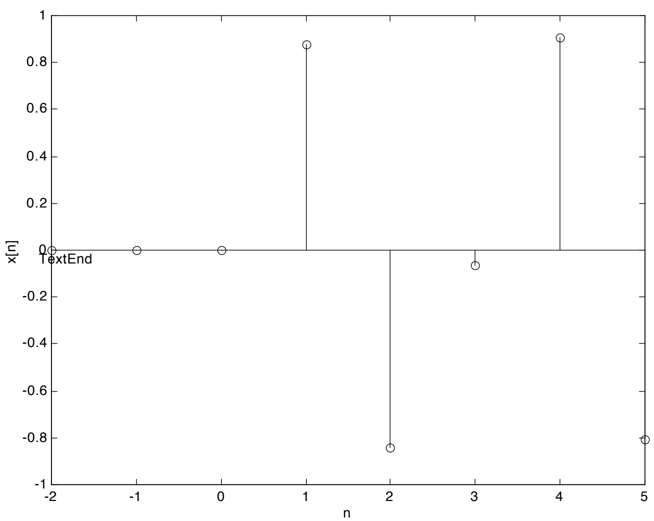


Graphical convolution by decomposition

2. Decompose input into sum of scaled delayed impulses

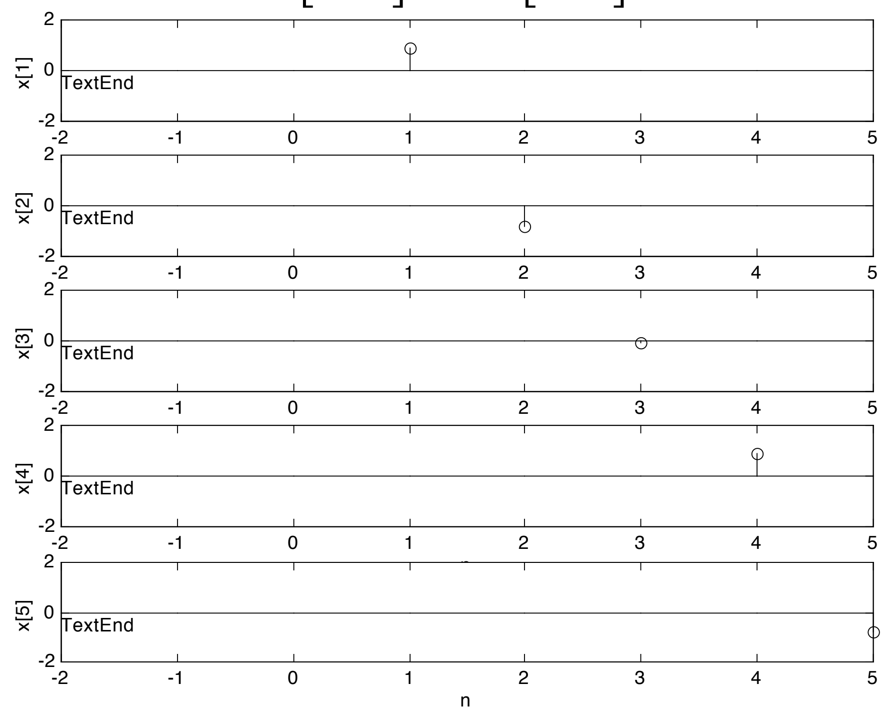
Input

$$x[n] = \sin(2\pi \cdot 0.33n)u[n]$$



Input as impulses

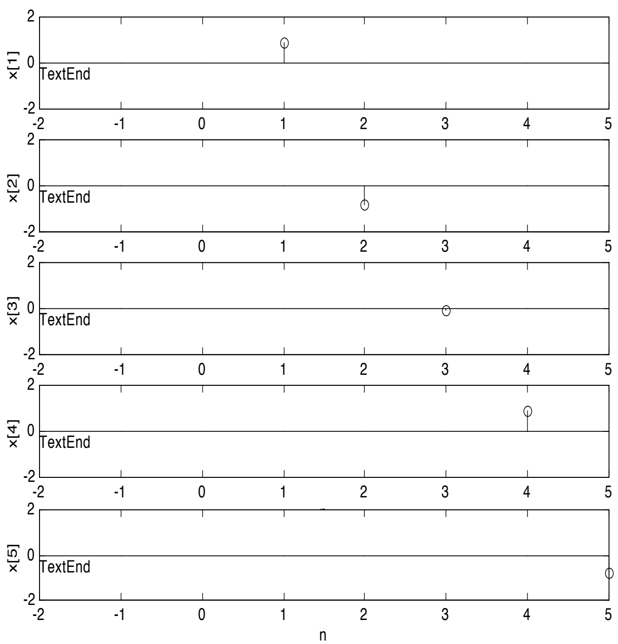
$$x[n] = 0.88\delta[n-1] - 0.84\delta[n-2] - 0.06\delta[n-3]$$
$$+ 0.90\delta[n-4] - 0.81\delta[n-5]$$



Graphical convolution by decomposition

3. find impulse responses to each impulse

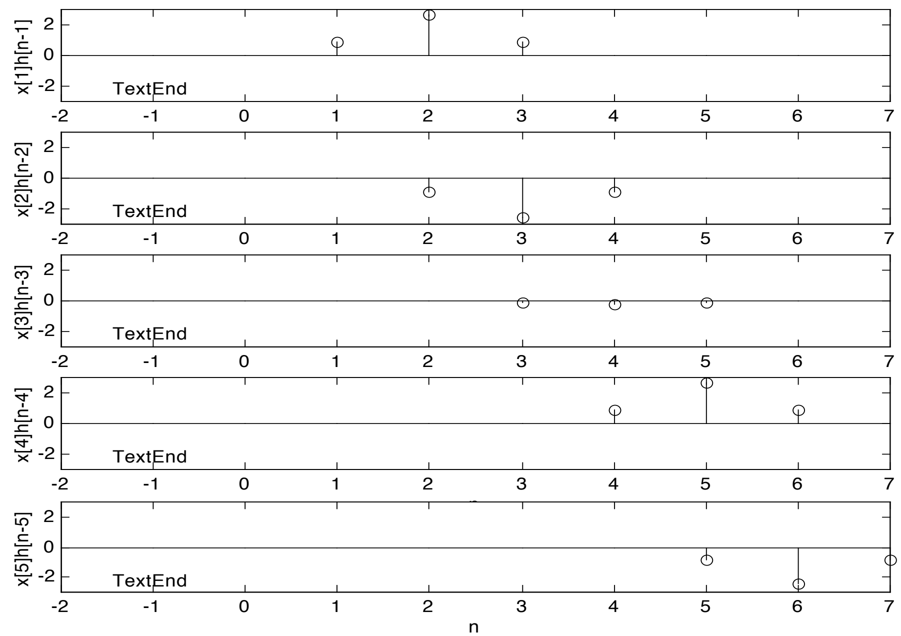
Input as impulses



FIR →

Impulse responses

$$h[n] = b_0\delta[n] + b_1\delta[n-1] + b_2\delta[n-2]$$



$$x_1[n-1] = 0.88\delta[n-1]$$

$$x_1[n-2] = -0.84\delta[n-2]$$

$$x_1[n-3] = -0.06\delta[n-3]$$

$$y_1[n] = 0.88(h[n-1])$$

$$y_2[n] = -0.84(h[n-2])$$

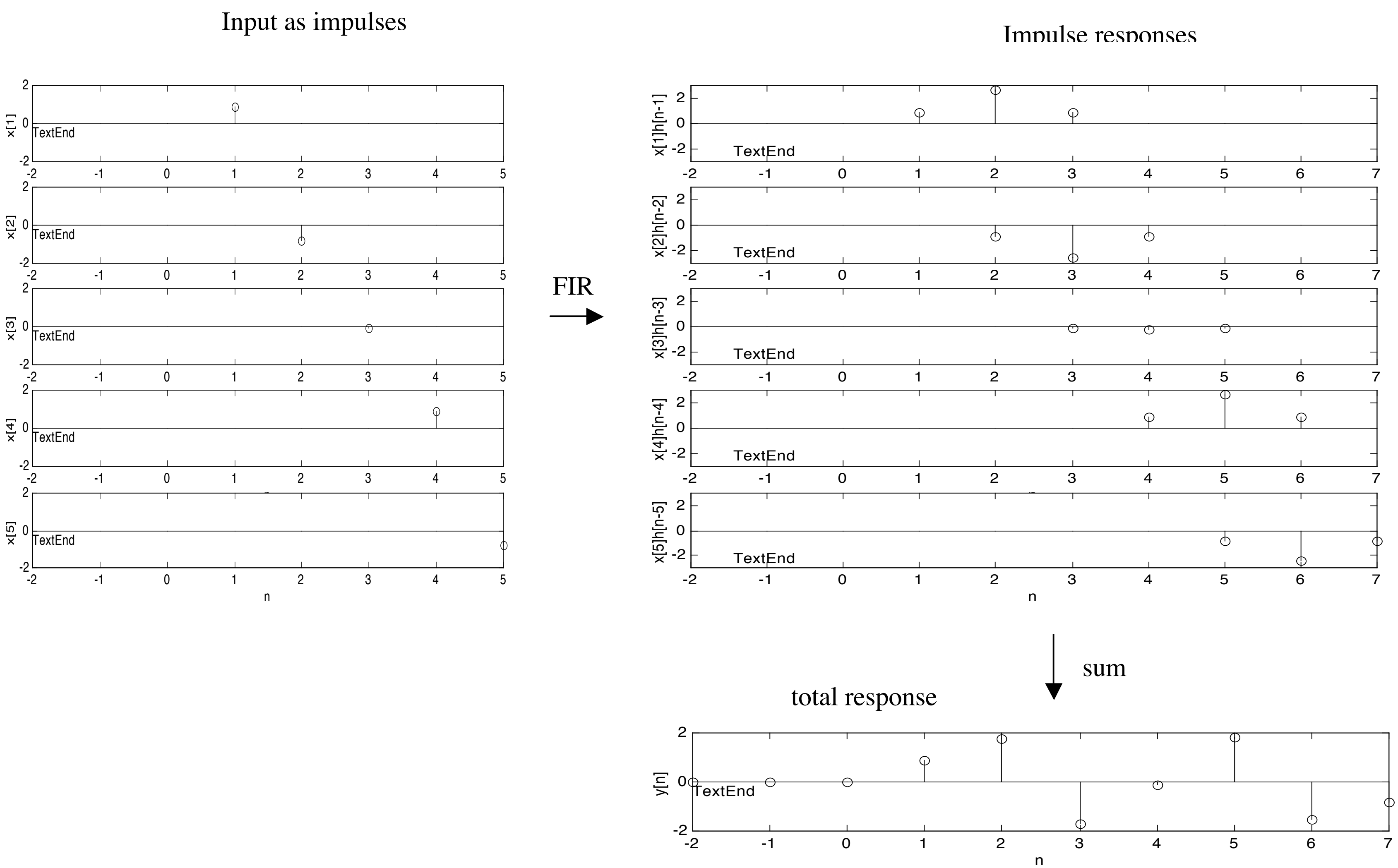
$$y_3[n] = -0.06(h[n-3])$$

$$y_4[n] = -0.06(h[n-4])$$

$$y_5[n] = -0.81(h[n-5])$$

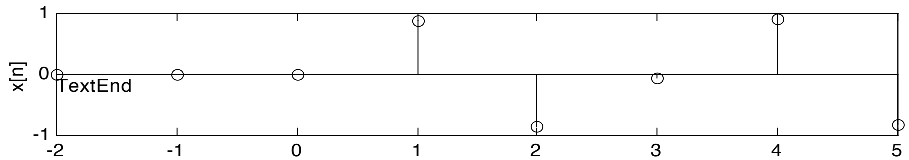
Graphical convolution by decomposition

3. sum impulse responses to get total response

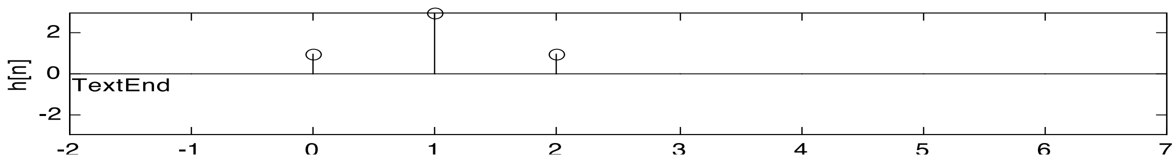


Graphical convolution by decomposition

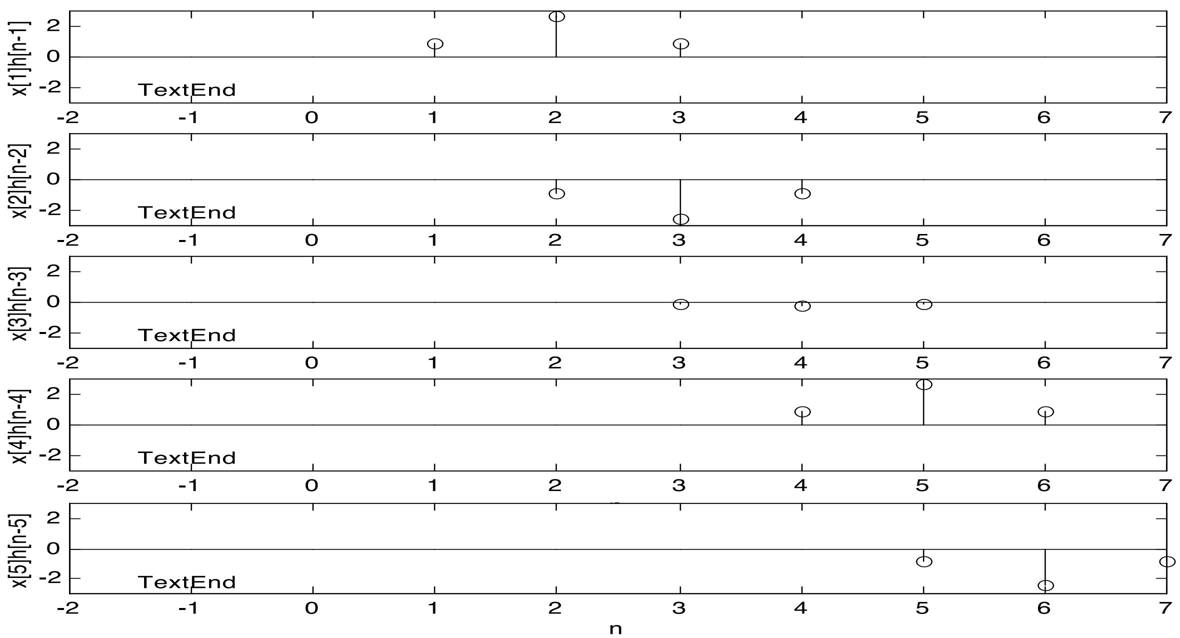
Input



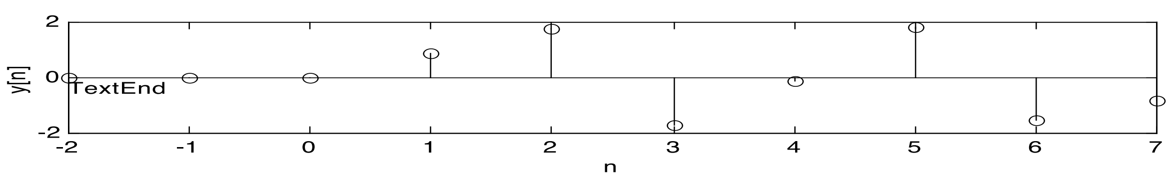
Impulse response



Impulse responses



total response



Synthetic polynomial multiplication

n	-2	-1	0	1	2	3	4	5
x[n]	0	0	0	0.88	-0.84	-0.06	0.90	-0.81
h[n]			1	3	1			
=====	=====	=====	=====	=====	=====	=====	=====	=====
			0	0	0			
				0.88	2.64	0.88		
					-0.84	-2.52	-0.84	
						-0.06	-0.18	-0.06
							0.9	2.7
								-0.81
=====	=====	=====	=====	=====	=====	=====	=====	=====
y[n]	0	0	0	0.88	1.80	-1.7	-0.12	1.83

try $h_1[n] * h_2[n]$ $h_1[n]=[1/3,1/3,1/3]$ $h_2[n]=[1/3,-1/3,1/3]$

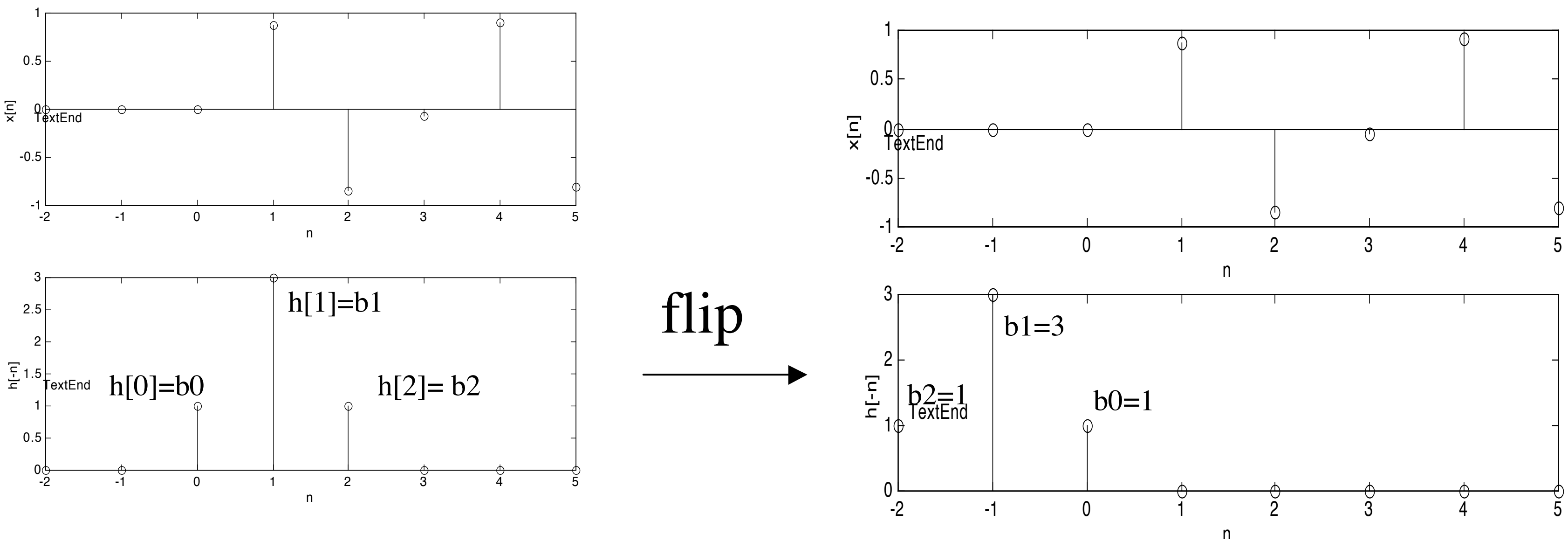
Graphical Convolution

$$y[n] = h[n] * x[n] = x[n] * h[n]$$

$$y[n] = \sum_{k=0}^{M} h[k]x[n-k] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$

sum

multiply shift flip



$$y[n] = x[n-2]h[n-(n-2)] + x[n-1]h[n-(n-1)] + x[n]h[n-n]$$

$$y[n] = h[0]x[n] + h[1]x[n-1] + h[2]x[n-2]$$

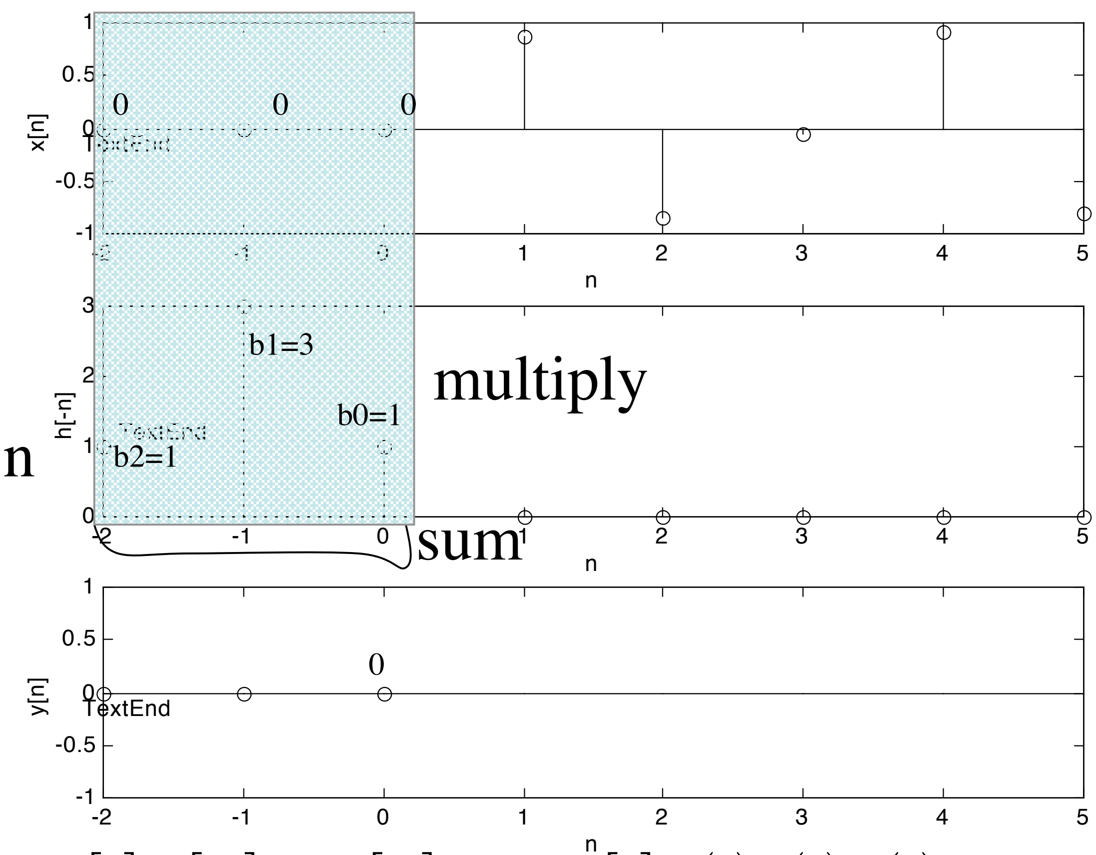
Graphical Convolution

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

sum, multiply, shift, flip

n=0

flip/
shift by n



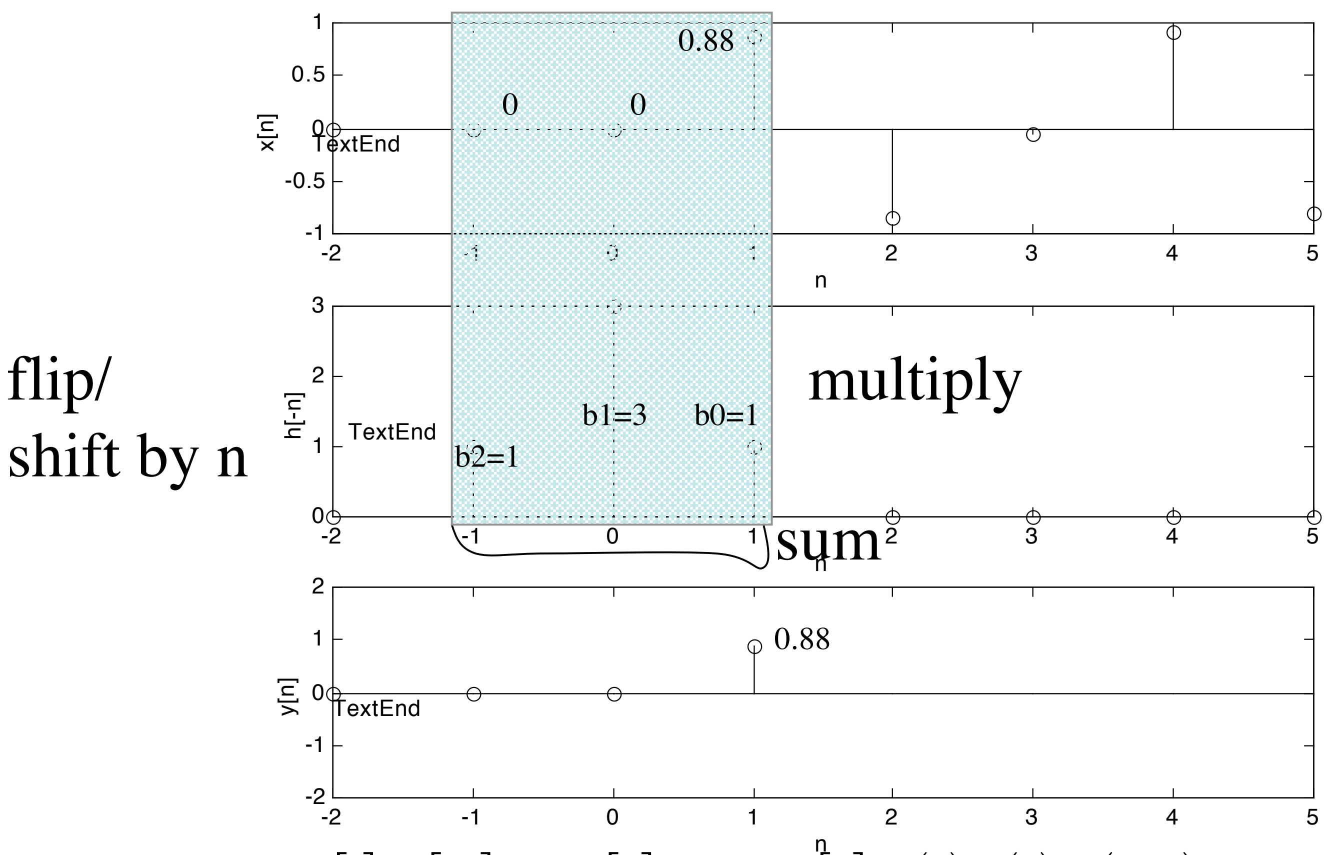
$$y[0] = x[-2]h[2] + x[-1]h[1] + x[0]h[0] \quad = (0)1 + (0)3 + (0)1 = 0$$

Graphical Convolution

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

sum → $\sum$; multiply → $x[k]h$; shift → $h[n$; flip → $-k$

n=1



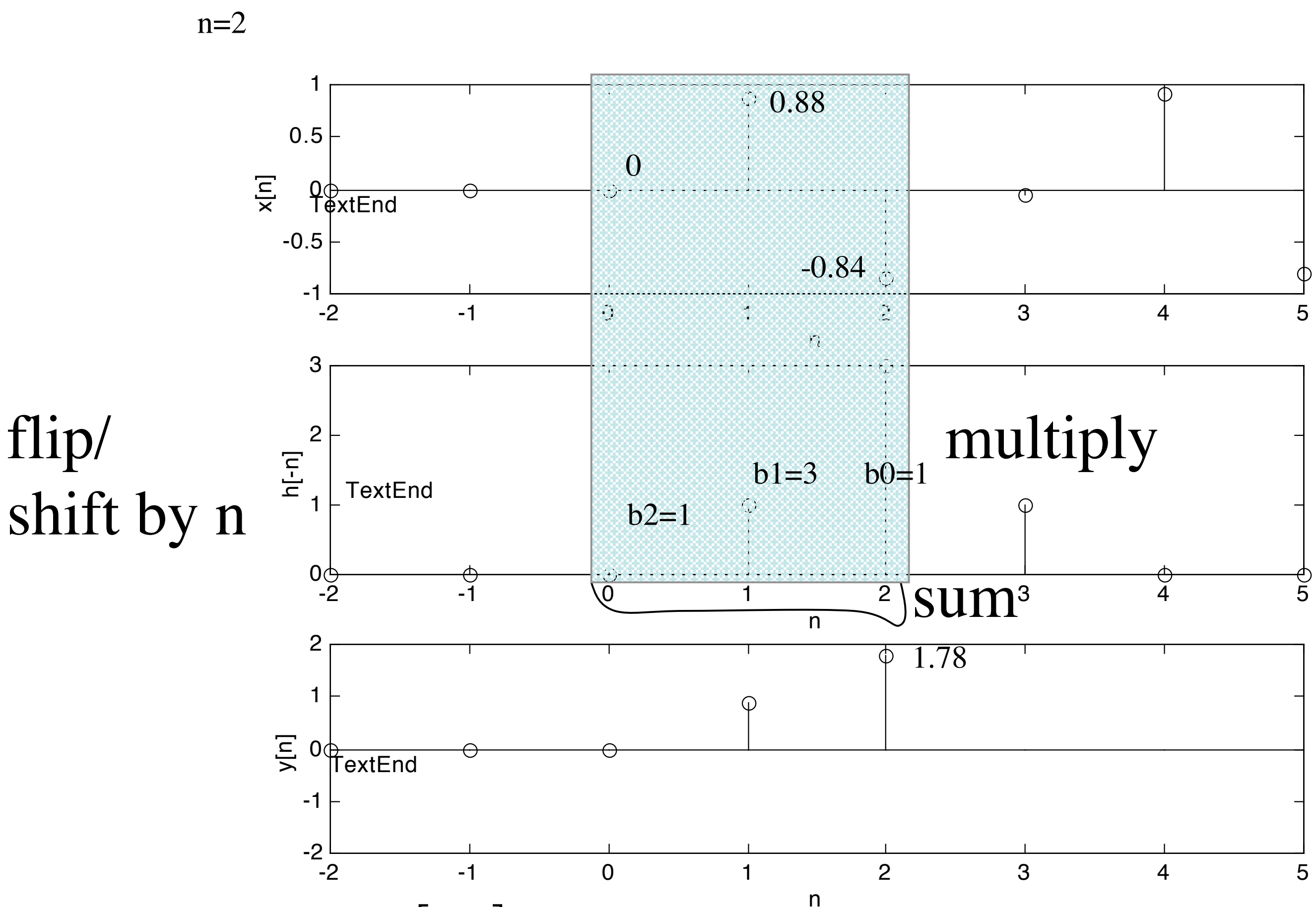
$y[1] = x[-1]h[2] + x[0]h[1] + x[1]h[0] \quad = (0)1 + (0)3 + (0.88)1 = 0.88$

Graphical Convolution

sum

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

multiply shift flip

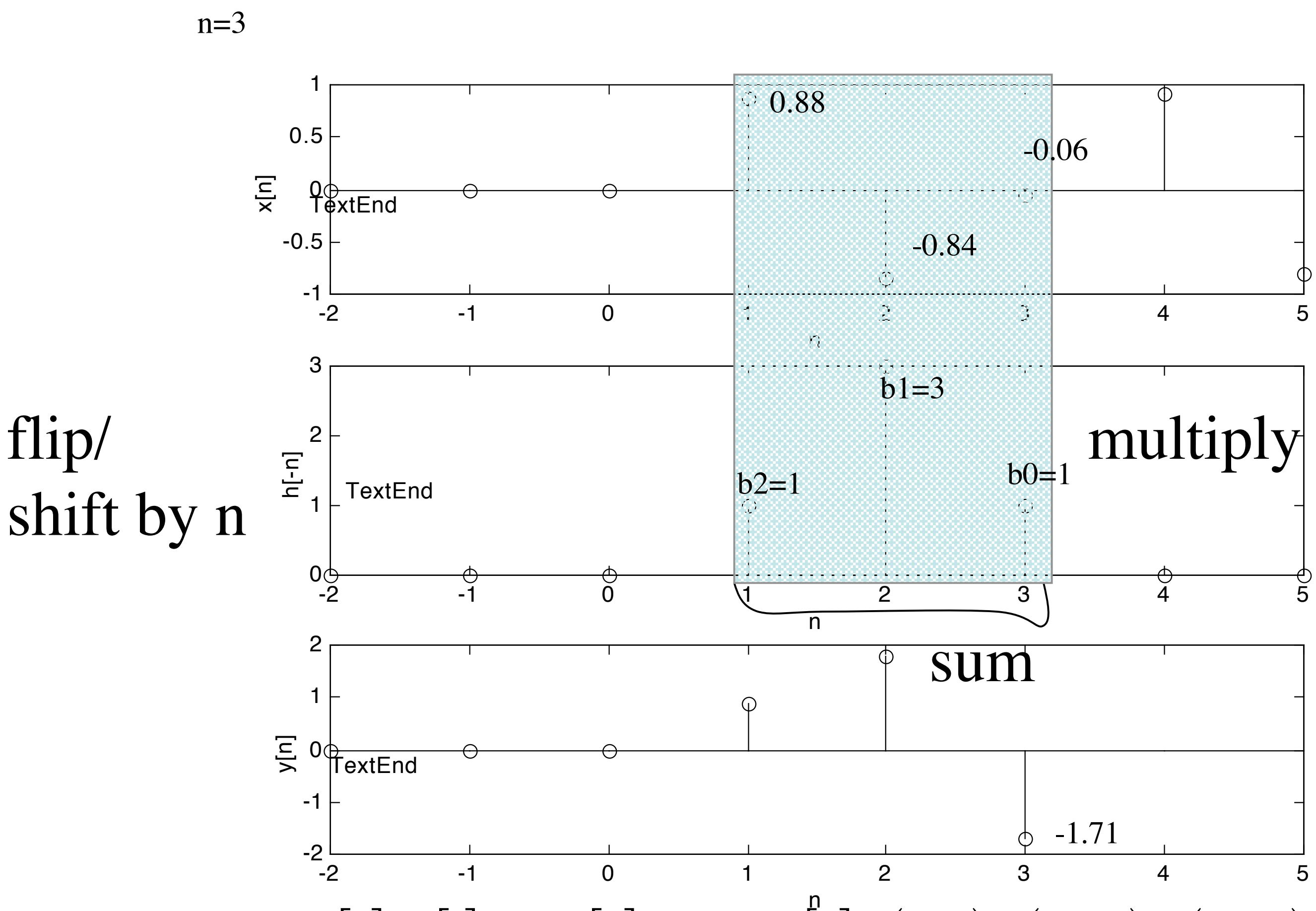


$$y[2] = x[0(\ )]h[2] + x[1]h[1] + x[2]h[0] \;= (0)1 + (0.88)3 + (-0.84)1 = 1.78$$

Graphical Convolution

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

sum, multiply, shift, flip

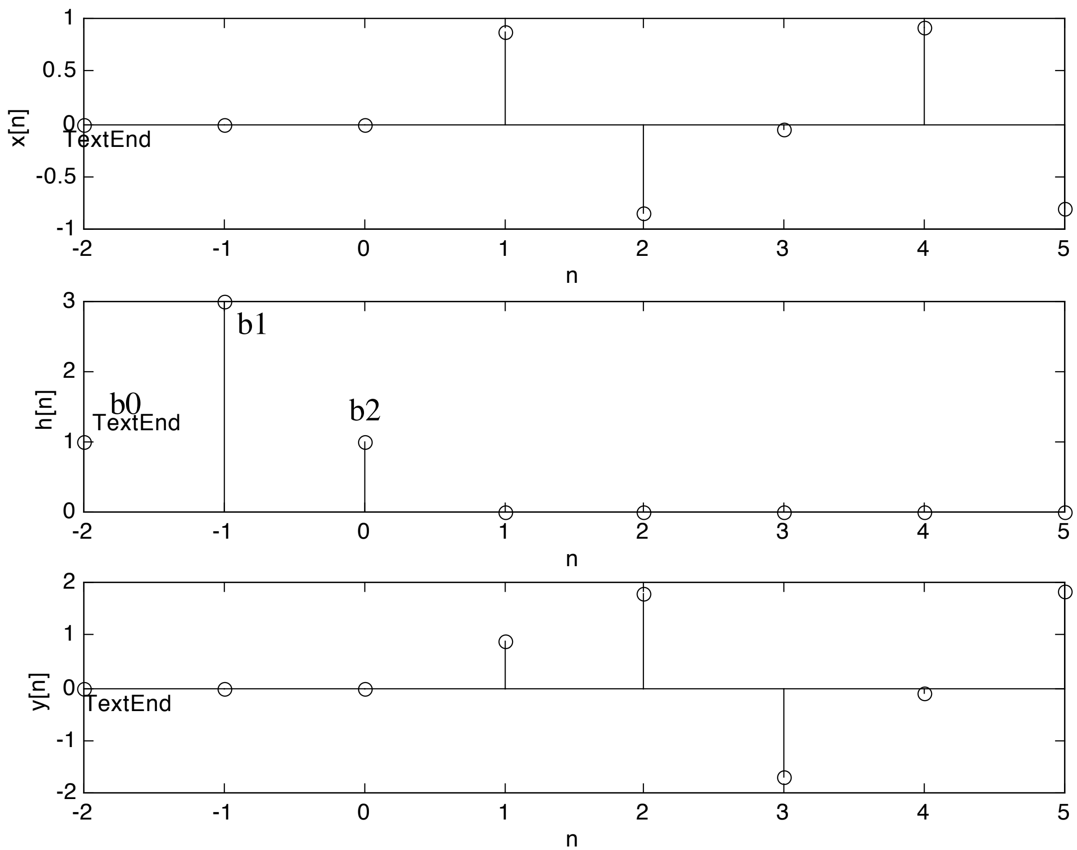


$$y[3] = x[1]h[2] + x[2]h[1] + x[3]h[0] = (0.88)1 + (-0.84)3 + (-0.06)1 = -1.72$$

Graphical Convolution

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

$$y[n] = x[k] * h[k]$$



Homework:

p5_1: $$y(n) := \frac{1}{L}\cdot\left[\sum_{k=0}^{L-1} a^{n-k}\cdot u(n-k)\right]$$

L-point running average for input sequence $x[n]=a^n u[n]$, $n \geq 0$

hint: $$\sum_{k=M}^{N} \alpha^k = \frac{\alpha^M - \alpha^{N+1}}{1-\alpha}$$

let z=n-k

k=n-z

$$\frac{1}{L}\cdot\left[\sum_{n-z=0}^{L-1} a^z\cdot u(z)\right]$$

$$\frac{1}{L}\cdot\left[\sum_{z=n}^{n-(L-1)} a^z\cdot u(z)\right]$$

remember $n \geq 0$

p5_6: FIR & delays

Homework:

p5_1:

$$y(n) := \frac{1}{L}\cdot\left[\sum_{k=0}^{L-1} a^{n-k}\cdot u(n-k)\right]$$

L-point running average for input sequence $x[n]=a^n u[n],\ n\geq 0$

hint:

$$\sum_{k=M}^{N} \alpha^k = \frac{\alpha^M - \alpha^{N+1}}{1-\alpha}$$

let $z=n-k$

$k=n-z$

$$\frac{1}{L}\cdot\left[\sum_{n-z=0}^{L-1} a^z\cdot u(z)\right]$$

$$\frac{1}{L}\cdot\left[\sum_{z=n}^{n-(L-1)} a^z\cdot u(z)\right]$$

remember $n\geq 0$

p5_6: FIR & delays

FIR and single delay

$y[n]=ax[n]+bx[n-1]$

Impulse response

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

$$x[n] = \delta[n] = \begin{cases} 1 & n = 0 \\ 0 & otherwise \end{cases}$$ Delta function

$$\downarrow$$

$$y[n]\Big|_{x=\delta[n]} = h[n] = \sum_{k=0}^{M} b_k \delta[n-k]$$

impulse response

$$y[n] = \sum_{k=-\infty}^{\infty} h[n] x[n-k]$$

convolution sum

LTI: FIR, IIR

Frequency response

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

convolution

$$x[n] = Ae^{j\phi}e^{j\hat{\omega}n}$$

Complex exponential input

$\hat{\omega} = \omega T_s$

$$\downarrow$$

$$y[n] = \sum_{k=0}^{M} h[k]Ae^{j\phi}e^{j\hat{\omega}(n-k)}$$

$$= \left(\sum_{k=0}^{M} h[k]e^{-j\hat{\omega}k}\right)Ae^{j\phi}e^{j\hat{\omega}n}$$

$$= H(\hat{\omega})Ae^{j\phi}e^{j\hat{\omega}n}$$

let

$$H(\hat{\omega}) = \sum_{k=0}^{M} h[k]e^{j\hat{\omega}k}$$

$H(\hat{\omega})$ frequency response

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

convolution

$$x[n] = Ae^{j\phi}e^{j\hat{\omega}n}$$

complex exponential input

$$\downarrow$$

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

$$H(\hat{\omega}) = \sum_{k=0}^{M} h[k]e^{j\hat{\omega}k}$$

frequency response
complex

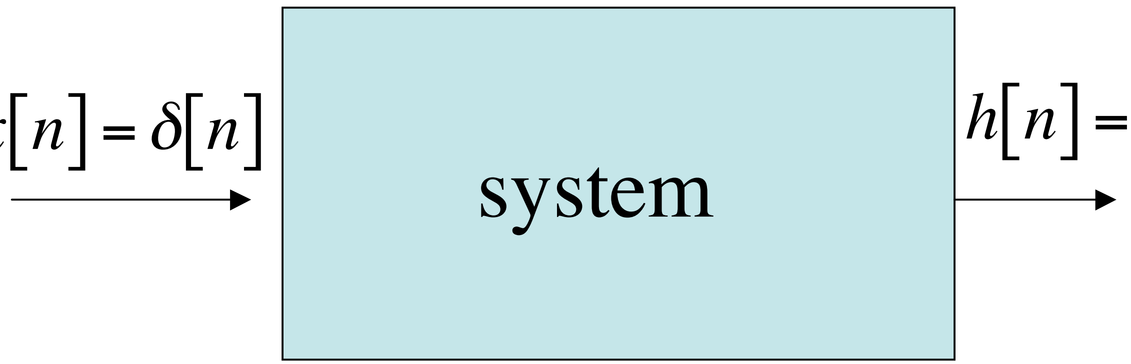
$$y[n] = |H(\hat{\omega})|Ae^{j(\phi + \angle H(\hat{\omega}))}e^{j\hat{\omega}n}$$

output same frequency
as input, but amplitude scaled
and a phase shift

LTI: FIR & IIR

$$\begin{bmatrix} n & x[n] \\ 0 & 1 \\ 1 & 0 \\ 2 & 0 \\ 3 & 0 \\ 4 & 0 \\ >5 & 0 \end{bmatrix}$$

$x[n] = \delta[n]$



$h[n] = y[n]\big|_{x[n]=\delta[n]}$

$$\begin{bmatrix} y[n] \\ 1/3 \\ 0 \\ 1/3 \\ 0 \\ 1/3 \\ 0 \end{bmatrix}$$

$y[n] = ?$

Ex. $h[n] = \frac{1}{3}\delta[n] + \frac{1}{3}\delta[n-2] + \frac{1}{3}\delta[n-4]$ FIR

$y[n] = \frac{1}{3}x[n] + \frac{1}{3}x[n-2] + \frac{1}{3}x[n-4]$

$$H(\hat{\omega}) = \sum_{k=0}^{4} h[k]e^{-j\hat{\omega}k}$$

$$= h[0]e^{-j\hat{\omega}0} + h[2]e^{-j\hat{\omega}2} + h[4]e^{-j\hat{\omega}4}$$

$$= \frac{1}{3} + \frac{1}{3}e^{-j\hat{\omega}2} + \frac{1}{3}e^{-j\hat{\omega}4}$$

Also try by inspection

$$= \frac{1}{3}\left(1 + e^{-j\hat{\omega}2} + e^{-j2\hat{\omega}4}\right) \longleftarrow$$

if b_k's symmetric, then factor out $e^{-j\hat{\omega}(M/2)}$ where M is the order of the filter. This leaves complex conjugate paired exponentials to transform into trigonometric functions (cosines/sines).

$$= \frac{1}{3}e^{-j\hat{\omega}2}\left(e^{j\hat{\omega}2} + 1 + e^{-j\hat{\omega}2}\right)$$

$$= \frac{1}{3}e^{-j\hat{\omega}2}\left(1 + 2\cos 2\hat{\omega}\right)$$

$$H(\hat{\omega}) = \tfrac{1}{3} e^{-j\hat{\omega}2}\left(1 + 2\cos 2\hat{\omega}\right)$$

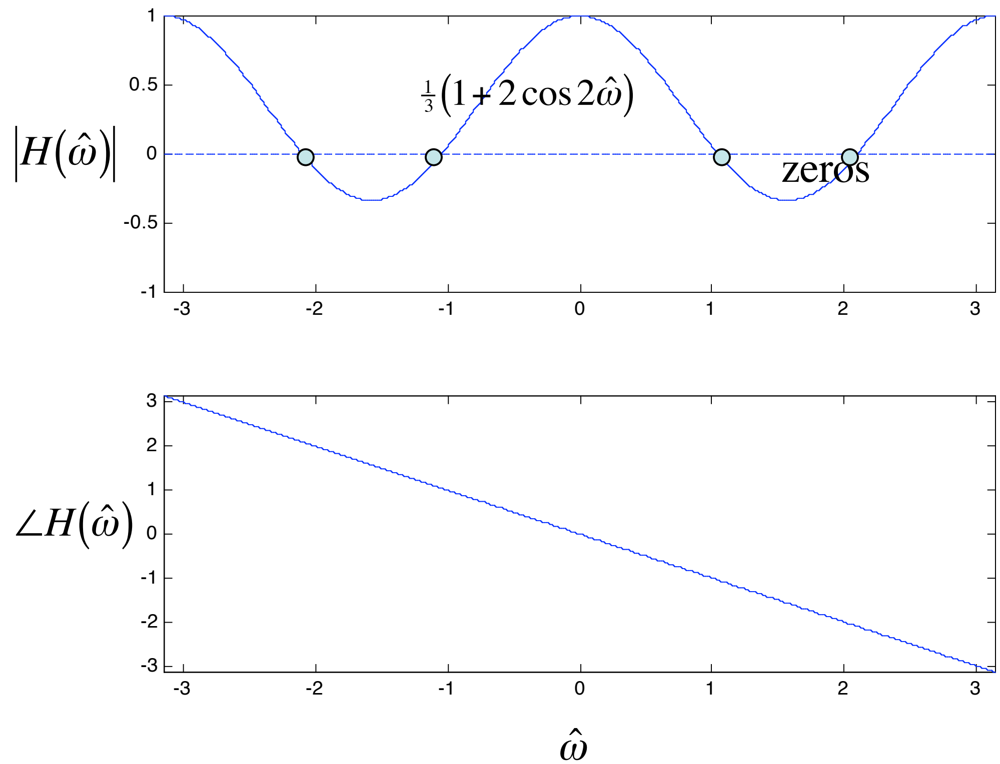
$$\left|H(\hat{\omega})\right| = \tfrac{1}{3}\left|\left(1 + 2\cos 2\hat{\omega}\right)\right|$$

Note: $\left|H\left(\tfrac{\pi}{3}\right)\right| = 0$

$\left|H\left(\tfrac{2\pi}{3}\right)\right| = 0$

$\angle H(\hat{\omega}) = -2\hat{\omega}$ linear phase

$\angle H(-\hat{\omega}) = -\angle H(\hat{\omega})$



principal value of phase fn

$-\pi < \angle H(\hat{\omega}) < \pi$ if not, add multiples of 2π

Want positive magnitudes, $\left|H(\hat{\omega})\right| \geq 0$
so absorb negative sign into phase by adding
an additional π at each zero

$$H(\hat{\omega}) = \tfrac{1}{3} e^{-j2\hat{\omega}}(1 + 2\cos 2\hat{\omega})$$

$$|H(\hat{\omega})| = \tfrac{1}{3}|(1 + 2\cos 2\hat{\omega})|$$

Note: $|H(\tfrac{\pi}{3})| = 0$

$|H(\tfrac{2\pi}{3})| = 0$

$$\angle H(\hat{\omega}) = -2\hat{\omega}$$

linear phase

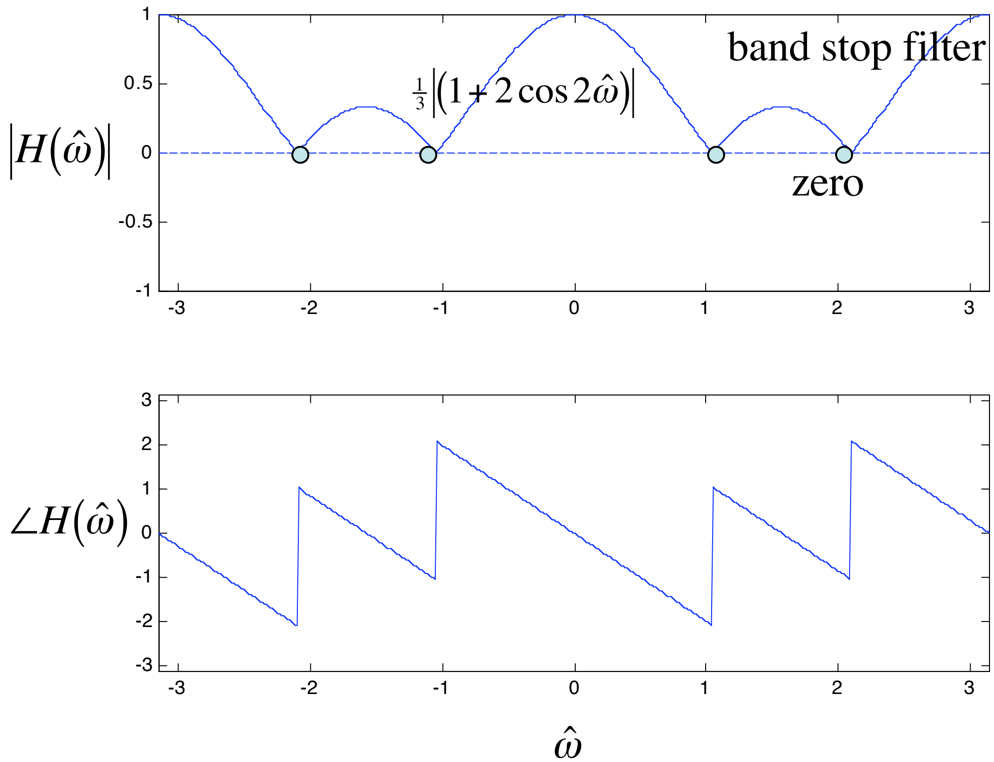
$$= \begin{cases} -2\hat{\omega} & 0 \le \hat{\omega} < \pi/3 \\ -2\hat{\omega} + \pi & \pi/3 \le \hat{\omega} < 2\pi/3 \\ -2\hat{\omega} + 2\pi & 2\pi/3 \le \hat{\omega} < \pi \end{cases}$$

phase odd function

$$\angle H(-\hat{\omega}) = -\angle H(\hat{\omega})$$

principal value of phase fn

$$-\pi < \angle H(\hat{\omega}) < \pi$$



Linear Phase

delay of n_0 sample periods

$$y[n] = x[n - n_0]$$

$$H(\hat{\omega}) = e^{-j\hat{\omega}n_0}$$

$$|H(\hat{\omega})| = 1 \qquad \angle H(\hat{\omega}) = -n_0\hat{\omega}$$ linear phase

FIR filters are linear phase if the coefficients are symmetric

higher frequencies need larger phase shifts than lower frequencies to achieve same time delay

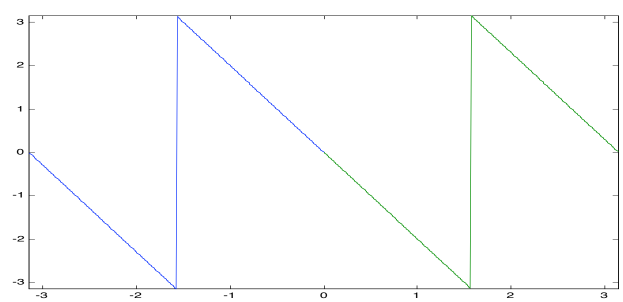
$$y = \sin(\omega(t + nT_s))$$
$$= \sin(\omega t + \omega n T_s)$$
$$= \sin(\omega t + \phi)$$
$$\phi = T_s n \omega$$

linear phase,
2 sample delay

$$\angle H(\hat{\omega}) = -2\hat{\omega}$$

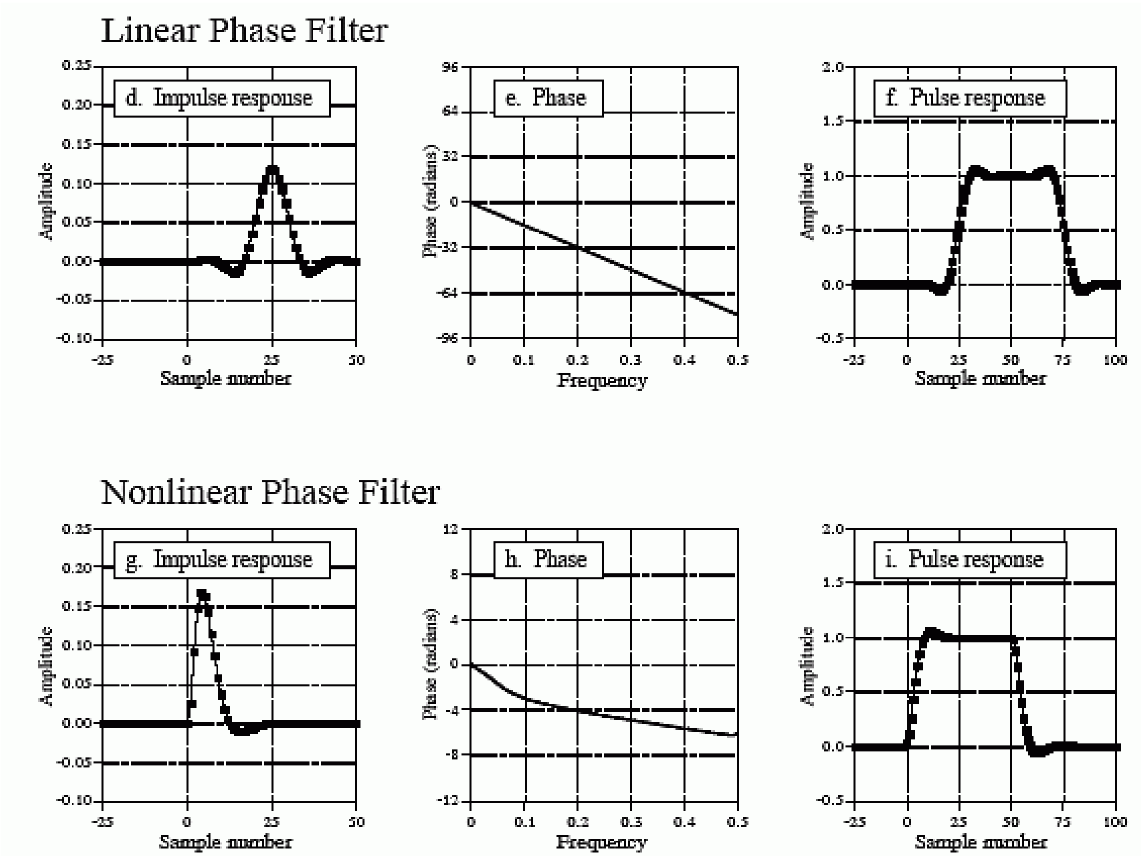
$$= \begin{cases} -2\hat{\omega} & 0 \le \hat{\omega} < \pi/2 \\ -2\hat{\omega} + 2\pi & \pi/2 \le \hat{\omega} < 3\pi/2 \end{cases}$$

$\angle H(\hat{\omega})$



$\hat{\omega}$

Linear Phase



“It turns out that, within very generous tolerances, humans are insensitive to [audio] phase shifts. ...”– Floyd E. Toole, PhD
Vice President Acoustical Engineering
Harman International Industries, Inc.

“For data transmission, a nonlinear phase delay causes intersymbol interference which increases error rate, particulary if the signal-to-noise ration is poor” - Digital Signal Processing in Communication Systems By Marvin E. Frerking

“These are the pulse responses of each of the filters.The pulse response is nothing more than a positive going step response followed by a negative going step response. The pulse response is used here because it displays what happens to both the rising and falling edges in a signal.

Here is the important part: zero and linear phase filters have left and right edges that look the same, while nonlinear phase filters have left and right edges that look different.

Many applications cannot tolerate the left and right edges looking different. One example is the display of an oscilloscope, where this difference could be misinterpreted as a feature of the signal being measured. Another example is in video processing. Can you imagine turning on your TV to find the left ear of your favorite actor looking different from his right ear?”
http://www.dspguide.com/ch19/4.htm

```
 FREQZ Z-transform digital filter frequency response.
    When N is an integer, [H,W] = FREQZ(B,A,N) returns the N-point frequency
    vector W in radians and the N-point complex frequency response vector H
    of the filter B/A:
                                   -1                      -nb
         jw  B(z)   b(1) + b(2)z + .... + b(nb+1)z
      H(e) = ---- = ----------------------------
                                -1                       -na
           A(z)    1   + a(2)z + .... + a(na+1)z
    given numerator and denominator coefficients in vectors B and A.
<snip>
 FREQZ(B,A,...) with no output arguments plots the magnitude and
    unwrapped phase of B/A in the current figure window.
```

$$H(\hat{\omega}) = \tfrac{1}{3} e^{-2j\hat{\omega}}\left(1 + 2\cos 2\hat{\omega}\right) = \tfrac{1}{3} + \tfrac{1}{3} e^{-j\hat{\omega}2} + \tfrac{1}{3} e^{-j\hat{\omega}4}$$

$$z^{-1} = e^{-j\hat{\omega}}$$

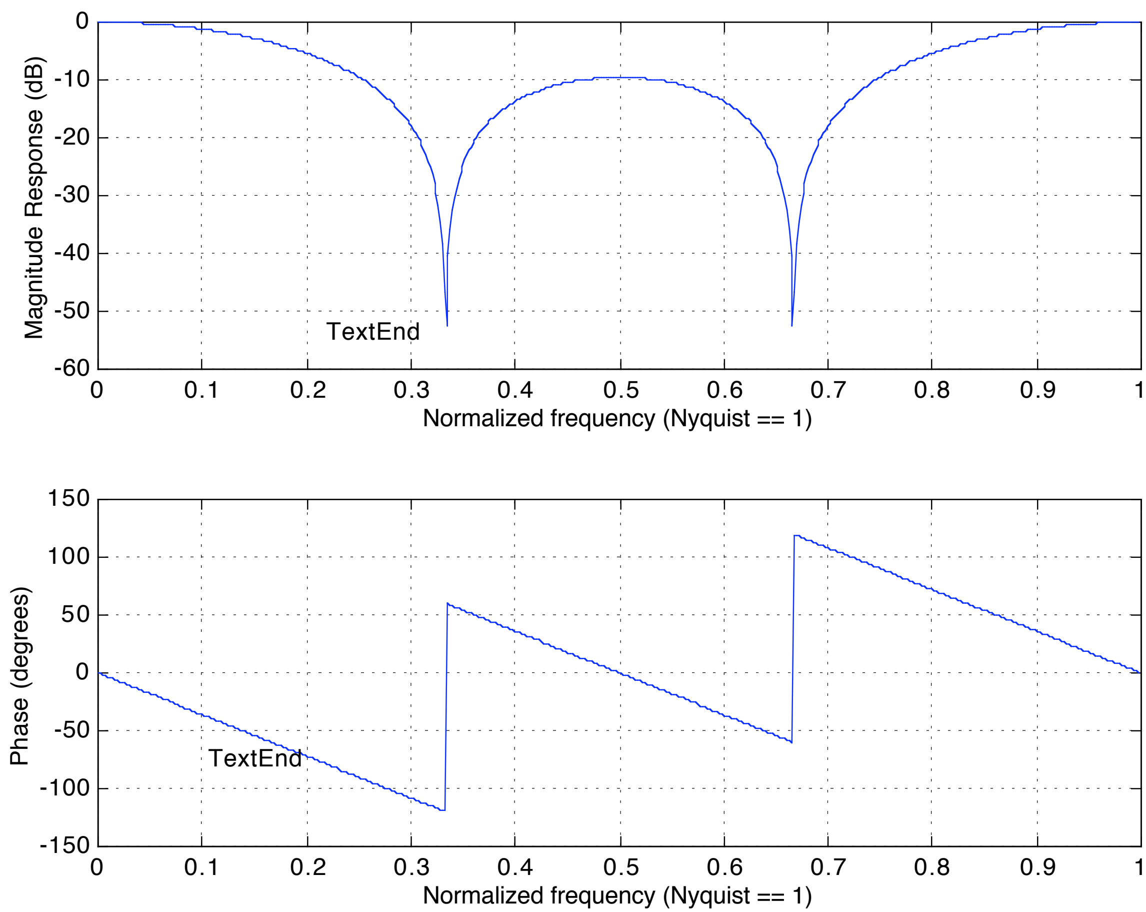
$$H(\hat{\omega}) = \frac{\tfrac{1}{3} + \tfrac{1}{3} z^{-2} + \tfrac{1}{3} z^{-4}}{1} \longrightarrow \begin{array}{l} b(1) = \tfrac{1}{3}, b(2) = 0, b(3) = \tfrac{1}{3}, b(4) = 0, b(5) = \tfrac{1}{3} \\ a(1) = 1 \end{array}$$

```
>> freqz([1/3,0,1/3,0,1/3],[1])
```

$$H(\hat{\omega}) = \tfrac{1}{3} e^{-j2\hat{\omega}}\left(1 + 2\cos 2\hat{\omega}\right) = \tfrac{1}{3} + \tfrac{1}{3} e^{-j\hat{\omega}2} + \tfrac{1}{3} e^{-j\hat{\omega}4}$$

```
>> freqz([1/3,0,1/3,0,1/3],[1])
```

Bode Plot (frequency response curve, amp and phase)



Magnitude response is plotted on a logarithmic scale.

decibels (dB) = $20\log_{10}(|H|)$

Note: In this plot the normalized frequency goes from DC to Nyquist ($\hat{\omega} = \pi$), so this is just one side.
We normally plot from
$-\pi < \hat{\omega} < \pi$.
Remember:
For real filter coefficients, magnitude is an even function; phase is an odd function

Superposition and the frequency response

$$x[n] = 3 + 3\cos(0.6\pi n)$$ input

$$y[n] = \tfrac{1}{3}x[n] + \tfrac{1}{3}x[n-2] + \tfrac{1}{3}x[n-4]$$ FIR filter

sample domain

$$y[n] = 1 + \cos(0.6\pi n) + 1 + \cos(0.6\pi(n-2)) + 1 + \cos(0.6\pi(n-4))$$

$$= 3 + \cos(0.6\pi n)$$

$$+ \cos(0.6\pi n)\cos(1.2\pi) + \sin(0.6\pi n)\sin(1.2\pi)$$

$$+ \cos(0.6\pi n)\cos(2.4\pi) + \sin(0.6\pi n)\sin(2.4\pi)$$

$$= 3 + \left[1 + \cos(1.2\pi) + \cos(2.4\pi)\right]\cos(0.6\pi n)$$

$$+ \left[\sin(1.2\pi) + \sin(2.4\pi)\right]\sin(0.6\pi n)$$

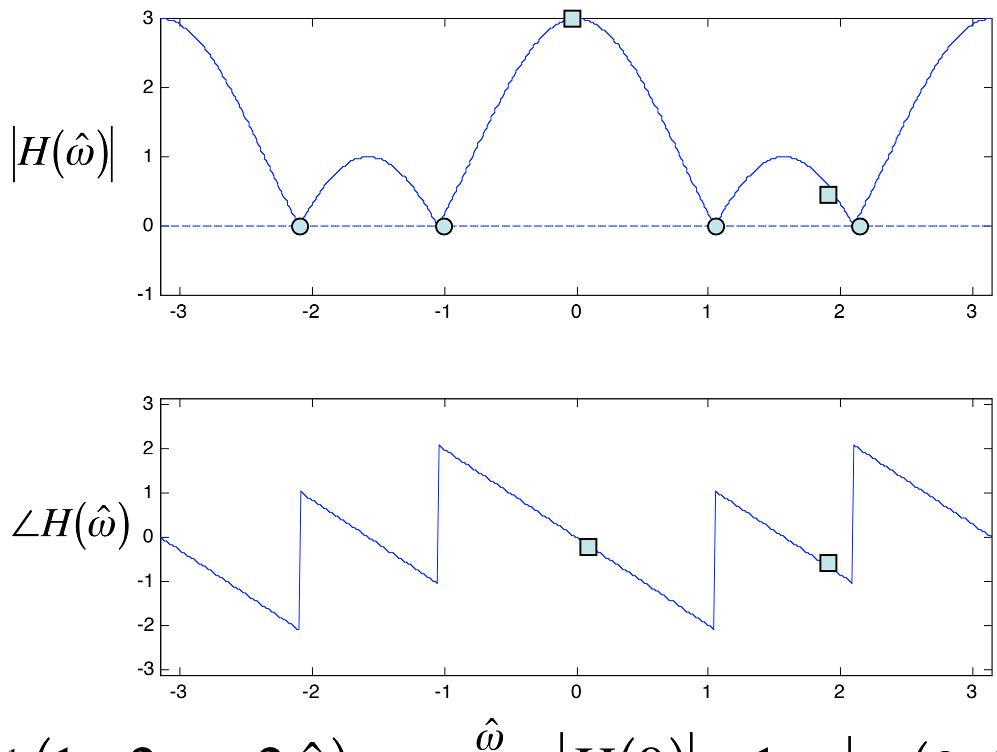
$$= 3 + A\cos(0.6\pi n) + B\sin(0.6\pi n)$$

$$= 3 + \sqrt{A^2 + B^2}\cos(0.6\pi n + \tan^{-1}(B/A))$$

$$= 3 + 0.618\cos(0.6\pi n - 0.2\pi)$$

frequency domain

$$x[n] = 3 + 3\cos(0.6\pi n)$$



closer $\hat{\omega}$ to a zero, the smaller the output.

$$|H(\hat{\omega})| = \tfrac{1}{3}(1 + 2\cos 2\hat{\omega}) \qquad |H(0)| = 1 \quad |H(0.6\pi)| = 0.206$$

$$\angle H(\hat{\omega}) = -2\hat{\omega} + \pi \qquad \angle H(0) = 0 \quad \angle H(-2 \cdot 0.6\pi + \pi) = -0.2\pi$$

$$y[n] = 3(1) + 3(0.206)\cos(0.6\pi n - 0.2\pi)$$
$$= 3 + 0.618\cos(0.6\pi n - 0.2\pi)$$

chirp