EE-2025 Spring-2000

Lecture 10

Linearity & Time-Invariance

18-Feb-00

Info: Web-CT, Lab, HW

- Lab Quiz next week
- Lab #5: Image Processing
  - Lab #6 also
  - Sampling and Reconstruction
  - Blurring & Deconvolution (De–Blur)
- Quiz #2 (3–March) Coverage:
  - Prob Sets #4, #5, #6 and #7

READING ASSIGNMENTS

- This Lecture:
  - Chapter 5, pp. 133–152
- Other Reading:
  - Recitation: Ch. 5, pp. 127–133, 142–146
    - CONVOLUTION
  - Next Lecture: Chapter 6, start

LAB IMAGES (TRUE)

- Getting TRUE SIZE comparisons is hard: use an image display program

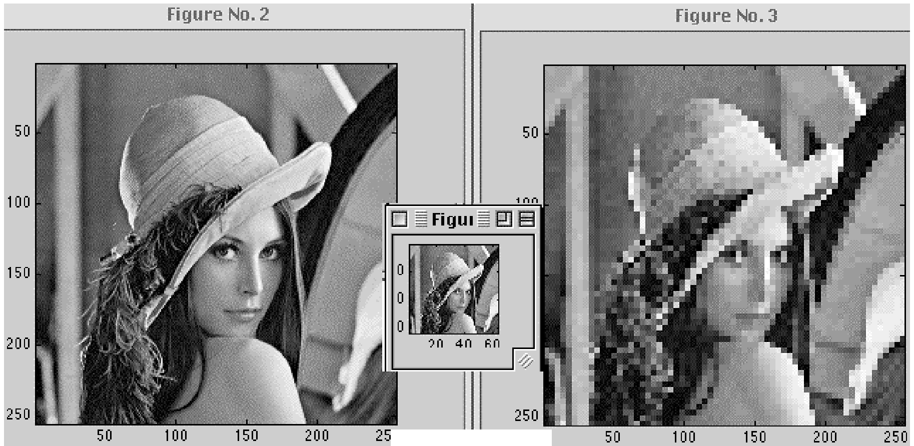


Image Display Procedure

- Example: 256 by 256 Lenna (512 is OK)
- Make MATLAB Figures in separate windows
- ALT–PRINT–SCREEN captures the active window (Win–95)
- Paste into “Paint” program
  - Under Win–95 Accessories
- Print after arranging images

LECTURE OBJECTIVES

- BLOCK DIAGRAM REPRESENTATION
  - Components for Hardware
  - Connect Simple Filters Together to Build More Complicated Systems
- GENERAL PROPERTIES of FILTERS
  - LINEARITY
  - TIME–INVARIANCE
  - ==> CONVOLUTION

LTI SYSTEMS

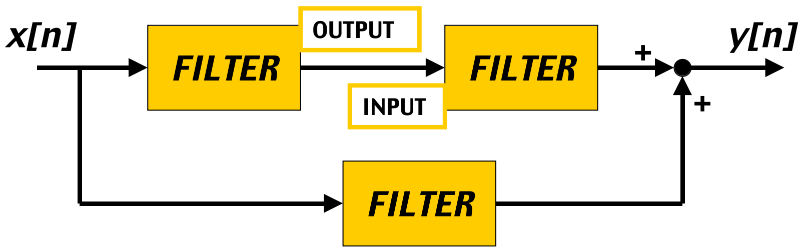
OVERVIEW

- IMPULSE RESPONSE, h[n]
  - FIR case: same as $\{b_k\}$
- CONVOLUTION
  - GENERAL: y[n] = x[n]*h[n]
- GENERAL CLASS of SYSTEMS
  - LINEAR and TIME–INVARIANT
- ALL LTI have h[n] & use convolution !

DIGITAL FILTERING

- CONCENTRATE on the FILTER (DSP)
- DISCRETE–TIME SIGNALS
  - FUNCTIONS of n, the “time index”
  - INPUT x[n]
  - OUTPUT y[n]

BUILDING BLOCKS



- BUILD UP COMPLICATED FILTERS
  - FROM SIMPLE MODULES
  - Ex: FILTER MODULE MIGHT BE 3-pt FIR

GENERAL FIR FILTER

- FILTER COEFFICIENTS $\{b_k\}$
  - DEFINE THE FILTER

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

  - For example, $\{b_k\} = \{3, -1, 2, 1\}$

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

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

MATLAB for FIR FILTER

- `yy = conv(bb,xx)`
  - VECTOR `bb` contains Filter Coefficients
  - DSP-First: `yy = firfilt(bb,xx)`
- FILTER COEFFICIENTS $\{b_k\}$

Conv2() ***for images***

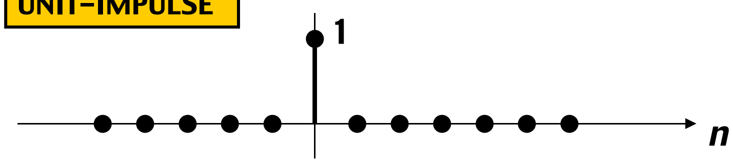
$$y[n] = \sum_{k=0}^{M} b_k x[n-k]$$

SPECIAL INPUT SIGNALS

- x[n] = SINUSOID — FREQUENCY RESPONSE
- x[n] has only one NON-ZERO VALUE

$$\delta[n] = \begin{cases} 1 & n = 0 \\ 0 & n \neq 0 \end{cases}$$

UNIT-IMPULSE



FIR IMPULSE RESPONSE

- Convolution = Filter Definition
  - Filter Coeffs = Impulse Response

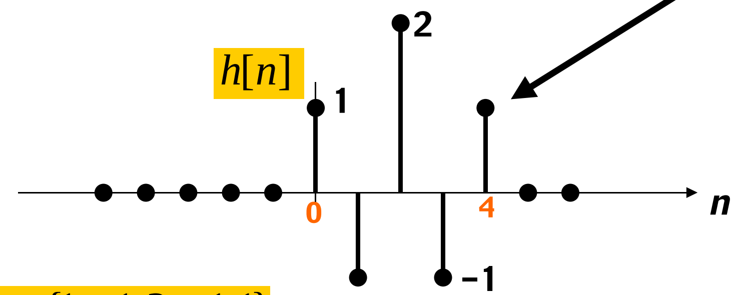
n	$n<0$	0	1	2	3	$\dots$	M	$M+1$	$n>M+1$
$x[n]=\delta[n]$	0	1	0	0	0	0	0	0	0
$y[n]=h[n]$	0	b_0	b_1	b_2	b_3	$\dots$	b_M	0	0

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

MATH FORMULA for h[n]

- Use SHIFTED IMPULSES to write h[n]

$$h[n]=\delta[n]-\delta[n-1]+2\delta[n-2]-\delta[n-3]+\delta[n-4]$$



$$\{b_k\}=\{1,-1,2,-1,1\}$$

LTI: Convolution

- Output = Convolution of x[n] & h[n]
  - NOTATION: y[n] = x[n]*h[n]
  - Here is the FIR case:

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

FINITE LIMITS

FINITE LIMITS

Same as b_k

CONVOLUTION Example

$$h[n]=\delta[n]-\delta[n-1]+2\delta[n-2]-\delta[n-3]+\delta[n-4]$$

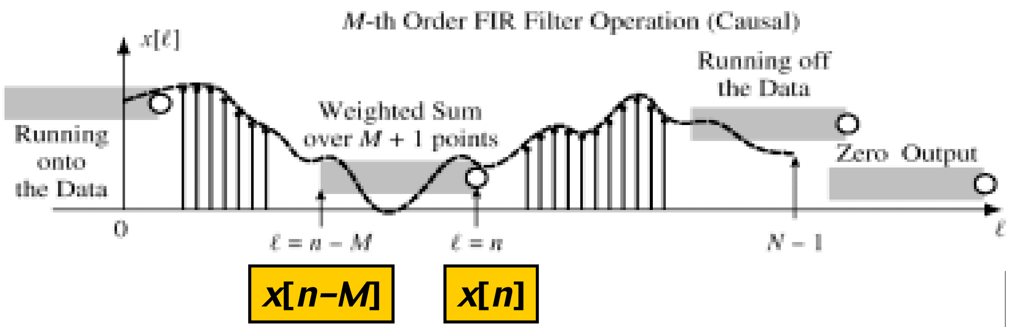
$$x[n]=u[n]$$

n	−1	0	1	2	3	4	5	6	7
$x[n]$	0	1	1	1	1	1	1	1	...
$h[n]$	0	1	−1	2	−1	1	0	0	0
	0	1	1	1	1	1	1	1	1
	0	0	−1	−1	−1	−1	−1	−1	−1
	0	0	0	2	2	2	2	2	2
	0	0	0	0	−1	−1	−1	−1	−1
	0	0	0	0	0	1	1	1	1
$y[n]$	0	1	0	2	1	2	2	2	...

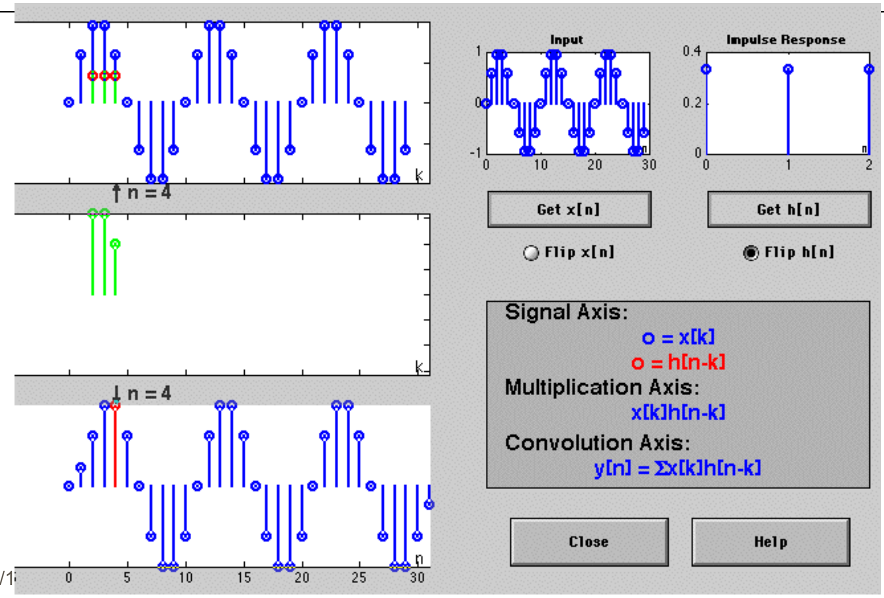
GENERAL FIR FILTER

- SLIDE a Length–L WINDOW over x[n]

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



CONVDEMO: MATLAB GUI



FILTERING EXAMPLE

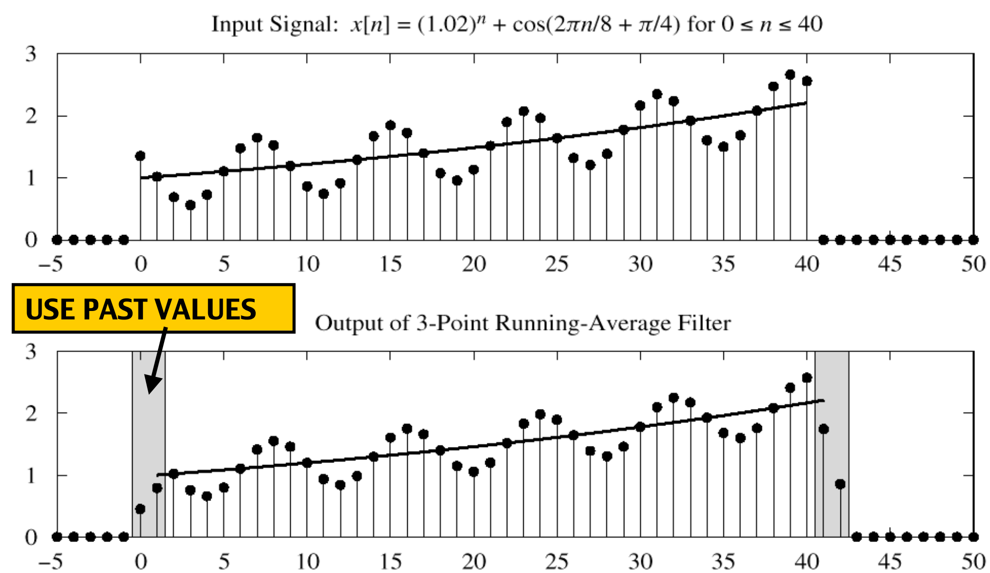
- 7–point AVERAGER
  - Removes cosine
    - By making its amplitdue (A) smaller

$$y_7[n] = \sum_{k=0}^{6} (\tfrac{1}{7})\, x[n-k]$$

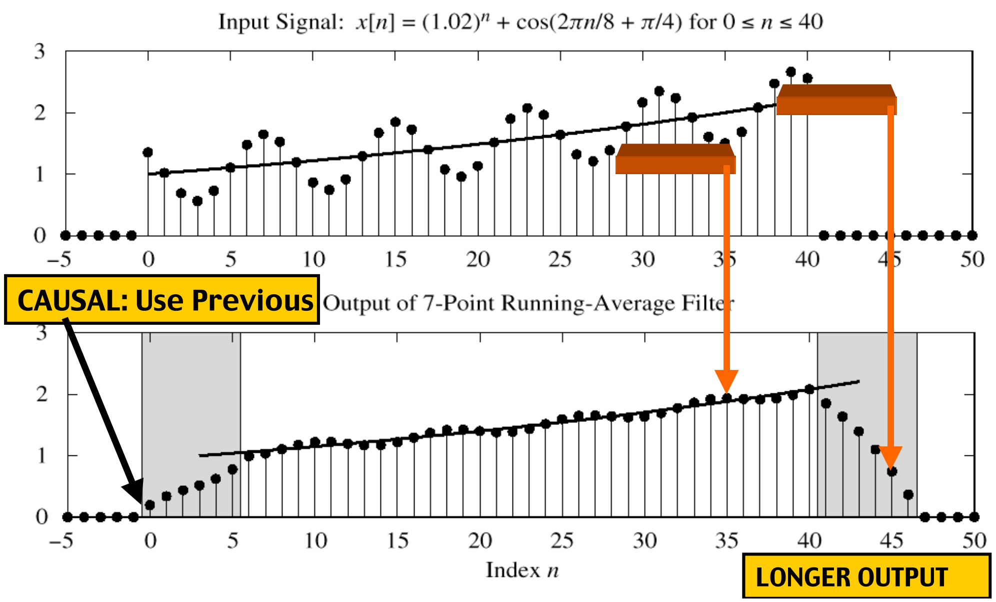
- 3–point AVERAGER
  - Changes A slightly

$$y_3[n] = \sum_{k=0}^{2} (\tfrac{1}{3})\, x[n-k]$$

3-pt AVG EXAMPLE



7-pt FIR EXAMPLE (AVG)



HARDWARE STRUCTURES

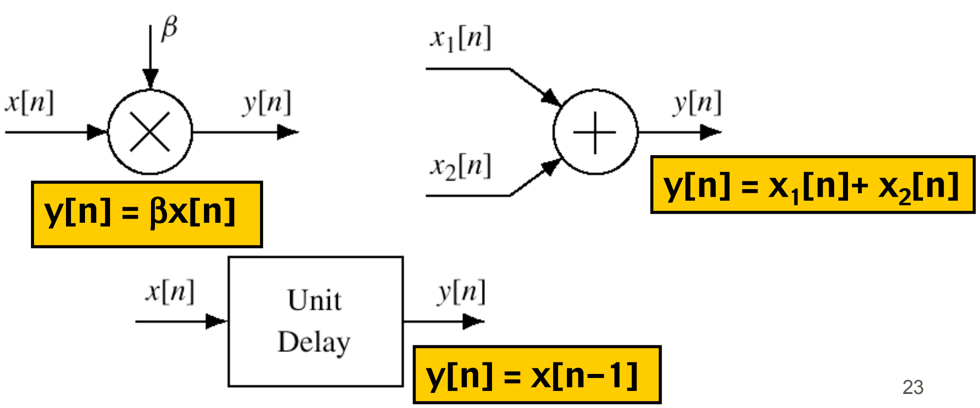
$$y[n] = \sum_{k=0}^{M} b_k x[n-k]$$

- INTERNAL STRUCTURE of "FILTER"
  - WHAT COMPONENTS ARE NEEDED?
  - HOW DO WE "HOOK" THEM TOGETHER?
- SIGNAL FLOW GRAPH NOTATION

HARDWARE ATOMS

- Add, Multiply & Store

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



FIR STRUCTURE

- Direct Form

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

SIGNAL FLOW GRAPH

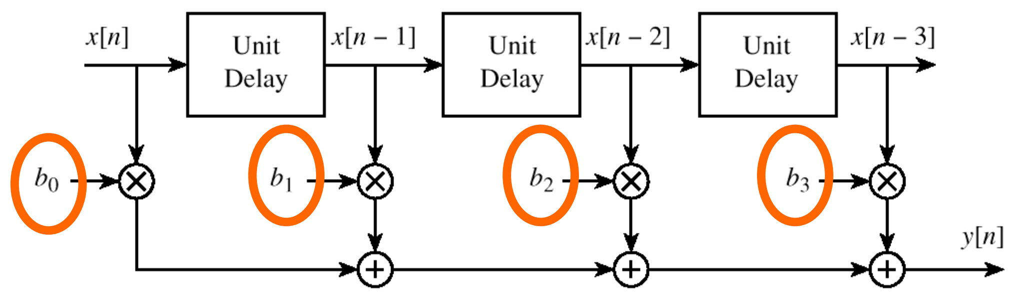
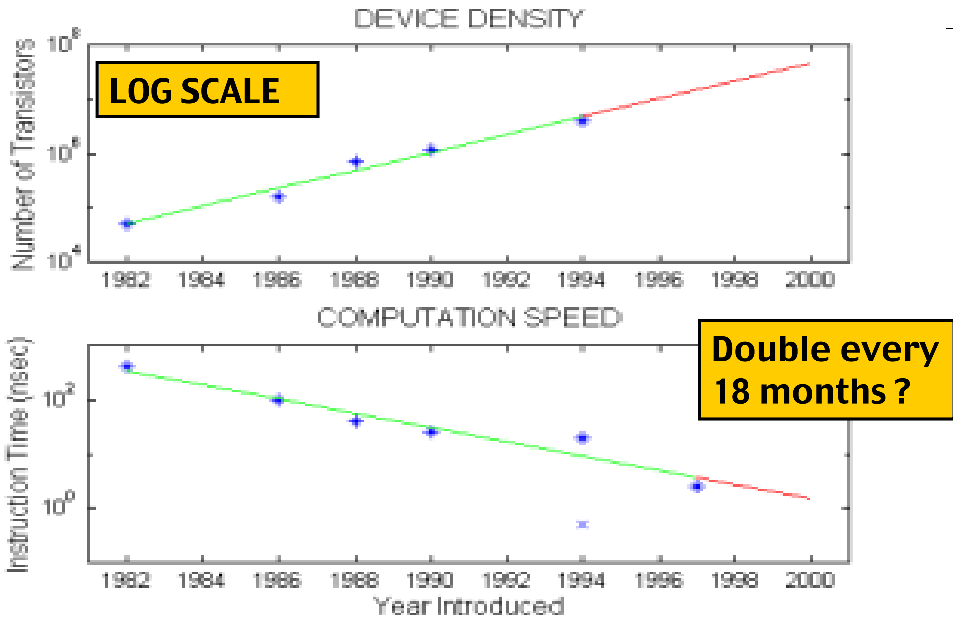


Figure 5.13 Block-diagram structure for the Mth order FIR filter.

Moore's Law for TI DSPs



SYSTEM PROPERTIES

- MATHEMATICAL DESCRIPTION
- TIME–INVARIANCE
- LINEARITY
- CAUSALITY
  - "No output prior to input"

TIME-INVARIANCE

- IDEA:
  - "Time–Shifting the input will cause the same time–shift in the output"
- EQUIVALENTLY,
  - We can prove that
    - The time origin (n=0) is picked arbitrary

TESTING Time-Invariance

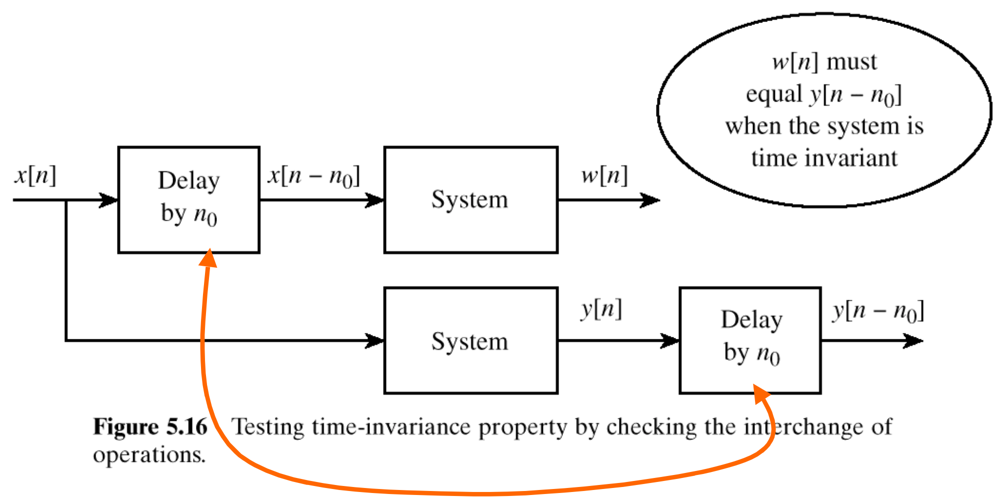


Figure 5.16 Testing time-invariance property by checking the interchange of operations.

LINEAR SYSTEM

- LINEARITY = Two Properties
- SCALING
  - "Doubling x[n] will double y[n]"
- SUPERPOSITION:
  - "Adding two inputs gives an output that is the sum of the individual outputs"

TESTING LINEARITY

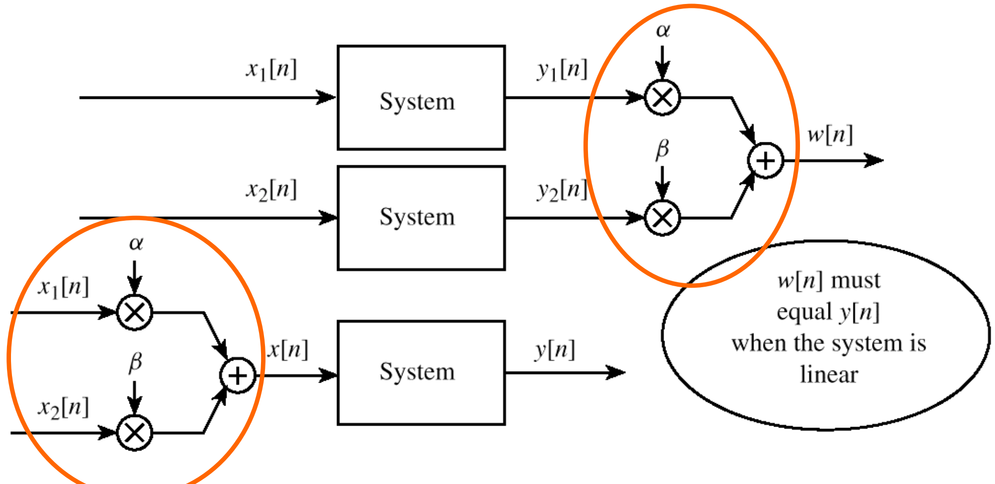


Figure 5.17 Testing linearity by checking the interchange of operations.

LTI SYSTEMS

- LTI: Linear & Time-Invariant
- COMPLETELY CHARACTERIZED by:
  - IMPULSE RESPONSE h[n]
  - CONVOLUTION: y[n] = x[n]*h[n]
    - The "rule" can be re-written as convolution
- FIR Example: h[n] is same as b_k

CASCADE SYSTEMS

- Does the order of S_1 & S_2 matter?
  - NO, LTI SYSTEMS can be rearranged !!!
  - WHAT ARE THE FILTER COEFFS? $\{b_k\}$

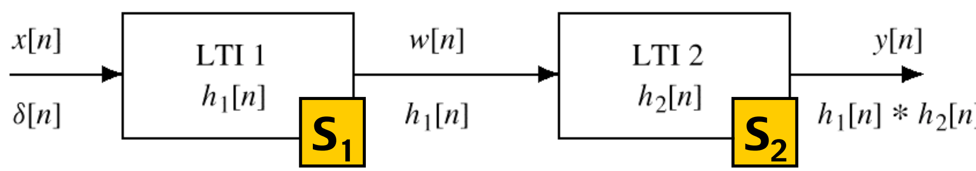


Figure 5.19 A Cascade of Two LTI Systems.