

Digital Signal Processing

II. Discrete signals and systems

II.1 Discrete signals

Representation

A discrete signal can be represented:

- ▶ graphically
- ▶ in table form
- ▶ as a vector: $x[n] = [..., 0, 0, 1, 3, 4, 5, 0, ...]$
 - ▶ an **arrow** indicates the origin of time ($n = 0$). -if the arrow is missing, the origin of time is at the first element -the dots ... indicate that the value remains the same from that point onwards

Examples: at blackboard

Notation: $x[4]$ represents the value of the fourth sample in the signal $x[n]$

Basic signals

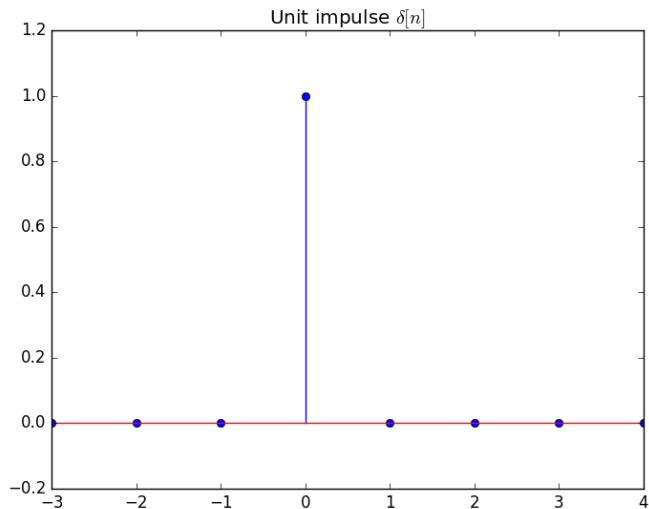
Some elementary signals are presented below.

Unit impulse

Contains a single non-zero value of 1 located at time 0. It is denoted with $\delta[n]$.

$$\delta[n] = \begin{cases} 1 & \text{if } n = 0 \\ 0 & \text{otherwise} \end{cases}.$$

Representation



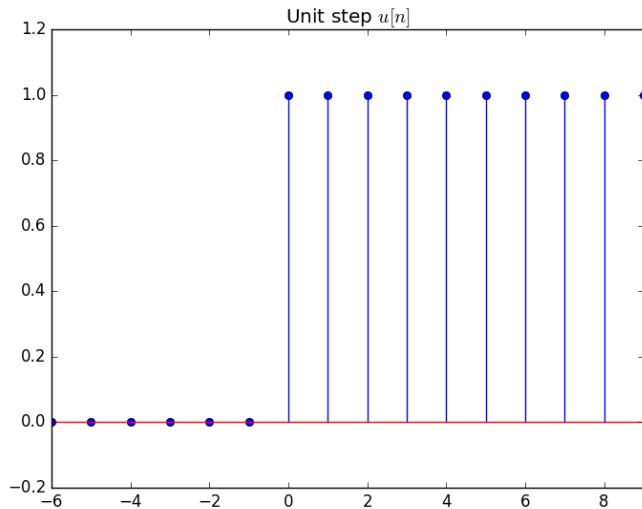
Unit step

Unit step

It is denoted with $u[n]$.

$$u[n] = \begin{cases} 1 & \text{if } n \geq 0 \\ 0 & \text{otherwise} \end{cases}.$$

Representation



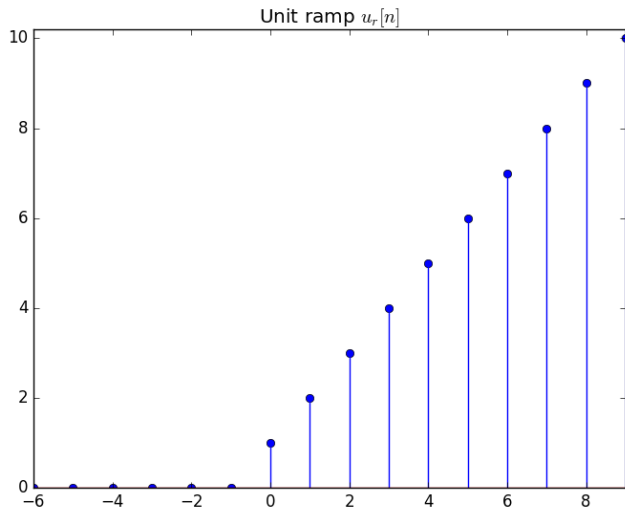
Unit ramp

Unit ramp

It is denoted with $u_r[n]$.

$$u_r[n] = \begin{cases} n & \text{if } n \geq 0 \\ 0 & \text{otherwise} \end{cases}.$$

Representation



Exponential signal

Exponential signal

It does not have a special notation. It is defined by:

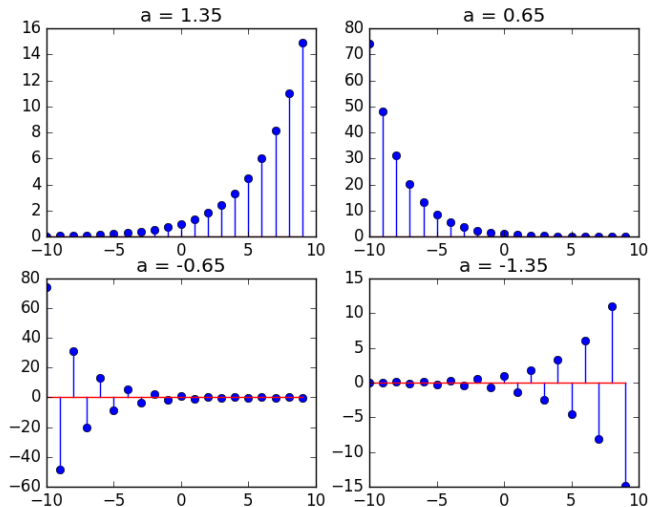
$$x[n] = a^n.$$

a can be a real or a complex number. Here we consider only the case when a is real.

Depending on the value of a , we have four possible cases:

1. $a \geq 1$
2. $0 \leq a < 1$
3. $-1 < a < 0$
4. $a \leq -1$

Representation



II.2 Types of discrete signals

Signals with finite energy

- ▶ The **energy of a discrete signal** is defined as

$$E = \sum_{n=-\infty}^{\infty} (x[n])^2.$$

- ▶ If E is finite, the signal is said to have finite energy.
- ▶ Examples:
 - ▶ unit impulse has finite energy
 - ▶ unit step does not

Signals with finite power

- ▶ The **average power of a discrete signal** is defined as

$$P = \lim_{N \rightarrow \infty} \frac{\sum_{n=-N}^N (x[n])^2}{2N + 1}.$$

- ▶ In other words, the average power is the average energy per sample.
- ▶ If P is finite, the signal is said to have finite power.
- ▶ A signal with finite energy has finite power ($P = 0$ if the signal has infinite length). A signal with infinite energy can have finite or infinite power.
- ▶ Example: unit step has finite power $P = \frac{1}{2}$ (see proof at blackboard).

Periodic and non-periodic signals

- ▶ A signal is called **periodic** if its values repeat themselves after a certain time (known as **period**).

$$x[n] = x[n + N], \forall t$$

- ▶ The **fundamental period** of a signal is the minimum value of N .
- ▶ Periodic signals have infinite energy, and finite power equal to the power of a single period.

Even and odd signals

- ▶ A real signal is **even** if it satisfies the following symmetry:

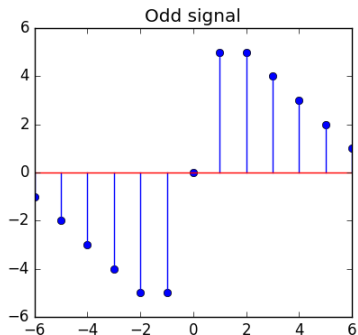
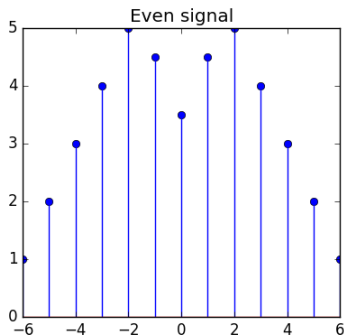
$$x[n] = x[-n], \forall n.$$

- ▶ A real signal is **odd** if it satisfies the following anti-symmetry:

$$-x[n] = x[-n], \forall n.$$

- ▶ There exist signals which are neither even nor odd.

Even and odd signals: example



Even and odd parts of a signal

- ▶ Every signal can be written as the sum of an even signal and an odd signal:

$$x[n] = x_e[n] + x_o[n]$$

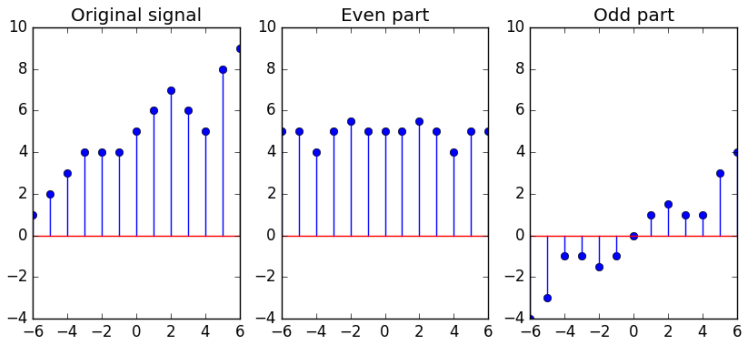
- ▶ The even and the odd parts of the signal can be found as follows:

$$x_e[n] = \frac{x[n] + x[-n]}{2}.$$

$$x_o[n] = \frac{x[n] - x[-n]}{2}.$$

- ▶ Proof: check that $x_e[n]$ is even, $x_o[n]$ is odd, and their sum is $x[n]$

Even and odd parts: example

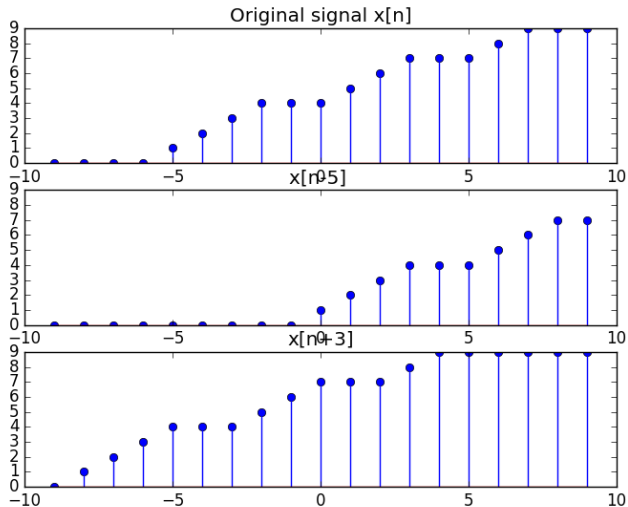


II.3 Basic operations with discrete signals

Time shifting

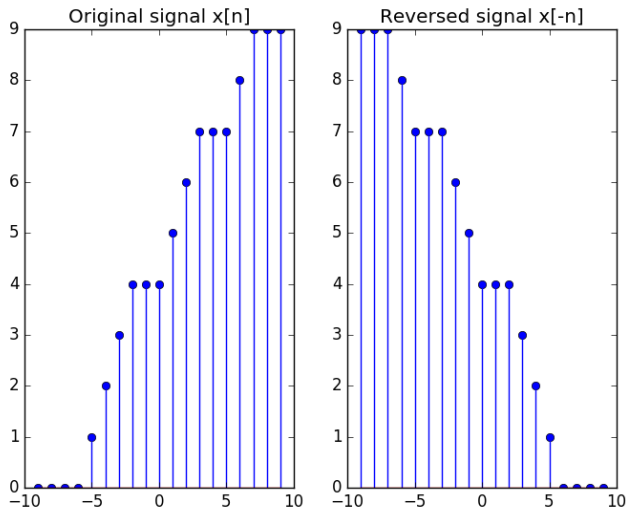
- ▶ The signal $x[n - k]$ is $x[n]$ **delayed with k time units**
 - ▶ Graphically, $x[n - k]$ is shifted k units to the **right** compared to the original
- ▶ The signal $x[n + k]$ is $x[n]$ **anticipated with k time units**
 - ▶ Graphically, $x[n + k]$ is shifted k units to the **left** compared to the original signal.

Time shifting: representation



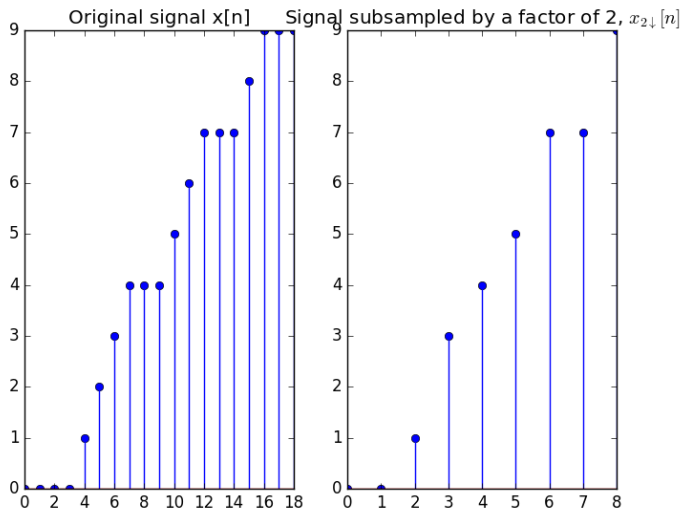
Time reversal

- ▶ Changing the variable n to $-n$ produces a signal $x[-n]$ which mirrors $x[n]$.



Subsampling

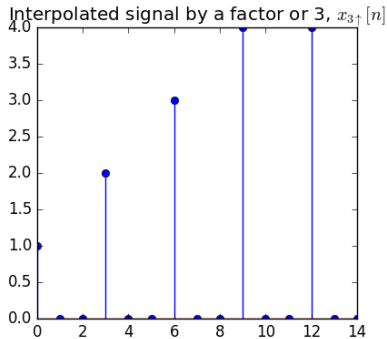
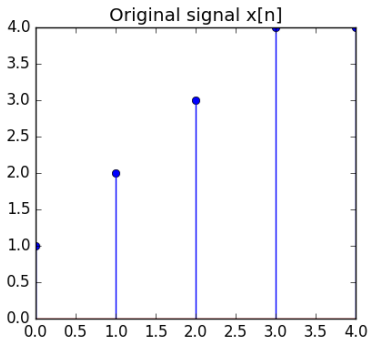
- ▶ $x_{M\downarrow}[n] = x[Mn]$ is a **subsampled** version of $x[n]$ with a factor of M
 - ▶ Keep only 1 sample out of M samples from the original signal $x[n]$



Interpolation

- **Interpolation** by a factor of L adds L of zeros between two samples in the original signal.

$$x_{L\uparrow} = \begin{cases} x[\frac{n}{L}] & \text{if } \frac{n}{L} \in \mathbb{N} \\ 0 & \text{otherwise} \end{cases}.$$



Mathematical operations

- ▶ A signal $x[n]$ can be **scaled** by a constant A , i.e. each sample is multiplied by A :

$$y[n] = Ax[n].$$

- ▶ Two signals $x_1[n]$ and $x_2[n]$ can be **summed** by summing the individual samples:

$$y[n] = x_1[n] + x_2[n]$$

- ▶ Two signals $x_1[n]$ and $x_2[n]$ can be **multiplied** by multiplying the individual samples:

$$y[n] = x_1[n] \cdot x_2[n]$$

II.4 Discrete systems

Definition

- ▶ **System** = a device or algorithm which produces an **output signal** based on an **input signal**
- ▶ We will only consider systems with a single input and a single output
- ▶ Figure here: blackboard.
- ▶ Common notation:
 - ▶ $x[n]$ is the input
 - ▶ $y[n]$ is the output
 - ▶ H is the system.

Notations

- ▶ Notations:

$$y[n] = H[x[n]]$$

(“the system H applied to the input $x[n]$ produces the output $y[n]$ ”)

$$x[n] \xrightarrow{H} y[n]$$

(“the input $x[n]$ is transformed by the system H into $y[n]$ ”)

Equations

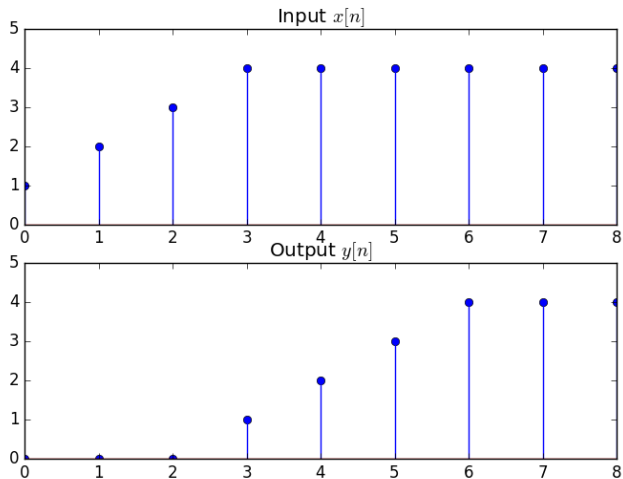
- Usually, a system is described by the **input-output equation** (or **difference equation**) which explains how $y[n]$ is defined in terms of $x[n]$.

Examples:

1. $y[n] = x[n]$ (the identity system)
2. $y[n] = x[n - 3]$
3. $y[n] = x[n + 1]$
4. $y[n] = \frac{1}{3}(x[n + 1] + x[n] + x[n - 1])$
5. $y[n] = \max(x[n + 1], x[n], x[n - 1])$
6. $y[n] = (x[n])^2 + \log_{10} x[n - 1]$
7. $y[n] = \sum_{k=-\infty}^n x[k] = x[n] + x[n - 1] + x[n - 2] + \dots$

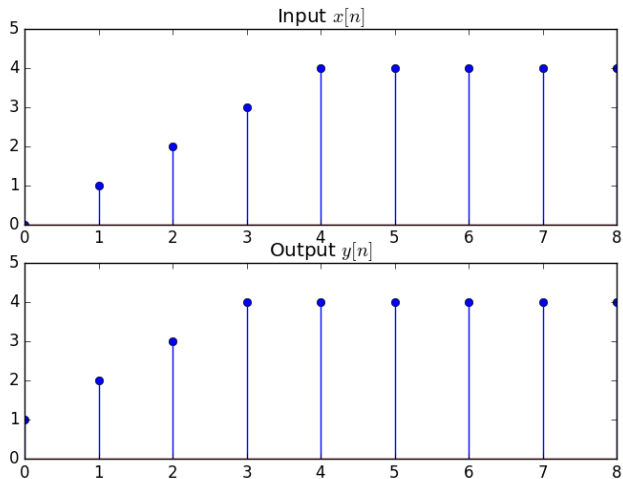
Example

$$y[n] = x[n - 3]$$



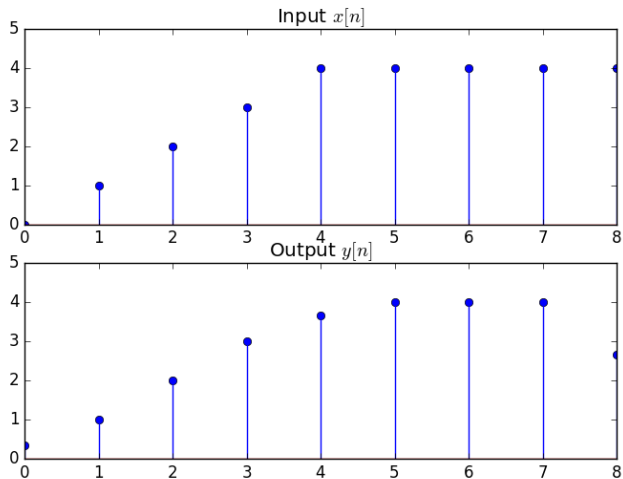
Example

$$y[n] = x[n + 1]$$



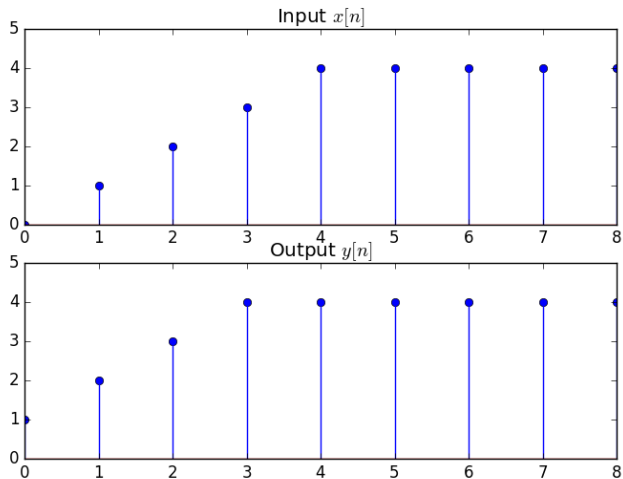
Example

$$y[n] = (x[n+1] + x[n] + x[n-1])/3$$



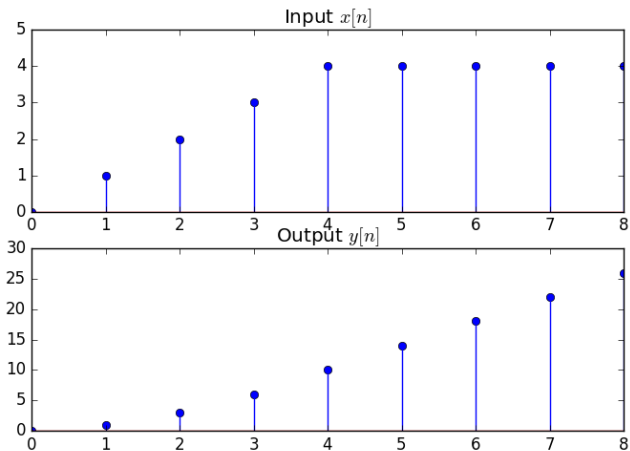
Example

$$y[n] = \max(x[n+1], x[n], x[n-1])$$



Example

$$y[n] = \sum_{k=-\infty}^n x[k] = x[n] + x[n-1] + x[n-2] + \dots$$



Recursive systems

- ▶ The last system $y[n] = \sum_{k=-\infty}^n x[k] = x[n] + x[n-1] + x[n-2] + \dots$ can be also written in **recursive form**

$$y[n] = y[n-1] + x[n],$$

- ▶ Need to start from an **initial condition**

$$y[n_0] = \sum_{k=-\infty}^{n_0} x[k]$$

- ▶ Recursive systems always have one or more initial conditions.
- ▶ For recursive systems, the output signal depends on:
 - ▶ the input signal
 - ▶ **and** on initial conditions
- ▶ The initial conditions must always be specified for a recursive system
 - ▶ If not specified : implicitly assumed they are 0 (**relaxed** system)
- ▶ A recursive system with non-zero initial conditions can produce an output signal even in the absence of an input ($x[n] = 0$)

Representation of systems

- ▶ The operation of a system can be described graphically (see examples on blackboard):
 - ▶ summation of two signals
 - ▶ scaling of a signal with a constant
 - ▶ multiplication of two signals
 - ▶ delay element
 - ▶ anticipation element
 - ▶ other blocks for more complicated math operations

II.4 Classification of discrete systems

Memoryless / systems with memory

- ▶ **Memoryless (or static):** output at time n depends only on the input **from the same moment n**
- ▶ Otherwise, the system **has memory (dynamic)**
- ▶ Examples:
 - ▶ memoryless: $y[n] = (x[n])^3 + 5$
 - ▶ with memory: $y[n] = (x[n])^3 + x[n - 1]$

Memoryless / systems with memory

- ▶ Memory of size N :
 - ▶ output at time n $y[n]$ depends only up to the last N inputs, $x[n - N], x[n - (N - 1)], \dots, x[n]$,
 - ▶ if N is finite: the system has **finite memory**
 - ▶ if $N = \infty$, the system has infinite memory
- ▶ Examples:
 - ▶ finite memory of order 4: $y[n] = x[n] + x[n - 2] + x[n - 4]$
 - ▶ infinite memory: $y[n] = \sum_{k=-\infty}^n x[k] = x[n] + x[n - 1] + x[n - 2] + \dots$

Time-Invariant and Time-Variant systems

- ▶ A relaxed system H is **time-invariant** if and only if:

$$x[n] \xrightarrow{H} y[n]$$

implies

$$x[n - k] \xrightarrow{H} y[n - k],$$

$\forall x[n], \forall k.$

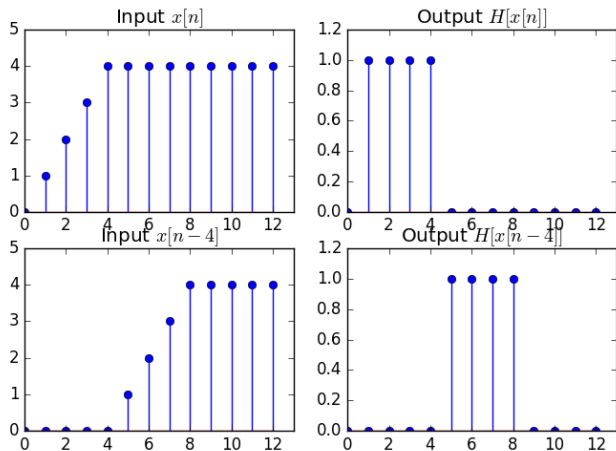
- ▶ Delaying the input signal with k will only delay the output with the same amount, otherwise the output is not affected
 - ▶ Must be true for all input signals, for all possible delays (positive or negative)
- ▶ Otherwise, the system is said to be **time-variant**

Time-Invariant and Time-Variant systems

- ▶ Examples:
 - ▶ $y[n] = x[n] - x[n - 1]$ is time-invariant
 - ▶ $y[n] = n \cdot x[n]$ is not time-invariant
- ▶ A system is time-invariant if it depends on n only through the input signal $x[n]$

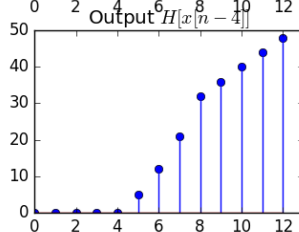
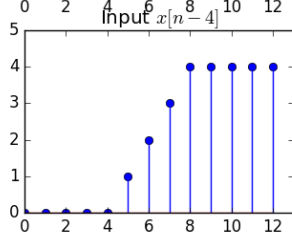
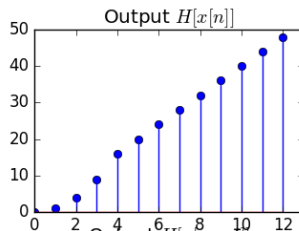
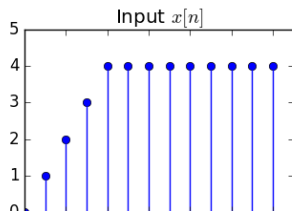
Example

Time-invariant system $y[n] = x[n] - x[n-1]$



Another example

Time-variant system $y[n] = n \cdot x[n]$



Linear and nonlinear systems

- ▶ A system H is **linear** if:

$$H [ax_1[n] + bx_2[n]] = aH [x_1[n]] + bH [x_2[n]] .$$

- ▶ Composed of two parts:
 - ▶ Applying the system to a sum of two signals = applying the system to each signal, and adding the results
 - ▶ Scaling the input signal with a constant a is the same as scaling the output signal with a
- ▶ The same relation will be true for a sum of many signals, not just two

Linear and nonlinear systems

- ▶ Advantage of linear systems
 - ▶ Complicated input signals can be decomposed into a sum of smaller parts
 - ▶ The system can be applied to each part independently
 - ▶ Then the results are added back
- ▶ Examples:
 - ▶ linear system: $y[n] = 3x[n] + 5x[n - 2]$
 - ▶ nonlinear system: $y[n] = 3(x[n])^2 + 5x[n - 2]$

Linear and nonlinear systems

- ▶ For a system to be linear, the input samples $x[n]$ must not undergo non-linear transformations.
- ▶ **The only transformations** of the input $x[n]$ allowed to take place in a linear system are:
 - ▶ scaling (multiplication) with a constant
 - ▶ delaying
 - ▶ summing different delayed versions of the signal (not summing with a constant)

Causal and non-causal systems

- ▶ **Causal**: the output $y[n]$ depends only on the current input $x[n]$ and the past values $x[n-1]$, $x[n-2]$, ..., but not on the future samples $x[n+1]$, $x[n+2]$, ...
- ▶ Otherwise the system is **non-causal**.
- ▶ A causal system can operate in real-time
 - ▶ we need only the input samples from the past
 - ▶ non-causal systems need samples from the future
- ▶ Examples:
 - ▶ $y[n] = x[n] - x[n-1]$ is causal
 - ▶ $y[n] = x[n+1] - x[n-1]$ is non-causal
 - ▶ $y[n] = x[-n]$ is non-causal

Stable and unstable systems

- ▶ **Bounded** signal: if there exists a value M such that all the samples of the signal are smaller than M , in absolute values

$$x[n] \in [-M, M]$$

$$|x[n]| \leq M$$

- ▶ **Stable** system: if for any bounded input signal it produces a bounded output signal
 - ▶ not necessarily with the same M
 - ▶ known as BIBO (Bounded Input \rightarrow Bounded Output)
- ▶ In other words: when the input signal has bounded values, the output signal does not go towards ∞ or $-\infty$.

Stable and unstable systems

- ▶ Examples:

- ▶ $y[n] = (x[n])^3 - x[n + 4]$ is stable

- ▶ $y[n] = \frac{1}{x[n] - x[n-1]}$ is unstable

- ▶ $y[n] = \sum_{k=-\infty}^n x[k] = x[n] + x[n-1] + x[n-2] + \dots$ is unstable

Impulse response of Linear Time-Invariant (LTI) systems

Linear Time-Invariant (LTI) systems

- ▶ Notation: An **LTI** system (**L**inear **T**ime-**I**nvariant) is a system which is simultaneously **linear** and **time-invariant**.
- ▶ LTI systems can be described via either (or both):
 1. the **impulse response** $h[n]$
 2. the **difference equation**

$$\begin{aligned}y[n] &= - \sum_{k=1}^N a_k y[n-k] + - \sum_{k=1}^M b_k x[n-k] \\&= - a_1 y[n-1] - a_2 y[n-2] - \dots - a_N y[n-N] + b_0 x[n] + b_1 x[n-1] + \dots + b_M x[n-M]\end{aligned}$$

The impulse response

- ▶ **Impulse response** of a system = output (response) of when the input signal is the impulse $\delta[n]$:

$$h[n] = H(\delta[n])$$

- ▶ The impulse response of a LTI system **fully characterizes the system**:
 - ▶ based on $h[n]$ we can compute the response of the system to **any** input signal
 - ▶ all the properties of LTI systems can be described via characteristics of the impulse response

Signals are a sum of impulses

- ▶ Any signal can be composed as **a sum of scaled and delayed impulses** $\delta[n]$.
- ▶ Example:
 $x[n] = \{3, 1, -5, 0, 2\} = 3\delta[n] + \delta[n - 1] - 5\delta[n - 2] + 2\delta[n - 2]$
- ▶ In general

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

i.e. a sum of impulses $\delta[n]$, delayed with k and scaled with the corresponding value $x[k]$

Convolution

- ▶ The response of a LTI system to a sum of impulses, delayed with k and scaled with $x[k]$, **is a sum of impulse responses, delayed with k and scaled with $x[k]$.**
 - ▶ The input signal is composed of separate impulses
 - ▶ LTI system \rightarrow each impulse will generate its own response
 - ▶ output signal is the sum of impulse responses, delayed and scaled

$$\begin{aligned}y[n] &= H(x[n]) \\&= H\left(\sum_{k=-\infty}^{\infty} x[k]\delta[n-k]\right) \\&= \sum_{k=-\infty}^{\infty} x[k]H(\delta[n-k]) \\&= \sum_{k=-\infty}^{\infty} x[k]h[n-k].\end{aligned}$$

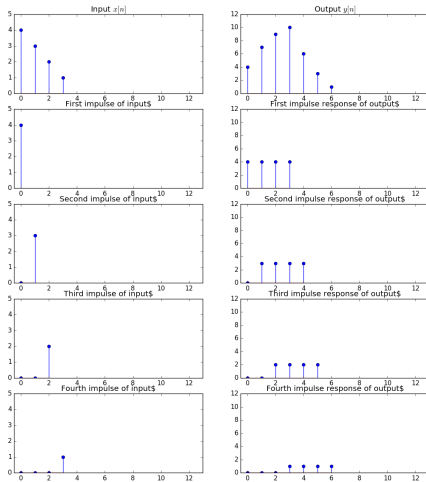
Convolution

- ▶ This operation = the **convolution** of two signals $x[n]$ and $h[n]$

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

- ▶ The response of a LTI system to an input signal $x[n]$ is **the convolution of $x[n]$ with the system's impulse response $h[n]$**

Example



Properties of convolution

- Convolution is commutative (the order of the two signals doesn't matter):

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

Proof: make variable change $(n-k) \rightarrow l$, change all in equation

- Convolution is associative

$$(a[n] * b[n]) * c[n] = a[n] * (b[n] * c[n])$$

(No proof)

- The unit impulse is neutral element for convolution

Properties of LTI systems expressed with $h[n]$

1. Identity system

- ▶ A system with $h[n] = \delta[n]$ produces a response equal to the input, $y[n] = x[n], \forall x[n]$.
- ▶ Proof: $\delta[n]$ is neutral element for convolution.

Properties of LTI systems expressed with $h[n]$

2. Series connection is commutative

- ▶ LTI systems connected in series can be interchanged in any order
- ▶ Proof: by commutativity of convolution.
- ▶ LTI systems connected in series are equivalent to a single system with

$$h_{equiv}[n] = h_1[n] * h_2[n] * \dots * h_N[n]$$

Properties of LTI systems expressed with $h[n]$

3. Parallel connection means sum

LTI systems connected in parallel are equivalent to a single system with

$$h_{equiv}[n] = h_1[n] + h_2[n] + \dots + h_N[n]$$

Properties of LTI systems expressed with $h[n]$

4. Response of LTI systems to unit step

- ▶ If the input signal is $u[n]$, the response of the system is

$$s[n] = u[n] * h[n] = h[n] * u[n] = \sum_{k=-\infty}^{\infty} h[k]u[n-k] = \sum_{k=-\infty}^n h[k]$$

Properties of LTI systems expressed with $h[n]$

► Proof:

- The signal $\sum_{k=-\infty}^n h[k]$ is a *discrete-time integration* of $h[n]$
- The unit step $u[n]$ itself is the discrete-time integral of the unit impulse:

$$u[n] = \sum_{k=-\infty}^n \delta[k]$$

$$\delta[n] = u[n] - u[n-1]$$

- Therefore the system response to the integral of the impulse = the integral of the system response to the impulse
- The interchanging of the integration with the system is due to the linearity of the system and is valid for all signals:

$$H\left(\sum_{k=-\infty}^n x[k]\right) = \sum_{k=-\infty}^n H(x[k])$$

Relation between LTI system properties and $h[n]$

1. Causal LTI systems and their $h[n]$

If a LTI system is causal, then

$$h[n] = 0, \forall n < 0$$

► Proof:

- $y[n] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$,
- $y[n]$ does not depend on $x[n+1], x[n+2], \dots$
- it means that these terms are multiplied with 0
- the value $x[n+1]$ is multiplied with $h[n-(n+1)] = h[-1]$, $x[n+2]$ is multiplied with $h[n-(n+2)] = h[-2]$, and so on
- Therefore:

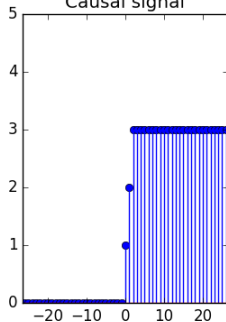
$$h[n] = 0, \forall n < 0$$

Causal signals and causal systems

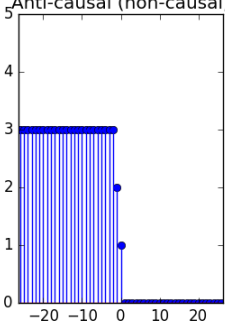
- ▶ A signal which is 0 for $n < 0$ is called a *causal signal*
- ▶ Otherwise the signal is *non-causal*
- ▶ We can say that *a system is causal if and only if it has a causal impulse response*
- ▶ Further definitions:
 - ▶ a signal which 0 for $n > 0$ is called an *anti-causal* signal
 - ▶ a signal which has non-zero values both for some $n > 0$ and for some $n < 0$ (and thus is neither causal nor non-causal) is called *bilateral*.

Example

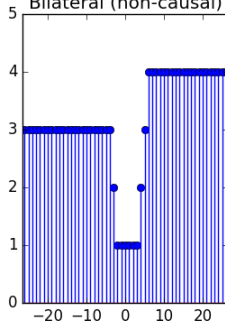
Causal signal



Anti-causal (non-causal)



Bilateral (non-causal)



2. Stable systems and their $h[n]$

- ▶ Considering a bounded input signal, $|x[n]| \leq A$, the absolute value of the output is:

$$\begin{aligned}|y[n]| &= \left| \sum_{k=-\infty}^{\infty} x[k]h[n-k] \right| \\ &\leq \sum_{k=-\infty}^{\infty} |x[k]h[n-k]| \\ &= \sum_{k=-\infty}^{\infty} |x[k]| |h[n-k]| \\ &\leq A \sum_{k=-\infty}^{\infty} |h[n-k]| \end{aligned}$$

- ▶ Therefore **a LTI system is stable if**

$$\sum_{k=-\infty}^{\infty} |h[n]| < \infty$$

3. Memoryless systems and their $h[n]$ (Exercise)

Exercises:

- ▶ What can we say about the impulse response $h[n]$ of a memoryless system?
- ▶ What about a system with finite memory M ?

FIR and IIR systems

- ▶ The **support** of a discrete signal = the smallest interval of n such that the signal is 0 everywhere outside the interval.
- ▶ Examples: at whiteboard
- ▶ Depending on the support of the impulse response, discrete LTI systems can be **FIR** or **IIR** systems.

FIR systems

- ▶ A **F**inite **I**mpulse **R**esponse (**FIR**) system has an impulse response with finite support
 - ▶ i.e. the impulse response is 0 outside a certain interval.
- ▶ For a causal system:
 - ▶ $h[n] = 0$ for $n < 0$
 - ▶ therefore $h[n] = 0$ for $n < 0$ or $n \geq M$, for some M
 - ▶ The convolution becomes:

$$y[n] = \sum_{k=0}^M h[k]x[n-k] = h[0] \cdot x[n] + h[1] \cdot x[n-1] + \dots h[M] \cdot x[n-M]$$

- ▶ For a causal FIR system, the output is a linear combination of the last M input samples (has finite memory M)

- ▶ An **I**nfinite **I**mpulse **R**esponse (**IIR**) system has an impulse response with infinite support
 - ▶ i.e. the impulse response never becomes completely 0 forever.
- ▶ Causal system: the output $y[n]$ potentially depends on all the preceding input samples
 - ▶ from the convolution equation
- ▶ An IIR system has infinite memory

Recursive / non-recursive implementations

- ▶ **Recursive** implementation: compute $y[n]$ based partly on the previous output samples $y[n-1], y[n-2], \dots$
 - ▶ more efficient
- ▶ For a recursive LTI system, the output $y[n]$ depends on:
 - ▶ the last N samples of the output, $y[n-1], \dots, y[n-N]$
 - ▶ and the current and the last M samples of the input, $x[0], x[1], \dots, x[n-M]$.
- ▶ Example:

$$y[n] = \frac{1}{n+1} \sum_0^n x[n]$$

can be rewritten in recursive form:

$$y[n] = n \cdot y[n-1] + x[n]$$

Recursive / non-recursive implementations

- ▶ **Non-recursive** system: the output $y[n]$ is computed based only on last M samples of the input, $x[0]$, $x[1]$, \dots $x[n-M]$.
- ▶ FIR systems can always be implemented non-recursively, but may also be implemented in a recursive way
- ▶ IIR systems can only be implemented recursively
 - ▶ otherwise they would need infinite memory

Initial conditions for recursive systems

- ▶ Recursive systems rely on previous outputs \rightarrow the previous values must be always available
- ▶ We need some starting values at the start moment (**the initial conditions** of the system)
- ▶ Notes:
 - ▶ Output signal depends on the input **and** on the initial conditions
 - ▶ A system with non-zero initial conditions produces an output even when the input signal is zero
 - ▶ This output is called *zero-input response*, $y_{zi}[n]$
 - ▶ A system with initial conditions equal to 0 is called *relaxed*
 - ▶ The output of a relaxed system to an input signal is called *zero-state response*, $y_{zs}[n]$ (also called *forced response*)
- ▶ For linear systems, the output of a system is always the sum of the forced response and the natural response:

$$y[n] = y_{zs}[n] + y_{zi}[n]$$