Digital Signal Processing for Music

Part 6: LTI Systems & Convolution

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Georgia Tech Center for Music Technology

lecture content

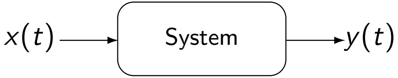
overview

1. LTI systems and their properties
2. convolution

systems
introduction

a system:

- any process producing an output signal in response to an input signal



name examples for systems in signal processing/the real world

systems
introduction

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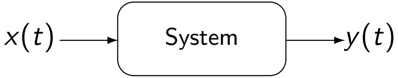
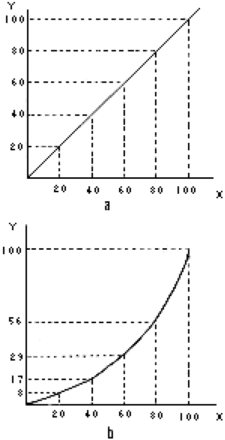


name examples for systems in signal processing/the real world

- filters, effects
- vocal tract
- room
- (audio) cable
- ...

systems
linearity and non-linearity

- examples for mostly linear systems:
  - room
  - eq
- examples for non-linear systems:
  - diode
  - vacuum tube



http://www.sfu.ca/sonic-studio/handbook/Linear.html

1. **homogeneity**:

$$f(ax) = af(x)$$

2. **superposition** (additivity):

$$f(x + y) = f(x) + f(y)$$

systems

time invariance

- does not change with time:

$$f(x(t-\tau)) = f(x)(t-\tau)$$

LTI: Linear Time-invariant Systems

are a great simplification for many real-world systems we would like to model — circuits, spring-mass-damper systems, etc.

systems

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systems
LTI system example

velocity of mass an a table

1. hammer gives *impulse*
2. system *responds* with velocity

linearity:
double force, double velocity, multiple strikes add up

time invariance:
system reacts the same whether I do it now or tomorrow

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systems

other system characteristics

- **causality**:
  output depends only on past and present input

- **BIBO stability**:
  output is bounded for bounded input

convolution
introduction

we know how a system reacts to an impulse, but what of a more complex input signal

convolution

introduction

we know how a system reacts to an impulse, but what of a more complex input signal

- assume that the signal is constructed from many densely packed impulses

$\Rightarrow$ output is superposition of all individual responses

convolution
introduction

we know how a system reacts to an impulse, but what of a more complex input signal

- assume that the signal is constructed from many densely packed impulses

⇒ output is superposition of all individual responses

convolution

$$y(t) = (x * h)(t) := \int\limits_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau$$

convolution

animation

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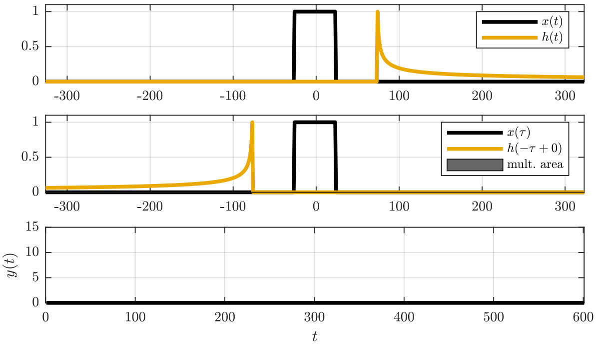
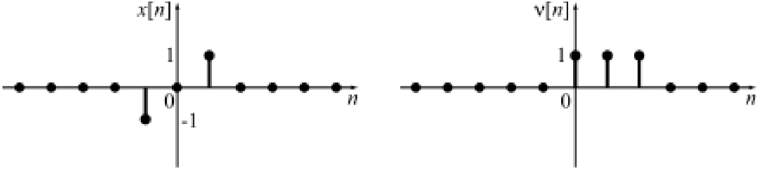


matlab source: matlab/animateConvolution.m compute the convolution of the following two signals



steps:

1. flip one signal
2. multiply the two signals
3. integrate the result
4. shift
5. go to 2.

convolution

identity and impulse response

$$
\begin{aligned}
x(t) &= \delta(t) * x(t) \\
h(t) &= \delta(t) * h(t)
\end{aligned}
$$

- describes the response of a system to an impulse as a function of time
- as an impulse includes all frequencies, the resulting IR defines the response for all frequencies
- the convolution of $\delta(t)$ with a signal/impulse response results in that impulse response

convolution

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convolution

properties

$$y(t) = x(t) * h(t) = \int\limits_{-\infty}^{\infty} h(\tau) \cdot x(t-\tau) d\tau$$

- **commutativity**

$$h(t) * x(t) = x(t) * h(t)$$

- **associativity**

$$\big(g(t) * h(t)\big) * x(t) = g(t) * \big(h(t) * x(t)\big)$$

- **distributivity**

$$g(t) * \big(h(t) + x(t)\big) = \big(g(t) * h(t)\big) + \big(g(t) * x(t)\big)$$

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convolution

derivation: commutativity

$$h(t) * x(t) = x(t) * h(t)$$

substituting $\tau' = t - \tau$:

$$\begin{aligned} x(t) * h(t) &= \int\limits_{-\infty}^{\infty} h(\tau) \cdot x(t-\tau) d\tau \\ &= \int\limits_{-\infty}^{\infty} h(t-\tau') \cdot x(\tau') d(t-\tau') \\ &= \int\limits_{-\infty}^{\infty} x(\tau') \cdot h(t-\tau') d\tau' \end{aligned}$$

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convolution
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changing the order of sums and shifting the operands as shown below:

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convolution
derivation: distributivity

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systems

summary

- **LTI system**: approximation of many real-world systems
  - properties:
    - linearity 1: homogeneity (scaling)
    - linearity 2: superposition (additivity)
    - time invariance (system doesn't change)
    - causality (no future input)
    - BIBO — bounded input bounded output
- **impulse response** is a complete description of an LTI system
- **convolution**: describes process of generating output of LTI system from input
  - properties:
    - commutative
    - associative
    - distributive

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