EE-2025 Fall-2001

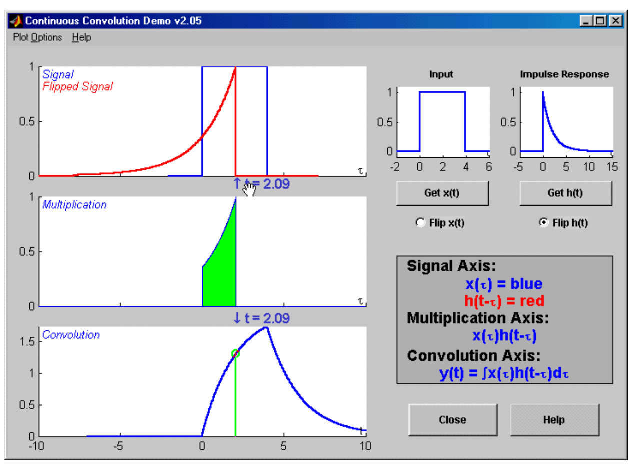
Lecture 16
Convolution (Continuous-Time)
29-Oct-01

Info: Web-CT, Lab, HW

- Calendar:
  - Quiz #3 is 19-Nov (Monday)
- Get NEW CHAPTERS (Ch 10 – 13)
  - PDF or Bookstore
- Prob Set #8 is due this week
- Lab #8 is due 31-Oct thru 6-Nov
  - Demo your DTMF decoder in Lab
- Quiz #2: Resolve any grade changes by Friday (2-Nov)

Lab #9 GUIs

- Download 2 convolution demos



LECTURE

READING ASSIGNMENTS

- This Lecture:
  - Chapter 10, pp. 1017-1045
- Other Reading:
  - Recitation: Ch. 10, all, pp. 1000-1045
  - Next Lecture: Start reading Chapter 11

LECTURE OBJECTIVES

- Review of C-T LTI systems
- **Evaluating convolutions**
  - **Examples**
  - **Impulses**
- LTI Systems
  - Stability and causality
  - Cascade and parallel connections

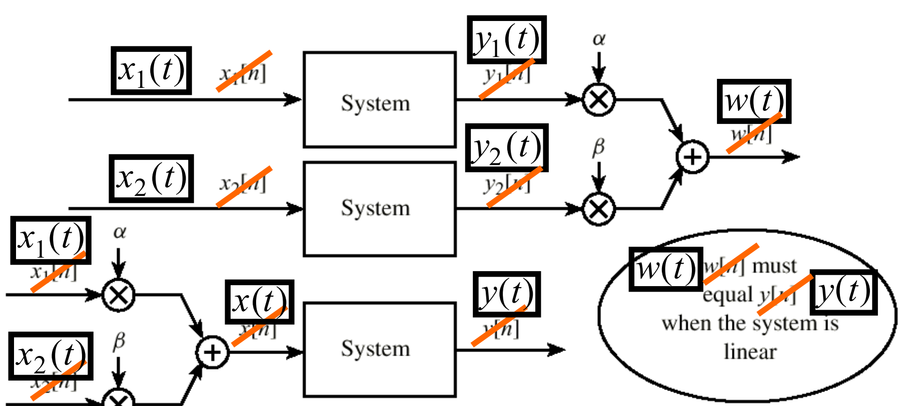
Linear and Time-Invariant (LTI) Systems

- If a continuous-time system is both linear and time-invariant, then the output *y(t)* is related to the input *x(t)* by a ***convolution integral***

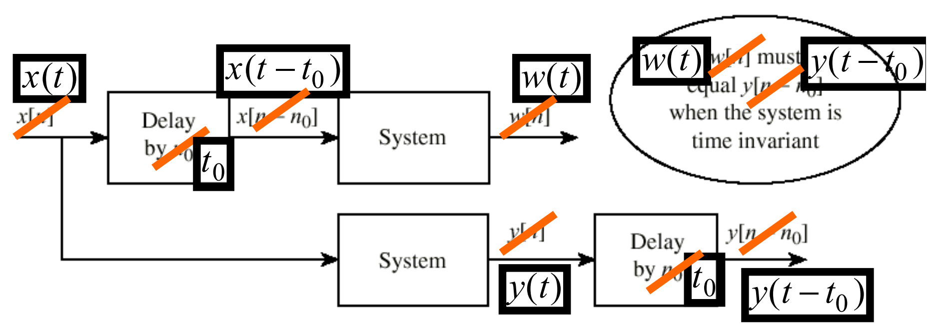
$$y(t) = \int_{-\infty}^{\infty} x(\tau)h(t-\tau)d\tau = x(t) * h(t)$$

system.

Testing for Linearity



Testing Time-Invariance



Ideal Delay: $y(t) = x(t - t_d)$

- Linear

$$ax_1(t - t_d) + bx_2(t - t_d) = ay_1(t) + by_2(t)$$

- and Time-Invariant

$$\begin{aligned} w(t) &= x((t - t_0) - t_d) \\ y(t - t_0) &= x((t - t_0) - t_d) \end{aligned}$$

Integrator: $y(t) = \int_{-\infty}^{t} x(\tau)d\tau$

- Linear

$$\int_{-\infty}^{t} [ax_1(\tau) + bx_2(\tau)]d\tau = ay_1(t) + by_2(t)$$

- And Time-Invariant

$$w(t) = \int_{-\infty}^{t} x(\tau - t_0)d\tau \qquad \text{let } \sigma = \tau - t_0$$

$$\Rightarrow \quad w(t) = \int_{-\infty}^{t - t_0} x(\sigma)d\sigma = y(t - t_0)$$

Modulator: $y(t) = [A + x(t)]\cos\omega_c t$

- ***Not*** linear--obvious because

$$[A + ax_1(t) + bx_2(t)] \neq$$

$$[A + ax_1(t)] + [A + bx_2(t)]$$

- ***Not*** time-invariant

$$w(t) = [A + x(t - t_0)]\cos\omega_c t \neq y(t - t_0)$$

Linear and Time-Invariant (LTI) Systems

- If a continuous-time system is both linear and time-invariant, then the output *y(t)* is related to the input *x(t)* by a ***convolution integral***

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

system.

Convolution of Impulses, etc.

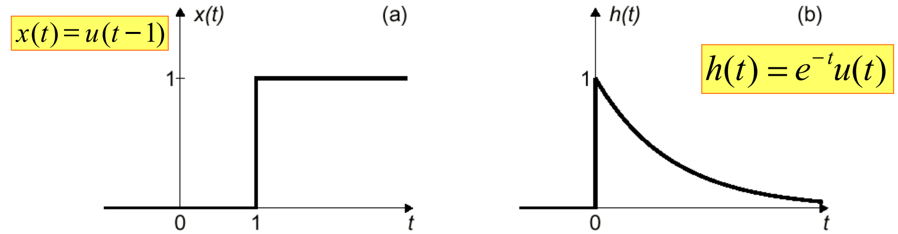
- Convolution of two impulses

$$\delta(t-t_1)*\delta(t-t_2)=\delta(t-t_1-t_2)$$

- Convolution of step and shifted impulse

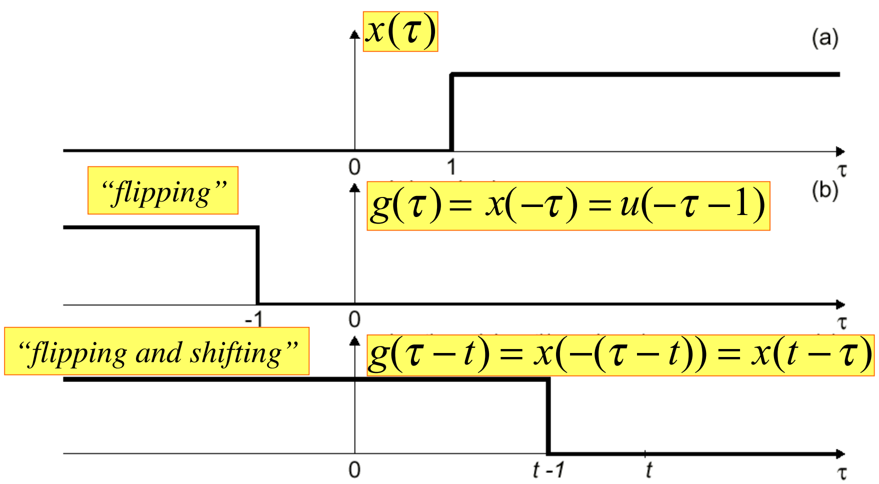
$$u(t)*\delta(t-t_0)=u(t-t_0)$$

Evaluating a Convolution

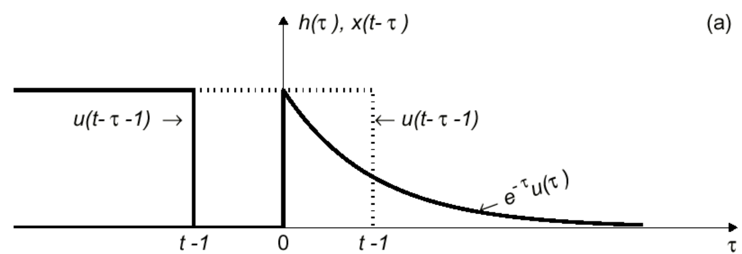


$$y(t)=\int_{-\infty}^{\infty}h(\tau)x(t-\tau)d\tau=h(t)*x(t)$$

"Flipping and Shifting"



Evaluating the Integral

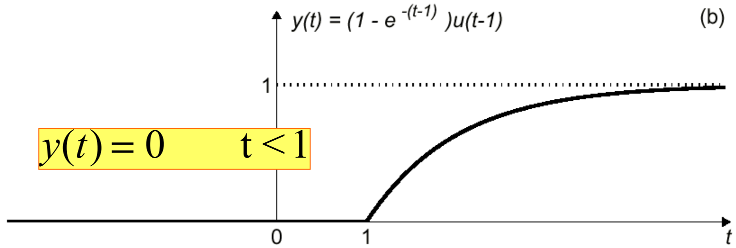


$$
\begin{aligned}
y(t) &= 0 && t-1<0\\
&= \int_0^{t-1} e^{-\tau}d\tau && t-1\geq 0
\end{aligned}
$$

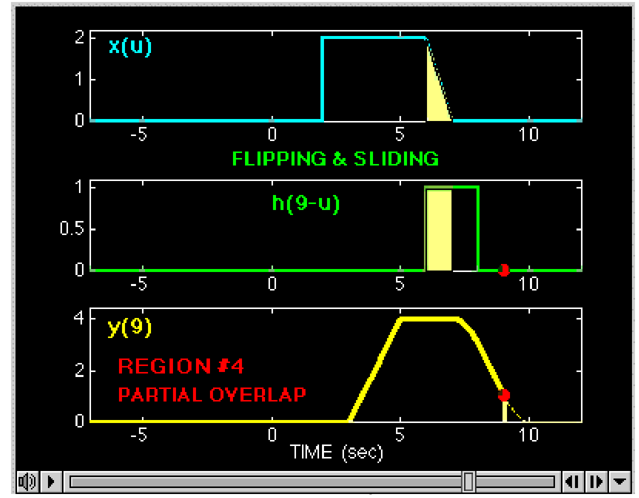
Solution

$$y(t) = \int_0^{t-1} e^{-\tau} d\tau = -e^{-\tau}\Big|_0^{t-1}$$

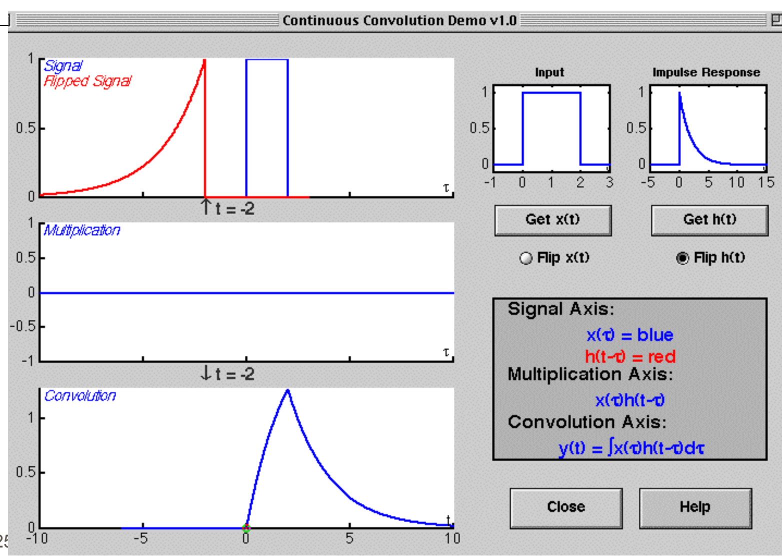
$$= 1 - e^{-(t-1)} \qquad t \geq 1$$



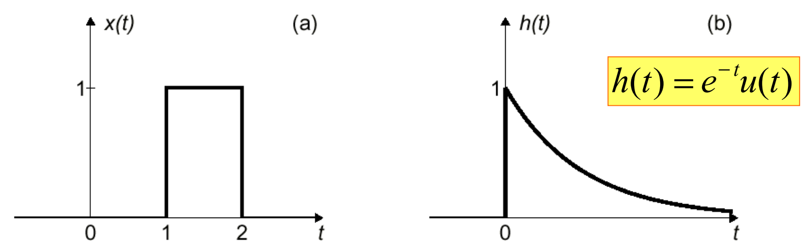
Convolution Movie



Convolution GUI

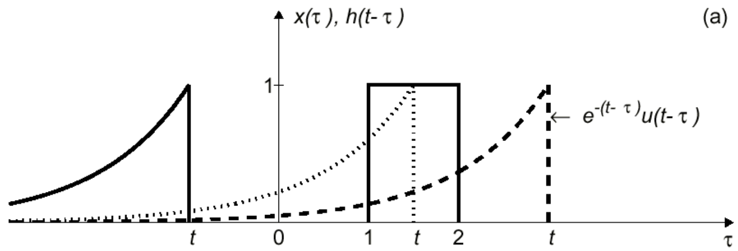


Another Convolution Example



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

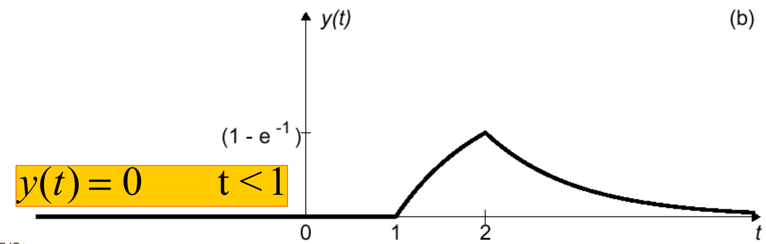
Evaluating the Integral



$$y(t) = 0 \qquad t<1$$
$$= \int_1^t e^{-(t-\tau)}d\tau \qquad 1 \le t \le 2$$
$$= \int_1^2 e^{-(t-\tau)}d\tau \qquad 2 \le t$$

Solution

$$y(t) = \int_1^t e^{-(t-\tau)}d\tau = e^{-(t-\tau)}\Big|_1^t = 1 - e^{-(t-1)} \qquad 1 \le t \le 2$$
$$= \int_1^2 e^{-(t-\tau)}d\tau = e^{-(t-\tau)}\Big|_1^2 = e^{-(t-2)} - e^{-(t-1)} \qquad 2 \le t$$



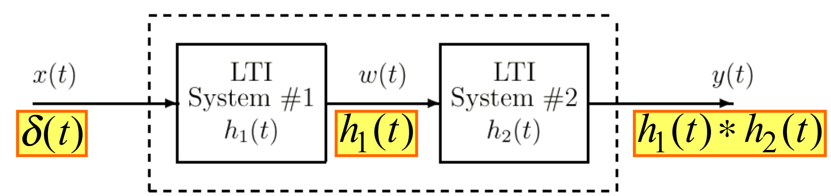
Convolution is Commutative

$$h(t)*x(t) = \int_{-\infty}^{\infty} h(\tau)x(t-\tau)d\tau$$

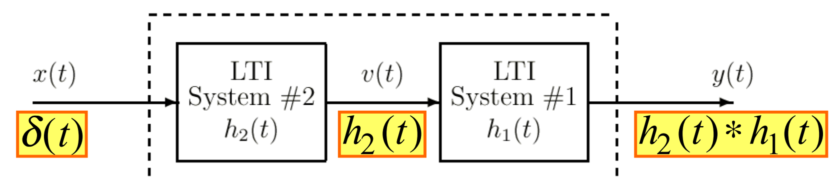
let $\sigma = t - \tau$ and $d\sigma = -d\tau$

$$h(t)*x(t) = -\int_{\infty}^{-\infty} h(t-\sigma)x(\sigma)d\sigma$$
$$= \int_{-\infty}^{\infty} h(t-\sigma)x(\sigma)d\sigma = x(t)*h(t)$$

Cascade of LTI Systems



$$h(t) = h_1(t)*h_2(t) = h_2(t)*h_1(t)$$



(b)

Stability

- A system is stable if every bounded input produces a bounded output.
- A continuous-time *LTI system* is stable if and only if

$$\int_{-\infty}^{\infty} |h(t)| dt < \infty$$

Causal Systems

- A system is causal if and only if $y(t_0)$ depends only on $x(\tau)$ for $\tau \leq t_0$.
- An LTI system is causal if and only if

$$h(t) = 0 \quad \text{for} \quad t < 0$$

Convolution is Linear

- Substitute $x(t)=ax_1(t)+bx_2(t)$

$$\begin{aligned} y(t) &= \int_{-\infty}^{\infty} [ax_1(\tau) + bx_2(\tau)]h(t-\tau)d\tau \\ &= a\int_{-\infty}^{\infty} x_1(\tau)h(t-\tau)d\tau + b\int_{-\infty}^{\infty} x_2(\tau)h(t-\tau)d\tau \\ &= ay_1(t) + by_2(t) \end{aligned}$$

Therefore, convolution is linear.

Convolution is Time-Invariant

- Substitute $x(t-t_0)$

$$\begin{aligned} w(t) &= \int_{-\infty}^{\infty} h(\tau)x((t-\tau)-t_o)d\tau \\ &= \int_{-\infty}^{\infty} h(\tau)x((t-t_o)-\tau)d\tau \\ &= y(t-t_o) \end{aligned}$$