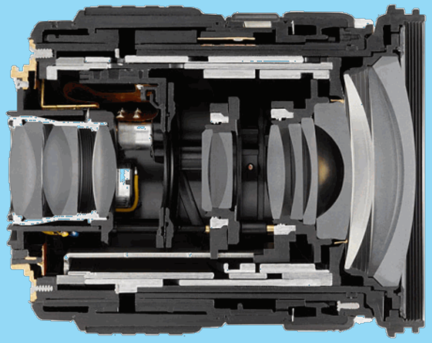

Optics

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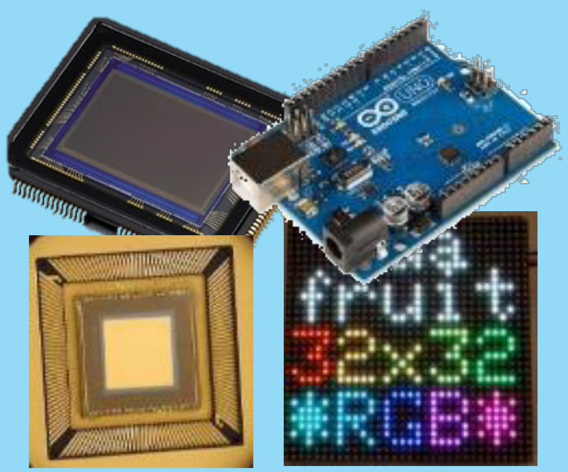


Sensors
&
devices

+

Signal
processing
&
algorithms

COMPUTATIONAL METHODS FOR IMAGING (AND VISION)

LECTURE 10: INTRO TO LSI IMAGING SYSTEMS

PROF. JOHN MURRAY-BRUCE

WHERE ARE WE

WE ARE HERE!

Week	Date	Main Topic	Lecture	Readings	Homework Out	Homework Due
1	11-Jan-21		Introduction to computational imaging - Forward and Inverse problems - Common computational imaging problems			
	13-Jan-21		Vectors - Preliminaries			
2	18-Jan-21		Dr. Martin Luther King, Jr. Holiday (no class)			
	20-Jan-21	Mathematical preliminaries	Vectors and Vector Spaces - Subspaces, Finite dimensional spaces	IIP Appendix A; FSP 2.1 - 2.2		
3	25-Jan-21		Vector Spaces - Hilbert spaces	IIP Appendix B; FSP 2.3		
	27-Jan-21		Bases and Frames I - Orthonormal and Reisz Bases	IIP Appendix C; FSP 2.4 and 2.B	HW 1	
4	1-Feb-21		Bases and Frames II - Orthogonal Bases - Linear operators	IIP Appendix C; FSP 2.5 and 2.B		
	3-Feb-21		Fourier Analysis I - FT (1D and 2D) - FT properties	IIP 2.1, Appendix D; FSP 4.4		
5	8-Feb-21		Sampling and Interpolation - BL functions - Sampling	IIP 2.2, 2.3; FSP 5.4, 5.5		HW 1
	10-Feb-21		Fourier Analysis II (DFT)	IIP 2.4; FSP 3.6	HW 2	
6	15-Feb-21	Forward Modeling	LSI imaging: Forward problem I - Convolution	IIP 2.5 - 2.6, 3		
	17-Feb-21		LSI imaging: Forward problem I - Transfer functions	IIP 2.6		
7	22-Feb-21		LSI imaging: Forward problem I - Linear operators	IIP 3		
	24-Feb-21		LSI imaging: Forward problem I - Linear operators, Adjoints, and Inverses		HW 3	HW 2
8	1-Mar-21		Mid-term Exams			
	3-Mar-21		LSI imaging: Forward problem II - Sampling and Discretization: Matrix-vector form	IIP 2.7, 4		
9	8-Mar-21		LSI imaging: Forward problem II - Convolution matrix			
	10-Mar-21		LSI imaging: Forward problem II - Sampling and Discretization: Matrix-vector form - PSF, and Transfer functions			HW3

OUTLINE

- Linear Space Invariant (LSI) Imaging Systems
- Properties of LSI (imaging) systems
- Convolution - definition & properties

LEARNING GOALS

- To be able to identify LSI systems
- Identify the convolution integral
- Compute 1D and 2D convolutions

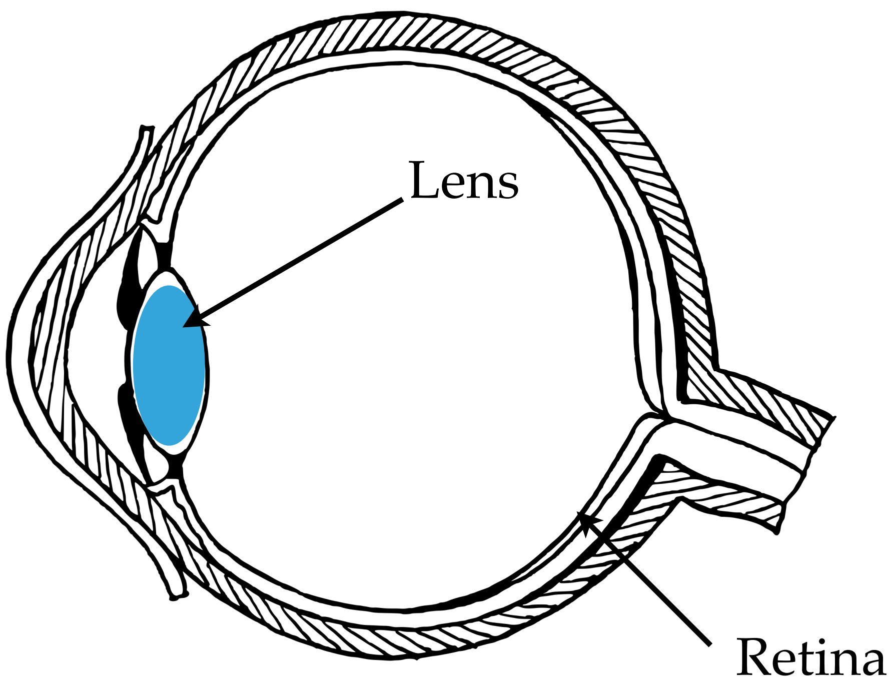
READING

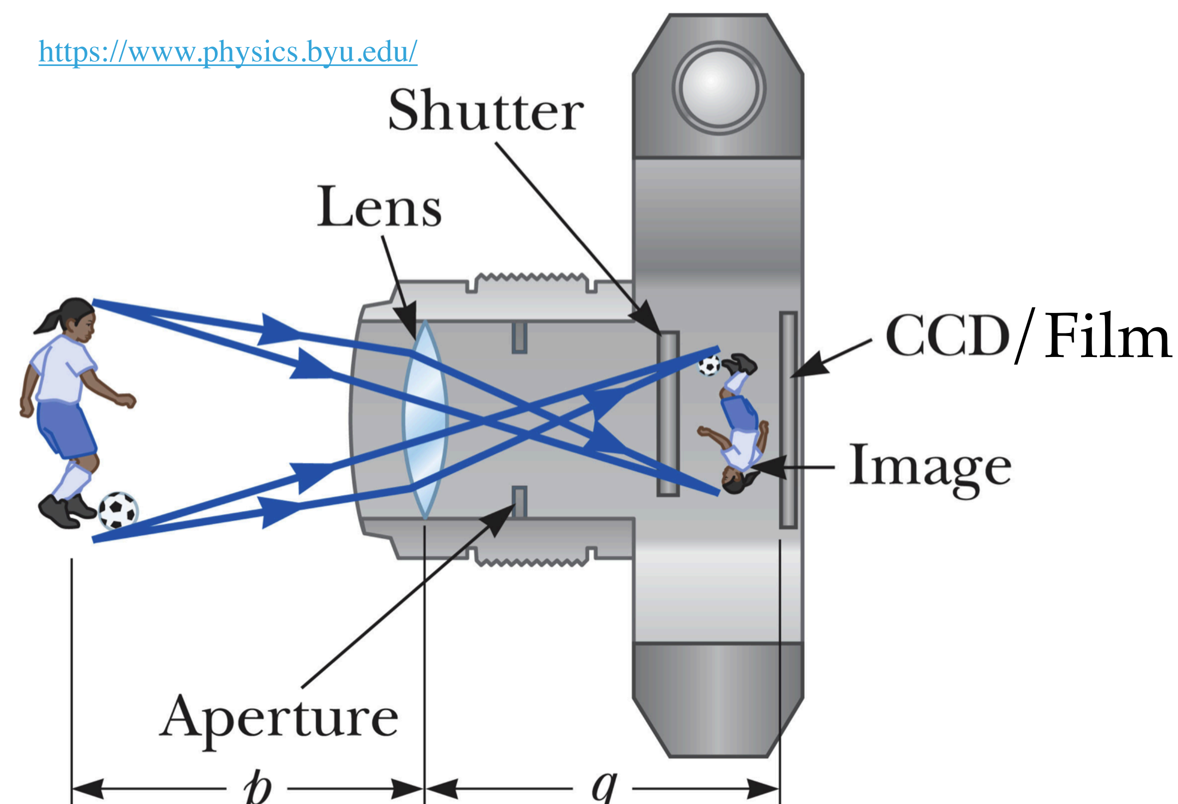
- IIP 2.5 - 2.6
- IIP 3.1 - 3.3

OVERVIEW

IMAGING SYSTEMS

IMAGING SYSTEMS
SIMPLISTIC VIEW



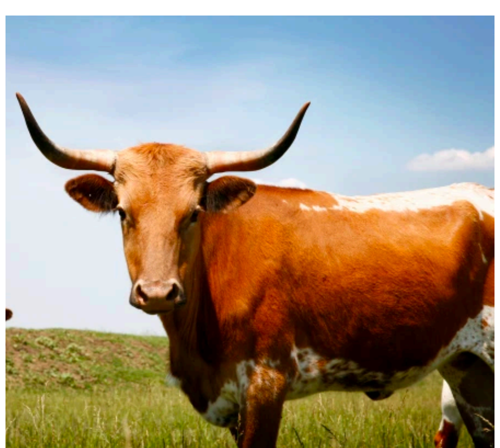


- **Pupil** allows light passage
- **Lens** focuses light to retina
- Muscles control size of pupil and focus of lens

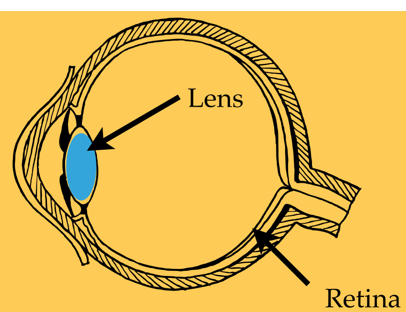
- **Aperture** – light passage
- **Lens** focuses light to film
- Changing shape of lens difficult, but can slide lens along optical axis.

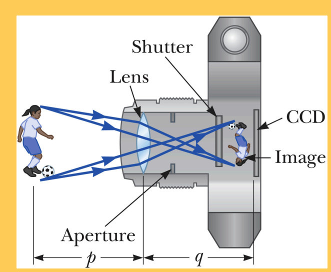
IMAGING SYSTEMS
LINEAR SHIFT INVARIANT

- **Linear space/shift invariant** imaging systems
  - The imaging system, observes some input and produces an output which is a "modification" of the input
  - Modifies the input signal, or equivalently, the signal's Fourier spectrum
  - Can model the **imaging system as a function**, and the **input signal as another function**



$g_{\text{in}}(x, y)$





LINEAR SPACE INVARIANT IMAGING SYSTEM

H

$h(x, y)$

$g_{\text{out}}(x, y)$

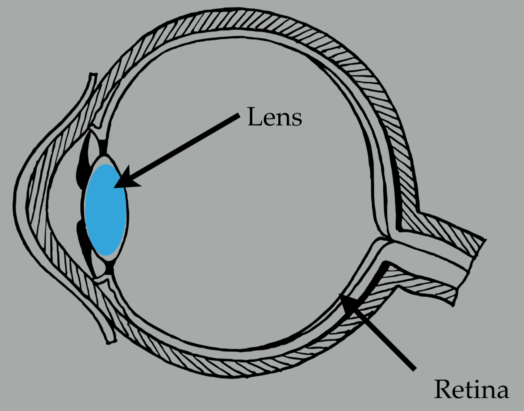
https://www.physics.byu.edu/

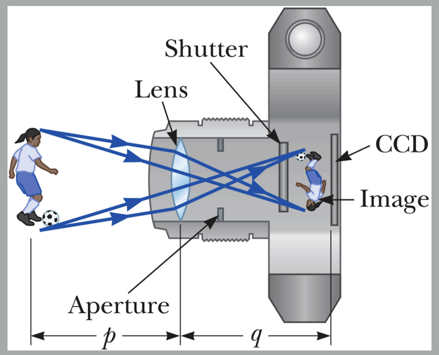
IMAGING SYSTEMS MEET SIGNAL PROCESSING

- **How can we use one function to modify another?**
  - Fundamental question in signal processing
  - Thus, we need an understanding of foundational signal processing techniques
- Easier/common to **tackle this question in the frequency domain** (i.e. the Fourier transform domain)
  - [PREVIEW] **Convolution integral:** describes this input-output relationship

OVERVIEW

LINEAR SHIFT INVARIANT IMAGING SYSTEMS

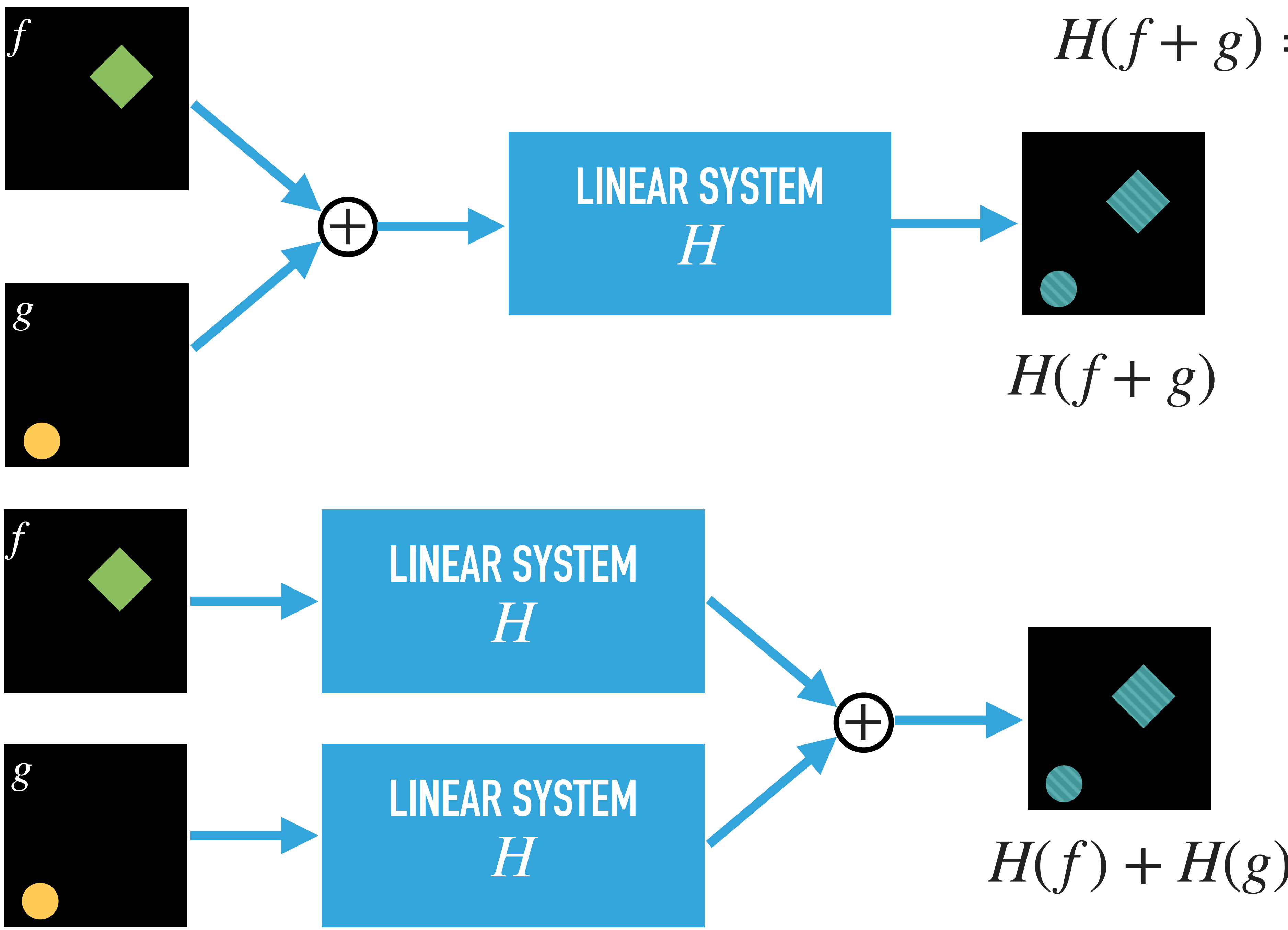




LINEAR SYSTEM
PROPERTIES

Distributive property holds: i.e.

$$H(f+g) = H(f) + H(g)$$



SPACE (OR SHIFT) INVARIANT SYSTEM

PROPERTIES

- The operator is the same at any point in space
  - Put differently, the model H does not depend on spatial position (x, y)

SPACE (OR SHIFT) INVARIANT SYSTEM
PROPERTIES

- The operator is the same at any point in space
  - Put differently, the model H does not change depending on spatial position (x, y)

LINEAR SPACE INVARIANT SYSTEMS & CONVOLUTION

- Take FT, manipulate frequency spectrum of signal, and then take the inverse FT
  - **Linearity:** $\mathscr{F}\{f(x) + g(x)\} = \mathscr{F}\{f(x)\} + \mathscr{F}\{g(x)\} = F(\omega) + G(\omega)$
  - **Shift:** $\mathscr{F}\{f(x - x_0)\} = e^{-\mathrm{j}\omega x_0}\mathscr{F}\{f(x)\} = e^{-\mathrm{j}\omega x_0}F(\omega)$

- **Natural next question is, what about multiplication?**
  - $\mathscr{F}\{f(x)\}\,\mathscr{F}\{g(x)\} = F(\omega)\,G(\omega)$ **= ?**

Suppose the problem is solved and see what has to have happened!

A STAR IS BORN

CONVOLUTION

LINEAR SPACE INVARIANT SYSTEMS & CONVOLUTION
CONVOLUTION INTEGRAL

- **What about multiplication of spectra?**
  - **Prove that** $\mathscr{F}\{f(x)\}\,\mathscr{F}\{g(x)\} = F(\omega)\,G(\omega) = \mathscr{F}\{f(x) \star g(x)\}$
  - **Convolution** in the spatial (or temporal) domain is multiplication in frequency.
  - **Question before we proceed:**
    What are the FT integrals for $f(x)$ and $g(x)$?
    - $F(\omega) =$
    - $G(\omega) =$

1. $F(\omega) = \int_{-\infty}^{\infty} f(x)e^{-\mathrm{j}\omega x}\,\mathrm{d}x$

2. $G(\omega) = \int_{-\infty}^{\infty} g(x)e^{-\mathrm{j}\omega x}\,\mathrm{d}x$

$$= \int_{-\infty}^{\infty} g(y)e^{-\mathrm{j}\omega y}\,\mathrm{d}y$$

CONVOLUTION

PROOF: FOURIER TRANSFORM OF CONVOLUTION

$$
\begin{aligned}
\mathcal{F}\{f(x)\}\,\mathcal{F}\{g(x)\} &= F(\omega)G(\omega) \\
&= \int_{-\infty}^{\infty} f(x)e^{-j\omega x}\mathrm{d}x \int_{-\infty}^{\infty} g(y)e^{-j\omega y}\mathrm{d}y \\
&= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x)e^{-j\omega x}g(y)e^{-j\omega y}\,\mathrm{d}x\,\mathrm{d}y \\
&= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x)\,g(y)e^{-j\omega(x+y)}\,\mathrm{d}x\,\mathrm{d}y.
\end{aligned}
$$

Let $x' = x + y$, now substitute for $y = x' - x$ and $\mathrm{d}y = \mathrm{d}x'$. Thus,

$$
\begin{aligned}
\mathcal{F}\{f(x)\}\,\mathcal{F}\{g(x)\} &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x)\,g(x'-x)e^{-j\omega x'}\,\mathrm{d}x\,\mathrm{d}x' \\
&= \int_{-\infty}^{\infty}\left(\int_{-\infty}^{\infty} f(x)\,g(x'-x)\,\mathrm{d}x\right)e^{-j\omega x'}\,\mathrm{d}x' = \mathcal{F}\left\{f(x') \star g(x')\right\}.
\end{aligned}
$$

The last equality follows when we define: $f(x') \star g(x') := \left(\int_{-\infty}^{\infty} f(x)\,g(x'-x)\,\mathrm{d}x\right)$

$$F(\omega)G(\omega) = \mathcal{F}\left\{f(x') \star g(x')\right\} \quad \text{or} \quad \mathcal{F}^{-1}\left\{F(\omega)G(\omega)\right\} = f(x') \star g(x')$$

LINEAR SPACE INVARIANT SYSTEMS & CONVOLUTION

CONVOLUTION INTEGRAL

- **What about multiplication of spectra?**
  - $\mathscr{F}\{f(x)\}\,\mathscr{F}\{g(x)\} = F(\omega)\,G(\omega) = \mathscr{F}\{f(x) \star g(x)\}$

$$f(x) \star g(x) = \int_{-\infty}^{+\infty} f(x')g(x-x')\,\mathrm{d}x'$$

  - *(And a "star" is born!)*
- **Convolution in the space/time domain is multiplication in frequency!**
  - A very important FT property: $f(x) \star g(x) \longleftrightarrow F(\omega)\,G(\omega)$
  - Computing product in frequency domain is much faster than computing the convolution integral in the time/spatial domain

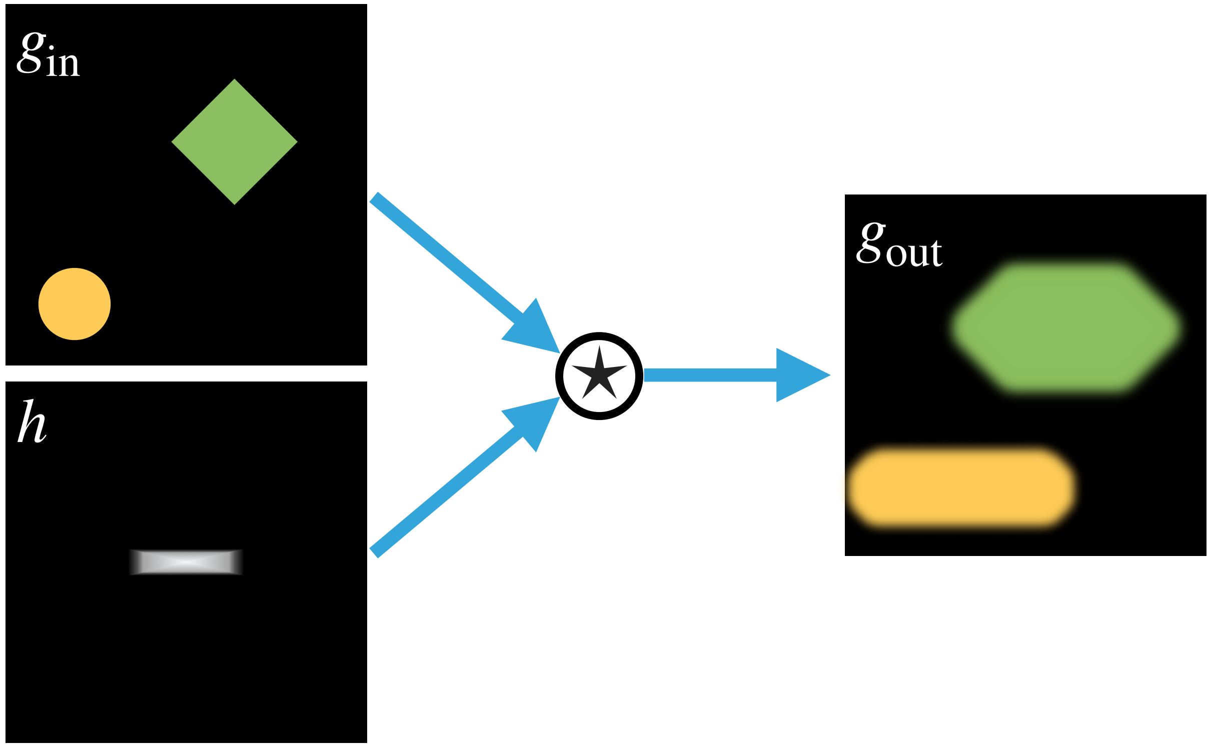
LINEAR SPACE INVARIANT IMAGING SYSTEMS & CONVOLUTION

- **LSI system:** Linear in the input and also shift invariant
  - Input described by function $g_{\text{in}}(x)$ and system by $h(x)$
- **Convolution integral (1D):**

$$g_{\text{out}}(x) \star h(x) = \int_{-\infty}^{+\infty} g_{\text{in}}(x')h(x-x')\,\mathrm{d}x'$$

  - Relates input and output of LSI imaging system
  - Convolution integral is linear in input and shift-invariant

For an imaging system, h is called the **Point Spread Function (PSF)**



LINEAR SPACE INVARIANT SYSTEMS & CONVOLUTION

2D CONVOLUTION INTEGRAL

- **2D Convolution:**

$$f(x,y) \star g(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x',y')g(x-x',y-y')\,\mathrm{d}x'\mathrm{d}y'$$

- **FT Property:** Convolution of two functions in space is equivalent to multiplication of their frequency spectra

$$f(x,y) \star g(x,y) \longleftrightarrow F(\omega_x,\omega_y)\,G(\omega_x,\omega_y)$$

QUICK SUMMARY

LINEAR SPACE INVARIANT SYSTEMS
&
CONVOLUTION

LINEAR SPACE INVARIANT SYSTEM

Linear: so the distributive property, $H(f+g) = H(f) + H(g)$, holds.

Space invariant: operator is the same at any point in space. H does not depend on (x, y).

Convolution of system response with input, gives the system output.

CONVOLUTION

Convolution:

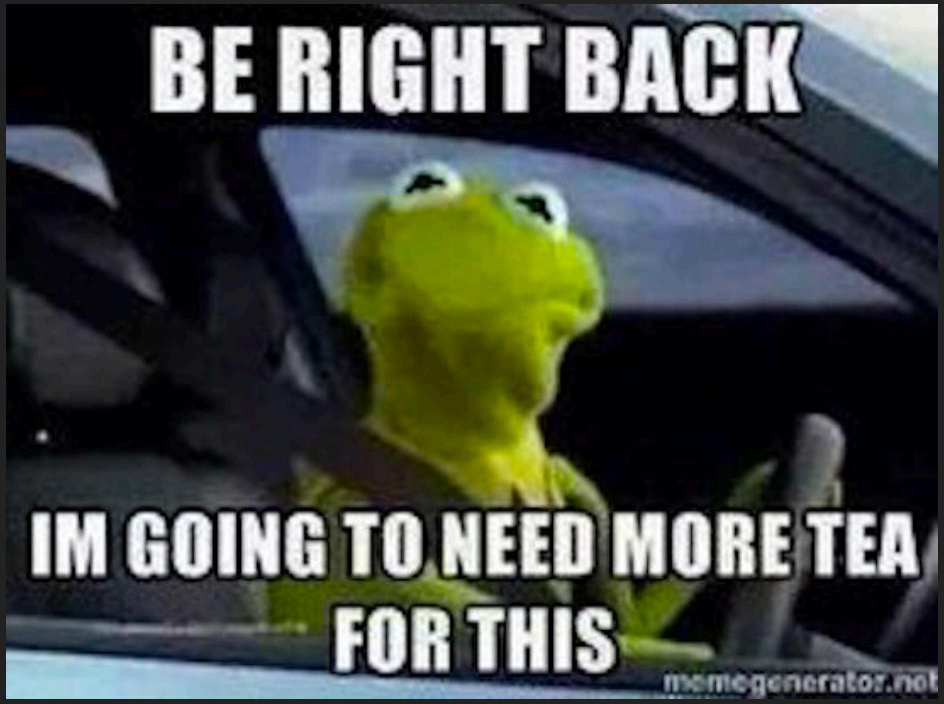
$$g(x,y) \star h(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x',y')h(x-x',y-y')\,\mathrm{d}x'\mathrm{d}y'$$

Convolution integral relates the output g_{out} of the system h to any input g_{in} to that system.

The **convolution** of two functions is itself a **"new" function**.

The FT of the convolution of two functions in space is the product of their respective FTs, i.e.:

$$g(x) \star h(x) \longleftrightarrow G(\omega)H(\omega)$$



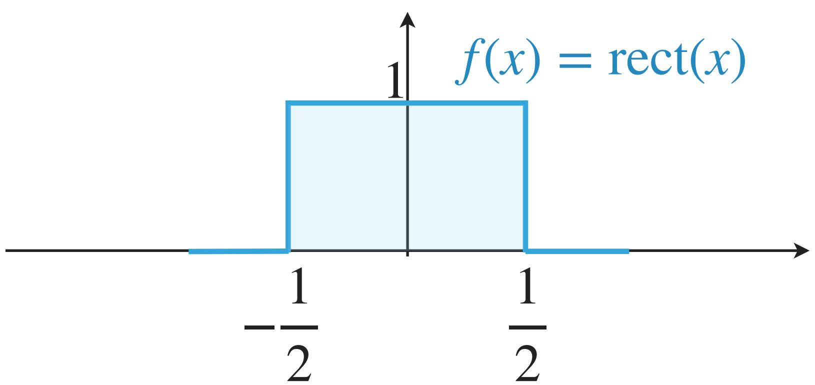
EXAMPLES

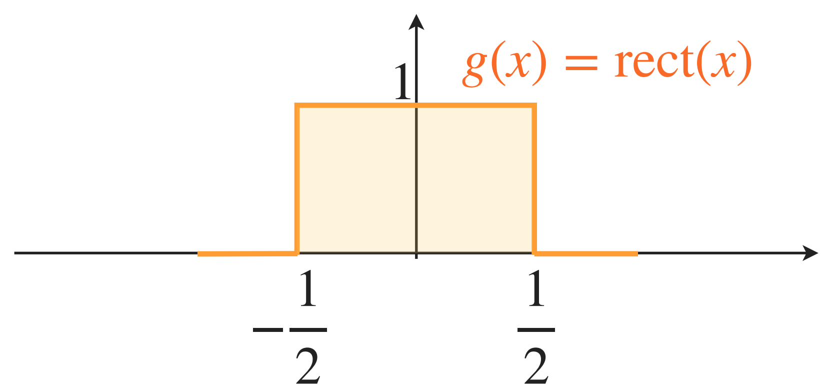
CONVOLUTION

CONVOLUTION

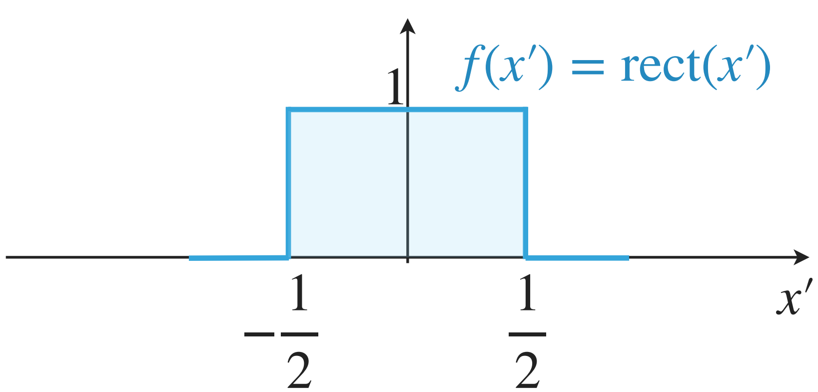
EXAMPLE 1: CONVOLUTION OF BOX-CAR FUNCTION WITH ITSELF

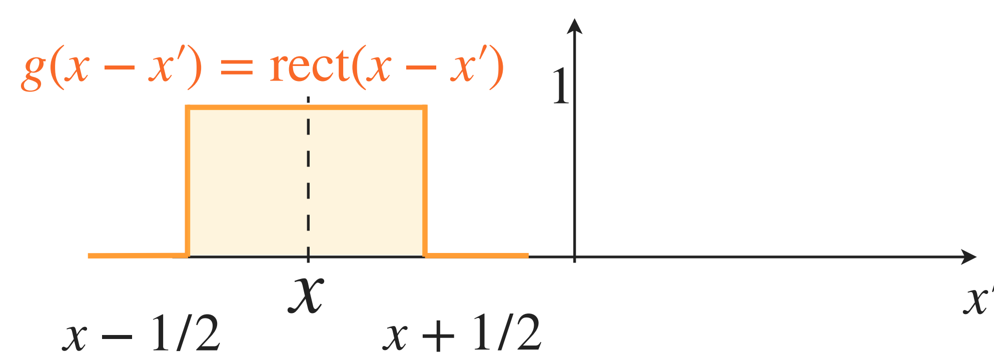
- Compute the convolution between $f(x) = \mathrm{rect}(x)$ and $g(x) = \mathrm{rect}(x)$





1. Convolution formula: $f(x) \star g(x) = \displaystyle\int_{-\infty}^{\infty} f(x')\, g(x - x')\, \mathrm{d}x'$
2. Plot $f(x') = \mathrm{rect}(x')$ and $g(x - x') = \mathrm{rect}(x - x') = \mathrm{rect}(-(x' - x))$





CONVOLUTION

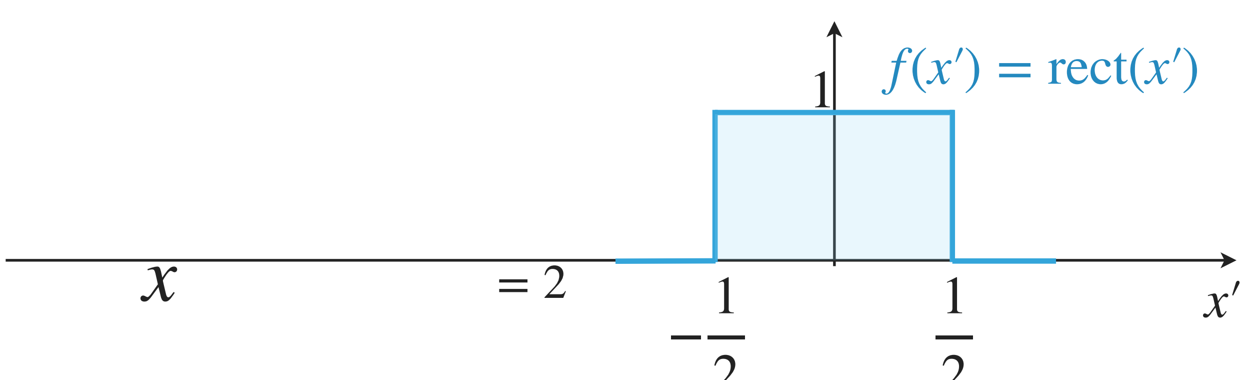
EXAMPLE 1: CONVOLUTION OF BOX-CAR FUNCTION WITH ITSELF

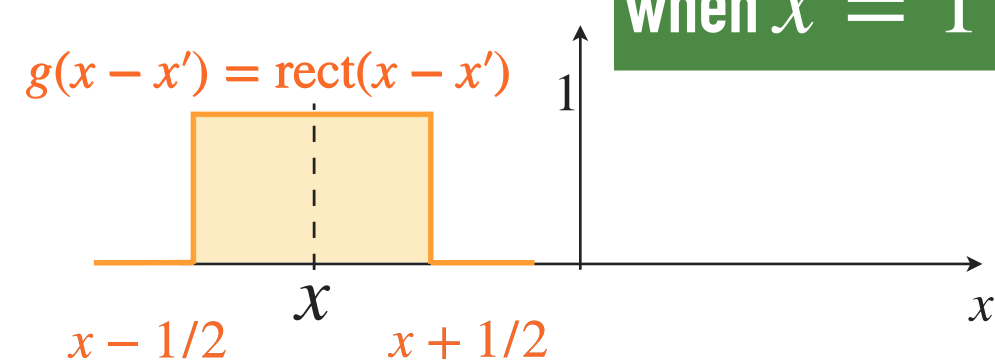
1. **Convolution formula:** $f(x) \star g(x) = \int_{-\infty}^{\infty} f(x')\, g(x - x')\, \mathrm{d}x'$
2. **Plot:** $f(x') = \mathrm{rect}(x')$ and $g(x - x') = \mathrm{rect}(x - x') = \mathrm{rect}(-(x' - x))$
3. **Limits of integral:** $f(x) \star g(x) = \int_{-\infty}^{\infty} \mathrm{rect}(x')\, \mathrm{rect}(x - x')\, \mathrm{d}x'$

$f(x) \star g(x) = \int_{-1/2}^{x+(1/2)} 1\, \mathrm{d}x'$, when $-1 \le x \le 0$.

Similarly, $f(x) \star g(x) = \int_{x-1/2}^{(1/2)} 1\, \mathrm{d}x'$, when $0 < x \le 1$.

They first overlap when $x = 1$





CONVOLUTION

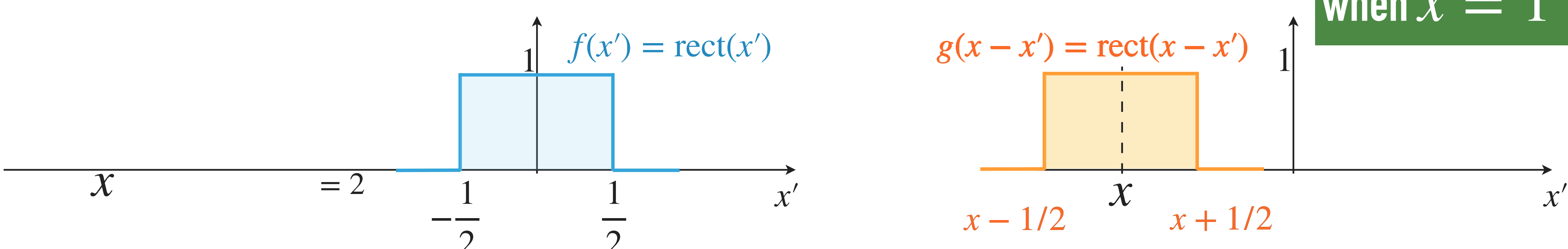
EXAMPLE 1: CONVOLUTION OF BOX-CAR FUNCTION WITH ITSELF

5. We thus have that:

$$f(x) \star g(x) = \begin{cases} \int_{-1/2}^{x+(1/2)} 1 \, \mathrm{d}x', & \text{when} \quad -1 \leq x \leq 0; \\ \int_{x-(1/2)}^{1/2} 1 \, \mathrm{d}x', & \text{when} \quad -0 < x \leq 1; \\ 0 & \text{otherwise.} \end{cases}$$

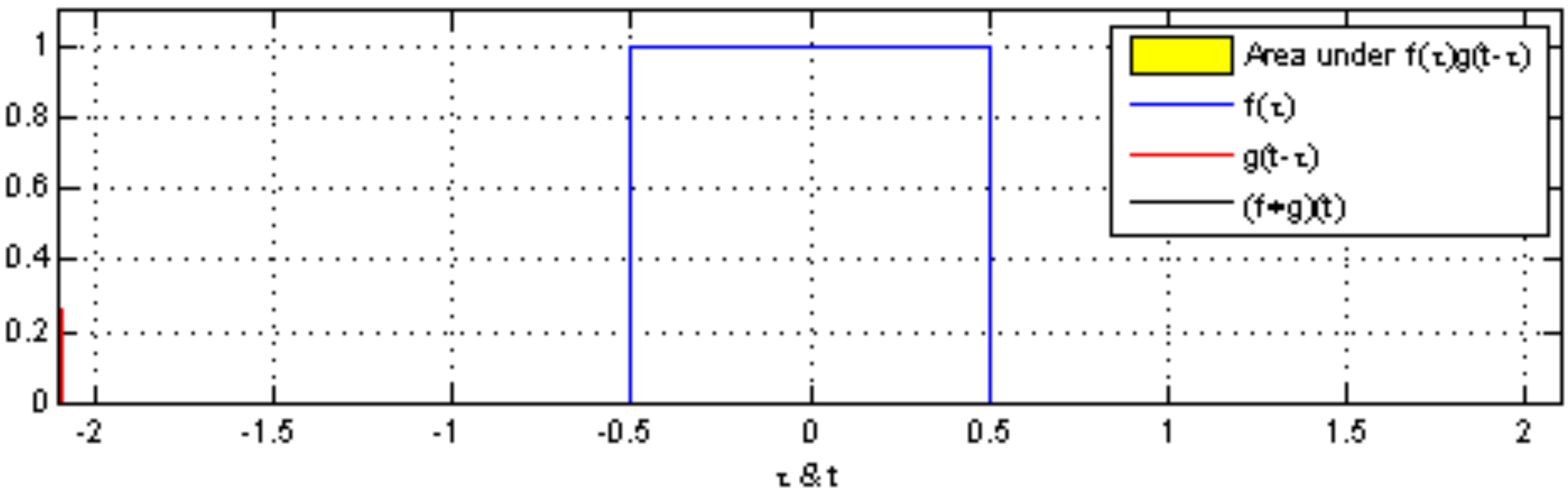
$$f(x) \star g(x) = \begin{cases} x + 1, & \text{when} \quad -1 \leq x \leq 0; \\ 1 - x, & \text{when} \quad -0 < x \leq 1; \\ 0 & \text{otherwise.} \end{cases}$$

They first overlap when $x = 1$



CONVOLUTION

EXAMPLE 1: CONVOLUTION OF BOX-CAR FUNCTION WITH ITSELF (GRAPHICAL)



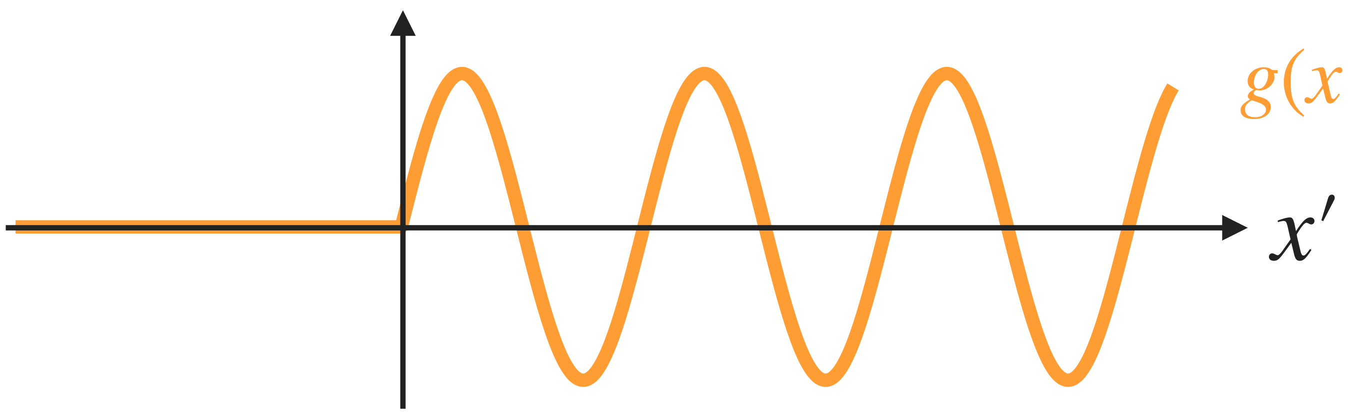
Animated

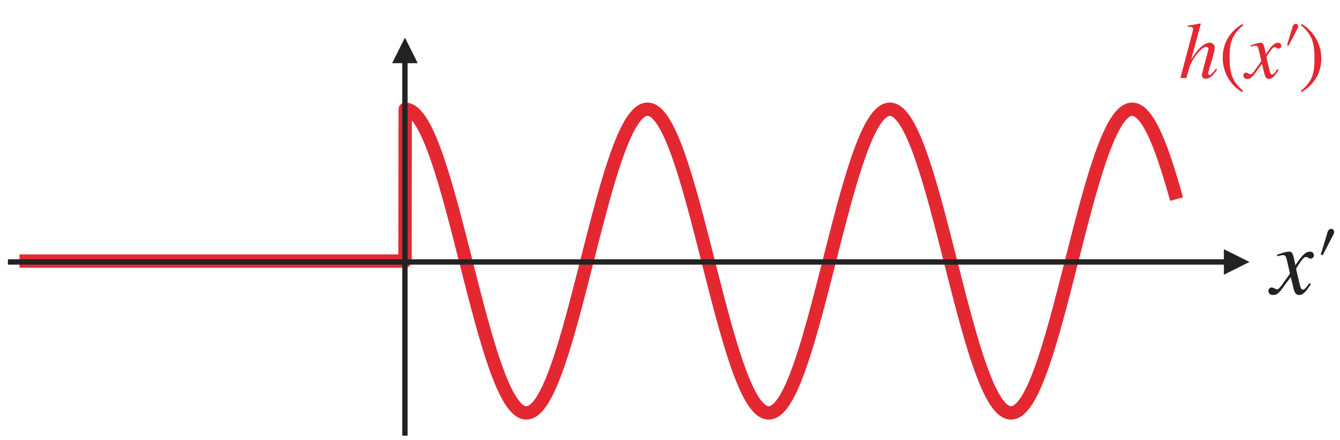
CONVOLUTION

EXAMPLE 2

- Convolve $g(x) = \sin(x)\,u(x)$ and $h(x) = \cos(x)\,u(x)$
- **Solution:** Start from the definition of the convolution integral

$$\int_{-\infty}^{\infty} g(x')h(x-x')\,\mathrm{d}x' = \int_{-\infty}^{\infty} \sin(x')u(x')\,\cos(x-x')u(x-x')\,\mathrm{d}x'$$





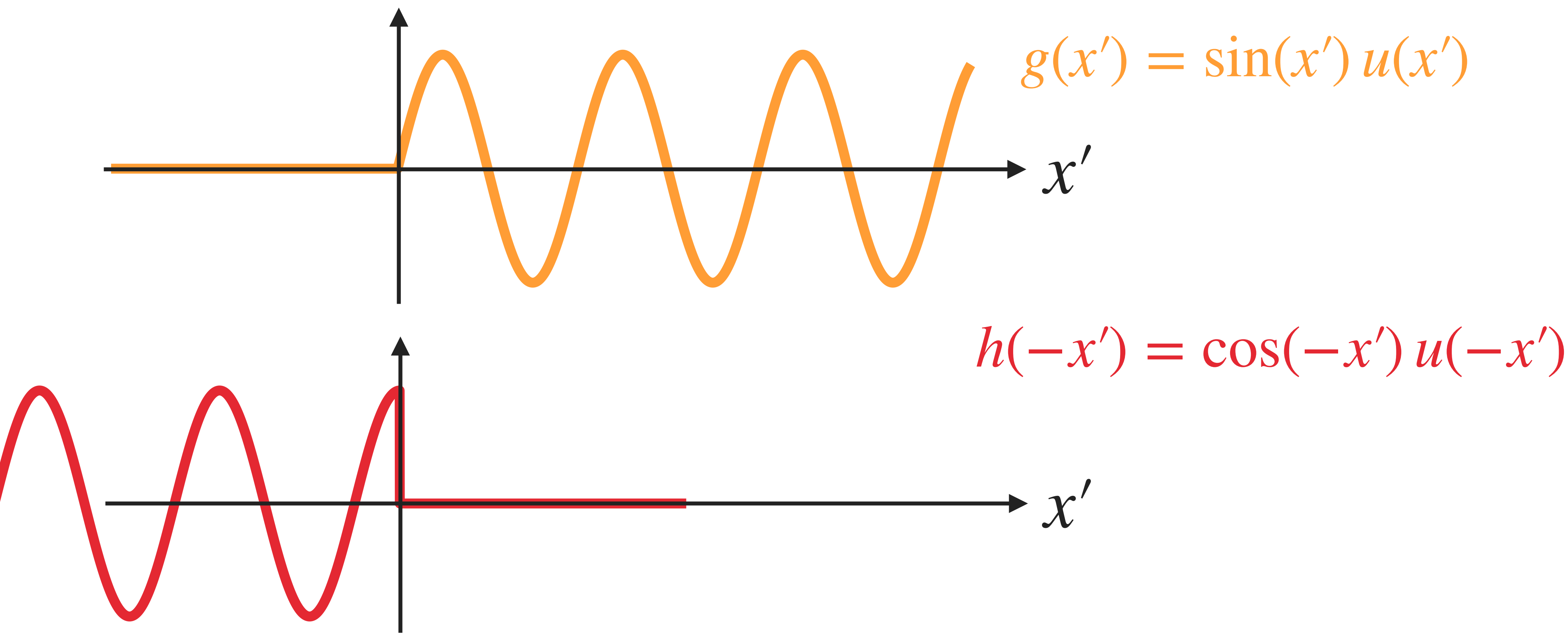
Replace x' in $h(x')$ with $-x'$

CONVOLUTION

EXAMPLE 2

- Convolve $g(x) = \sin(x)\,u(x)$ and $h(x) = \cos(x)\,u(x)$
- **Solution:** Start from the definition of the convolution integral

$$\int_{-\infty}^{\infty} g(x')h(x-x')\,\mathrm{d}x' = \int_{-\infty}^{\infty} \sin(x')u(x')\;\cos(x-x')u(x-x')\,\mathrm{d}x'$$

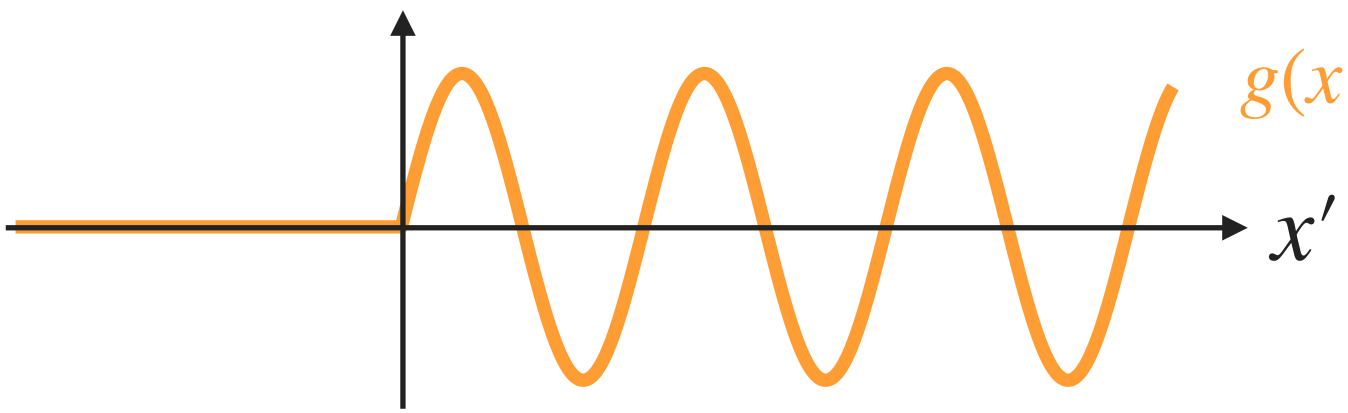


Replace x' in $h(-x')$ with $x' - x$

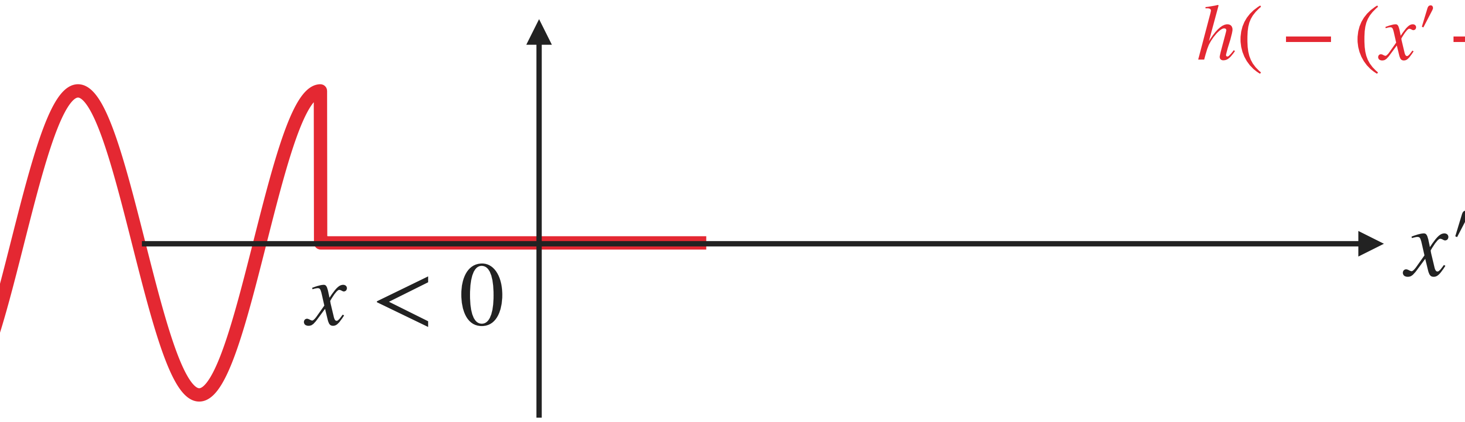
CONVOLUTION
EXAMPLE 2

- Convolve $g(x) = \sin(x)\,u(x)$ and $h(x) = \cos(x)\,u(x)$
- **Solution:** Start from the definition of the convolution integral

$$\int_{-\infty}^{\infty} g(x')h(x-x')\,\mathrm{d}x' = \int_{-\infty}^{\infty} \sin(x')u(x')\ \cos(x-x')u(x-x')\,\mathrm{d}x'$$



$$g(x') = \sin(x')\,u(x')$$



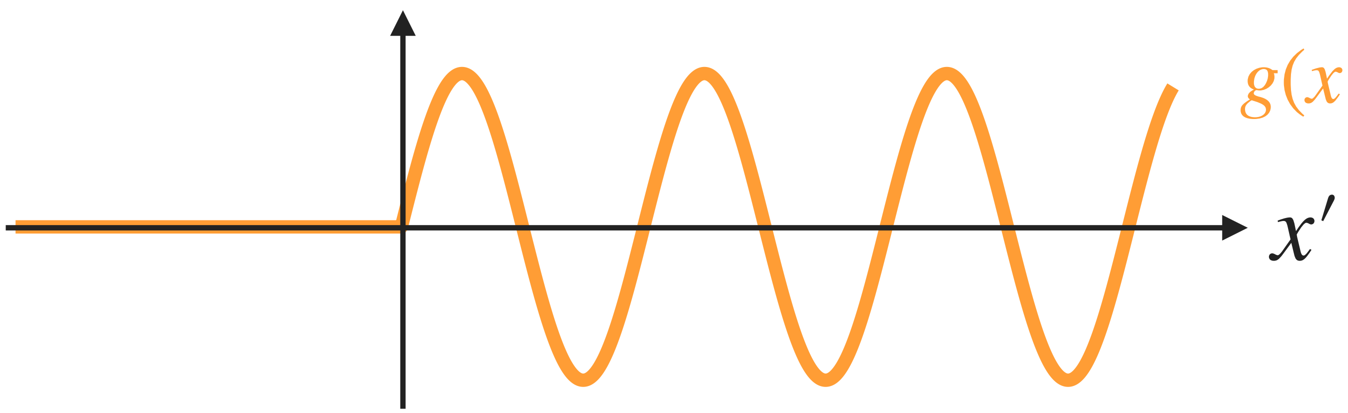
$$\begin{aligned} h(-(x'-x)) = h(x-x') &\\ = \cos(-(x'-x))\,u(-(x'-x)) &\\ = \cos(x-x')\,u(x-x') & \end{aligned}$$

CONVOLUTION

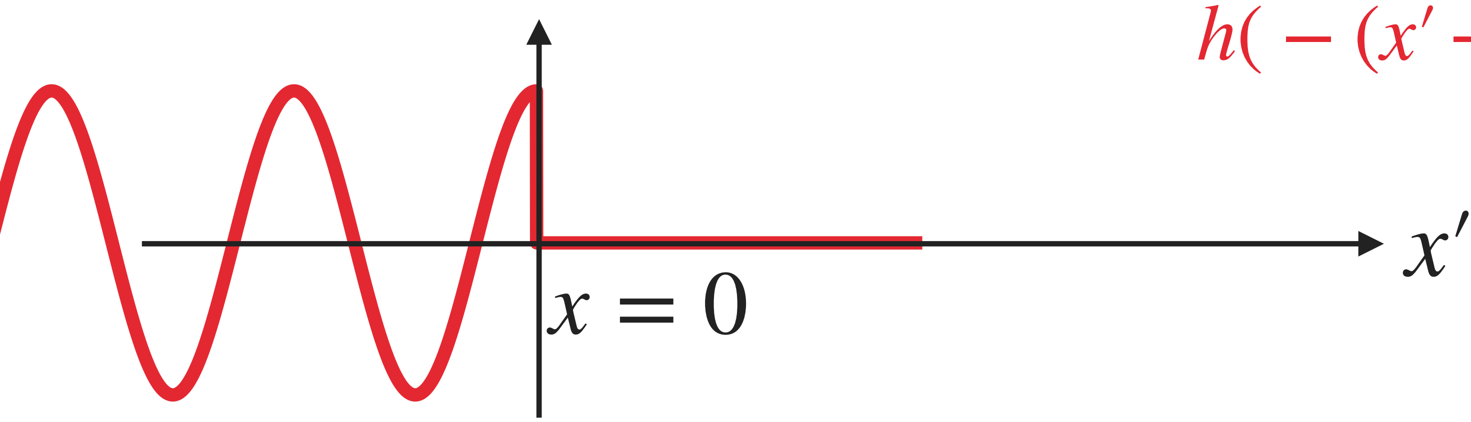
EXAMPLE 2

- Convolve $g(x) = \sin(x)\,u(x)$ and $h(x) = \cos(x)\,u(x)$
- **Solution:** Start from the definition of the convolution integral

$$\int_{-\infty}^{\infty} g(x')h(x-x')\,\mathrm{d}x' = \int_{-\infty}^{\infty} \sin(x')u(x')\;\cos(x-x')u(x-x')\,\mathrm{d}x'$$



$$g(x') = \sin(x')\,u(x')$$



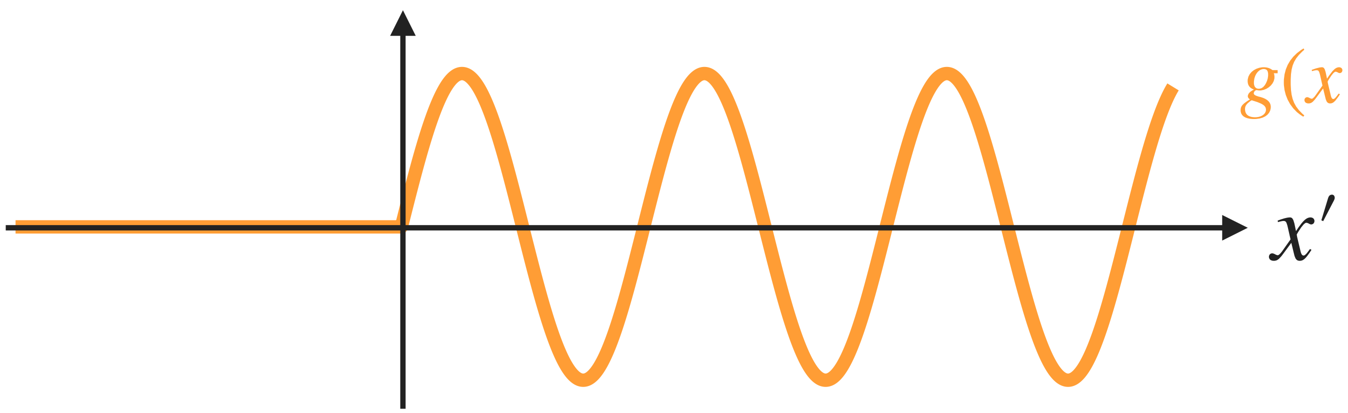
$$\begin{aligned} h(-(x'-x)) &= h(x-x') \\ &= \cos(-(x'-x))\,u(-(x'-x)) \\ &= \cos(x-x')\,u(x-x') \end{aligned}$$

CONVOLUTION

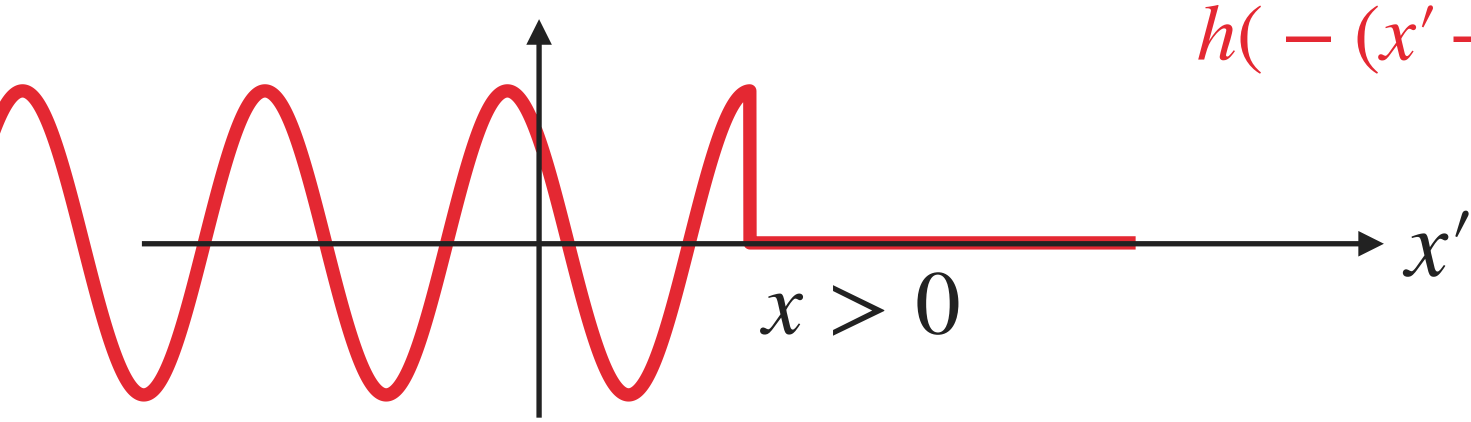
EXAMPLE 2

- Convolve $g(x) = \sin(x)\,u(x)$ and $h(x) = \cos(x)\,u(x)$
- **Solution:** Start from the definition of the convolution integral

$$\int_{-\infty}^{\infty} g(x')h(x-x')\,\mathrm{d}x' = \int_{-\infty}^{\infty} \sin(x')u(x')\ \cos(x-x')u(x-x')\,\mathrm{d}x'$$



$g(x') = \sin(x')\,u(x')$



$$\begin{aligned} h(-(x'-x)) &= h(x-x') \\ &= \cos(-(x'-x))\,u(-(x'-x)) \\ &= \cos(x-x')\,u(x-x') \end{aligned}$$

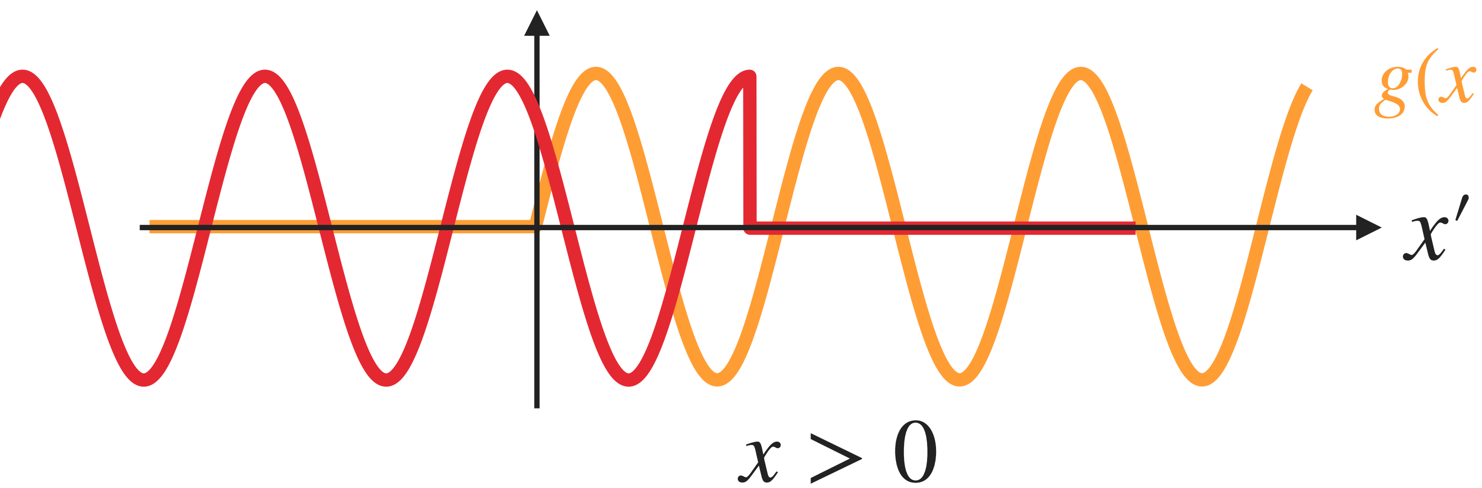
Multiply both functions

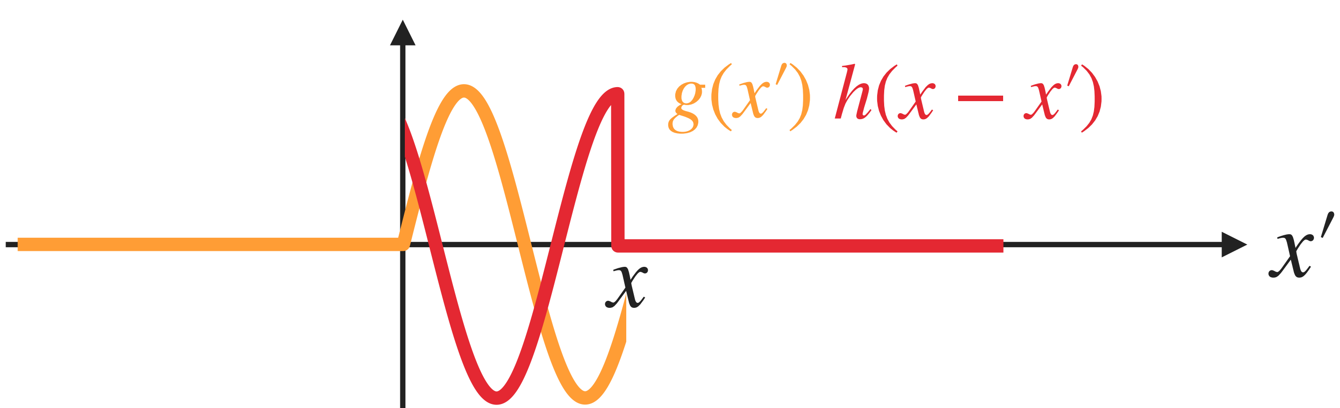
CONVOLUTION

EXAMPLE 2

- Convolve $g(x) = \sin(x)\,u(x)$ and $h(x) = \cos(x)\,u(x)$
- **Solution:** Start from the definition of the convolution integral

$$\int_{-\infty}^{\infty} g(x')h(x-x')\,\mathrm{d}x' = \int_{-\infty}^{\infty} \sin(x')u(x')\,\cos(x-x')u(x-x')\,\mathrm{d}x'$$





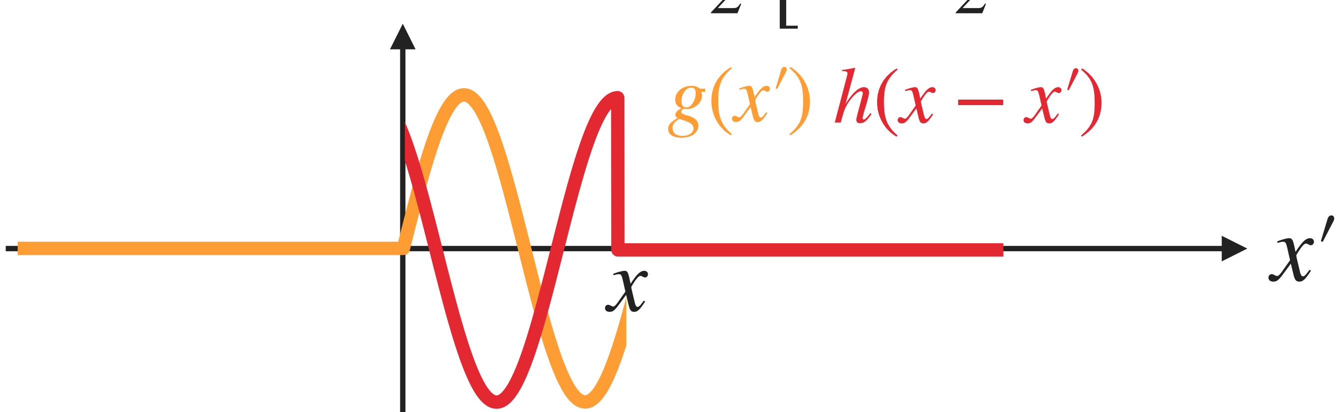
This gives us the limits for our integral

CONVOLUTION

EXAMPLE 2

- Convolve $g(x) = \sin(x)\, u(x)$ and $h(x) = \cos(x)\, u(x)$
- **Solution:** Start from the definition of the convolution integral

$$\begin{aligned}
\int_{-\infty}^{\infty} g(x')h(x-x')\,\mathrm{d}x' &= \int_{-\infty}^{\infty} \sin(x')u(x')\ \cos(x-x')u(x-x')\,\mathrm{d}x' \\
&= \int_{0}^{x} \sin(x')u(x')\ \cos(x-x')u(x-x')\,\mathrm{d}x' \\
&= \int_{0}^{x} \sin(x')\ \cos(x-x')\,\mathrm{d}x' \\
&= \frac{1}{2}\int_{0}^{x} \sin(x-2x') + \sin(x)\,\mathrm{d}x' \\
&= \frac{1}{2}\left[\frac{\cos(x-2x')}{2} + x'\sin(x)\right]_0^x = \frac{1}{2}x\sin(x)
\end{aligned}$$



WHAT WE COVERED TODAY

- Linear shift/space invariant systems
  - Definition & properties
- Convolution & examples
- **Matlab**
  - Computing 1D and 2D FFT
  - Displaying DFT
  - Filtering in DFT domain

NEXT TIME!

MORE LSI SYSTEMS