Signals and Systems I

Lecture 4

Last Lecture

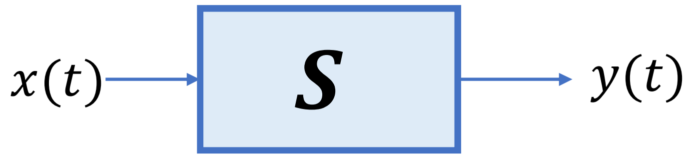
- more on $u(t)$ & $\delta(t)$
- Building Signals from other Signals
- Closed form expression for signals

"Closed form expression" is a mathematical expression that can be evaluated in a finite number of operations.

Today

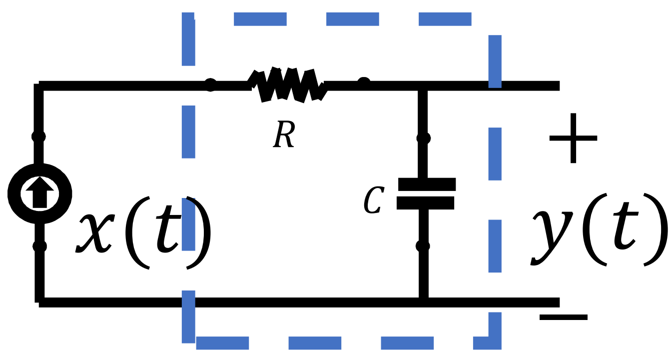
- System Classification:
    - Continuous Time/Discrete Time
    - Digital /Analog
    - Linear / Nonlinear
    - Time Invariant / Time Varying
    - Causal / Non-Causal
    - Memoryless/ With Memory
    - Invertible / Noninvertible

Systems: processes signals, operates on signals and generates signals



$$y(t) = \boldsymbol{S}(x(t))$$

$Example:\ y(t) = 3x(t-7)$ or RC circuit:



$y(t) = \frac{1}{C}\int_{t_0}^{t} x(t)dt + V_C(t_0)$ where $V_C(t_0)$ is the initial condition and t_0 is the start time

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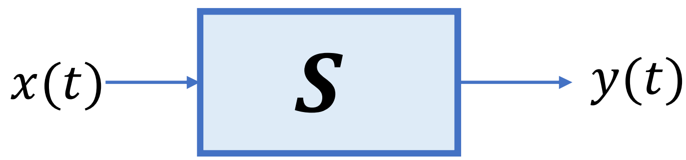

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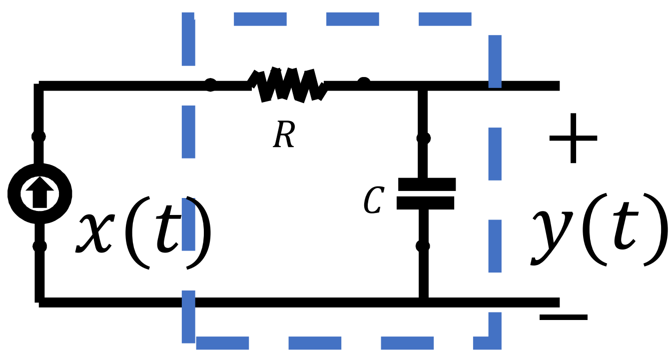

There are two types of systems around us, the existing ones in nature and the manmade ones. We study existing systems for the purpose of understanding and <u>analyzing</u> them and also to <u>design</u> new systems.

$y(t) = \frac{1}{C}\int_{t_0}^{t} x(t)dt + V_C(t_0)$ where $V_C(t_0)$ is the initial condition and t_0 is the start time

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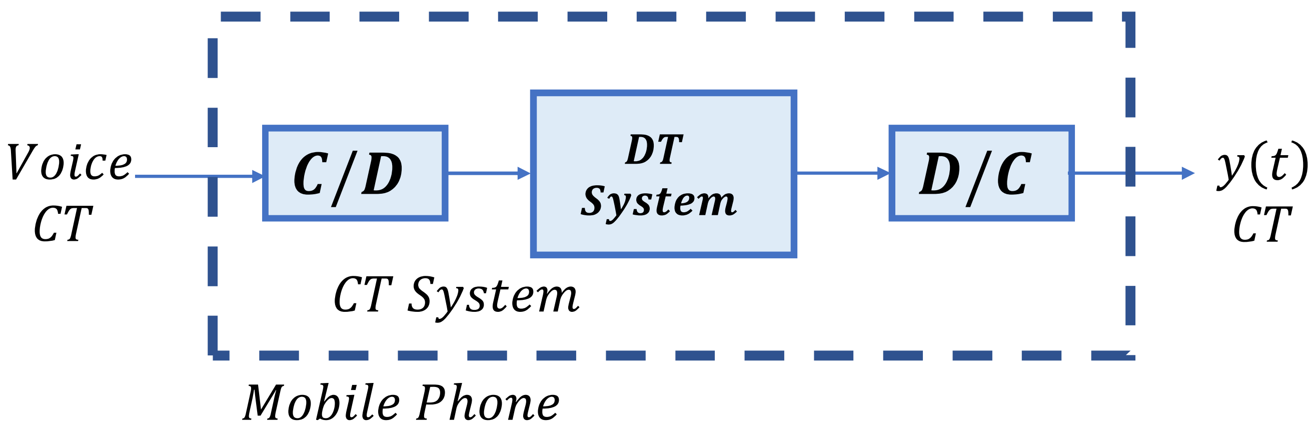
Systems Classification

Continuous Time (CT) or Discrete Time (DT)

- If input and output of a system are CT ⟶ the system is CT
- If input and output of a system are DT ⟶ the system is DT

Examples

CT system



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Systems Classification

Analog or Digital Systems

- If input and output of a system are Analog ⟶ the system is Analog
- If input and output of a system are Digital ⟶ the system is Digital

Analog example: Radio, Digital example: computers

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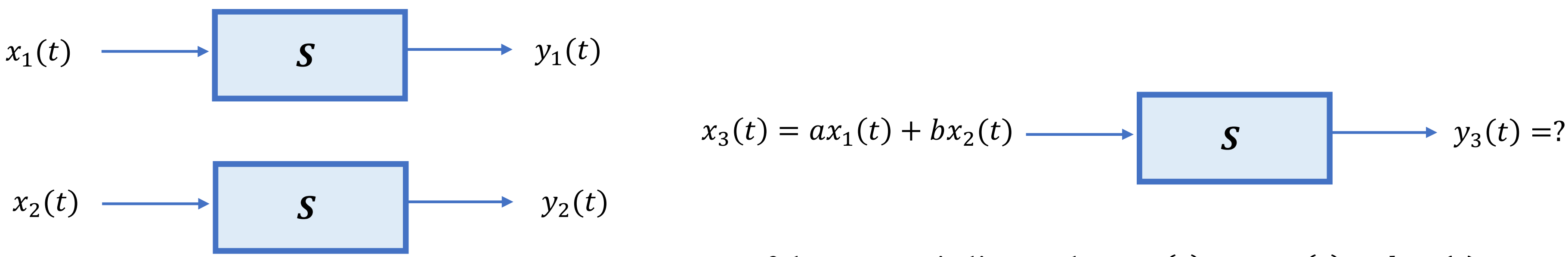
Systems Classification

Linear or Non-Linear Systems

The system is called *Linear* if outputs of linear combinations of inputs is the same linear combination of linear combination of their outputs.



If the system is linear, then $y_3(t) = ay_1(t) + by_2(t)$

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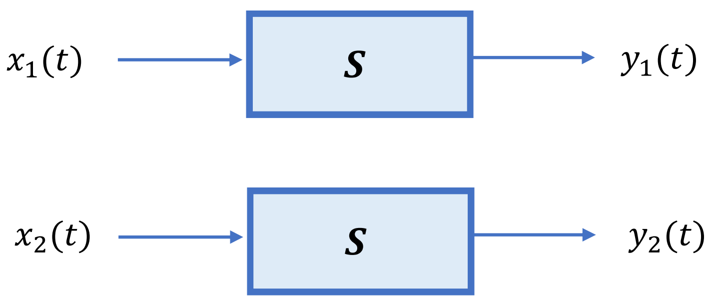

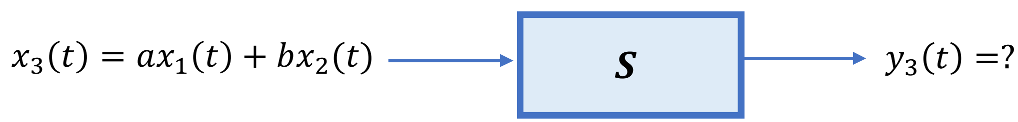

If the system is linear, then $y_3(t) = ay_1(t) + by_2(t)$

If a system is linear, then output of the system to $x(t) = 0$ is always $y(t) = 0$.
why? $x_1(t) = x_2(t)$, $a = 1$, $b = -1$, $x_3(t) = x_1(t) - x_1(t) = 0 \longrightarrow y_3(t) = y_1(t) - y_1(t) = 0$ ✓

Can linear systems have initial conditions that generate nonzero output? no

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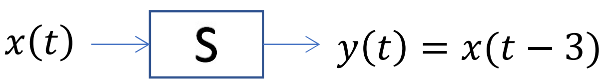
Linear/ Nonlinear Systems

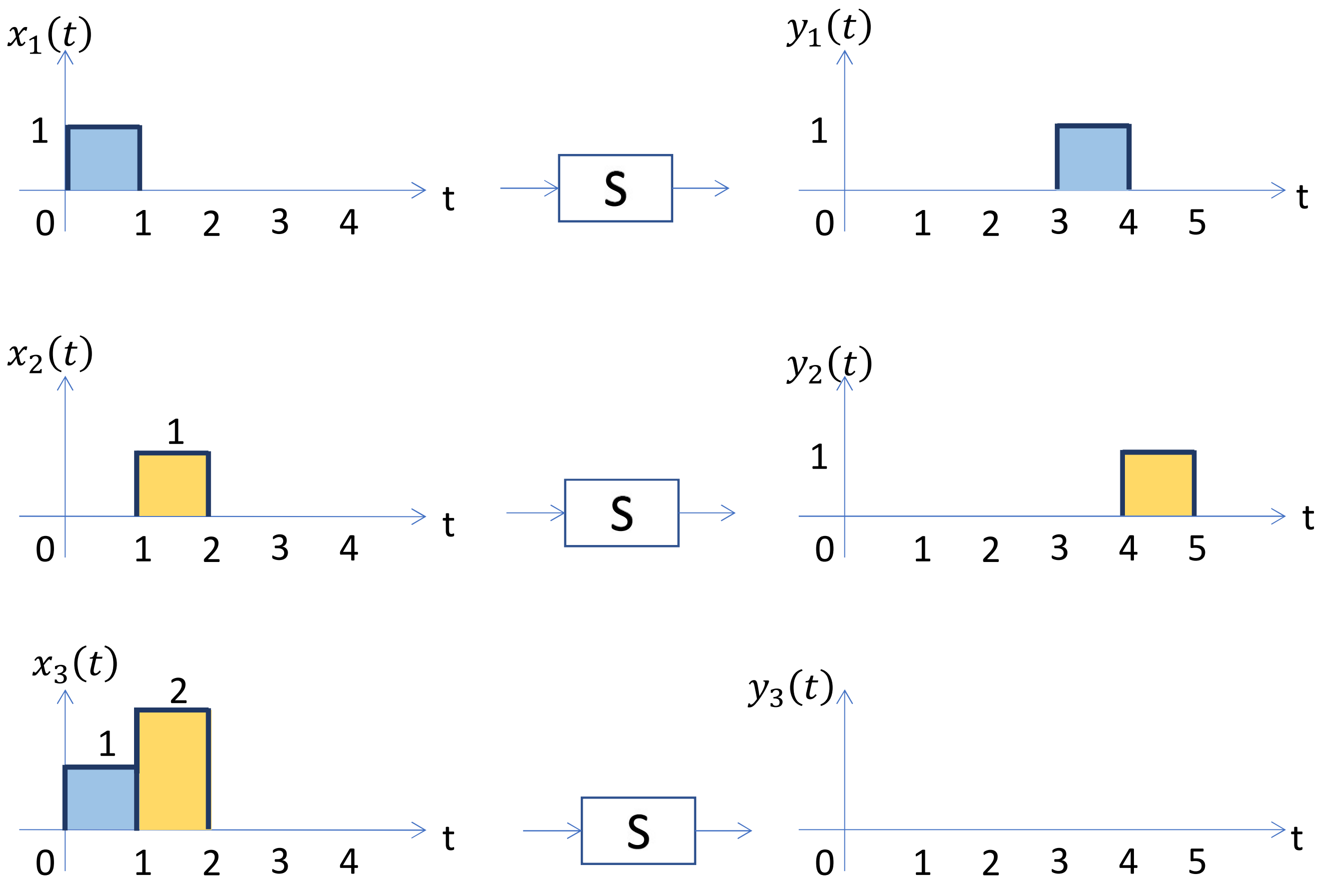
Example:



$$x_3(t) = x_1(t) + 2x_2(t)$$

linear combination of $x_1(t)$ and $x_2(t)$.

what is $y_3(t)$?



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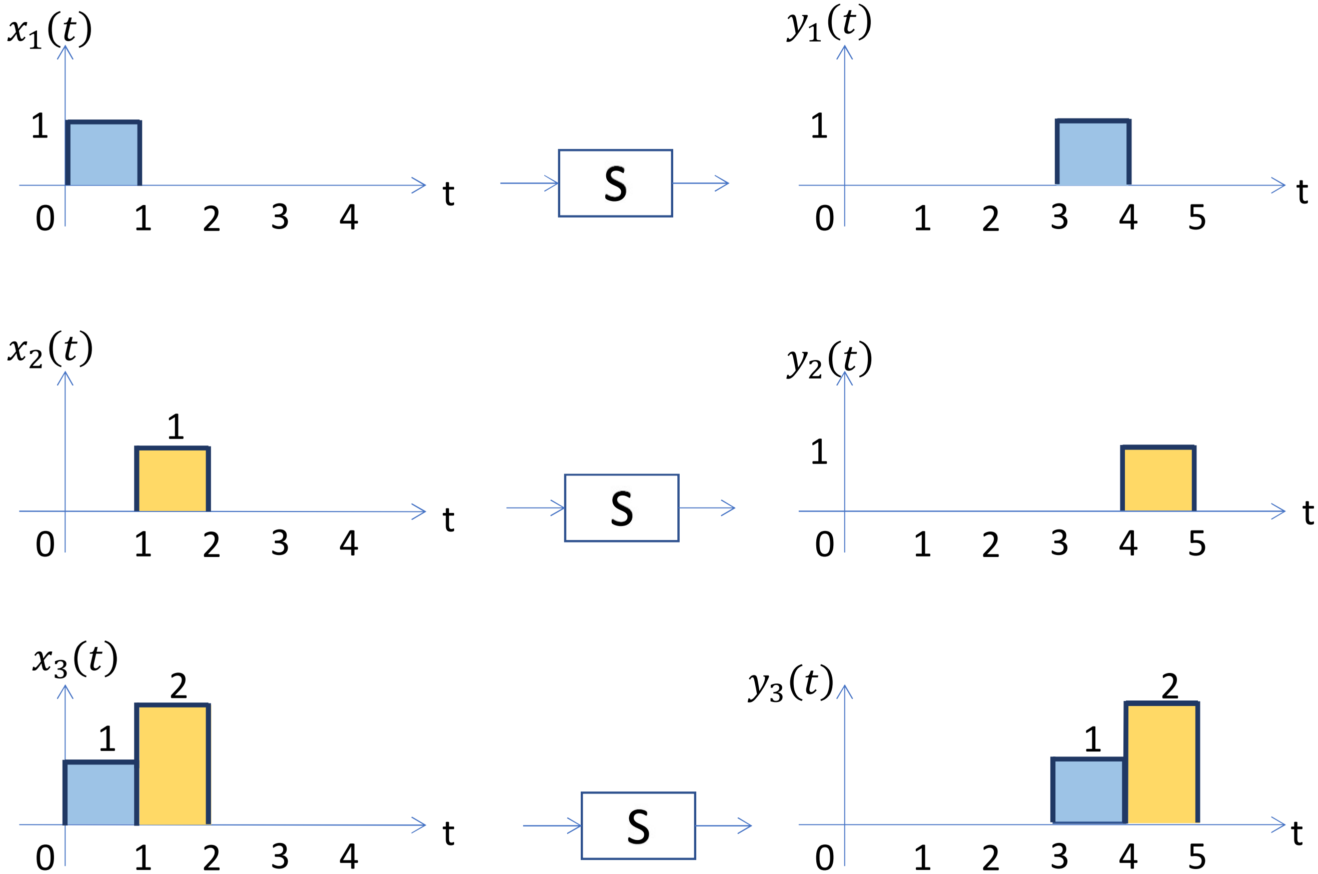
Linear/ Nonlinear Systems

Example:

$x(t) \rightarrow$ S $\rightarrow y(t) = x(t-3)$



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$y_3(t) = x_3(t-3)$

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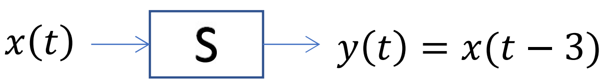
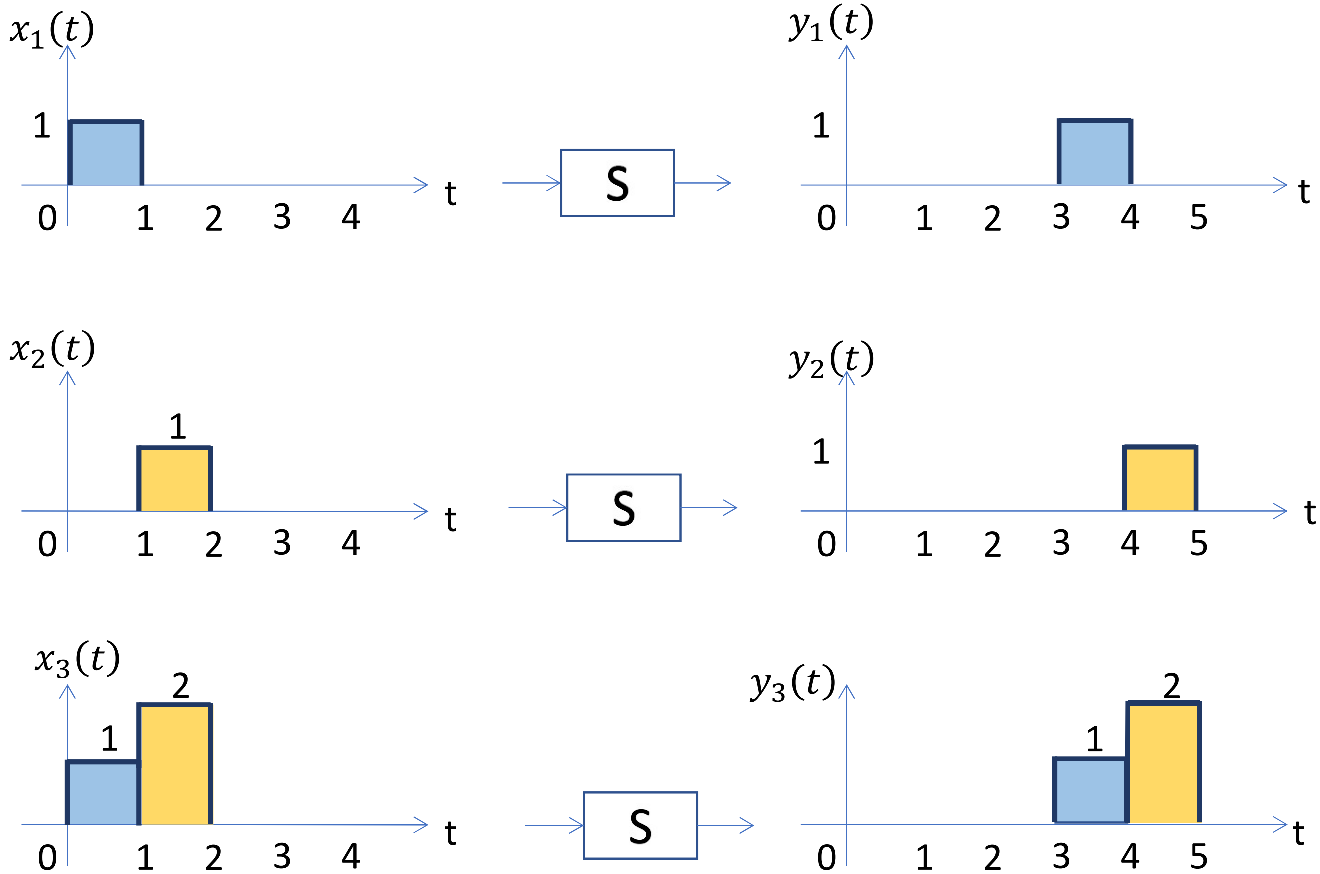
Linear/ Nonlinear Systems

Example:





$x_3(t) = x_1(t) + 2x_2(t)$

linear combination of $x_1(t)$ and $x_2(t)$.

what is $y_3(t)$?

$y_3(t) = x_3(t-3)$
$= y_1(t) + 2y_2(t)$

Can we conclude that the system is linear?

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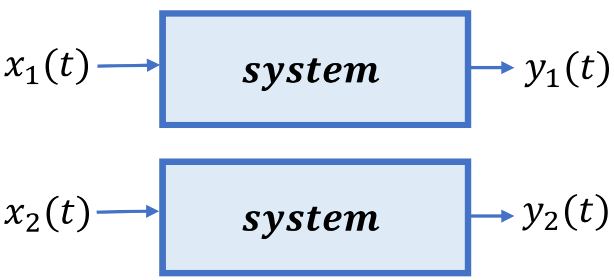
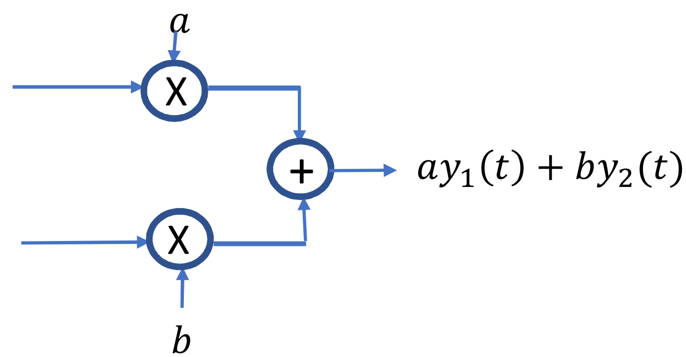
Linear/ Nonlinear Systems

Five steps for checking whether a system is linear or not

Step 1: Find output of the system to $x_1(t)$ and $x_2(t)$

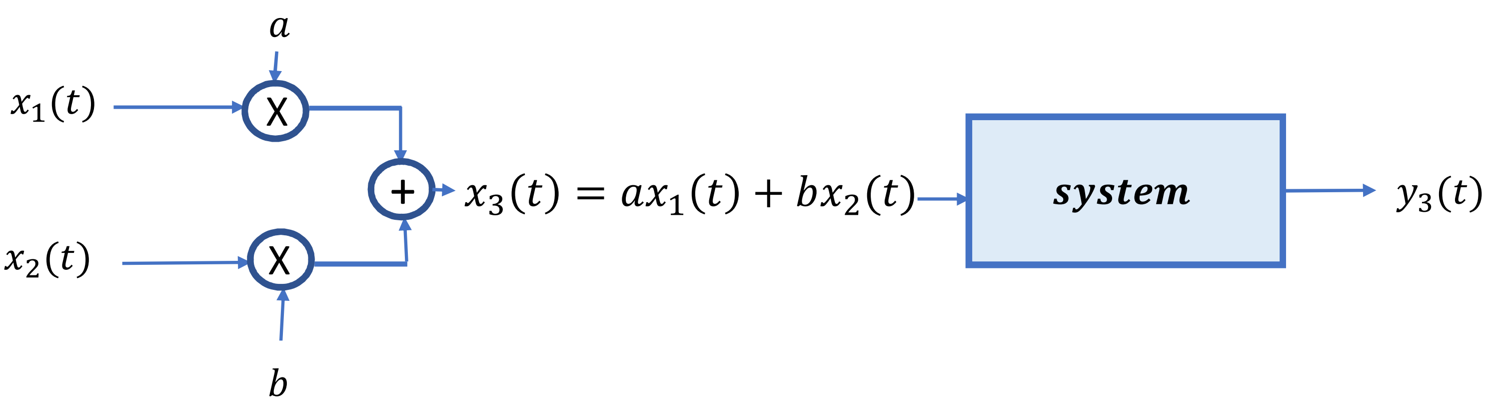


Step 2: Build linear combination of $y_1(t)$ and $y_2(t)$



Step 3: Build $x_3(t)$

Step 4: Find the out put of the system to $x_3(t)$



Step 5:
Check if result of step 2 is the same as result of step 4:

If the answer is yes, the system is **linear**

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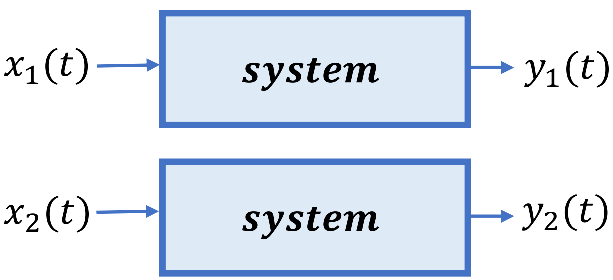
Linear/ Nonlinear Systems

Check the steps for $y(t) = x(t-3)$

Step 1: Find output of the system to $x_1(t)$ and $x_2(t)$



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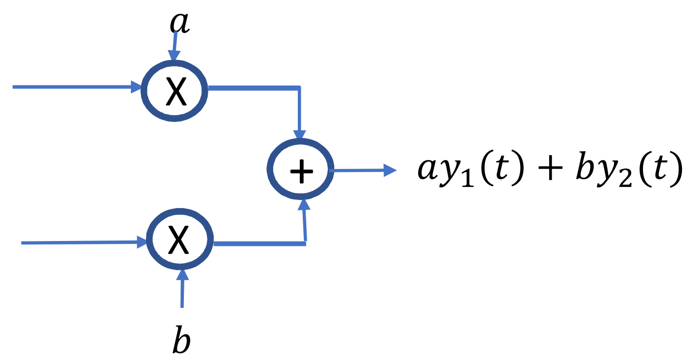

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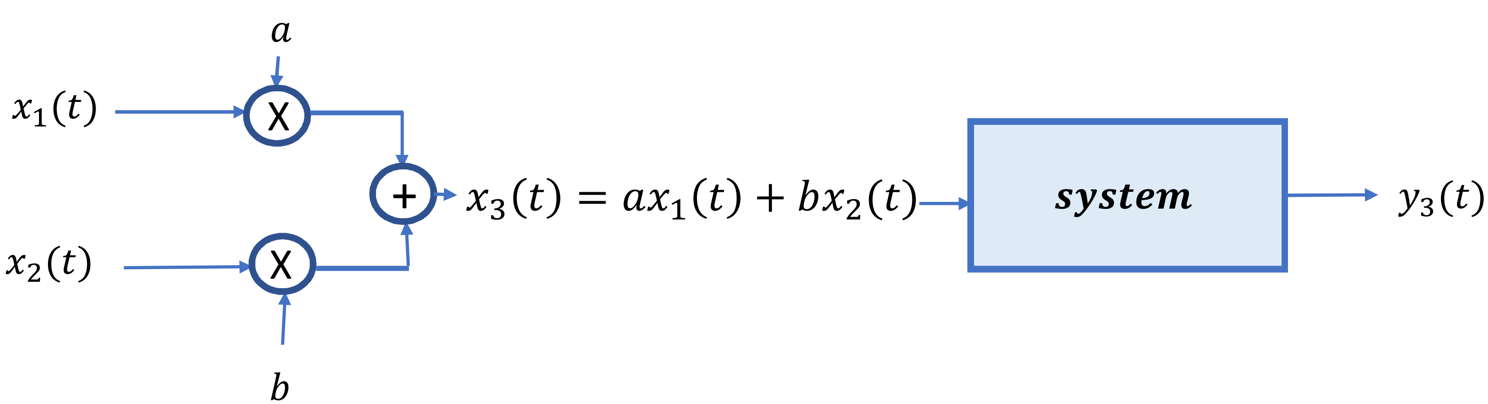

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Linear/ Nonlinear Systems

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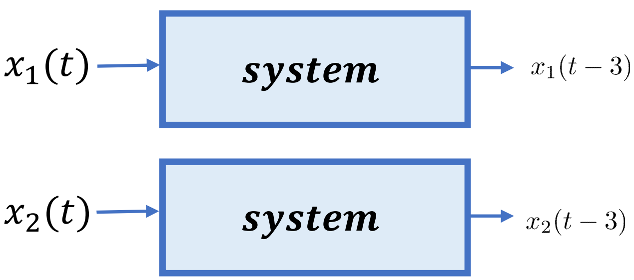

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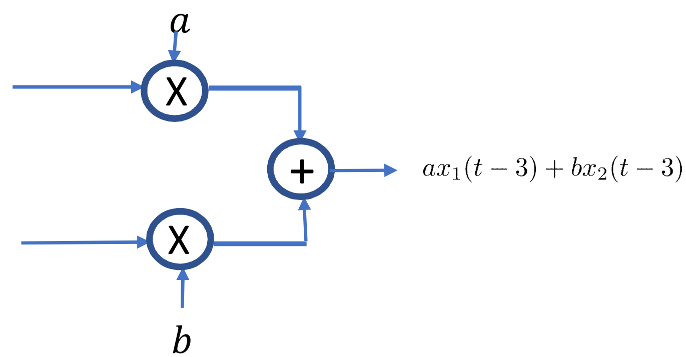

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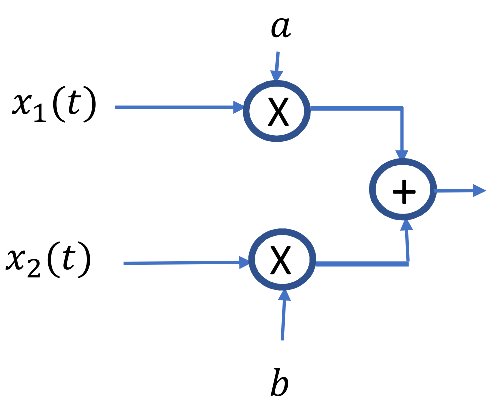
The two are the same so the system is **linear**

Step 3: Build $x_3(t)$



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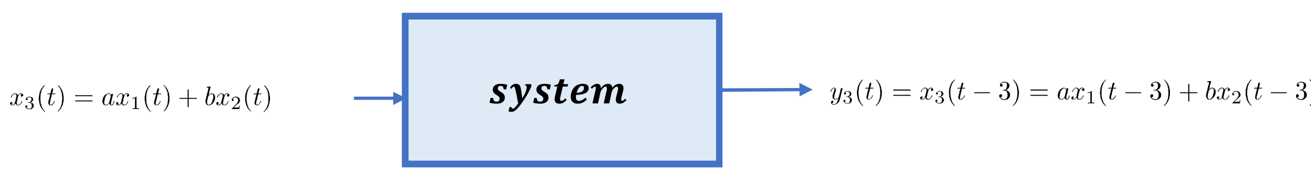

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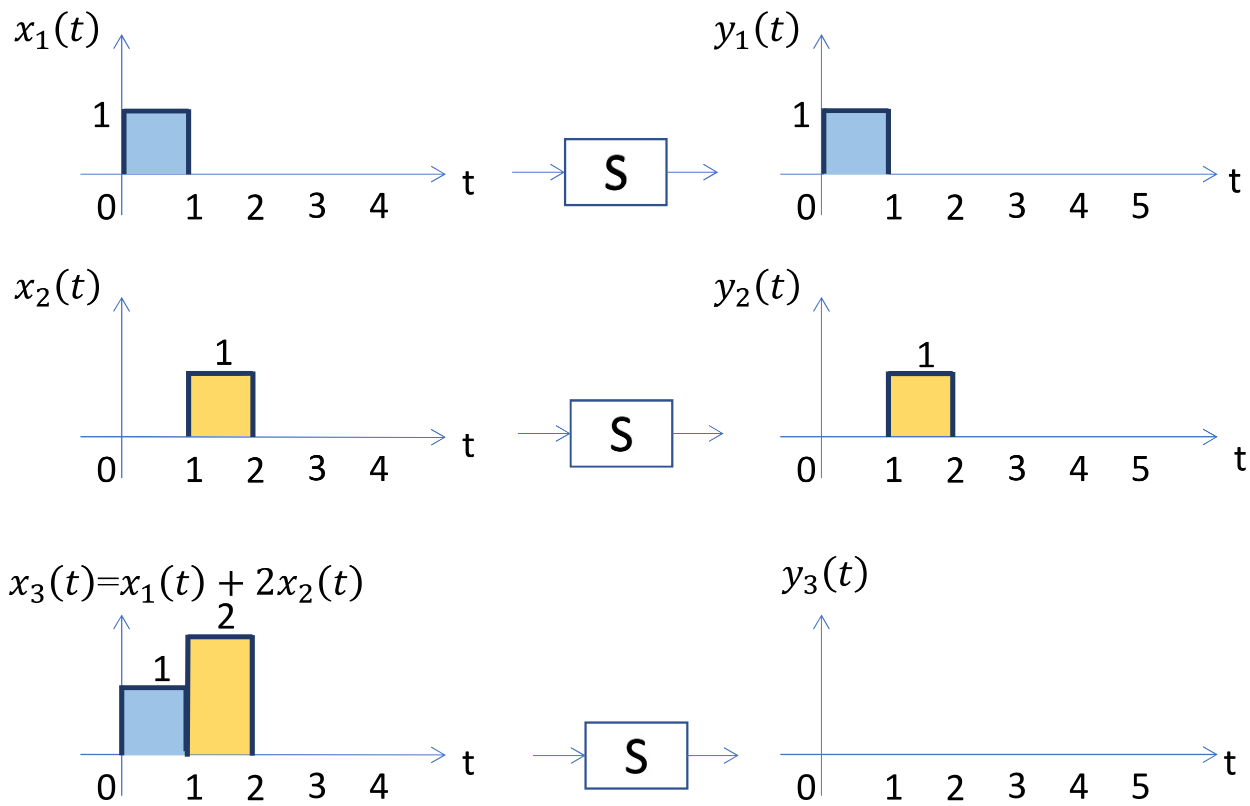
Linear/ Nonlinear Systems

Example 2: $y(t) = x^2(t)$

$x_3(t) = x_1(t) + 2x_2(t)$
linear combination of $x_1(t)$ and $x_2(t)$.

what is $y_3(t)$?



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Linear/ Nonlinear Systems

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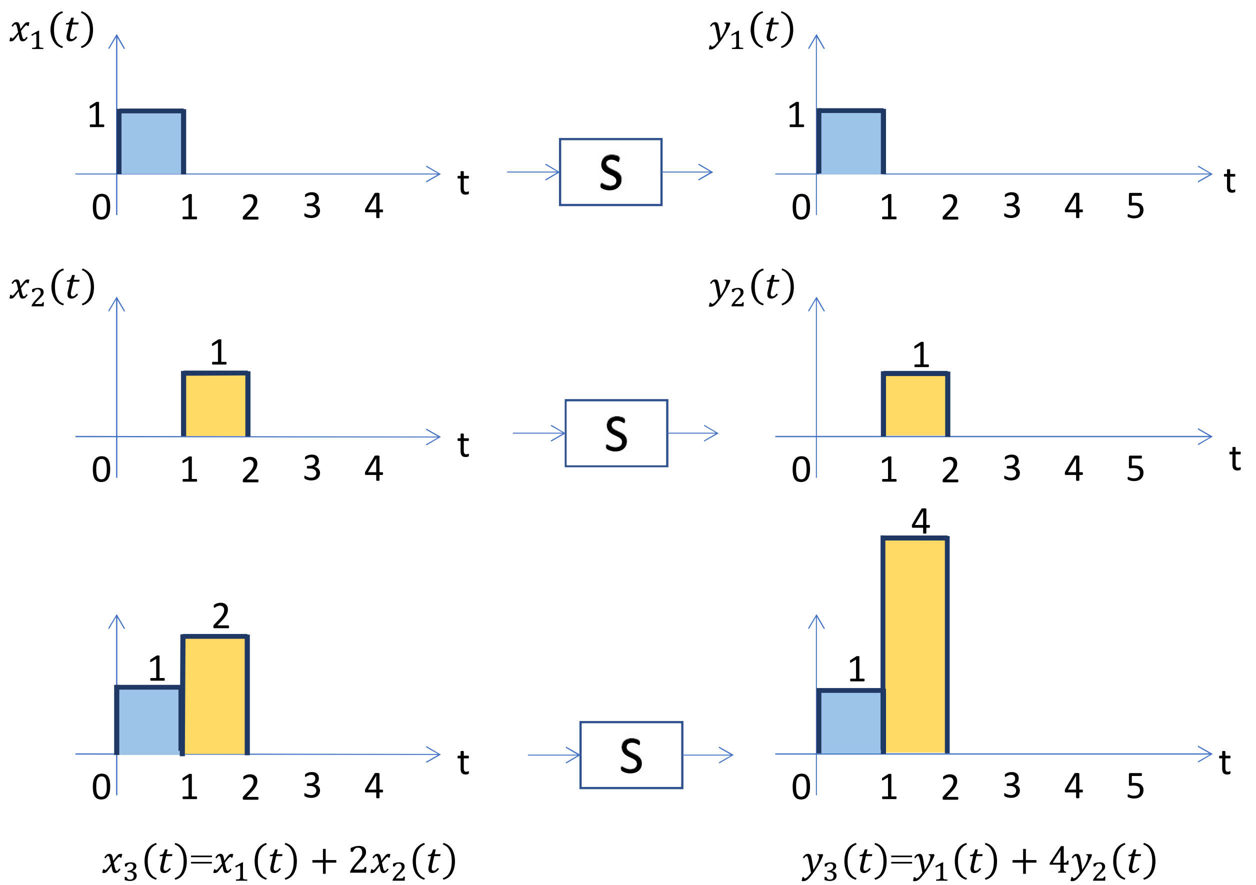
what is $y_3(t)$?

$$y_3(t) = x_3^2(t)$$

$$= y_1^2 + 4y_2(t)$$

not linear!



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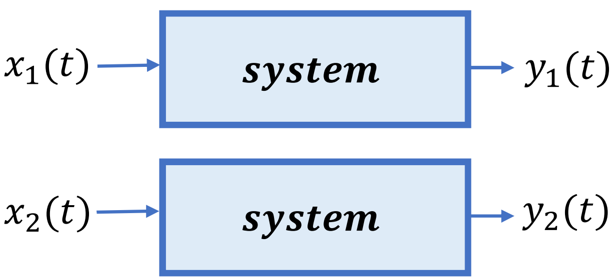
Linear/ Nonlinear Systems

Check the steps for $y(t) = x^2(t)$

Step 1: Find output of the system to $x_1(t)$ and $x_2(t)$



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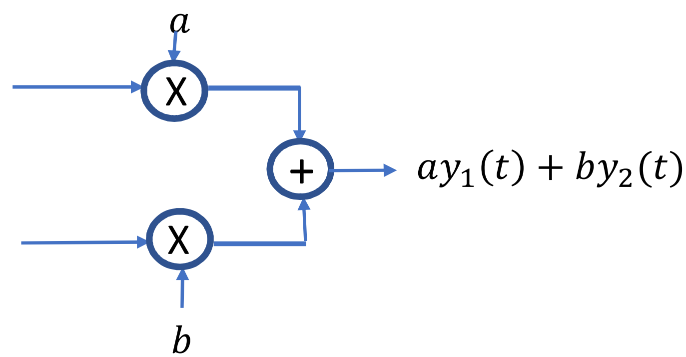

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If yes, the system is **Linear**

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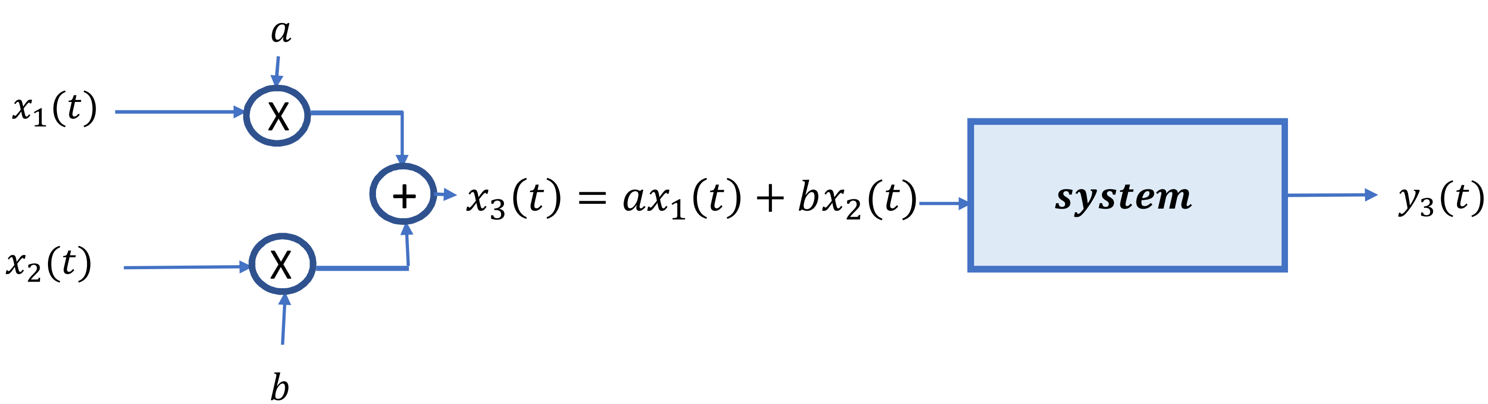

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Linear/ Nonlinear Systems

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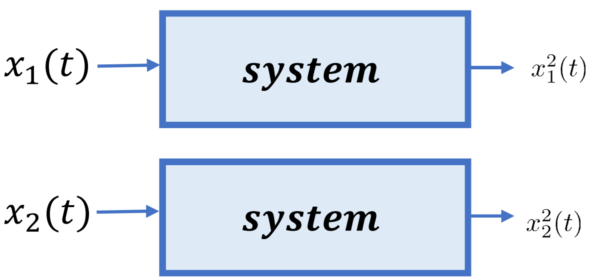

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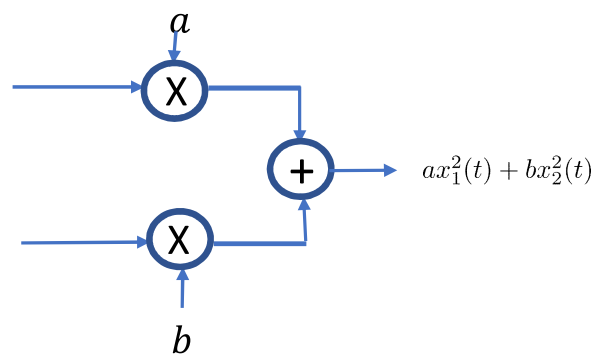

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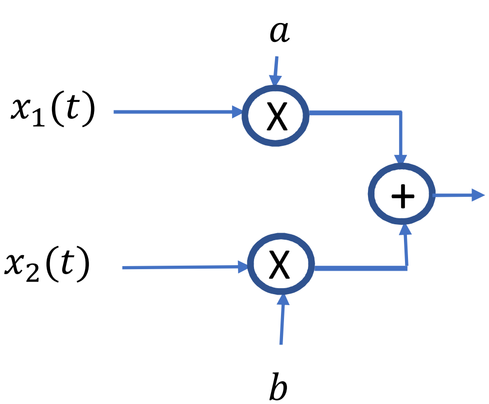
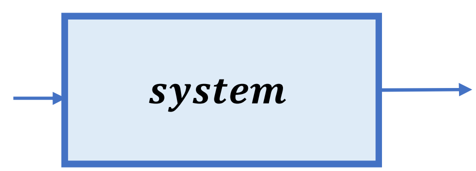


$x_3(t) = ax_1(t) + bx_2(t)$

Step 4: Find the out put of the system to $x_3(t)$



$y_3(t) = x_3^2(t) = (ax_1(t) + bx_2(t))^2$
$= a^2x_1^2(t) + b^2x_2^2(t) + 2abx_1(t)x_2(t)$

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Linear/ Nonlinear Systems

Check the steps for $y(t) = x(t) - 3$

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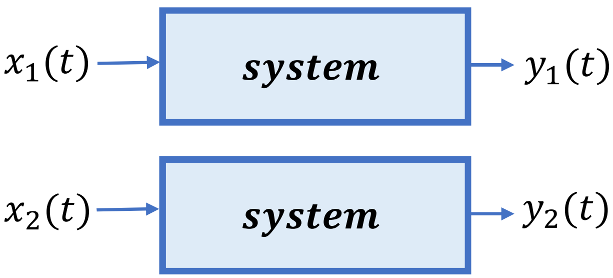

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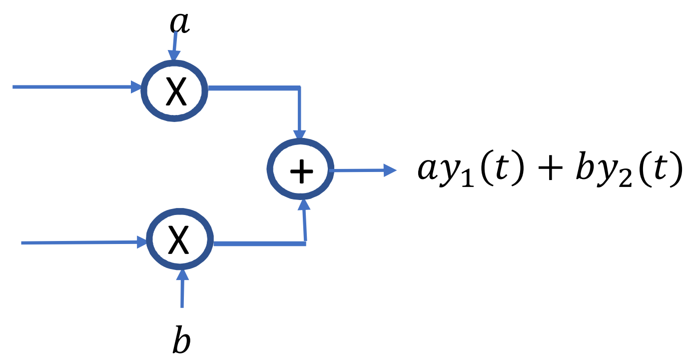

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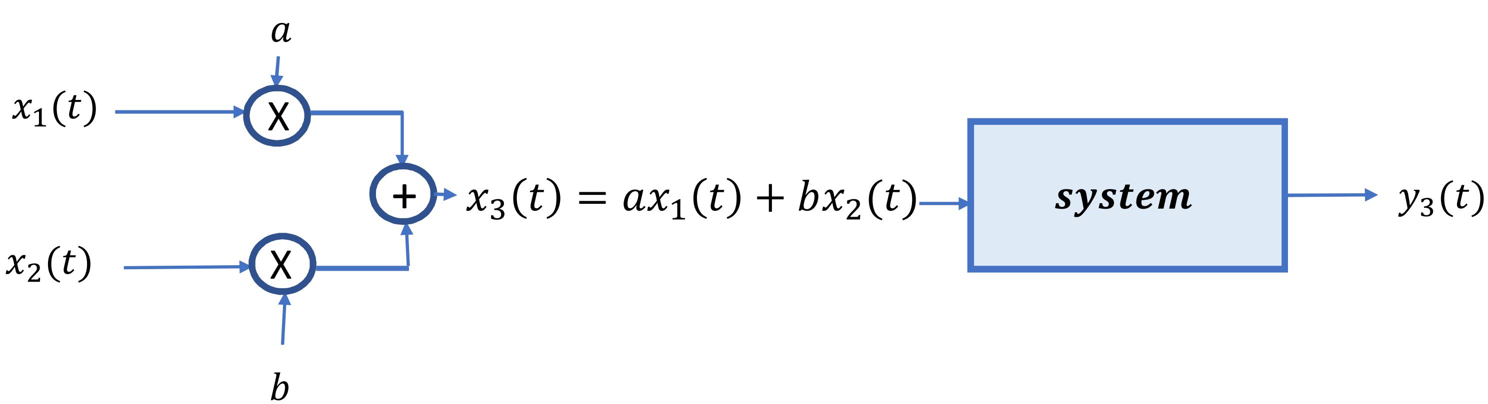

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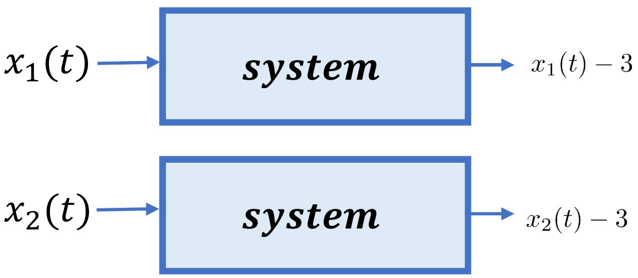

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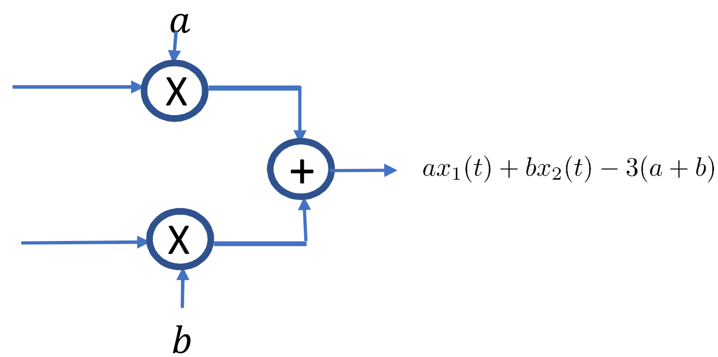

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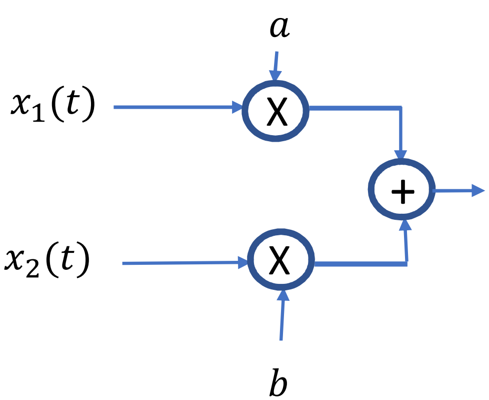

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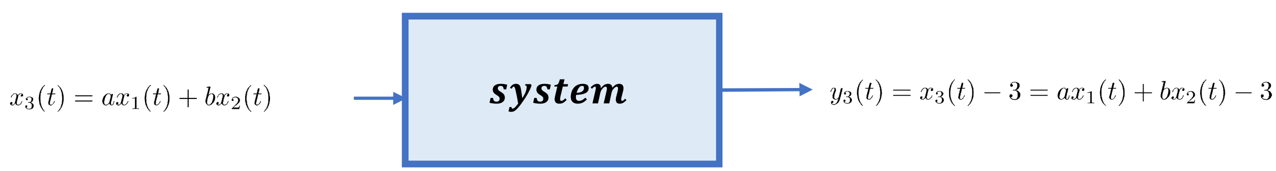

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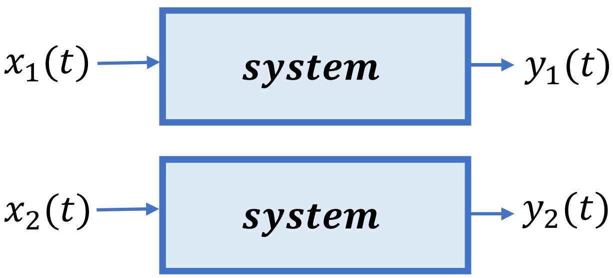
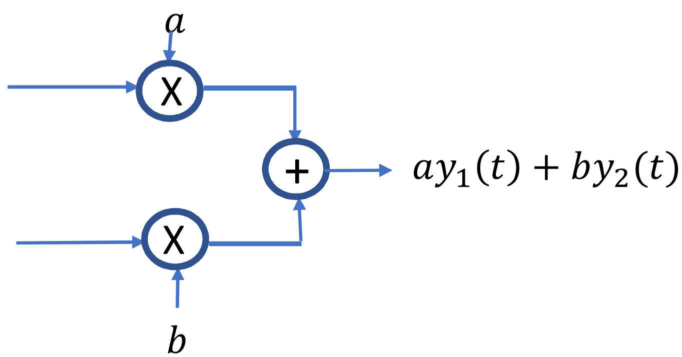
Linear/ Nonlinear Systems

Check the steps for $y(t) = x(2t)$

Step 1: Find output of the system to $x_1(t)$ and $x_2(t)$



Step 2: Build linear combination of $y_1(t)$ and $y_2(t)$



Step 5:
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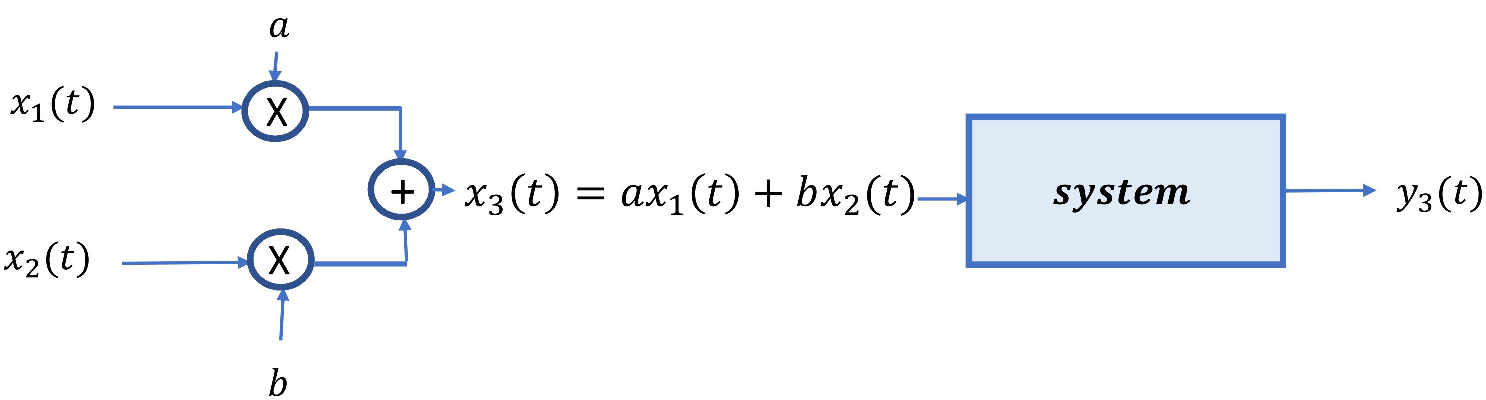
If yes, the system is **Linear**

Step 3: Build $x_3(t)$

Step 4: Find the out put of the system to $x_3(t)$



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Linear/ Nonlinear Systems

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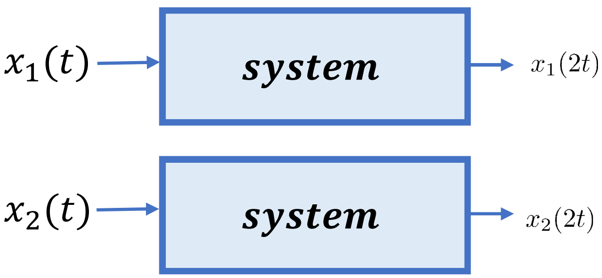

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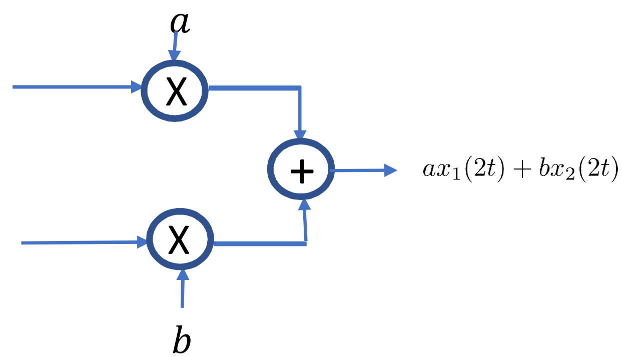

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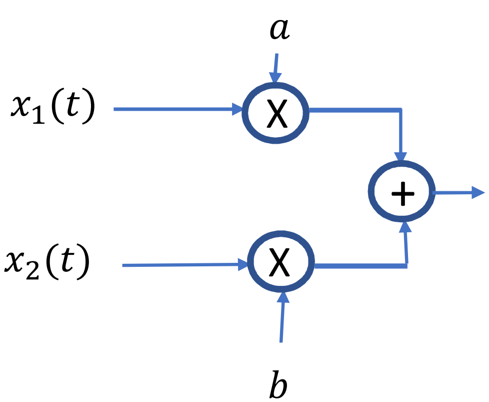
Step 3: Build $x_3(t)$



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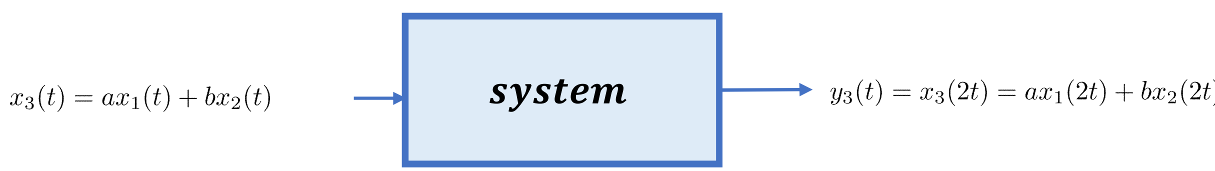

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Linear/ Nonlinear Systems

Check the steps for $y(t) = t^2 x(t)$

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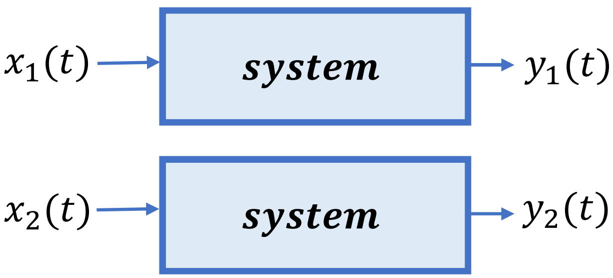

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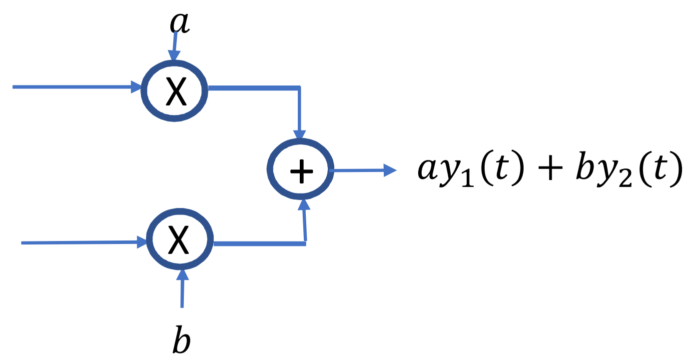

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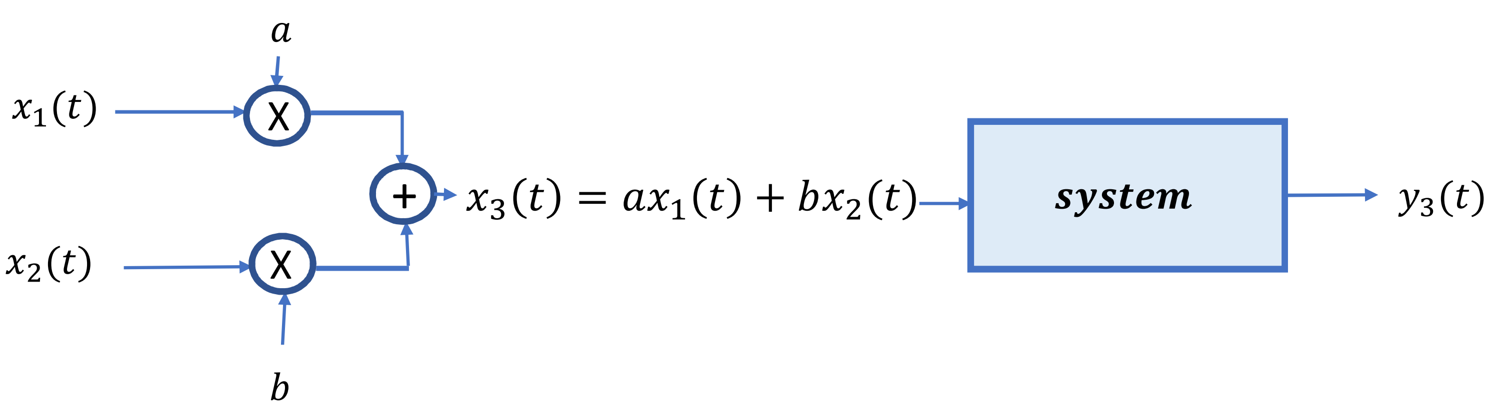
Step 3: Build $x_3(t)$

Step 4: Find the out put of the system to $x_3(t)$



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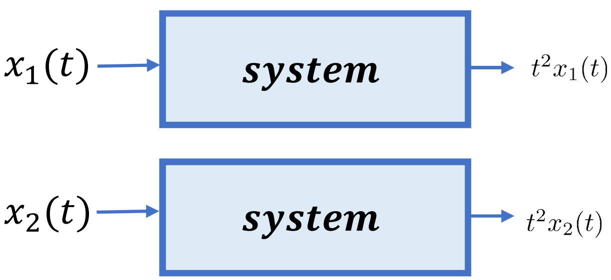
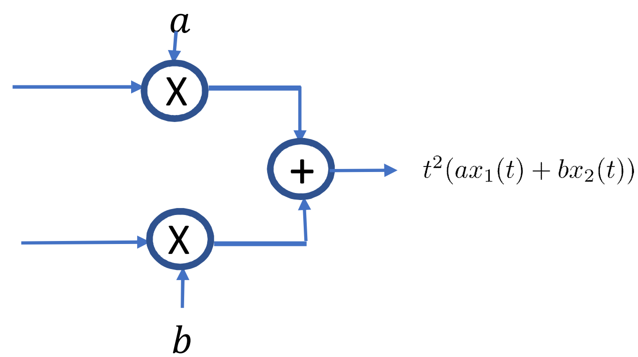
Linear/ Nonlinear Systems

Check the steps for $y(t) = t^2 x(t)$

Step 1: Find output of the system to $x_1(t)$ and $x_2(t)$



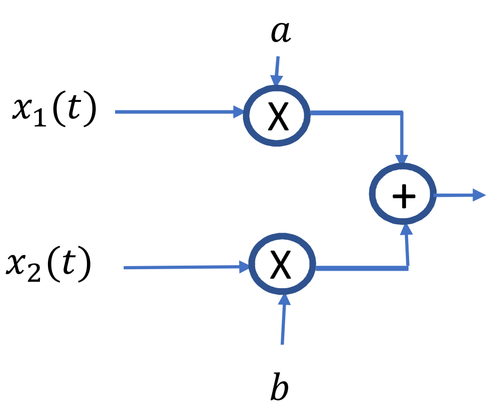
Step 2: Build linear combination of $y_1(t)$ and $y_2(t)$



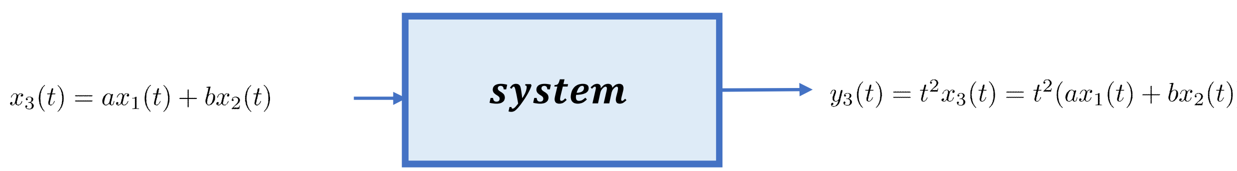
Step 5:
Check if result of step 2 is the same as result of step 4:

The two are the same so the system is **Linear**

Step 3: Build $x_3(t)$



Step 4: Find the out put of the system to $x_3(t)$



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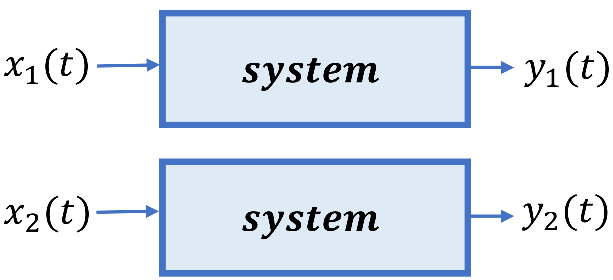
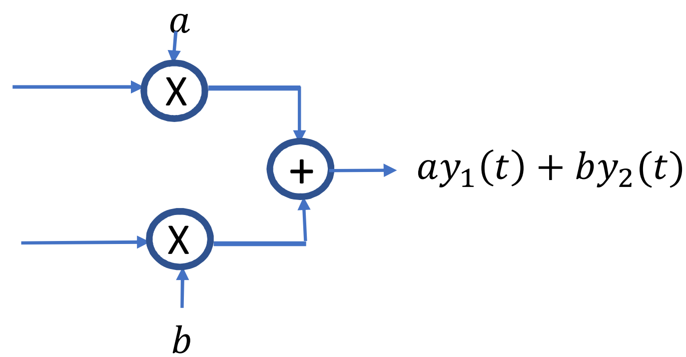
Linear/ Nonlinear Systems

Check the steps for a system with following equation $\frac{dy(t)}{dt} + t^2 y(t) = 2tx(t)$

Step 1: Find output of the system to $x_1(t)$ and $x_2(t)$



Step 2: Build linear combination of $y_1(t)$ and $y_2(t)$

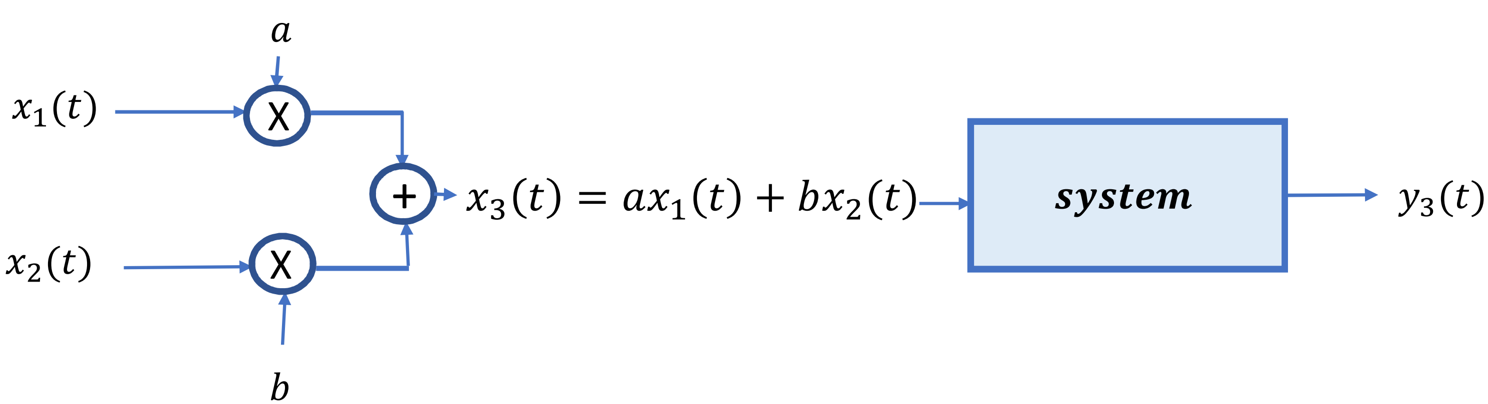


Step 5:
Check if result of step 2 is
the same as result of step 4:

If yes, the system is **Linear**

Step 3: Build $x_3(t)$

Step 4: Find the out put of the system to $x_3(t)$

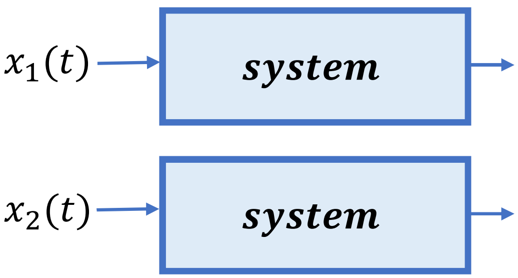


Soosan Beheshti, Ryerson University

Linear/ Nonlinear Systems

Check the steps for a system with following equation $\frac{dy(t)}{dt} + t^2y(t) = 2tx(t)$

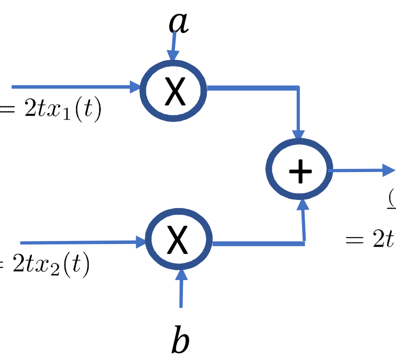
Step 1: Find output of the system to $x_1(t)$ and $x_2(t)$



$\frac{dy_1(t)}{dt} + t^2y_1(t) = 2tx_1(t)$

$\frac{dy_2(t)}{dt} + t^2y_2(t) = 2tx_2(t)$

Step 2: Build linear combination of $y_1(t)$ and $y_2(t)$



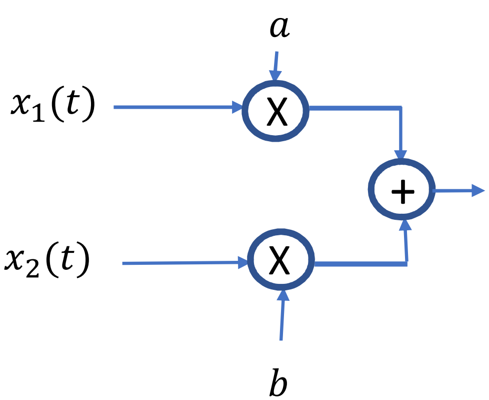
$\frac{(d(ay_1(t)+by_2(t))}{dt} + t^2(ay_1 + by_2(t))$
$= 2t(ax_1(t) + bx_2(t))$

Step 5:
Check if result of step 2 is the same as result of step 4:

Here we can replace $y_3(t)$ is step 4 with $ay_1(t) + by_2(t)$ in step 2 as both equations then become identical.

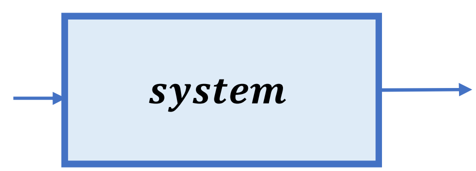
so the system **Linear**

Step 3: Build $x_3(t)$



$x_3(t) = ax_1(t) + bx_2(t)$

Step 4: Find the out put of the system to $x_3(t)$



$\frac{dy_3(t)}{dt} + t^2y_3(t) = 2tx_3(t)$
$\frac{dy_3(t)}{dt} + t^2y_3(t) = 2t(ax_1(t) + bx_2(t))$

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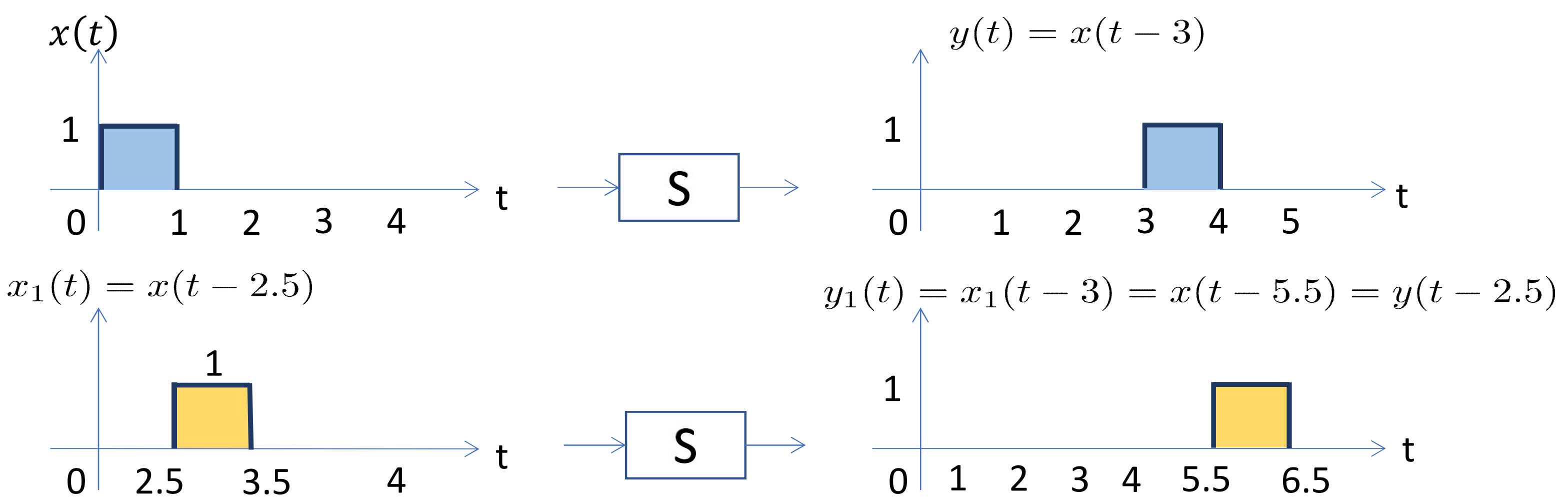
Time Invariant(TI) / Time Variant (TV) Systems

System S with output $y(t) = S((x(t))$ is TI if and only if

$$y(t-T) = S\big(x(t-T)\big)$$

"Time shift T in input results in time shift T in output."

Example:



Time Invariant(TI) / Time Variant (TV) Systems

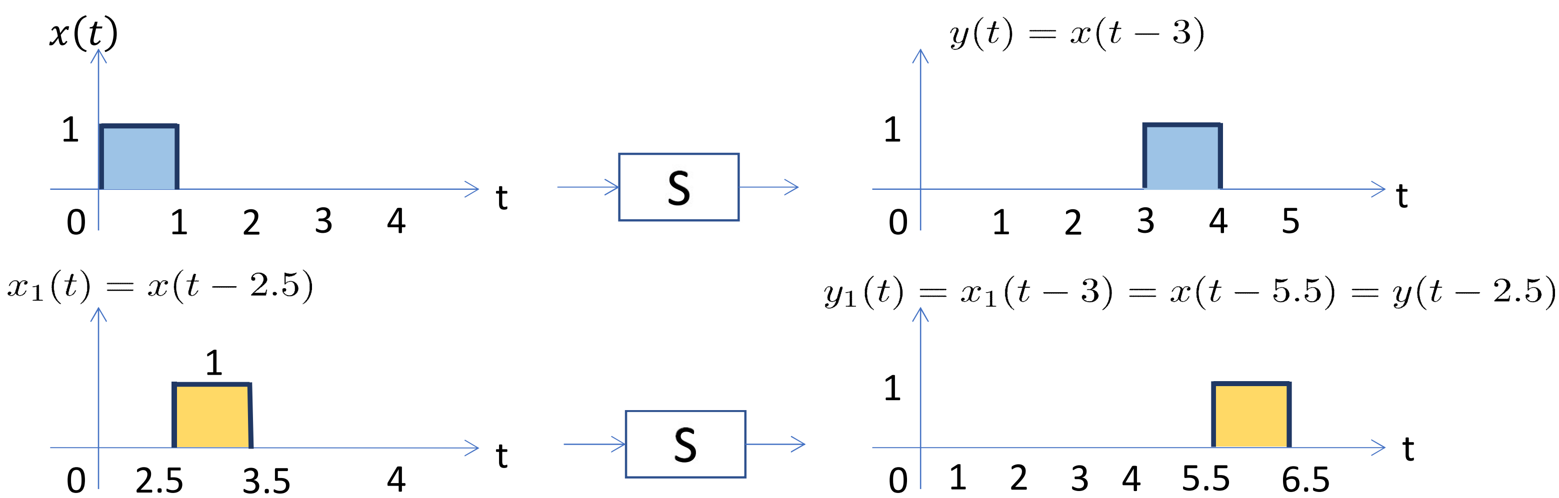
System S with output $y(t) = S((x(t))$ is TI if and only if

$$y(t-T) = S\big(x(t-T)\big)$$

"Time shift T in input results in time shift T in output."

Holds for $T = 2.5$
is the system TI?

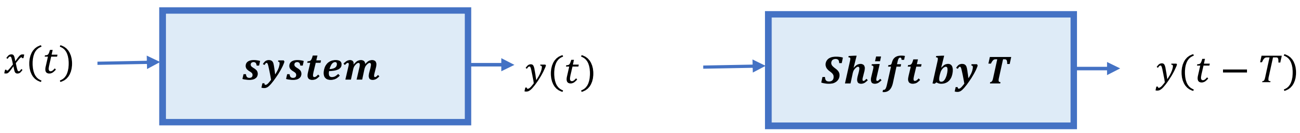
Example:



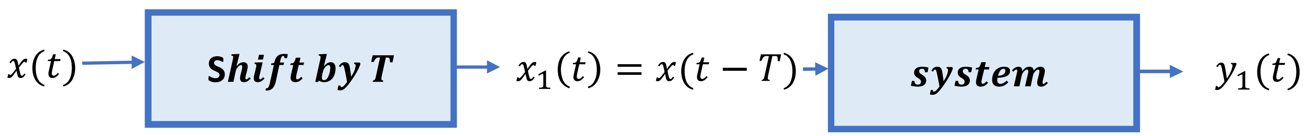
Time Invariant(TI) / Time Variant (TV) Systems

Three steps to check if a system is TI:

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 2: Find the output of system to shifted version $x(t)$



Step 3:
Check if result of step 1 is the same as result of step 2:

If the answer is yes, the system is **Time Invariant**

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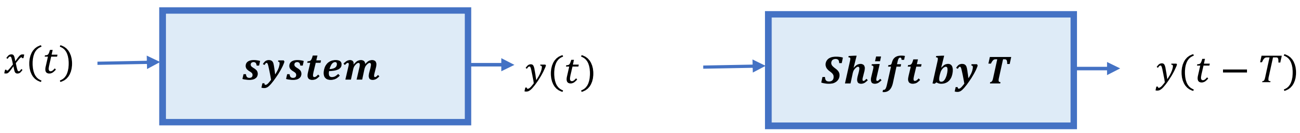
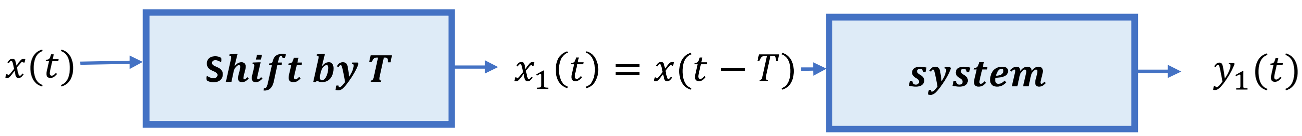
Time Invariant(TI) / Time Variant (TV) Systems

Check the steps for $y(t) = x(t-3)$

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 2: Find the output of system to shifted version $x(t)$



Step 3:
Check if result of step 1 is the same as result of step 2:

If the answer is yes, the system is **Time Invariant**

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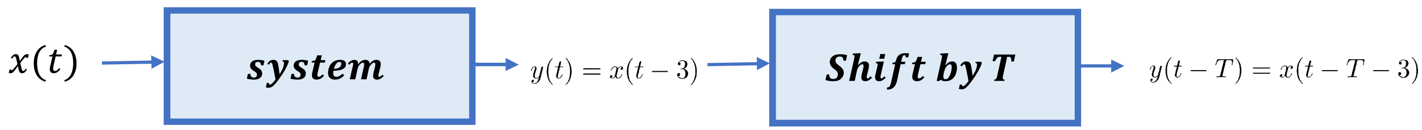
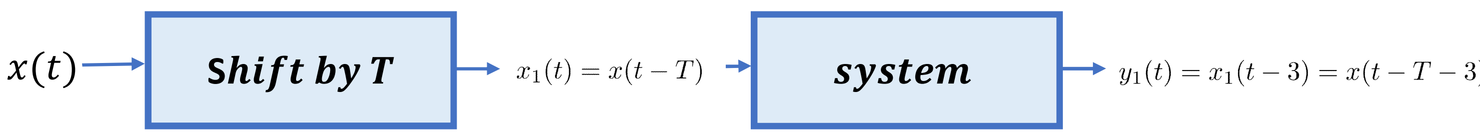
Time Invariant(TI) / Time Variant (TV) Systems

Check the steps for $y(t) = x(t-3)$

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 2: Find the output of system to shifted version $x(t)$



Step 3:
Check if result of step 1 is the same as result of step 2:

Resuts of step 1 and step 2 are the same the system is
Time Invariant

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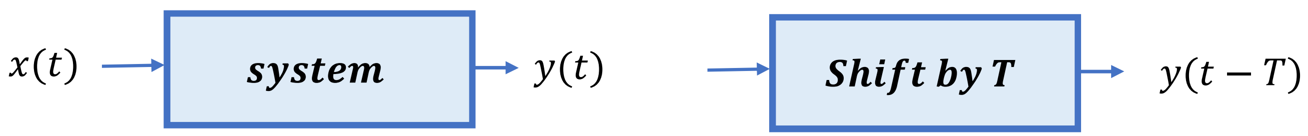
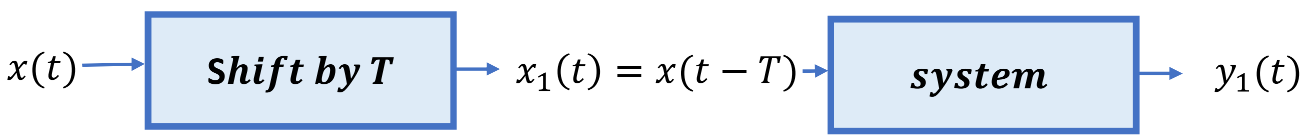
Time Invariant(TI) / Time Variant (TV) Systems

Check the steps for $y(t) = x^2(t)$

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 2: Find the output of system to shifted version $x(t)$



Step 3:
Check if result of step 1 is
the same as result of step 2:

If the answer is yes,
the system is **Time Invariant**

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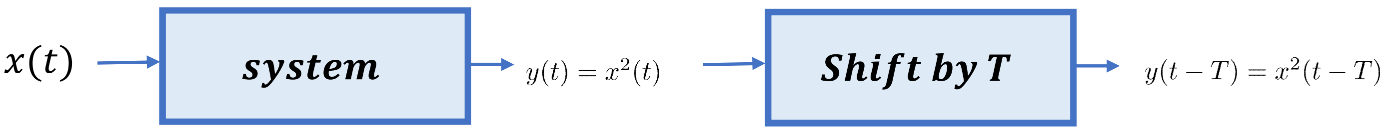
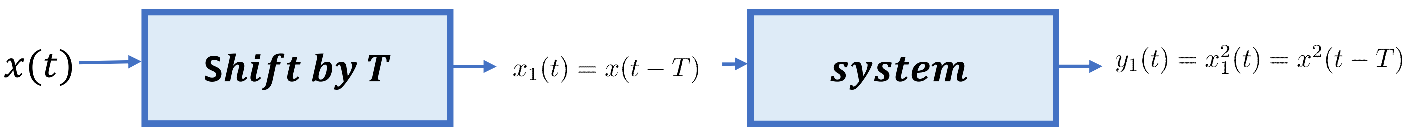
Time Invariant(TI) / Time Variant (TV) Systems

Check the steps for $y(t) = x^2(t)$

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 2: Find the output of system to shifted version $x(t)$



Step 3:
Check if result of step 1 is the same as result of step 2:

Resuts of step 1 and step 2 are the same the system is
Time Invariant

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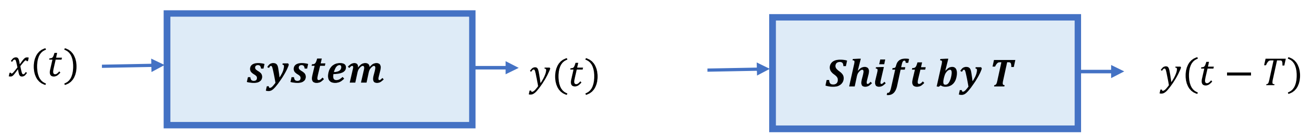
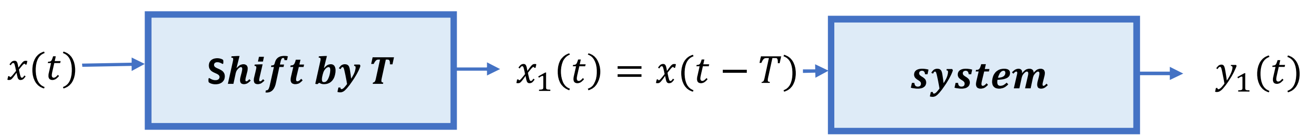
Time Invariant(TI) / Time Variant (TV) Systems

Check the steps for $y(t) = x(t) + 3$

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 2: Find the output of system to shifted version $x(t)$



Step 3:
Check if result of step 1 is the same as result of step 2:

If the answer is yes,
the system is **Time Invariant**

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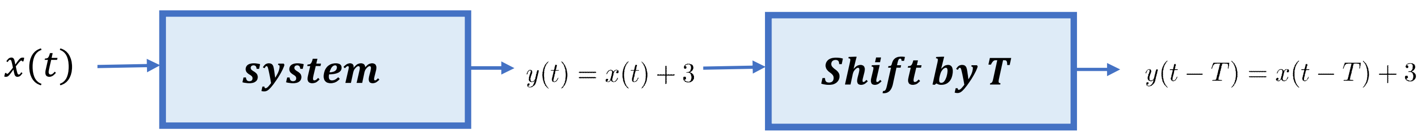
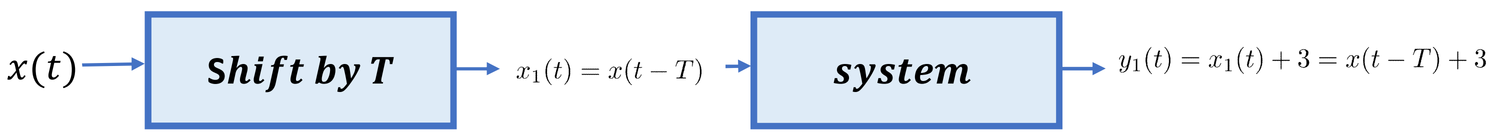
Time Invariant(TI) / Time Variant (TV) Systems

Check the steps for $y(t) = x(t) + 3$

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 2: Find the output of system to shifted version $x(t)$



Step 3:
Check if result of step 1 is the same as result of step 2:

Resuts of step 1 and step 2 are the same the system is
Time Invariant

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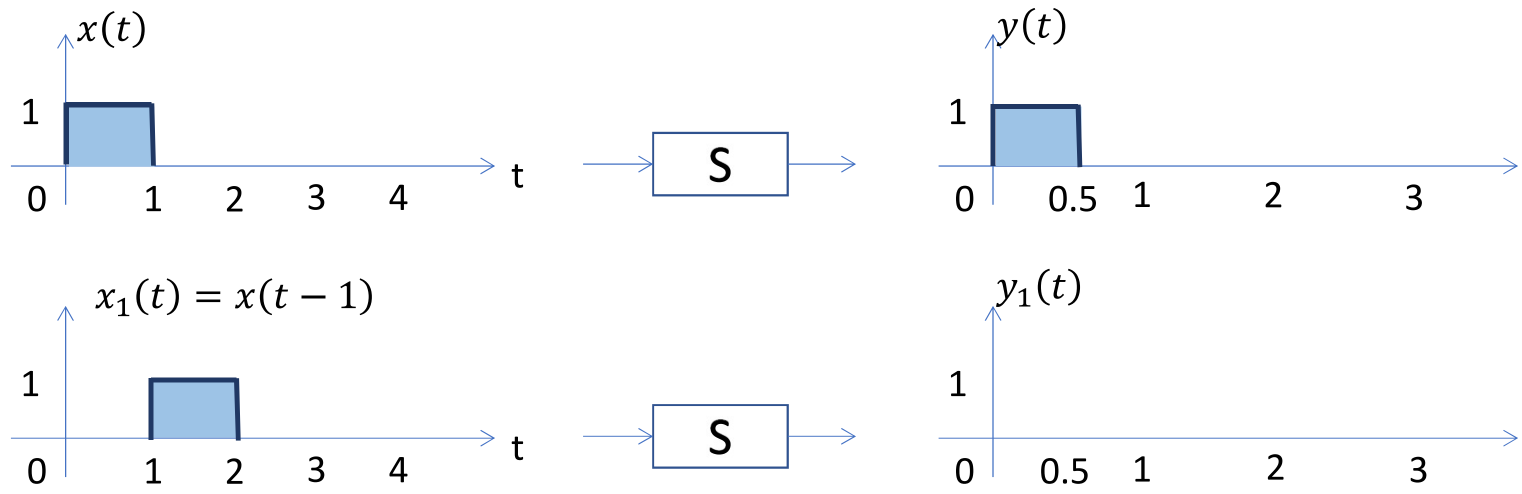
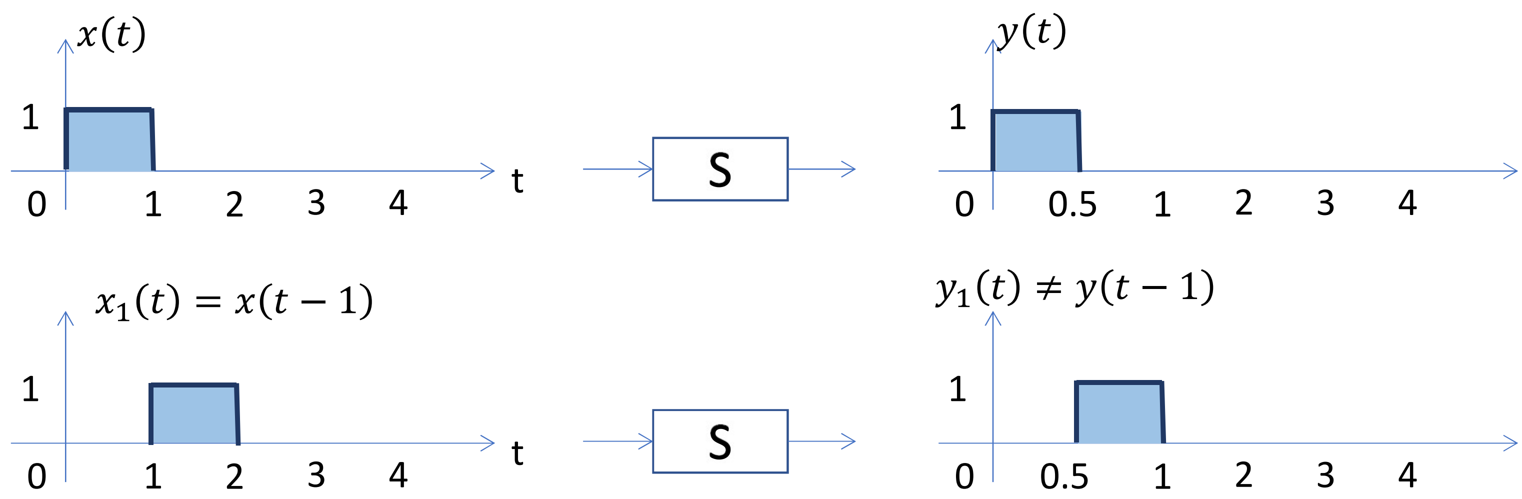
Time Invariant(TI) / Time Variant (TV) Systems

Is $y(t) = x(2t)$ Time Invariant?



Time Invariant(TI) / Time Variant (TV) Systems

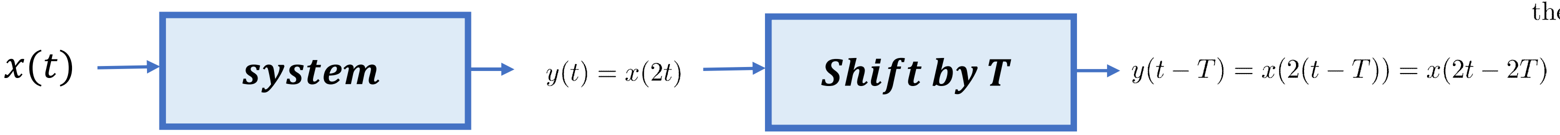
Is $y(t) = x(2t)$ Time Invariant?



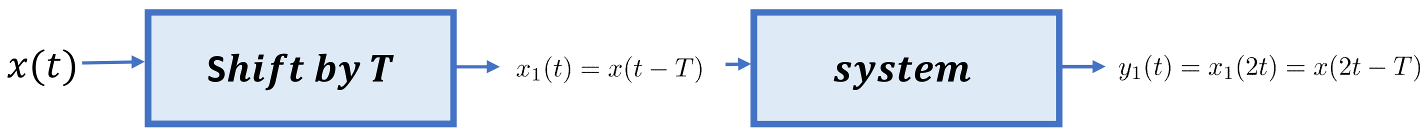
Time Invariant(TI) / Time Variant (TV) Systems

Check the steps for $y(t) = x(2t)$

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 2: Find the output of system to shifted version $x(t)$



Step 3:
Check if result of step 1 is the same as result of step 2:

Resuts of step 1 and step 2 are not the same, the system is
Time Varying

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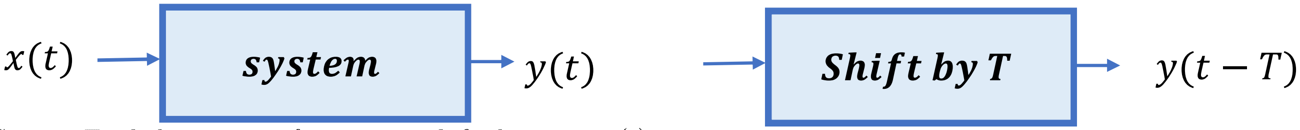
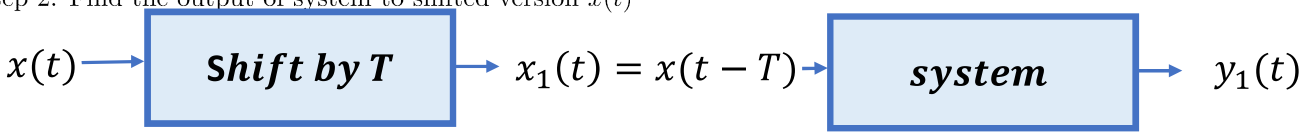
Time Invariant(TI) / Time Variant (TV) Systems

Is system $y(t) = x(-t)$ Linear? is it time invariant?

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



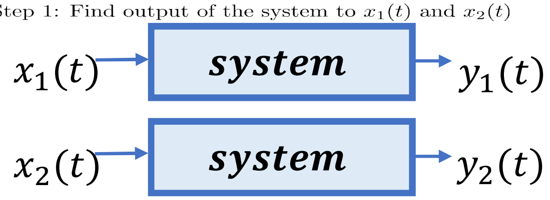
Step 2: Find the output of system to shifted version $x(t)$



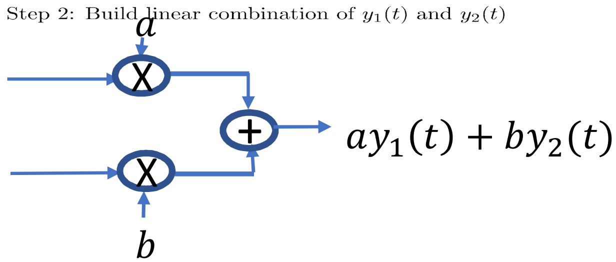
Step 3:
Check if result of step 1 is
the same as result of step 2:

If the answer is yes,
the system is **Time Invariant**

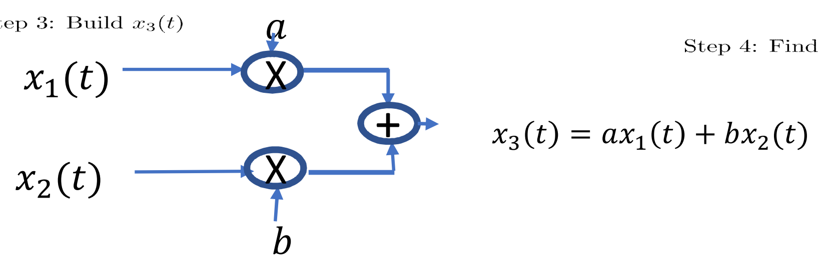
Step 1: Find output of the system to $x_1(t)$ and $x_2(t)$



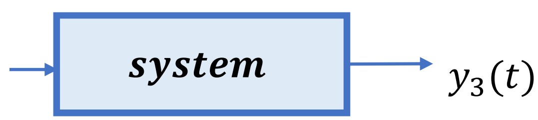
Step 2: Build linear combination of $y_1(t)$ and $y_2(t)$



Step 3: Build $x_3(t)$



Step 4: Find the out put of the system to $x_3(t)$



Step 5:
Check if result of step 2 is
the same as result of step 4:

If yes, the system is **Linear**

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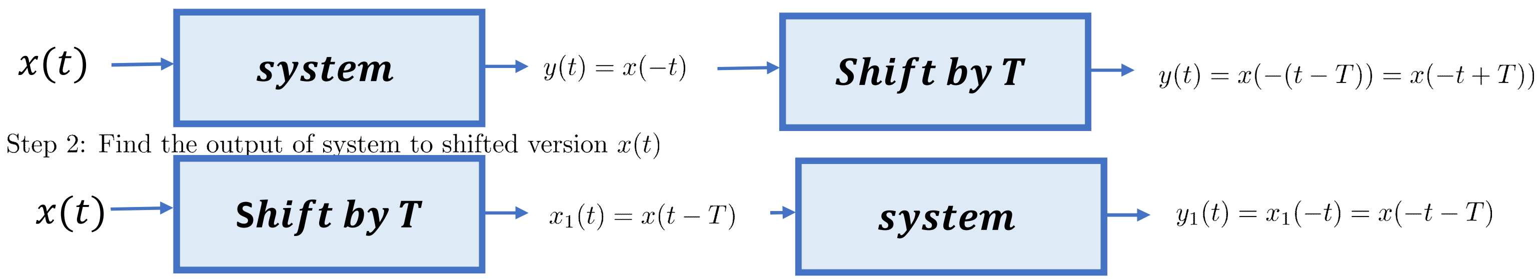
Time Invariant(TI) / Time Variant (TV) Systems

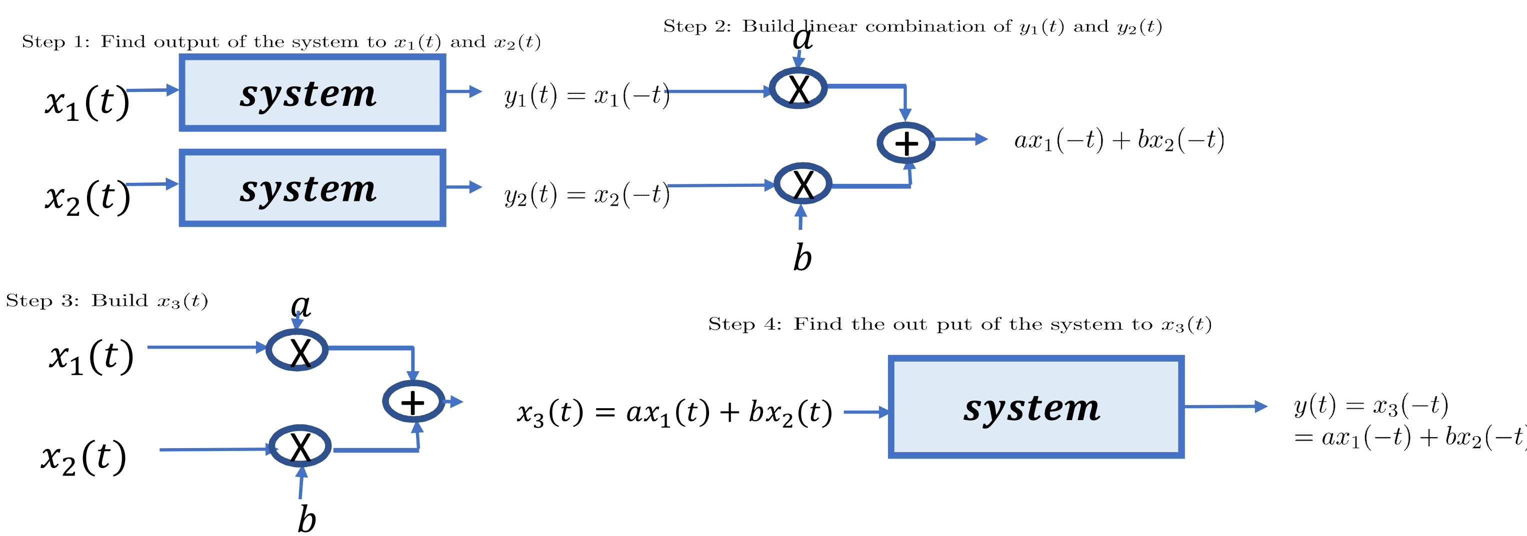
Is system $y(t) = x(-t)$ Linear? is it time invariant?

Step 1: Write $y(t)$, the output of the system to $x(t)$ and shift it by T



Step 3:
The result of step 1 is not
the same as result of step 2:

The system is **Time Varying**



Step 5:
The result of step 2 is
the same as result of step 4:

The system is **Linear**

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System Classification: Memoryless (instantaneous)/with memory(dynamic)

Memoryless system's output at time *t* only depends on input at time *t*. Otherwise the system is with memory!

Which of these systems are memoryless?

✓ (a) $x(t) \rightarrow$ **S** $\rightarrow t + x(t)$

(b) $x(t) \rightarrow$ **S** $\rightarrow x(t+2) = y(t)$

(c) $x(t) \rightarrow$ **S** $\rightarrow x(t-1) + x(t)$

✓ (d) $x(t) \rightarrow$ **S** $\rightarrow e^{x(t)}$

(e) $x(t) \rightarrow$ **S** $\rightarrow x(-t) = y(t)$

(f) $x(t) \rightarrow$ **S** $\rightarrow \int_{-\infty}^{\infty} x(v)dv = y(t)$

(g) $x(t) \rightarrow$ **S** $\rightarrow \int_{-\infty}^{t} x(v)dv = y(t)$

✓ (h) $x(t) \rightarrow$ **S** $\rightarrow x^2(t)$

Any system that takes the derivative or integral of the input has memory!

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System Classification: Causal/ Non-Causal Systems

Causal system's output at time t_0 only depends on input values at time t_0 and at times before t_0, i.e., only depends on $t \leq t_0$.

Which of these systems are causal?

- ✓ (a) $x(t) \rightarrow \boxed{S} \rightarrow t + x(t)$
- (b) $x(t) \rightarrow \boxed{S} \rightarrow x(t+2) = y(t)$
- ✓ (c) $x(t) \rightarrow \boxed{S} \rightarrow x(t-1) + x(t)$
- ✓ (d) $x(t) \rightarrow \boxed{S} \rightarrow e^{x(t)} = y(t)$
- (e) $x(t) \rightarrow \boxed{S} \rightarrow x(-t) = y(t)$
- (f) $x(t) \rightarrow \boxed{S} \rightarrow \int_{-\infty}^{\infty} x(v)dv = y(t)$
- ✓ (g) $x(t) \rightarrow \boxed{S} \rightarrow \int_{-\infty}^{t} x(v)dv = y(t)$
- ✓ (h) $x(t) \rightarrow \boxed{S} \rightarrow x^2(t)$

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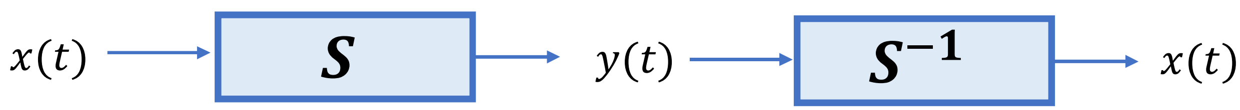
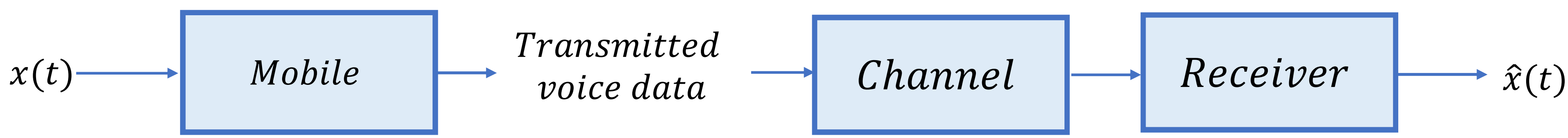
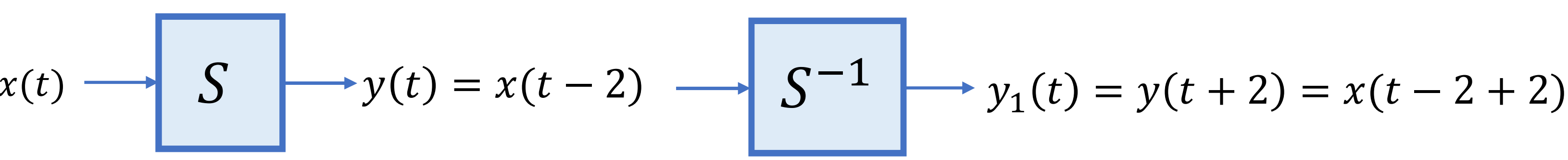
System Classification: Invertible/ Non-invertible Systems

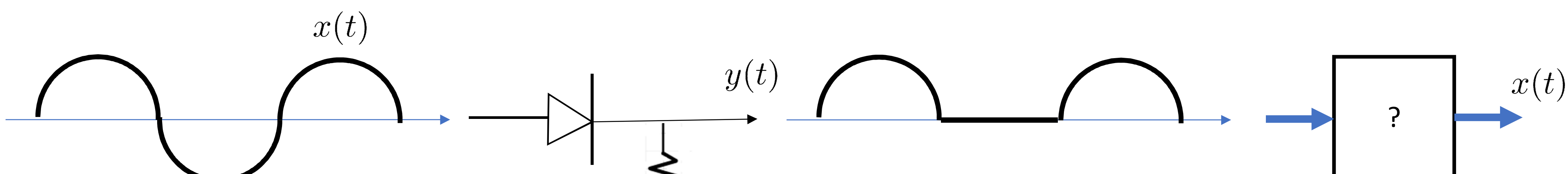
System S is invertible if there exists a system S^{-1} such that:



(Important desired property in design of many systems such as communications systems).







Does S^{-1} exist?

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System Classification: Invertible/ Non-invertible Systems

Which of these systems are invertible?

(a) $x(t) \rightarrow \boxed{S} \rightarrow t + x(t)$

(b) $x(t) \rightarrow \boxed{S} \rightarrow x(t+2)$

(c) $x(t) \rightarrow \boxed{S} \rightarrow x(t-1) + x(t)$

(d) $x(t) \rightarrow \boxed{S} \rightarrow e^{x(t)}$

(e) $x(t) \rightarrow \boxed{S} \rightarrow x(-t)$

(f) $x(t) \rightarrow \boxed{S} \rightarrow \int_{-\infty}^{\infty} x(v)dv$

(g) $x(t) \rightarrow \boxed{S} \rightarrow \int_{-\infty}^{t} x(v)dv$

(h) $x(t) \rightarrow \boxed{S} \rightarrow x^2(t)$

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System Classification: Stable/Unstable Systems

External stability or Bounded input/Bounded output (BIBO) stability

If $|x(t)| < C_1, \ \forall t \rightarrow \exists \ c > 0 : |y(t)| < C \ \forall t$

We will discuss Internal Stability later

Serious concepts in design of Control Systems (ELE639)

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System Classification: Stable/Unstable Systems

Which of these systems are externally stable?

- ✓ (a) $x(t) \rightarrow$ **S** $\rightarrow t + x(t)$
- ✓ (b) $x(t) \rightarrow$ **S** $\rightarrow x(t+2)$
- ✓ (c) $x(t) \rightarrow$ **S** $\rightarrow x(t-1) + x(t)$
- ✓ (d) $x(t) \rightarrow$ **S** $\rightarrow e^{x(t)}$
- ✓ (e) $x(t) \rightarrow$ **S** $\rightarrow x(-t)$
- (f) $x(t) \rightarrow$ **S** $\rightarrow \int_{-\infty}^{\infty} x(v)dv$
- (g) $x(t) \rightarrow$ **S** $\rightarrow \int_{-\infty}^{t} x(v)dv$
- ✓ (h) $x(t) \rightarrow$ **S** $\rightarrow x^2(t)$

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