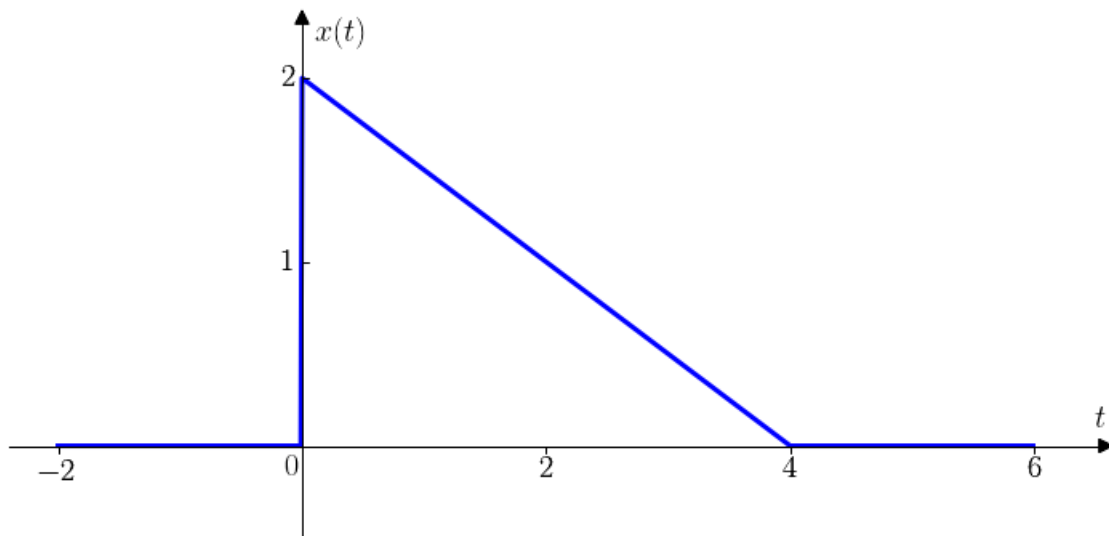Due Friday, 17 October 2025, by 11:59pm to Gradescope.
Covers material up to Lecture 4.
100 points total.

1. (22 points) **Elementary signals.**
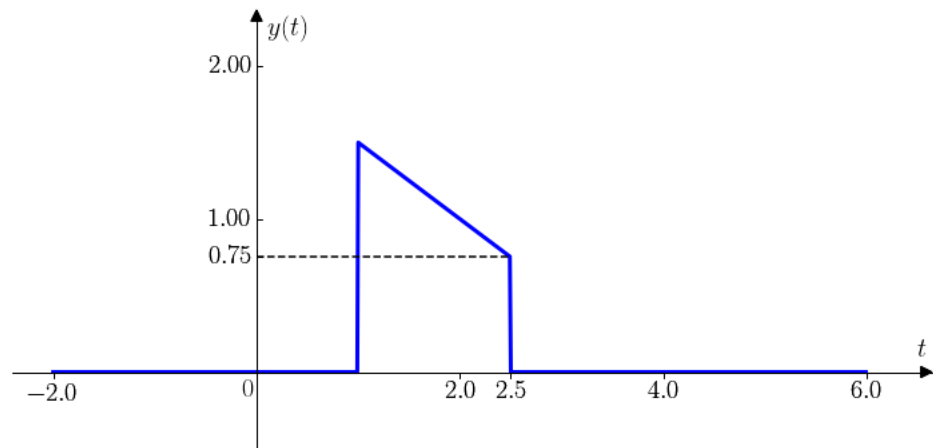
   (a) (9 points) Consider the signal $x(t)$ shown below. Sketch the following:

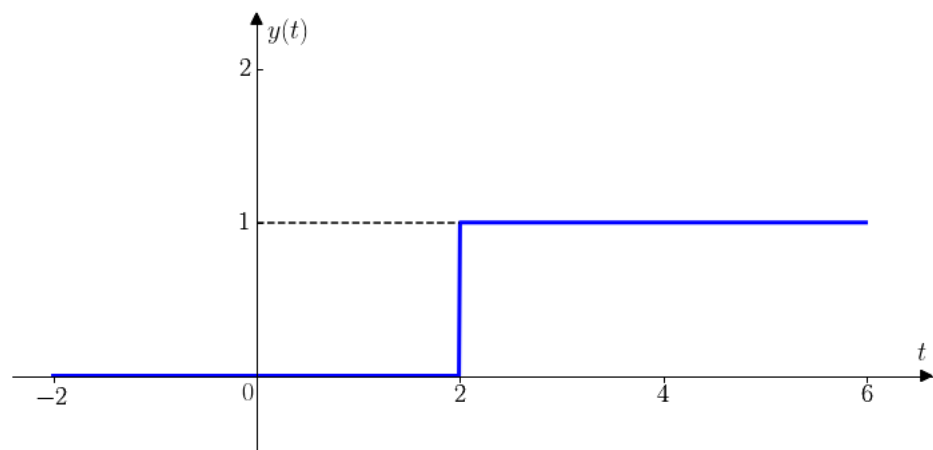   i. $y(t) = x(t)\left(u(t-1) - u(2t-5)\right)$

   Solution: If we look at $u(t-1) - u(2t-5)$, we'll see that it is equal to 1 between $t = 1$ and $t = 2.5$, and equals 0 elsewhere. Therefore, its multiplication with $x(t)$ will be:
$$y(t) = \begin{cases} x(t) & 0 \leq t < 2.5 \\ 0 & else \end{cases}$$

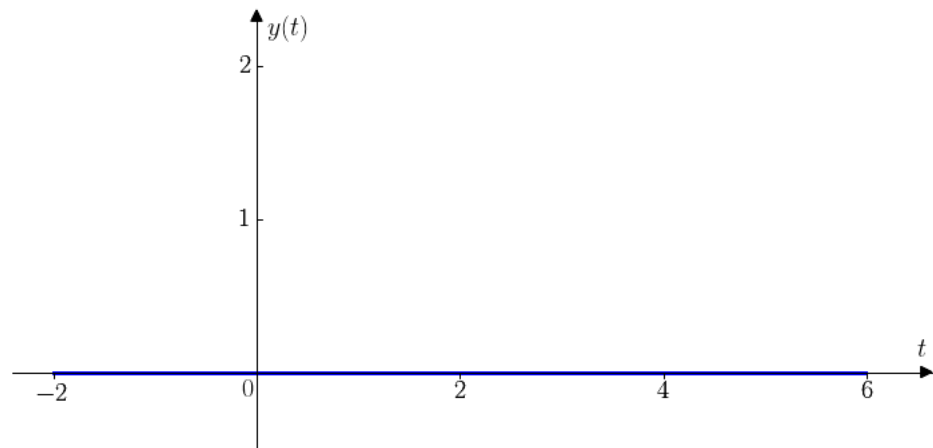ii. $y(t) = \int_{-\infty}^{t} \delta(\tau - 2)x(\tau)d\tau$

Solution: Using the sifting property,

iii. $y(t) = x(t) - \left(2u(t) - \frac{1}{2}r(t) + \frac{1}{2}r(t-4)\right)$

Solution:

(b) (9 points) Evaluate these integrals:

   i. $\int_{-\infty}^{\infty} f(t+1)\delta(t+1)dt$

   Solution:
   Using the sifting property, we first have: $f(t+1)\delta(t+1) = f(0)\delta(t+1)$. Therefore,

   $$\int_{-\infty}^{\infty} f(t+1)\delta(t+1)dt = f(0)\int_{-\infty}^{\infty}\delta(t+1)dt = f(0).$$

   ii. $\int_t^{\infty} e^{-2\tau}u(\tau - 1)d\tau$

   Solution:
   To evaluate this integral, we have to consider two cases; the first one is when $t \geq 1$ and the second one is when $t < 1$. This is because $u(\tau - 1)$ is one when $\tau \geq 1$ and zero otherwise. Thus, if $t \geq 1$, then:

   $$\int_t^{\infty} e^{-2\tau}u(\tau - 1)d\tau = \int_t^{\infty} e^{-2\tau}d\tau = \left.\frac{e^{-2\tau}}{-2}\right|_t^{\infty} = \frac{e^{-2t}}{2}$$

   If $t < 1$, then:

   $$\int_t^{\infty} e^{-2\tau}u(\tau - 1)d\tau = \int_1^{\infty} e^{-2\tau}d\tau = \left.\frac{e^{-2\tau}}{-2}\right|_1^{\infty} = \frac{e^{-2}}{2}$$

   .

   iii. $\int_0^{\infty} f(t)(\delta(t-1) + \delta(t+1))dt$

   Solution:
   The integral can be decomposed as follows:

   $$\int_0^{\infty} f(t)\delta(t-1)dt + \int_0^{\infty} f(t)\delta(t+1)dt$$

   Using the sifting property for the first integral, we have:

   $$\int_0^{\infty} f(t)\delta(t-1)dt = \int_0^{\infty} f(1)\delta(t-1)dt = f(1)$$

   The second integral is zero, because $\delta(t+1)$ is centred at $t = -1$ and the limits of the integration do not include $t = -1$. Therefore,

   $$\int_0^{\infty} f(t)(\delta(t-1) + \delta(t+1))dt = f(1)$$

(c) (4 points) Let b be a positive constant. Show the following property for the delta function:

$$\delta(bt) = \frac{1}{b}\delta(t)$$

Hint: what function is "delta-like"?

Solution:

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We know that $\delta(t)$ is defined as follows:

$$\delta(t) = \lim_{\Delta \to 0} \text{rect}_\Delta(t)$$

Therefore,

$$\delta(bt) = \lim_{\Delta \to 0} \text{rect}_\Delta(bt)$$

The rectangle $\text{rect}_\Delta(bt)$ is shown in Fig. 2. Let $\Delta' = \Delta/b$, then the same rectangle can be written as:

$$\text{rect}_\Delta(bt) = \frac{1}{b}\text{rect}_{\Delta'}(t)$$

Therefore,

$$\delta(bt) = \lim_{\Delta \to 0} \text{rect}_\Delta(bt) = \lim_{\Delta' \to 0} \frac{1}{b}\text{rect}_{\Delta'}(t) = \frac{1}{b}\delta(t)$$

Note: we can extend this argument to $b < 0$. In general for any $b \neq 0$, we have:
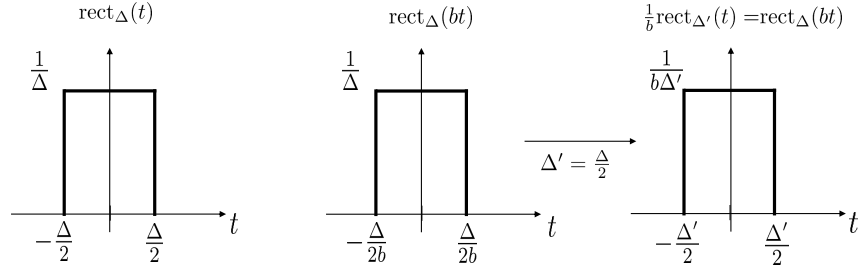
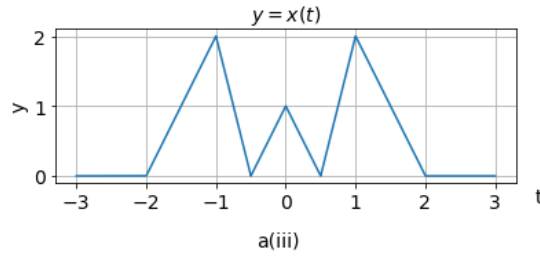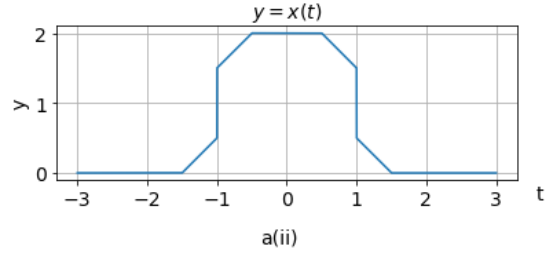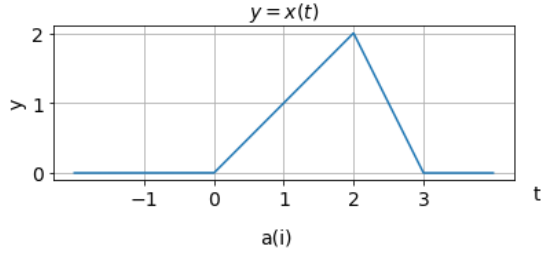$$\delta(bt) = \frac{1}{|b|}\delta(t)$$

Figure 1:

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2. (23 points) **Expression for signals.**

   (a) (15 points) Write the following signals as a combination (sums or products) of unit triangles $\Delta(t)$ and unit rectangles $\text{rect}(t)$.


a(i)

a(ii)

a(iii)

Solution:

   i. Fig. a)We can see this signal as the sum of two shifted unit triangles, where the first one is scaled by $3/2$, i.e., $x(t) = \Delta(t-1) + 2\Delta(t-2)$.

   ii. Fig. b) We can express this signal as the sum of two triangles one shifted to the left and the second to the right. Now the parts of these two triangles that are lifted by one for $-1 \leq t \leq 1$ can be obtained by adding a rectangle function. Therefore, $x(t) = \Delta(t-0.5) + \Delta(t+0.5) + \text{rect}(t/2)$.

   iii. Fig. c) One way to represent this signal is to find an expression for each triangle in terms of the unit triangle. The central triangle can be expressed as: $\Delta(2t)$. The triangle that is on the right side can be expressed as the sum of two triangles that are time-scaled and shifted: $2\Delta(2(t-1)) + \Delta(2(t-3/2))$. Similarly, the part that is on the left can be expressed as follows: $2\Delta(2(t+1)) + \Delta(2(t+3/2))$. Therefore, $x(t) = 2\Delta(2(t+1)) + \Delta(2(t+3/2)) + \Delta(2t) + 2\Delta(2(t-1)) + \Delta(2(t-3/2))$

   (b) (8 points) Express each of the signals shown below as sums of scaled and time shifted unit-step functions.

Solution:

   i. $x_a(t) = u(t+2) + u(t+1) + u(t+0.5) - u(t-0.5) - u(t-1) - u(t-2)$
   ii. $x_b(t) = u(t+2) + u(t+1) - 3u(t-1.5) + u(t-3)$

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y = x(t) (b(i)) and y = x(t) (b(ii))
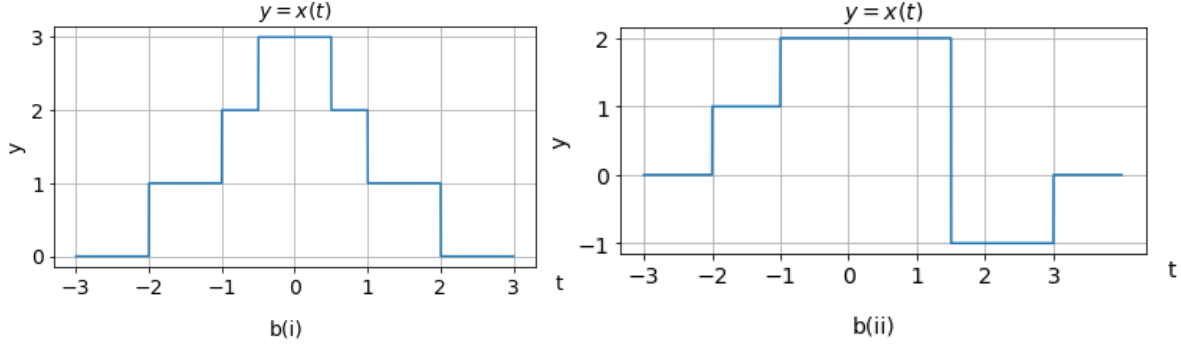
3. (30 points) **System properties.**

(a) (20 points) A system with input $x(t)$ and output $y(t)$ can be time-invariant, causal or stable. Determine which of these properties hold for each of the following systems. Explain your answer.

i. $y(t) = |x(t)| + x(2t)$

Solution:
Time-invariance: If we delay the input by τ, i.e., $x_\tau(t) = x(t - \tau)$, the output is:

$$y_\tau(t) = |x_\tau(t)| + x_\tau(2t) = |x(t - \tau)| + x(2t - \tau)$$

On the other hand,
$$y(t - \tau) = |x(t - \tau)| + x(2(t - \tau))$$

Since $y(t - \tau) \neq y_\tau(t)$, the system is time-variant.
Causality: Since the output can depend on future values of the input, the system is not causal. For instance, the output at $t = 2$ depends on $x(4)$.
Stability: If $|x(t)| \leq B_x$ for any t, then

$$|y(t)| = ||x(t)| + x(2t)| \leq |x(t)| + |x(2t)| \leq 2B_x$$

The output is also bounded, the system is then stable.

ii. $y(t) = \int_{t-T}^{t+T} x(\lambda)d\lambda$, where T is positive and constant.

Solution:
Time-invariance: If we delay the input by τ, i.e., $x_\tau(t) = x(t - \tau)$, the output is:

$$y_\tau(t) = \int_{t-T}^{t+T} x_\tau(\lambda)d\lambda = \int_{t-T}^{t+T} x(\lambda - \tau)d\lambda$$

Let $\lambda' = \lambda - \tau$, then

$$y_\tau(t) = \int_{t-T-\tau}^{t+T-\tau} x(\lambda')d\lambda' = \int_{(t-\tau)-T}^{(t-\tau)+T} x(\lambda')d\lambda'$$

which is equal to $y(t - \tau)$. The system is then time-invariant.

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Causality: The system is integrating values of $x(t)$ from $t - T$ to $t + T$. The output depends on future values of $x(t)$, therefore it is not causal.

Stability: If $|x(t)| \leq B_x$ for any t, then

$$|y(t)| = \left| \int_{t-T}^{t+T} x(\lambda)d\lambda \right| \leq \int_{t-T}^{t+T} |x(\lambda)|\, d\lambda \leq \int_{t-T}^{t+T} B_x d\lambda = 2TB_x$$

The output is also bounded, the system is then stable.

iii. $y(t) = (t + 1) \int_{-\infty}^{t} x(\lambda)d\lambda$

Solution:

Time-invariance: If we delay the input by τ, i.e., $x_\tau(t) = x(t - \tau)$, the output is:

$$y_\tau(t) = (t + 1) \int_{-\infty}^{t} x_\tau(\lambda)d\lambda = (t + 1) \int_{-\infty}^{t} x(\lambda - \tau)d\lambda$$

Let $\lambda' = \lambda - \tau$, then

$$y_\tau(t) = (t + 1) \int_{-\infty}^{t-\tau} x(\lambda')d\lambda'$$

On the other hand,

$$y(t - \tau) = (t - \tau + 1) \int_{-\infty}^{t-\tau} x(\lambda)d\lambda$$

Therefore $y(t - \tau) \neq y_\tau(t)$. The system is then time variant.

Causality: The system is integrating values of $x(t)$ up to time t. The output does not depend on future values of $x(t)$, the system is then causal.

Stability: Even if $x(t)$ is absolutely bounded, the integral:

$$\int_{-\infty}^{t} x(\lambda)d\lambda$$

cannot in general be bounded, the system is unstable. For instance, suppose $x(t) = 1$, then $\int_{-\infty}^{t} 1 d\lambda \to \infty$. Another example, suppose $x(t) = u(t)$, then

$$y(t) = (t + 1) \int_{-\infty}^{t} u(\lambda)d\lambda = (t + 1) \int_{0}^{t} 1 d\lambda = (t + 1)t$$

$(t + 1)t$ cannot be bounded as $t \to \infty$, because $(t + 1)t \to \infty$ as $t \to \infty$.

iv. $y(t) = 1 + x(t)\cos(\omega t)$

Solution:

Time-invariance: If we delay the input by τ: $x_\tau(t) = x(t - \tau)$, the output is:

$$y_\tau(t) = 1 + x_\tau(t)\cos(\omega t) = 1 + x(t - \tau)\cos(\omega t)$$

On the other hand,

$$y(t - \tau) = 1 + x(t - \tau)\cos(\omega(t - \tau))$$

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Since $y(t - \tau) \neq y_\tau(t)$. The system is then time-variant.

Causality: Since the output does not depend on any future values of the input, the system is causal.

Stability: If $|x(t)| \leq B_x$ for any t, then

$$|y(t)| = |1 + x(t)\cos(\omega t)| \leq 1 + |x(t)| \leq 1 + B_x$$

The output is also bounded, the system is then stable.

v. $y(t) = \frac{1}{1+x^2(t)}$

Solution:

Time-invariance: If we delay the input by τ, i.e., $x_\tau(t) = x(t - \tau)$, the output is:

$$y(t) = \frac{1}{1 + x_\tau^2(t)} = \frac{1}{1 + x^2(t - \tau)}$$

On the other hand,

$$y(t - \tau) = \frac{1}{1 + x^2(t - \tau)}$$

Therefore $y(t - \tau) = y_\tau(t)$. The system is then time invariant.

Causality: The output depends on present value of the input. The system is then causal.

Stability: We have the denominator:

$$1 + x^2(t) \geq 1 \implies \frac{1}{1 + x^2(t)} \leq 1$$

for any t. This implies that $y(t) \leq 1$. Moreover $y(t) > 0$, therefore for any t, we always have $|y(t)| \leq 1$. The system is always stable.
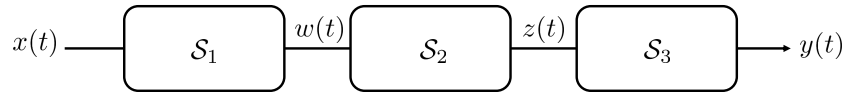
(b) (6 points) Consider the following three systems:

$$\mathcal{S}_1 : w(t) = x(t/2)$$

$$\mathcal{S}_2 : z(t) = \int_{-\infty}^{t} w(\tau)d\tau$$

$$\mathcal{S}_3 : y(t) = \mathcal{S}_3(z(t))$$

The three systems are connected in series as illustrated here:

Choose the third system $\mathcal{S}_3$, such that overall system is equivalent to the following system:

$$y(t) = \int_{-\infty}^{t-1} x(\tau)d\tau$$

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Solution: We first express $z(t)$ in terms of $x(t)$:

$$z(t) = \int_{-\infty}^{t} w(\tau)d\tau = \int_{-\infty}^{t} x(\tau/2)d\tau$$

Let $\tau' = \tau/2$, then $d\tau' = d\tau/2$ and $\tau \leq t \implies \tau' = \tau/2 \leq t/2$,

$$z(t) = 2 \int_{-\infty}^{t/2} x(\tau')d\tau'$$

To obtain the required $y(t)$ from $z(t)$, we need first to do a time-scaling by 2 for $z(t)$. This step gives us:

$$z(2t) = 2 \int_{-\infty}^{t} x(\tau')d\tau'$$

The second step is to do a right shift by 1:

$$z(2(t-1)) = 2 \int_{-\infty}^{t-1} x(\tau')d\tau'$$

Therefore, the third system is as follows:

$$y(t) = \frac{1}{2}z(2(t-1))$$

(c) (4 points) In part (b), you saw an example of three systems connected in series. In general, systems can be interconnected in series or in parallel to form what we call cascaded systems. The figure below shows the difference between a series cascade and a parallel cascade. *Note that parts (b) and (c) are unrelated.*

(a) Series Cascade
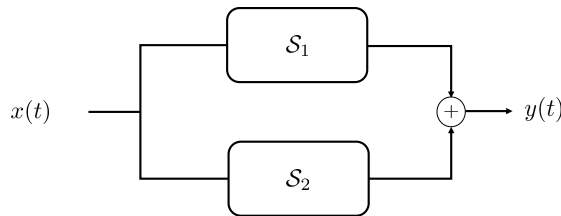
(b) Parallel Cascade

i. (2 points) Show that the series cascade of any two time-invariant systems is also time-invariant.

Solution:
Suppose the output of $\mathcal{S}_1$ is $y_1(t)$ when the input is $x(t)$, and that the output of $\mathcal{S}_2$ is $y(t)$ when the input is $y_1(t)$. If we delay $x(t)$ by τ (the input to the first system is now $x(t - \tau)$), then the output of the first system is $y_1(t - \tau)$. This is because the system is time-invariant. $y_1(t - \tau)$ is now the input to the second system. Again, since the second system is time-invariant, the output of the second system is $y(t - \tau)$. Therefore, for the overall system, when we apply $x(t - \tau)$ as input, we get $y(t - \tau)$ as output. The series cascade is then time-invariant.

ii. (2 points) Show that the parallel cascade of any two time-invariant systems is also time-invariant.

Solution:
Suppose for input $x(t)$, we get the outputs $y_1(t)$ and $y_2(t)$ respectively from S_1 and S_2. Therefore, $y(t) = y_1(t) + y_2(t)$. If we delay the input by τ (the input is now $x(t - \tau)$), then we get $y_1(t - \tau)$ and $y_2(t - \tau)$ respectively from S_1 and S_2 because both systems are time-invariant. Therefore, the output is $y_1(t-\tau)+y_2(t-\tau)$ which is equal to $y(t - \tau)$. Thus, the overall system is time-invariant.

iii. (*Optional*) Can you think of two **time-variant** systems, whose series cascade is **time-invariant**? Can you think of two **time-variant** systems, whose parallel cascade is **time-invariant**?

Solution:
Yes, for series cascade: $S_1 : y(t) = x(t/2)$ and $S_2 : y(t) = x(2t)$
For parallel cascade: $S_1 : y(t) = x(t) - tx(t)$ and $S_2 : y(t) = x(t) + tx(t)$

4. (10 points) **Power and energy of complex signals**

(a) (5 points) Is $x(t) = Ae^{j\omega t} + Be^{-j\omega t}$ a power or energy signal? A and B are both real numbers, not necessarily equal. If it is an energy signal, compute its energy. If it is a power signal, compute its power. (*Hint: Use the fact that the square magnitude of a complex number v is: $|v|^2 = v^*v$, where v^* is the complex conjugate of the complex number v.*)

Solution:
$x(t)$ is a periodic signal, therefore it is not an energy signal (its energy goes to infinity). It is a power signal. To calculate its power, we compute first the magnitude of $x(t)$:

$$|x(t)|^2 = x(t)x(t)^* = (Ae^{j\omega t} + Be^{-j\omega t})(Ae^{-j\omega t} + Be^{j\omega t})$$
$$= A^2 + ABe^{j2\omega t} + ABe^{-j2\omega t} + B^2$$
$$= A^2 + B^2 + 2AB\cos(2\omega t)$$

Therefore, the power of $x(t)$:

$$
\begin{aligned}
P &= \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} \left(A^2 + B^2 + 2AB \cos(2\omega t) \right) dt \\
&= \lim_{T \to \infty} \frac{1}{2T} \left(2TA^2 + 2TB^2 + AB \frac{\sin(2\omega t)}{\omega} \Big|_{-T}^{T} \right) \\
&= \lim_{T \to \infty} \frac{1}{2T} \left(2TA^2 + 2TB^2 + 2AB \frac{\sin(2\omega T)}{\omega} \right) \\
&= A^2 + B^2
\end{aligned}
$$

(b) (5 points) Is $x(t) = e^{-(1+j\omega)t} u(t-1)$ an energy signal or power signal? Again, if it is an energy signal, compute its energy. If it is a power signal, compute its power.

Solution:

The magnitude of $x(t)$ is given by:

$$
|x(t)| = e^{-t} u(t-1)
$$

Therefore, its energy is:

$$
E = \int_{1}^{\infty} e^{-2t} dt = \frac{e^{-2t}}{-2} \Big|_{t=1}^{\infty} = \frac{e^{-2}}{2}
$$

Therefore, it is an energy signal. Its power is then 0.

5. (15 points) **Python tasks**

For this question, please check the provided jupyter notebook solution file.