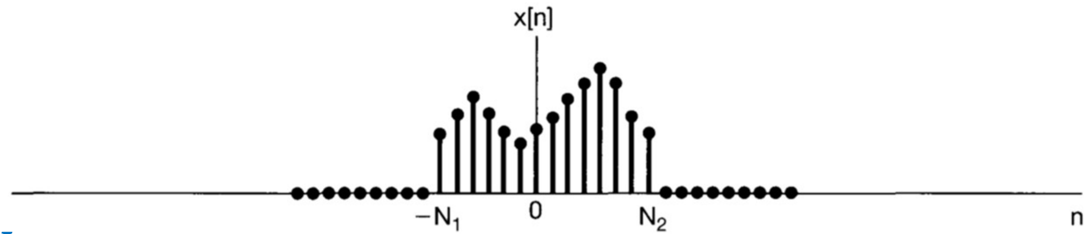
# The Discrete-Time Fourier Transform (ch.5)

- ❑ Representation of aperiodic signals - Discrete Fourier transform
- ❑ Fourier transform for periodic signals
- ❑ Properties of discrete-time Fourier transform
- ❑ The convolution property
- ❑ The multiplication property
- ❑ Duality
- ❑ Systems characterized by difference equations

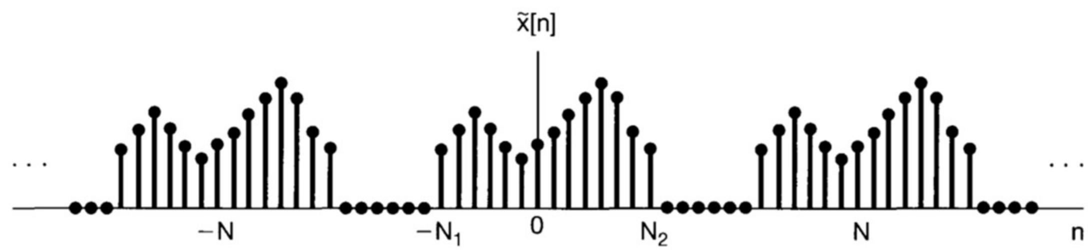
# Discrete Fourier Transform

## *Representation of aperiodic signals*

- Consider a general sequence of finite duration: $x[n] = 0$ if $n < N_1$ or $n > N_2$



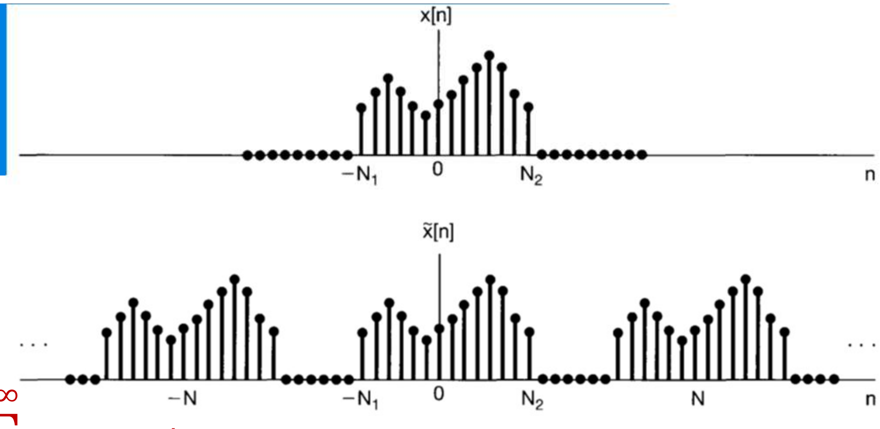

- Periodic extension of $x[n]$ with $N$




- FS representation of $\tilde{x}[n]$

$$\tilde{x}[n] = \sum_{k=\langle N\rangle} a_k e^{jk(2\pi/N)n} \qquad a_k = \frac{1}{N}\sum_{n=\langle N\rangle} \tilde{x}[n] e^{-jk(2\pi/N)n}$$

# Discrete Fourier Transform




## ***Representation of aperiodic signals***

- FS coefficients of $\tilde{x}[n]$

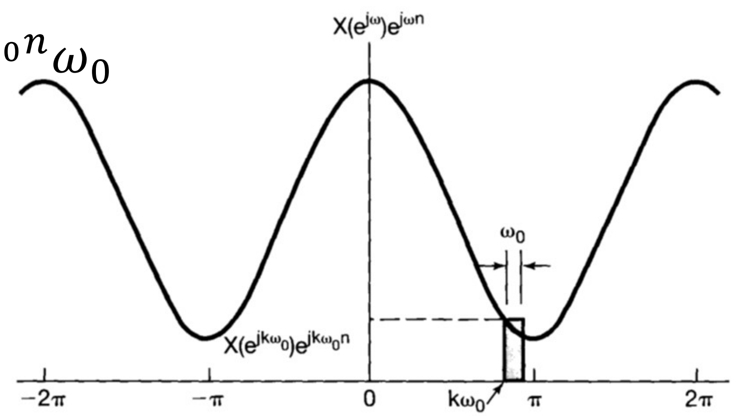
$$a_k = \frac{1}{N}\sum_{n=\langle N\rangle} \tilde{x}[n]e^{-jk(2\pi/N)n}$$

Define $X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x[n]e^{-j\omega n}$

$$= \frac{1}{N}\sum_{n=-N_1}^{N_2} x[n]e^{-jk(2\pi/N)n} = \frac{1}{N}\boxed{\sum_{n=-\infty}^{+\infty} x[n]e^{-jk(2\pi/N)n}} = \frac{1}{N}X(e^{jk\omega_0})$$

- FS of $\tilde{x}[n]$

$$\tilde{x}[n] = \sum_{k=\langle N\rangle}\frac{1}{N}X(e^{jk\omega_0})e^{jk\ {}_0 n} = \frac{1}{2\pi}\sum_{k=\langle N\rangle}X(e^{jk\ {}_0})e^{jk\omega_0 n}\omega_0$$




- $N \to \infty$, $\tilde{x}[n] \to x[n]$

$$x[n] = \frac{1}{2\pi}\int_{2\pi} X(e^{j\omega})\, e^{j\omega n} d\omega$$

# Discrete Fourier Transform

***FT pairs***

$$X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x[n]e^{-j\omega n}$$ Fourier transform (FT)

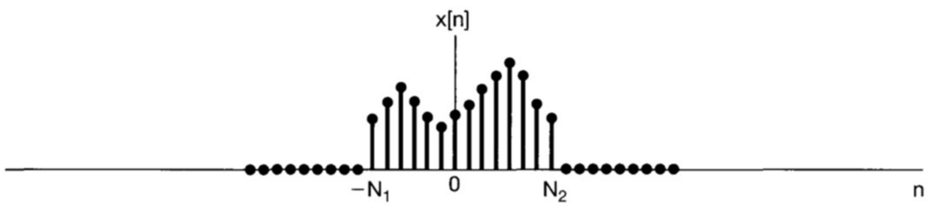
$$x[n] = \frac{1}{2\pi}\int_{2\pi} X(e^{j\omega})\, e^{j\omega n} d\omega$$ Inverse Fourier transform

- ❑ $x[n]$ is a linear combination (specifically, an integral) of complex exponentials at different frequencies
- ❑ $X(e^{j\omega})(d\omega/2\pi)$ is the weight for different frequencies
- ❑ $X(e^{j\omega})$ is called the spectrum

# Discrete Fourier Transform

## FT vs. FS

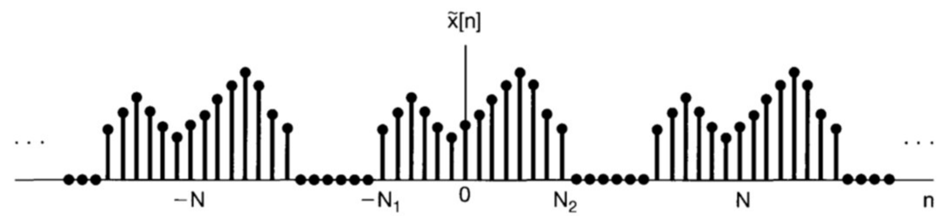
Fourier transform (FT)




$$x[n] = \frac{1}{2\pi}\int_{2\pi} X\left(e^{j\omega}\right) e^{j\omega n} d\omega$$

$$X\left(e^{j\omega}\right) = \sum_{n=-\infty}^{+\infty} x[n] e^{-j\omega n}$$

Fourier series (FS)




$$\tilde{x}[n] = \sum_{k=\langle N\rangle} a_k e^{jk(2\pi/N)n}$$

$$a_k = \frac{1}{N}\sum_{n=\langle N\rangle} \tilde{x}[n] e^{-j\ (2\pi/N)n}$$

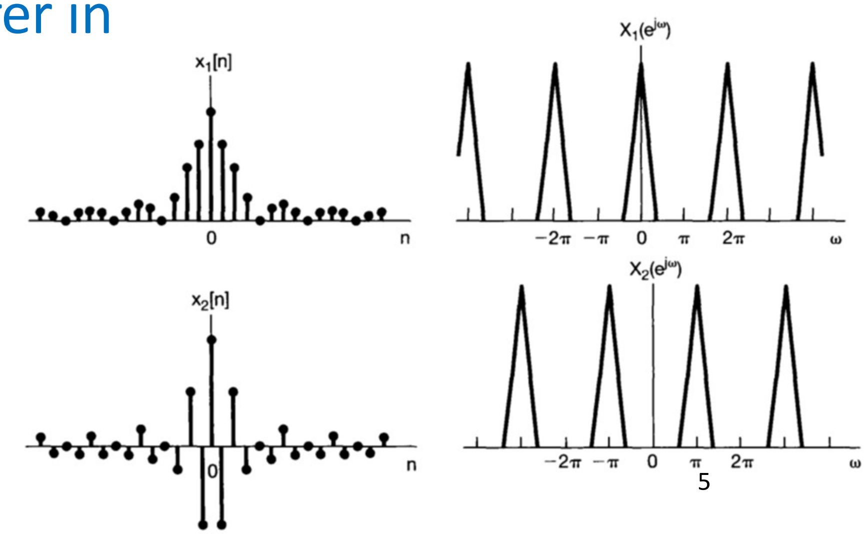
$a_k = \frac{1}{N} X(e^{j\omega})$ with $\omega = k(2\pi/N)$

# Discrete Fourier Transform

## ***Discrete FT vs. continuous FT***

| Discrete FT | Continuous FT |
|---|---|
| $x[n] = \frac{1}{2\pi}\int_{2\pi} X\left(e^{j\omega}\right) e^{j\omega n} d\omega$ | $x(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} X(j\omega) e^{j\omega t} d\omega$ |
| $X\left(e^{j\omega}\right) = \sum_{n=-\infty}^{+\infty} x[n] e^{-j\omega n}$ | $X(j\omega) = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} dt$ |

- Discrete-time complex exponentials that differ in frequency by a multiple of $2\pi$ are identical
  - $X(e^{j\omega})$ is periodic
  - Finite interval of integration in the synthesis equation for $x[n]$
  - $\omega = 0, 2\pi, 4\pi, \cdots \Rightarrow$ low-frequency
  - $\omega = \pi, 3\pi, 5\pi, \cdots \Rightarrow$ high-frequency



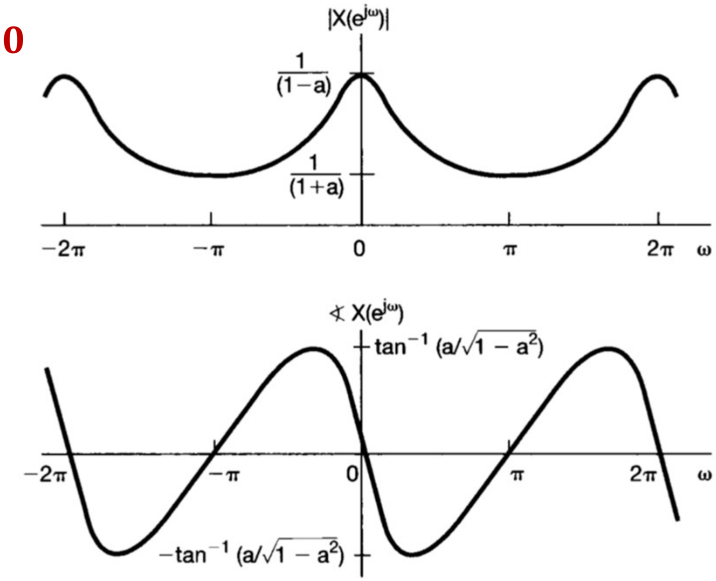
## Examples

$$x[n] = a^n u[n], |a| < 1 \qquad X(e^{j\omega}) = ?$$

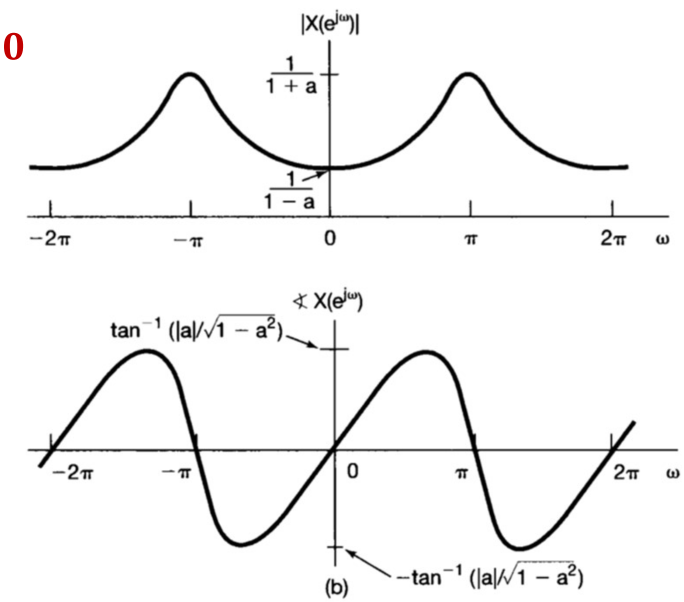
Solution

$$X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} a^n u[n] e^{-j\omega n} = \sum_{n=0}^{\infty} \left(ae^{-j}\ \ \right)^n = \frac{1}{1 - ae^{-j\omega}}$$

$a > 0$



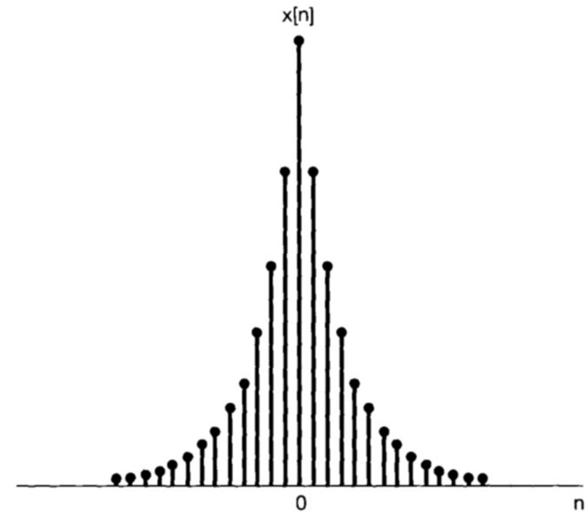

$a < 0$



# Discrete Fourier Transform

***Examples***

$$x[n] = a^{|n|}, |a| < 1 \qquad X(e^{j\omega}) = ?$$



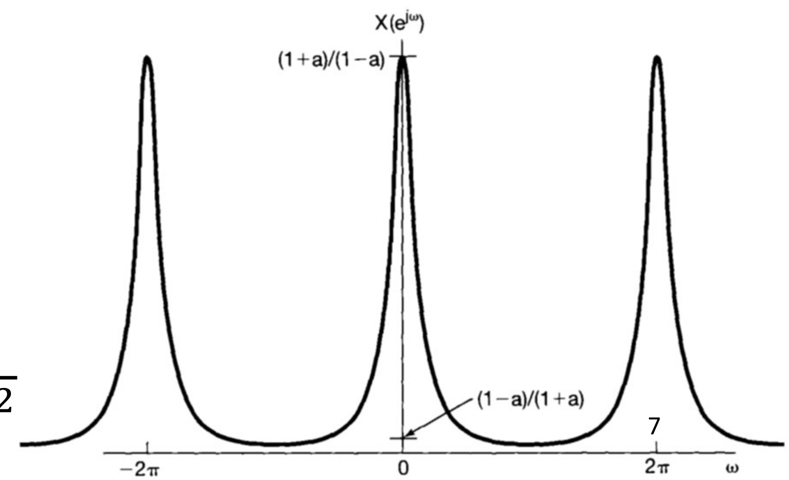

Solution

$$X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} a^{|n|} e^{-j}$$

$$= \sum_{n=0}^{\infty} a^{n} e^{-j\omega n} + \sum_{n=-\infty}^{-1} a^{-n} e^{-j\omega n}$$

$$= \sum_{n=0}^{\infty} (a e^{-j} \quad )^{n} + \sum_{m=1}^{\infty} (a e^{j\omega})^{m}$$

$$= \frac{1}{1 - a e^{-j\omega}} + \frac{a e^{j\omega}}{1 - a e^{j\omega}} = \frac{1 - a^2}{1 - 2a\cos\omega + a^2}$$



## Discrete Fourier Transform

***Examples***

$$x[n] = \begin{cases} 1, & |n| \le N_1 \\ 0, & |n| > N_1 \end{cases} \qquad X(e^{j\omega}) = ?$$

### Solution

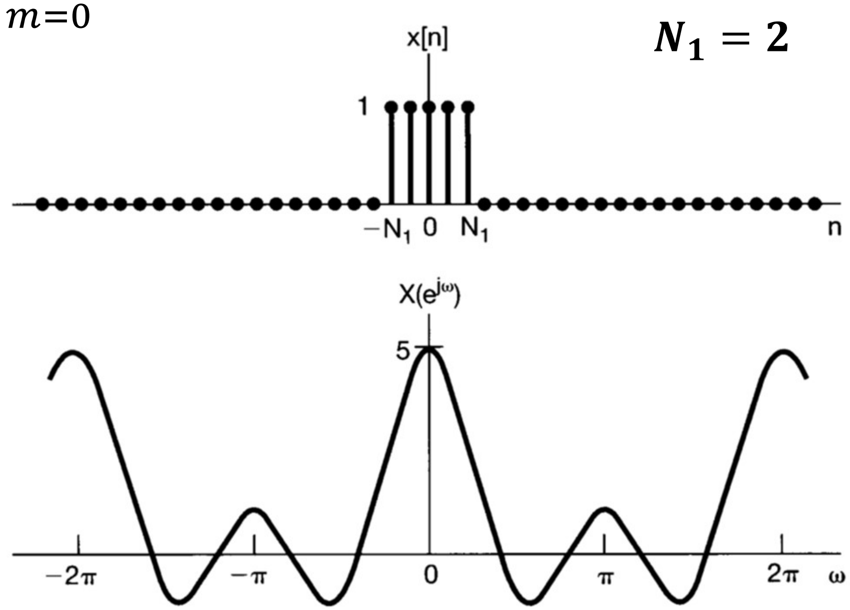
$$X(e^{j\omega}) = \sum_{n=-N_1}^{N_1} e^{-j\omega n} = \sum_{m=0}^{2N_1} e^{-j\omega(m-N_1)} = e^{j\omega N_1} \sum_{m=0}^{2N_1} e^{-j\omega m}$$

$$= e^{j\omega \quad 1}\left(\frac{1-e^{-j\omega(2N_1+1)}}{1-e^{-j\omega}}\right)$$

$$= \frac{e^{-j\omega/2}\left(e^{j\omega(N_1+1/2)} - e^{-j\omega(N_1+1/2)}\right)}{e^{-j \quad /2}\left(e^{j\omega/2} - e^{-j\omega/2}\right)}$$

$$= \frac{\sin[\omega(N_1+1/2)]}{\sin(\omega/2)}$$

$\boldsymbol{N_1 = 2}$



# Discrete Fourier Transform

***Convergence of FT***

- ❑ For the analysis equation $$X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x[n]e^{-j\omega n}$$
  - Finite energy condition $$\sum_{n=-\infty}^{+\infty} |x[n]|^2 < \infty$$
  - Absolutely summable $$\sum_{n=-\infty}^{+\infty} |x[n]| < \infty$$
- ❑ For the synthesis equation $$x[n] = \frac{1}{2\pi}\int_{2\pi} X(e^{j\omega})e^{j\omega n}d\omega$$
  - No convergence issues (finite interval of integration)

# Discrete Fourier Transform

***Examples*** $x[n] = \delta[n]$ $\quad X(e^{j\omega}) = ?$

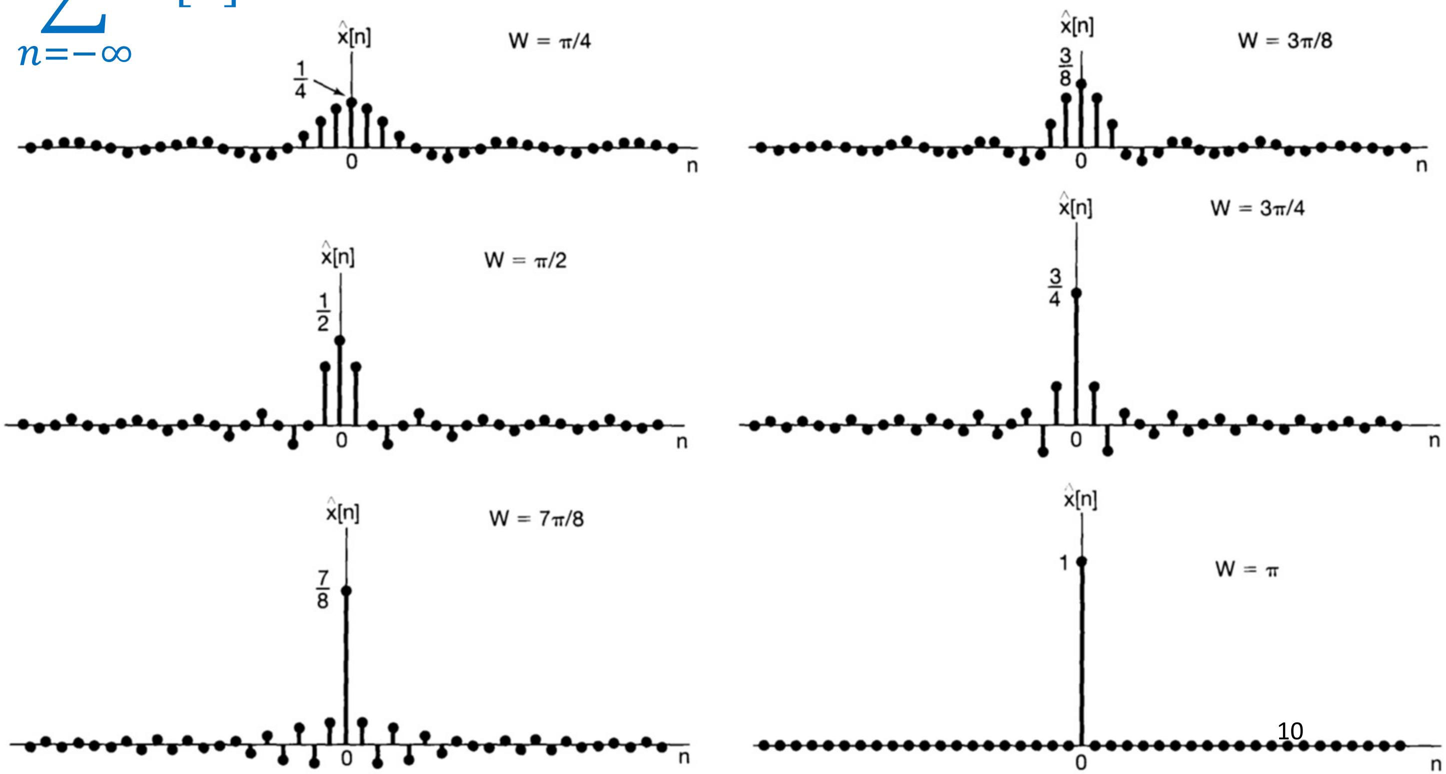
- Solution 1 $\quad X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} \delta[n] e^{-j\omega n} = 1$

- Solution 2

$$\hat{x}[n] = \frac{1}{2\pi} \int_{-W}^{W} e^{j\omega n} d\omega$$

$$= \frac{\sin Wn}{\pi n}$$

$$\lim_{W \to \pi} \hat{x}[n] = \delta[n]$$



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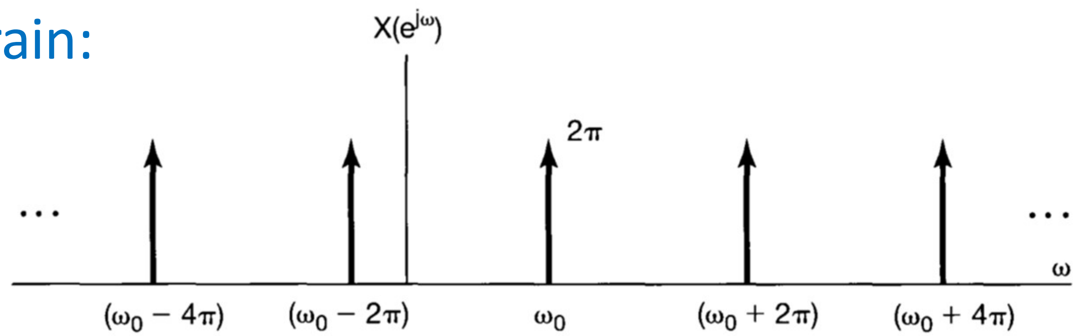
# Fourier transform for periodic signals

- Consider the sinusoidal signal

$$x[n] = e^{j\omega_0 n}$$

- The FT should be a periodic pulse train:

$$X(e^{j\omega}) = \sum_{l=-\infty}^{+\infty} 2\pi\delta(\omega - \omega_0 - 2\pi l)$$




- Check validity: evaluate the inverse transform

$$\frac{1}{2\pi}\int_{2\pi} X(e^{j\omega})e^{j\omega n}d\omega \quad = \frac{1}{2\pi}\int_{2\pi} \sum_{l=-\infty}^{+\infty} 2\pi\delta(\omega - \omega_0 - 2\pi l)\, e^{j\omega n}d\omega$$

$$= e^{j(\omega_0 + 2\pi r)n}$$ Fixed in one period $l = r$ cause $\int_{2\pi}$

$$= e^{j\omega_0 n}$$

# Fourier transform for periodic signals

- Consider a periodic sequence

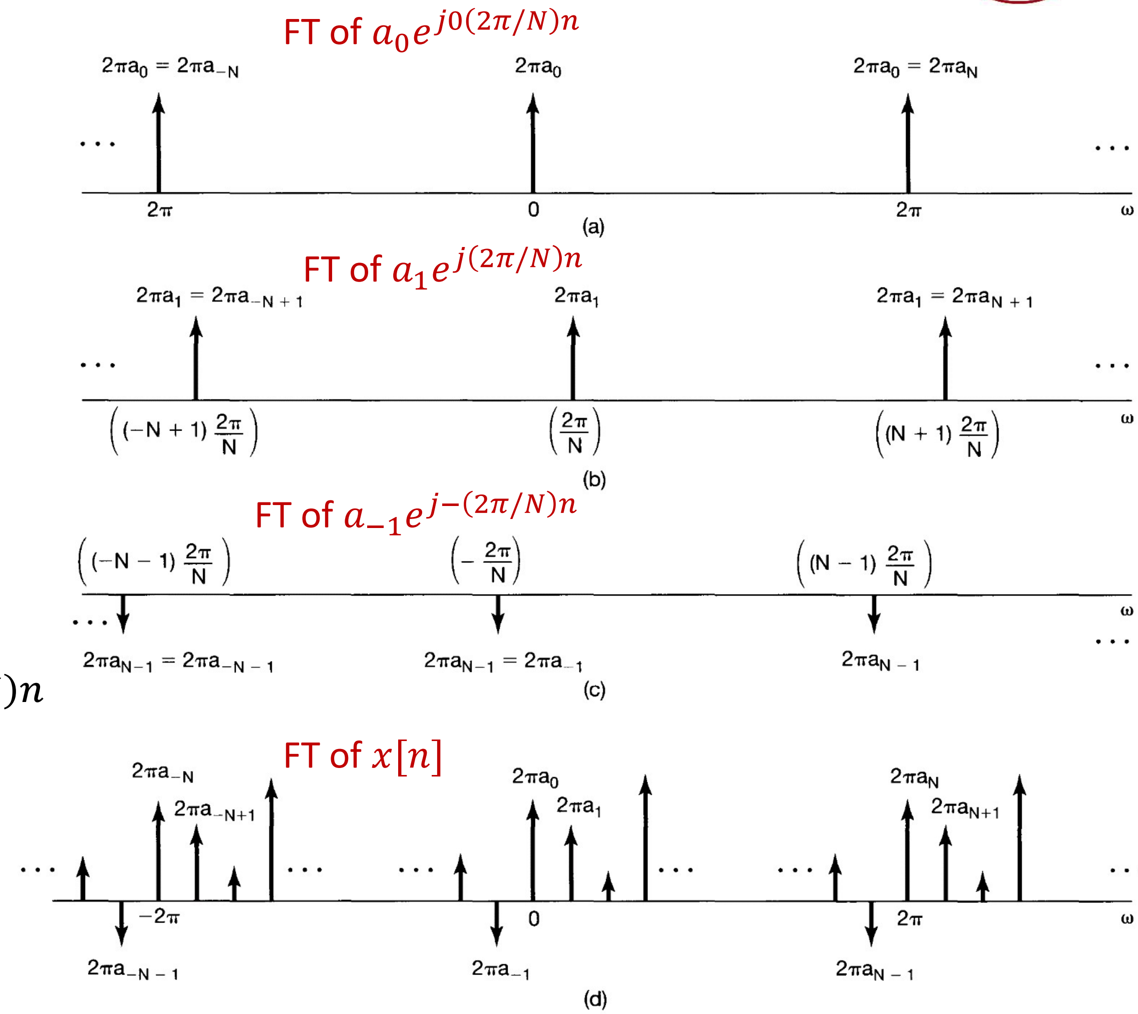
$$x[n] = \sum_{k=\langle N\rangle} a_k e^{jk(2\pi/N)n}$$

- FT

$$X(e^{j\omega}) = \sum_{k=-\infty}^{+\infty} 2\pi a_k \delta(\omega - 2\pi k/N)$$

- Verify

$$x[n] = a_0 + a_1 e^{j(2\pi/N)n} + a_2 e^{j2(2\pi/N)n} + \cdots + a_{N-1} e^{j(N-1)(2\pi/N)n}$$



# Fourier transform for periodic signals

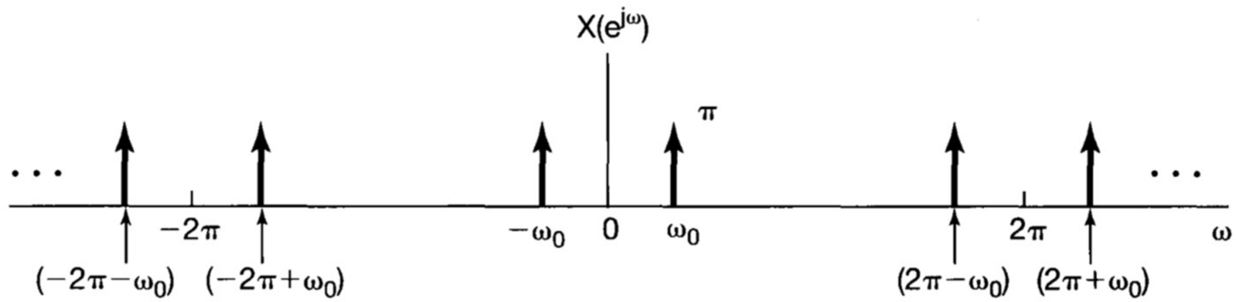
***Examples***

$$x[n] = \cos\omega_0 n = \frac{1}{2}e^{j\omega_0 n} + \frac{1}{2}e^{-j\omega_0 n}, \omega_0 = \frac{2\pi}{5} \qquad X(e^{j\omega}) = ?$$

## Solution

$$X(e^{j\omega}) = \sum_{l=-\infty}^{+\infty} \pi\delta\left(\omega - \frac{2\pi}{5} - 2\pi l\right) + \sum_{l=-\infty}^{+\infty} \pi\delta\left(\omega + \frac{2\pi}{5} - 2\pi l\right)$$

$$= \pi\delta\left(\omega - \frac{2\pi}{5}\right) + \pi\delta\left(\omega + \frac{2\pi}{5}\right), -\pi < \omega < \pi$$



# Fourier transform for periodic signals

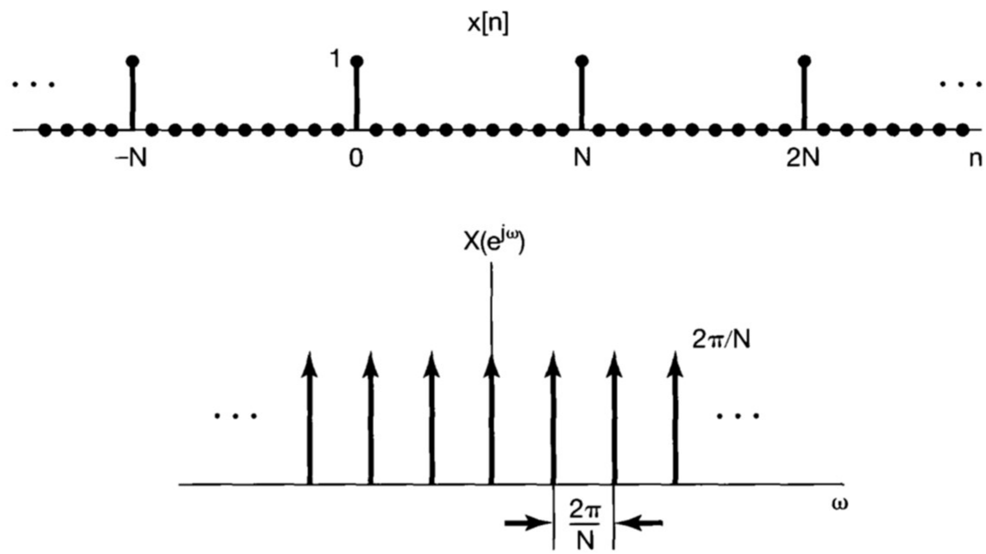
***Examples***

$$x[n] = \sum_{k=-\infty}^{+\infty} \delta[n - kN] \qquad\qquad X(e^{j\omega}) = ?$$

## Solution

$$a_k = \frac{1}{N} \sum_{n=\langle N \rangle} x[n] e^{-jk(2\pi/N)n} = \frac{1}{N}$$

$$X(e^{j\omega}) = \frac{2\pi}{N} \sum_{k=-\infty}^{+\infty} \delta\left(\omega - \frac{2\pi k}{N}\right)$$



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# Properties of discrete-time Fourier Transform

***Short notation for FT pairs***

$$x[n] = \frac{1}{2\pi}\int_{2\pi} X\left(e^{j\omega}\right) e^{j\omega n} d\omega$$

$$X\left(e^{j\omega}\right) = \sum_{n=-\infty}^{+\infty} x[n] e^{-j\omega n}$$

$$x[n] \xleftrightarrow{\mathcal{F}} X\left(e^{j\omega}\right)$$

$$X\left(e^{j\omega}\right) = \mathcal{F}\{x[n]\}$$

$$x[n] = \mathcal{F}^{-1}\left\{X\left(e^{j\omega}\right)\right\}$$

# Properties of discrete-time Fourier Transform

***Periodicity*** In contrast to continuous FT

$$X\left(e^{j(\omega+2\pi)}\right) = X\left(e^{j\omega}\right)$$

***Linearity***

$$x_1[n] \xleftrightarrow{\mathcal{F}} X_1\left(e^{j\omega}\right)$$

$$\Longrightarrow ax_1[n] + bx_2[n] \xleftrightarrow{\mathcal{F}} aX_1\left(e^{j\omega}\right) + bX_2\left(e^{j\omega}\right)$$

$$x_2[n] \xleftrightarrow{\mathcal{F}} X_2\left(e^{j\omega}\right)$$

# Properties of discrete-time Fourier Transform

## *Time shifting and frequency shifting*

$$x[n] \xleftrightarrow{\mathcal{F}} X(e^{j\omega}) \implies \begin{cases} x[n-n_0] \xleftrightarrow{\mathcal{F}} e^{-j\omega n_0}X(e^{j\omega}) \\ e^{j\omega_0 n}x[n] \xleftrightarrow{\mathcal{F}} X(e^{j(\omega-\omega_0)}) \end{cases}$$

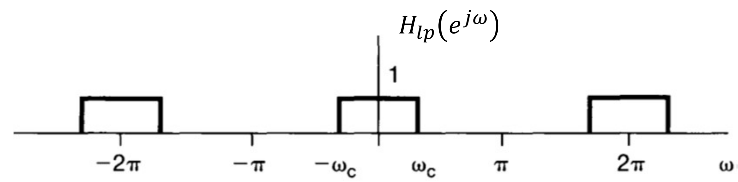
## *Examples*

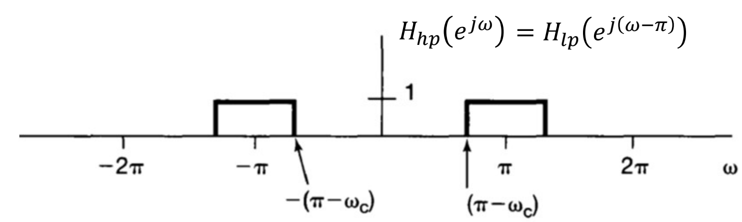
Low-pass filter $\implies$ High-pass filter

$$H_{lp}(e^{j\omega}) \quad \xRightarrow{\text{shift by } \pi} \quad H_{hp}(e^{j\omega}) = H_{lp}(e^{j(\omega-\pi)})$$

$$\Big\updownarrow \mathcal{F} \qquad\qquad\qquad \Big\updownarrow \mathcal{F}$$

$$h_{lp}[n] \qquad\qquad h_{hp} = e^{j\pi n}h_{lp}[n] = (-1)^n h_{lp}[n]$$



# Properties of discrete-time Fourier Transform

## ***Conjugation and Conjugate Symmetry***

- Conjugation property

$$x[n] \xleftrightarrow{\mathcal{F}} X(e^{j\omega}) \quad \Longrightarrow \quad x^*[n] \xleftrightarrow{\mathcal{F}} X^*(e^{-j\omega})$$

- Conjugation Symmetry

$$\boxed{X(e^{j\omega}) = X^*(e^{-j\omega}) \quad [x[n] \text{ real}]} \quad \Longrightarrow \quad \begin{cases} \mathcal{E}v\{x[n]\} \xleftrightarrow{\mathcal{F}} \mathcal{R}e\{X(e^{j\omega})\} \\ \mathcal{O}d\{x[n]\} \xleftrightarrow{\mathcal{F}} j\mathcal{I}m\{X(e^{j\omega})\} \end{cases}$$

$\mathcal{R}e\{X(e^{j\omega})\}$ is even, $\mathcal{I}m\{X(e^{j\omega})\}$ is odd.

# Properties of discrete-time Fourier Transform

***Time reversal***

$$x[n] \xleftrightarrow{\mathcal{F}} X\left(e^{j\omega}\right) \quad \Longrightarrow \quad x[-n] \xleftrightarrow{\mathcal{F}} X\left(e^{-j\omega}\right)$$

- $x[n]$ even, $X\left(e^{j\omega}\right)$ even; $x[n]$ odd, $X\left(e^{j\omega}\right)$ odd

  Recall: $x[n]$ real: $X\left(e^{j\omega}\right) = X^*\left(e^{-j\omega}\right)$

  $$\Downarrow$$

- $x[n]$ real and even $\Longrightarrow$ $X\left(e^{j\omega}\right)$ real and even

  $x[n]$ real and odd $\Longrightarrow$ $X\left(e^{j\omega}\right)$ odd and purely imaginary

# Properties of discrete-time Fourier Transform

***Time reversal***

$$x[n] \xleftrightarrow{\mathcal{F}} X(e^{j\omega}) \quad \Longrightarrow \quad x[-n] \xleftrightarrow{\mathcal{F}} X(e^{-j\omega})$$

- If $x[n]$ real

$$\left.\begin{aligned}\mathcal{F}\{x[n]\} &= \mathcal{F}\{\mathcal{E}v\{x[n]\}\} + \mathcal{F}\{\mathcal{O}d\{x[n]\}\} \\ &= \mathcal{R}e\{X(e^{j\omega})\} + j\mathcal{I}m\{X(e^{j\omega})\}\end{aligned}\right\} \Longrightarrow \left\{\begin{aligned}\mathcal{E}v\{x[n]\} &\xleftrightarrow{\mathcal{F}} \mathcal{R}e\{X(e^{j\omega})\} \\ \mathcal{O}d\{x[n]\} &\xleftrightarrow{\mathcal{F}} j\mathcal{I}m\{X(e^{j\omega})\}\end{aligned}\right.$$

# Properties of discrete-time Fourier Transform

***Differencing and accumulation***

- If $x[n] \overset{\mathcal{F}}{\longleftrightarrow} X(e^{j\omega})$

- Then

$$x[n] - x[n-1] \overset{\mathcal{F}}{\longleftrightarrow} (1 - e^{-j}\quad)X(e^{j\omega})$$

$$\sum_{m=-\infty}^{n} x[m] \overset{\mathcal{F}}{\longleftrightarrow} \frac{1}{1 - e^{-j\omega}} X(e^{j\omega}) + \underbrace{\pi X(e^{j0}) \sum_{k=-\infty}^{+\infty} \delta(\omega - 2\pi k)}_{\text{DC component}}$$

# Properties of discrete-time Fourier Transform

***Differencing and accumulation***

- Examples  Determine FT of unit sept $x[n] = u[n]$

Solution

$$g[n] = \delta[n] \xleftrightarrow{\mathcal{F}} G(e^{j\omega}) = 1 \qquad x[n] = \sum_{m=-\infty}^{n} g[m]$$

$$X(e^{j\omega}) = \frac{1}{1-e^{-j\omega}} G(e^{j\omega}) + \pi G(e^{j0}) \sum_{k=-\infty}^{+\infty} \delta(\omega - 2\pi k)$$

$$= \frac{1}{1-e^{-j}} + \pi \sum_{k=-\infty}^{+\infty} \delta(\omega - 2\pi k)$$

# Properties of discrete-time Fourier Transform

## *Time expansion*

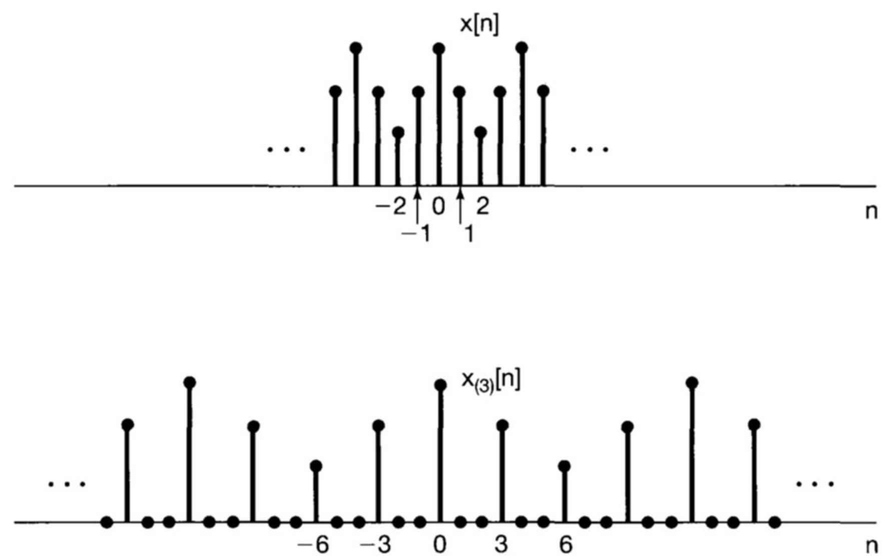
- Recall the continuous time property

$$x(at) \overset{\mathcal{F}}{\longleftrightarrow} \frac{1}{|a|} X\left(\frac{j\omega}{a}\right)$$

- Try to define $x[an]$
  - $a$ should be an integer and $a > 1$
  - not merely speed up, but also resample $x[n]$

- Define instead

$$x_{(k)}[n] = \begin{cases} x[n/k], & \text{if } n \text{ is a multiple of } k \\ 0, & \text{if } n \text{ is not a multiple of } k \end{cases}$$



# Properties of discrete-time Fourier Transform

## *Time expansion*

$$x_{(k)}[n] = \begin{cases} x[n/k], & \text{if } n \text{ is a multiple of } k \\ 0, & \text{if } n \text{ is not a multiple of } k \end{cases}$$

$$x[n] \overset{\mathcal{F}}{\longleftrightarrow} X(e^{j\omega})$$

$$x_{(k)}[n] \overset{\mathcal{F}}{\longleftrightarrow} X_{(k)}(e^{j\omega}) = X(e^{jk\omega})$$

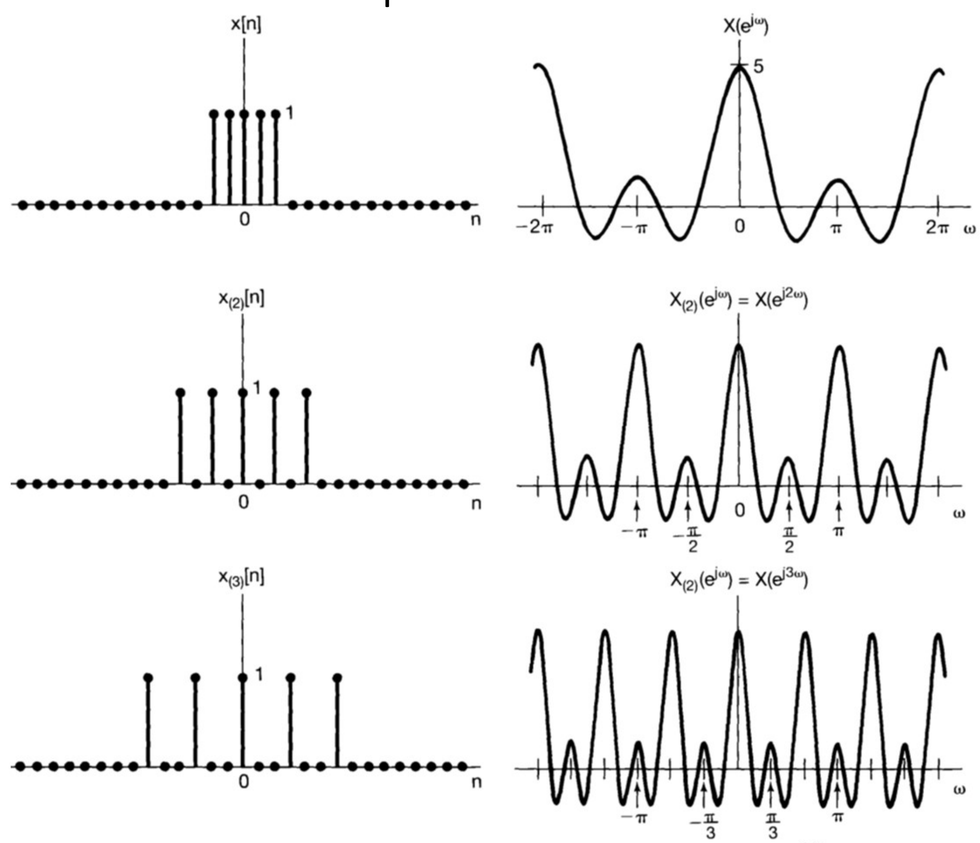
$$X_{(k)}(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x_{(k)}[n] e^{-j\omega n}$$

$n = rk$

$$= \sum_{r=-\infty}^{+\infty} x_{(k)}[rk] e^{-j\omega r}$$

$x_{(k)}[rk] = x[r]$

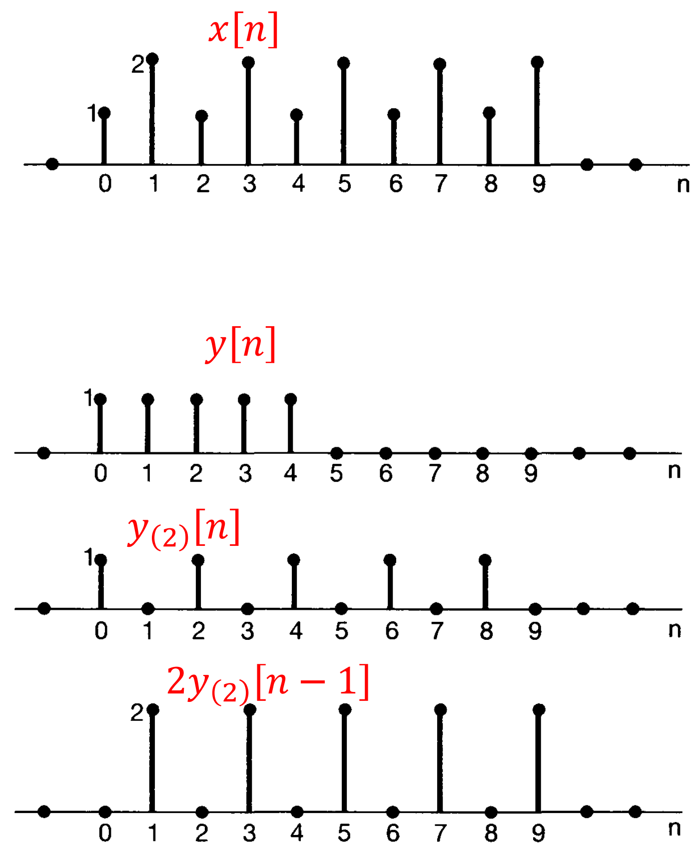
$$X_{(k)}(e^{j\omega}) = \sum_{r=-\infty}^{+\infty} x[r] e^{-j(k\omega)r} = X(e^{jk\omega})$$



# Properties of discrete-time Fourier Transform

***Examples***

$$X(e^{j\omega}) = ?$$




## Solution

$$x[n] = y_{(2)}[n] + 2y_{(2)}[n-1]$$

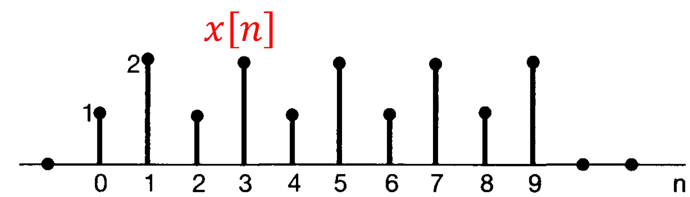
where $y[n] = \begin{cases} 1, 0 \le n \le 5 \\ 0, \quad\quad \text{else} \end{cases}$

$$y_2[n] = \begin{cases} y[n/2], n \text{ is even} \\ 0, \quad\quad n \text{ is odd} \end{cases}$$

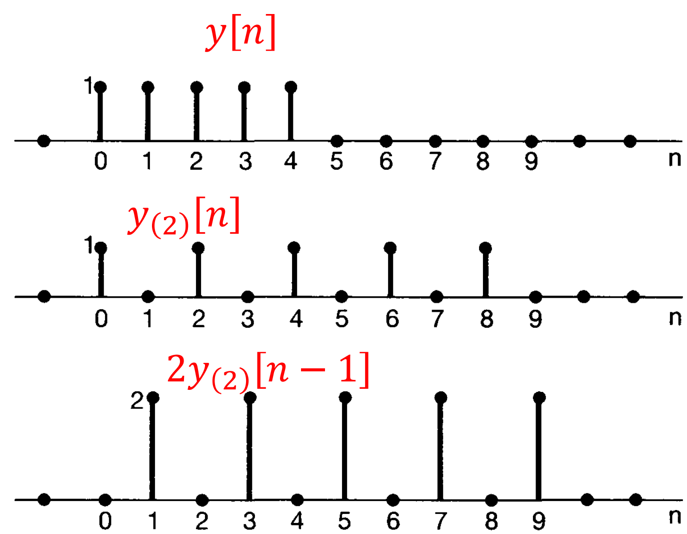
# Properties of discrete-time Fourier Transform

***Examples***

$$X(e^{j\omega}) = ?$$




$$x[n] = y_{(2)}[n] + 2y_{(2)}[n-1]$$




Solution

$$Y(e^{j\omega}) = e^{-j2\omega}\frac{\sin(5\omega/2)}{\sin(\omega/2)}$$

- Using the time expansion property

$$y_{(2)}[n] \stackrel{\mathcal{F}}{\longleftrightarrow} Y_2(e^{j\omega}) = Y(e^{j2\omega}) = e^{-j4\omega}\frac{\sin(5\omega)}{\sin(\omega)}$$

- Using the linearity and time-shifting properties

$$2y_{(2)}[n-1] \stackrel{\mathcal{F}}{\longleftrightarrow} 2e^{-j5\omega}\frac{\sin(5\omega)}{\sin(\omega)}$$

$$X(e^{j\omega}) = e^{-j4\omega}(1+2e^{-j\omega})\left(\frac{\sin(5\omega)}{\sin(\omega)}\right)$$

# Properties of discrete-time Fourier Transform

## *Differentiation in frequency*

$$nx[n] \overset{\mathcal{F}}{\longleftrightarrow} j\frac{dX(e^{j\omega})}{d\omega}$$

- Consider

$$x[n] \overset{\mathcal{F}}{\longleftrightarrow} X(e^{j\omega})$$

$$\frac{dX(e^{j\omega})}{d\omega} = \sum_{n=-\infty}^{+\infty} \boxed{-jnx[n]} e^{-j\omega n} \quad \Longrightarrow \quad -jnx[n] \overset{\mathcal{F}}{\longleftrightarrow} \frac{dX(e^{j\omega})}{d\omega}$$

$$\Longrightarrow \quad nx[n] \overset{\mathcal{F}}{\longleftrightarrow} j\frac{dX(e^{j\omega})}{d\omega}$$

## *Parseval's relation*

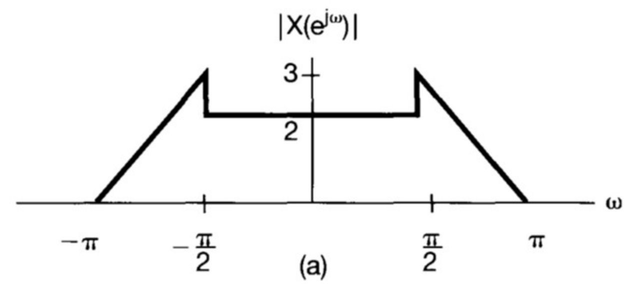
$$\sum_{n=-\infty}^{+\infty} |x[n]|^2 = \frac{1}{2\pi}\int_{2\pi} \left|X(e^{j\omega})\right|^2 d\omega$$

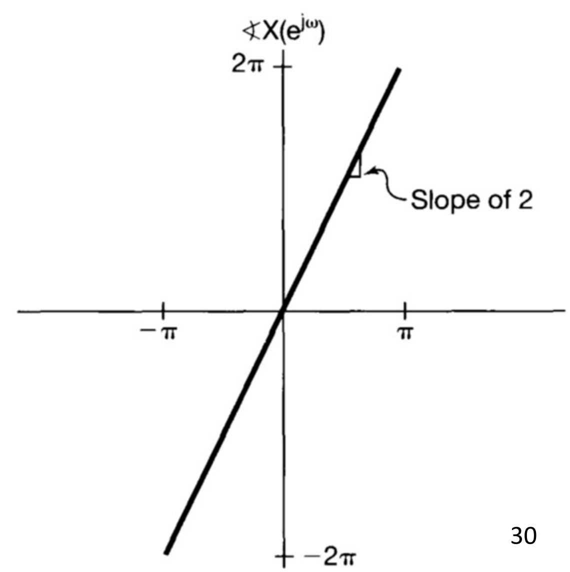
# Properties of discrete-time Fourier Transform

***Examples***

$$x[n] \overset{\mathcal{F}}{\longleftrightarrow} X(e^{j\omega})$$

- ❑ $x[n]$ is
  - Periodic?
    No
  - Real?
    Yes
  - Even?
    No
  - Of finite energy?
    Yes



# The Discrete-Time Fourier Transform (ch.5)

- ❑ Representation of aperiodic signals- Discrete Fourier transform
- ❑ Fourier transform for periodic signals
- ❑ Properties of discrete-time Fourier transform
- ❑ The convolution property
- ❑ The multiplication property
- ❑ Duality
- ❑ Systems characterized by difference equations

# The convolution property

$$x[n] \longrightarrow \boxed{h[n]} \longrightarrow y[n]$$

$$y[n] = x[n] * h[n] \stackrel{\mathcal{F}}{\longleftrightarrow} Y(e^{j\omega}) = X(e^{j\omega})H(e^{j\omega})$$

- $H(j\omega)$: Frequency response; FT of the impulse response of the system

# The convolution property

***Examples***

$$x[n] \longrightarrow \boxed{h[n]} \longrightarrow y[n]$$

$h[n] = \delta[n - n_0]$ and $X(e^{j\omega}) = \mathcal{F}\{x[n]\}$ $\qquad Y(e^{j\omega}) = ?$

Solution

$$h[n] = \delta[n - n_0]$$

$$H(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} \delta[n - n_0] e^{-j\omega n}$$

$$= e^{-j\omega n_0}$$

$$y[n] = x[n - n_0]$$

$$Y(e^{j\omega}) = e^{-j\omega n_0} X(e^{j\omega})$$

# The convolution property

***Examples***

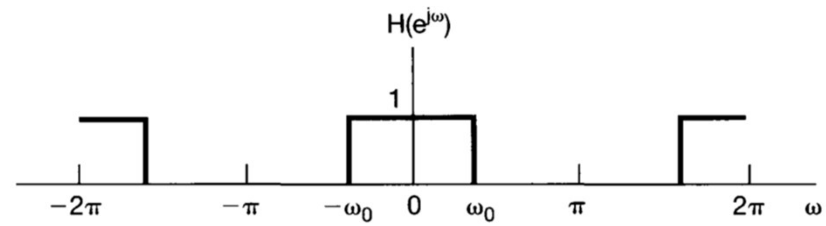
Determine the impulse response of an ideal low-pass filter

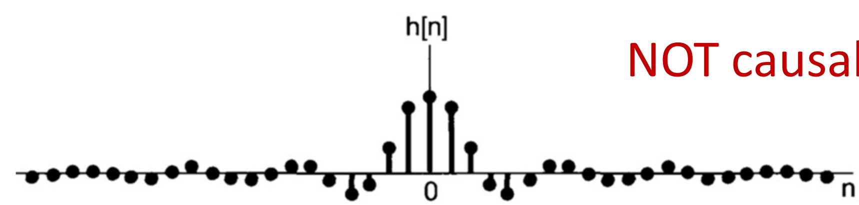
## Solution

$$h[n] = \frac{1}{2\pi}\int_{-\pi}^{\pi} H\left(e^{j\omega}\right)e^{j\omega}\ \ d\omega$$

$$= \frac{1}{2\pi}\int_{-\omega_0}^{\omega_0} e^{j\omega n} d\omega$$

$$= \frac{\sin \omega_0 n}{\pi n}$$




NOT causal

# The convolution property

***Examples***

$$x[n] \longrightarrow \boxed{h[n]} \longrightarrow y[n]$$

$$h[n] = \alpha^n u[n], (|\alpha| < 1) \quad x[n] = \beta^n u[n], (|\beta| < 1) \quad y[n] = ?$$

## Solution

$$H(e^{j\omega}) = \frac{1}{1 - \alpha e^{-j\omega}} \qquad X(e^{j\omega}) = \frac{1}{1 - \beta e^{-j\omega}} \qquad Y(e^{j\omega}) = \frac{1}{(1 - \alpha e^{-j\omega})(1 - \beta e^{-j\omega})}$$

When $\alpha \neq \beta$

$$Y(e^{j\omega}) = \frac{A}{1 - \alpha e^{-j\omega}} - \frac{B}{1 - \beta e^{-j\omega}} \qquad A = \frac{\alpha}{\alpha - \beta} \qquad B = \frac{\beta}{\alpha - \beta}$$

$$y[n] = \frac{\alpha}{\alpha - \beta}\alpha^n u[n] - \frac{\beta}{\alpha - \beta}\beta^n u[n] = \frac{1}{\alpha - \beta}(\alpha^{n+1}u[n] - \beta^{n+1}u[n])$$

# The convolution property

***Examples***

$$x[n] \longrightarrow \boxed{h[n]} \longrightarrow y[n]$$

$$h[n] = \alpha^n u[n], (|\alpha| < 1) \quad x[n] = \beta^n u[n], (|\beta| < 1) \quad y[n] = ?$$

Solution

$$H(e^{j\omega}) = \frac{1}{1 - \alpha e^{-j\omega}} \qquad X(e^{j\omega}) = \frac{1}{1 - \beta e^{-j\omega}} \qquad Y(e^{j\omega}) = \frac{1}{(1 - \alpha e^{-j\omega})(1 - \beta e^{-j\omega})}$$

When $\alpha = \beta$

$$Y(e^{j\omega}) = \frac{1}{(1 - \alpha e^{-j\omega})^2} = \frac{j}{\alpha} e^{j\omega} \frac{d}{d\omega}\left(\frac{1}{1 - \alpha e^{-j}}\right)$$

$$y[n] = (n+1)\alpha^n u[n+1] = (n+1)\alpha^n u[n]$$

# The convolution property

## ***Examples***

Consider the ideal band-stop filter, $Y(e^{j\omega}) = ?$

$$w_1[n] = e^{j\pi n}x[n]$$

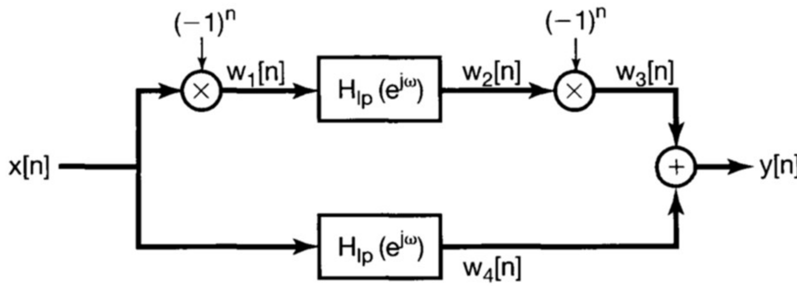
$$W_1(e^{j\omega}) = X(e^{j(\omega-\pi)})$$

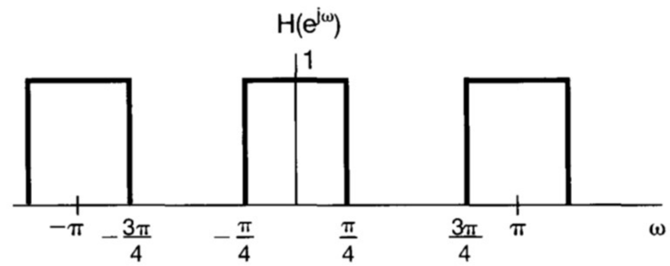
$$W_2(e^{j\omega}) = H_{lp}(e^{j\omega})X(e^{j(\omega-\pi)})$$

$$\begin{aligned} W_3(e^{j\omega}) &= W_2(e^{j(\omega-\pi)}) \\ &= H_{lp}(e^{j(\omega-\pi)})X(e^{j(\omega-2\pi)}) \\ &= H_{lp}(e^{j(\omega-\pi)})X(e^{j\omega}) \end{aligned}$$

$$W_4(e^{j\omega}) = H_{lp}(e^{j\omega})X(e^{j\omega})$$

$$Y(e^{j\omega}) = W_3(e^{j\omega}) + W_4(e^{j\omega}) = [H_{lp}(e^{j(\omega-\pi)}) + H_{lp}(e^{j\omega})]X(e^{j\omega})$$



# The Discrete-Time Fourier Transform (ch.5)

- ❑ Representation of aperiodic signals- Discrete Fourier transform
- ❑ Fourier transform for periodic signals
- ❑ Properties of discrete-time Fourier transform
- ❑ The convolution property
- ❑ The multiplication property
- ❑ Duality
- ❑ Systems characterized by difference equations

# The multiplication property

$$y[n] = x_1[n]x_2[n] \xleftrightarrow{\mathcal{F}} Y(e^{j\omega}) = \underbrace{\frac{1}{2\pi}\int_{2\pi} X_1(e^{j\theta})X_2(e^{j(\omega-\theta)})d\theta}_{\text{Periodic convolution}}$$

## Proof

$$Y(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} y[n]e^{-j\omega n} = \sum_{n=-\infty}^{+\infty} x_1[n]x_2[n]e^{-j\omega n}$$

$$x_1[n] = \frac{1}{2\pi}\int_{2\pi} X_1(e^{j\theta})e^{j\theta n}d\theta$$

$$Y(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x_2[n]\left\{\frac{1}{2\pi}\int_{2\pi} X_1(e^{j\theta})e^{j\theta n}d\theta\right\}e^{-j\omega n}$$

$$Y(e^{j\omega}) = \frac{1}{2\pi}\int_{2\pi} X_1(e^{j\theta})\left[\sum_{n=-\infty}^{+\infty} x_2[n]e^{-j(\omega-\theta)n}\right]d\theta$$

$$Y(e^{j\omega}) = \frac{1}{2\pi}\int_{2\pi} X_1(e^{j\theta})X_2(e^{j(\omega-\theta)})d\theta$$

# The multiplication property

***Examples***

$$x_1[n] = \frac{\sin(\pi n/2)}{\pi n} \qquad x_2[n] = \frac{\sin(3\pi n/4)}{\pi n}$$

$$x[n] = x_1[n]x_2[n] \qquad X(e^{j\omega}) = ?$$

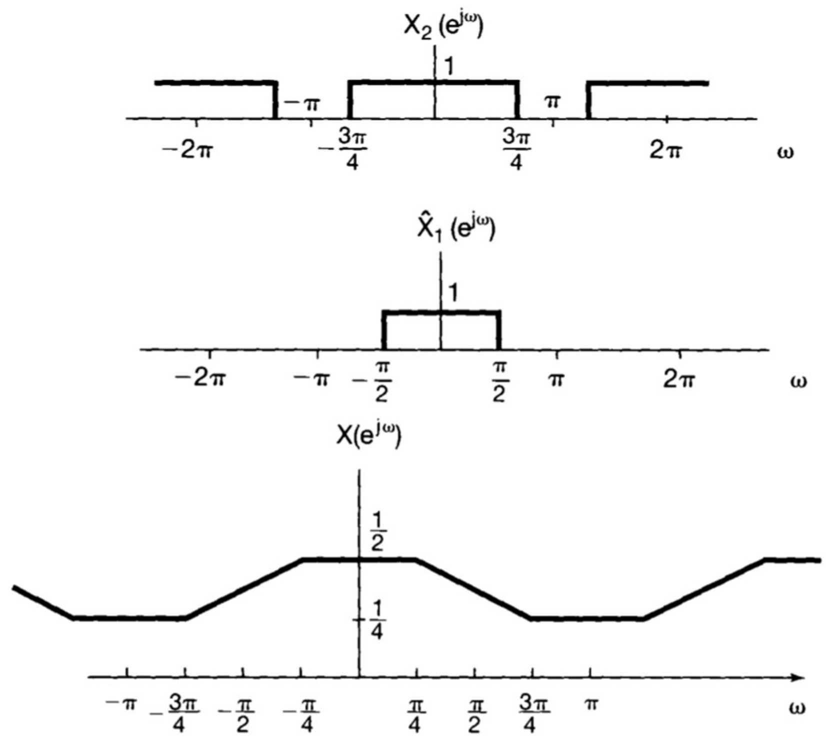
Solution

$$X(e^{j\omega}) = \frac{1}{2\pi}\int_{-\pi}^{\pi} X_1(e^{j\omega})X_2(e^{j(\omega-\theta)})d\theta$$

- Convert to ordinary convolution

Define $\hat{X}_1(e^{j\omega}) = \begin{cases} X_1(e^{j\omega}), & -\pi < \omega < \pi \\ 0, & \text{otherwise} \end{cases}$

$$X(e^{j\omega}) = \frac{1}{2\pi}\int_{-\pi}^{\pi} \hat{X}_1(e^{j\theta})X_2(e^{j(\omega-\theta)})d\theta = \frac{1}{2\pi}\int_{-\infty}^{\infty} \hat{X}_1(e^{j\theta})X_2(e^{j(\omega-\theta)})d\theta$$



# The Discrete-Time Fourier Transform (ch.5)

- Representation of aperiodic signals- Discrete Fourier transform
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- Systems characterized by difference equations

# Duality

## ***Duality in the discrete FS***

Consider $f[m] = \frac{1}{N} \sum_{r=\langle N \rangle} g[r] e^{-jr(2\pi/N)m}$    $f[m]$ and $g[r]$ are periodic

$m = k, r = n$    $m = n, r = -k$

$$f[k] = \frac{1}{N} \sum_{n=\langle N \rangle} g[n] e^{-jk(2\pi/N)n} \qquad f[n] = \frac{1}{N} \sum_{k=\langle N \rangle} g[-k] e^{jk(2\pi/N)n}$$

$$\Downarrow \qquad\qquad \Downarrow$$

$$\boxed{\mathrm{g}[n] \xrightarrow{\mathcal{FS}} f[k] \qquad\qquad f[n] \xrightarrow{\mathcal{FS}} \frac{1}{N} g[-k]}$$

Every property of the discrete FS has a dual.

- Examples

$$\begin{cases} x[n-n_0] \overset{\mathcal{FS}}{\longleftrightarrow} a_k e^{-jk(2\pi/N)n_0} \\ e^{jm(2\pi/N)n} x[n] \overset{\mathcal{FS}}{\longleftrightarrow} a_{k-m} \end{cases}$$

$$\begin{cases} \sum_{r=\langle N \rangle} x[r] y[n-r] \overset{\mathcal{FS}}{\longleftrightarrow} N a_k b_k \\ x[n] y[n] \overset{\mathcal{FS}}{\longleftrightarrow} \sum_{l=\langle N \rangle} a_l b_{k-l} \end{cases}$$

# Duality

***Examples***

$$x[n] = \begin{cases} \dfrac{1}{9}\dfrac{\sin(5\pi n/9)}{\sin(\pi n/9)}, & n \neq \text{multiple of } 9 \\ 5/9, & n = \text{multiple of } 9 \end{cases}$$

$a_k = ?$

①Dual in the frequency domain: $n \to k$

$$b_k = \begin{cases} \dfrac{1}{9}\dfrac{\sin(5\pi k/9)}{\sin(\pi k/9)}, & k \neq \text{multiple of } 9 \\ 5/9, & k = \text{multiple of } 9 \end{cases}$$

②Time domain signal

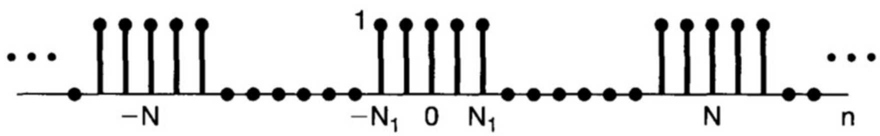
$$g[n] \xleftrightarrow{\mathcal{FS}} b_k$$

# Duality

## *Examples*

$$x[n] = \begin{cases} \dfrac{1}{9}\dfrac{\sin(5\pi n/9)}{\sin(\pi n/9)}, & n \neq \text{multiple of } 9 \\ 5/9, & n = \text{multiple of } 9 \end{cases}$$

$$a_k = ?$$




$$\Big\updownarrow \mathcal{FS}$$

$$\begin{cases} \dfrac{1}{N}\dfrac{\sin[2\pi k(N_1 + 1/2)/N]}{\sin(\pi k/N)}, & k \neq 0, \pm N, \pm 2N, \cdots \\ (2N_1 + 1)/N, & k = 0, \pm N, \pm 2N, \cdots \end{cases}$$

# Duality

***Examples***

$$x[n] = \begin{cases} \dfrac{1}{9}\dfrac{\sin(5\pi n/9)}{\sin(\pi n/9)}, & n \neq \text{multiple of } 9 \\ 5/9, & n = \text{multiple of } 9 \end{cases}$$

$$\boldsymbol{a_k} = \frac{1}{N} g[-k] = \begin{cases} 1/9, & |k| \leq 2 \\ 0, & 2 < |k| \leq 4 \end{cases}$$

③Duality

①Dual in the frequency domain: $n \rightarrow k$

$$b_k = \begin{cases} \dfrac{1}{9}\dfrac{\sin(5\pi k/9)}{\sin(\pi k/9)}, & k \neq \text{multiple of } 9 \\ 5/9, & k = \text{multiple of } 9 \end{cases}$$

②Time domain signal

$$g[n] = \begin{cases} 1, & |n| \leq 2 \\ 0, & 2 < |n| \leq 4 \end{cases}$$

$$g[n] \overset{\mathcal{FS}}{\longleftrightarrow} b_k$$

g[$n$] is periodic (N = 9)

# Duality

***Duality between discrete FT and continuous FS***

$$x[n] = \frac{1}{2\pi}\int_{2\pi} X(e^{j\omega})e^{j\omega n}d\omega$$

$$x(t) = \sum_{k=-\infty}^{+\infty} a_k e^{jk\omega_0 t}$$

$$X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x[n]e^{-j\omega n}$$

$$a_k = \frac{1}{T}\int_T x(t)e^{-jk\omega_0 t}dt$$

Discrete FT

Continuous FS

# Properties of discrete-time Fourier Transform

***Examples*** $x[n] = \dfrac{\sin(\pi n/2)}{\pi n}$ $\quad X(e^{j\omega}) = ?$

③Duality: $\frac{1}{N} g[-k]$? NO!

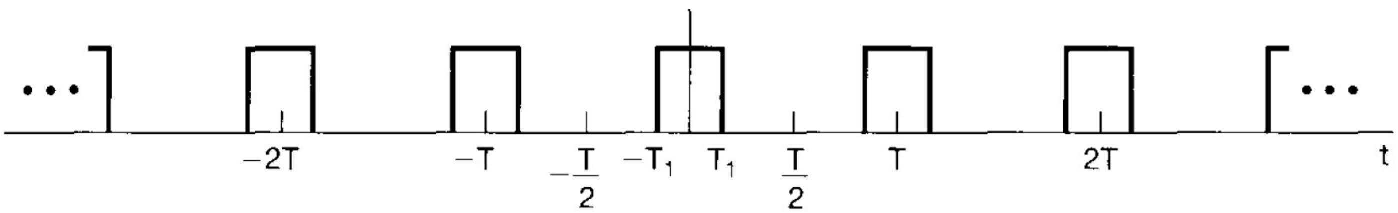
①Frequency domain: $n \to k$ (CT FS)

Solution

$$g(t) = \begin{cases} 1, & |t| \le T_1 \\ 0, & T_1 < |t| \le T \end{cases} \qquad a_k = \frac{\sin(k\pi/2)}{k\pi}$$

②CT signal

$$g(t) \xleftrightarrow{\mathcal{FS}} a_k$$




$$g(t) = \begin{cases} 1, & |t| \le T_1 \\ 0, & T_1 < |t| \le T \end{cases} \xleftrightarrow{\mathcal{FS}} a_k = \frac{\sin(k\omega_0 T_1)}{k\pi}, k \neq 0$$

$$\omega_0 T_1 = \pi/2 \Rightarrow T_1 = T/4$$

# Properties of discrete-time Fourier Transform

***Examples*** $x[n] = \dfrac{\sin(\pi n/2)}{\pi n}$ $X(e^{j\omega}) = ?$

Solution

①Frequency domain: $n \to k$ (CT FS)

$$a_k = \frac{\sin(k\pi/2)}{k\pi}$$

②CT signal

$$g(t) = \begin{cases} 1, & |t| \le T_1 \\ 0, & T_1 < |t| \le T \end{cases}$$

$$\frac{\sin(\pi k/2)}{\pi k} = \frac{1}{2\pi}\int_T g(t)e^{-jkt}dt = \frac{1}{2\pi}\int_{-T_1}^{T_1}(1)e^{-jkt}dt$$

$n = k, t = \omega, T_1 = T/4$

$$\frac{\sin(\pi n/2)}{\pi n} = \frac{1}{2\pi}\int_{-\pi/2}^{\pi/2}(1)e^{-jn\omega}d\omega$$

$$\frac{\sin(\pi n/2)}{\pi n} = \frac{1}{2\pi}\int_{-\pi/2}^{\pi/2}(1)e^{jn\omega}d\omega$$

$$\boxed{\therefore\ X(e^{j\omega}) = \begin{cases} 1, & |\omega| \le \pi/2 \\ 0, & \pi/2 < |\omega| \le \pi \end{cases}}$$

# Duality

## Summary FS and FT expressions

| | Continuous time | | Discrete time | |
|---|---|---|---|---|
| | **Time domain** | **Frequency domain** | **Time domain** | **Frequency domain** |
| Fourier Series | $x(t) = \sum_{k=-\infty}^{+\infty} a_k e^{jk\omega_0 t}$<br>continuous time<br>periodic in time | $a_k = \frac{1}{T_0}\int_{T_0} x(t)e^{-jk\omega_0 t}$<br>discrete frequency<br>aperiodic in frequency | $x[n] = \sum_{k=\langle N\rangle} a_k e^{jk(2\pi/N)n}$<br>discrete time<br>periodic in time | $a_k = \frac{1}{N}\sum_{k=\langle N\rangle} x[n]e^{-jk(2\pi/N)n}$<br>discrete frequency<br>periodic in frequency |
| Fourier Transform | $x(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} X(j\omega)e^{j\omega t}d\omega$<br>continuous time<br>aperiodic in time | $X(j\omega) = \int_{-\infty}^{+\infty} x(t)e^{-j\omega t}dt$<br>continuous frequency<br>aperiodic in frequency | $x[n] = \frac{1}{2\pi}\int_{2\pi} X(e^{j\omega})e^{j\omega n}$<br>discrete time<br>aperiodic in time | $X(e^{j\omega}) = \sum_{n=-\infty}^{+\infty} x[n]e^{-j\omega n}$<br>continuous frequency<br>periodic in frequency |

duality

duality

duality

# The Discrete-Time Fourier Transform (ch.5)

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- ❑ Systems characterized by difference equations

# System characterized by difference equations

$$\sum_{k=0}^{N} a_k y[n-k] = \sum_{k=0}^{M} b_k x[n-k]$$

$$\sum_{k=0}^{N} a_k e^{-jk\omega} Y\left(e^{j\omega}\right) = \sum_{k=0}^{M} b_k e^{-jk\omega} X\left(e^{j\omega}\right)$$

$$H\left(e^{j\omega}\right) = \frac{Y\left(e^{j\omega}\right)}{X\left(e^{j\omega}\right)} = \frac{\sum_{k=0}^{M} b_k e^{-jk\omega}}{\sum_{k=0}^{N} a_k e^{-jk\omega}}$$

# System characterized by difference equations

***Examples***

$$y[n] - ay[n-1] = x[n], |a| < 1 \qquad h[n] = ?$$

Solution

$$H(e^{j\omega}) = \frac{1}{1 - ae^{-j}}$$

$$h[n] = a^n u[n]$$

# System characterized by difference equations

***Examples***

$$y[n]-\frac{3}{4}y[n-1]+\frac{1}{8}y[n-2]=2x[n] \qquad h[n]=?$$

Solution

$$H\left(e^{j\omega}\right)=\frac{2}{1-\frac{3}{4}e^{-j\omega}+\frac{1}{8}e^{-j2\omega}}=\frac{2}{\left(1-\frac{1}{2}e^{-j\omega}\right)\left(1-\frac{1}{4}e^{-j\omega}\right)}$$

$$=\frac{4}{\left(1-\frac{1}{2}e^{-j}\quad\right)}-\frac{2}{\left(1-\frac{1}{4}e^{-j}\quad\right)}$$

$$h[n]=4\left(\frac{1}{2}\right)^{n}u[n]-2\left(\frac{1}{4}\right)^{n}u[n]$$

# System characterized by difference equations

***Examples***

$$y[n]-\frac{3}{4}y[n-1]+\frac{1}{8}y[n-2]=2x[n] \qquad x[n]=\left(\frac{1}{4}\right)^n u[n] \qquad y[n]=?$$

Solution

$$Y(e^{j\omega})=H(e^{j\omega})X(e^{j\omega})=\left[\frac{2}{\left(1-\frac{1}{2}e^{-j}\quad\right)\left(1-\frac{1}{4}e^{-j\omega}\right)}\right]\left[\frac{1}{1-\frac{1}{4}e^{-j\omega}}\right]$$

$$=\frac{2}{\left(1-\frac{1}{2}e^{-j\omega}\right)\left(1-\frac{1}{4}e^{-j\omega}\right)^2}=-\frac{4}{1-\frac{1}{4}e^{-j\omega}}-\frac{2}{\left(1-\frac{1}{4}e^{-j\omega}\right)^2}+\frac{8}{\left(1-\frac{1}{2}e^{-j\omega}\right)}$$

$$y[n]=\left\{-4\left(\frac{1}{4}\right)^n-2(n+1)\left(\frac{1}{4}\right)^n+8\left(\frac{1}{2}\right)^{\mathrm{n}}\right\}u[n]$$