Spring 2013

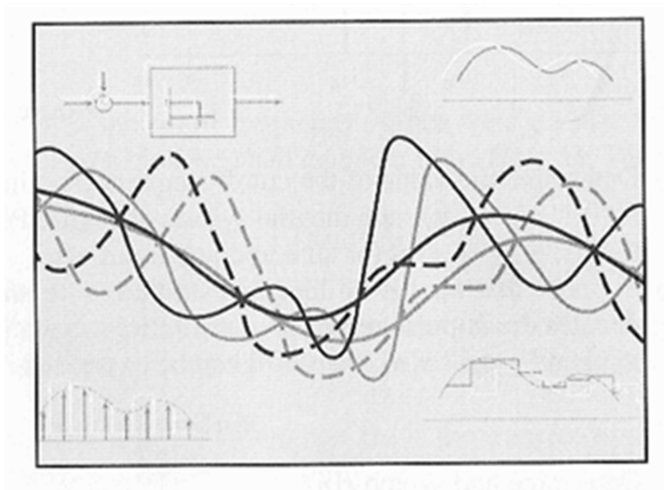
信號與系統
Signals and Systems

Chapter SS-7
Sampling

Feng-Li Lian

NTU-EE

Feb13 – Jun13



Figures and images used in these lecture notes are adopted from
"Signals & Systems" by Alan V. Oppenheim and Alan S. Willsky, 1997

Flowchart

Introduction (Chap 1)

LTI & Convolution (Chap 2)

Bounded/Convergent

Periodic

FS CT DT (Chap 3)

Aperiodic

FT CT (Chap 4) DT (Chap 5)

Unbounded/Non-convergent

LT CT (Chap 9)

zT DT (Chap 10)

Time-Frequency (Chap 6)

CT-DT (Chap 7)

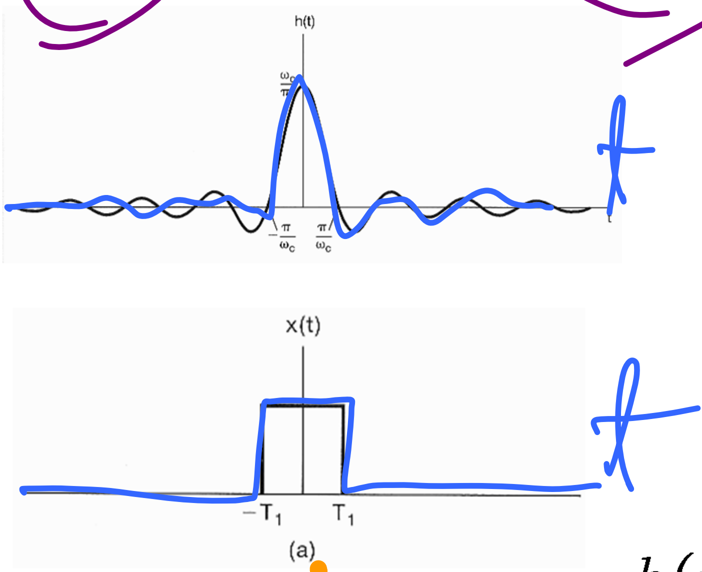
Communication (Chap 8)

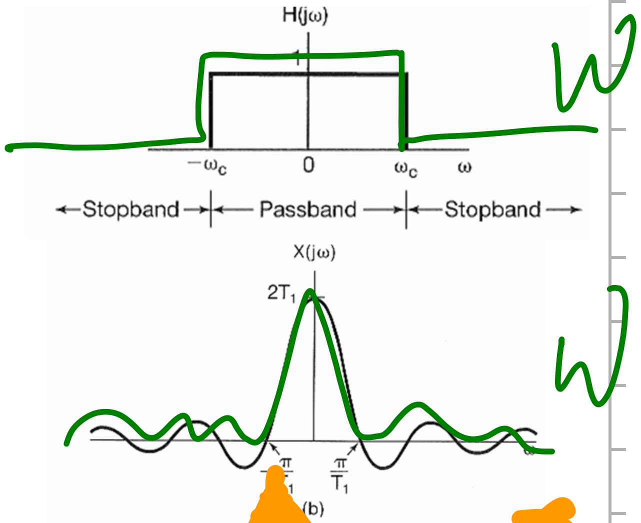
Control (Chap 11)

Digital Signal Processing (dsp-8)

- Time-Domain & Frequency-Domain Characterization:

CT

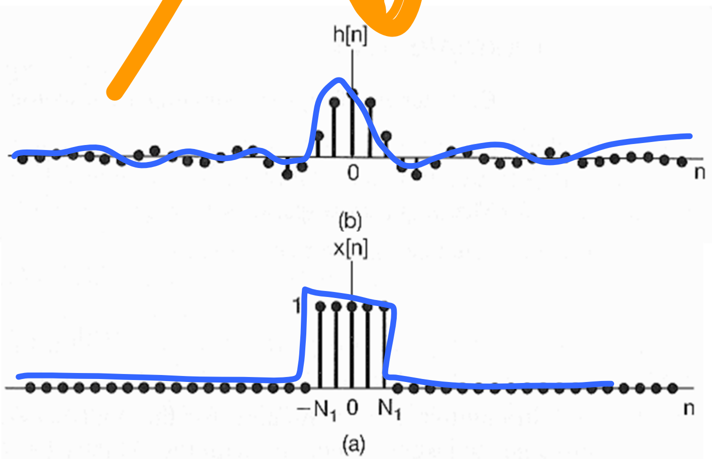


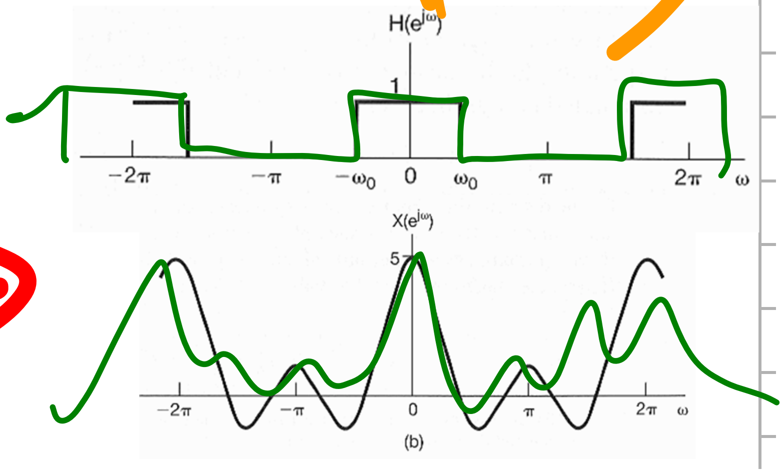


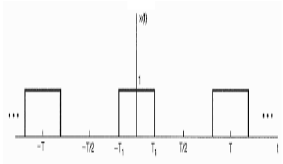
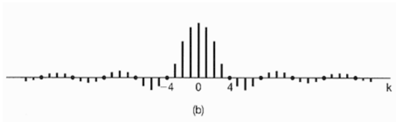
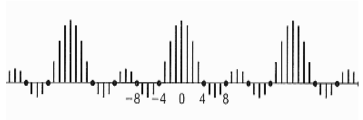
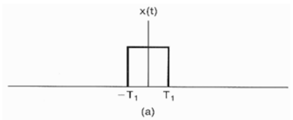
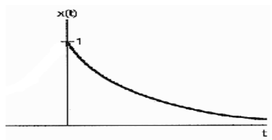
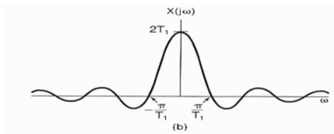
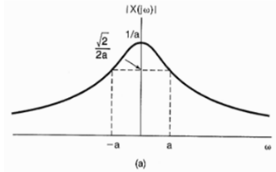
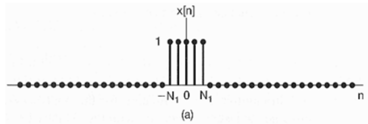
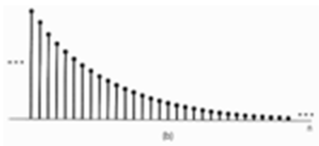
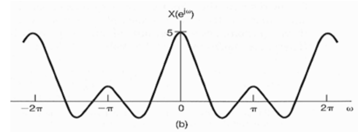
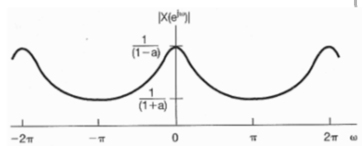
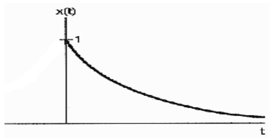
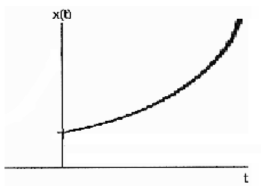
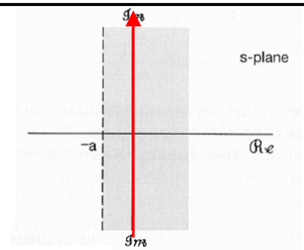
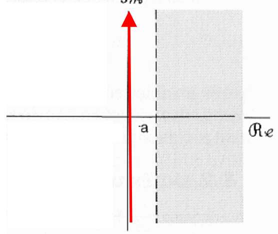
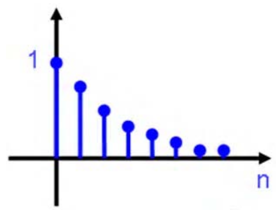
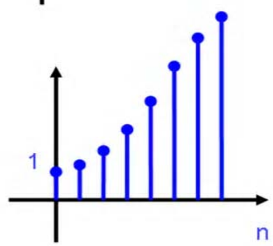
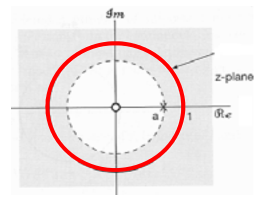
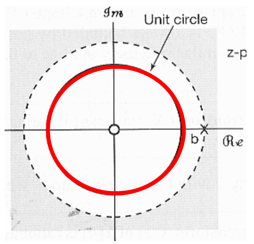
$$h(t) \overset{\mathcal{F}}{\longleftrightarrow} H(jw)$$

$$h[n] \overset{\mathcal{F}}{\longleftrightarrow} H(e^{jw})$$

DT



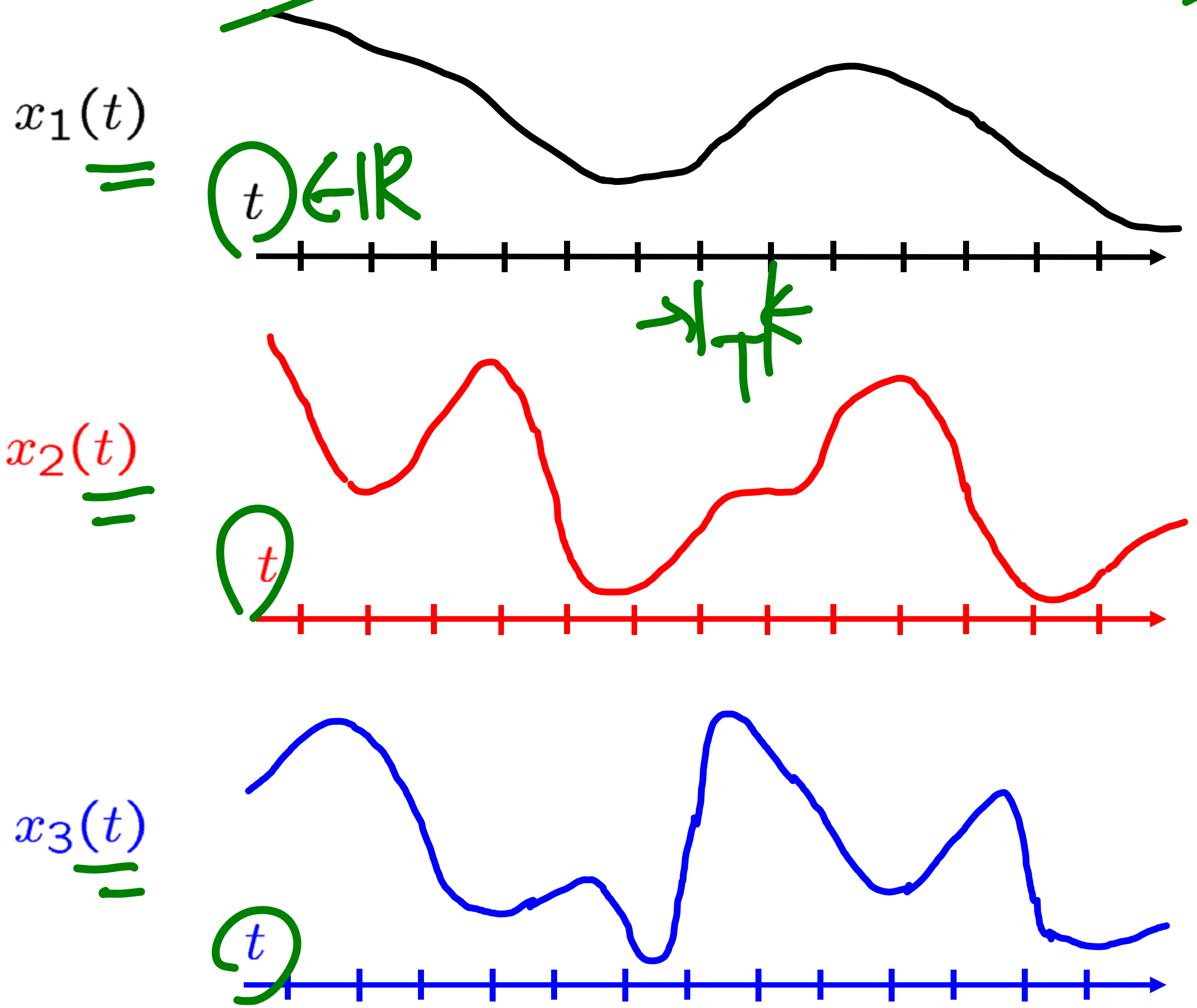


	CT time	CT frequency	DT time	DT frequency
FS				
FT	 	 	 	 
LT/zT	 	 	 	 

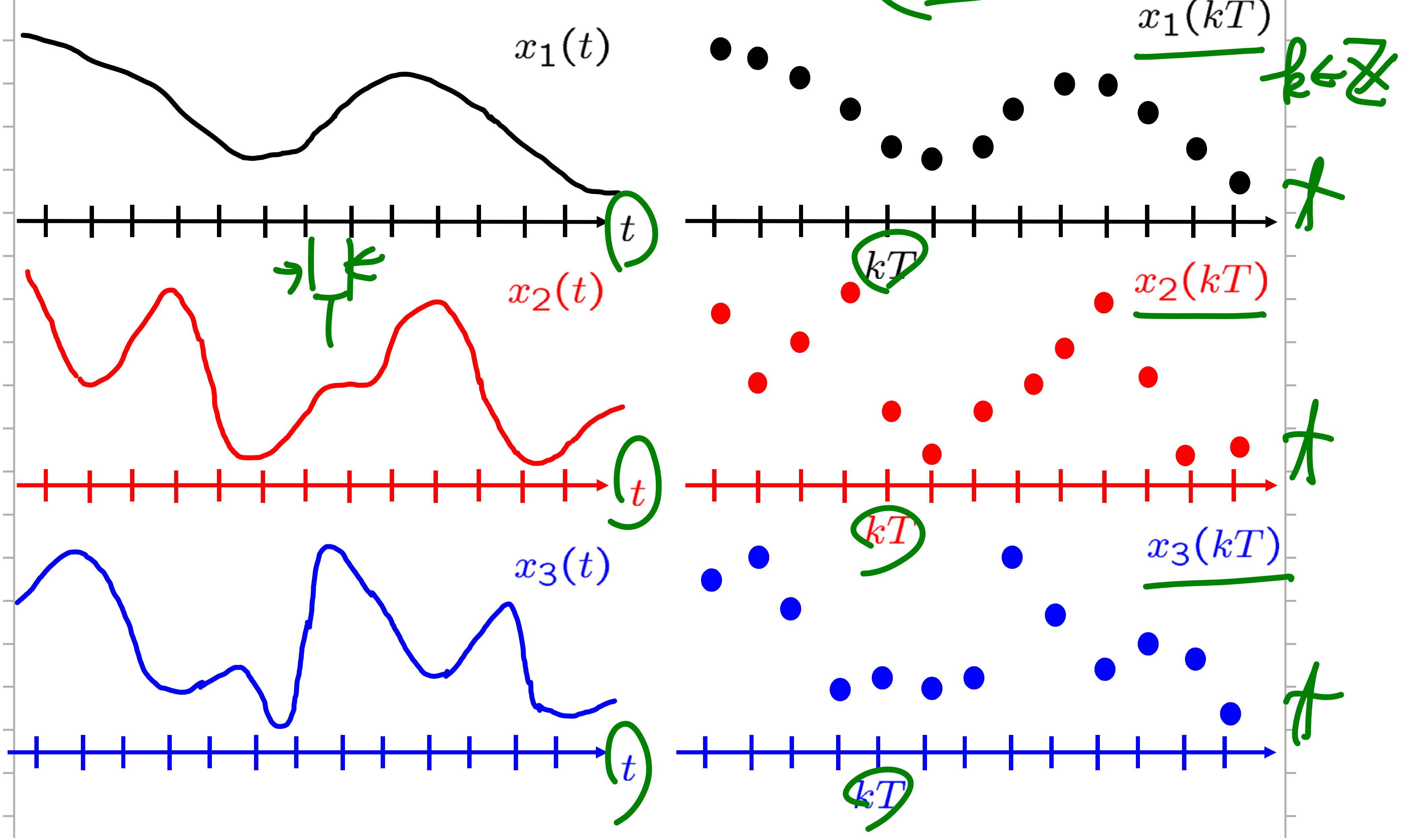
- Representation of a Continuous-Time Signal by its Samples: The Sampling Theorem
- Reconstruction of a Signal from its Samples Using Interpolation
- The Effect of Under-sampling: Aliasing
- Discrete-Time Processing of Continuous-Time Signals
- Sampling of Discrete-Time Signals

C.T.

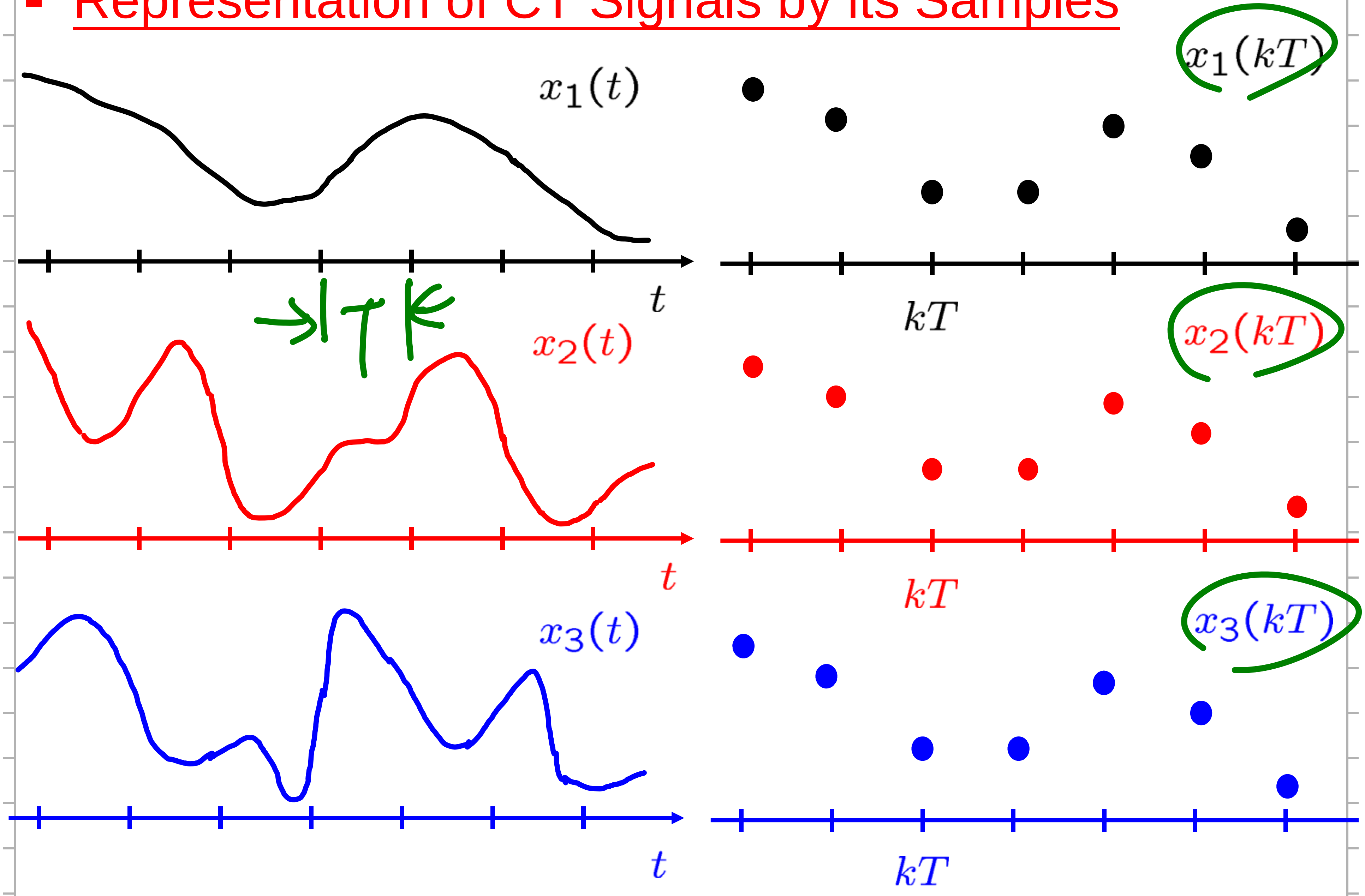
- Representation of CT Signals by Its Samples



- Representation of CT Signals by its Samples

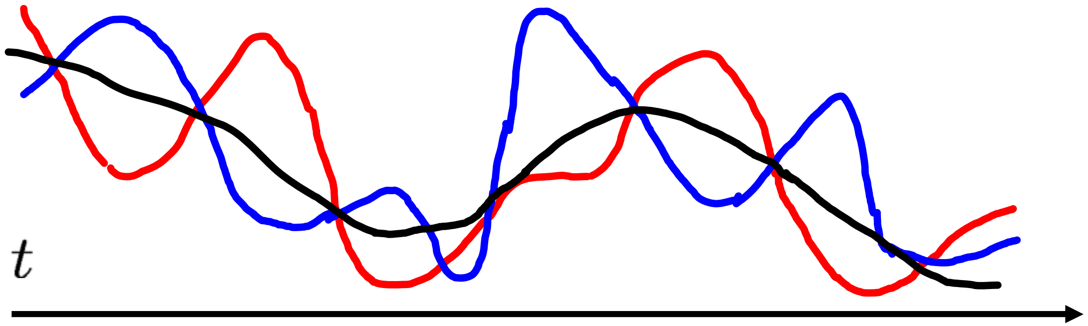


Representation of CT Signals by its Samples

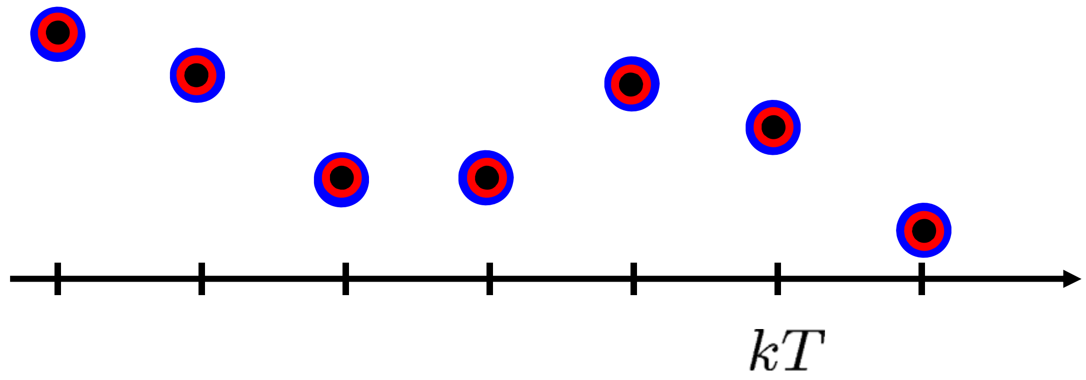


Representation of CT Signals by its Samples

$x_1(t) \neq x_2(t) \neq x_3(t)$



$x_1(kT) = x_2(kT) = x_3(kT)$

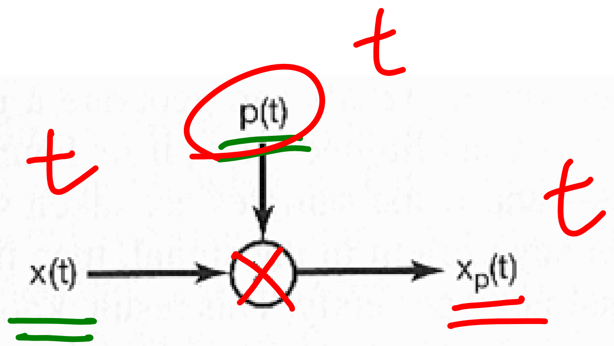


Impulse-Train Sampling:

$p(t)$: sampling function

T: sampling period

$w_s = \frac{2\pi}{T}$: sampling frequency

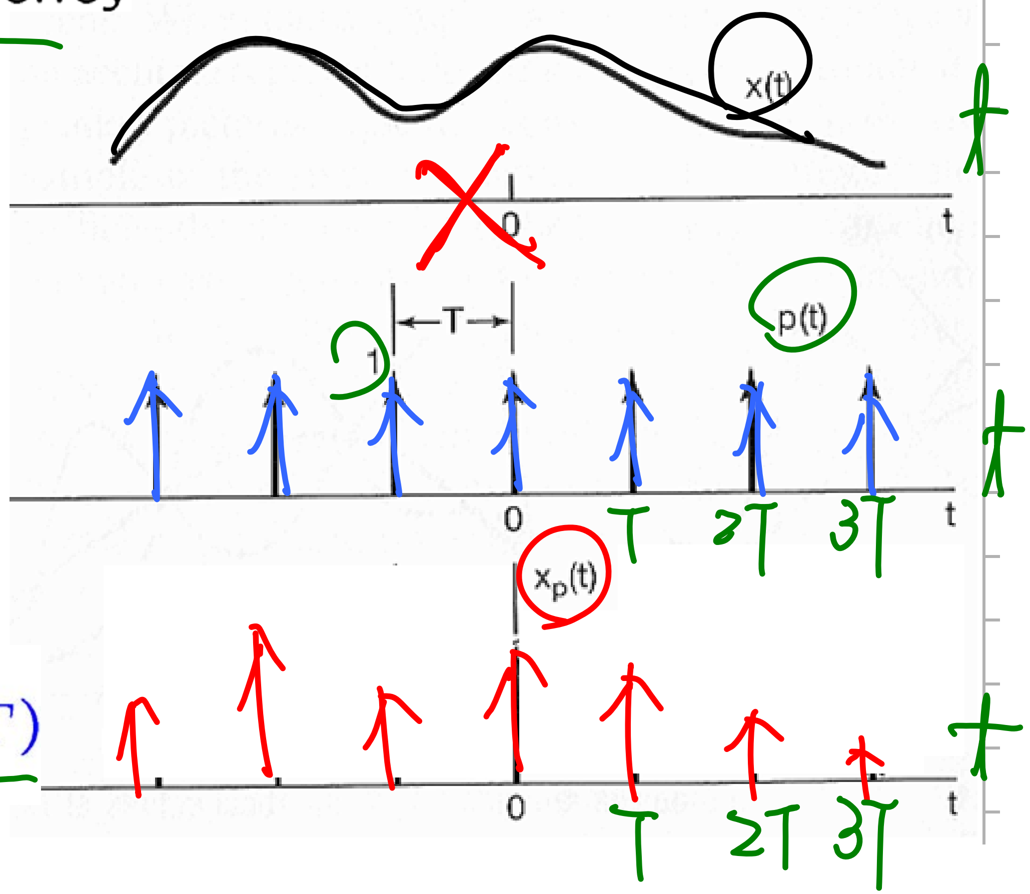


$$\Rightarrow \quad x_p(t) = \boxed{x(t)\,p(t)}$$

$$p(t) = \sum_{n=-\infty}^{+\infty} \delta(t - nT)$$

$$x_p(t) = \sum_{n=-\infty}^{+\infty} x(nT)\delta(t - nT)$$

$t = nT$



Impulse-Train Sampling:

From multiplication property,

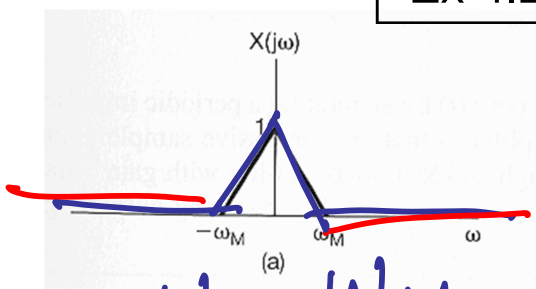
$$x_p(t) = x(t)\, p(t) \quad \overset{\mathcal{F}}{\longleftrightarrow} \quad X_p(jw) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} X(j\theta) P(j(w-\theta))d\theta$$

Eq 4.70, p. 322

$$= \frac{1}{T}\sum_{k=-\infty}^{+\infty} X(j(w-kw_s))$$

Ex 4.21, p. 323

$$x(t) \quad \overset{\mathcal{F}}{\longleftrightarrow} \quad X(jw)$$

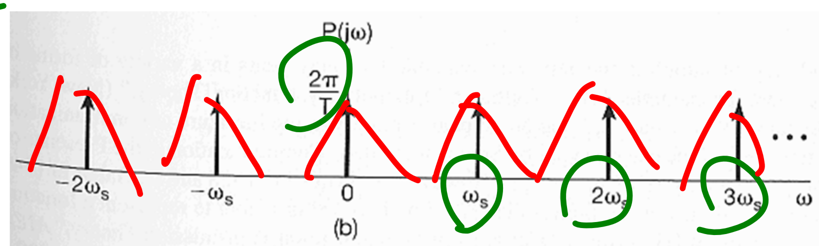


(a)

$-W_M \quad W_M$

$$p(t) \quad \overset{\mathcal{F}}{\longleftrightarrow} \quad P(jw) = \frac{2\pi}{T}\sum_{k=-\infty}^{+\infty} \delta(w-kw_s)$$

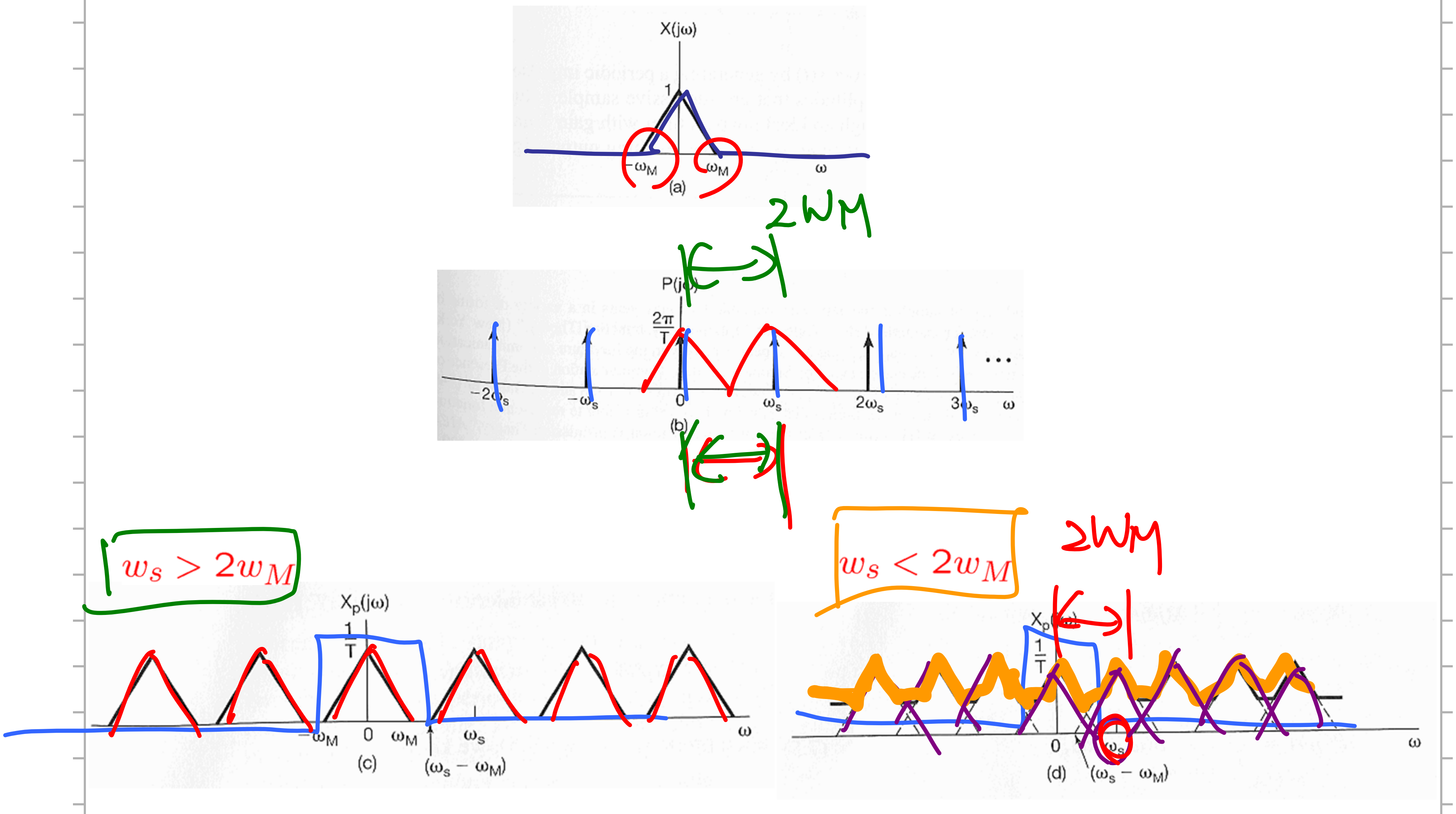
Ex 4.8, pp. 299-300



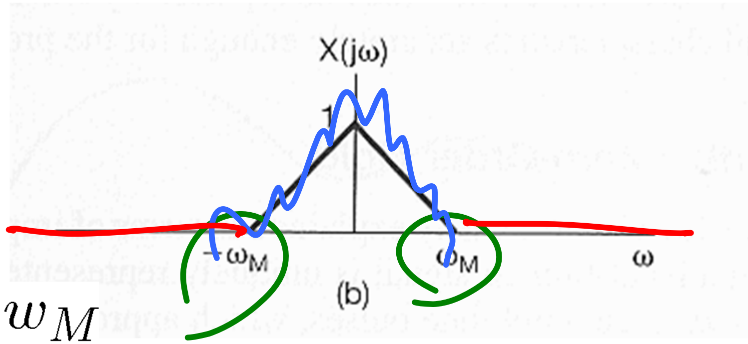
(b)

Impulse-Train Sampling:

Ex 4.21, 4.22, pp. 323-4



- The Sampling Theorem:



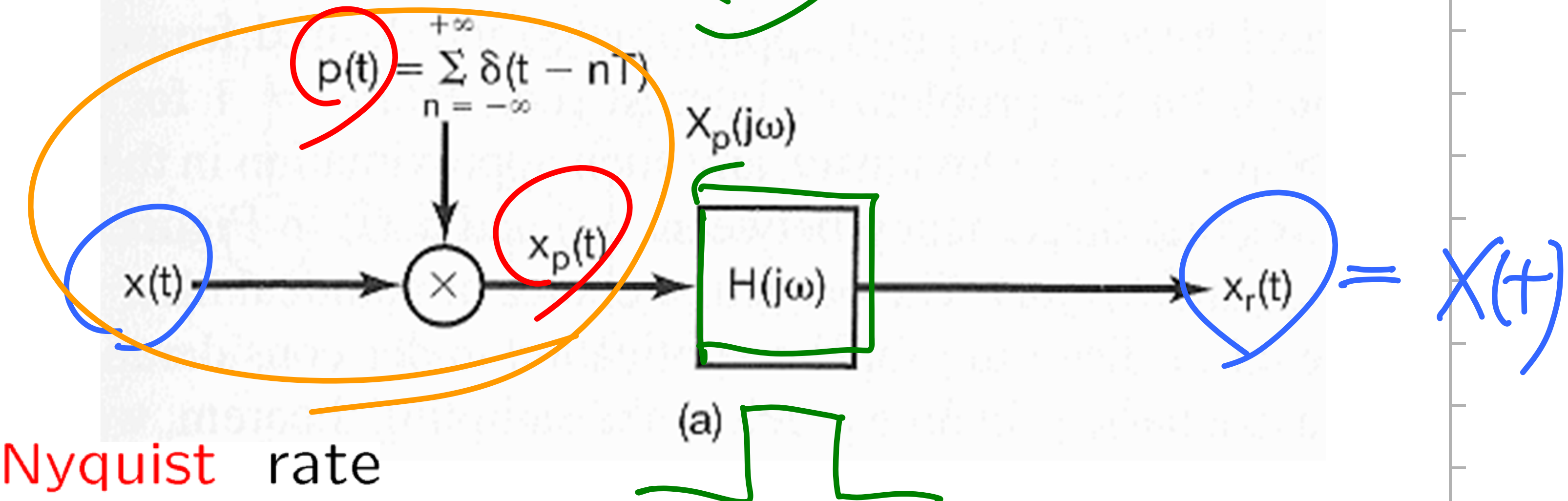
(b)

$x(t)$: a band-limited signal

with $X(jw) = 0$ for $|w| > w_M$

if $w_s > 2w_M$ where $w_s = \frac{2\pi}{T}$

$\Rightarrow$ $x(t)$ is uniquely determined by $x(nT)$, $n = 0, \pm 1, \pm 2, \ldots,$

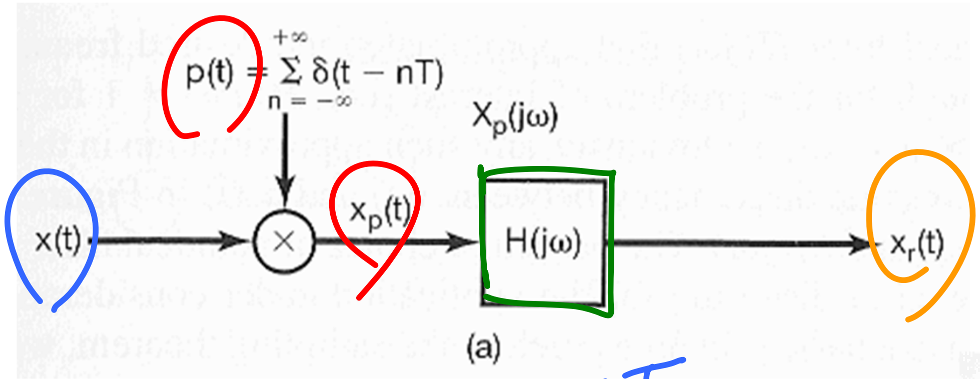


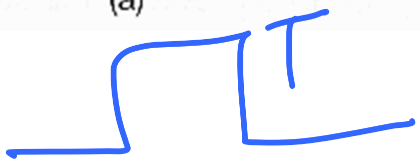
(a)

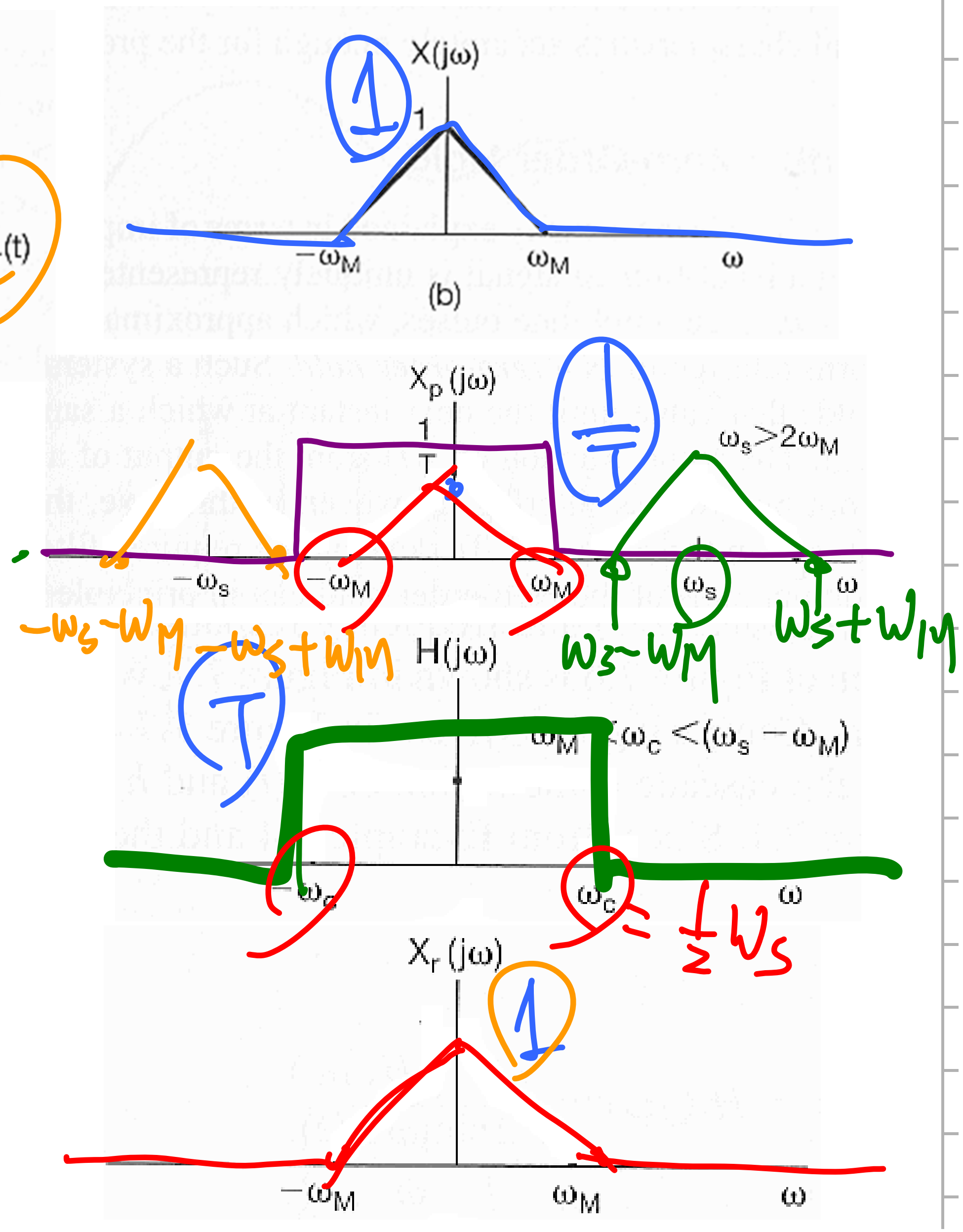
$\Rightarrow$ $2w_M$: Nyquist rate

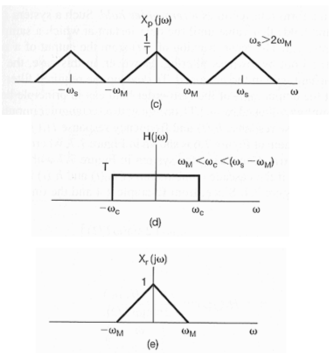
w_M : Nyquist frequency

▪ Exact Recovery by an Ideal Lowpass Filter:

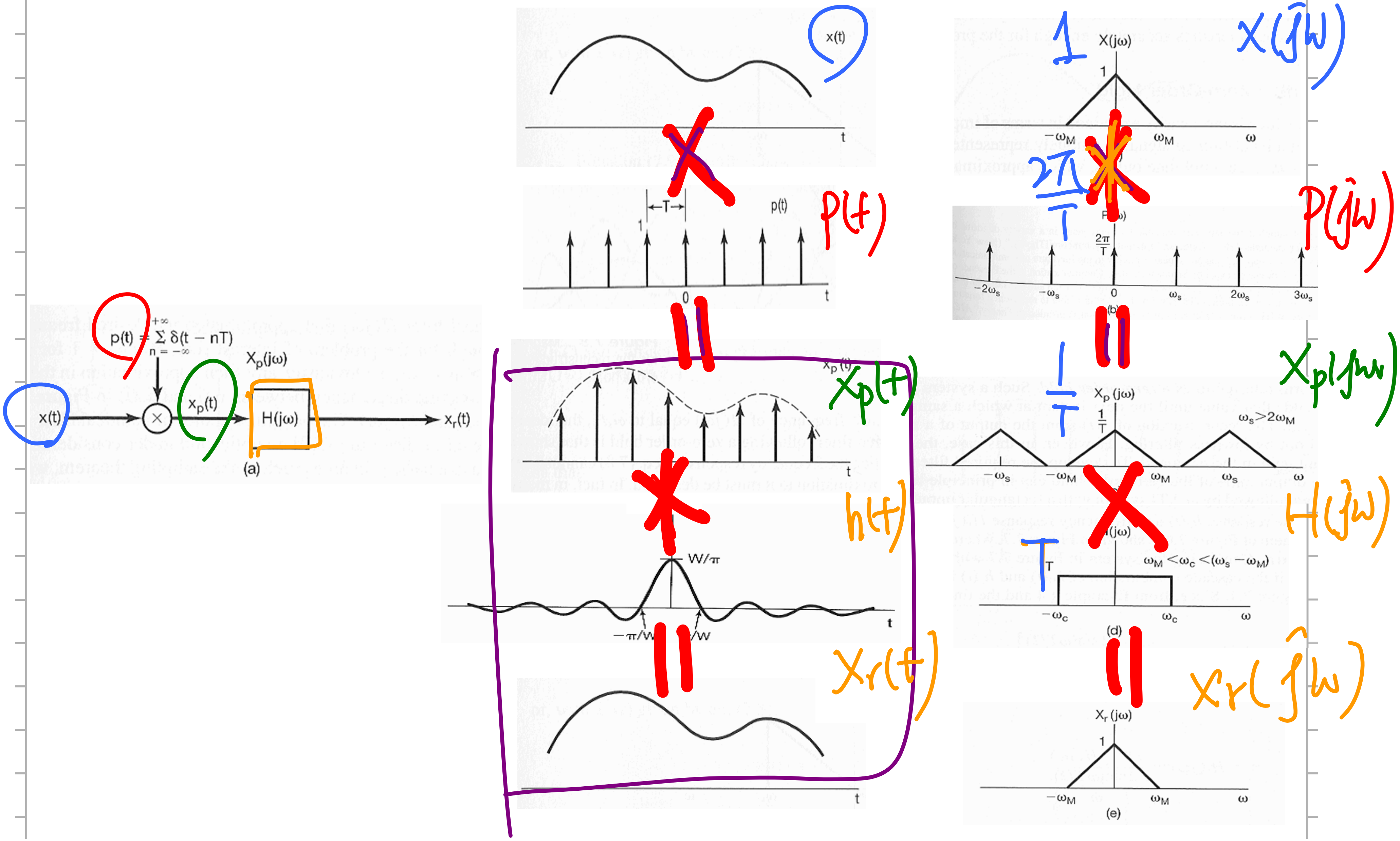




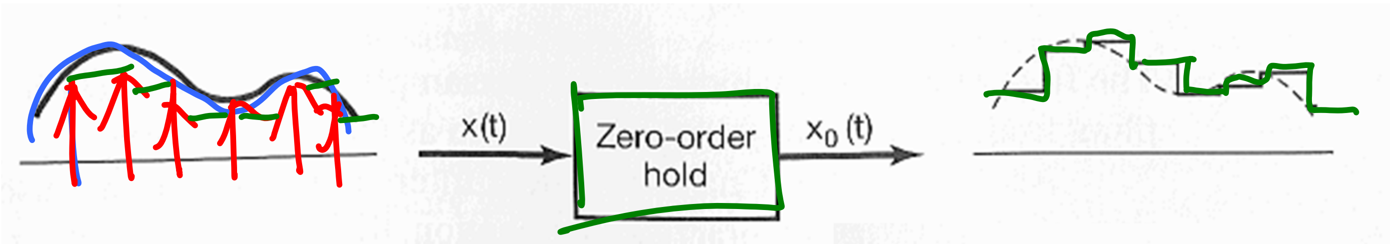


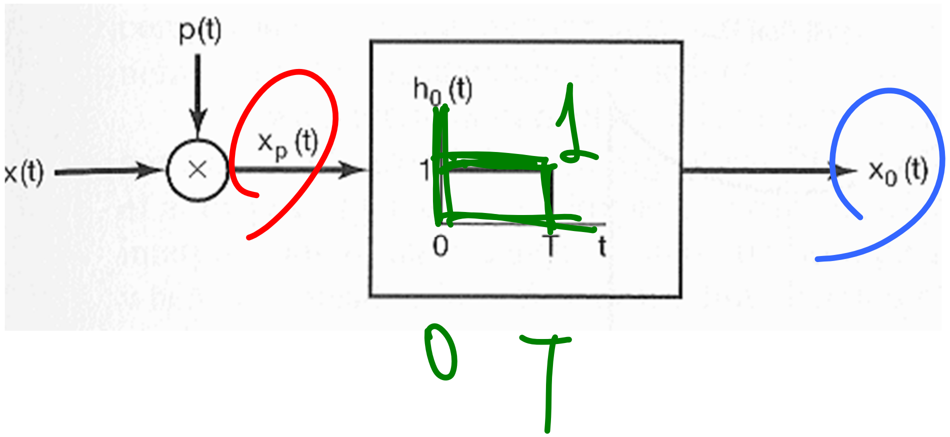


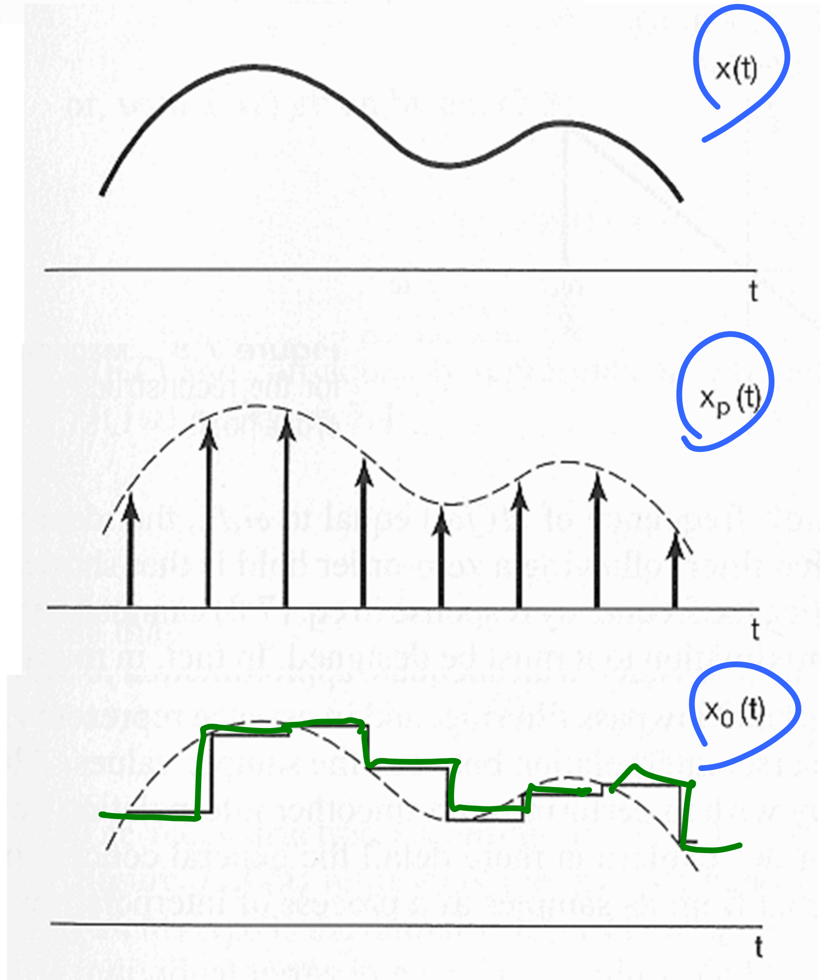
- Exact Recovery by an Ideal Lowpass Filter:



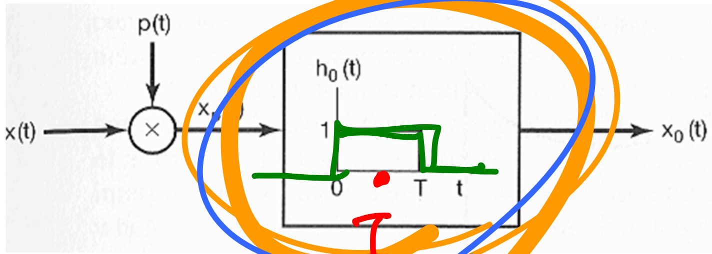
- Sampling with Zero-Order Hold:

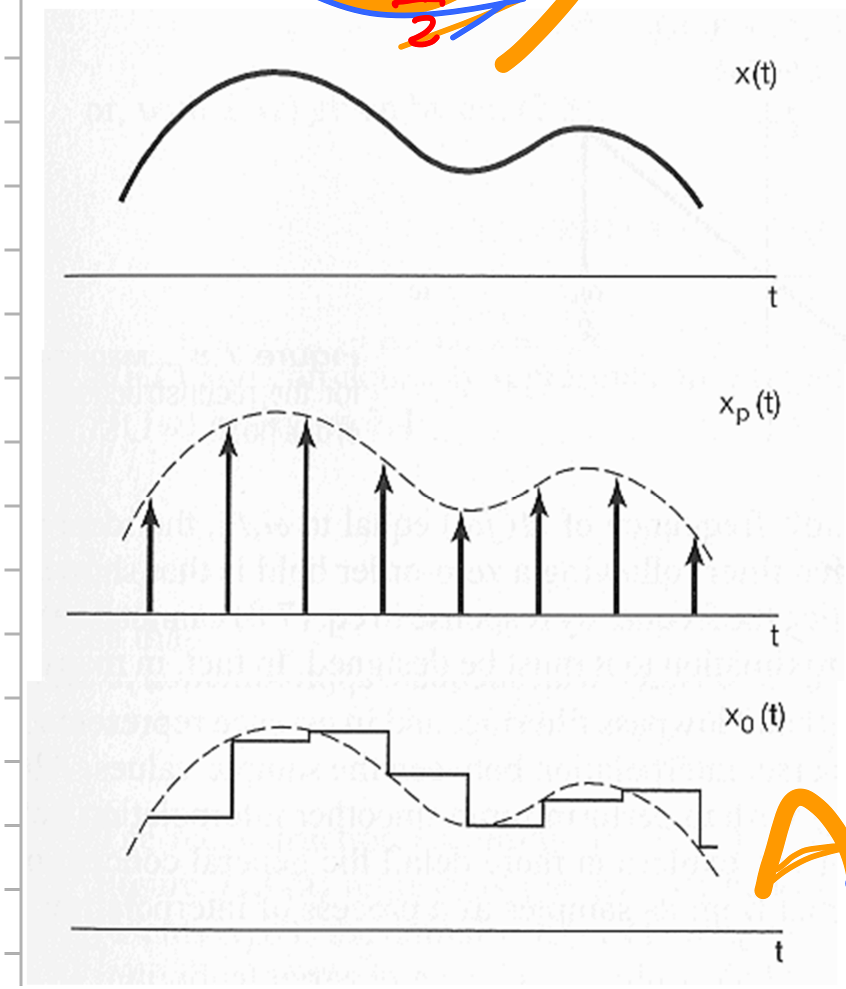




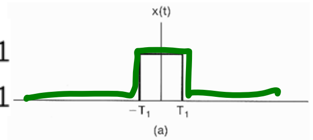


▪ Sampling with Zero-Order Hold:



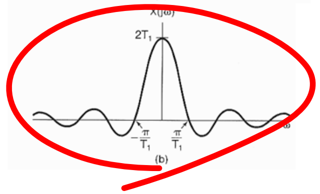


$$x(t) = \begin{cases} 1, & |t| < T_1 \\ 0, & |t| > T_1 \end{cases}$$



Ex 4.4, p. 293

$$X(jw) = 2\frac{\sin(wT_1)}{w}$$

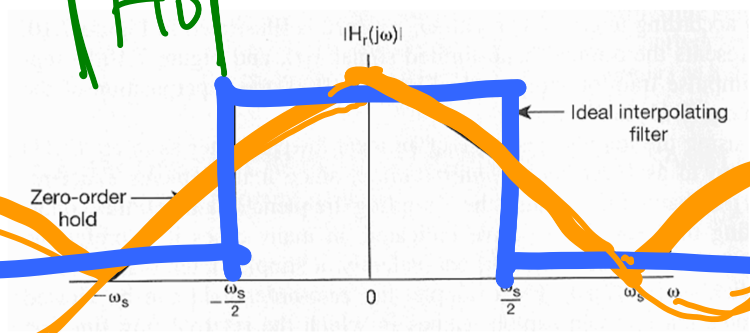


$$x(t - t_0) \xleftrightarrow{\mathcal{F}} e^{-jwt_0} X(jw)$$

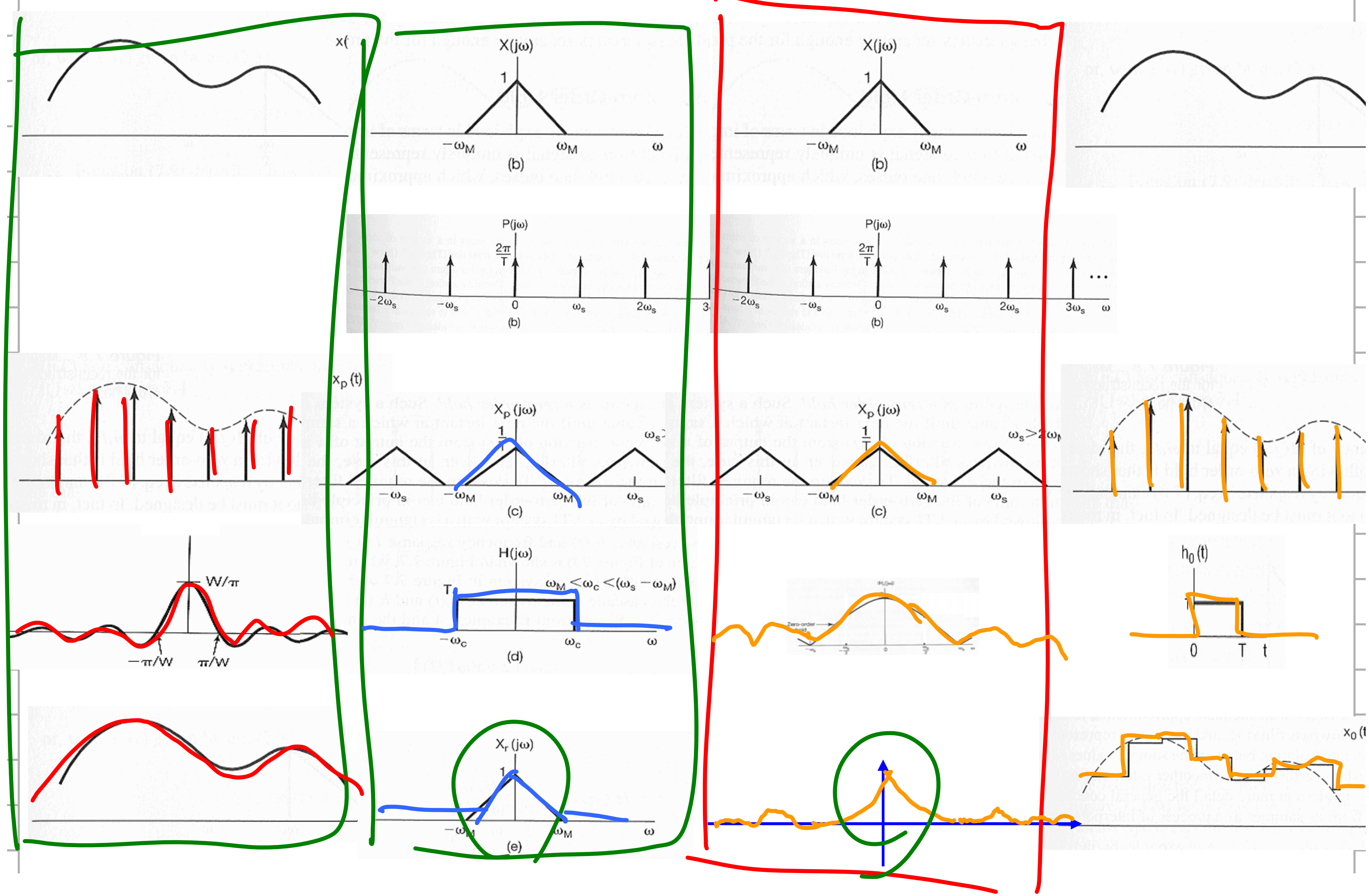
Eq 4.27, p. 301

$$H_0(jw) = e^{-jwT/2} \left[\frac{2\sin(wT/2)}{w} \right]$$

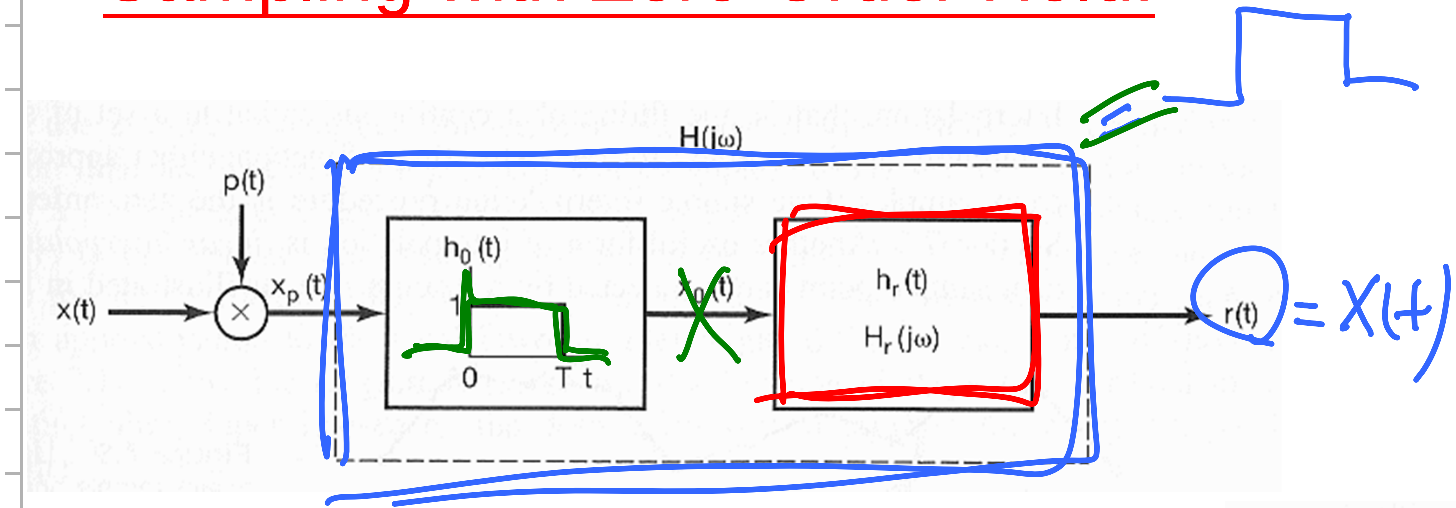
$|H_0|$



- With Ideal Lowpass Filter & with Zero-Order Hold:



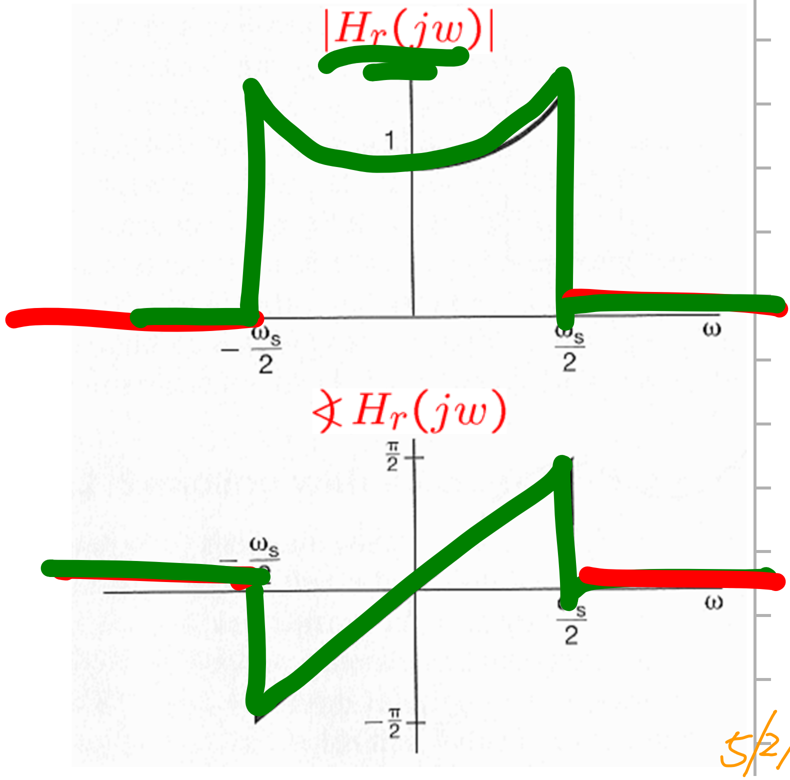
▪ Sampling with Zero-Order Hold:



$$H_0(jw) = e^{-jwT/2}\left[\frac{2\sin(wT/2)}{w}\right]$$

$$H(jw) = H_0(jw)H_r(jw)$$

$$\Rightarrow\ H_r(jw) = \frac{e^{jwT/2}H(jw)}{\frac{2\sin(wT/2)}{w}}$$



5/2/13
2:15pm

- Representation of a Continuous-Time Signal
  by its Samples: The Sampling Theorem
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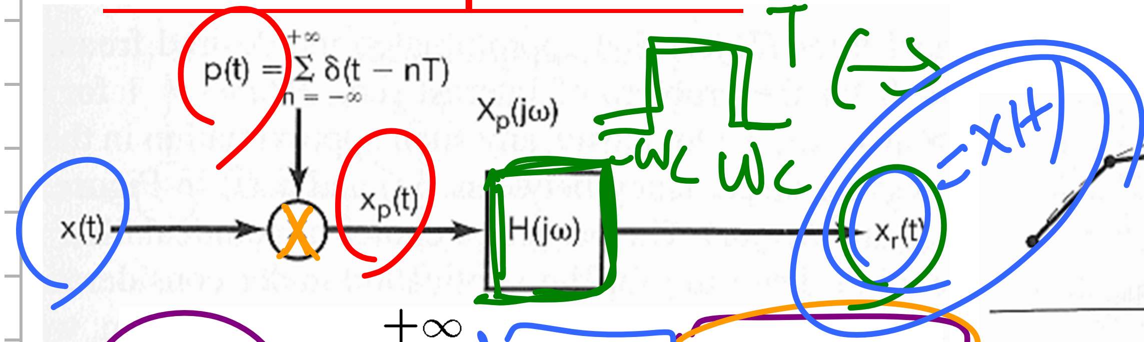
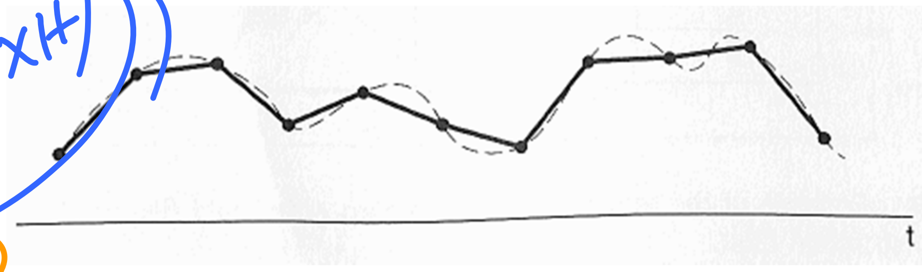
  Using Interpolation
- The Effect of Under-sampling: Aliasing
- Discrete-Time Processing
  of Continuous-Time Signals
- Sampling of Discrete-Time Signals

- Exact Interpolation:





$$x_p(t) = \sum_{n=-\infty}^{+\infty} x(nT)\,\delta(t-nT)$$

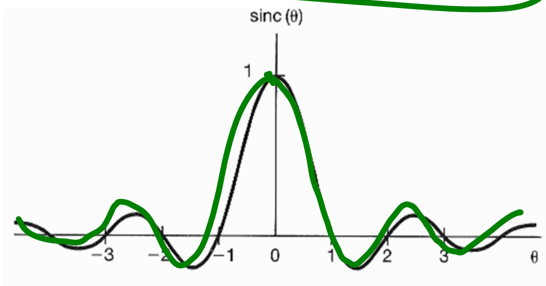
$$x_r(t) = x_p(t) * h(t)$$

ideal lowpass filter

with a magnitude of T

$$h(t) = T\,\frac{w_c}{\pi}\,\frac{\sin(w_c t)}{w_c t}$$

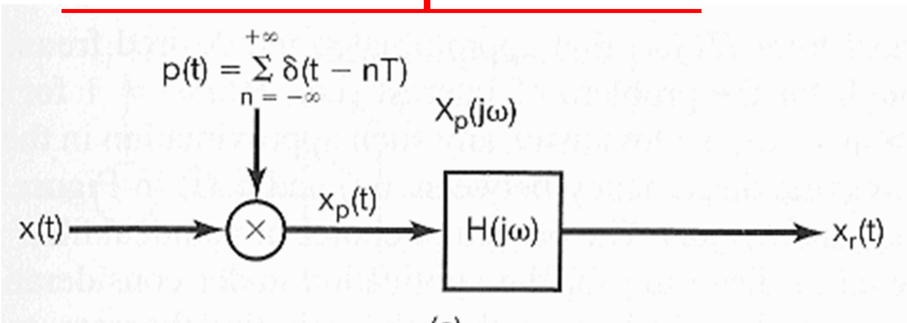
Ex 2.11, p. 110 $\quad x(t-t_0) = x(t) * \delta(t-t_0)$



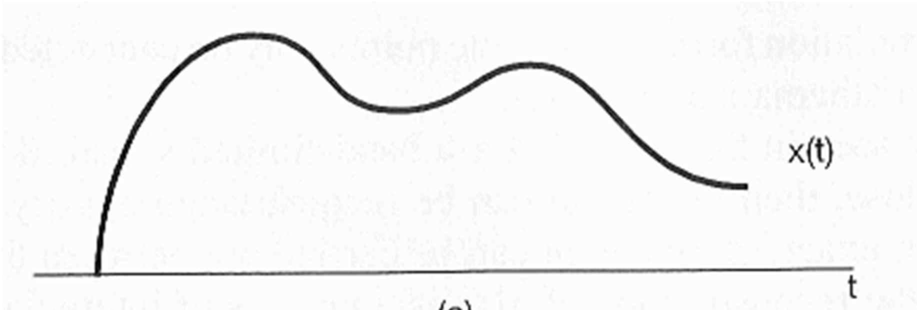
$$x_r(t) = \sum_{n=-\infty}^{+\infty} x(nT)\,h(t-nT)$$

$$x_r(t) = \sum_{n=-\infty}^{+\infty} x(nT)\,\frac{w_c T}{\pi}\,\frac{\sin(w_c(t-nT))}{w_c(t-nT)} = x(t)$$

Exact Interpolation:



(a)

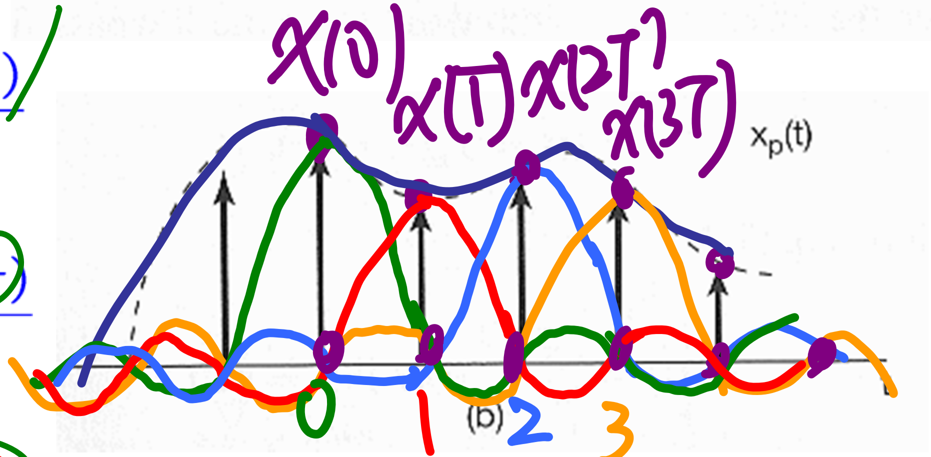


(a)

$$x_r(t) = \sum_{n=-\infty}^{+\infty} x(nT)\, \frac{\omega_c T}{\pi}\, \frac{\sin(\omega_c(t-nT))}{\omega_c(t-nT)}$$

$$\frac{\omega_c}{\pi}\, \frac{2\pi}{\omega_s}\, \frac{\sin \pi(\omega_c(t-nT)/\pi)}{\pi\omega_c(t-nT)/\pi}$$

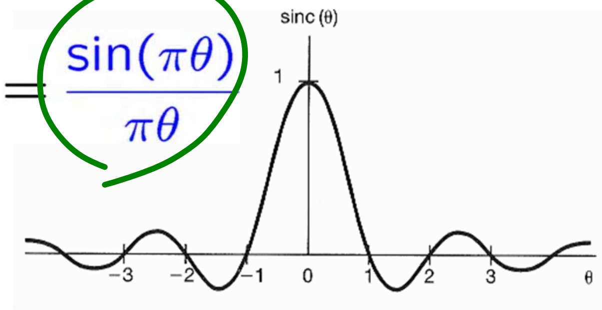
$$\frac{2\omega_c}{\omega_s}\, \text{sinc}(\omega_c(t-nT)/\pi)$$

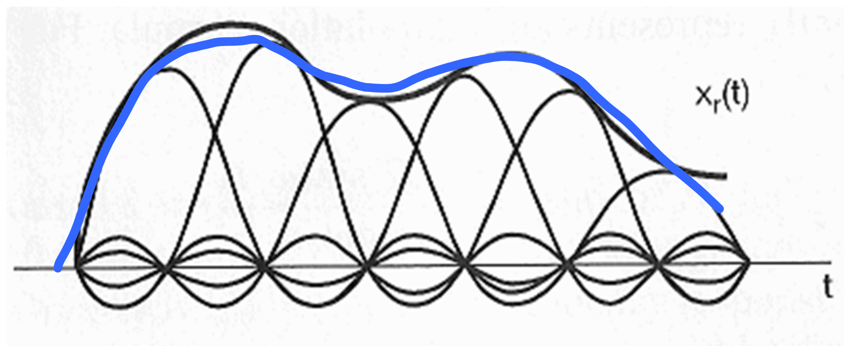


(b)

n=0
n=1
n=2
n=3

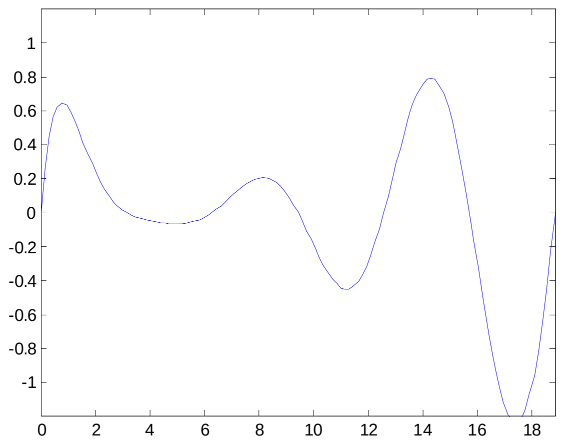
$$\text{sinc}(\theta) = \frac{\sin(\pi\theta)}{\pi\theta}$$

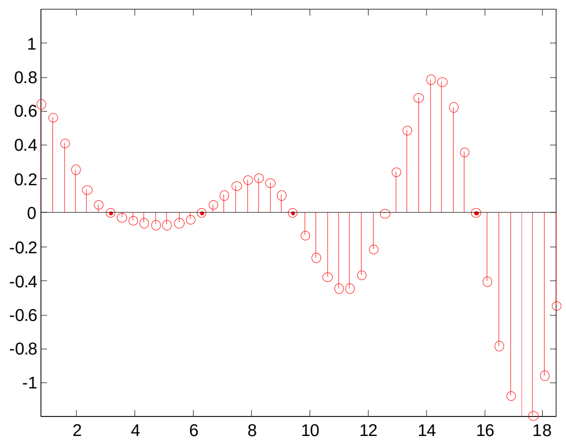


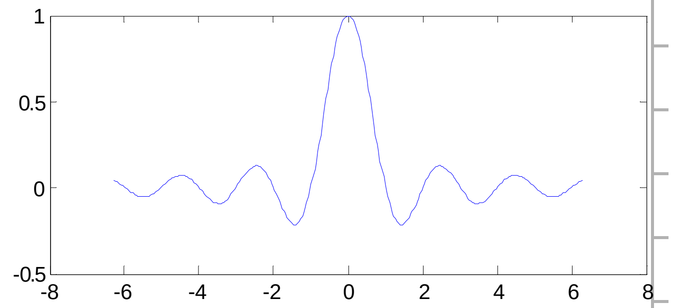


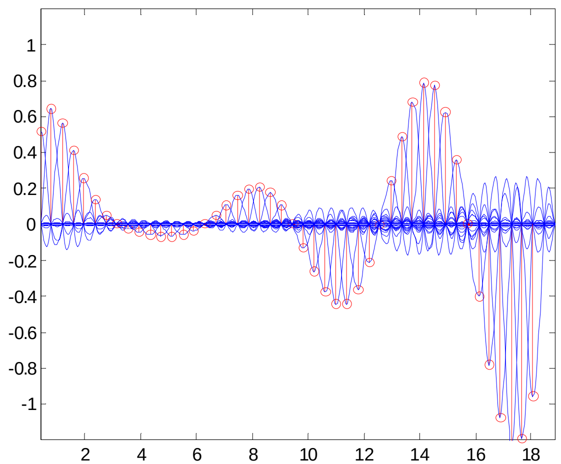
(c)

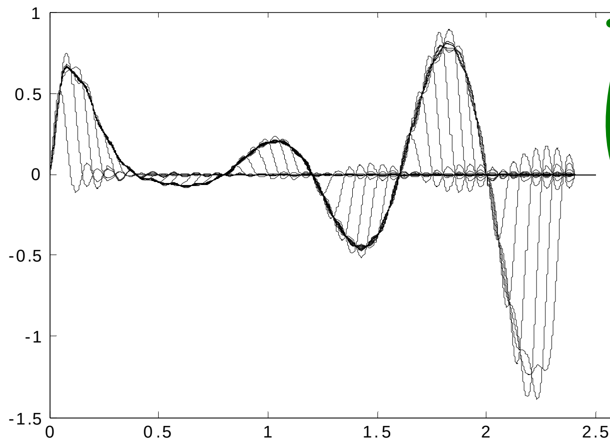
Reconstruction of a Signal from its Samples Using Interpolation

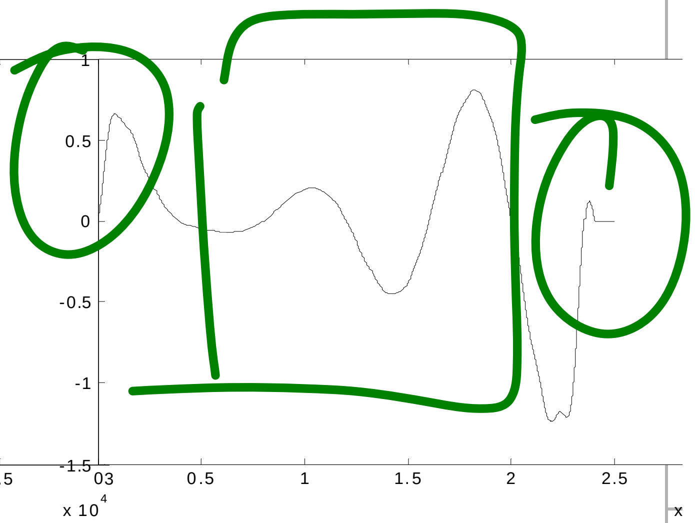




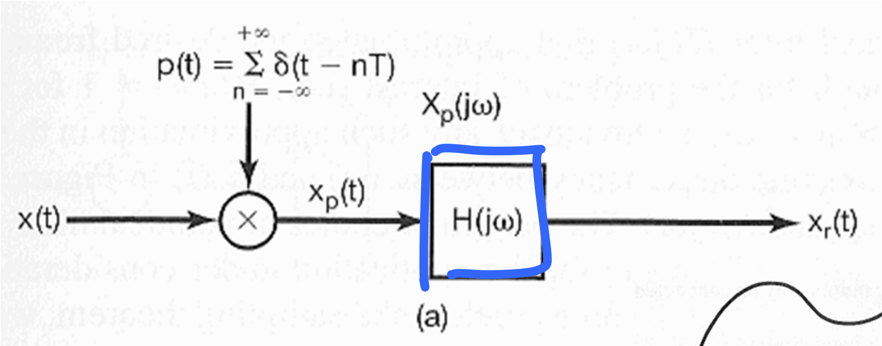


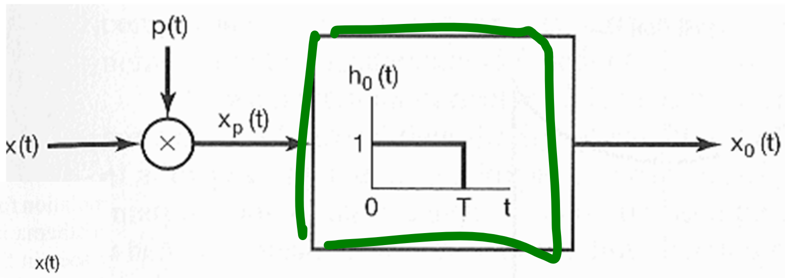


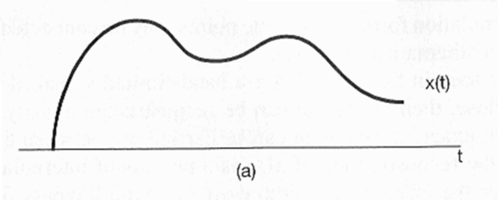


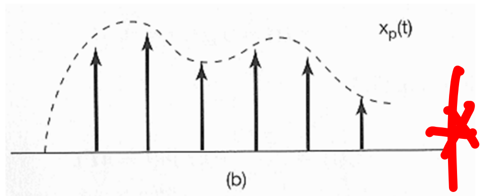


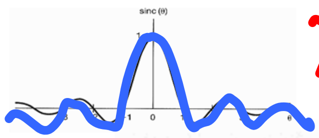
▪ Ideal Interpolating Filter & The Zero-Order Hold:

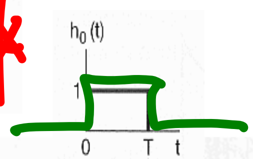


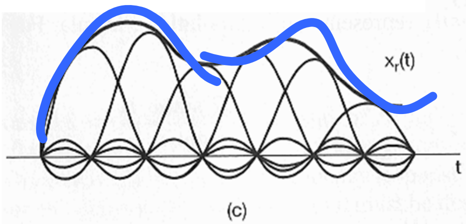


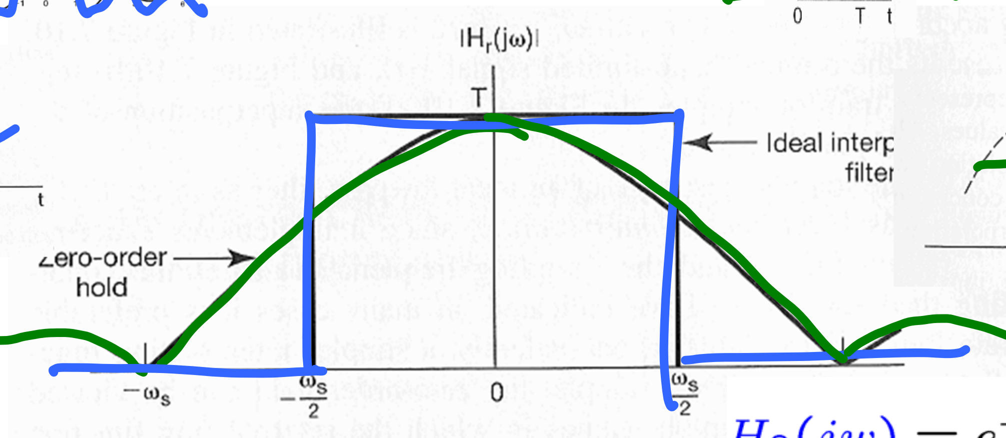


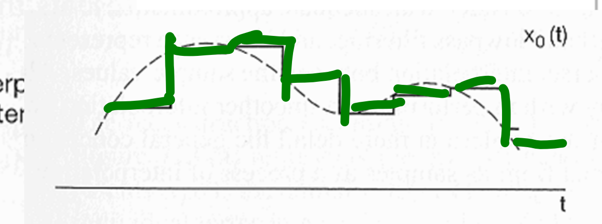










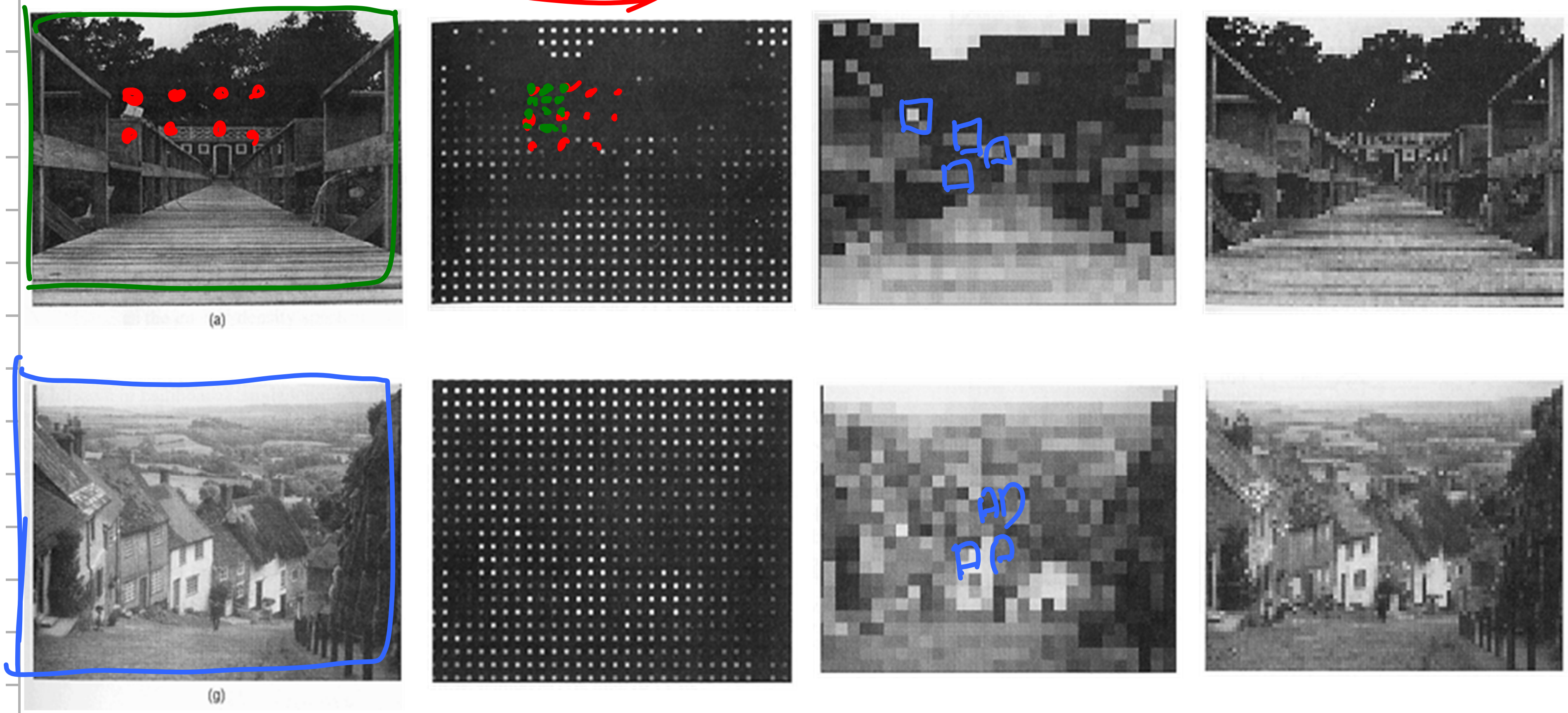


$$H_0(jw) = e^{-jwT/2}\left[\frac{2\sin(wT/2)}{w}\right]$$

Sampling & Interpolation of Images:

orignal image   impulse sampling   zero-order hold   zero-order hold

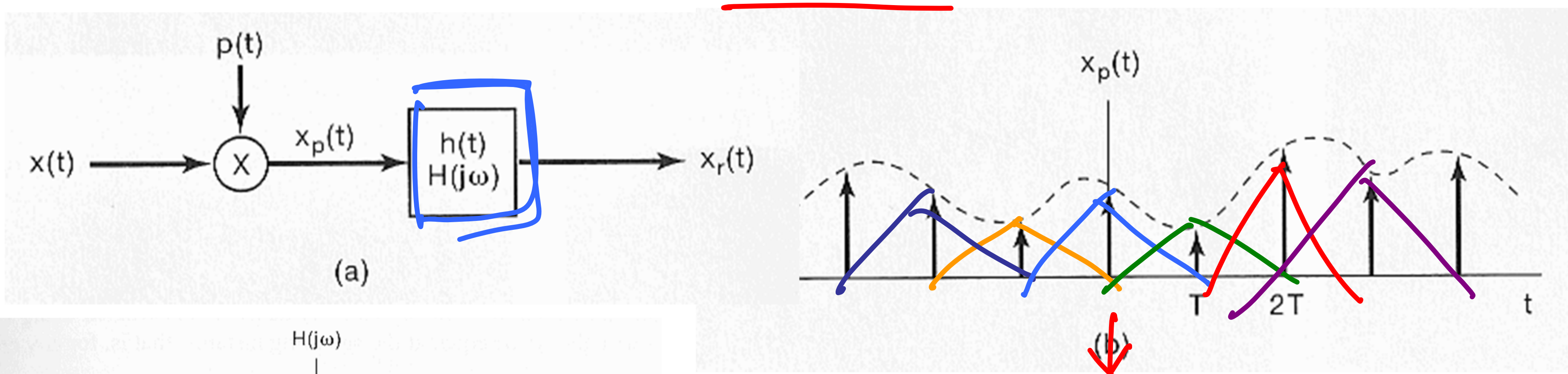
4 : 1

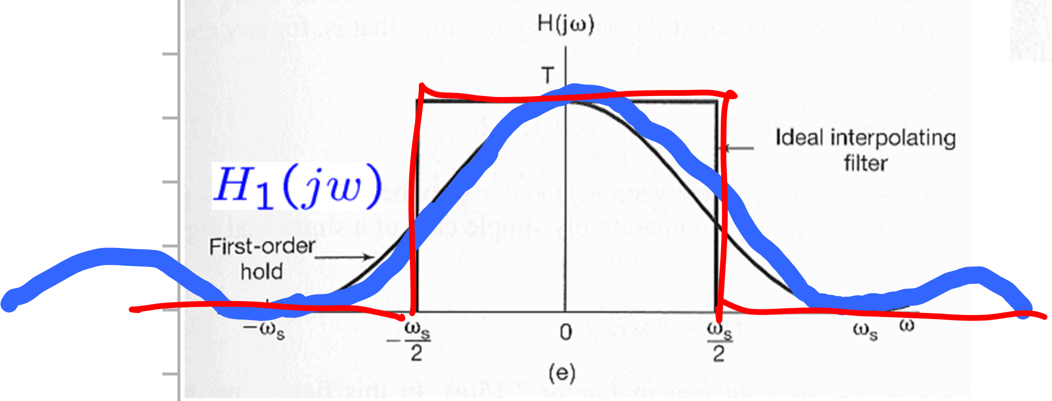


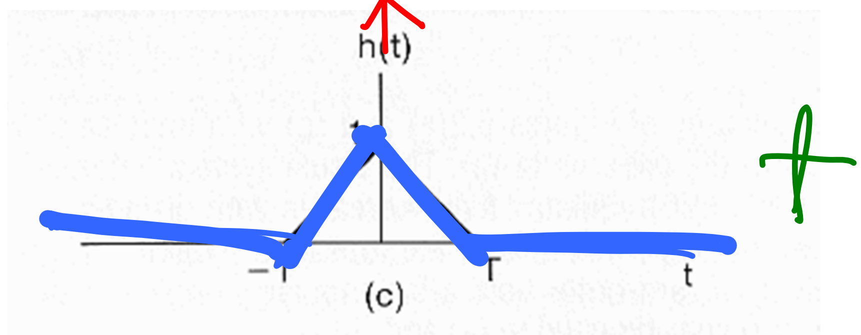
(a)

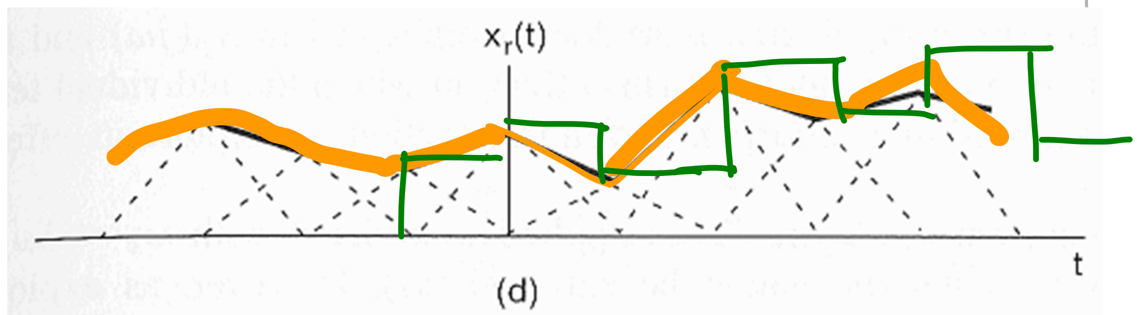
(g)

- **Higher-Order Holds:** 1st-order









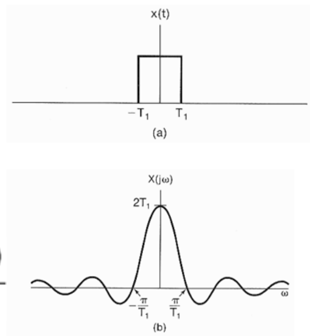
$$H_1(jw) = \frac{1}{T}\left[\frac{\sin(wT/2)}{w/2}\right]^2$$

Higher-Order Holds:

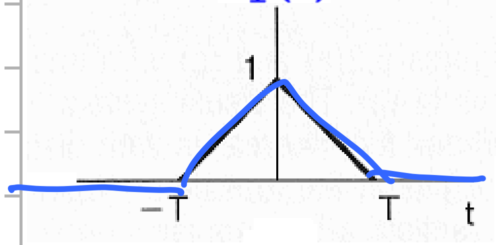
Ex 4.4, p. 293

$$x(t) = \begin{cases} 1, & |t| < T_1 \\ 0, & |t| > T_1 \end{cases}$$

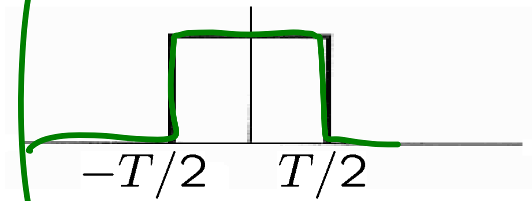
$$X(jw) = 2\frac{\sin(wT_1)}{w}$$

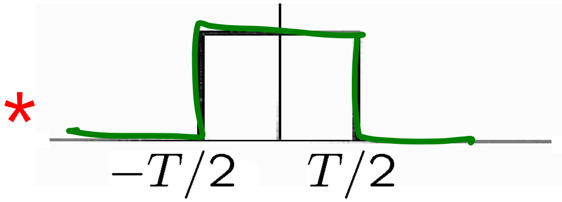


$h_1(t)$



$$= \frac{1}{T} \left(h_{sq}(t) * h_{sq}(t) \right)$$

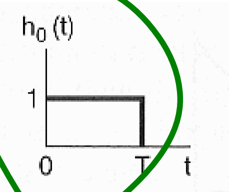


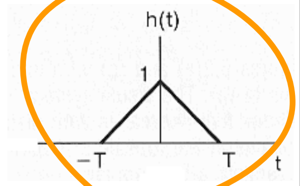


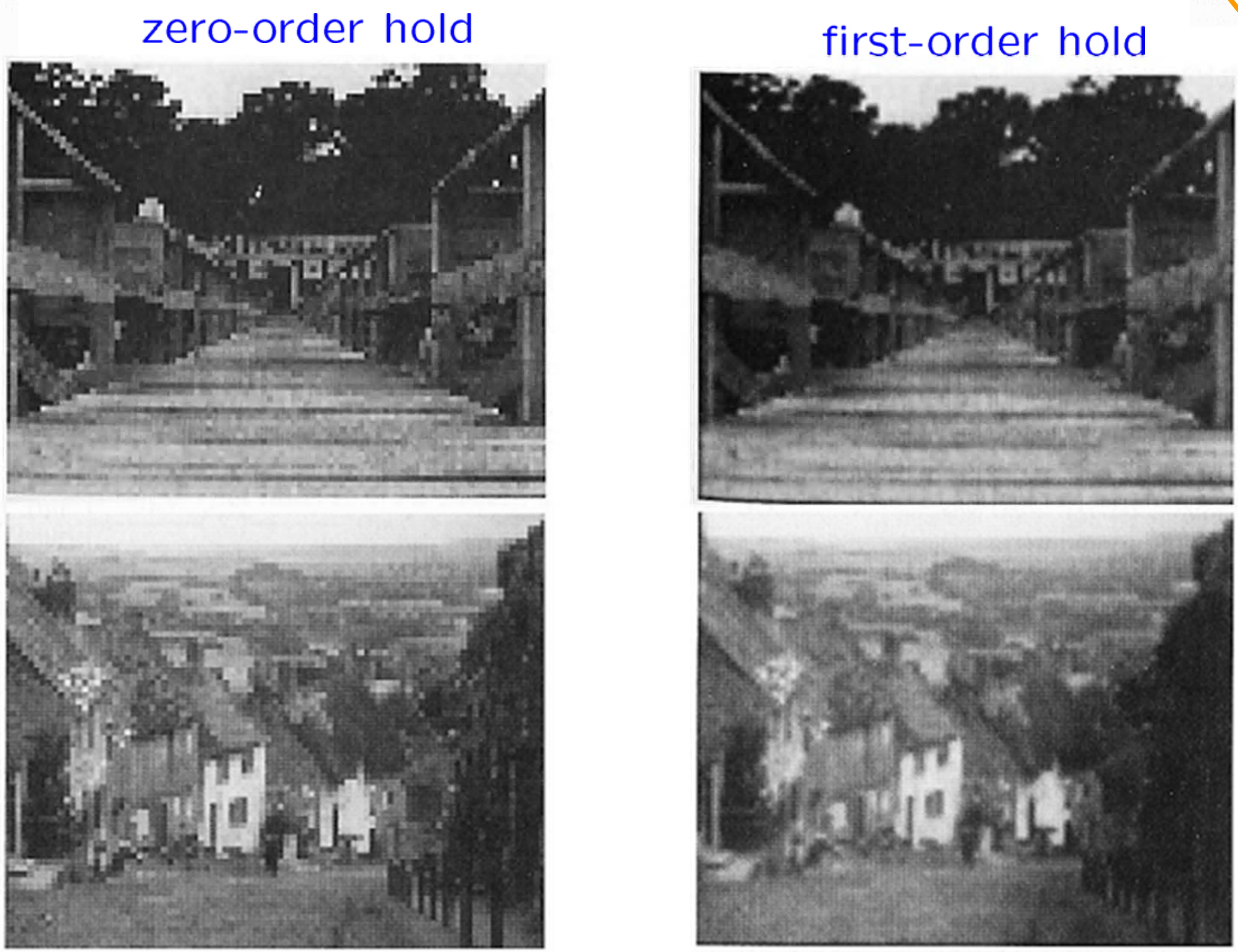
$$H_1(jw) = \frac{1}{T} \left(2\frac{\sin(wT/2)}{w} \times 2\frac{\sin(wT/2)}{w} \right)$$

$$= \frac{1}{T}\left[\frac{\sin(wT/2)}{w/2}\right]^2$$

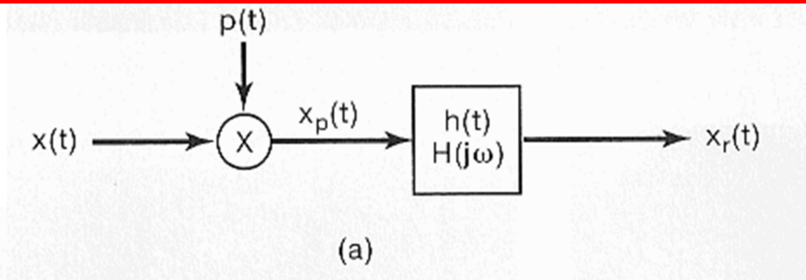
- First-Order Hold on Image Processing:

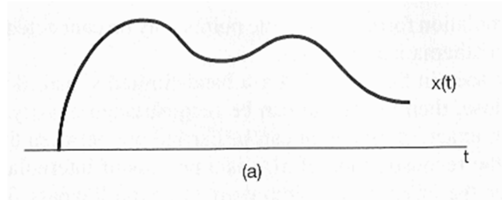


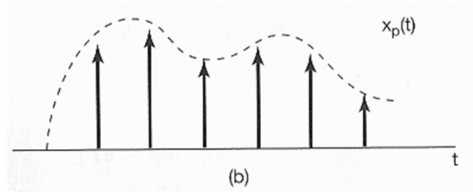




Three Filters: Ideal Lowpass, Zero-Order, First-Order

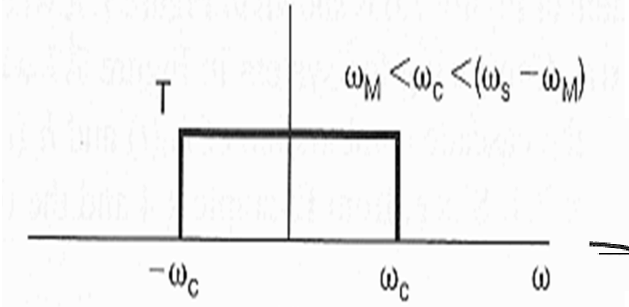


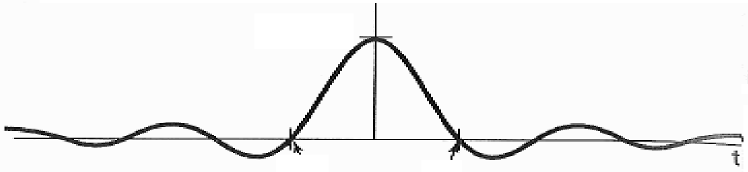


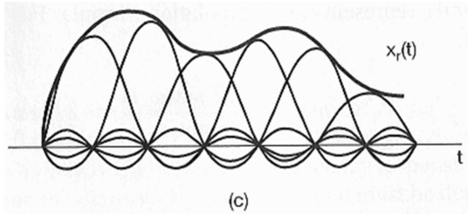


ideal lowpass

$$\omega_M < \omega_c < (\omega_s - \omega_M)$$

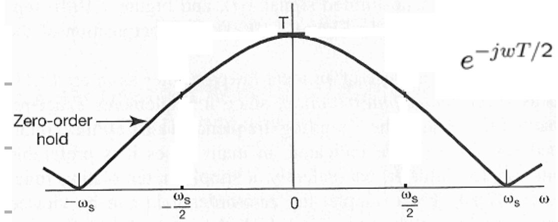


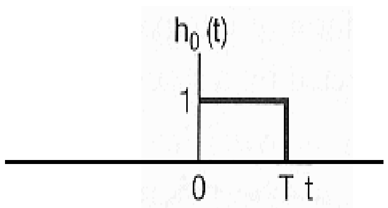


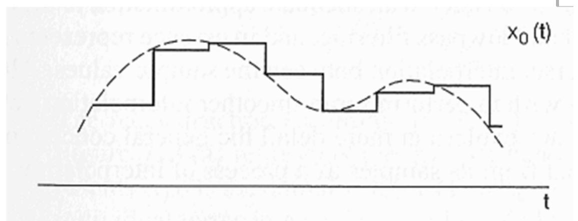


zero-order hold

$$H_0(jw) = e^{-jwT/2}\left[\frac{2\sin(wT/2)}{w}\right]$$

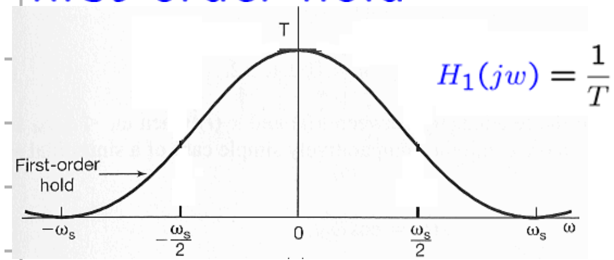


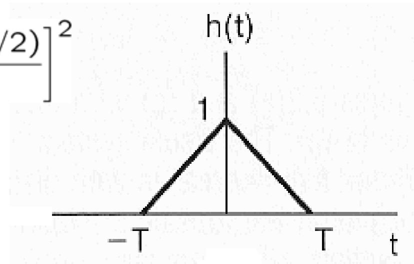


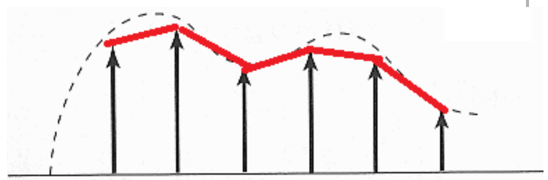


first-order hold

$$H_1(jw) = \frac{1}{T}\left[\frac{\sin(wT/2)}{w/2}\right]^2$$

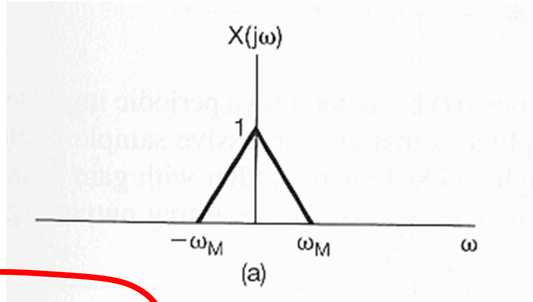


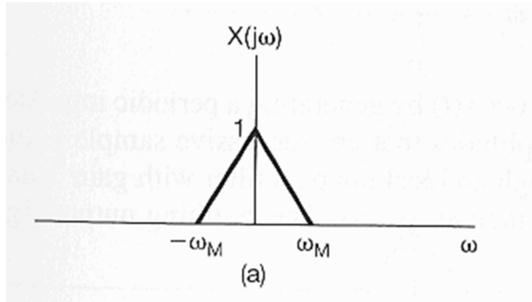




- Representation of a Continuous-Time Signal by its Samples: The Sampling Theorem
- Reconstruction of a Signal from its Samples Using Interpolation
- The Effect of Under-sampling: Aliasing
- Discrete-Time Processing of Continuous-Time Signals
- Sampling of Discrete-Time Signals

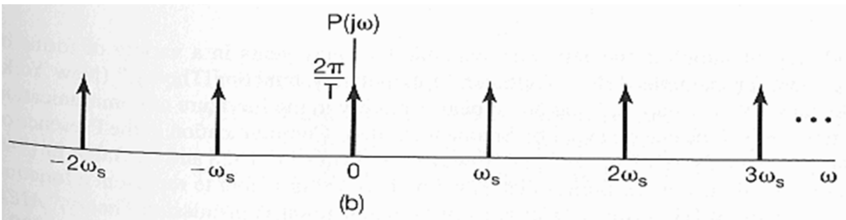
▪ Overlapping in Frequency-Domain: Aliasing

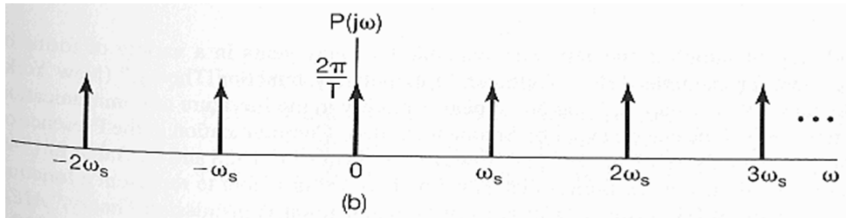


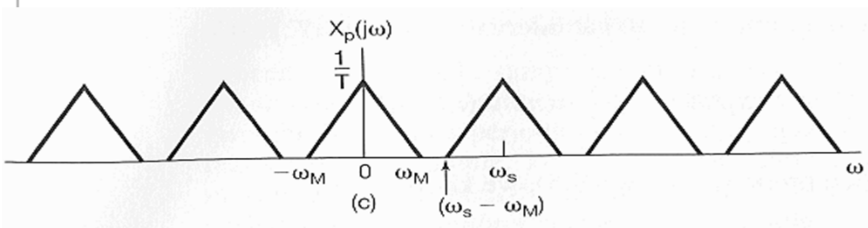


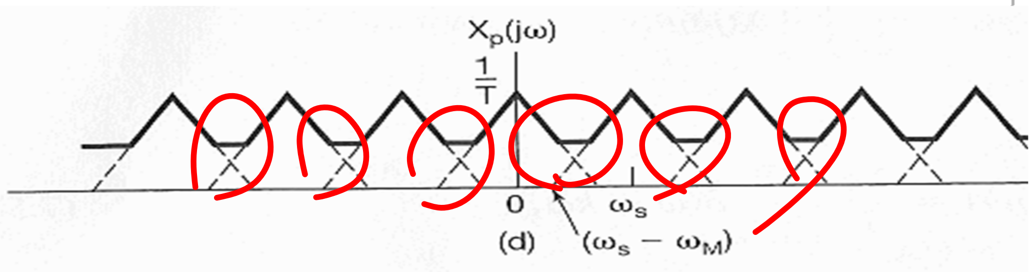
$w_s > 2w_M$

$w_s < 2w_M$

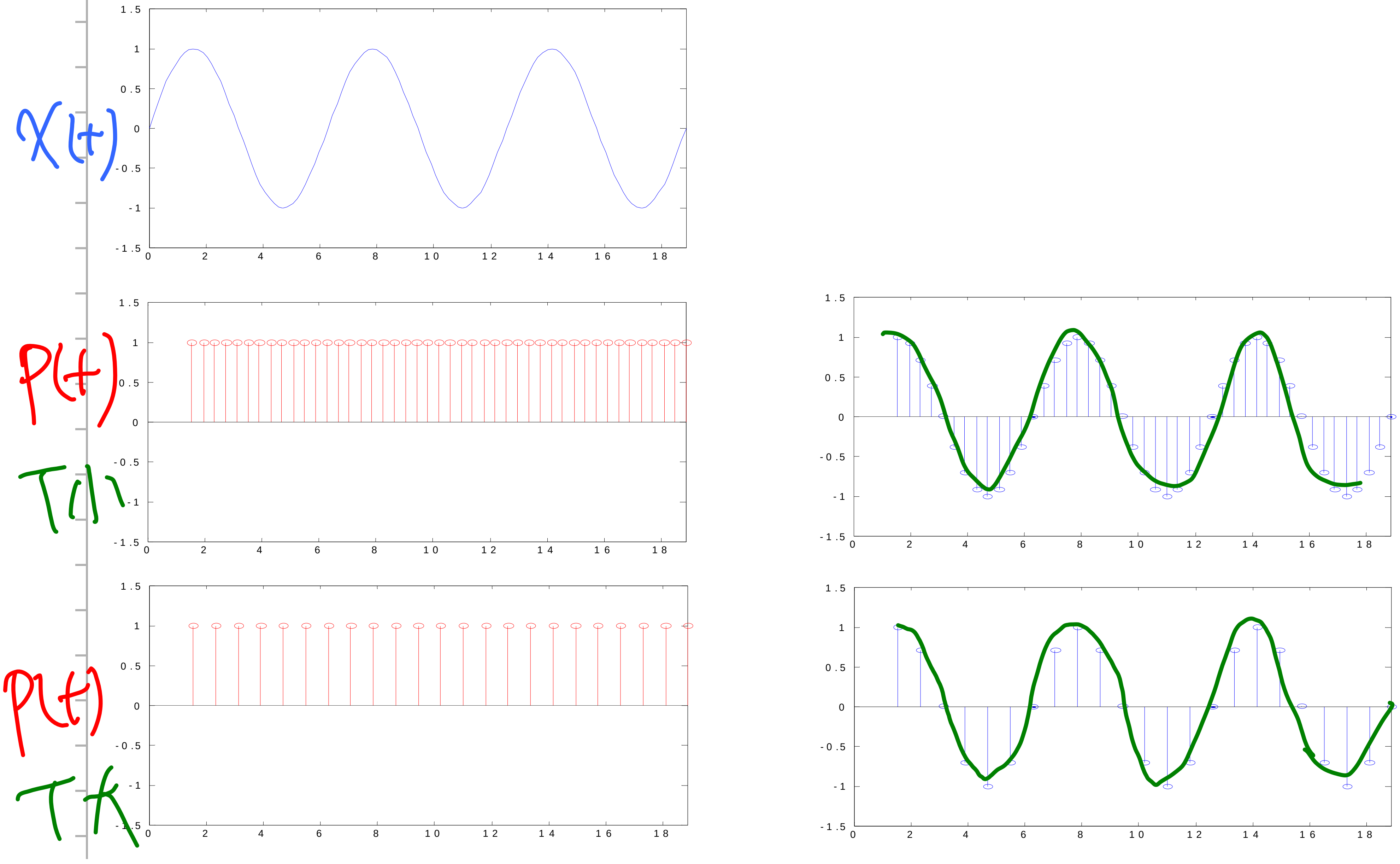






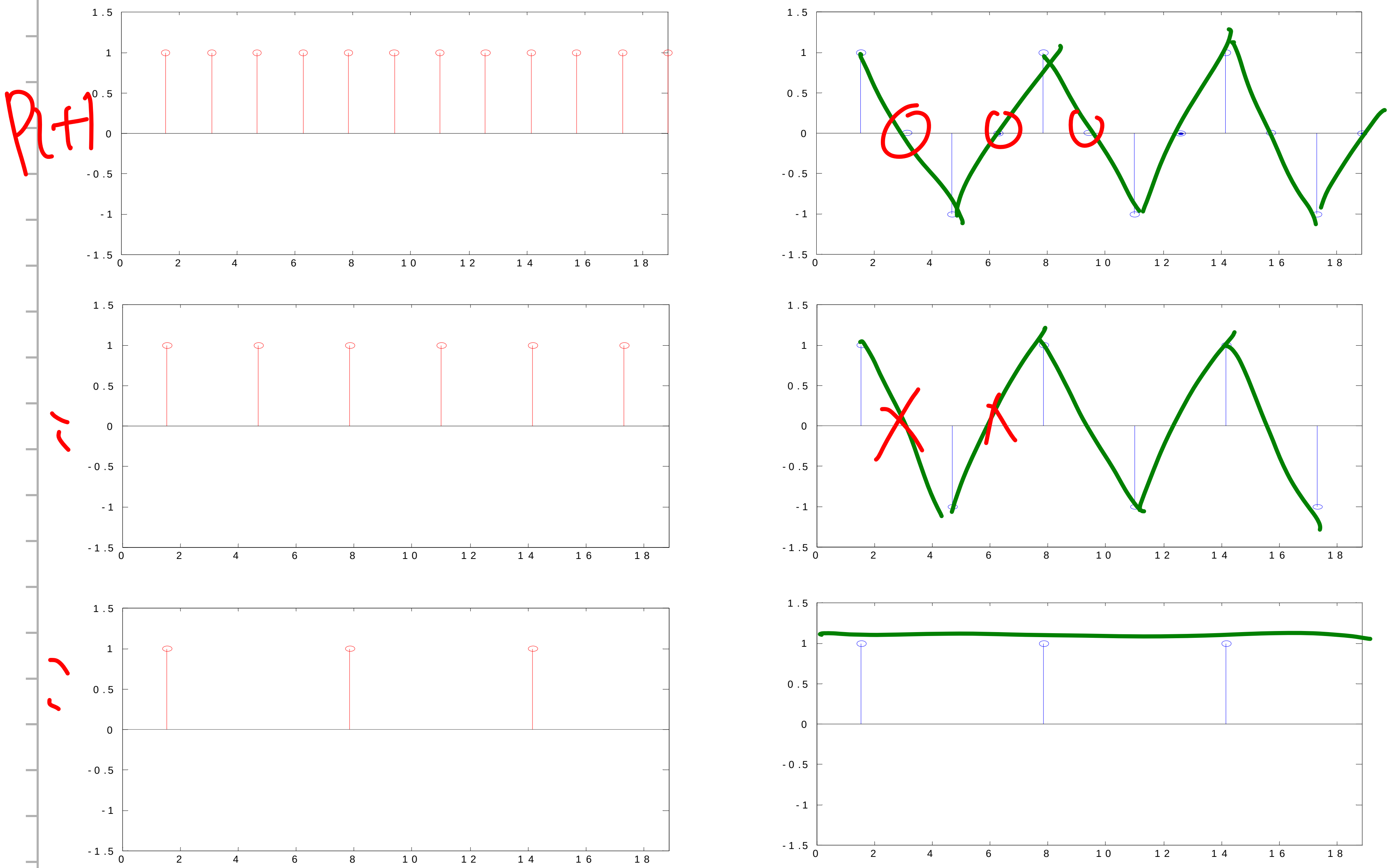


Overlapping in Frequency-Domain: Aliasing

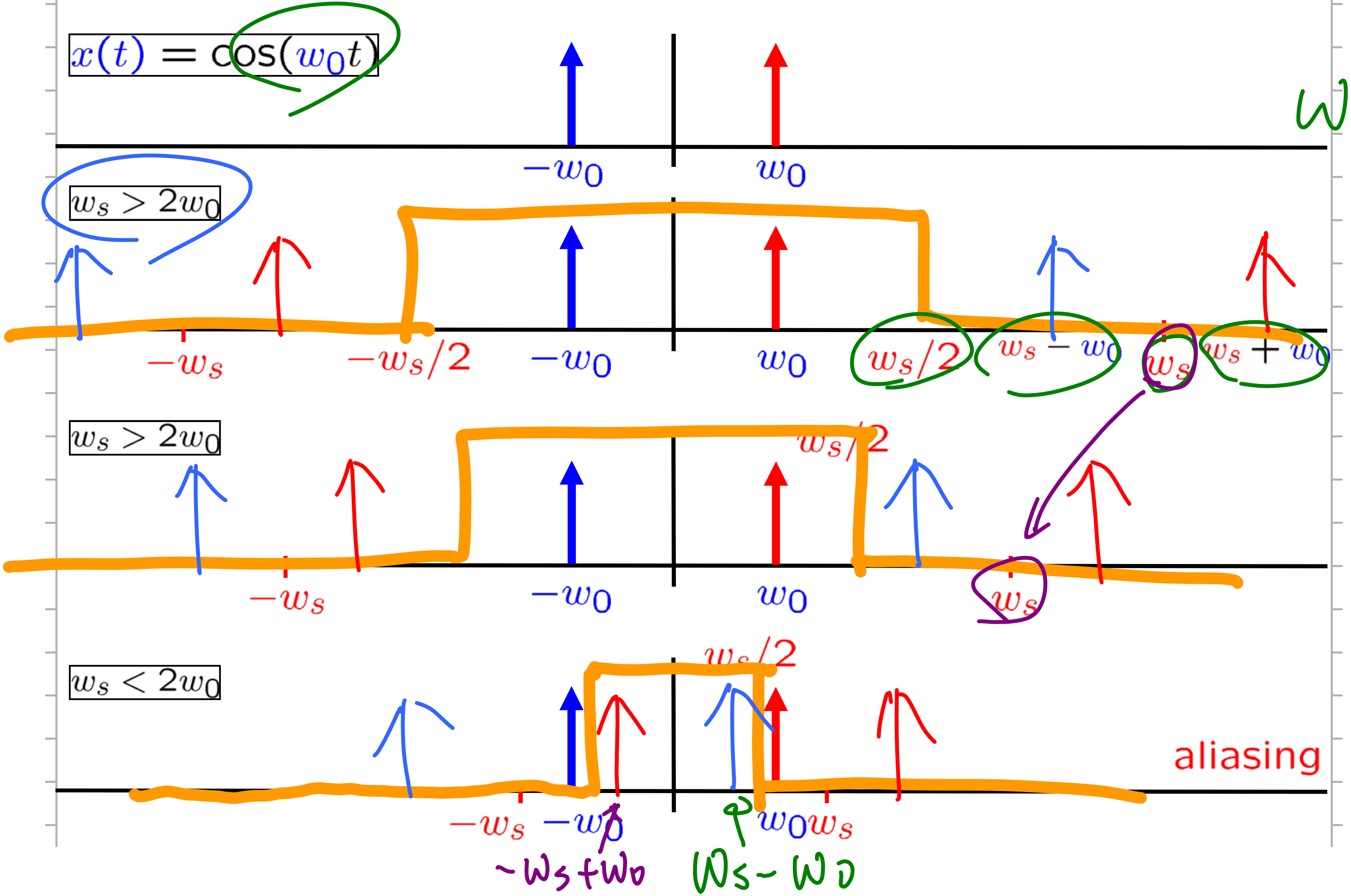


Effect of Under-sampling: Aliasing

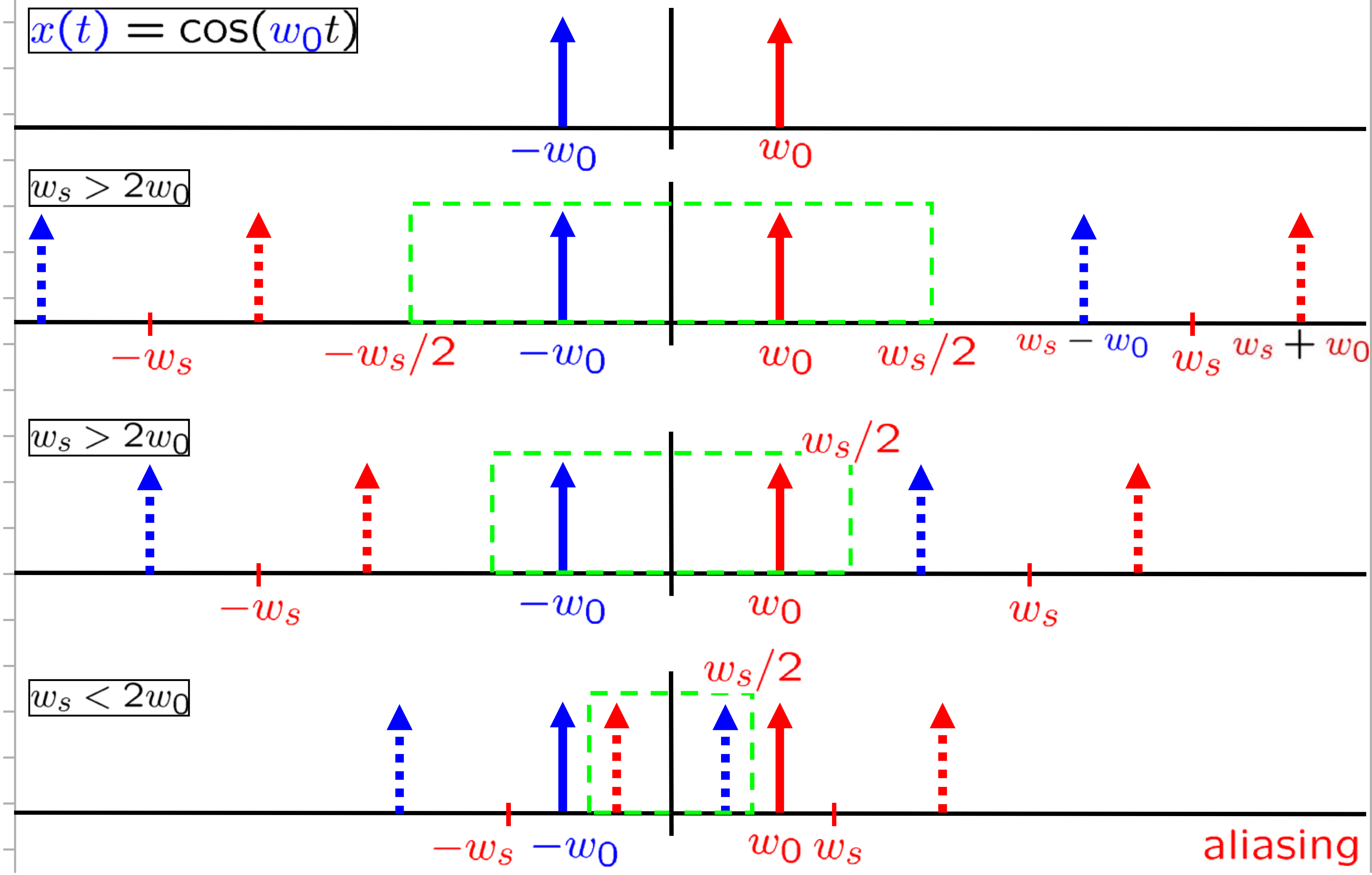
- Overlapping in Frequency-Domain: Aliasing



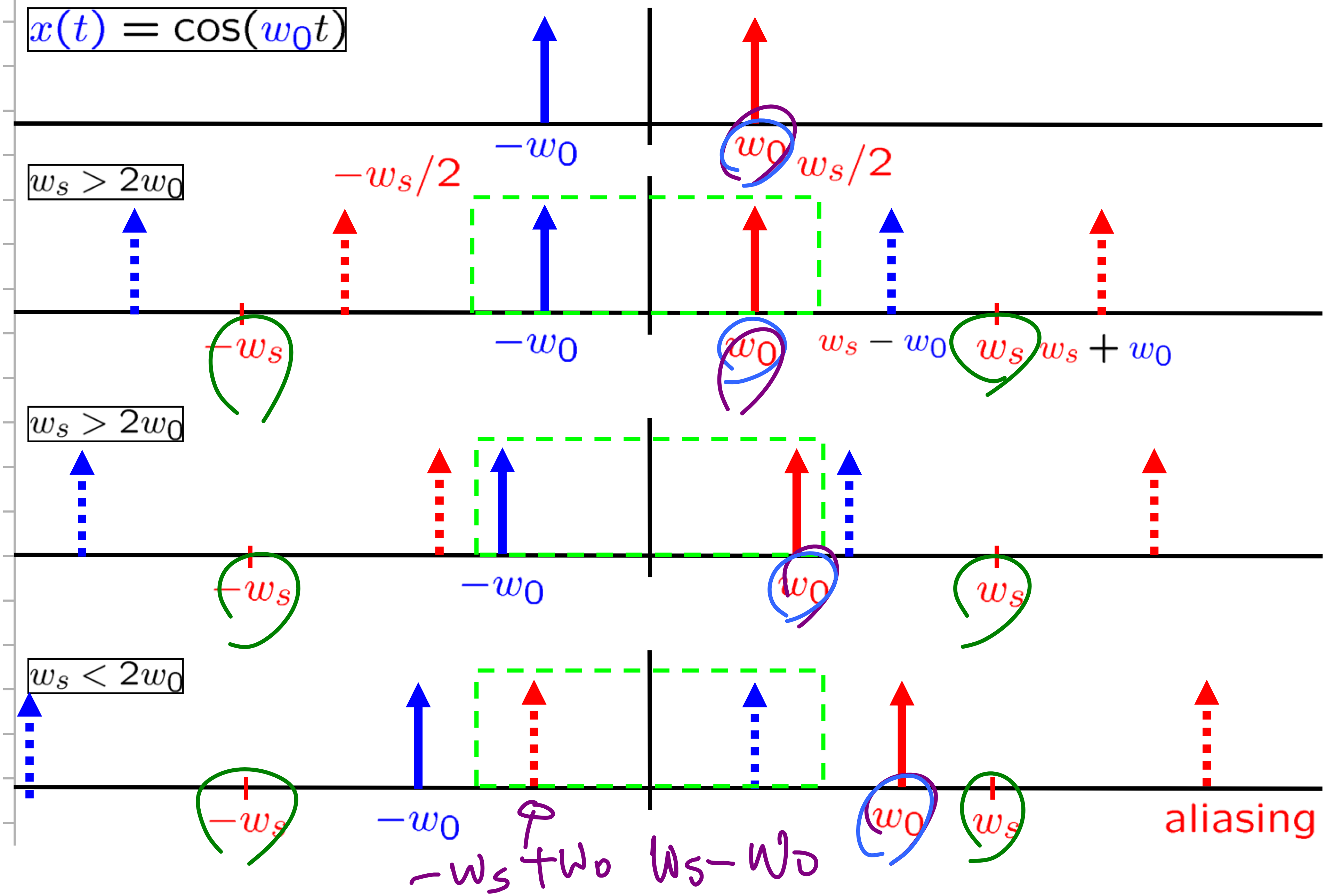
Overlapping in Frequency-Domain: Aliasing



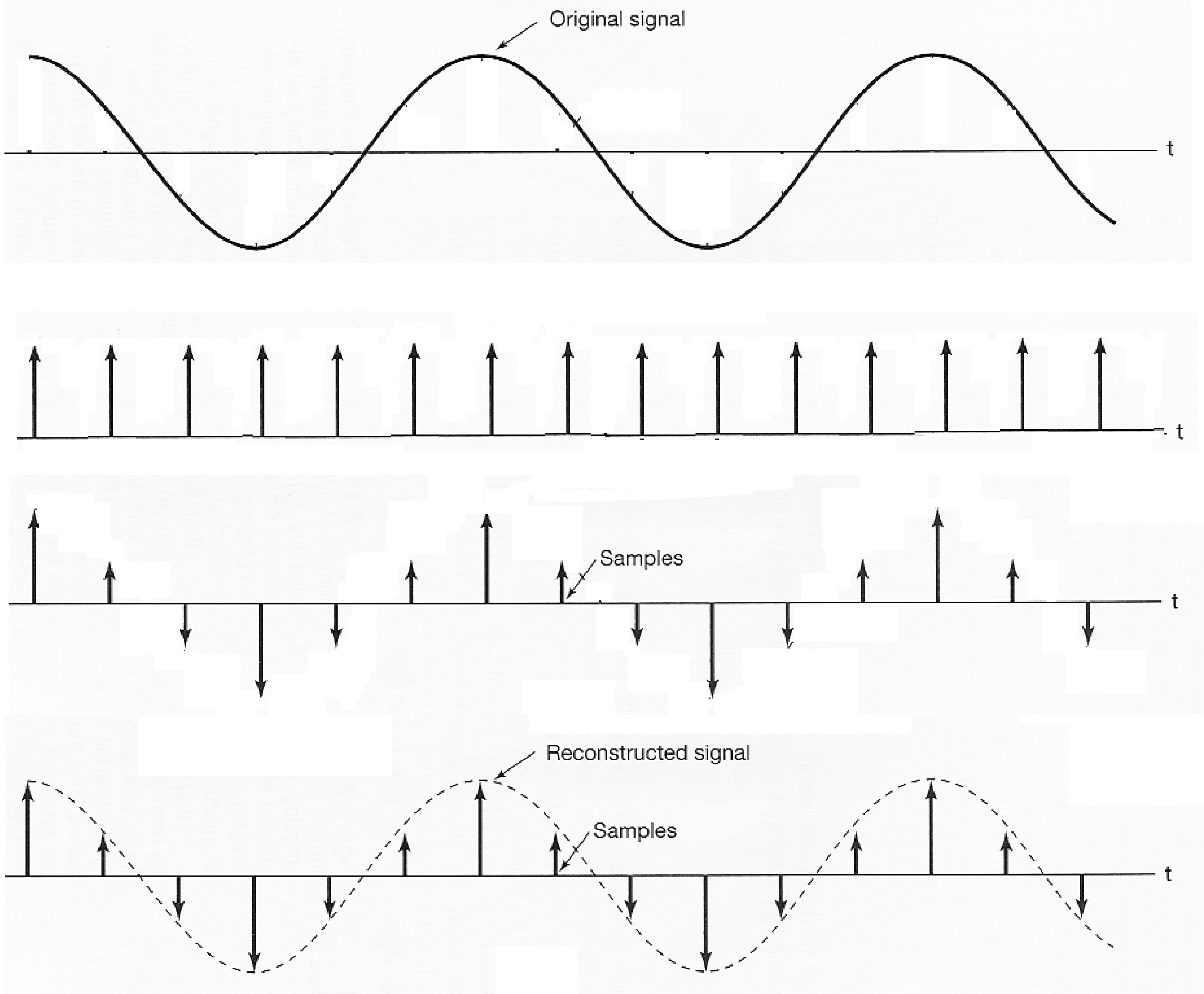
- Overlapping in Frequency-Domain: Aliasing



- Overlapping in Frequency-Domain: Aliasing

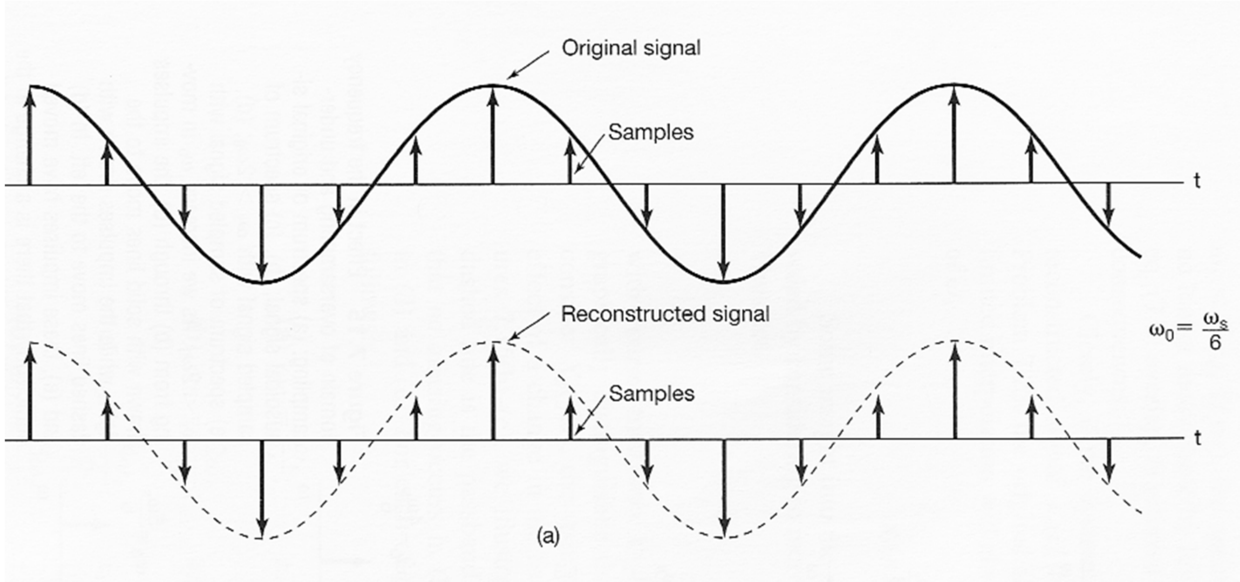


- Overlapping in Frequency-Domain: Aliasing

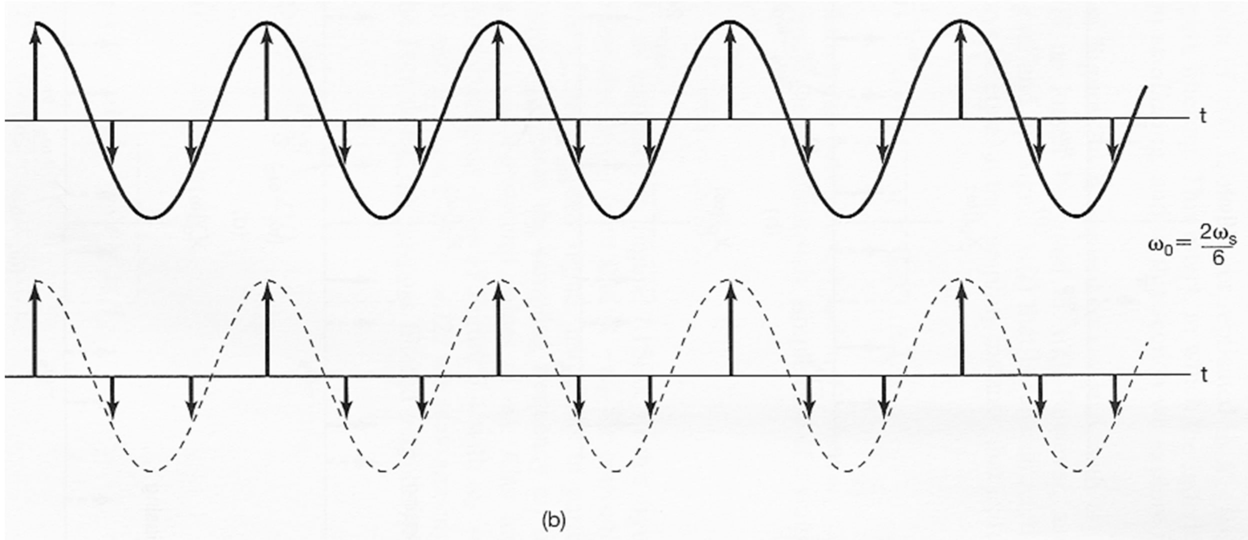


$$w_0 = \frac{w_s}{6}$$

- Overlapping in Frequency-Domain: Aliasing

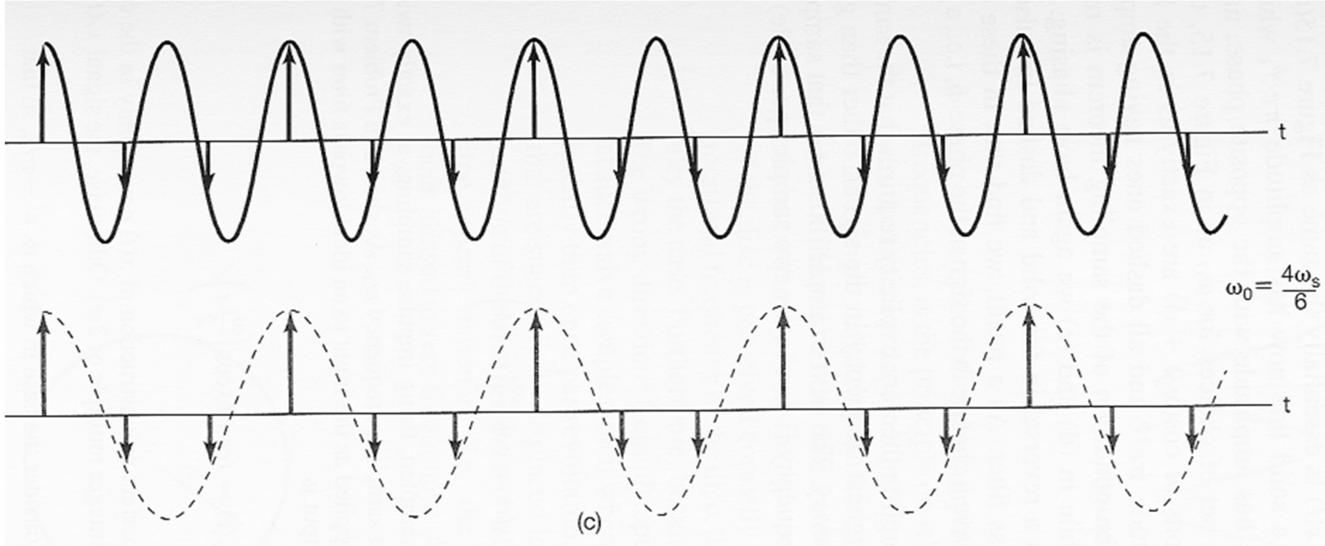


$$w_0 = \frac{w_s}{6}$$



$$w_0 = \frac{2w_s}{6}$$

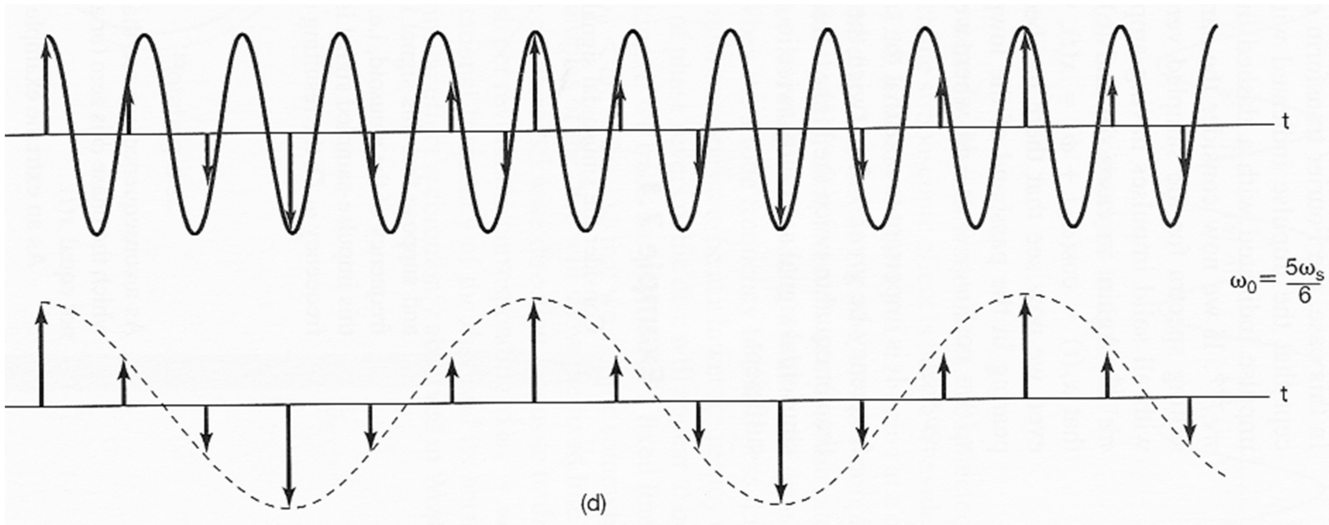
- Overlapping in Frequency-Domain: Aliasing



(c)

$$w_0 = \frac{4w_s}{6}$$

$$w_s - w_0 = w_s - \frac{4}{6}w_s$$
$$= \frac{2}{6}w_s$$



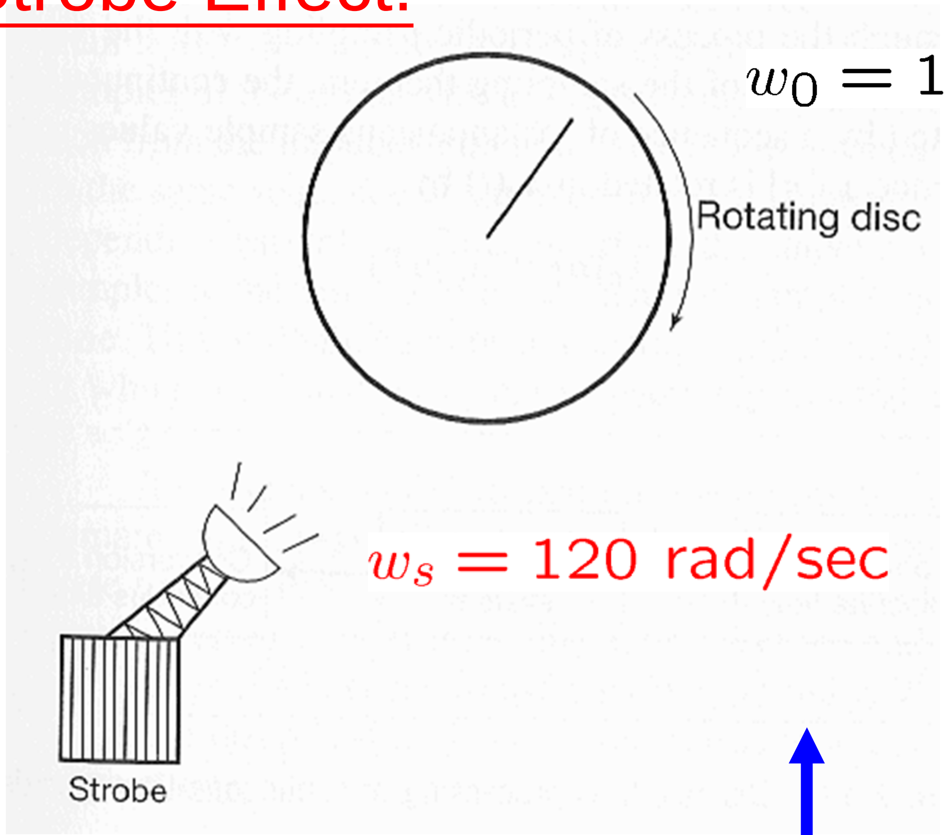
(d)

$$w_0 = \frac{5w_s}{6}$$

$$w_s - w_0 = w_s - \frac{5}{6}w_s$$
$$= \frac{1}{6}w_s$$

- Strobe Effect:

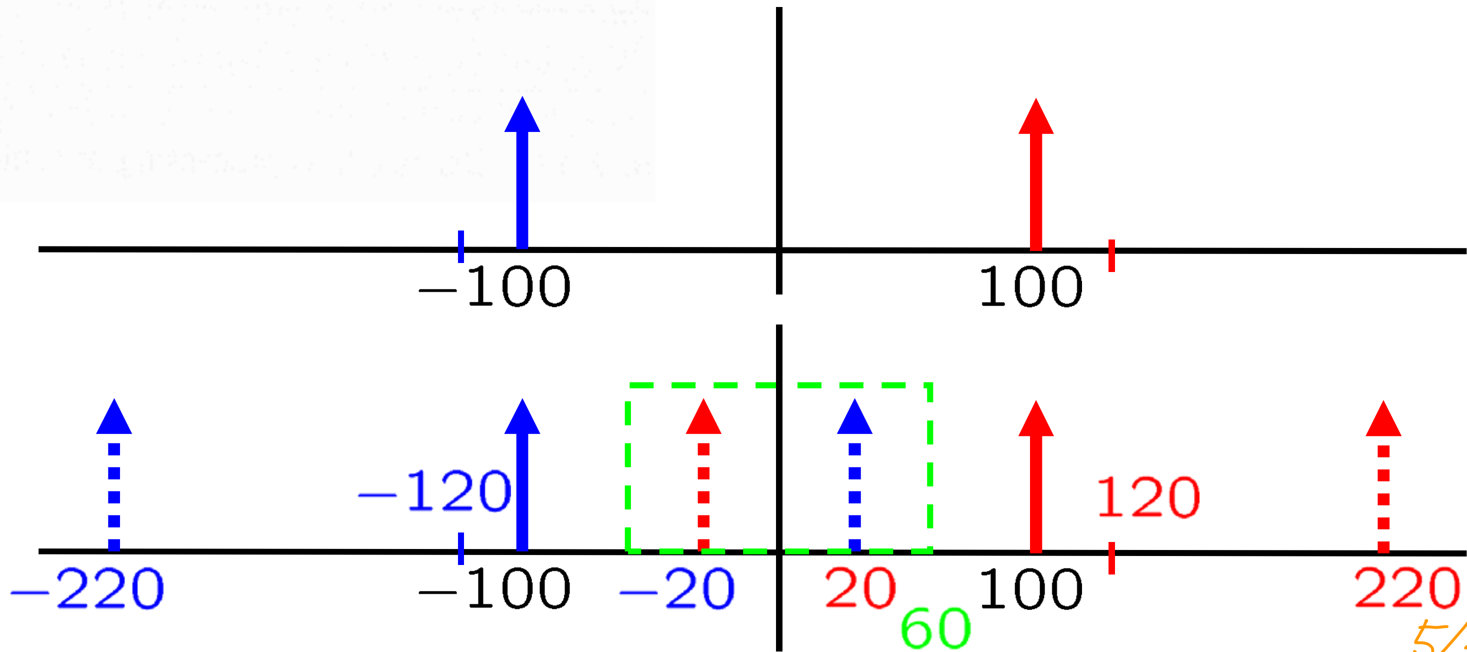
$$w_0 = 100 \text{ rad/sec}$$



$$w_s = 120 \text{ rad/sec}$$

$$\Rightarrow w = \pm w_s \pm w_0$$

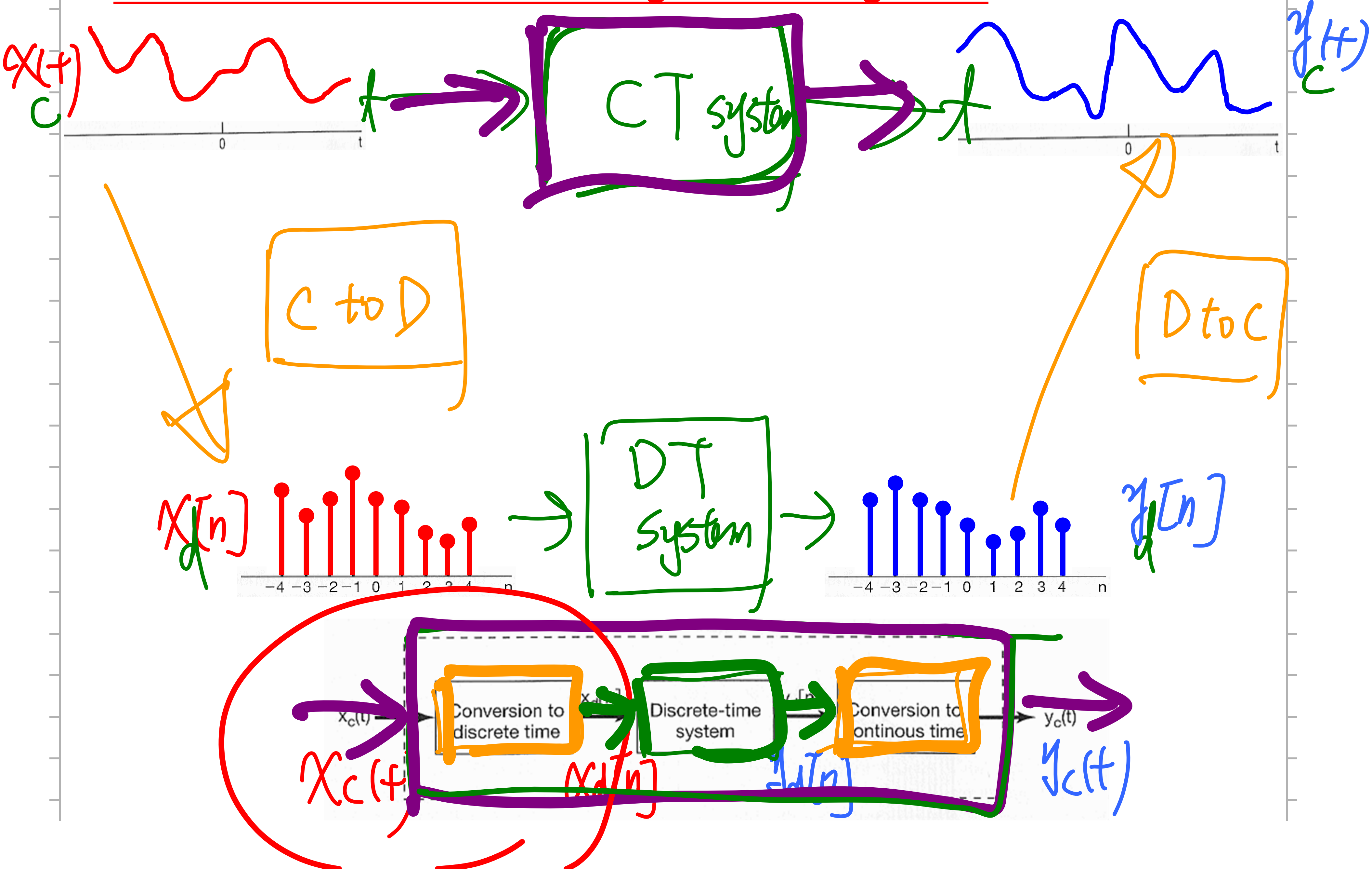
$$= +20, -20$$



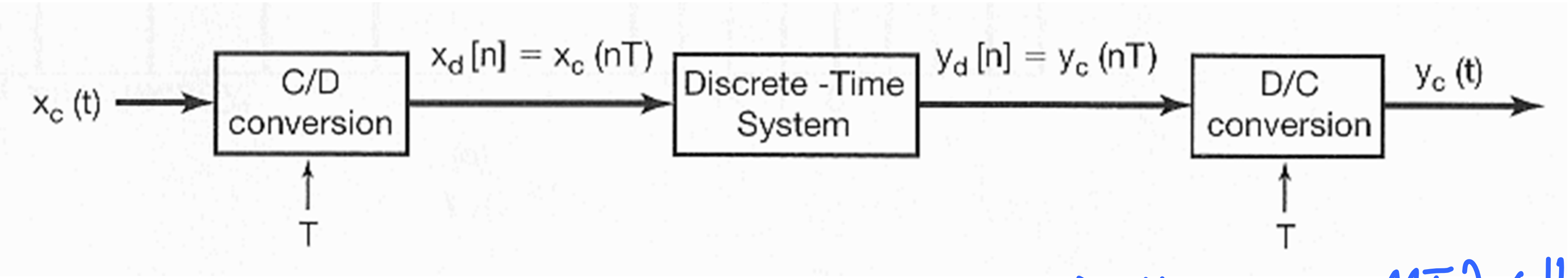
5/2/13
3:10 pm

- Representation of a Continuous-Time Signal by its Samples: The Sampling Theorem
- Reconstruction of a Signal from its Samples Using Interpolation
- The Effect of Under-sampling: Aliasing
- Discrete-Time Processing of Continuous-Time Signals
- Sampling of Discrete-Time Signals

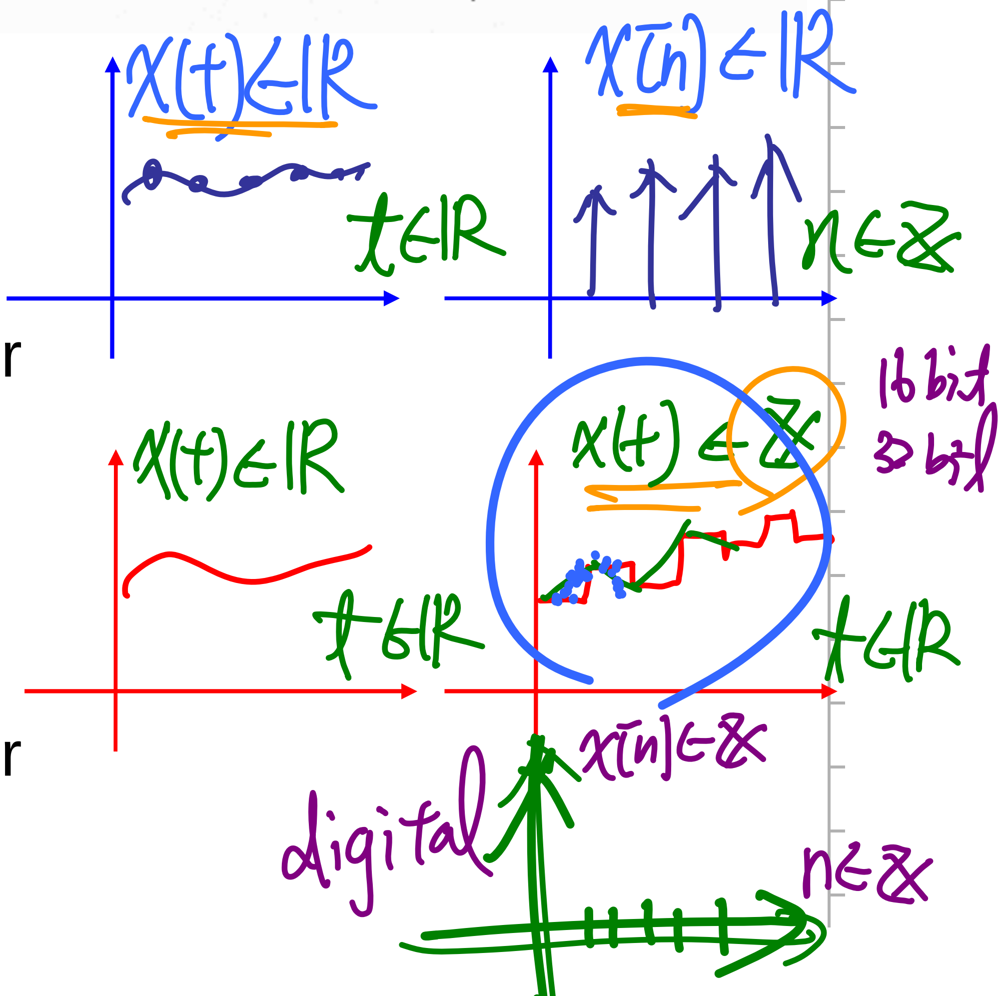
- Discrete-Time Processing of CT Signals:



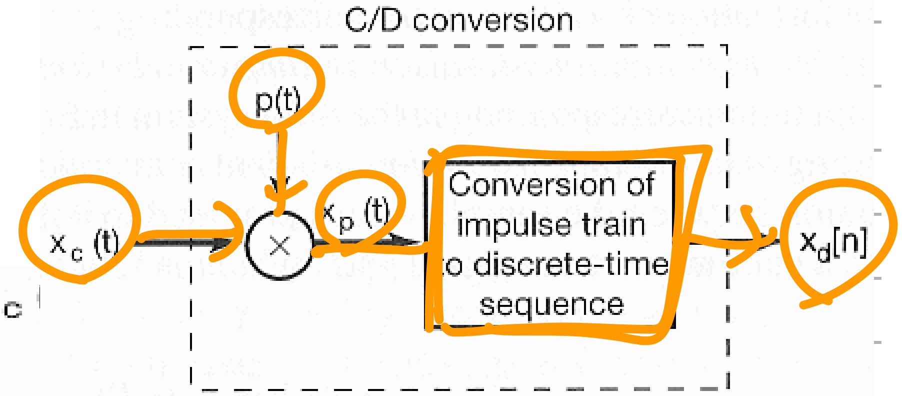
- C/D or A-to-D (ADC) and D/C or D-to-A (DAC):

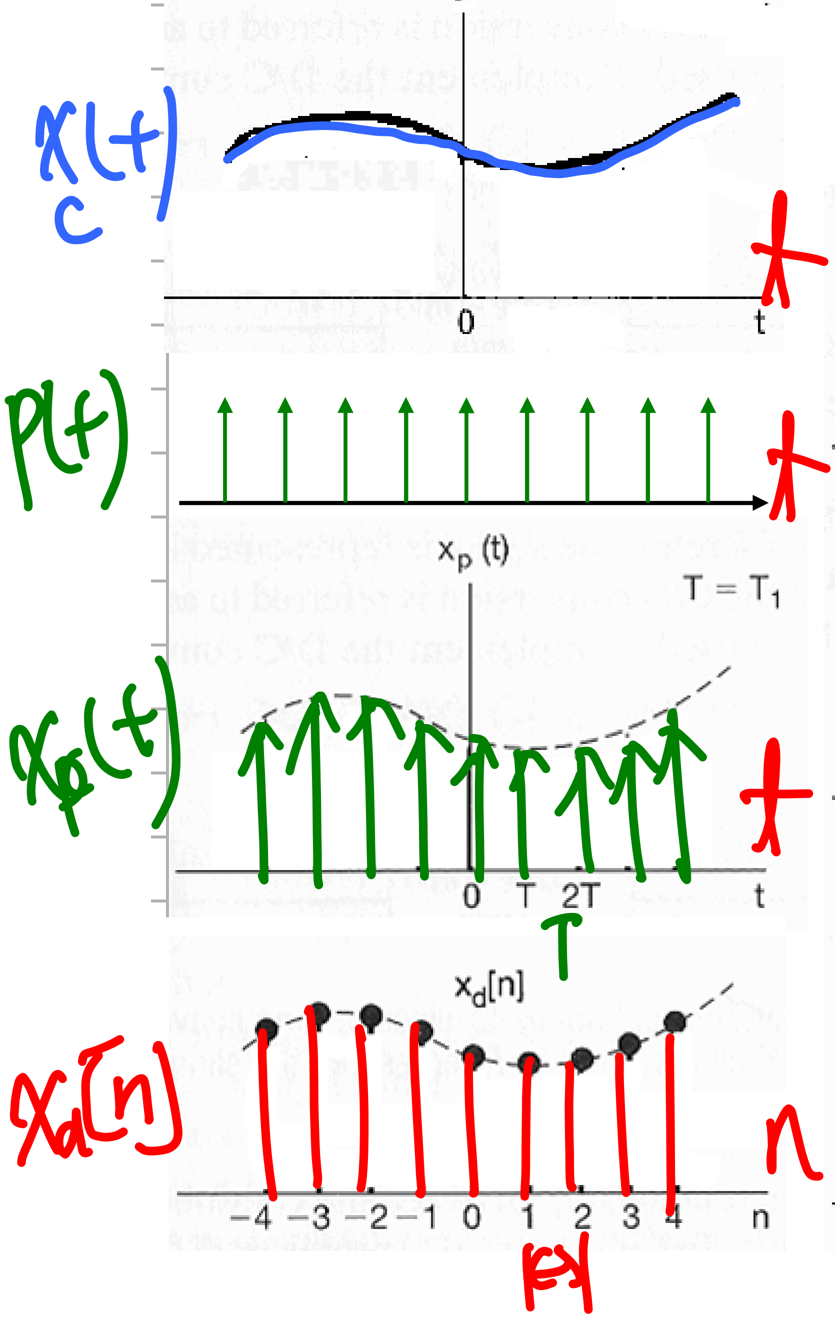


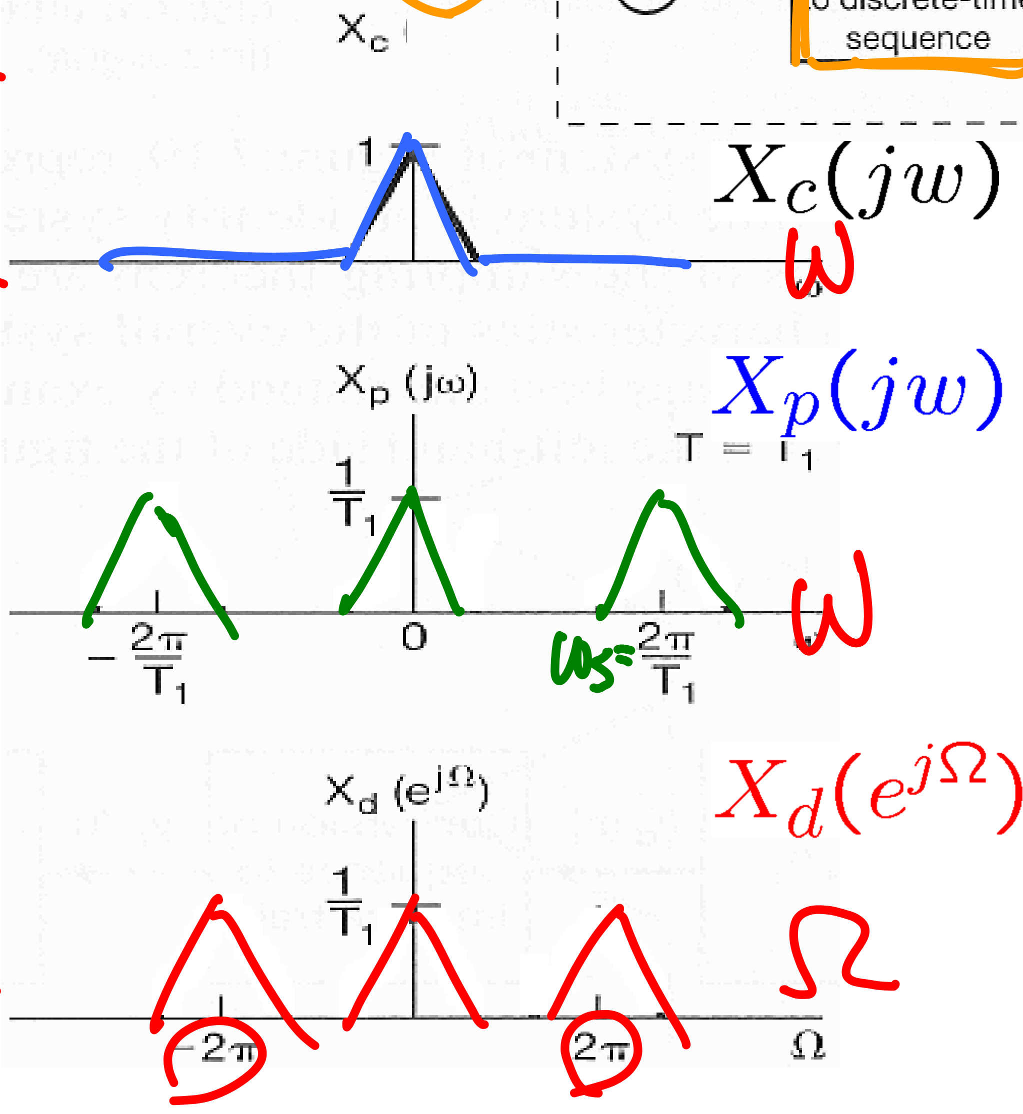
- C/D: continuous-to-discrete-time conversion
- A-to-D: analog-to-digital converter
- D/C: discrete-to-continuous-time conversion
- D-to-A: digital-to-analog converter

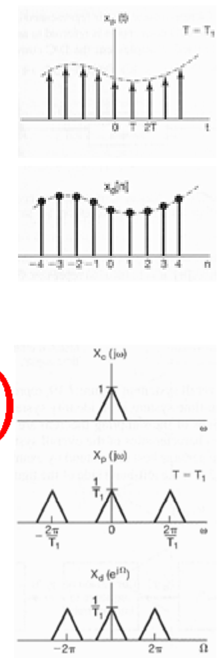


- C/D Conversion:



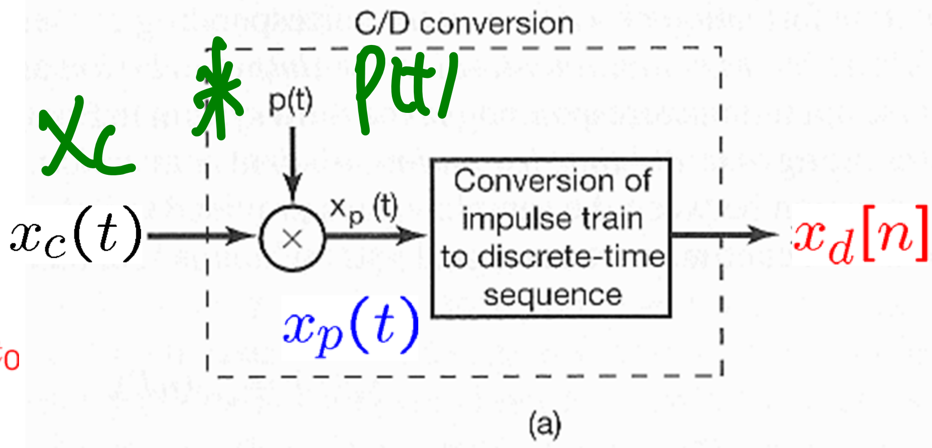






C/D Conversion:

$$x_p(t) = \sum_{n=-\infty}^{+\infty} x_c(nT)\delta(t-nT)$$



(a)

Table 4.2, p. 329

$$\delta(t-t_0) \overset{\mathcal{F}}{\longleftrightarrow} e^{-jwt_0}$$

$$X_p(jw) = \sum_{n=-\infty}^{+\infty} x_c(nT)e^{-jwnT} = \frac{1}{T}\sum_{k=-\infty}^{+\infty} X_c(j(w-kw_s))$$

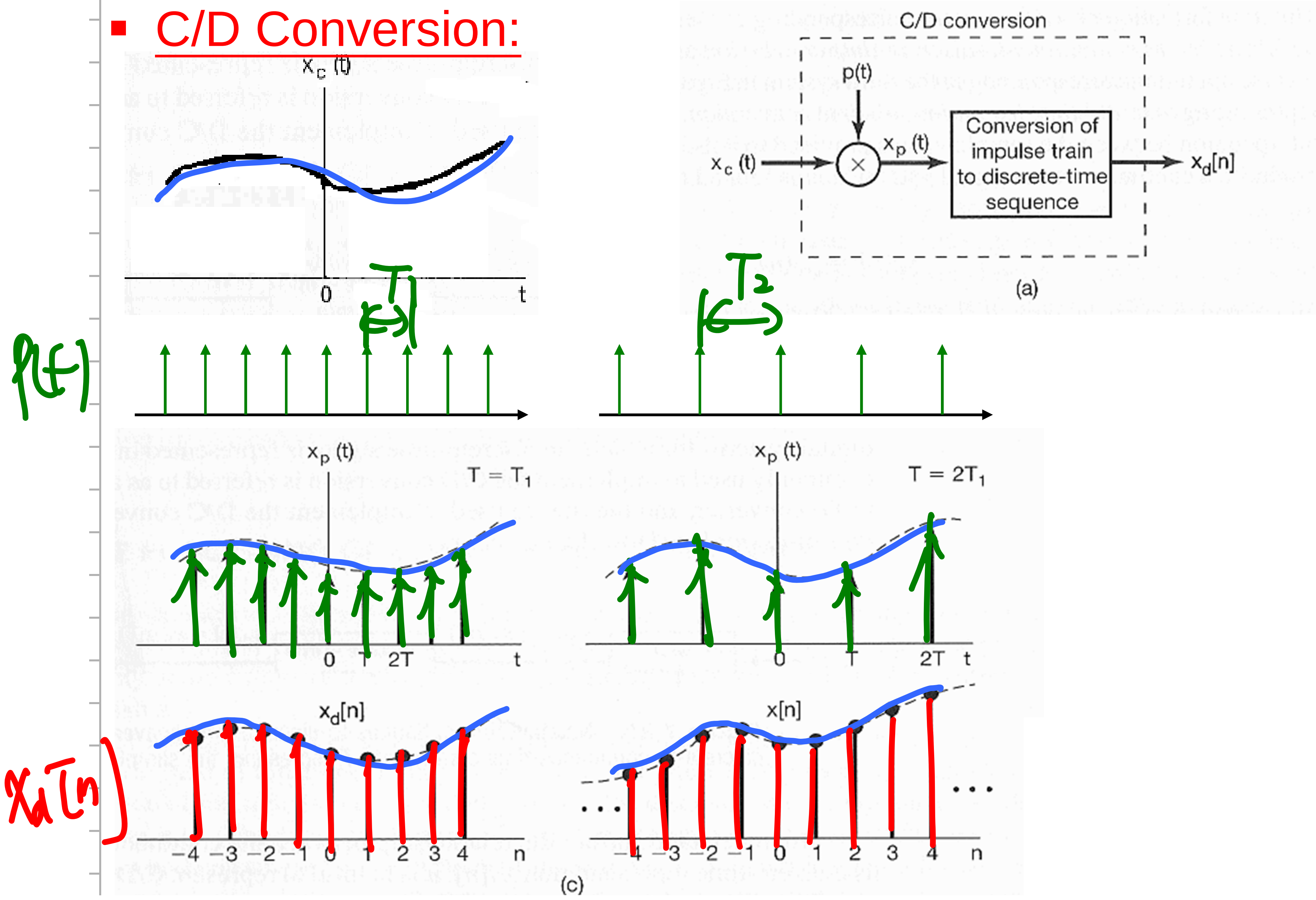
Eq 7.3, 7.6, p. 517

$$X_d(e^{j\Omega}) = \sum_{n=-\infty}^{+\infty} x_d[n]e^{-j\Omega n}$$

$$= \sum_{n=-\infty}^{+\infty} x_c(nT)e^{-j\Omega n} = \frac{1}{T}\sum_{k=-\infty}^{+\infty} X_c\left(j\left(\frac{\Omega}{T}-k\frac{2\pi}{T}\right)\right)$$

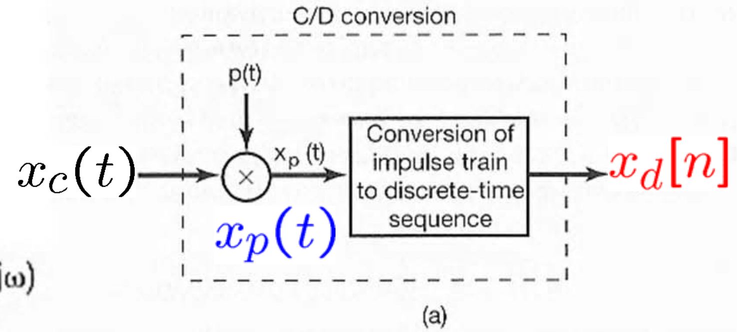
$$\Rightarrow \boxed{X_d(e^{j\Omega}) = X_p\left(j\frac{\Omega}{T}\right)}$$

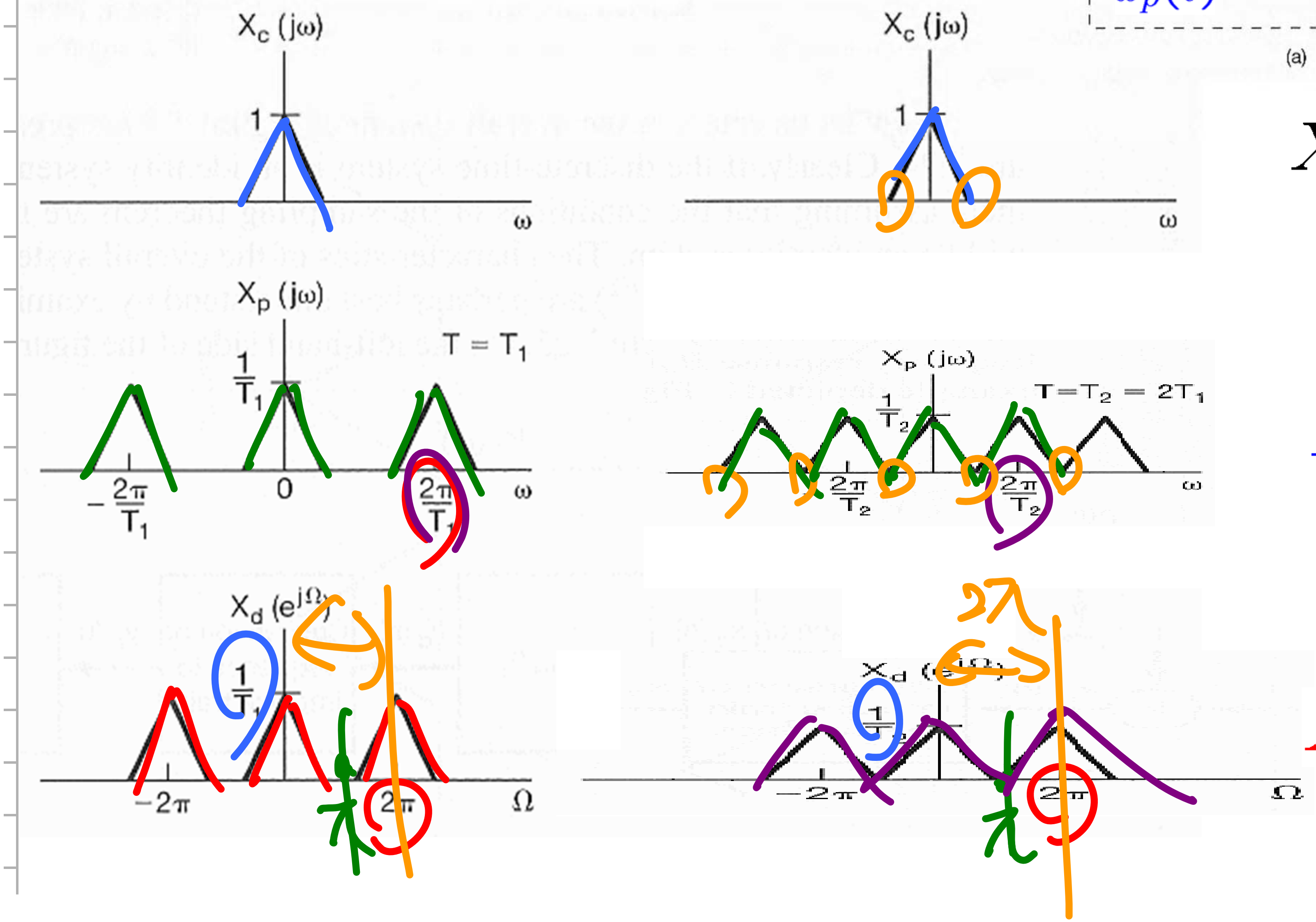
- C/D Conversion:



(c)

▪ C/D Conversion:



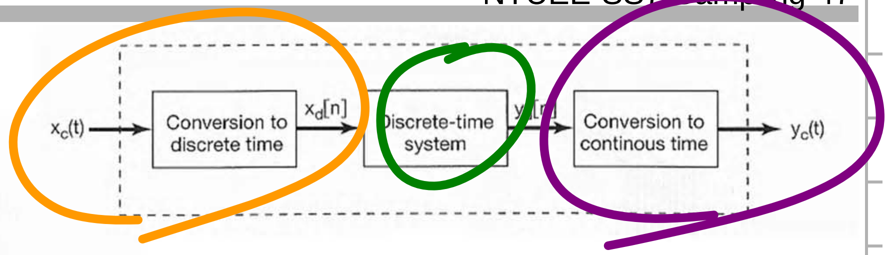


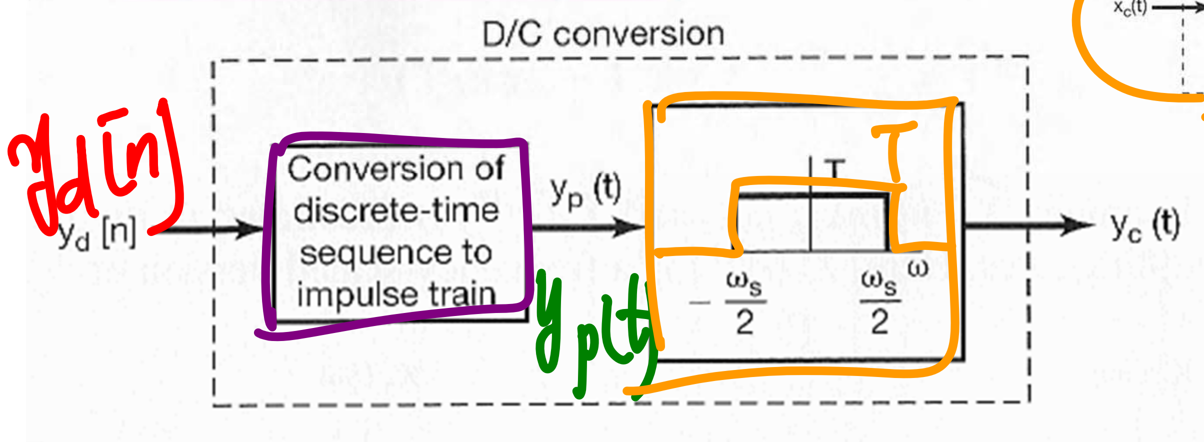
$X_c(jw)$

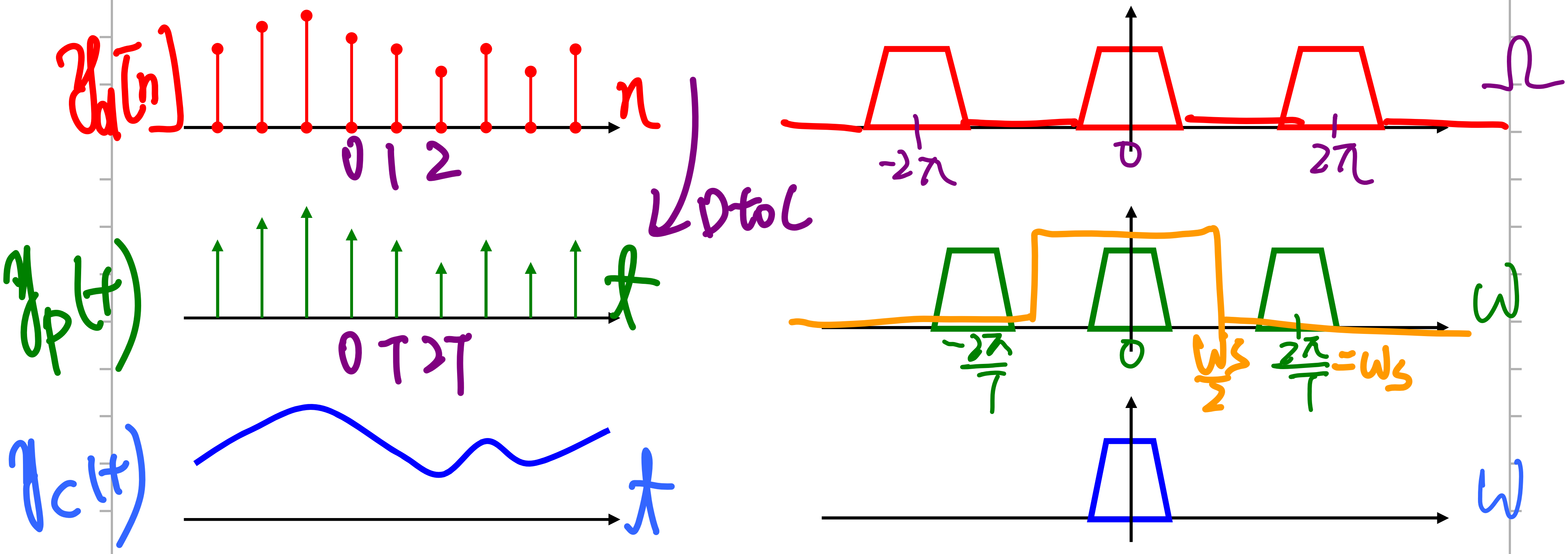
$X_p(jw)$

$X_d(e^{j\Omega})$

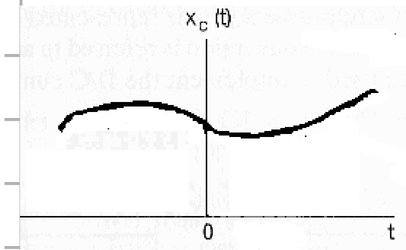
- **D/C Conversion:**



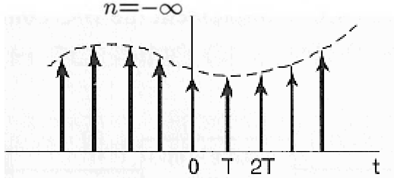


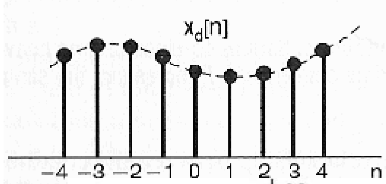


Overall System:



$$x_p(t) = \sum_{n=-\infty}^{+\infty} x_c(nT)\delta(t-nT)$$



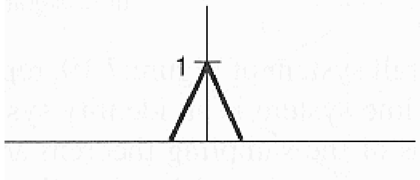


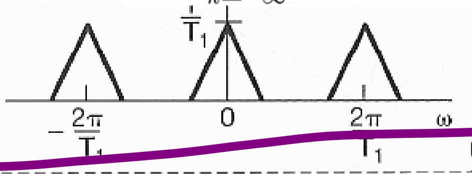
$$X_p(jw) = \sum_{n=-\infty}^{+\infty} x_c(nT)e^{-jwnT}$$

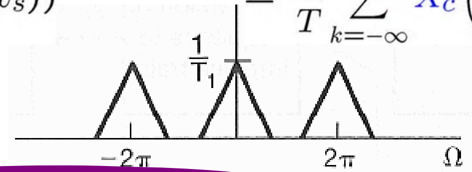
$$= \frac{1}{T}\sum_{k=-\infty}^{+\infty} X_c(j(w-kw_s))$$

$$X_d(e^{j\Omega}) = \sum_{n=-\infty}^{+\infty} x_d[n]e^{-j\Omega n} = \sum_{n=-\infty}^{+\infty} x_c(nT)e^{-j\Omega n}$$

$$= \frac{1}{T}\sum_{k=-\infty}^{+\infty} X_c\left(j\left(\frac{\Omega}{T}-k\frac{2\pi}{T}\right)\right)$$

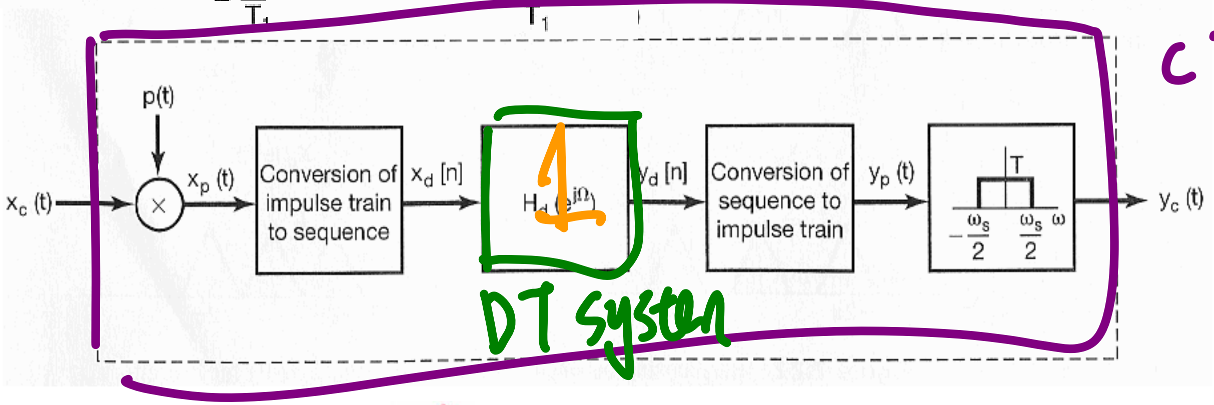


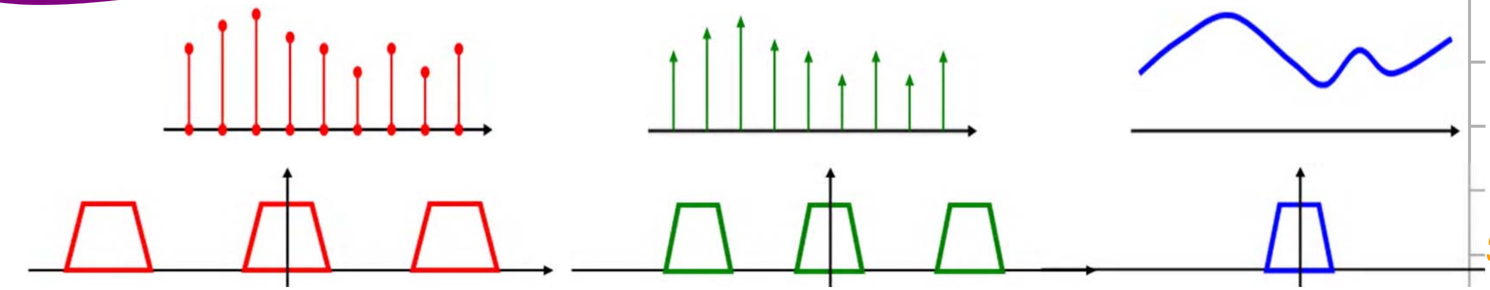




$$\Rightarrow X_d(e^{j\Omega}) = X_p\left(j\frac{\Omega}{T}\right)$$

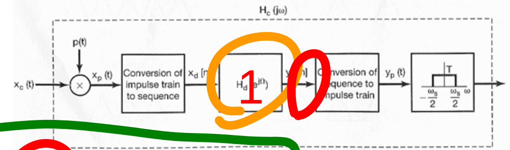
CT system



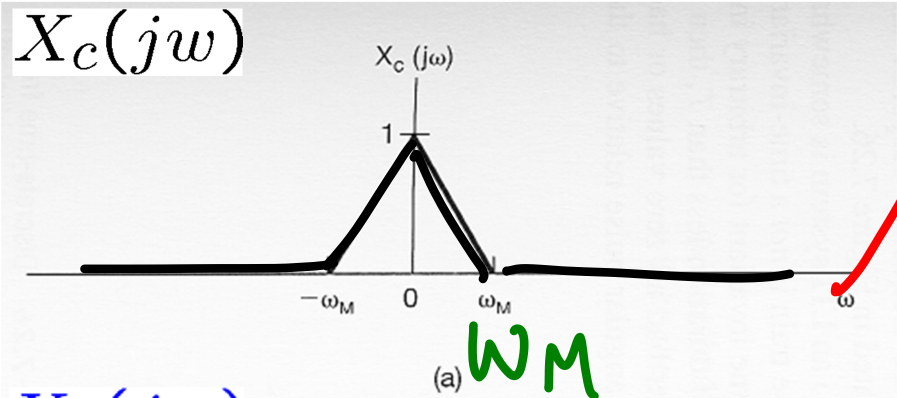


5/6/13
10:14 am

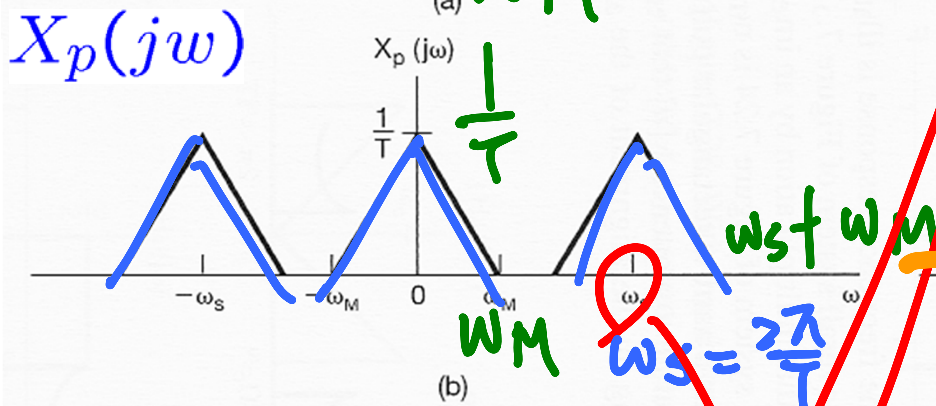
▪ Frequency-Domain Illustration:



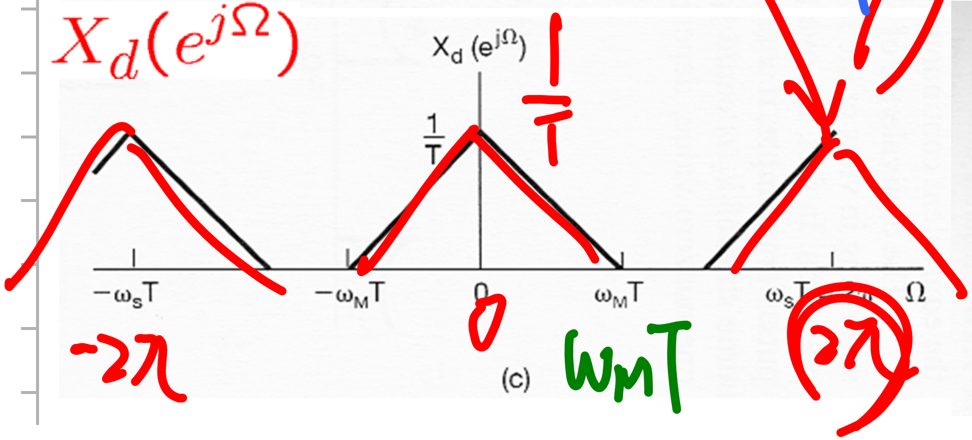
$$X_c(jw)$$



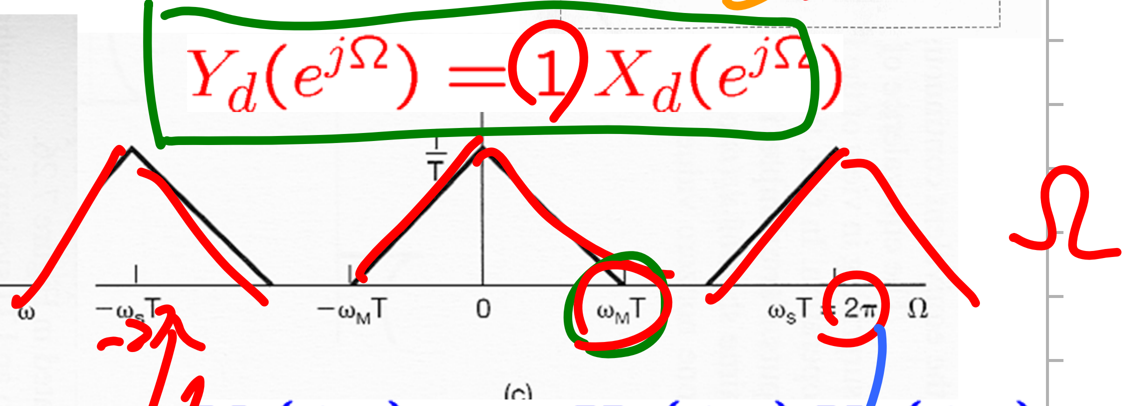
$$X_p(jw)$$



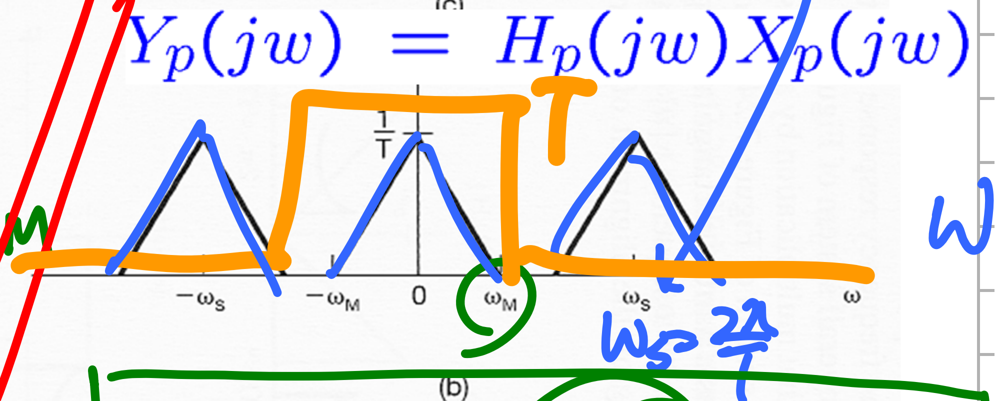
$$X_d(e^{j\Omega})$$



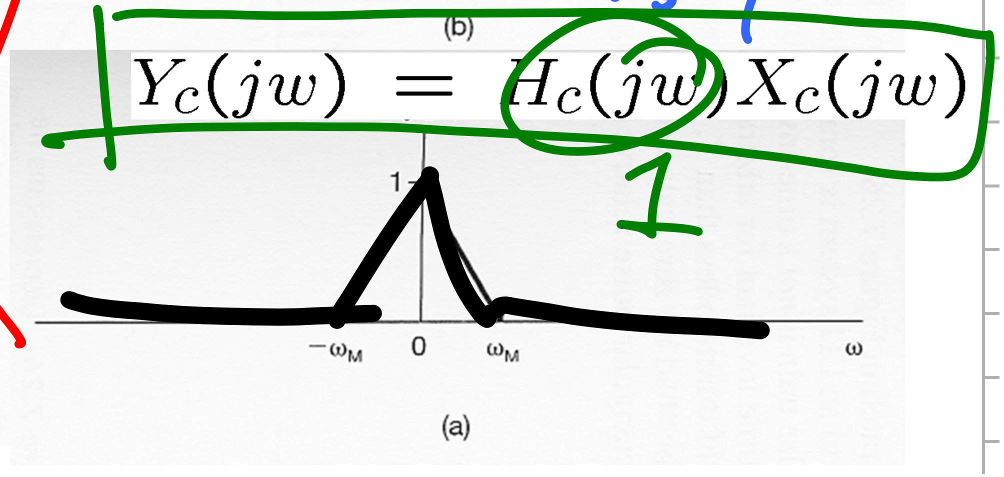
$$Y_d(e^{j\Omega}) = 1\, X_d(e^{j\Omega})$$



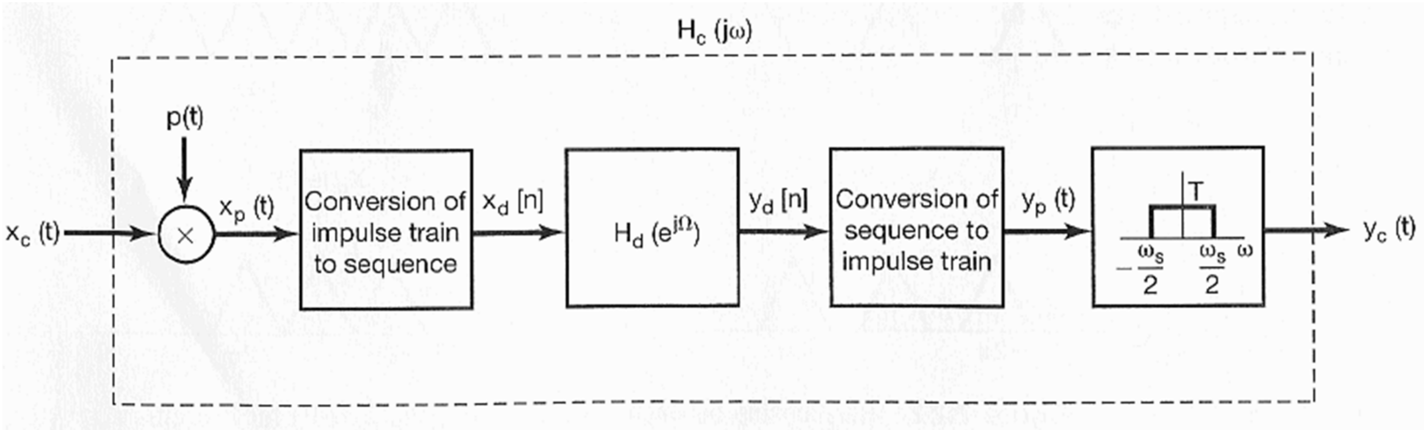
$$Y_p(jw) = H_p(jw) X_p(jw)$$



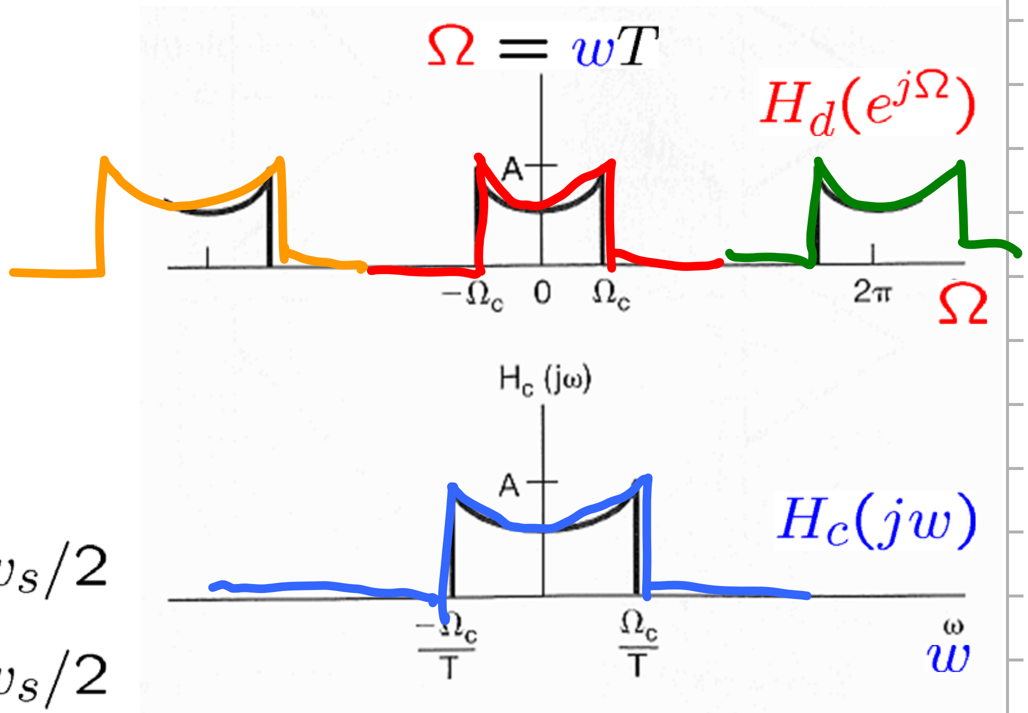
$$Y_c(jw) = H_c(jw) X_c(jw)$$



CT & DT Frequency Responses:

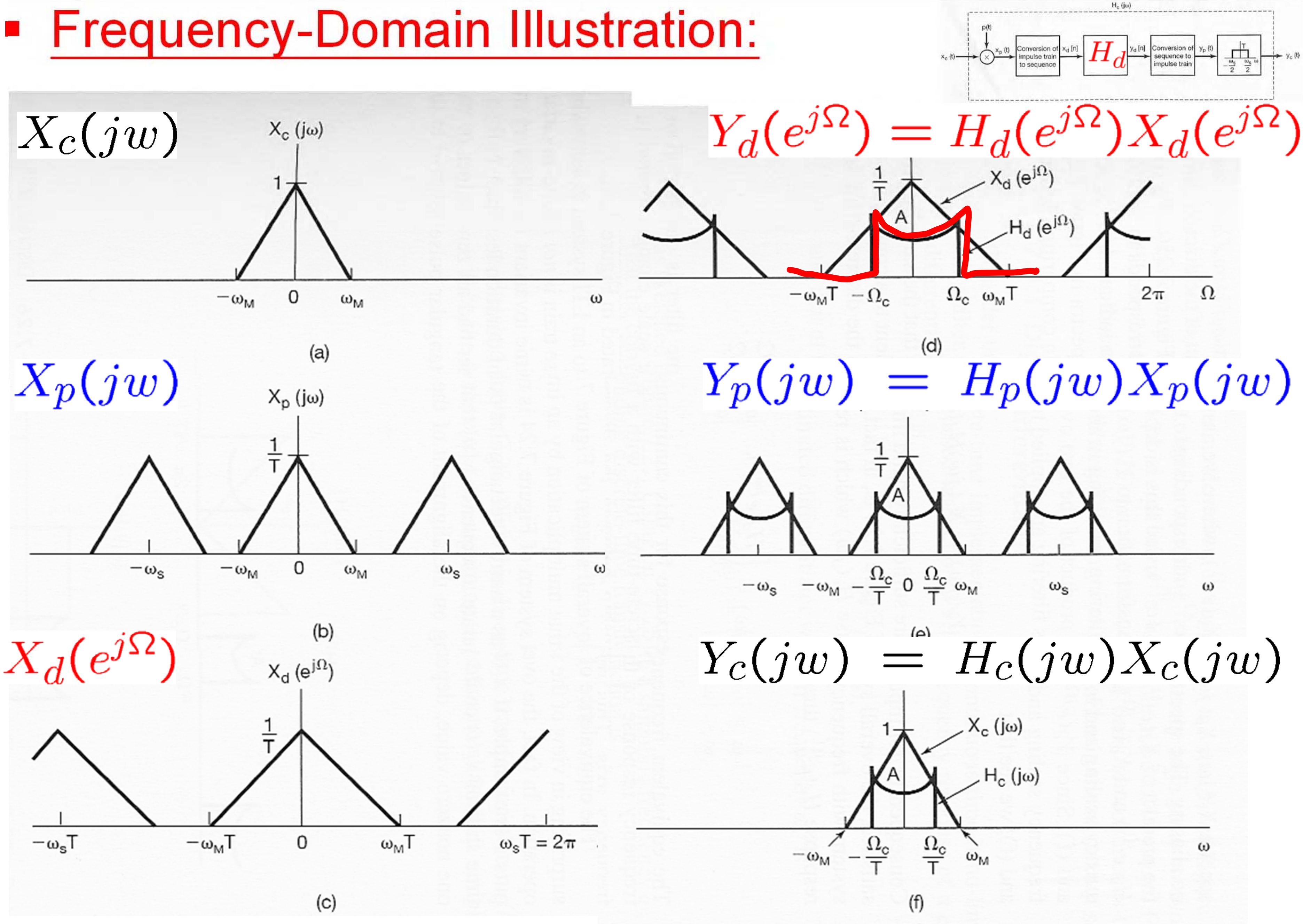


$$Y_c(jw) = X_c(jw)H_c(jw)$$



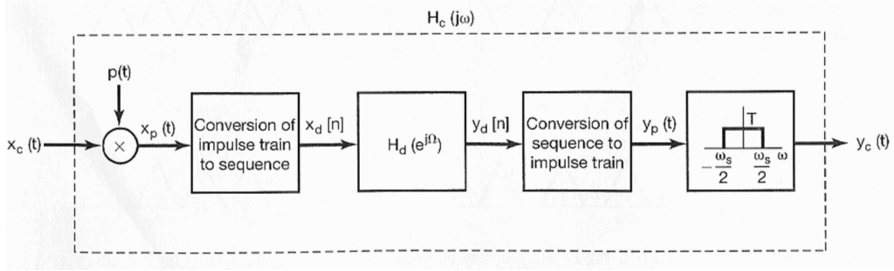
$$H_c(jw) = \begin{cases} H_d(e^{jwT}), & |w| < w_s/2 \\ 0, & |w| > w_s/2 \end{cases}$$

Frequency-Domain Illustration:



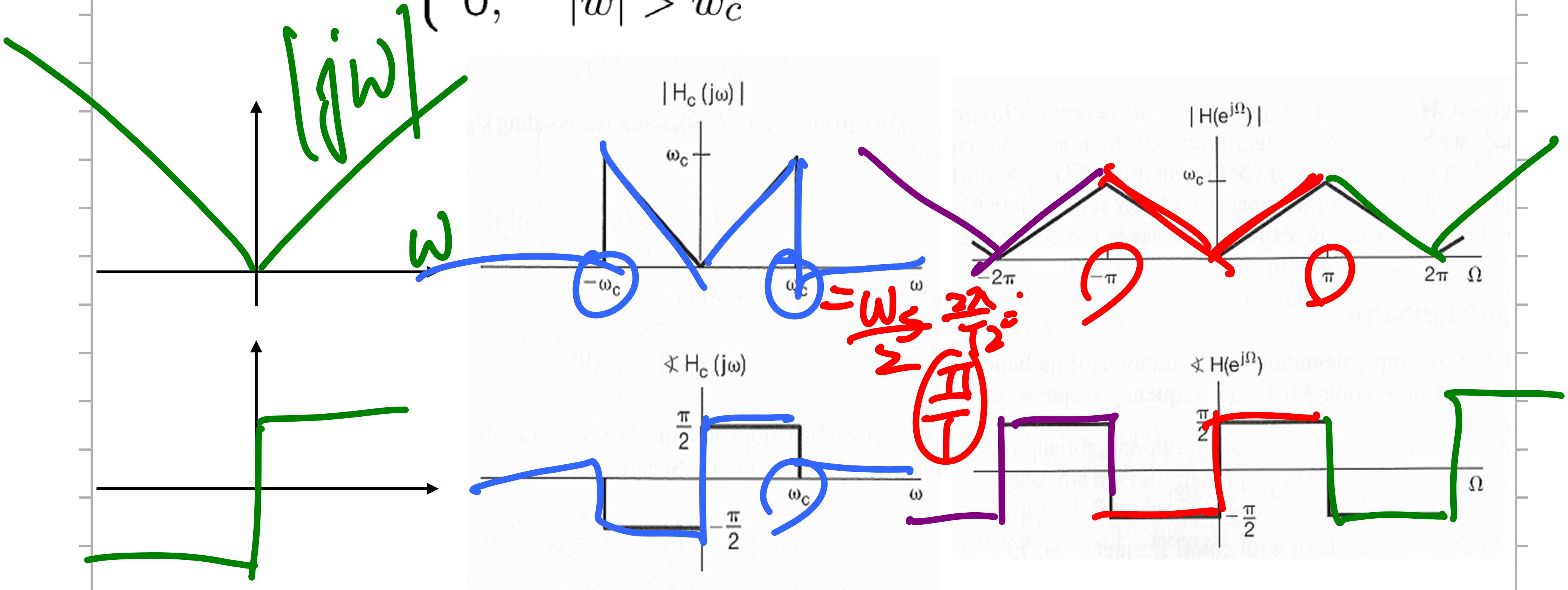
- Digital Differentiator: (band-limited)

Ex 4.16, p. 317



$$H_c(jw) = \begin{cases} jw, & |w| < w_c \\ 0, & |w| > w_c \end{cases}$$

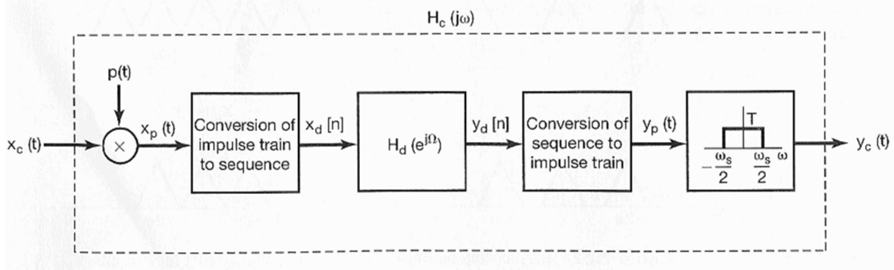
$$H_d(e^{j\Omega}) = j\left(\frac{\Omega}{T}\right), \quad |\Omega| < \pi$$



$$\Omega = wT, \;\; w_s = 2w_c$$

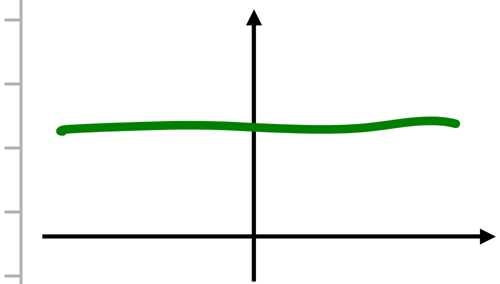
- Delay:
  (band-limited)

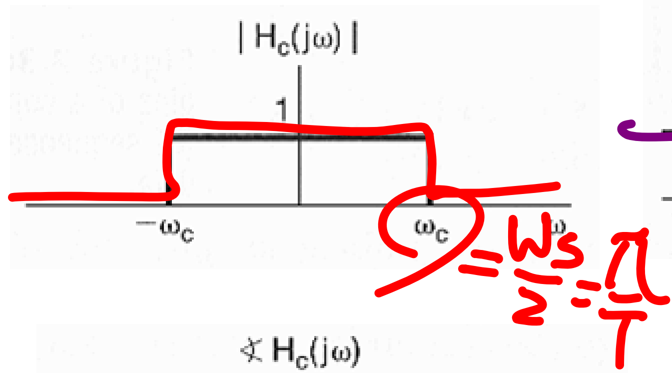
Ex 4.15, p. 317

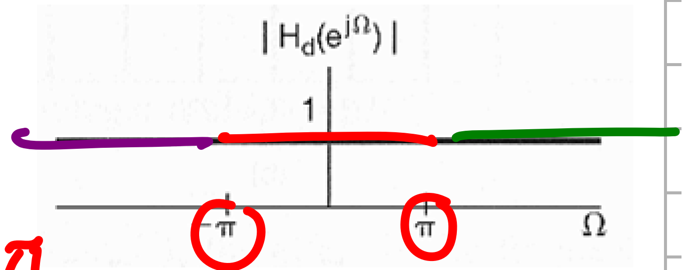


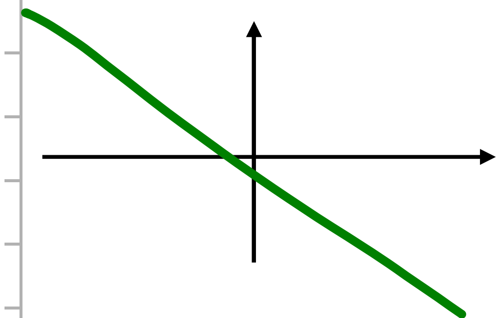
$$H_c(jw) = \begin{cases} e^{-jw\Delta}, & |w| < w_c \\ 0, & |w| > w_c \end{cases}$$

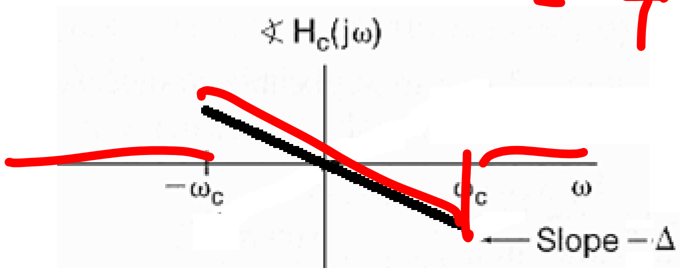
$$H_d(e^{j\Omega}) = e^{-j\Omega\Delta/T}, \quad |\Omega| < \pi$$

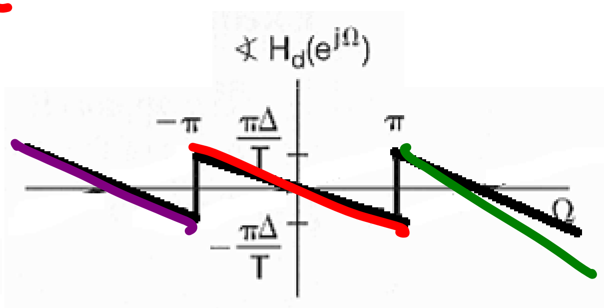












$$\Omega = wT, \; w_s = 2w_c$$

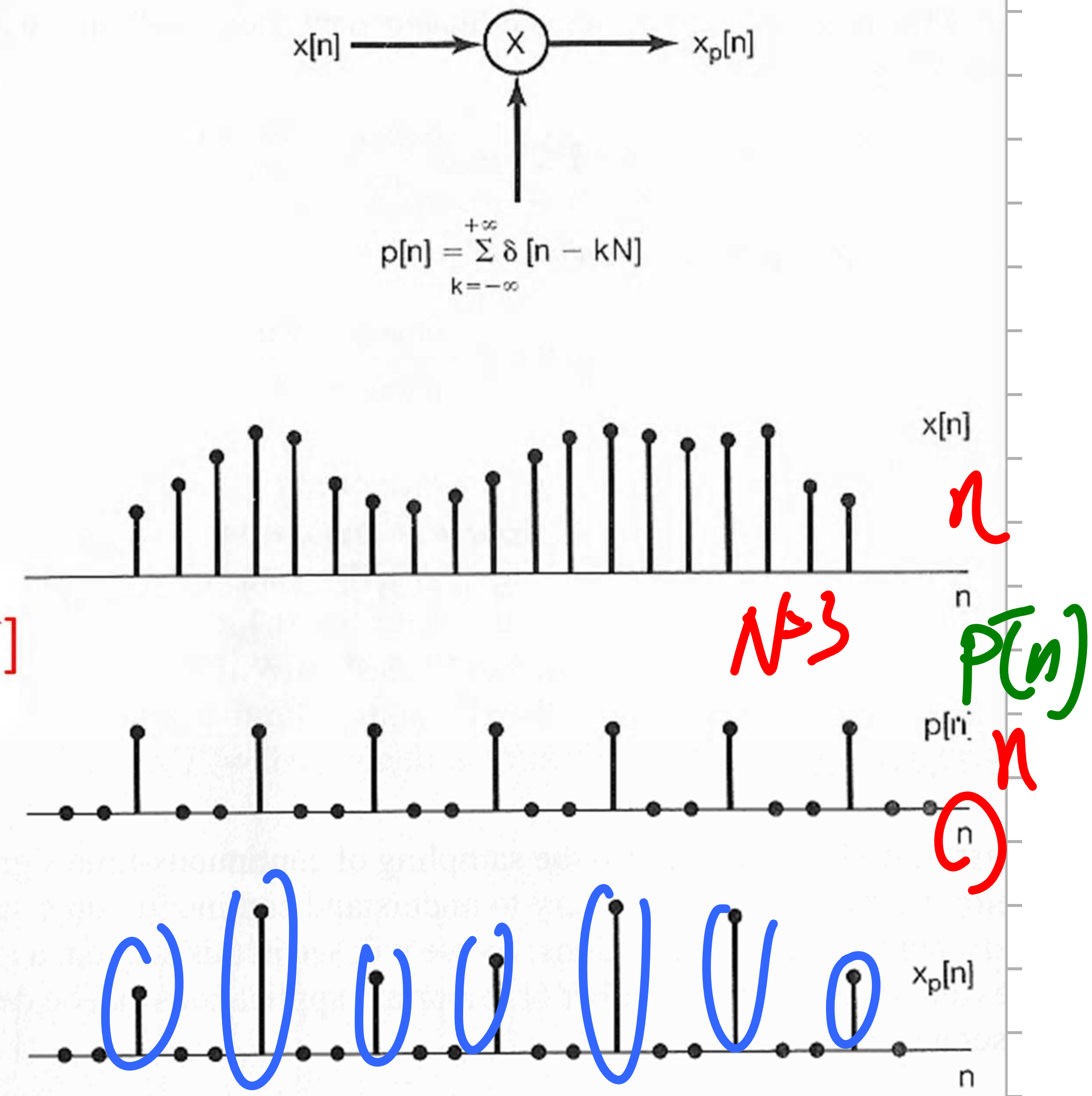
- Representation of a Continuous-Time Signal by its Samples: The Sampling Theorem
- Reconstruction of a Signal from its Samples Using Interpolation
- The Effect of Under-sampling: Aliasing
- Discrete-Time Processing of Continuous-Time Signals
- Sampling of Discrete-Time Signals

Impulse-Train Sampling:

$$x_p[n] = \begin{cases} x[n], & \text{if } n = kN \\ 0, & \text{otherwise} \end{cases}$$

$$x_p[n] = x[n]\, p[n]$$

$$= \sum_{k=-\infty}^{+\infty} x[kN]\, \delta[n - kN]$$

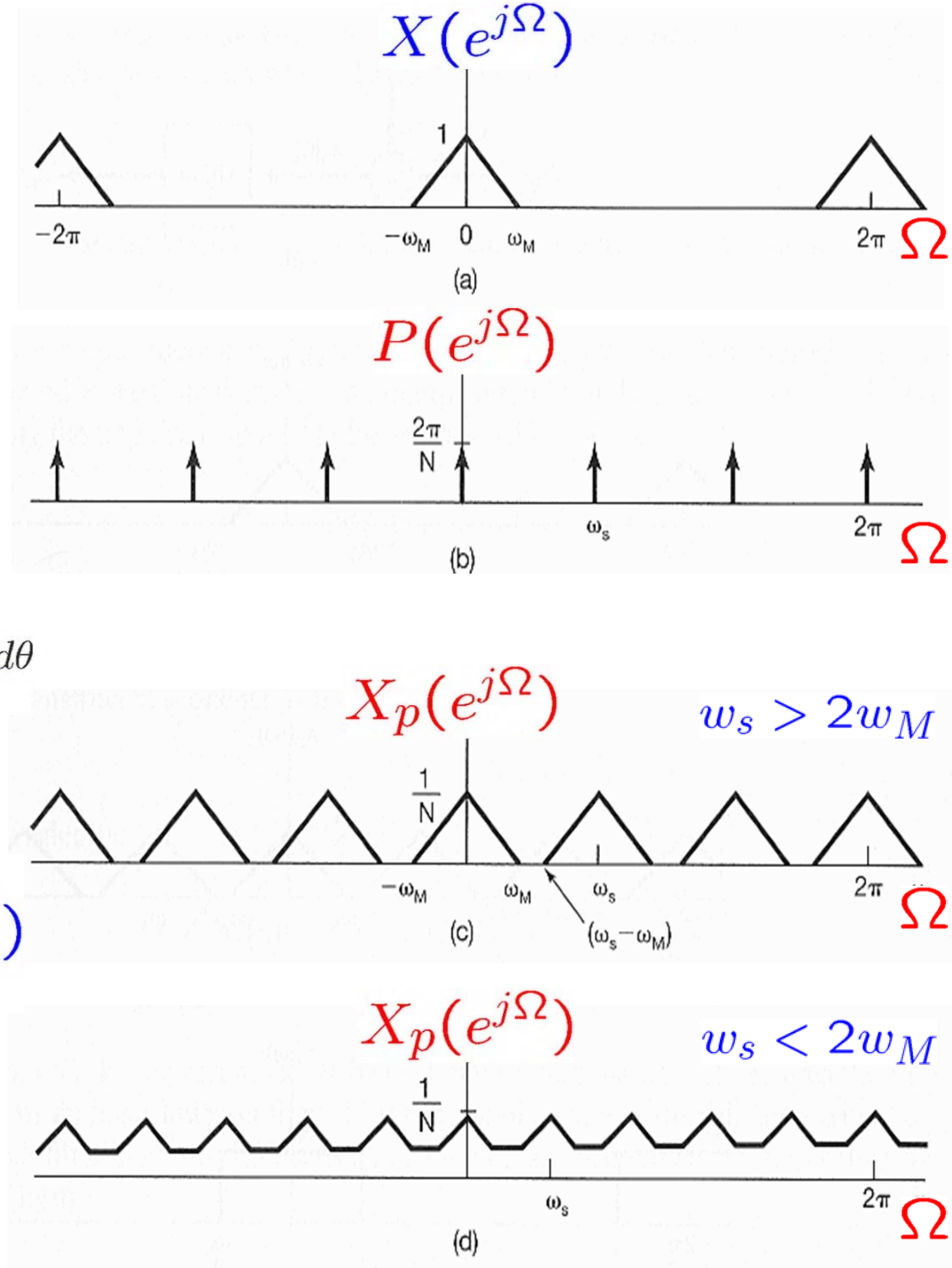


- Impulse-Train Sampling:

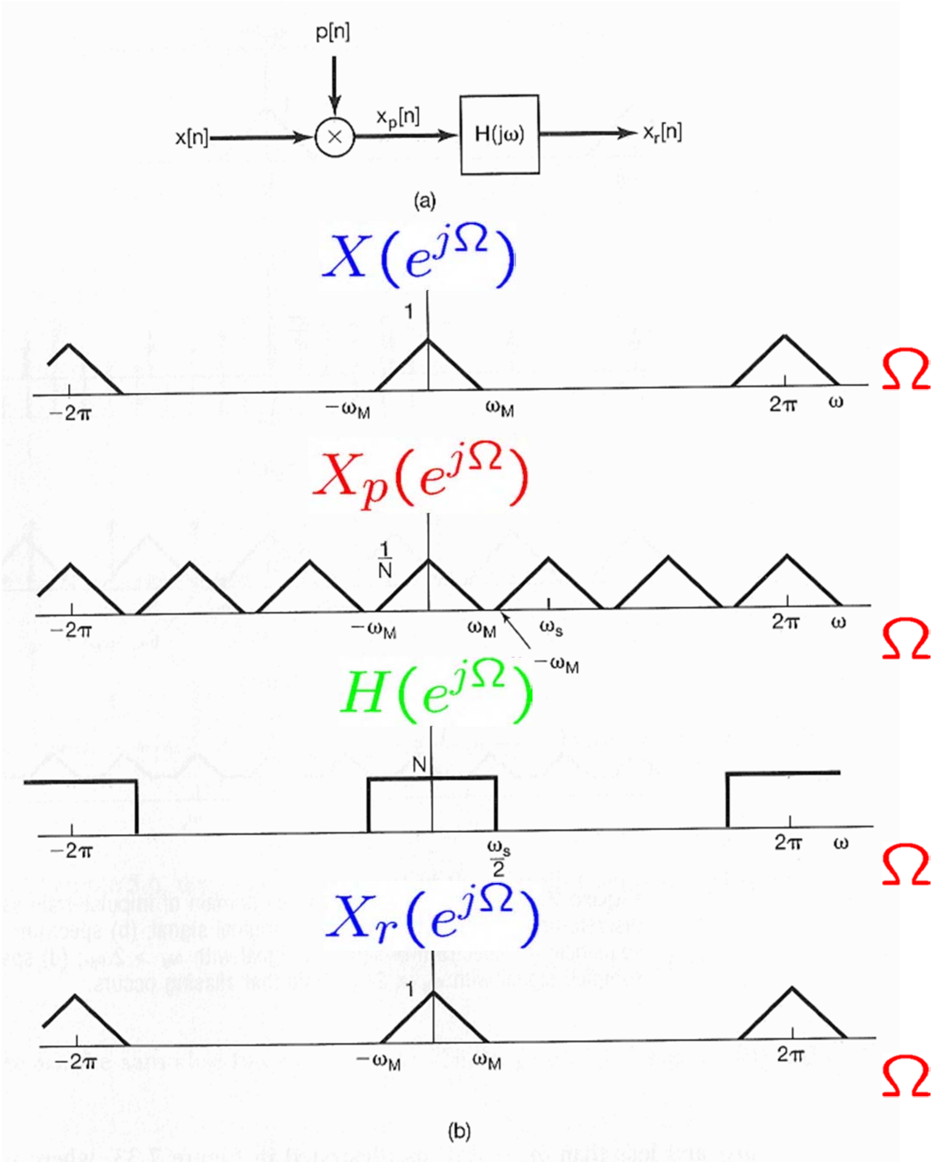
$$P(e^{j\Omega}) = \frac{2\pi}{N} \sum_{k=-\infty}^{+\infty} \delta(\Omega - k w_s)$$

$$X_p(e^{j\Omega}) = \frac{1}{2\pi} \int_{2\pi} P(e^{j\theta}) X(e^{j(\Omega-\theta)}) d\theta$$

$$\Rightarrow \; X_p(e^{j\Omega}) = \frac{1}{N} \sum_{k=0}^{N-1} X(e^{j(\Omega - k w_s)})$$

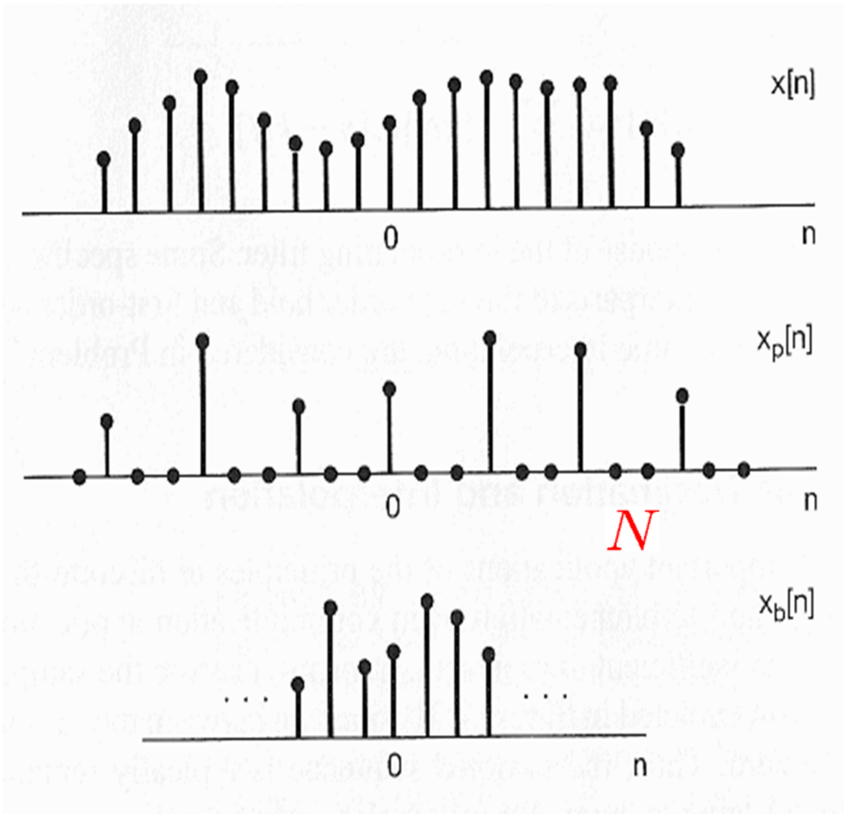


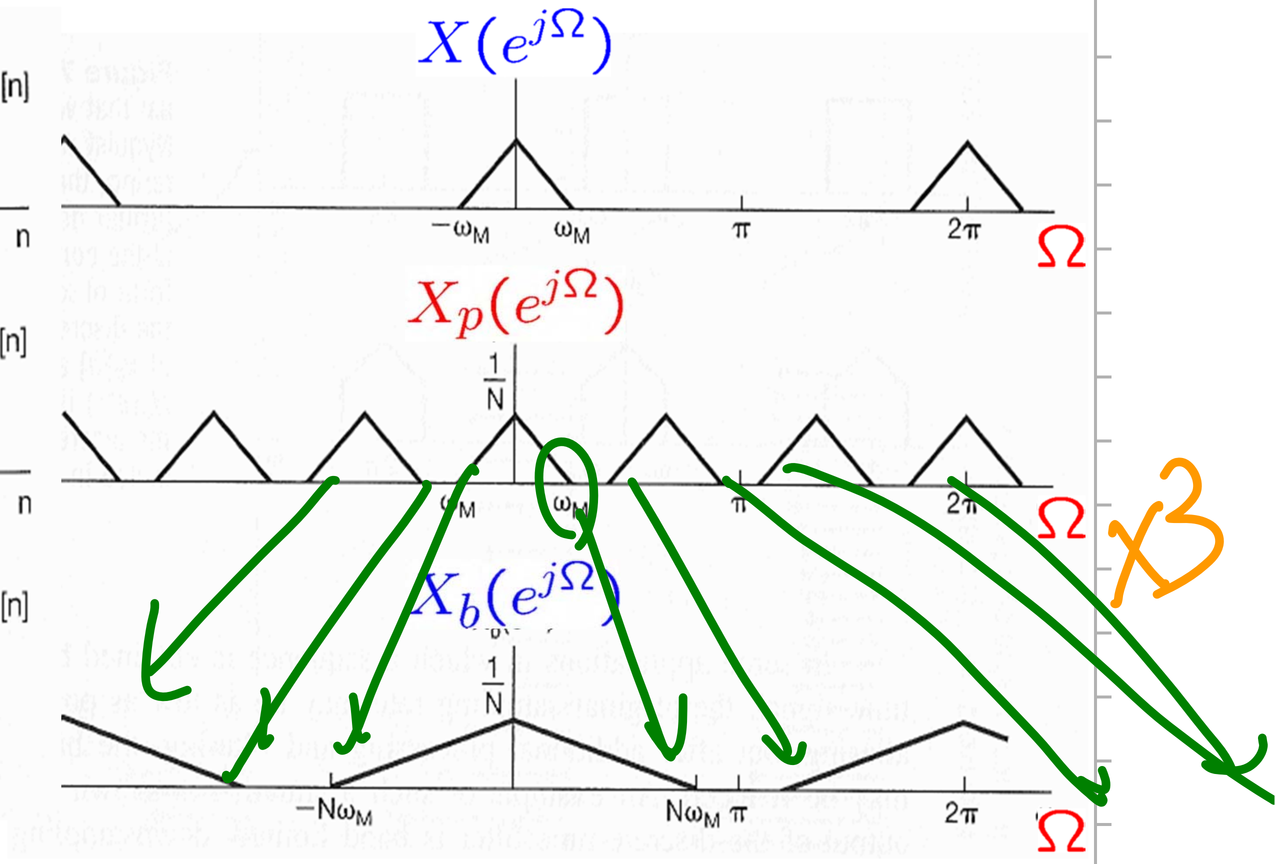
- Exact Recovery Using Ideal Lowpass Filter:



▪ DT Decimation & Interpolation: Down-sampling

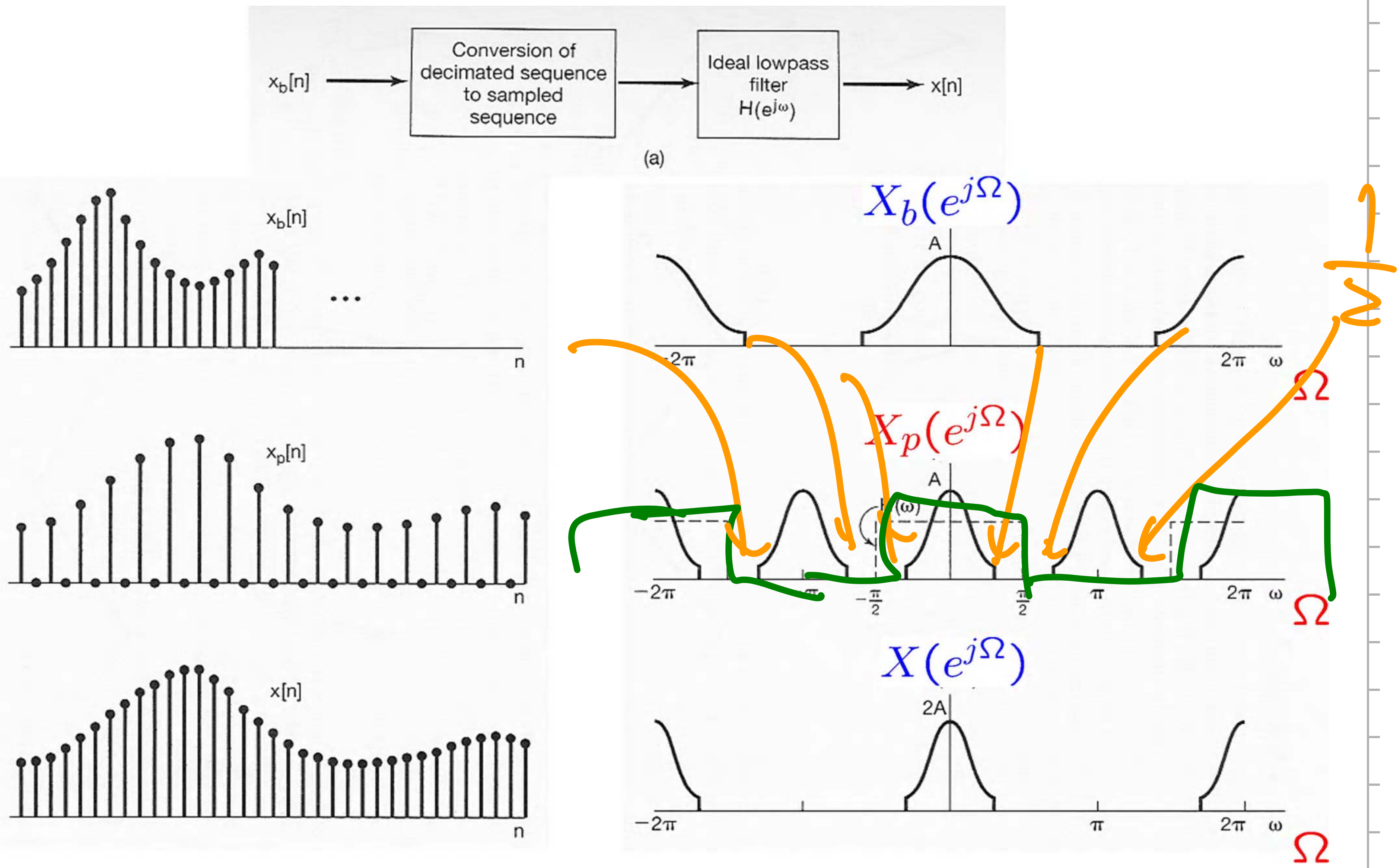
Eq 5.45, p. 378: Time expansion





$$X_b(e^{j\Omega}) = X_p(e^{j\Omega/N})$$

Higher Equivalent Sampling Rate: Up-sampling



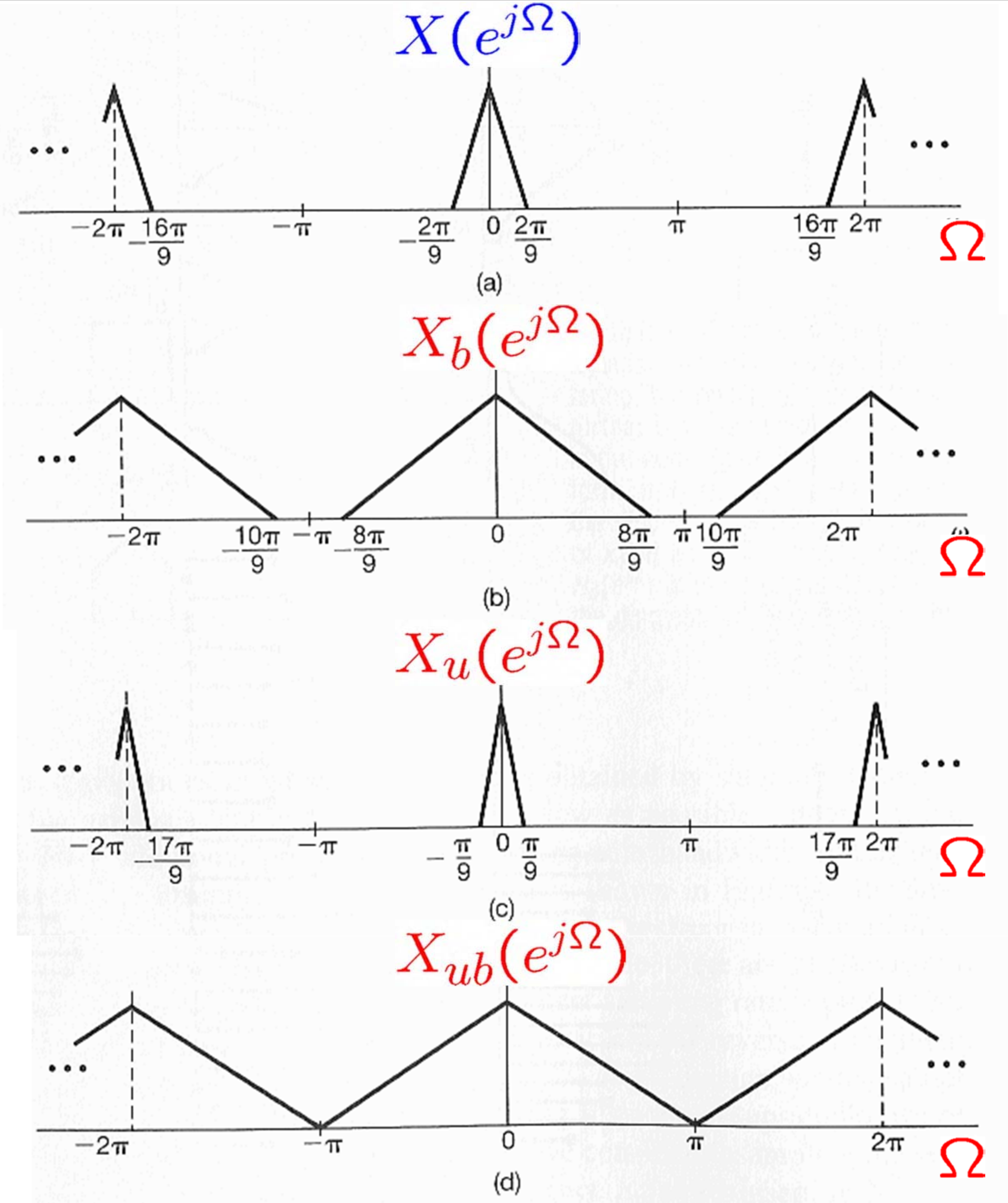
- Down-sampling + Up-sampling:

$$\frac{2\pi}{9} \times 4 < \pi$$

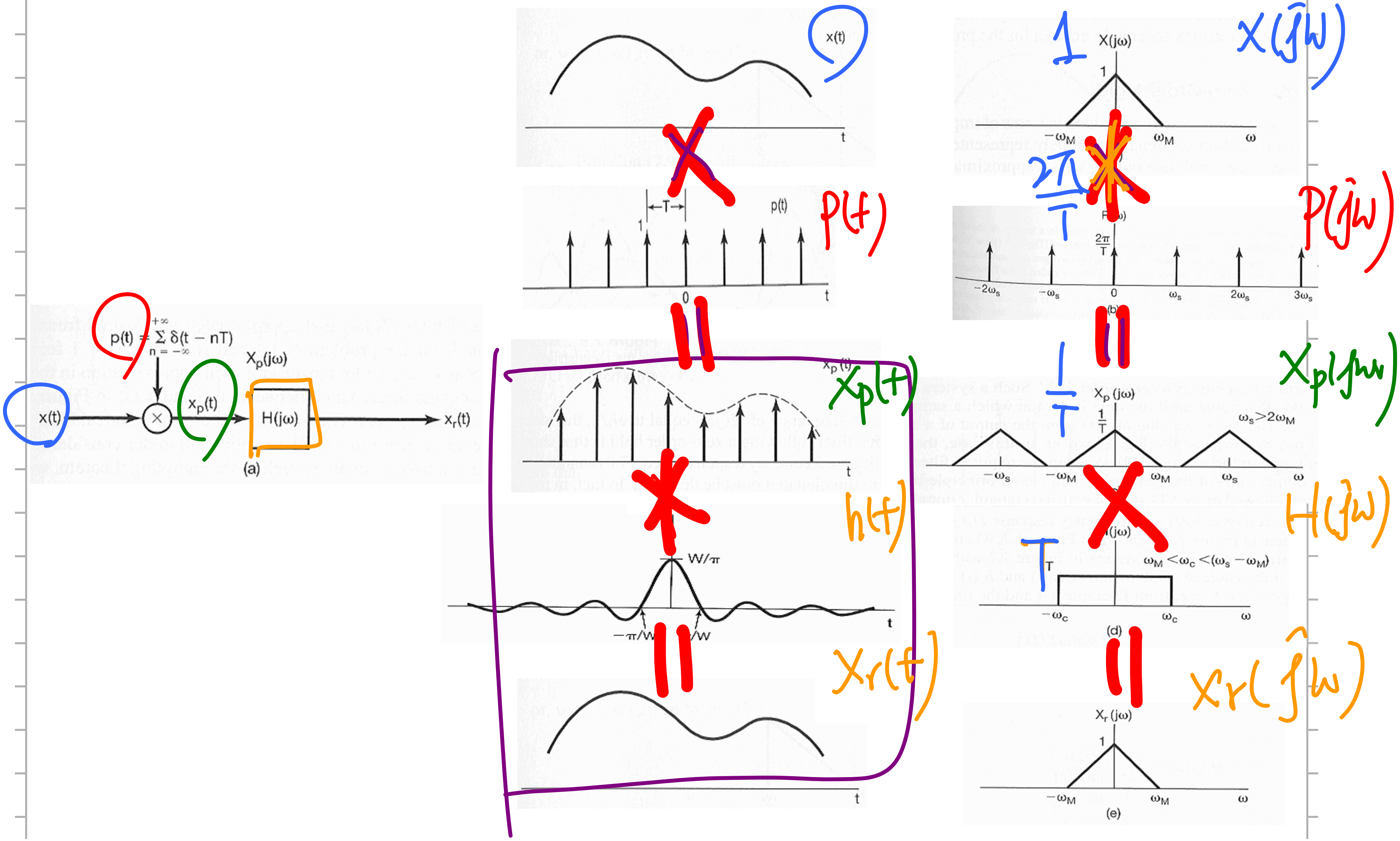
$$\frac{2\pi}{9} \times \frac{9}{2} = \pi$$

$$\frac{2\pi}{9} \times \frac{1}{2} = \frac{\pi}{9}$$

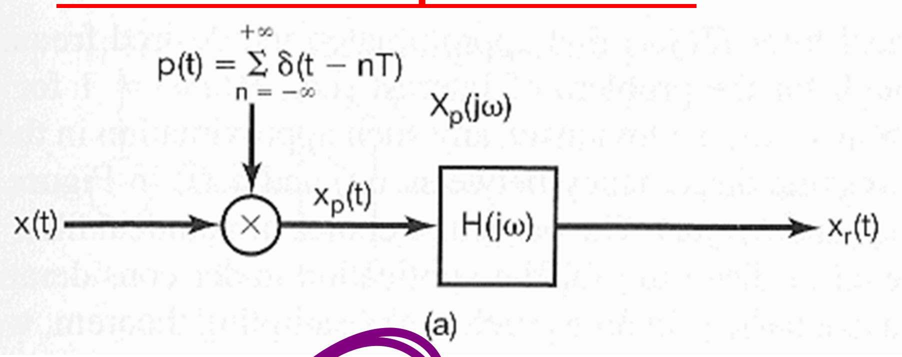
$$\frac{\pi}{9} \times 9 = \pi$$

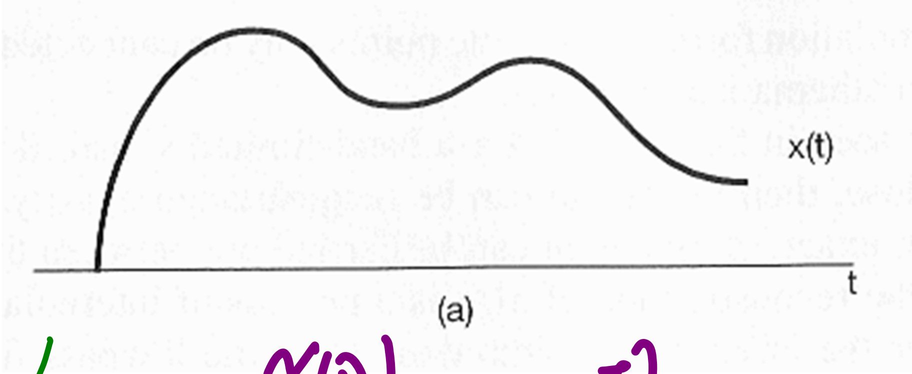


- Exact Recovery by an Ideal Lowpass Filter:



Exact Interpolation:

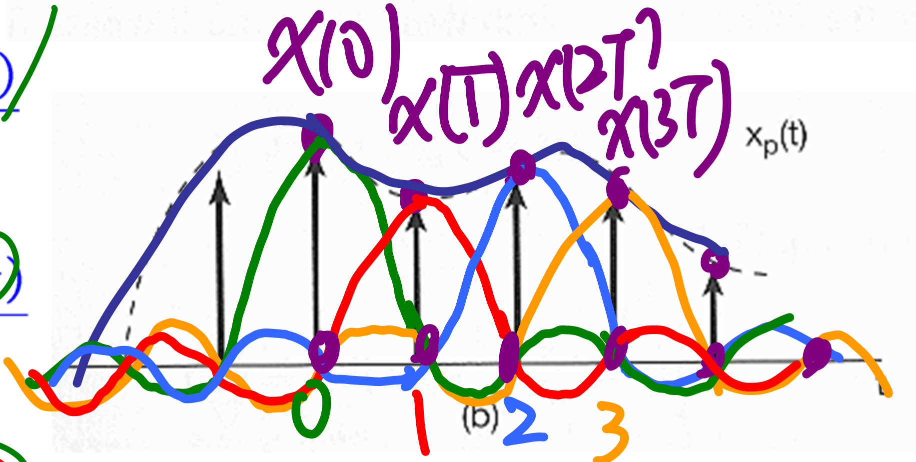




$$x_r(t) = \sum_{n=-\infty}^{+\infty} x(nT) \frac{w_c T}{\pi} \frac{\sin(w_c(t-nT))}{w_c(t-nT)}$$

$$= \frac{w_c}{\pi} \frac{2\pi}{w_s} \frac{\sin \pi(w_c(t-nT)/\pi)}{\pi w_c(t-nT)/\pi}$$

$$= \frac{2w_c}{w_s} \text{sinc}(w_c(t-nT)/\pi)$$



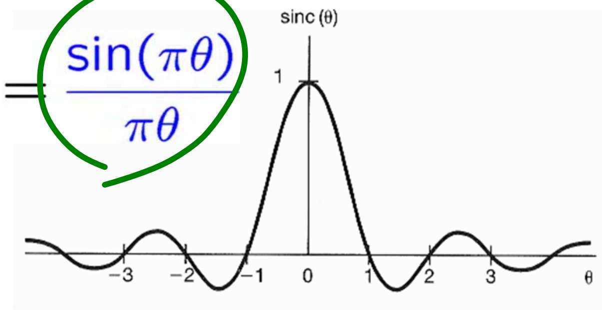
$n=0$

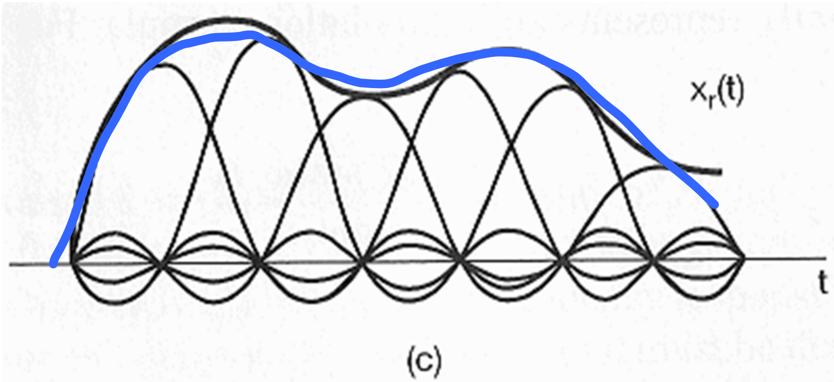
$n=1$

$n=2$

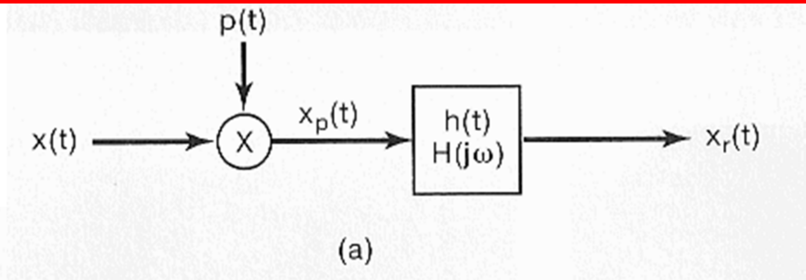
$n=3$

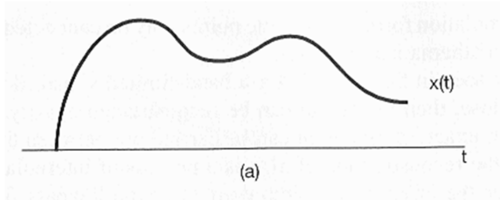
$$\text{sinc}(\theta) = \frac{\sin(\pi\theta)}{\pi\theta}$$

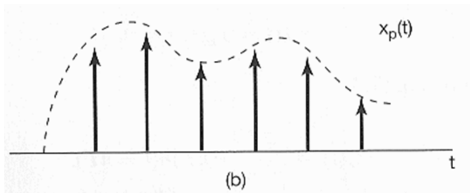




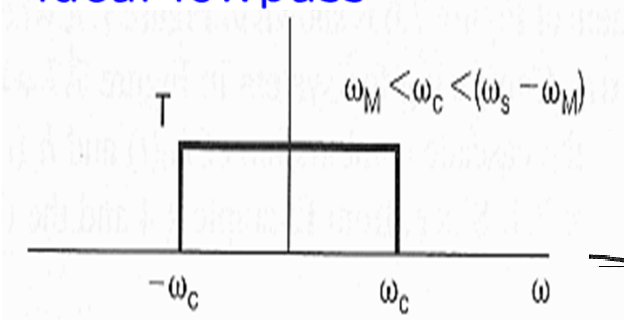
Three Filters: Ideal Lowpass, Zero-Order, First-Order

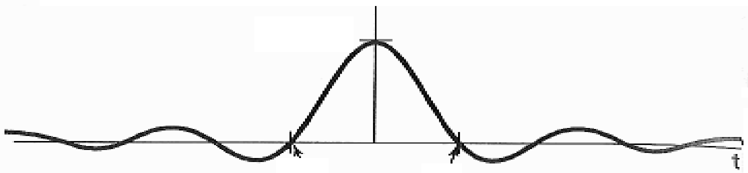


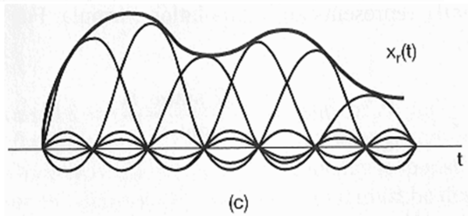




ideal lowpass

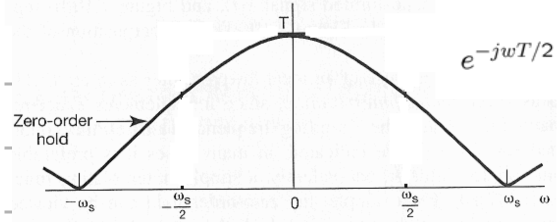


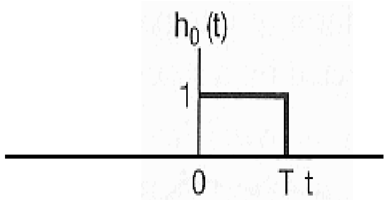


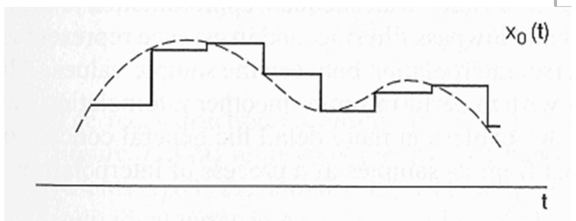


zero-order hold

$$H_0(jw) = e^{-jwT/2}\left[\frac{2\sin(wT/2)}{w}\right]$$

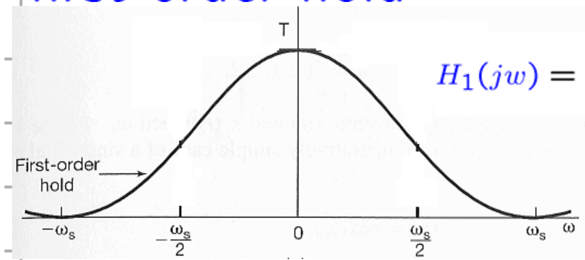


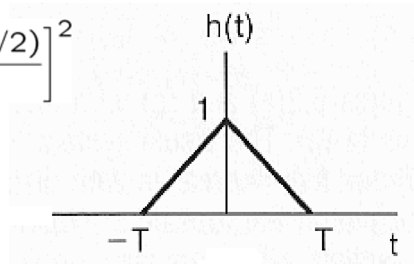


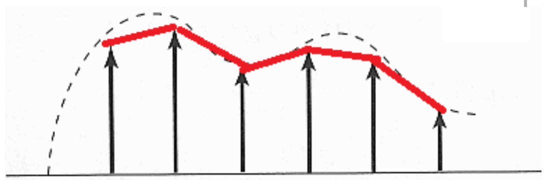


first-order hold

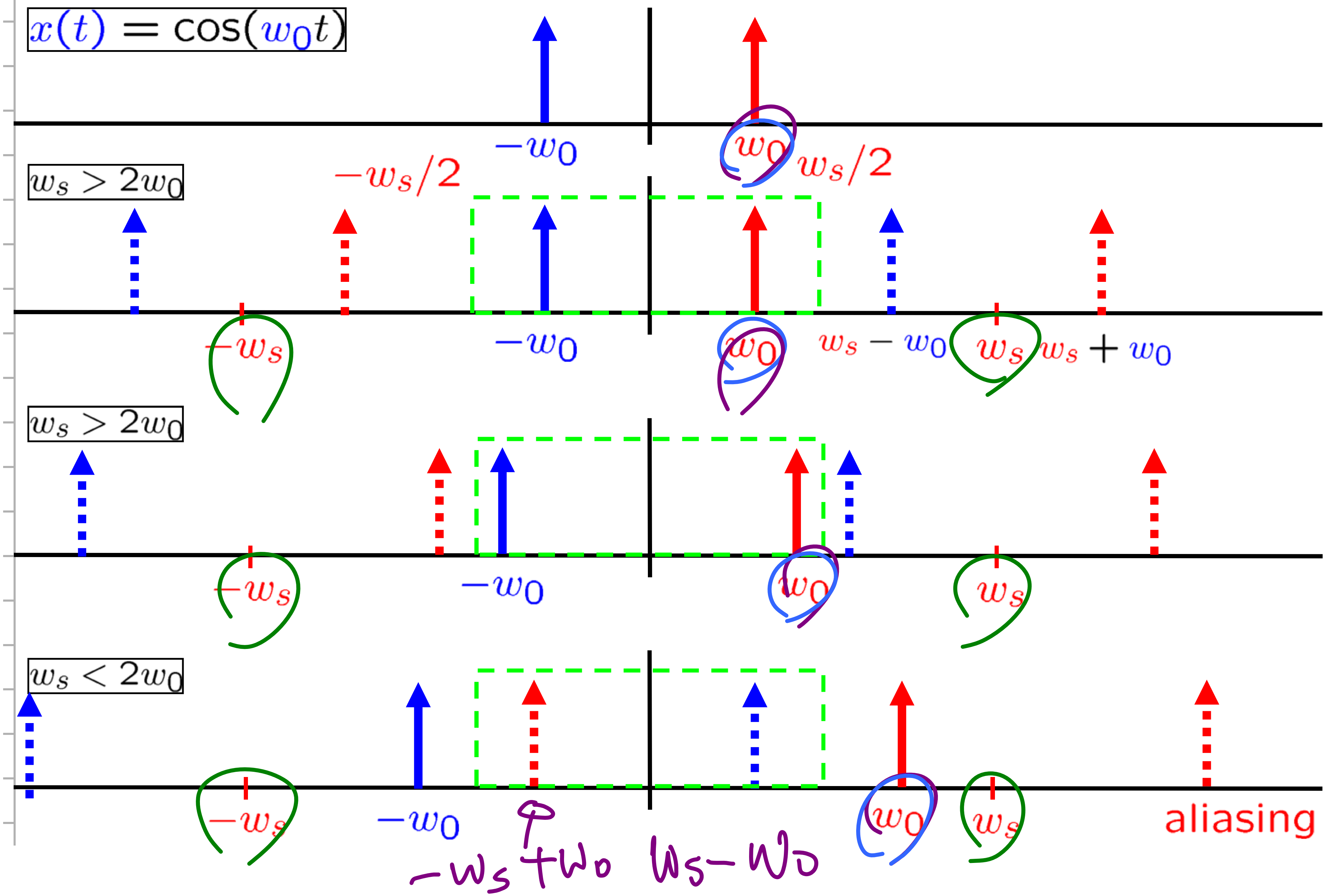
$$H_1(jw) = \frac{1}{T}\left[\frac{\sin(wT/2)}{w/2}\right]^2$$



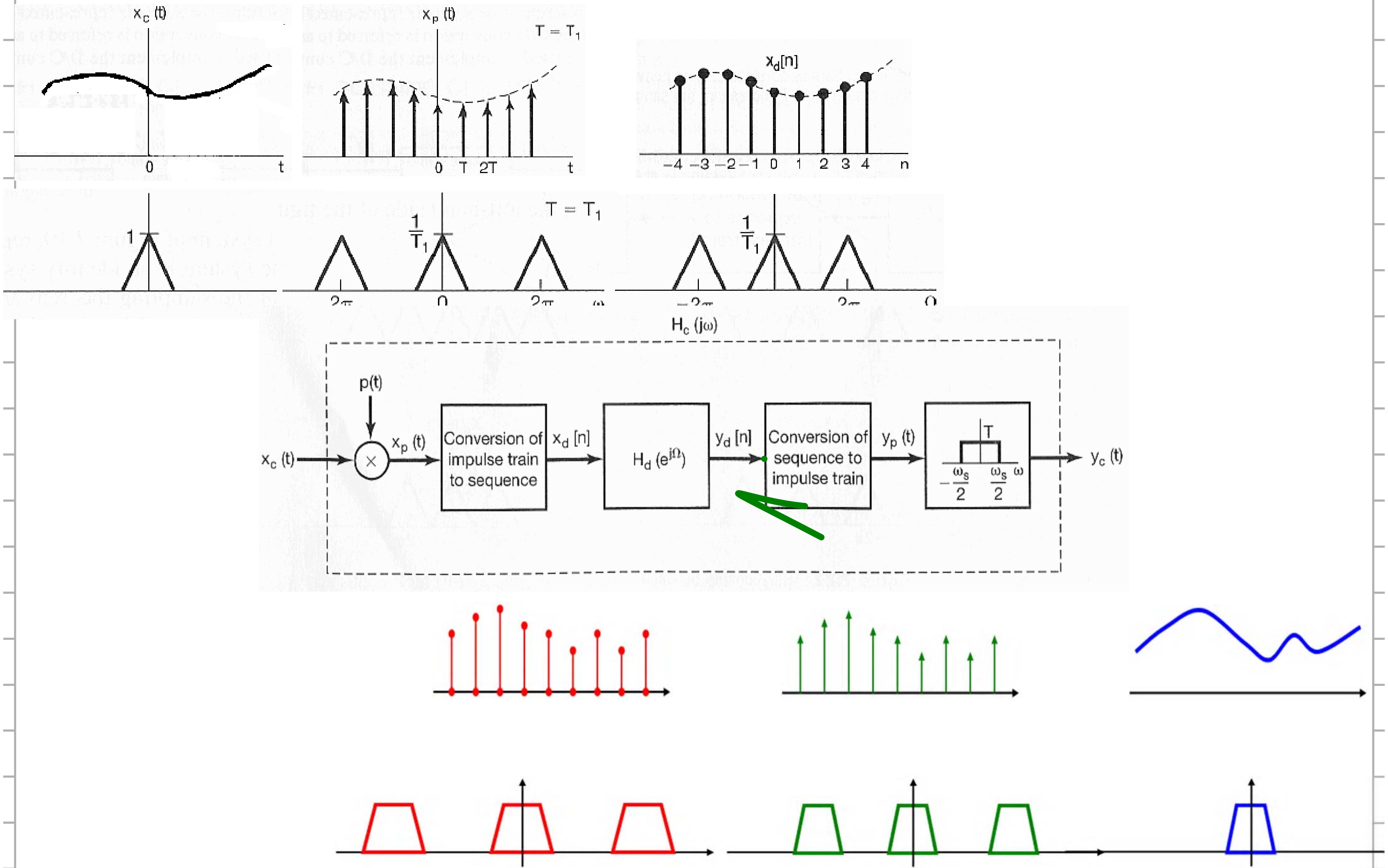




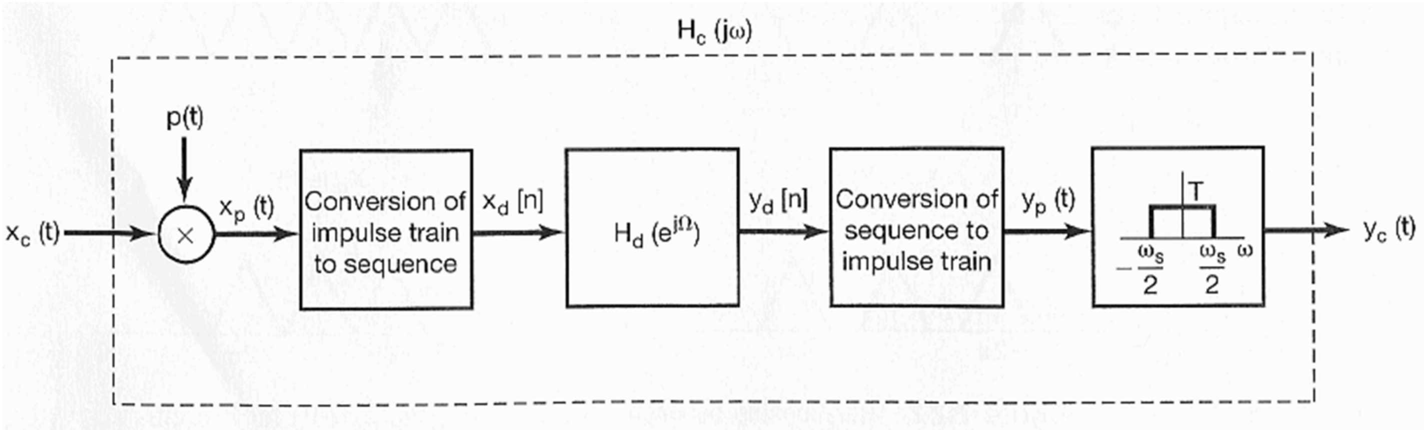
■ Overlapping in Frequency-Domain: Aliasing



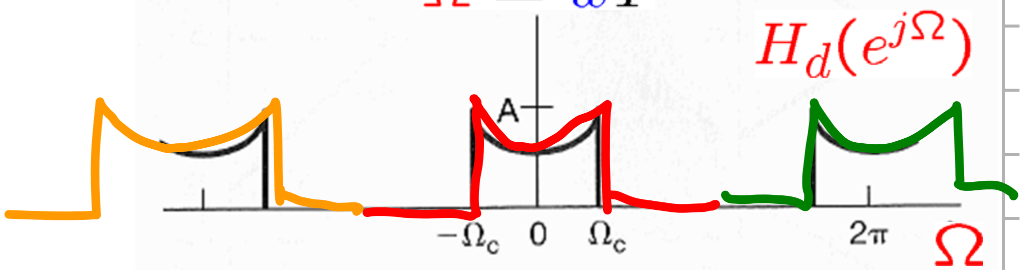
Discrete-Time Processing of CT Signals



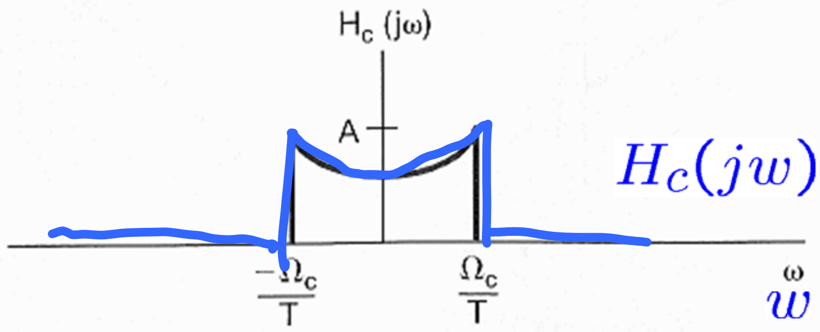
- CT & DT Frequency Responses:



$$\Omega = wT$$

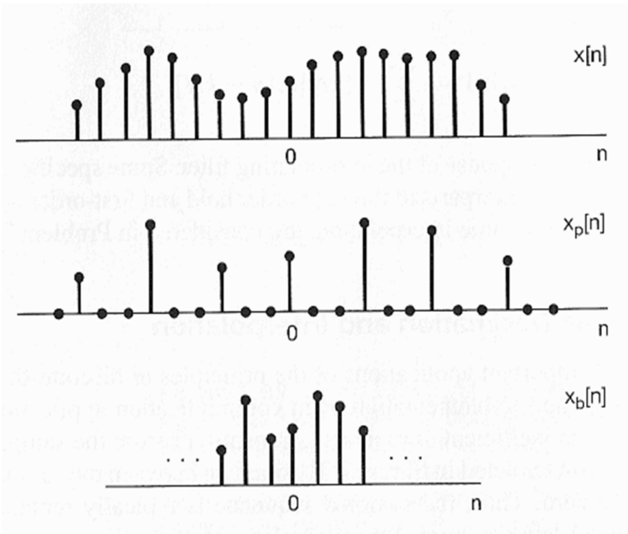


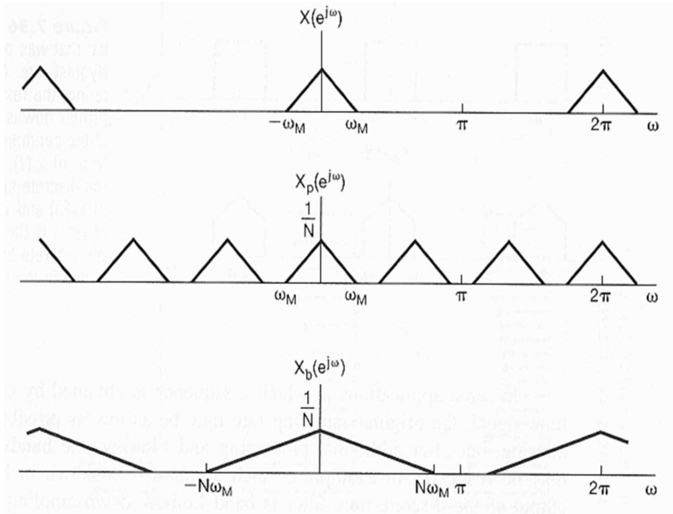
$$Y_c(jw) = X_c(jw)H_c(jw)$$



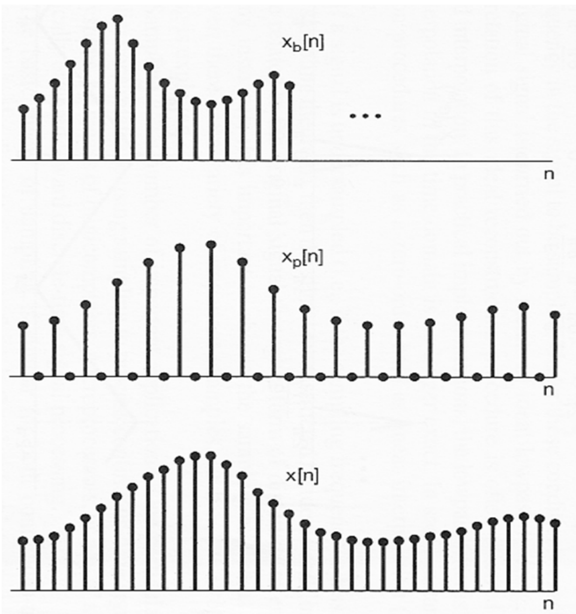
$$H_c(jw) = \begin{cases} H_d(e^{jwT}), & |w| < w_s/2 \\ 0, & |w| > w_s/2 \end{cases}$$

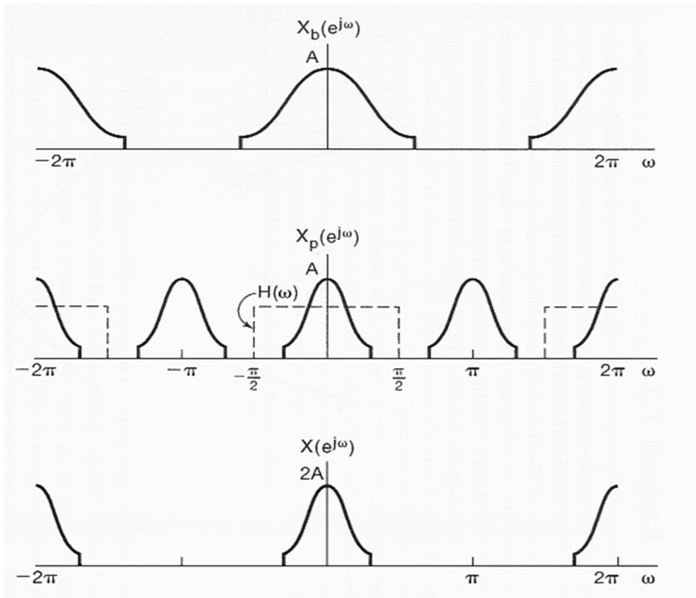
- Decimation (Down-sampling):



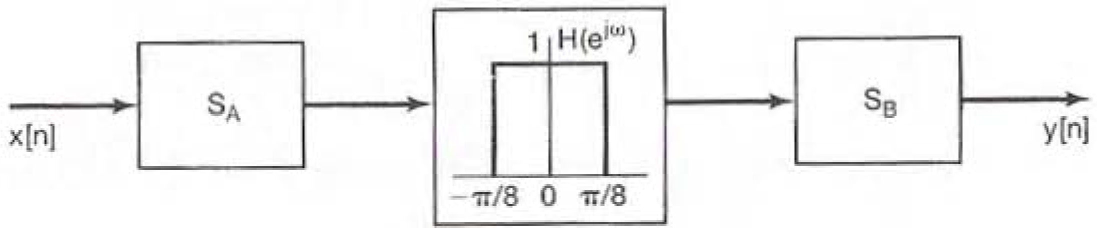


- Interpolation (Up-sampling):

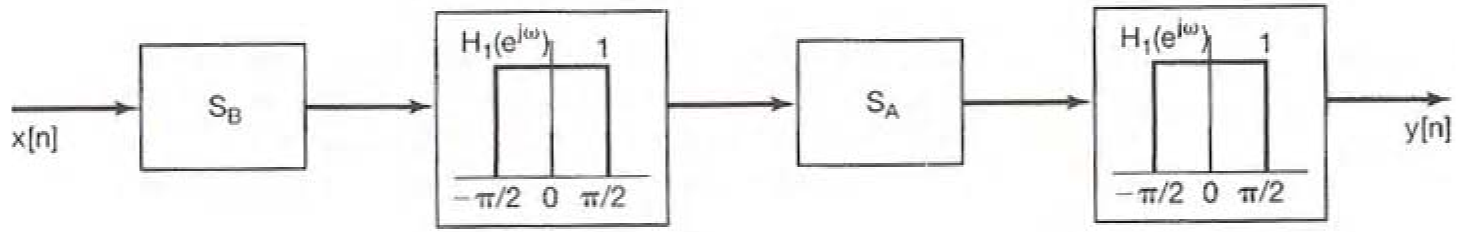




- Problem 7.20 (p.560):
- (a)

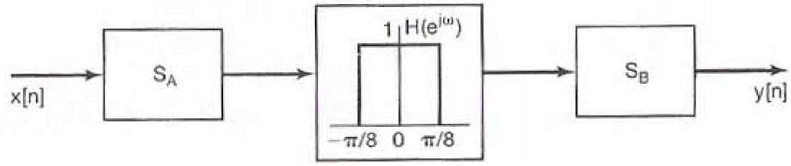


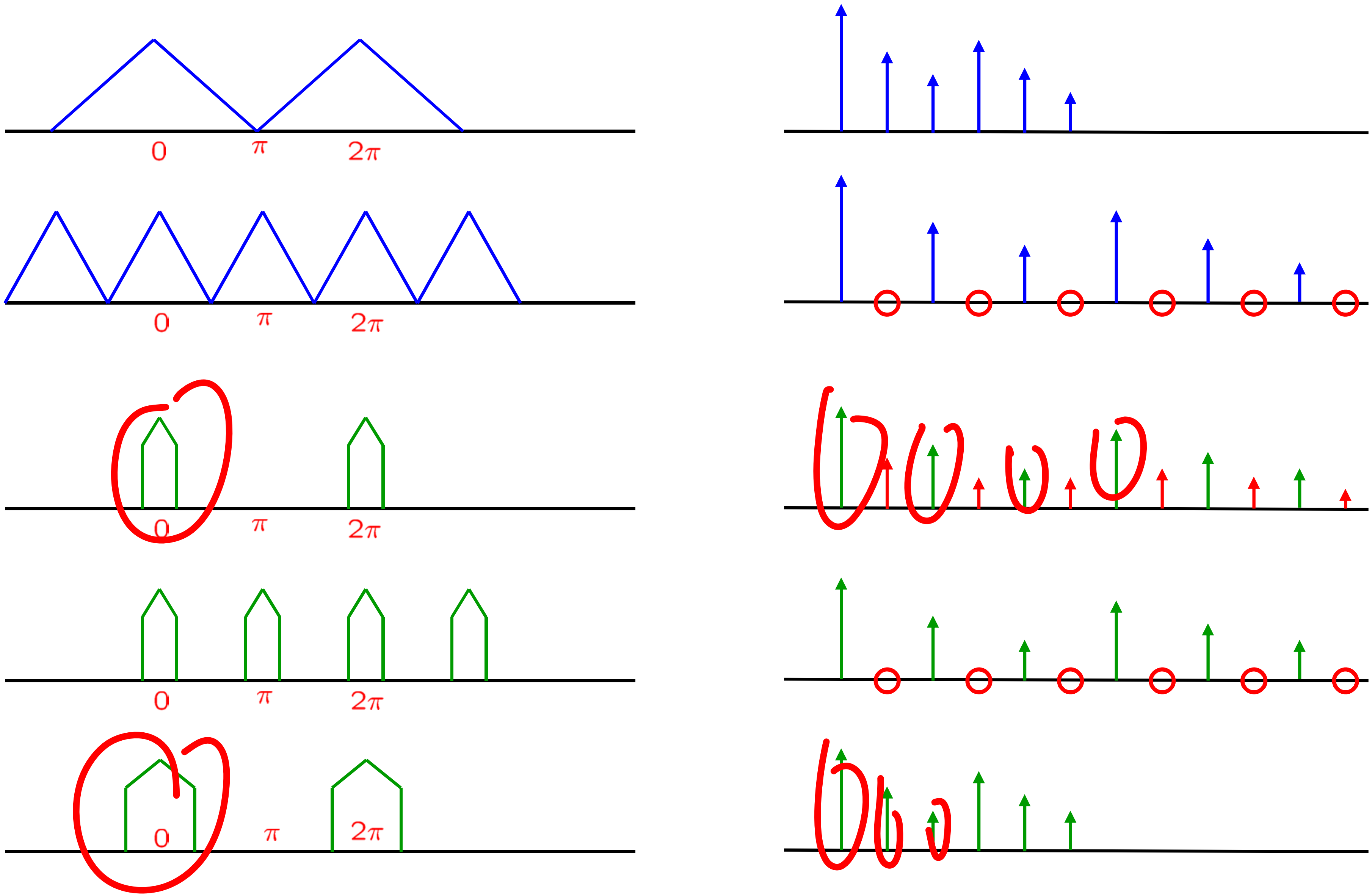
- (b)



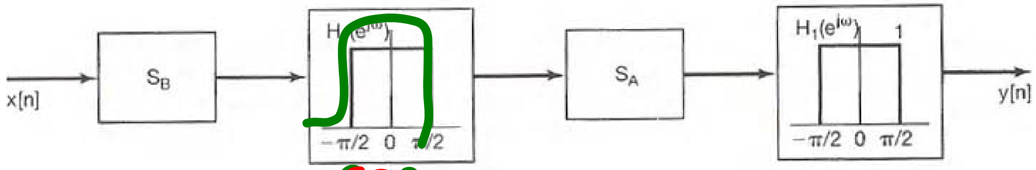
- S_A: Inserting one zero after each sample
- S_B: Decimation 2:1, extracting every second sample
- Which corresponds to low-pass filtering with $\omega_c = \pi/4$?

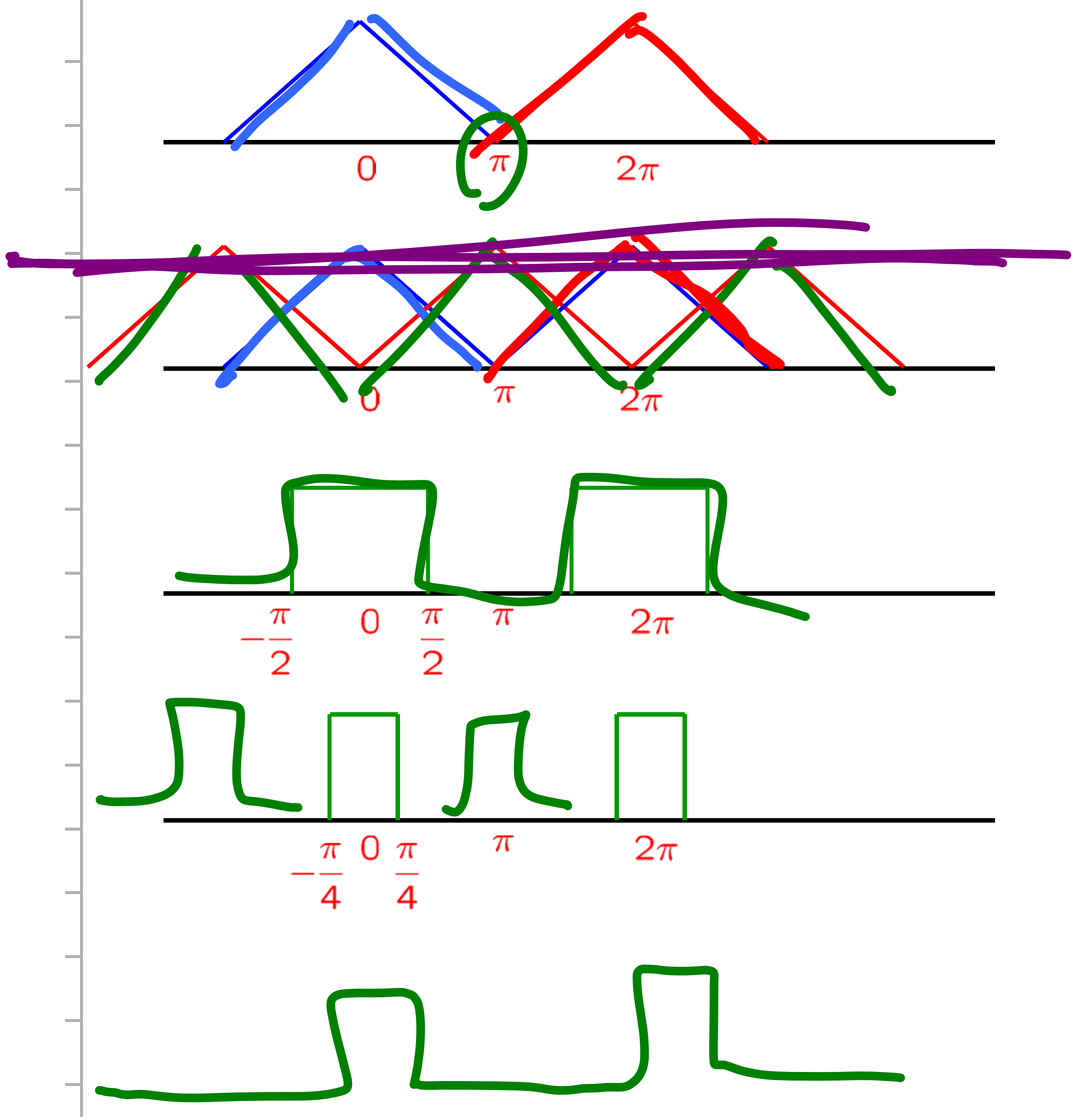
- Problem 7.20 (p.560):
- (a)



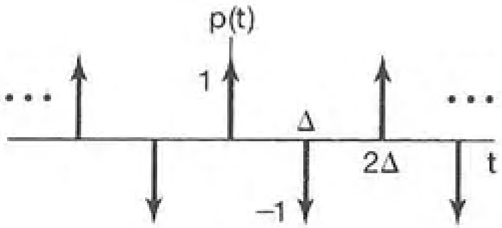


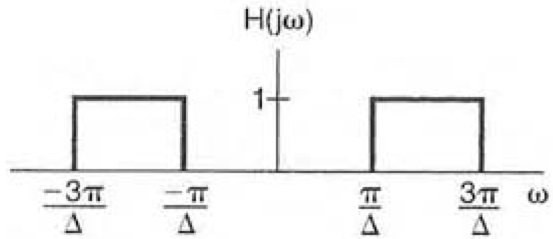
- Problem 7.20 (p.560):
- (b)

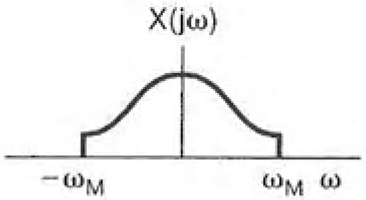


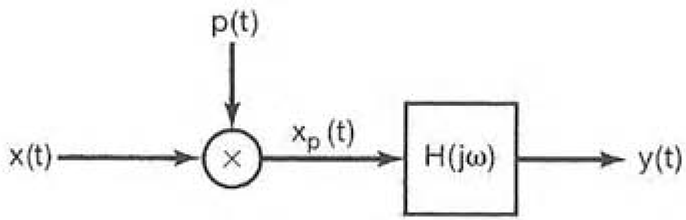


- Problem 7.23 (p.562):



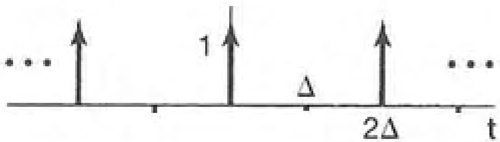




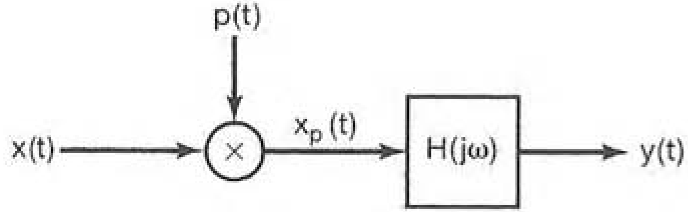


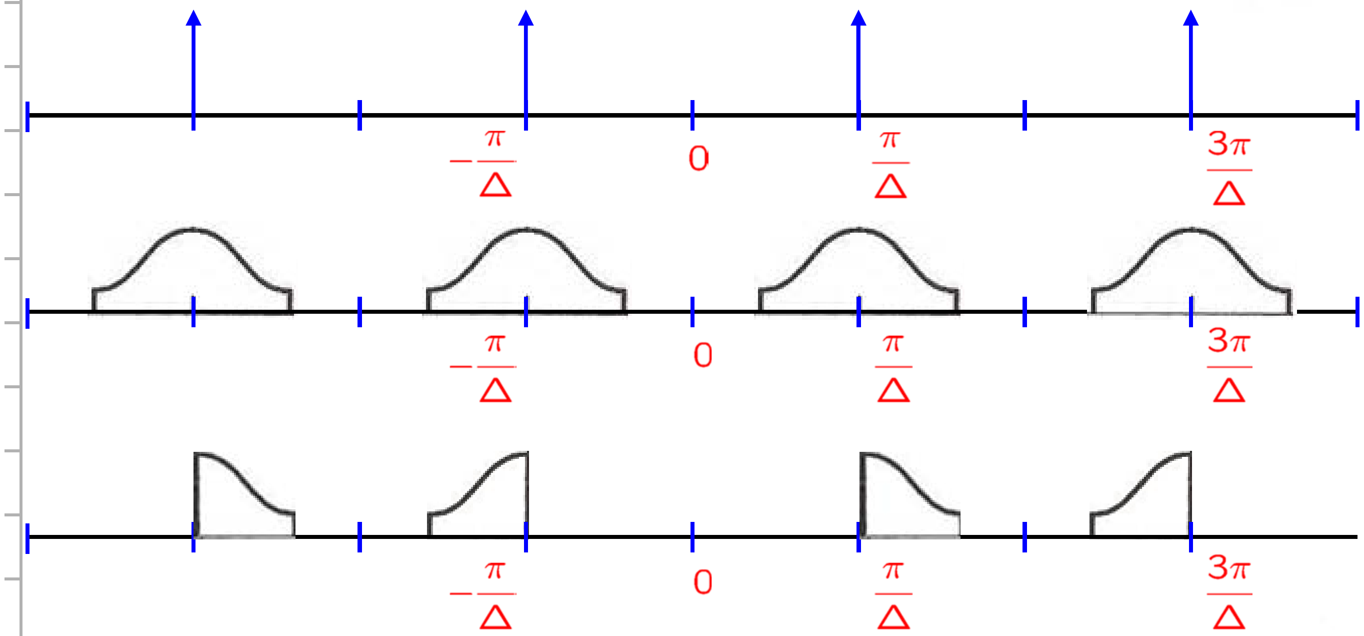
$p_1(t)$

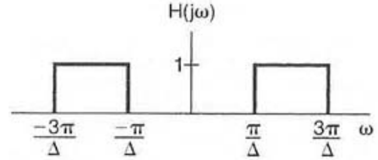
$$p(t) = p_1(t) - p_1(t - \Delta)$$

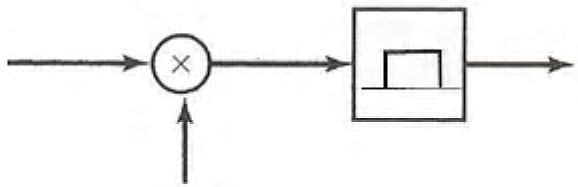


Problem 7.23 (p.562):

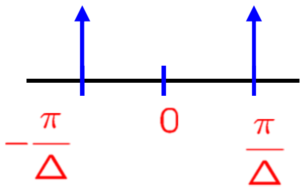


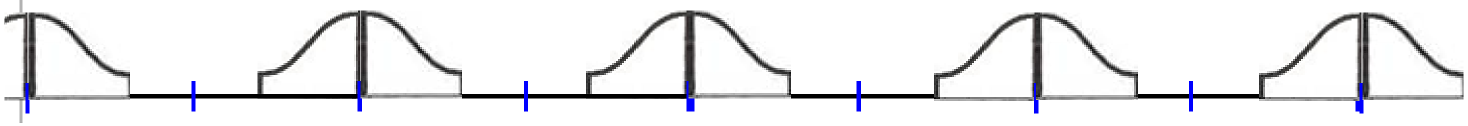


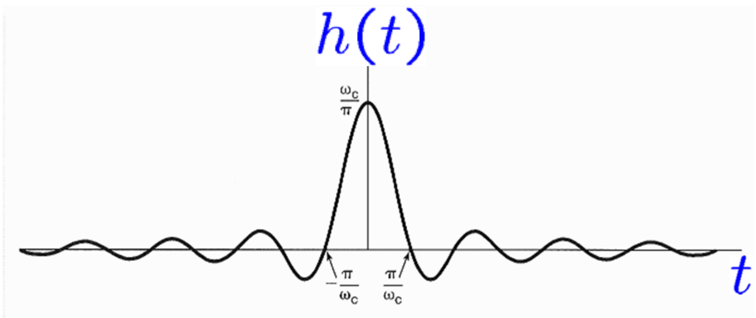


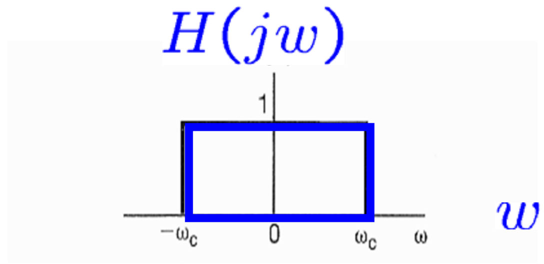


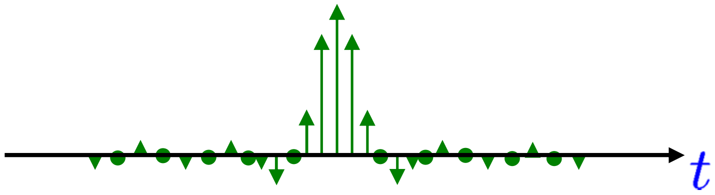
$\cos(\frac{\pi}{\Delta}t)$

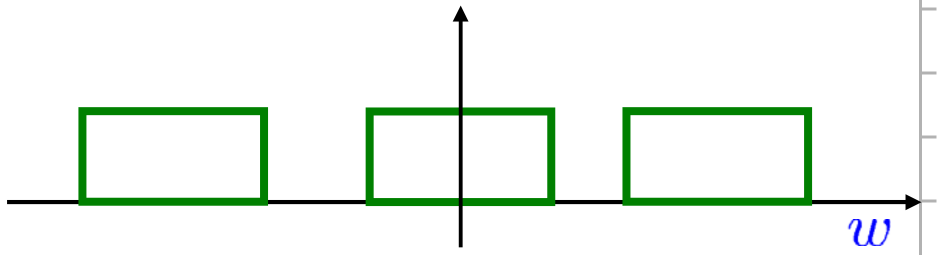








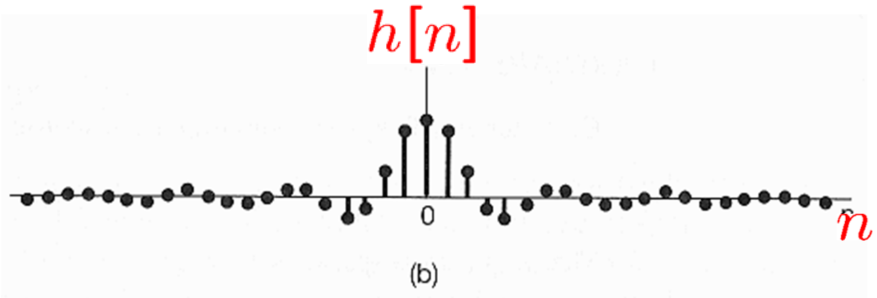


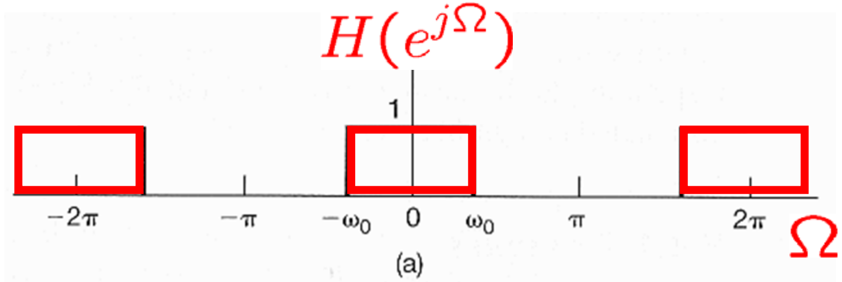


$$h(t) \xleftrightarrow{\mathcal{C.T.F.T.}} H(jw)$$

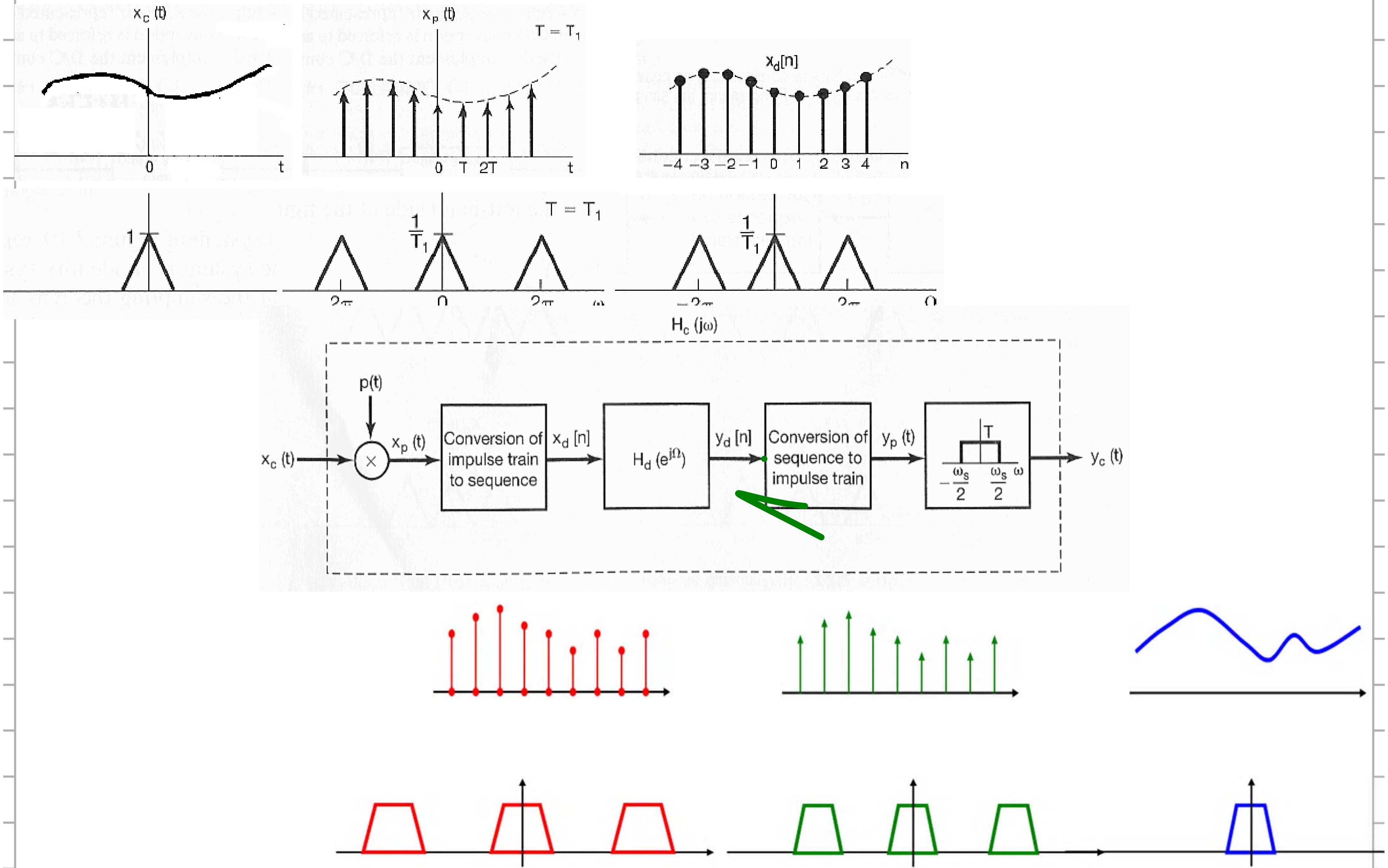
$$w_s = \frac{2\pi}{T} \qquad \Omega = wT$$

$$h[n] \xleftrightarrow{\mathcal{D.T.F.T.}} H(e^{j\Omega})$$





- Discrete-Time Processing of CT Signals



- Representation of of a CT Signal by Its Samples:
  - The Sampling Theorem
- Reconstruction of of a Signal from Its Samples
  - Using exact interpolation
  - Using zero-order hold
  - Using higher-order hold
- The Effect of Under-sampling
  - Overlapping in Frequency-Domain
  - Aliasing
- DT Processing of CT Signals
- Sampling of Discrete-Time Signals
  - Down-sampling
  - Up-sampling

Introduction (Chap 1)

LTI & Convolution (Chap 2)

Bounded/Convergent

Periodic

FS CT DT (Chap 3)

Aperiodic

FT CT (Chap 4) DT (Chap 5)

Unbounded/Non-convergent

LT CT (Chap 9)

zT DT (Chap 10)

Time-Frequency (Chap 6)

CT-DT (Chap 7)

Communication (Chap 8)

Control (Chap 11)

Digital Signal Processing (dsp-8)