Upsampling (5B)

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Please send corrections (or suggestions) to youngwlim@hotmail.com.

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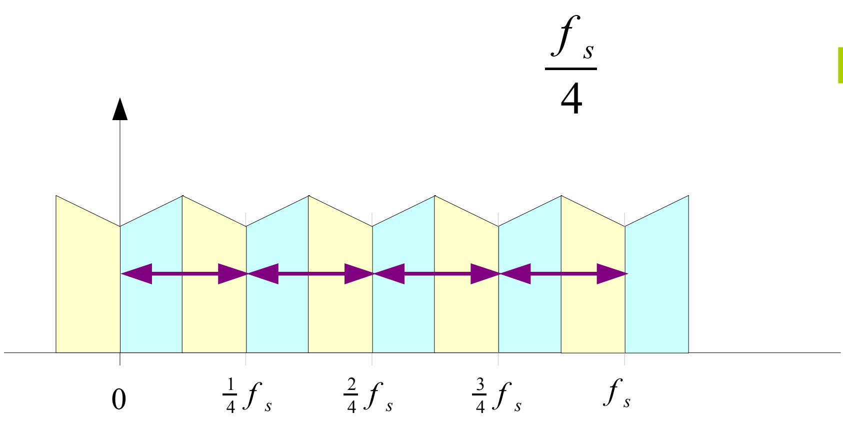
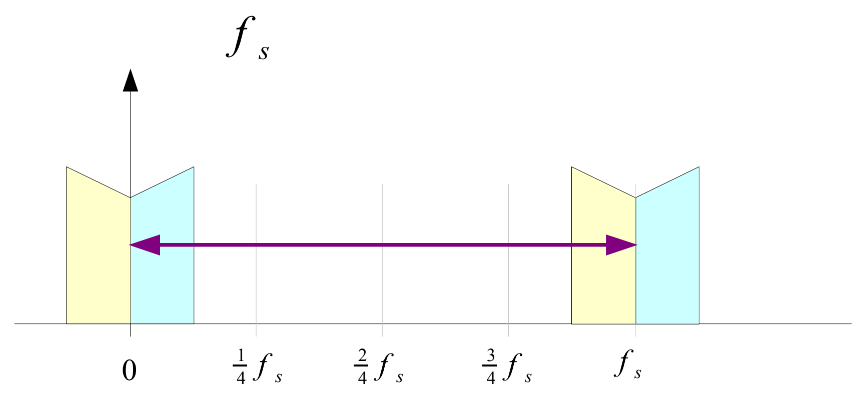
Band-limited Signal



UP

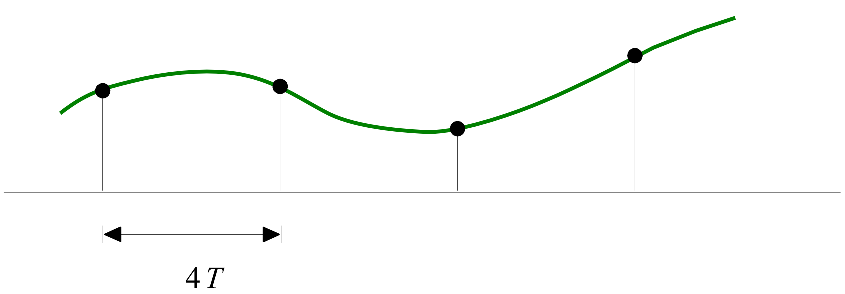


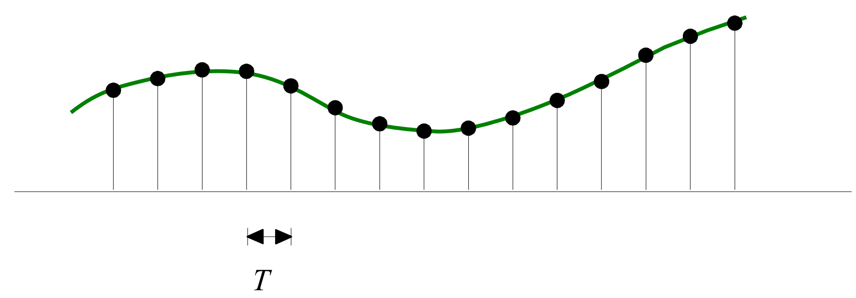
Sampling Frequency $\frac{1}{4}f_s$

Sampling Time $T = \frac{4}{f_s}$

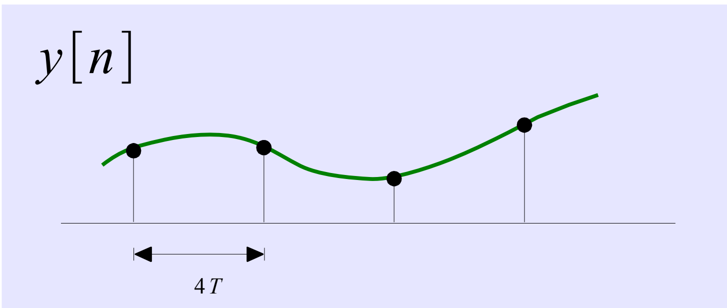
Sampling Frequency $f'_s = f_s$

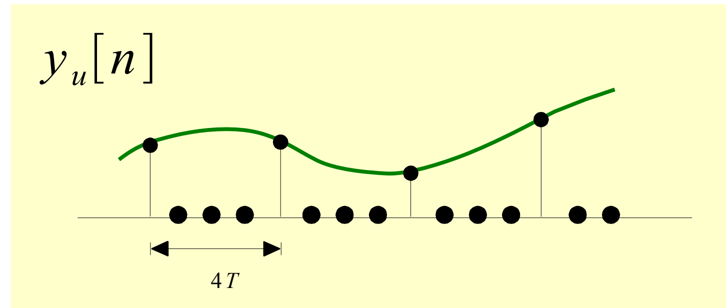
Sampling Time $T' = \frac{1}{f_s}$

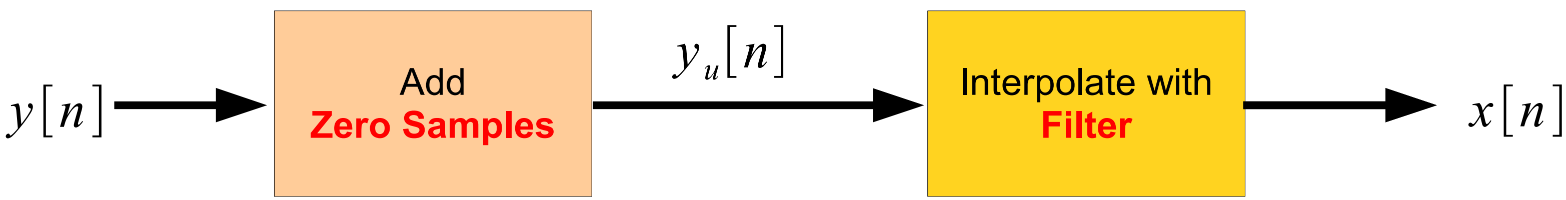




Time Sequence

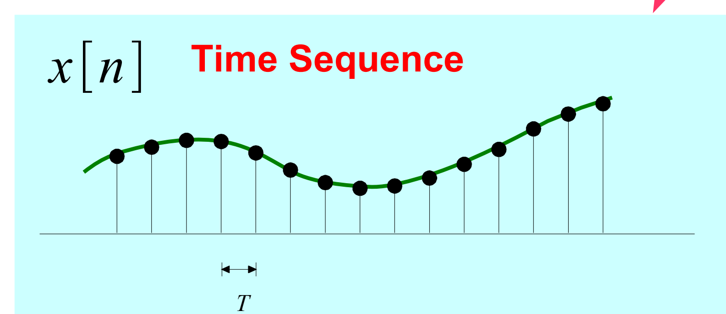




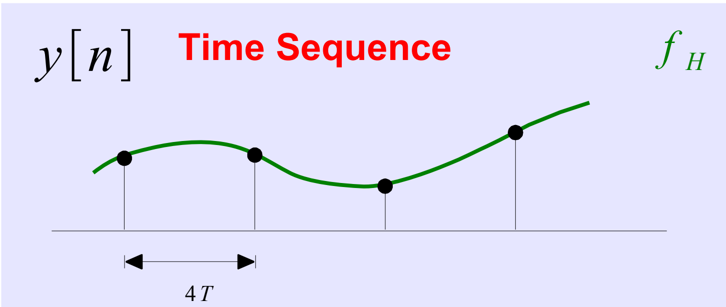


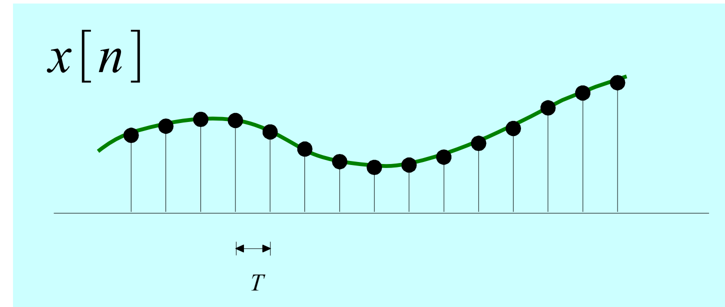
Ideal
Sampling

T **Sampling Period**

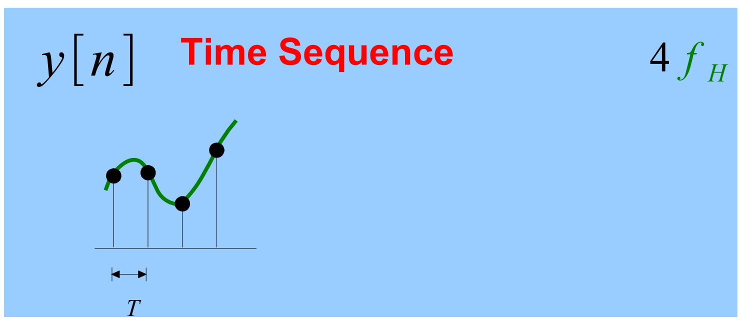


Normalized Radian Frequency





= The Same Time Sequence



$$\hat{\omega} = \omega \cdot T_s = \frac{\omega}{1/T_s}$$

$$\hat{\omega} = \frac{\omega}{f_s} = 2\pi \frac{f}{f_s}$$

Normalized to f_s

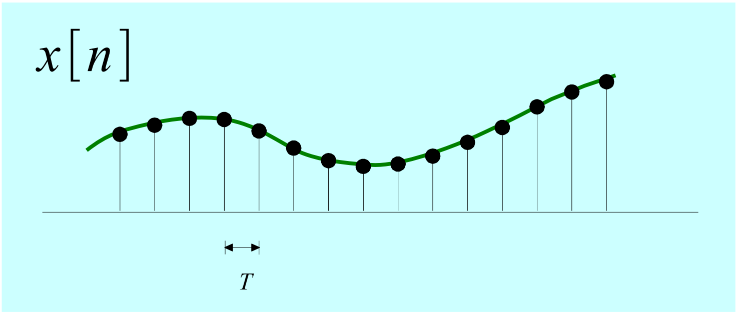
Normalized Radian Frequency

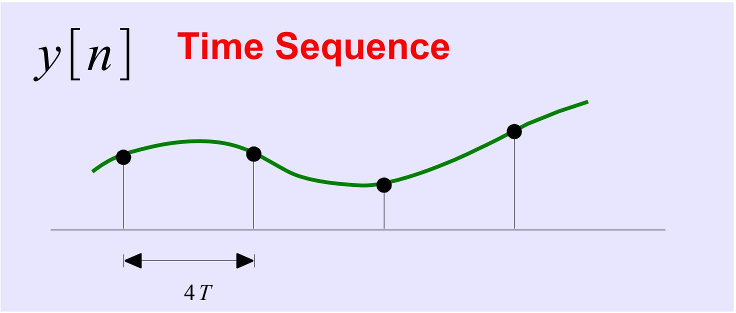
The Same Normalized Radian Frequency

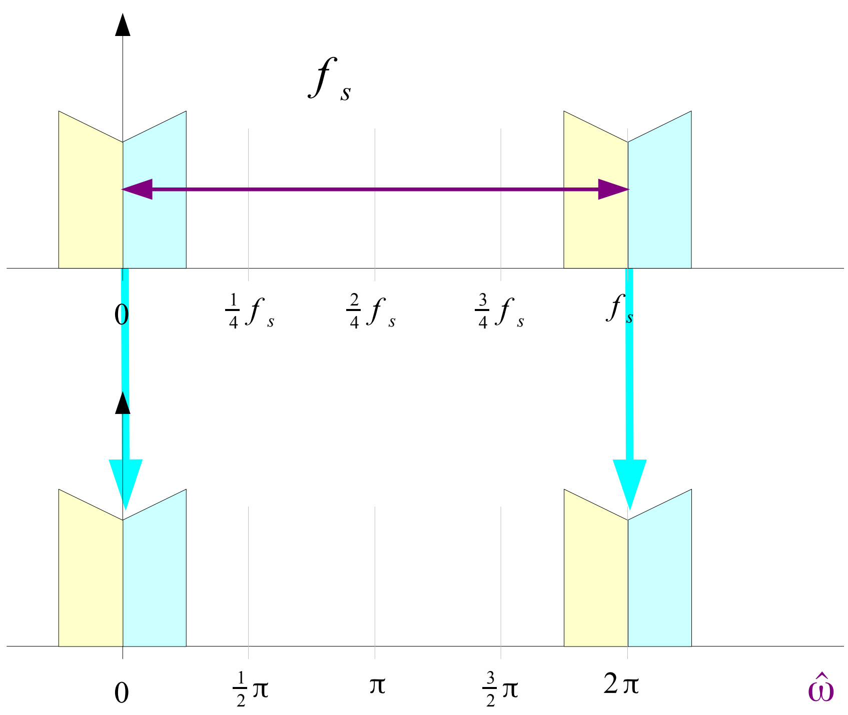
The Highest Frequency: $f_H, \quad 4 f_H$

$$\frac{f_H}{1/4T} = f_H \cdot 4T \qquad \frac{4 f_H}{1/T} = f_H \cdot 4T$$

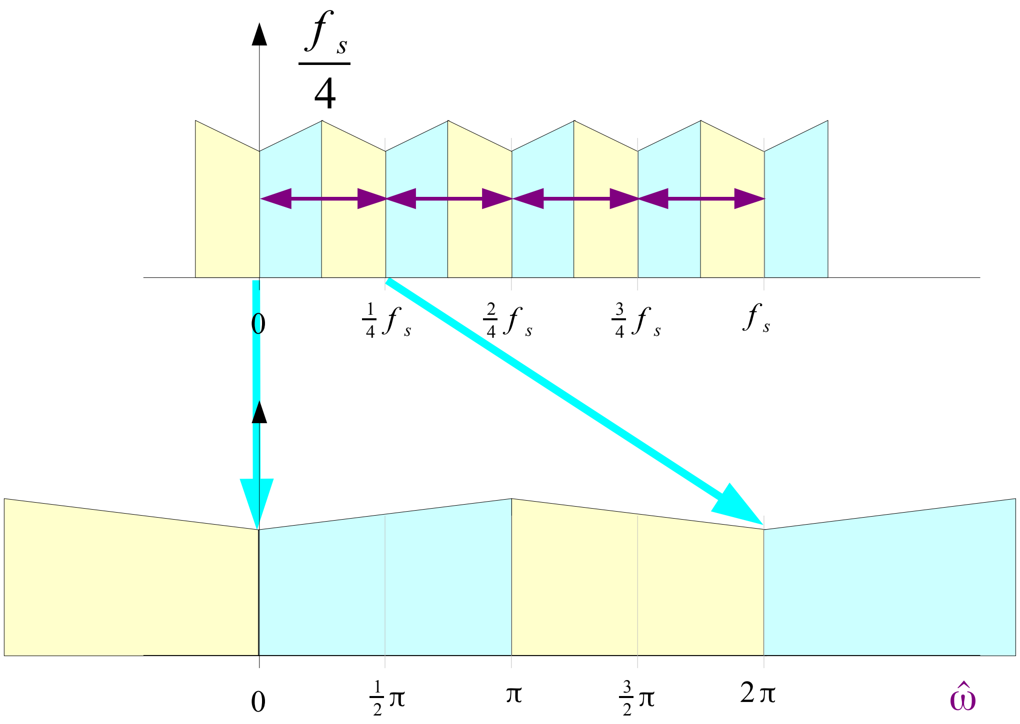
Adding Zero Samples





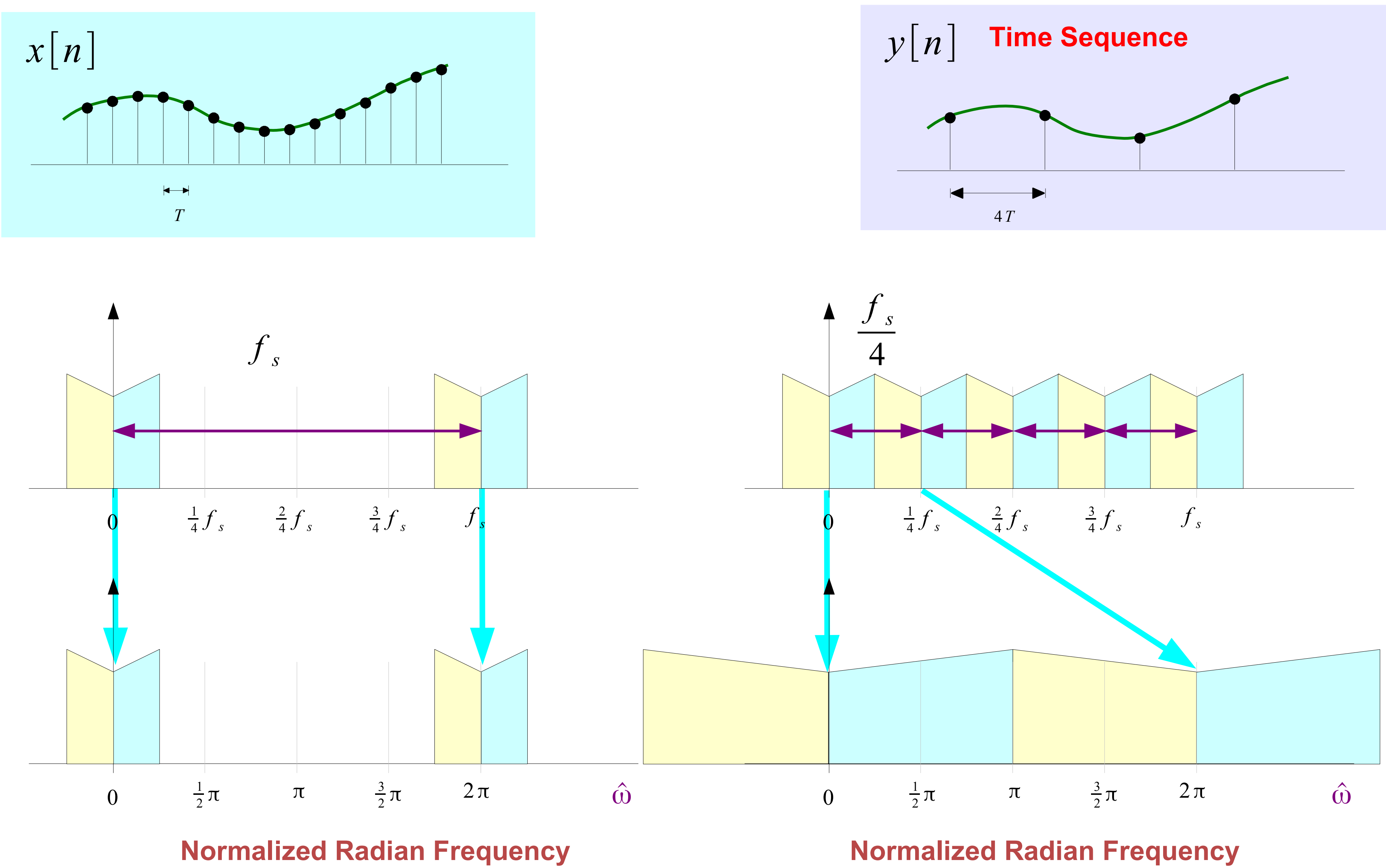


Normalized Radian Frequency

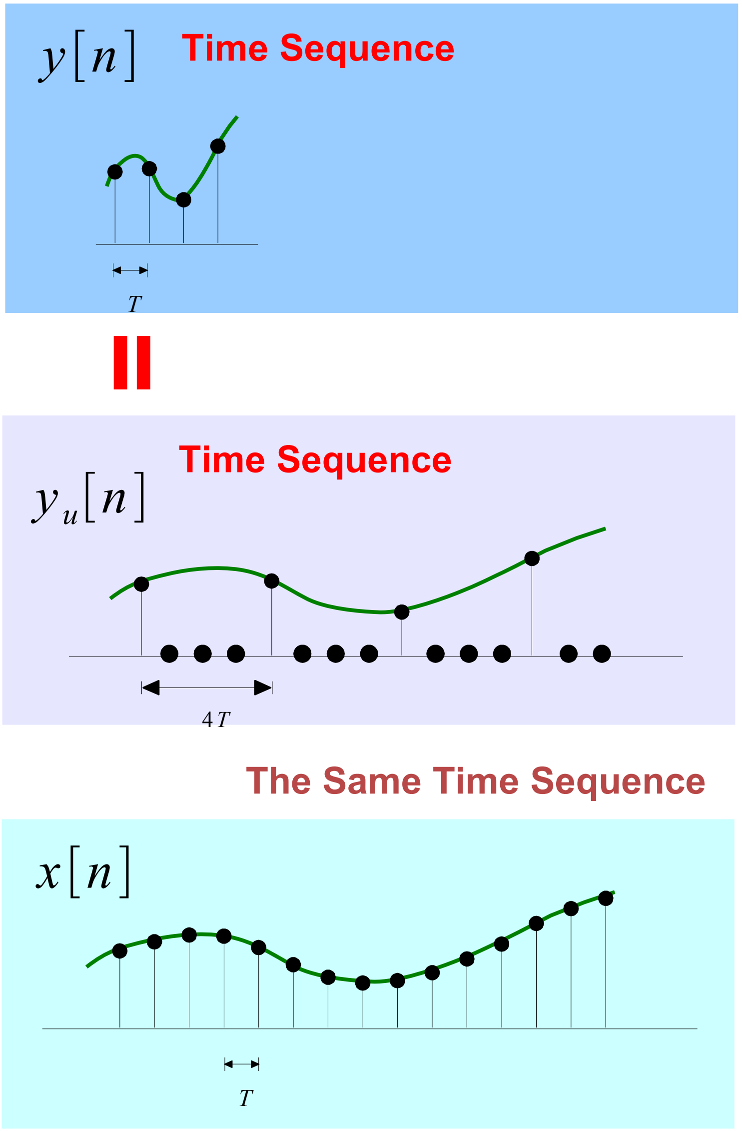


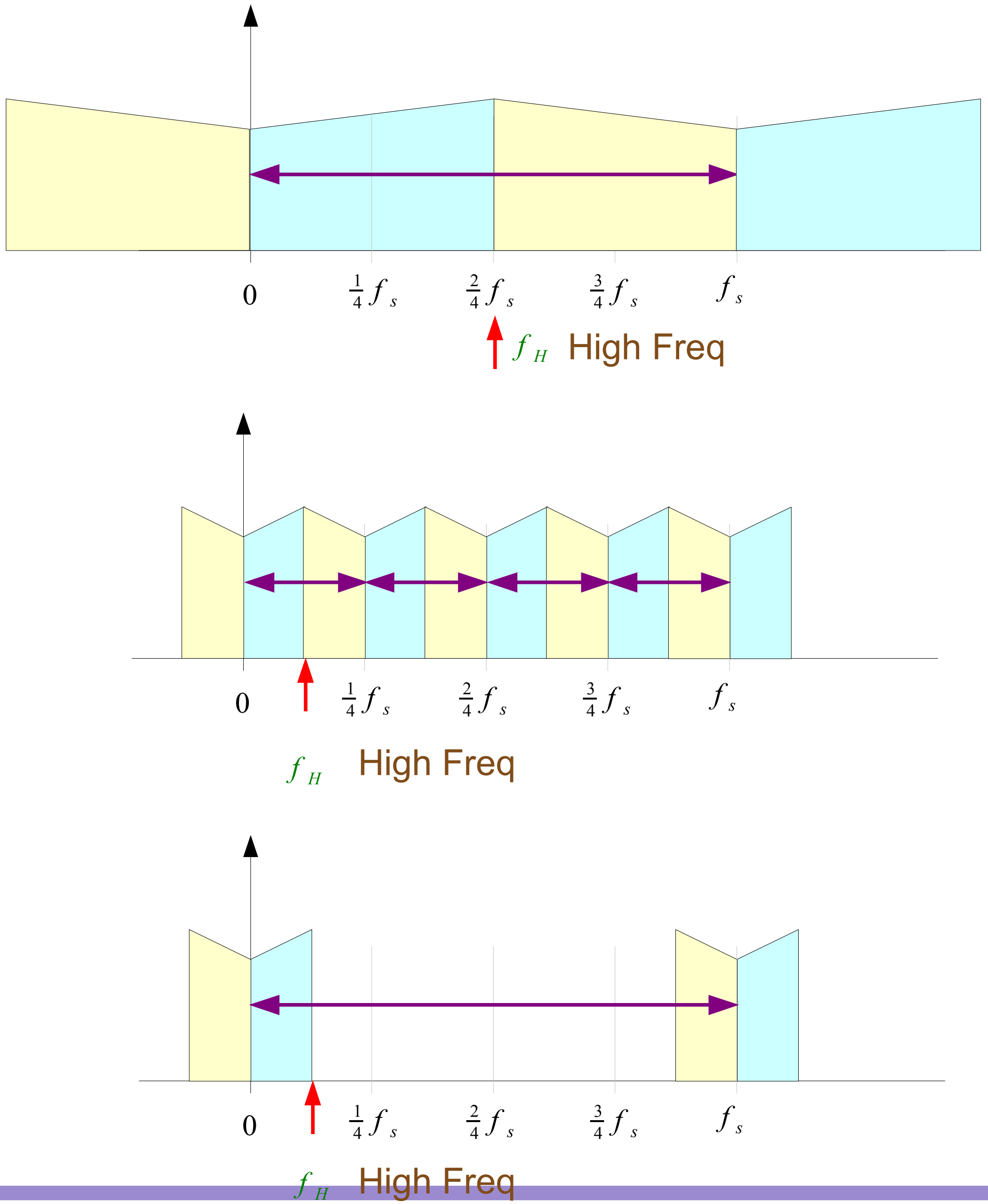
Normalized Radian Frequency

Adding Zero Samples

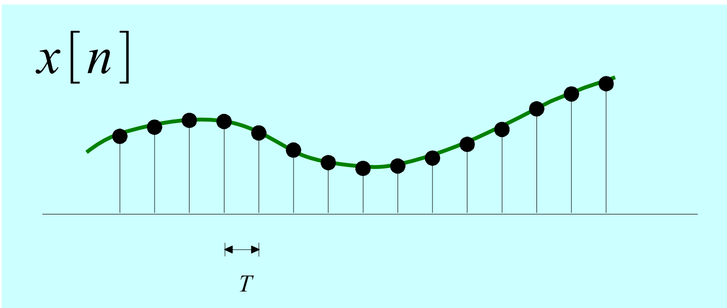


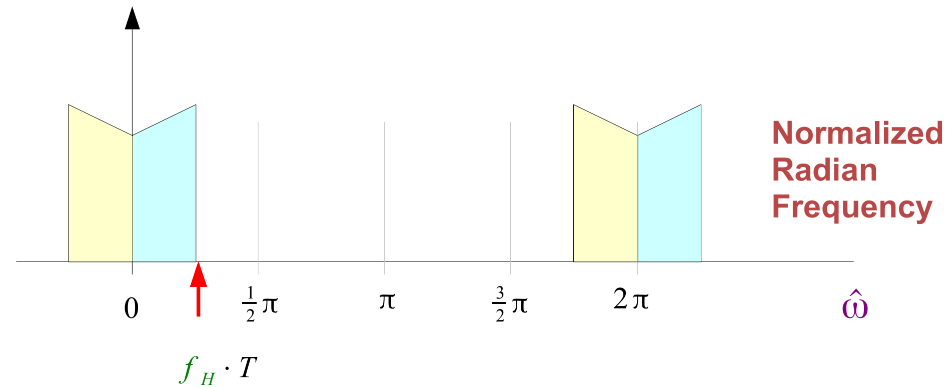
Time Sequence Spectrum in Linear Frequency

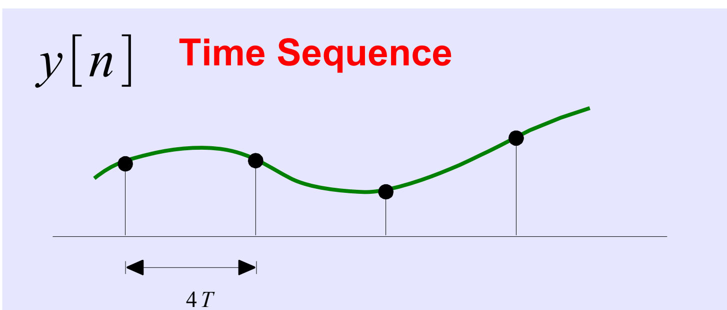


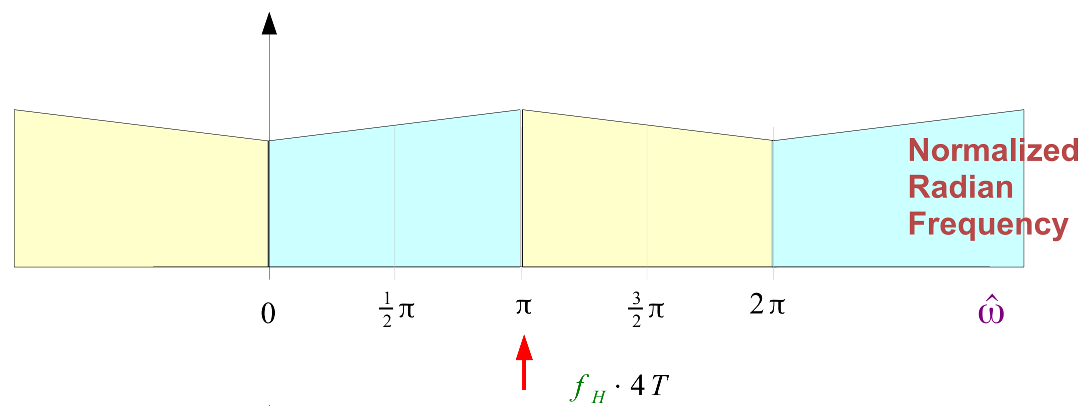


Time Sequence Spectrum in Normalized Frequency

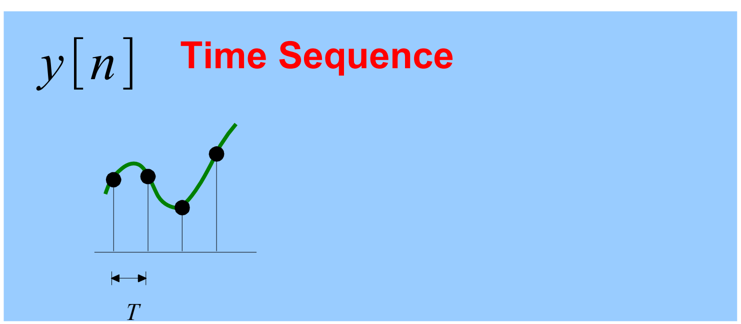


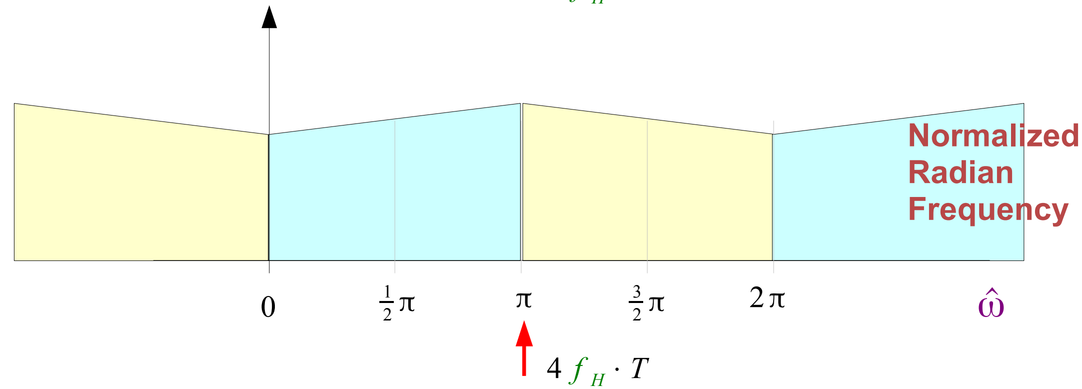






= The Same Time Sequence





Z-Transform Analysis

$$\delta_D[n] = \begin{cases} 1 & \text{if } n/D \text{ is an integer} \\ 0 & \text{otherwise} \end{cases}$$

$$v[n] = \delta_D[n] x[n]$$

$$V[z] = \cdots + v[0] z^{0} + v[D] z^{-D} + v[2D] z^{-2D} + \cdots$$

$y[n]$

$$V[z] = \sum_{n=-\infty}^{+\infty} v[n] z^{-n} = \sum_{m=-\infty}^{+\infty} v[mD] z^{-mD} = F(z^{D})$$

T **Sampling Period**

Z-Transform Analysis

$$\delta_2[n] = \frac{1}{2}\left(1+(-1)^n\right) = \frac{1}{2}\left(1+e^{-j\pi n}\right) = \begin{cases} 1 & \text{if } n/2 \text{ is an integer (even)} \\ 0 & \text{otherwise} \end{cases}$$

$$e^{-j\pi} = -1$$

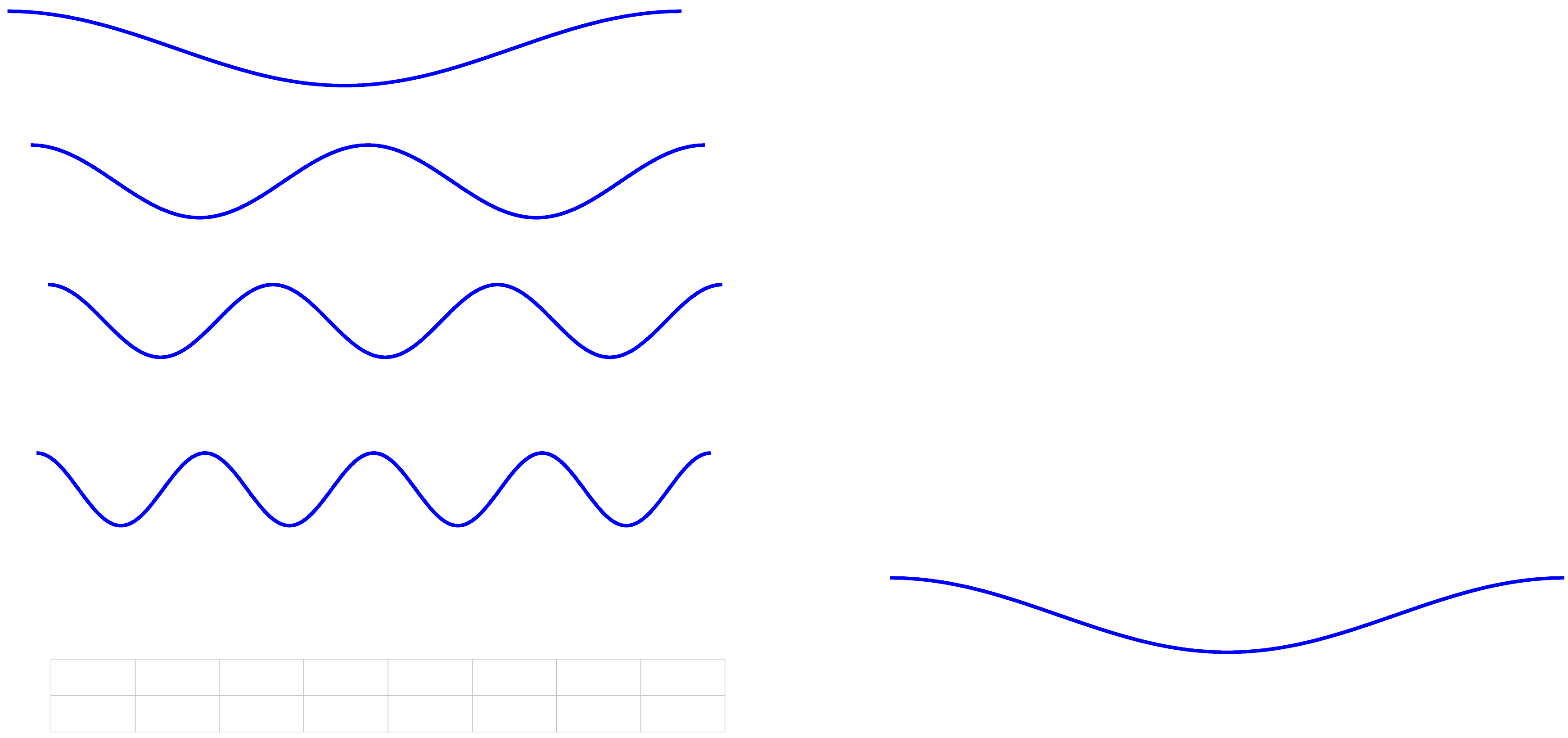
$$v[n] = \frac{1}{2}x[n] + \frac{1}{2}e^{-j\pi n}x[n] \qquad x[n] = e^{j\omega n}$$

$$v[n] = \frac{1}{2}e^{j\omega n} + \frac{1}{2}e^{-j\pi n}e^{j\omega n} = \frac{1}{2}e^{j\omega n} + \frac{1}{2}e^{+j(\omega-\pi)n}$$

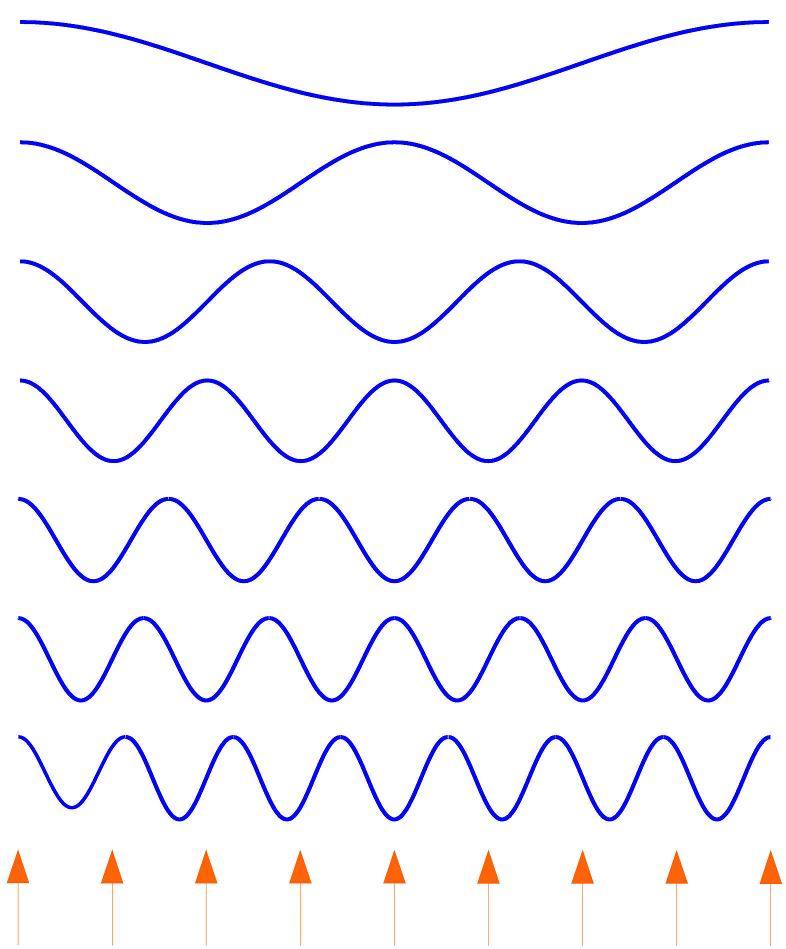
$$V(z) = \frac{1}{2}\sum_{n=-\infty}^{+\infty}\left(x[n]z^{-n} + x[n](-z)^{-n}\right) = \frac{1}{2}X(z) + \frac{1}{2}X(-z)$$

$$V(\omega) = V(e^{j\omega}) = \frac{1}{2}X(e^{j\omega}) + \frac{1}{2}X(e^{-j\pi}e^{j\omega}) = \frac{1}{2}X(\omega) + \frac{1}{2}X(\omega-\pi)$$

Measuring Rotation Rate



Signals with Harmonic Frequencies (1)



1 Hz *1 cycle / sec*
$$\cos(1 \cdot 2\pi t) = \frac{e^{+j(1\cdot 2\pi)t} + e^{-j(1\cdot 2\pi)t}}{2}$$

2 Hz *2 cycles / sec*
$$\cos(2 \cdot 2\pi t) = \frac{e^{+j(2\cdot 2\pi)t} + e^{-j(2\cdot 2\pi)t}}{2}$$

3 Hz *3 cycles / sec*
$$\cos(3 \cdot 2\pi t) = \frac{e^{+j(3\cdot 2\pi)t} + e^{-j(3\cdot 2\pi)t}}{2}$$

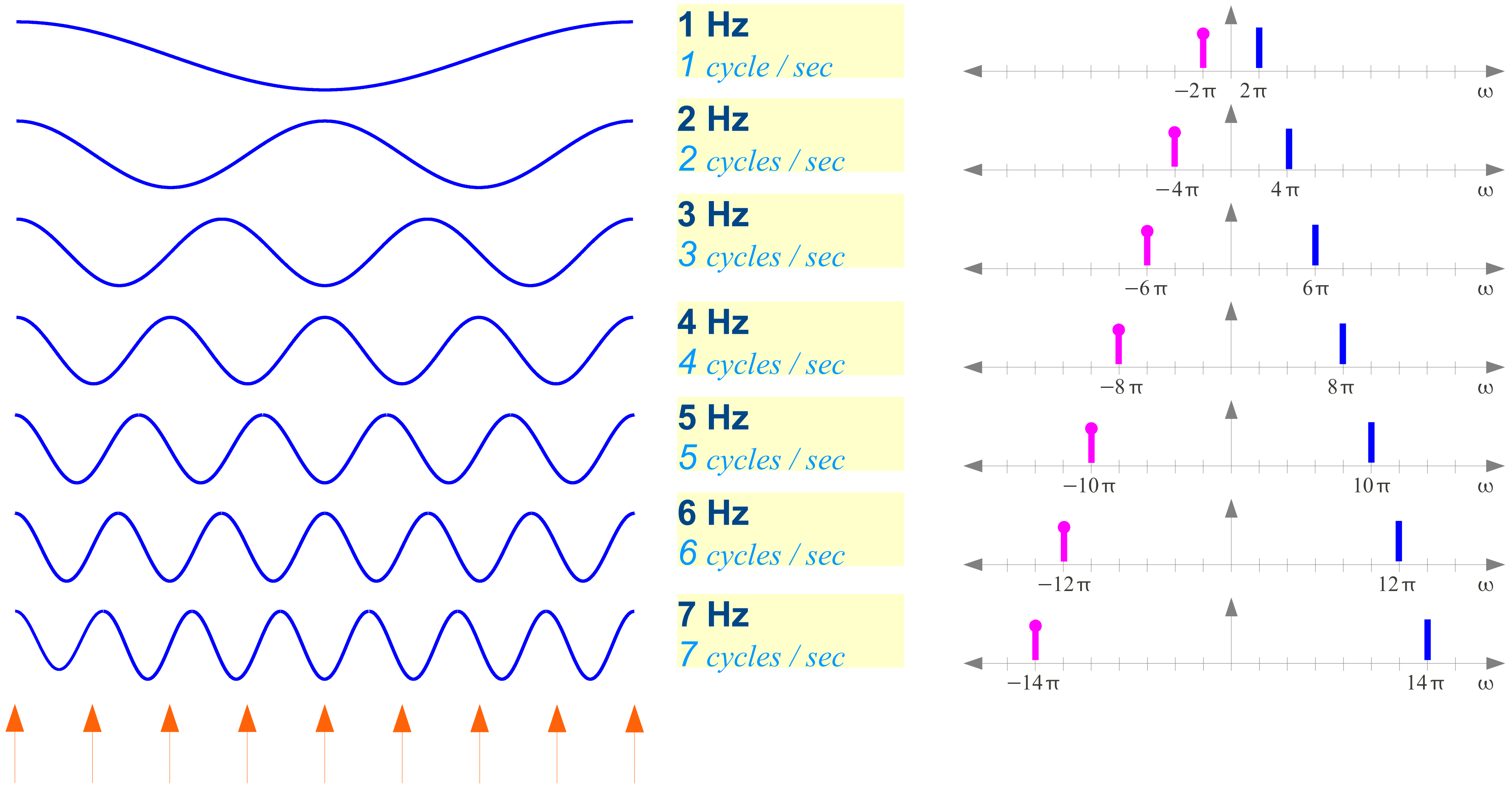
4 Hz *4 cycles / sec*
$$\cos(4 \cdot 2\pi t) = \frac{e^{+j(4\cdot 2\pi)t} + e^{-j(4\cdot 2\pi)t}}{2}$$

5 Hz *5 cycles / sec*
$$\cos(5 \cdot 2\pi t) = \frac{e^{+j(5\cdot 2\pi)t} + e^{-j(5\cdot 2\pi)t}}{2}$$

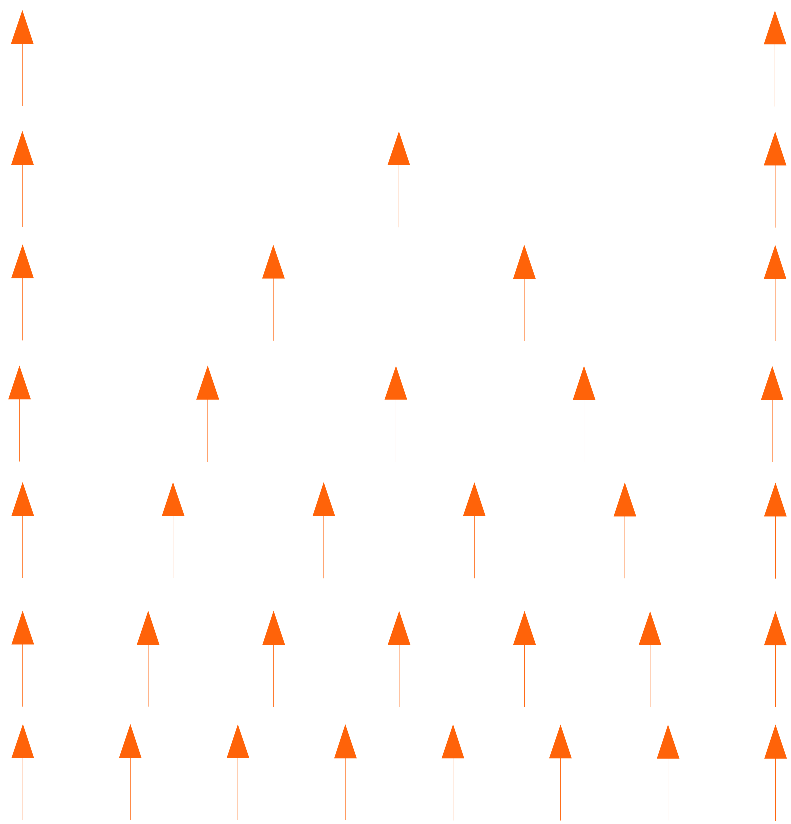
6 Hz *6 cycles / sec*
$$\cos(6 \cdot 2\pi t) = \frac{e^{+j(6\cdot 2\pi)t} + e^{-j(6\cdot 2\pi)t}}{2}$$

7 Hz *7 cycles / sec*
$$\cos(7 \cdot 2\pi t) = \frac{e^{+j(7\cdot 2\pi)t} + e^{-j(7\cdot 2\pi)t}}{2}$$

Signals with Harmonic Frequencies (2)



Sampling Frequency



1 Hz
1 sample / sec

2 Hz
2 samples / sec

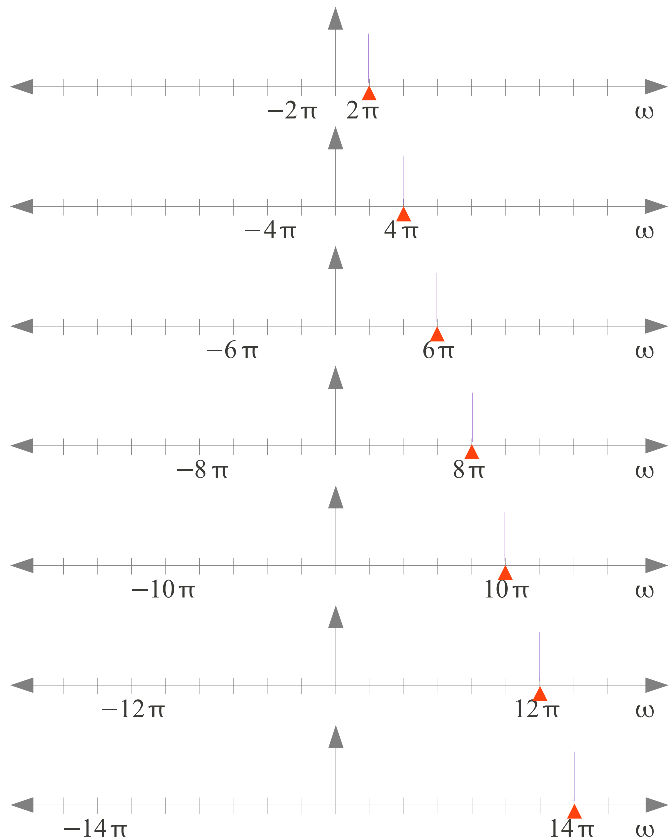
3 Hz
3 samples / sec

4 Hz
4 samples / sec

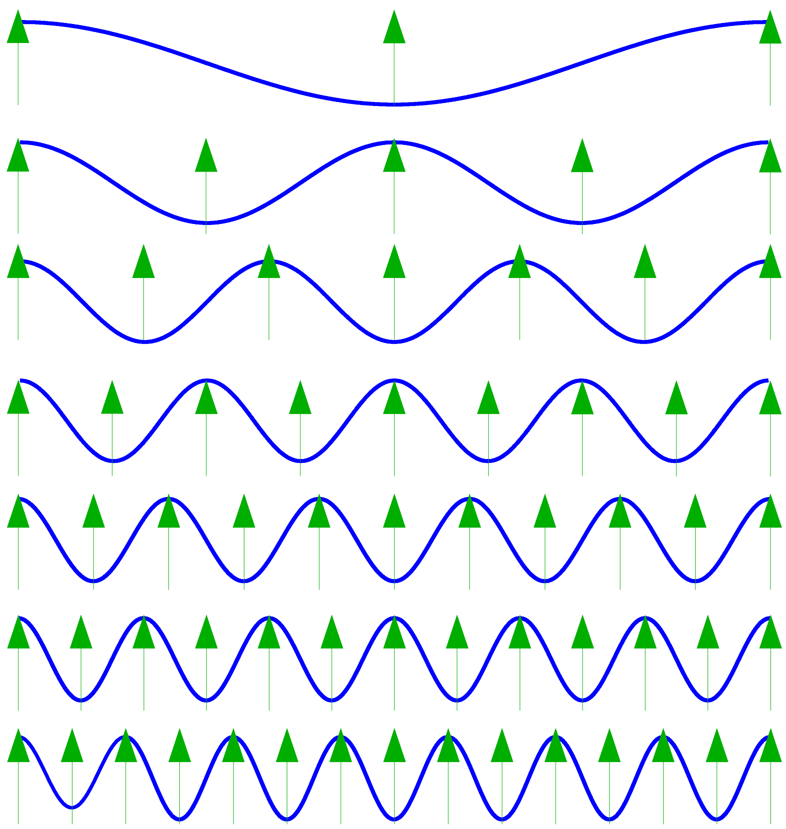
5 Hz
5 samples / sec

6 Hz
6 samples / sec

7 Hz
7 samples / sec

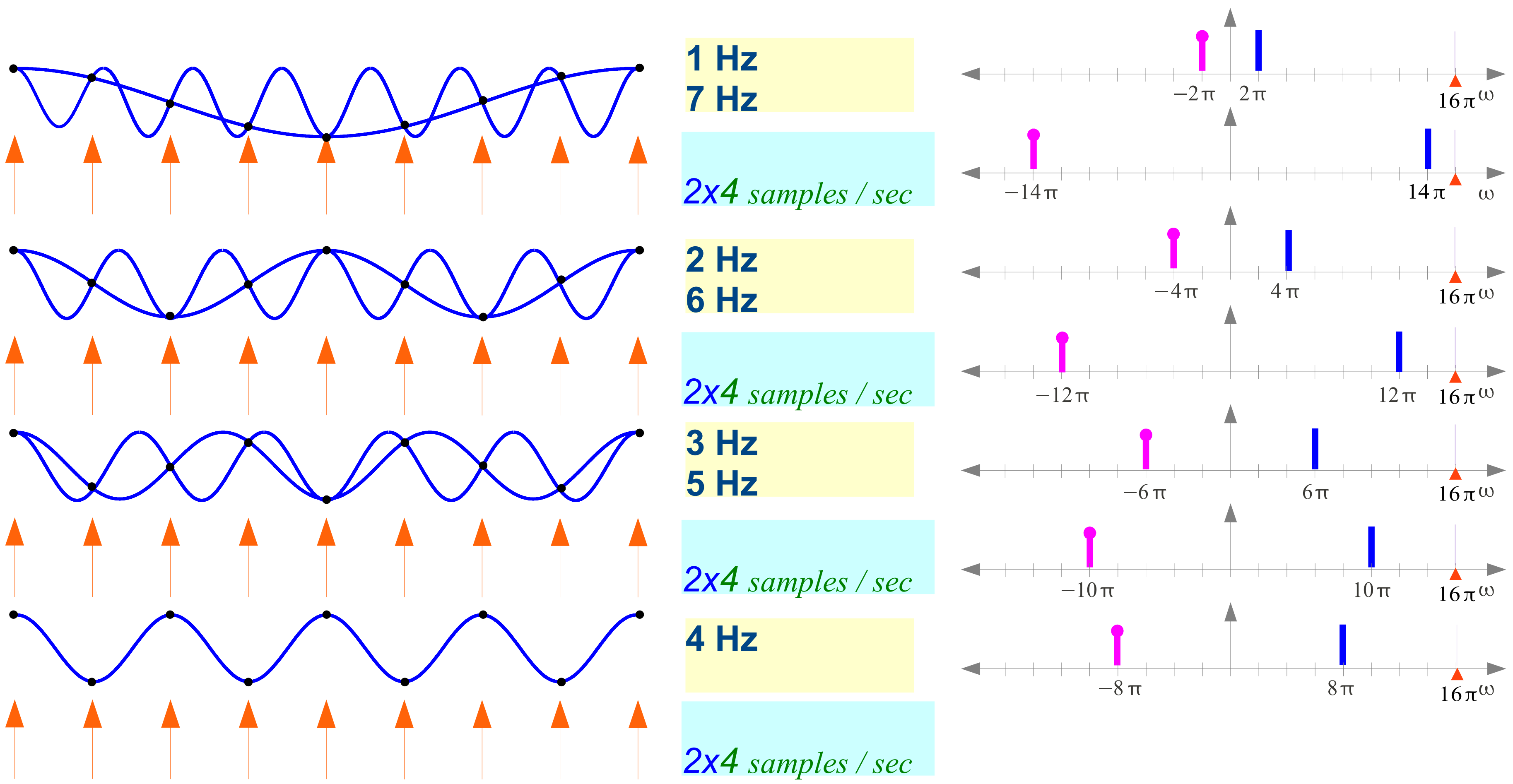


Nyquist Frequency



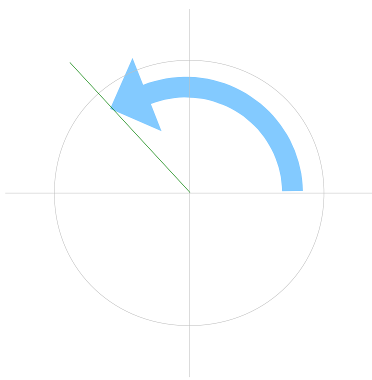
1 Hz *1 cycle / sec*	*2x1 sample / sec*
2 Hz *2 cycles / sec*	*2x2 samples / sec*
3 Hz *3 cycles / sec*	*2x3 samples / sec*
4 Hz *4 cycles / sec*	*2x4 samples / sec*
5 Hz *5 cycles / sec*	*2x5 samples / sec*
6 Hz *6 cycles / sec*	*2x6 samples / sec*
7 Hz *7 cycles / sec*	*2x7 samples / sec*

Aliasing


1 Hz
7 Hz
2x4 samples / sec
2 Hz
6 Hz
2x4 samples / sec
3 Hz
5 Hz
2x4 samples / sec
4 Hz
2x4 samples / sec
−2π
2π
16π
ω
−14π
14π
ω
−4π
4π
16π
ω
−12π
12π
16π
ω
−6π
6π
16π
ω
−10π
10π
16π
ω
−8π
8π
16π
ω

Sampling

$$\omega_s = 2\pi f_s \quad (rad/sec)$$

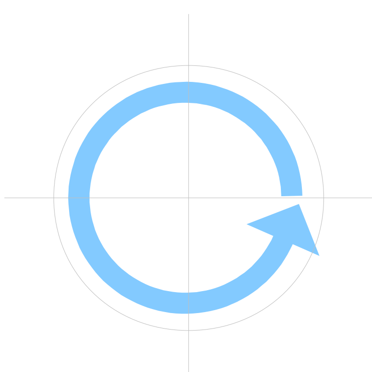


$$\omega_1 = 2\pi f_1 \qquad \omega_2 = 2\pi f_2$$

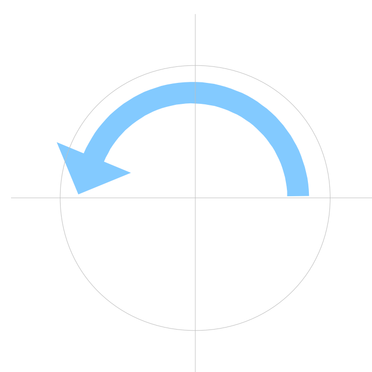
$$\omega_1 = \frac{\omega_s}{2} \quad (rad/sec) \qquad \omega_2 = -\frac{\omega_s}{2} \quad (rad/sec)$$

$$f_1 = \frac{f_s}{2} \quad (rad/sec) \qquad f_2 = -\frac{f_s}{2} \quad (rad/sec)$$

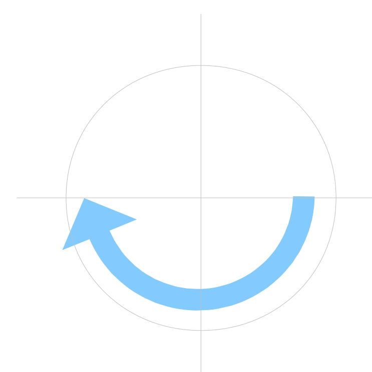
$$2\pi \, (rad) \;/\; T_s \, (sec)$$



$$\pi \, (rad) \;/\; T_s \, (sec)$$

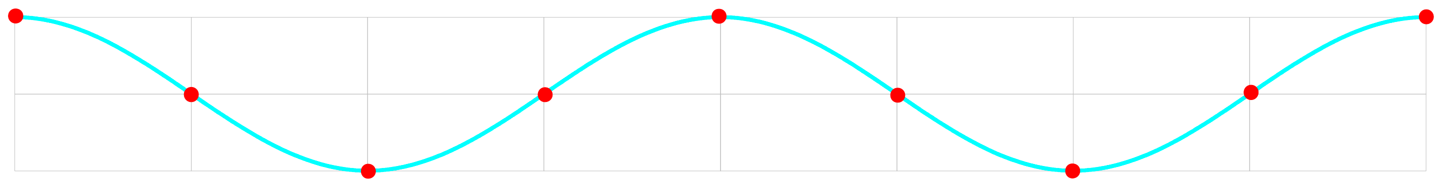


$$-\pi \, (rad) \;/\; T_s \, (sec)$$

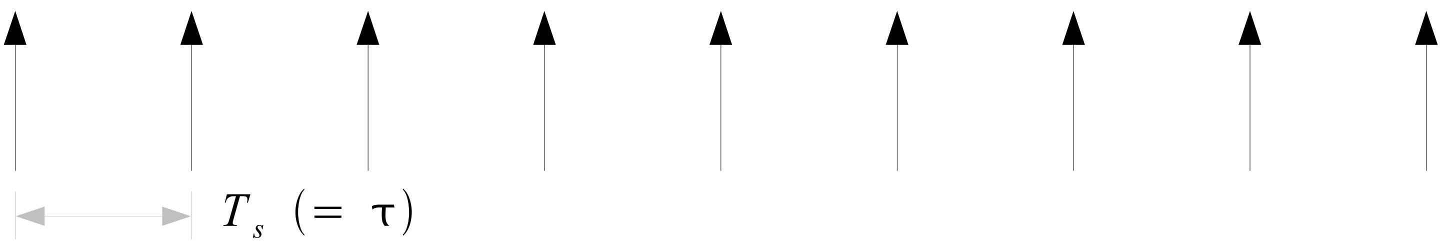


Sampling

$\omega_1 = 2\pi f_1 \ (rad/sec)$

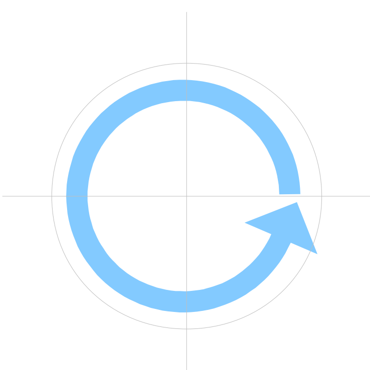


$\omega_s = 2\pi f_s \ (rad/sec)$

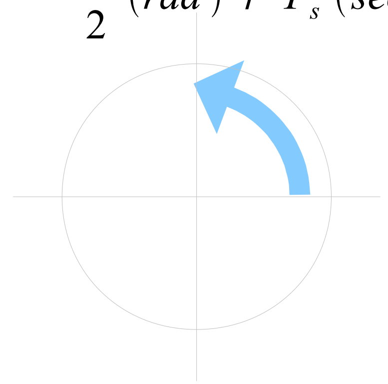


$T_s \ (= \tau)$

$2\pi \ (rad) \ / \ T_s \ (sec)$



$\frac{\pi}{2} \ (rad) \ / \ T_s \ (sec)$



For the period of T_s

Angular displacement $\frac{\pi}{2} \ (rad)$

$$\hat{\omega} = \omega \cdot T_s \ (rad)$$

$$= 2\pi f_1 \cdot T_s \ (rad)$$

$$= 2\pi \frac{f_s}{4} \cdot T_s \ (rad)$$

$$= \frac{\pi}{2} \ (rad)$$

Young Won Lim
9/28/12

Angular Frequencies in Sampling

continuous-time signals

Signal Frequency

$$f_0 = \frac{1}{T_0}$$

Signal Angular Frequency

$$\omega_0 = 2\pi f_0 \quad (rad/sec)$$

sampling sequence

Sampling Frequency

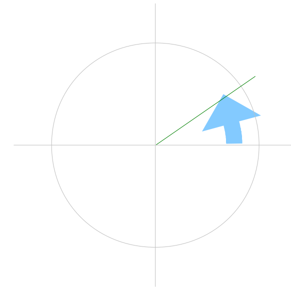
$$f_s = \frac{1}{T_s}$$

Sampling Angular Frequency

$$\omega_s = 2\pi f_s \quad (rad/sec)$$

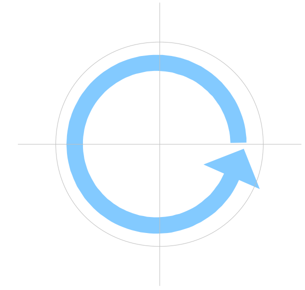
For 1 second

$$\omega_0 = 2\pi f_0 \quad (rad/sec)$$



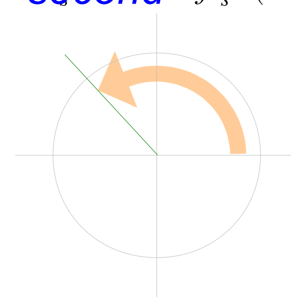
For 1 revolution

$$2\pi (rad) / T_0 (sec)$$



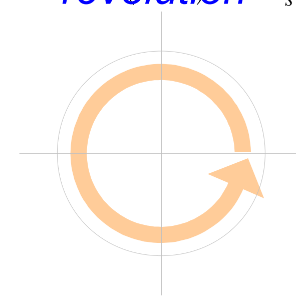
For 1 second

$$\omega_s = 2\pi f_s \quad (rad/sec)$$



For 1 revolution

$$2\pi (rad) / T_s (sec)$$



References

[1] http://en.wikipedia.org/
[2] J.H. McClellan, et al., Signal Processing First, Pearson Prentice Hall, 2003
[3] A "graphical interpretation" of the DFT and FFT, by Steve Mann
[4] R. Cristi, "Modern Digital Signal Processing"