Sampling Basics(1B)

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Young Won Lim

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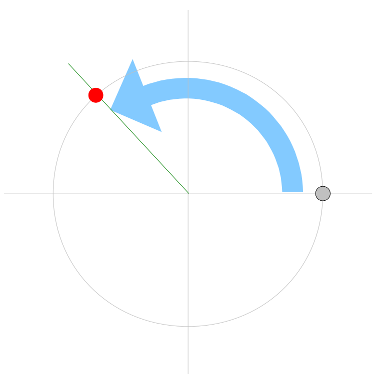
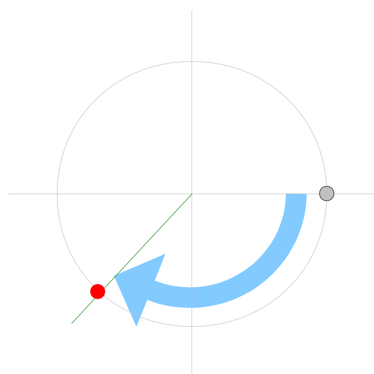
Angular Speed (Frequency)

$$\omega = \frac{2\pi}{T} = 2\pi f$$



$+\omega_0 \; rad \,/\, 1 \; sec$



$-\omega_0 \; rad \,/\, 1 \; sec$

$+\omega_0 \; (rad/sec)$

$-\omega_0 \; (rad/sec)$

RPM

$$rpm = revolutions \,/\, minute$$

$$\begin{aligned} 1 \; rpm &= 2\pi \; rad \,/\, 1 \; min \\ &= 2\pi \; rad \,/\, 60 \; sec \\ &= \frac{\pi}{30} \; rad/sec \end{aligned}$$

- **Negative Angles**

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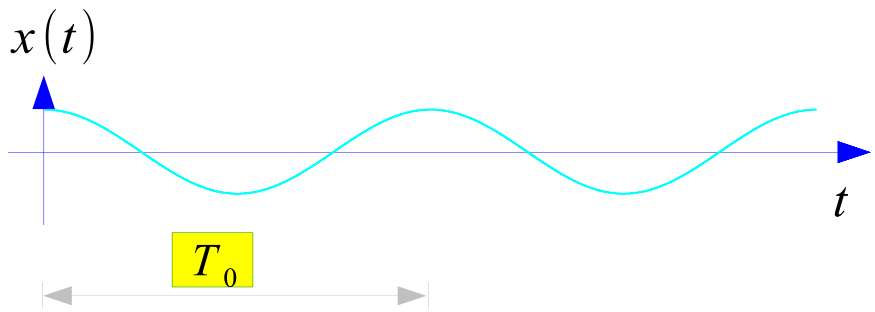
Angular Frequency and Sinusoid

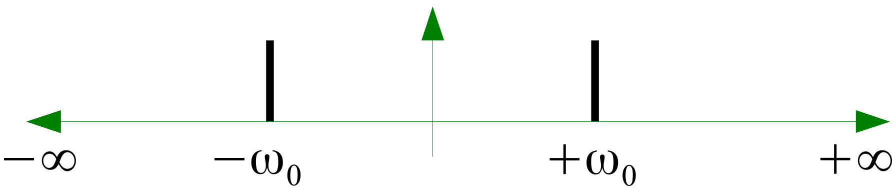
Time Domain



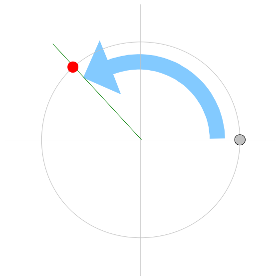
$$\omega_0 = \frac{2\pi}{T_0}$$

$$x(t) = A\cos(\omega_0 t) = \frac{A}{2}e^{j\omega_0 t} + \frac{A}{2}e^{-j\omega_0 t}$$

Frequency Domain

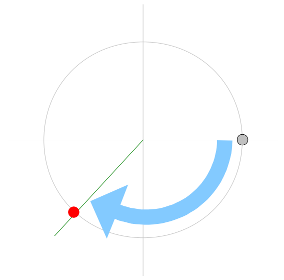


For 1 second



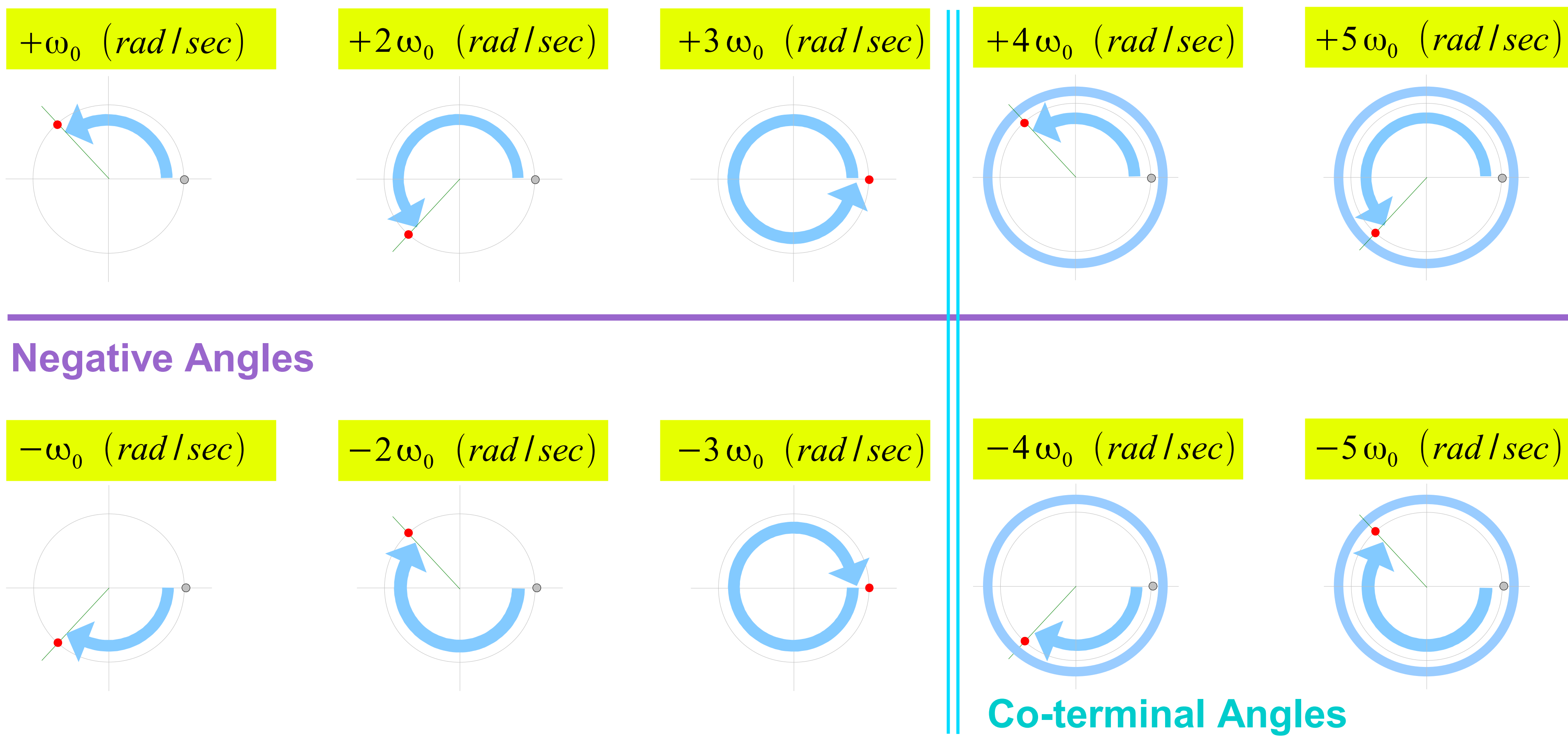
$+\omega_0 \ (rad/sec)$

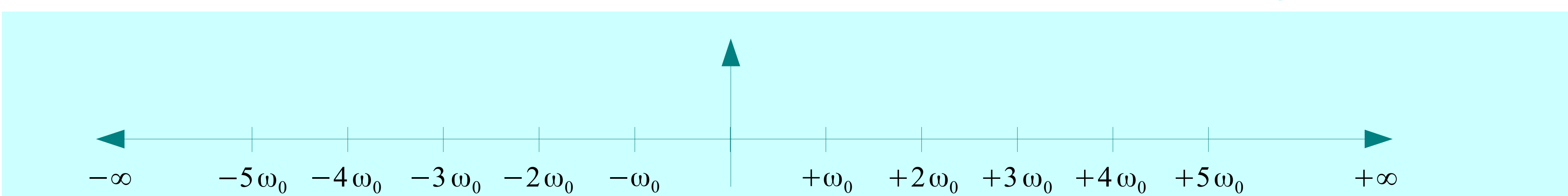
For 1 second



$-\omega_0 \ (rad/sec)$

Angular Speed Examples





Angular Speed and Frequency

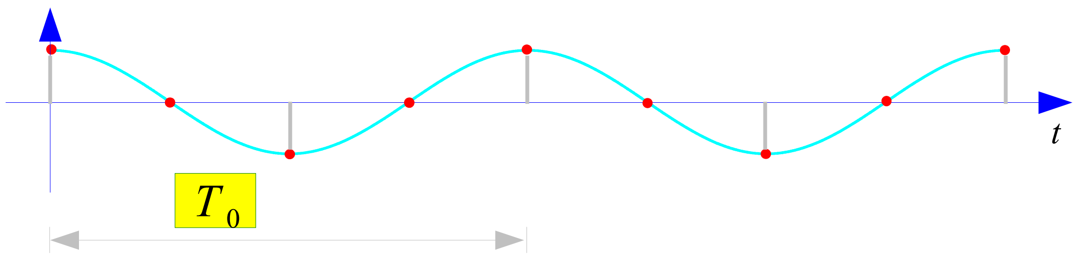
$$\omega = \frac{2\pi}{T} = 2\pi f$$

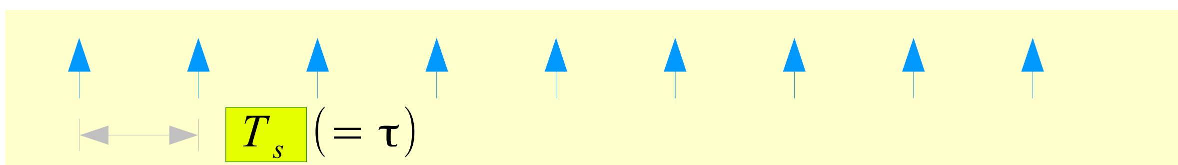
T (sec)	*0.01 sec*	*0.1 sec*	*1 sec*	*10 sec*	*100 sec*
f (Hz)	*100 Hz*	*10 Hz*	*1 Hz*	*0.1 Hz*	*0.01 Hz*
ω (rad/sec)	200π (rad/sec)	20π (rad/sec)	2π (rad/sec)	0.2π (rad/sec)	0.02π (rad/sec)
	= 628	*= 62.8*	*= 6.28*	*= 0.628*	*=0.0628*

Sampling

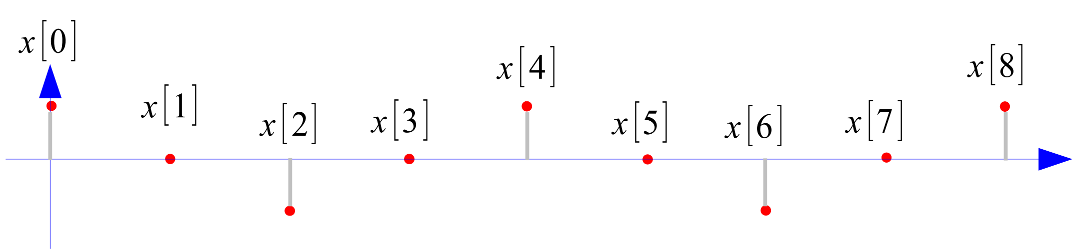
continuous-time signals

$$x(t) = A\cos(\omega_0 t)$$





discrete-time sequence



Sampling Time

$$T_s\ (=\tau)$$

Sequence Time Length

$$T = N \cdot T_s$$

Sampling Frequency

$$f_s = \frac{1}{T_s} \quad \textbf{(samples / sec)}$$

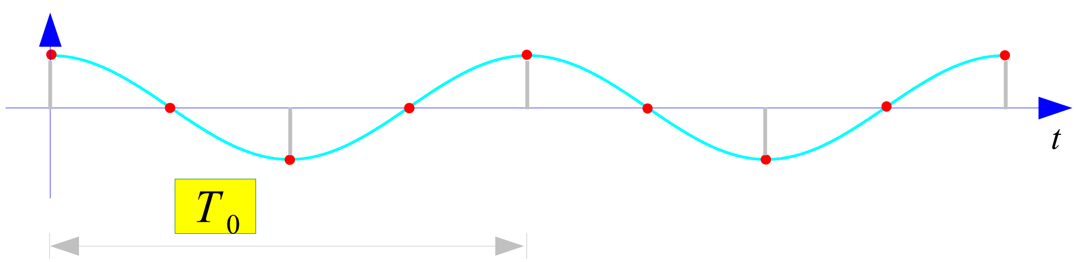
Signal's Frequency

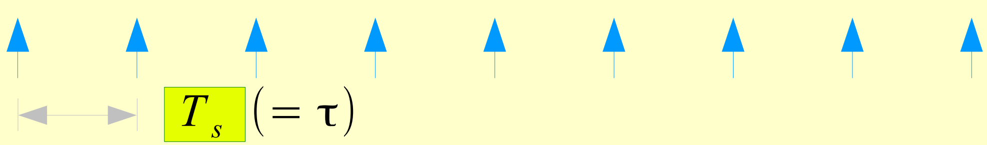
$$f_0 = \frac{1}{T_0} \quad \textbf{(cycles / sec)}$$

Sampling Frequency

continuous-time signals

$$x(t) = A\cos(\omega_0 t)$$





For 1 second

$\frac{1}{T_s}$ **(*samples / sec*)**

For 1 sample

1 **(*samples*)** / T_s **(*sec*)**

For 1 second

$\frac{1}{T_0}$ **(*cycles / sec*)**

For 1 cycle

1 **(*cycles*)** / T_0 **(*sec*)**

Sampling Time

$$T_s \; (= \tau)$$

Sequence Time Length

$$T = N \cdot T_s$$

Sampling Frequency

$$f_s = \frac{1}{T_s}$$ **(*samples / sec*)**

Signal's Frequency

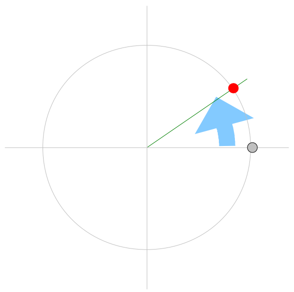
$$f_0 = \frac{1}{T_0}$$ **(*cycles / sec*)**

Angular Frequencies in Sampling

continuous-time signals

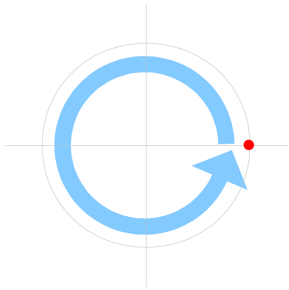
For 1 second

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

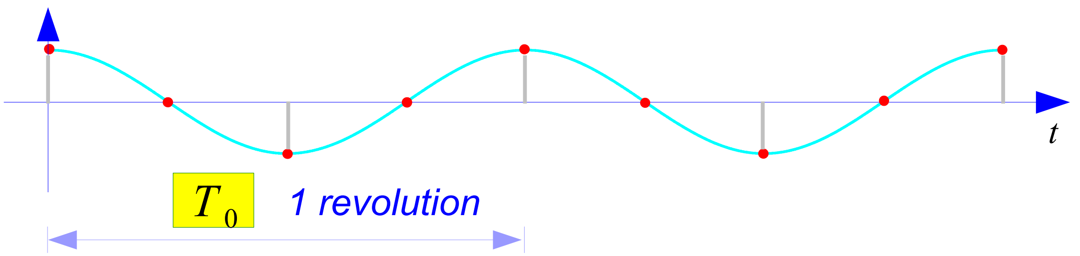


For 1 revolution

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



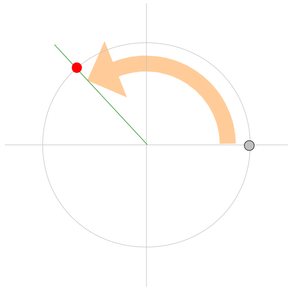
$x(t) = A\cos(\omega_0 t)$



sampling sequence

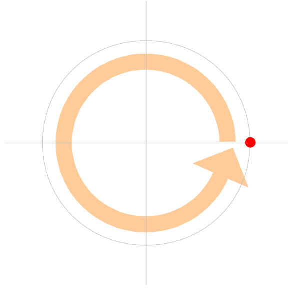
For 1 second

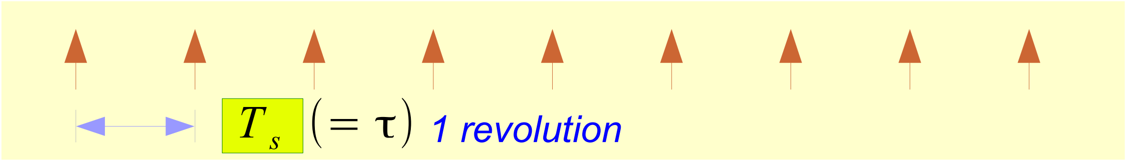
$\omega_s = 2\pi f_s \ (rad/sec)$



For 1 revolution

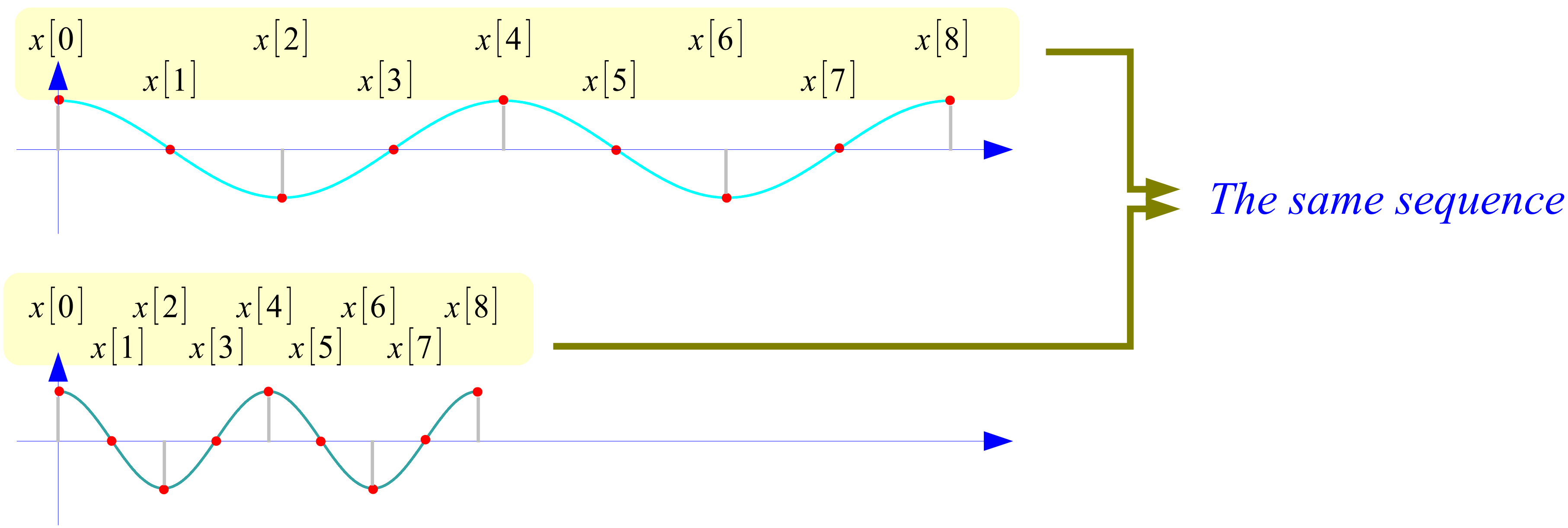
$2\pi \ (rad) \ / \ T_s \ (sec)$





Dimensionless Sequence

$$x[n] \Rightarrow \cdots, \; x[0], \; x[1], \; x[2], \; x[3], \; x[4], \; x[5], \; x[6], \; x[7], \; x[8], \; \cdots$$



<u>Infinite number</u> of continuous time signals

Sampling ⇒

The <u>same</u> discrete-time sequence

Sampling of Sinusoid Functions

$$x(t) = A\cos(\omega t + \phi)$$

$$t \rightarrow n\,T_s$$

$$x[n] = x(n\,T_s)$$

$$= A\cos(\omega \cdot n\,T_s + \phi)$$

$$= A\cos(\omega \cdot T_s\, n + \phi)$$

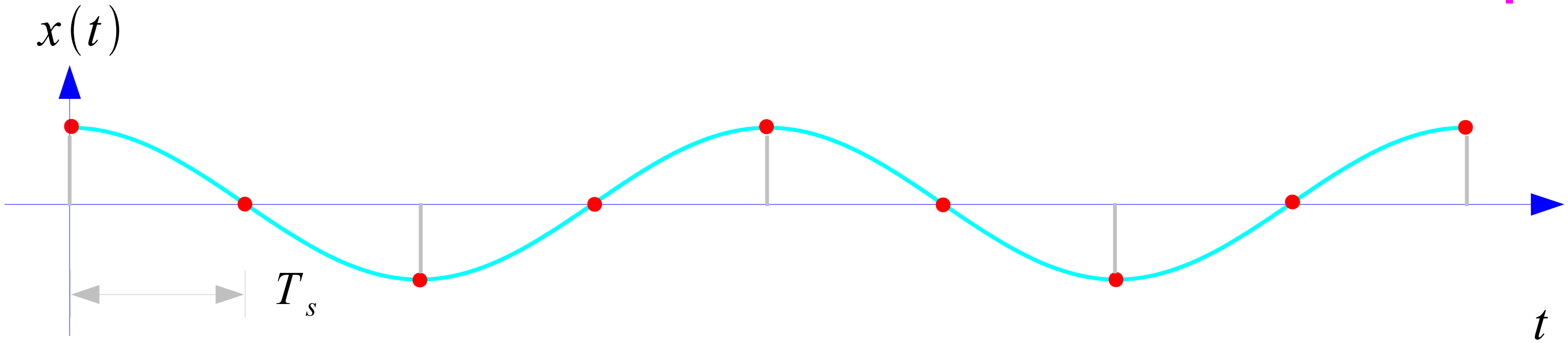
$$= A\cos(\hat{\omega} \cdot n + \phi)$$

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

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

Normalized to f_s

Normalized Radian Frequency



Normalized Radian Frequency (1)

continuous-time signals	Sampling	discrete-time sequence
$x(t)$	$t \rightarrow n\,T_s$	$x[n] = x(nT_s)$

Angular Frequency	Sampling	Normalized Radian Frequency
$\omega \quad (rad/sec)$	$\times\, T_s$	$\hat{\omega} = \omega \cdot T_s \quad (rad/sample)$

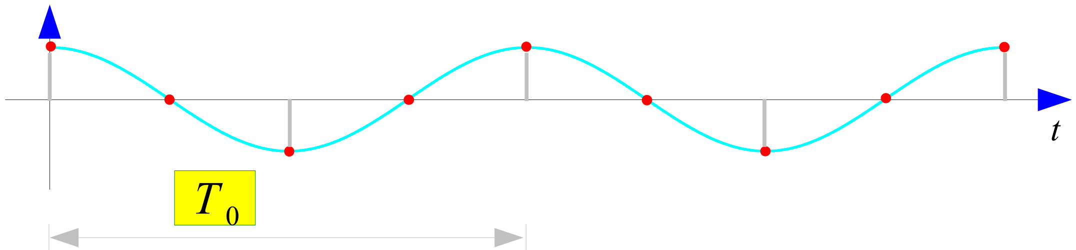
Angular Speed X Sampling Time

Normalized Radian Frequency
can be viewed as
"the angular displacement of a signal during the period of its sample time T_s"

- Negative Angles
  $\rightarrow$ folding
- Co-terminal Angles
  $\rightarrow$ periodic

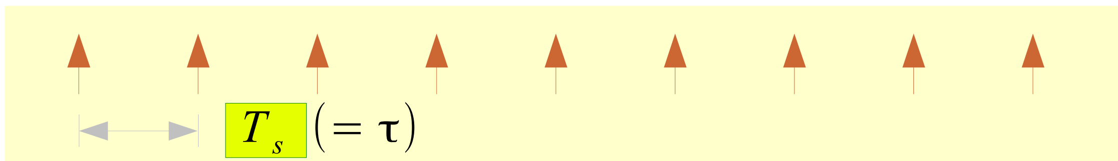
Normalized Radian Frequency (2)

$$x(t) = A\cos(\omega_0 t)$$



$$\omega_0 = 2\pi f_0$$

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



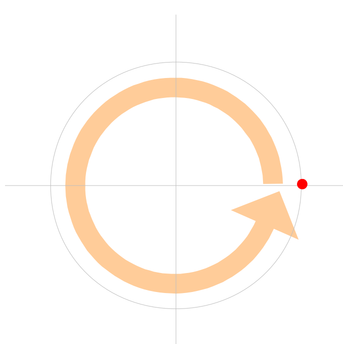
$$\omega_s = 2\pi f_s$$

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

sampling sequence

For 1 sample

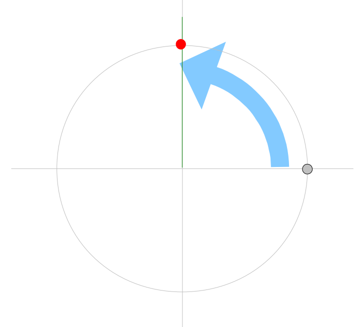
$$2\pi\,(rad) \;/\; T_s\,(sec)$$



continuous-time signals

For T_s second

$$\hat{\omega} = \omega_0 \cdot T_s \quad (rad/sample)$$



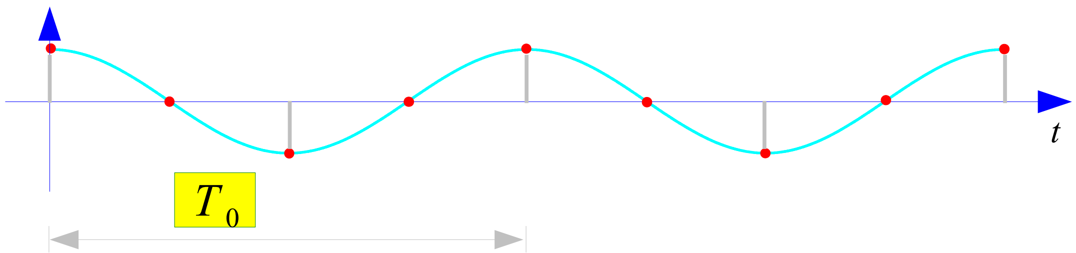
$$\hat{\omega} = \omega T_s$$

$$\hat{\omega} = \frac{\omega}{f_s}$$

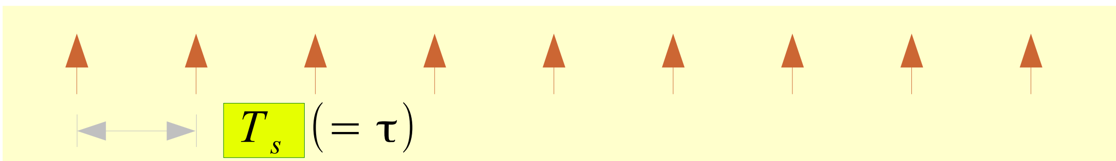
Signal's relative angle position after each of T_s second

Normalized Radian Frequency (3)

$$x(t) = A\cos(\omega_0 t)$$



$$\omega_0 = 2\pi f_0 \qquad f_0 = \frac{1}{T_0}$$



$$\omega_s = 2\pi f_s \qquad f_s = \frac{1}{T_s}$$

Normalized Frequency

$$\frac{f_0}{f_s} \; \frac{(cycle\,/\,sec)}{(sample\,/\,sec)} \;\Rightarrow\; \frac{f_0}{f_s} \; (cycle\,/\,sample)$$

Normalized Radian Frequency

$$2\pi \, \frac{(rad)}{(cycle)} \cdot \frac{f_0}{f_s} \, \frac{(cycle)}{(sample)} \;\Rightarrow\; \frac{\omega_0}{f_s} \; (rad\,/\,sample)$$

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

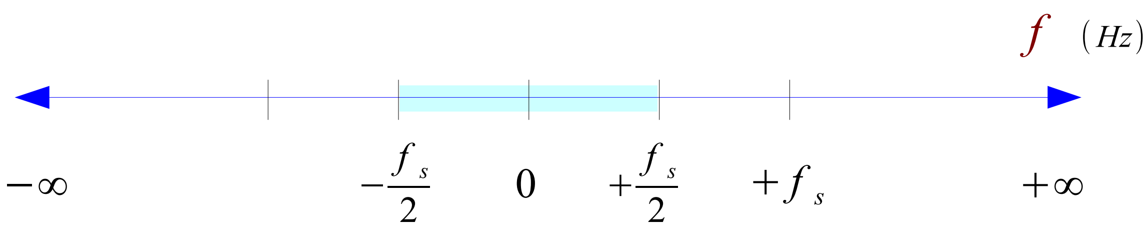
$$\hat{\omega} = \frac{\omega}{f_s} = 2\pi \frac{f}{f_s}$$

Normalized Radian Frequency (4)

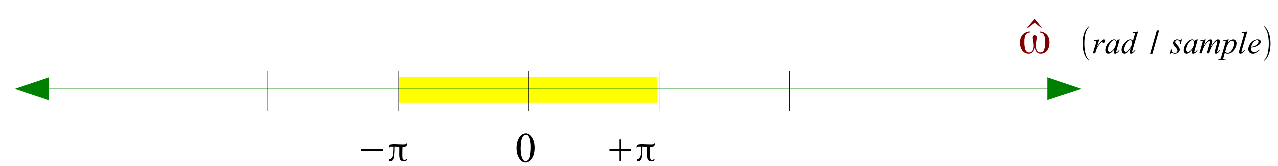
Consider $f \in \left(-\frac{f_s}{2}, \quad +\frac{f_s}{2} \right)$ → *then* $\frac{f}{f_s} \in \left(-\frac{1}{2}, \quad +\frac{1}{2} \right)$

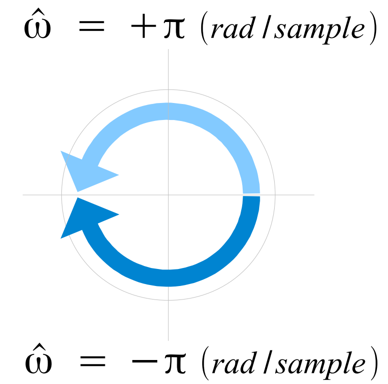
$$\hat{\omega} \in \left(-\pi, \quad +\pi \right)$$

Linear Frequency



Normalized Radian Frequency





Example (1)

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

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

$$\hat{\omega}_1 = \omega_1 \cdot T_s \quad (rad/sample)$$

$$\hat{\omega}_2 = \omega_2 \cdot T_s \quad (rad/sample)$$

Negative Angles

$$A\cos(\omega_1 t + \phi)$$

$$when \quad \omega_1 = +\frac{\omega_s}{2}$$

$$\hat{\omega}_1 = \pi\,(rad)$$

$$when \quad \omega_1 = -\frac{\omega_s}{2}$$

$$\hat{\omega}_1 = -\pi\,(rad)$$

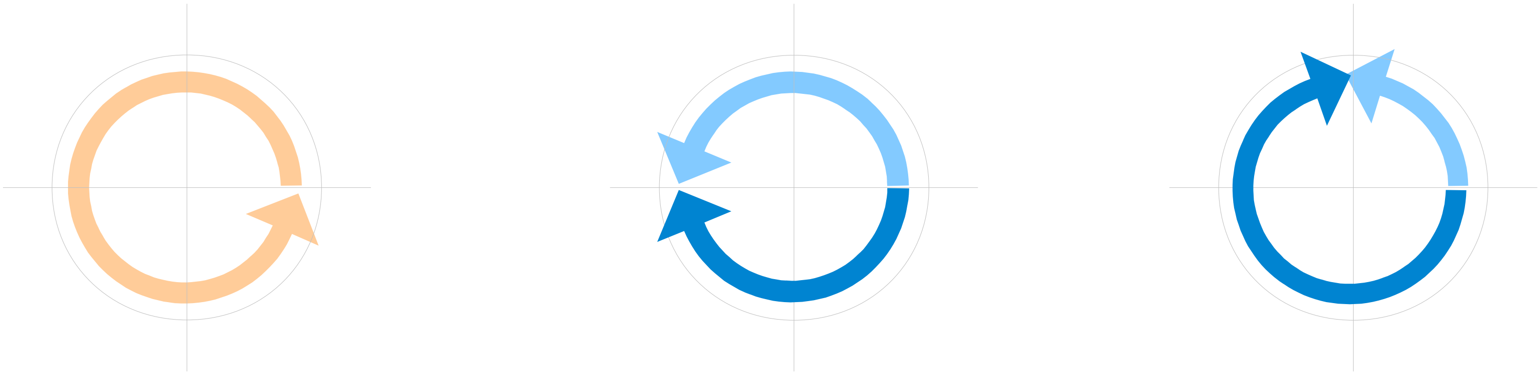
$$A\cos(\omega_2 t + \phi)$$

$$when \quad \omega_2 = +\frac{\omega_s}{4}$$

$$\hat{\omega}_2 = \frac{\pi}{2}\,(rad)$$

$$when \quad \omega_2 = -\frac{3\omega_s}{4}$$

$$\hat{\omega}_2 = -\frac{3\pi}{2}\,(rad)$$



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Example (2)

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

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

$\hat{\omega}_1 = \omega_1 \cdot T_s \ (rad/sample)$

$\hat{\omega}_2 = \omega_2 \cdot T_s \ (rad/sample)$

Co-terminal Angles

$A\cos(\omega_1 t + \phi)$

$when \quad \omega_1 = \frac{\omega_s}{2}$

$\hat{\omega}_1 = \pi\,(rad)$

$when \quad \omega_1 = \frac{\omega_s}{2} + \omega_s$

$\hat{\omega}_1 = \pi + 2\pi\,(rad)$

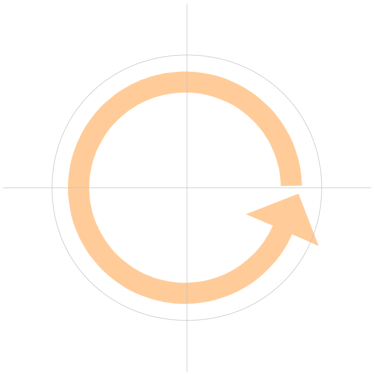
$A\cos(\omega_2 t + \phi)$

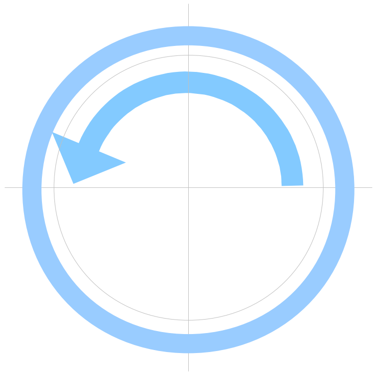
$when \quad \omega_2 = \frac{\omega_s}{4}$

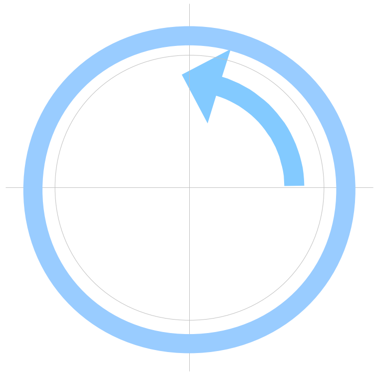
$\hat{\omega}_2 = \frac{\pi}{2}\,(rad)$

$when \quad \omega_2 = \frac{\omega_s}{4} + \omega_s$

$\hat{\omega}_2 = \frac{\pi}{2} + 2\pi\,(rad)$



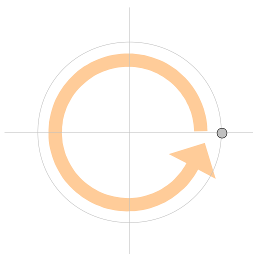




Co-terminal Angles (1)

For 1 sample

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

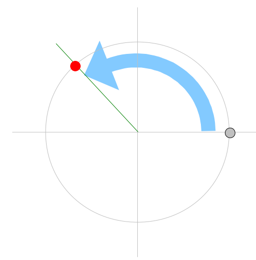


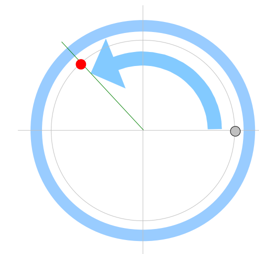
$\hat{\omega} = \omega \cdot T_s \quad (rad/sample)$

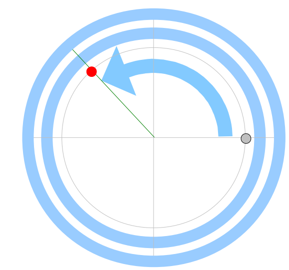
$= \omega / f_s \quad (rad/sample)$

For T_s second

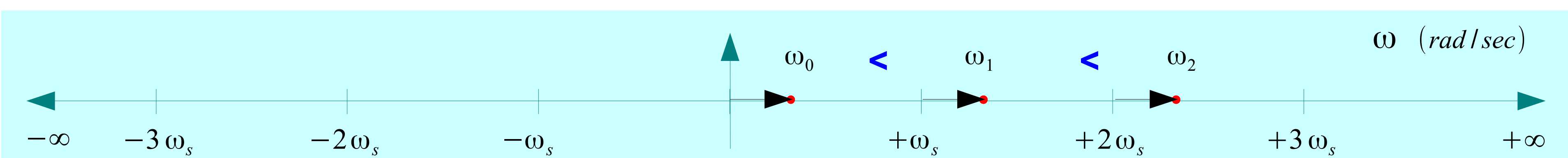
$\hat{\omega} = \omega \cdot T_s \quad (rad/sample)$

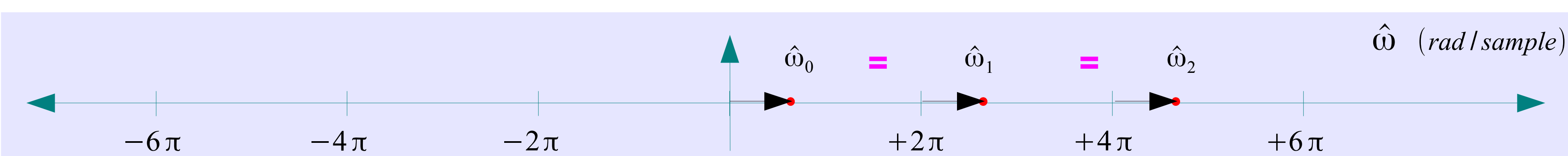






f_0	$f_0 + f_s$	$f_0 + 2f_s$
$\omega_0 = 2\pi f_0$	$\omega_1 = 2\pi(f_0 + f_s)$	$\omega_2 = 2\pi(f_0 + 2f_s)$
$\hat{\omega}_0 \quad (rad/sample)$	$\hat{\omega}_0 + 2\pi \quad (rad/sample)$	$\hat{\omega}_0 + 4\pi \quad (rad/sample)$

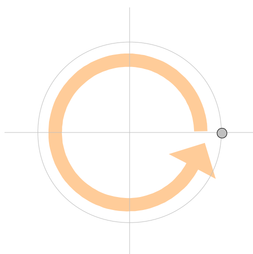




Co-terminal Angles (2)

For 1 sample

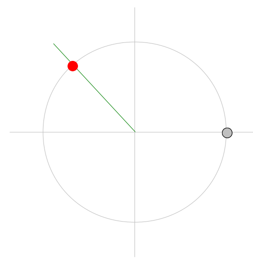
$2\pi\ (rad)\ /\ T_s\ (sec)$

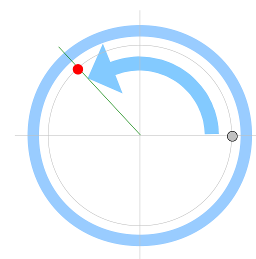


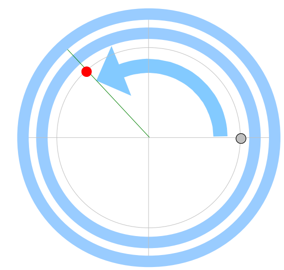
$\hat{\omega} = \omega \cdot T_s\ (rad/sample)$
$= \omega / f_s\ (rad/sample)$

For T_s second

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



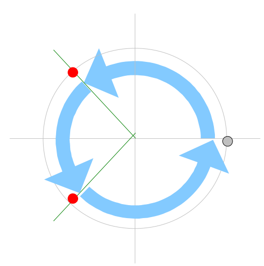


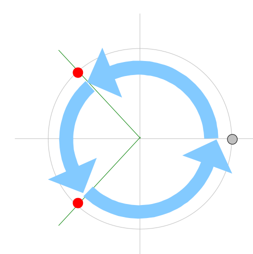


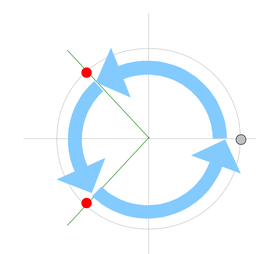
f_0	$f_0 + f_s$	$f_0 + 2f_s$
$\omega_0 = 2\pi f_0$	$\omega_1 = 2\pi(f_0 + f_s)$	$\omega_2 = 2\pi(f_0 + 2f_s)$
$\hat{\omega}_0\ (rad/sample)$	$\hat{\omega}_0 + 2\pi\ (rad/sample)$	$\hat{\omega}_0 + 4\pi\ (rad/sample)$

Co-terminal Angles

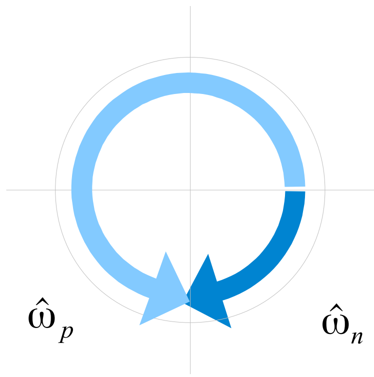
The same angular positions after each sample time.







Positive & Negative Angles (1)



$+ \quad -$

$$\hat{\omega}_p - \hat{\omega}_n = 2\pi$$

Positive Normalized Rad Freq

$$\hat{\omega}_p = 2\pi + \hat{\omega}_n$$

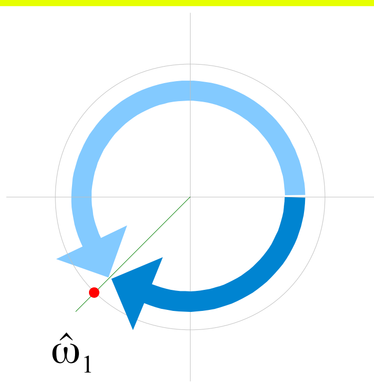
$+ \quad -$

Negative Normalized Rad Freq

$$\hat{\omega}_n = \hat{\omega}_p - 2\pi$$

$- \quad +$

$$\frac{f_s}{2} < f_1 < f_s$$



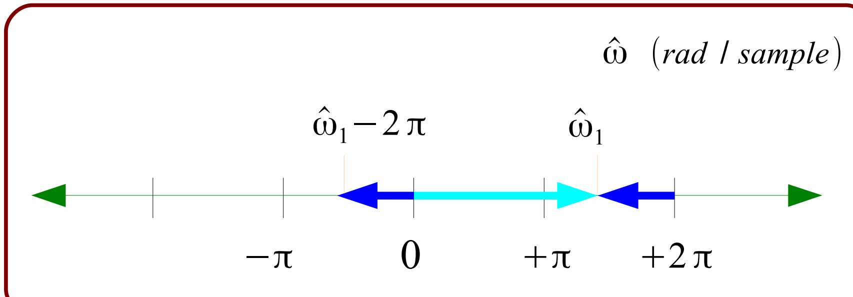
Positive Angle

$$+\pi < \hat{\omega}_1 < 2\pi$$

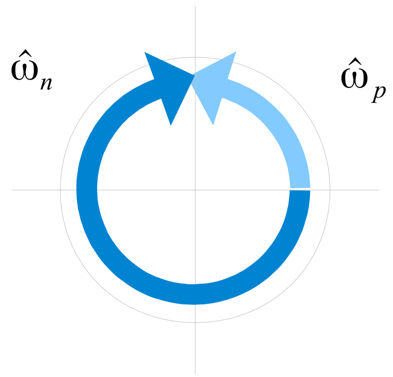
Negative Angle

$$-\pi < \hat{\omega}_1 - 2\pi < 0$$

Normalized Radian Frequency



Positive & Negative Angles (2)



$$\overset{+}{\hat{\omega}_p} - \overset{-}{\hat{\omega}_n} = 2\pi$$

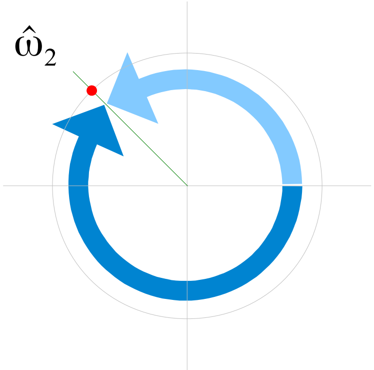
Positive Normalized Rad Freq

$$\underset{+}{\hat{\omega}_p} = 2\pi + \underset{-}{\hat{\omega}_n}$$

Negative Normalized Rad Freq

$$\underset{-}{\hat{\omega}_n} = \underset{+}{\hat{\omega}_p} - 2\pi$$

$$-f_s < f_2 < -\frac{f_s}{2}$$



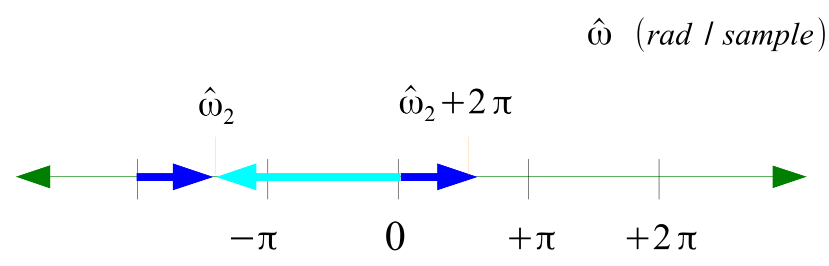
Negative Angle

$$-2\pi < \hat{\omega}_2 < -\pi$$

Positive Angle

$$0 < 2\pi + \hat{\omega}_2 < \pi$$

Normalized Radian Frequency



Young Won Lim
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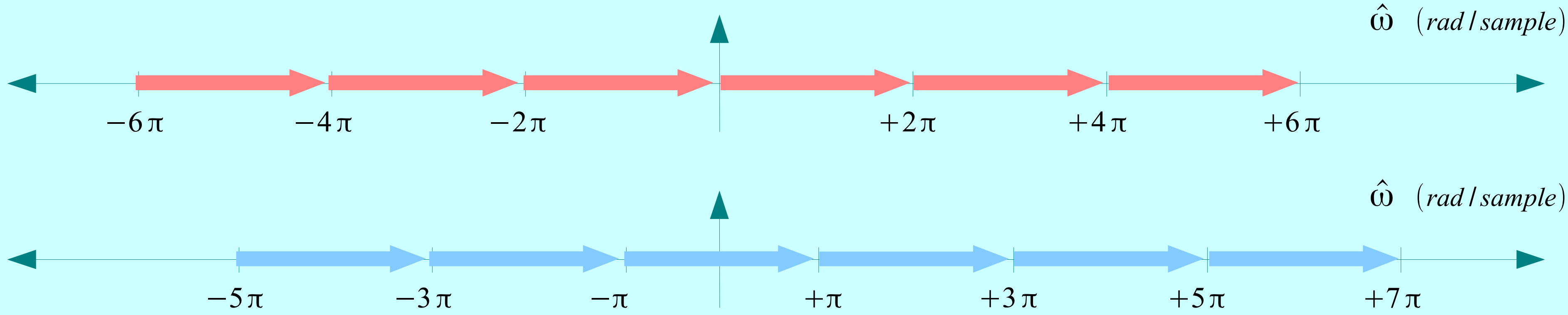
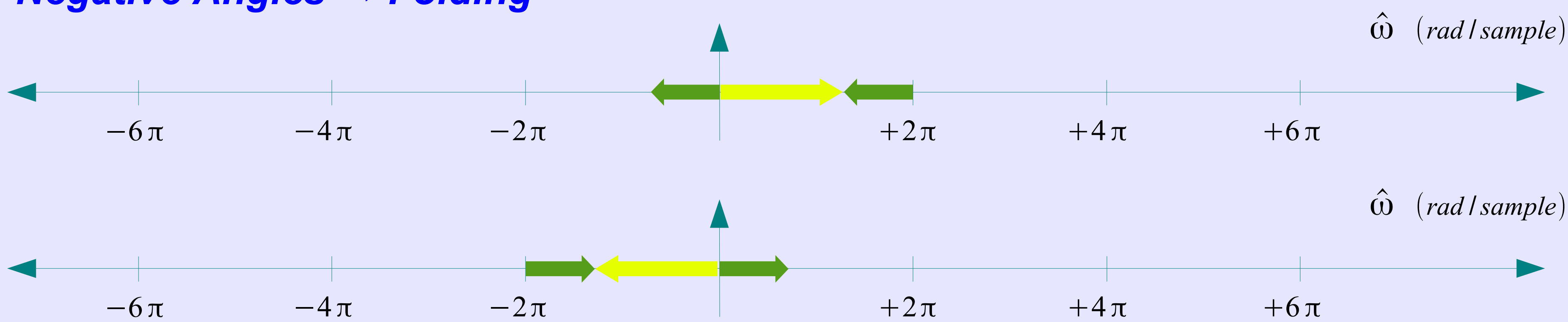
Periodic and Folding

Co-terminal Angles → Periodic



Negative Angles → Folding



References

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[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