Digital Signal Octave Codes (0A)

- Periodic Conditions

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

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Based on
M.J. Roberts, Fundamentals of Signals and Systems
S.K. Mitra, Digital Signal Processing : a computer-based approach 2nd ed
S.D. Stearns, Digital Signal Processing with Examples in MATLAB

Sampling and Normalized Frequency

$$\omega_0 t = 2\pi f_0 t$$

$$\omega_0 n T_s = 2\pi f_0 n T_s$$

$$= \frac{2\pi}{T_0} n T_s$$

$$= 2\pi n \frac{T_s}{T_0}$$

$$= 2\pi n F_0$$

$$t = n T_s$$

T_s : sampling period

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

T_0 : signal period

$$\frac{T_s}{T_0} = \frac{f_0}{f_s}$$

normalization

$$F_0 = f_0 T_s = \frac{f_0}{f_s}$$

normalization

Analog and Digital Frequencies

Analog Signal Frequency

$$\omega_0 t = 2\pi f_0 t$$

$t = nT_s$ $\qquad$ $t = nT_s$

$$n\omega_0 T_s = 2\pi n f_0 T_s$$

$\omega_0 T_s = \Omega_0$ $\qquad$ $f_0 T_s = F_0$

$$\Omega_0 n = 2\pi n F_0$$

Digital Signal Frequency

Multiplying by T_s – Normalization

$$\omega_0 t = 2\pi f_0 t$$

Analog Signal

$$\downarrow \cdot T_s \qquad \downarrow \cdot T_s$$

Normalization

$$\Omega_0 n = 2\pi n F_0$$

Digital Signal

Normalization

$$F_0 = f_0 \cdot T_s$$
$$= f_0 / f_s$$
$$= T_s / T_0$$

$f_0 \cdot T_s$ *Multiplied by* T_s

f_0 / f_s *Divided by* f_s

$$\Omega_0 = 2\pi F_0$$

Normalized Cyclic and Radian Frequencies

Normalized Cyclic Frequency

$$F_0 \ cycles/sample = \frac{f_0 \ \ cycles/second}{f_s \ samples/second}$$

Normalized Radian Frequency

$$\Omega_0 \ cycles/sample = \frac{\omega_0 \ \ cycles/second}{f_s \ samples/second}$$

Periodic Relation : N_0 and F_0

$$e^{j(2\pi(n+N_0)F_0)} = e^{j(2\pi n F_0)}$$

$$e^{j2\pi m} = 1$$

Digital Signal Period N_0
: the smallest integer

$$e^{j2\pi N_0 F_0} \quad \Rightarrow \quad e^{j2\pi m} = 1$$

Periodic Condition
: integer m

$$2\pi N_0 F_0 = 2\pi m$$

$$N_0 F_0 = m$$

Periodic Condition : N_0 and F_0

$$2\pi N_0 F_0 = 2\pi m$$

$$N_0 F_0 = m$$

$$N_0 = \frac{m}{F_0} = m \cdot \frac{T_0}{T_s}$$

Integer * Rational :
must be an Integer

Digital Signal Period N_0
: the *smallest* integer

Periodic Condition
: the *smallest* integer m

$$m \neq T_s$$

$$m = p$$

reduced form

Periodic Condition : N_0 and F_0 in a reduced form

Integer

reduced form

$$N_0 = \frac{m}{F_0} = m \cdot \frac{T_0}{T_s} = m \cdot \frac{q}{p}$$

Integer * Rational :
must be an Integer

Rational numbers

N_0 and F_0 in a reduced form : Examples

reduced form

$$F_0 = \boxed{\frac{p}{q}}$$

Rational

$$N_0 = \frac{m}{F_0} = m \cdot \frac{q}{p}$$

integer

$$N_0 \rightarrow q$$
$$m \rightarrow p$$

integers

the smallest integer m

$$\frac{1}{F_0} = \frac{2.678}{4.017} = \frac{2 \cdot 1.339}{3 \cdot 1.339} = \frac{2}{3}$$

$m = 3 \qquad m \neq 4.017$

$N_0 = 2 \qquad N_0 \neq 2.678$

$$\frac{1}{F_0} = \frac{10}{15} = \frac{2 \cdot 5}{3 \cdot 5} = \frac{2}{3}$$

$m = 3 \qquad m \neq 15$

$N_0 = 2 \qquad N_0 \neq 10$

Periodic Relations – Analog and Digital Cases

$$e^{j(2\pi(n+N_0)F_0)} = e^{j(2\pi n F_0)}$$

Digital Signal Period ***N_0***
: the smallest integer

$$N_0 = \frac{m}{F_0} = m \cdot \frac{T_0}{T_s}$$

$$k N_0 F_0 = \boxed{k \cdot m}$$

integer multiple of m
: *some* integers m

$$e^{j(2\pi f_0)(t+T_0)} = e^{j(2\pi f_0)t}$$

Analog Signal Period ***T_0***
: the smallest real number

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

$$k T_0 f_0 = \boxed{k \cdot 1}$$

all integers

Periodic Conditions – Analog and Digital Cases

$$N F_0 = k \cdot m$$

$$N = \frac{k \cdot m}{F_0}$$

Integer N_0

Rational F_0

<u>Minimum</u> Integer N_0

$$N_0 = q \qquad F_0 = \frac{p}{q}$$

$$m = p$$

reduced form

$$T f_0 = k \cdot 1$$

$$T = \frac{k \cdot 1}{f_0}$$

Real T_0

Real f_0

<u>Minimum</u> Real T_0

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

$$m = 1$$

$$N_0 = \frac{m}{p/q}$$

Periodic Conditions Examples

$$N F_0 = k \cdot m$$

$$N_0 = \frac{m}{F_0}$$

Integer N

given

$$F_0 = \frac{36}{19}$$

km: multiples of 36

$$N_0 = 36 \cdot \frac{19}{36} \qquad 1 \cdot m = 36$$

$$2 N_0 = 72 \cdot \frac{19}{36} \qquad 2 \cdot m = 72$$

$$3 N_0 = 108 \cdot \frac{19}{36} \qquad 3 \cdot m = 108$$

$$T f_0 = k \cdot 1$$

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

Real T

given

$$f_0 = \frac{36}{19}$$

k: all integers

$$T_0 = 1 \cdot \frac{19}{36} \qquad 1 \cdot 1 = 1$$

$$2 T_0 = 2 \cdot \frac{19}{36} \qquad 2 \cdot 1 = 2$$

$$3 T_0 = 3 \cdot \frac{19}{36} \qquad 3 \cdot 1 = 3$$

Periodic Condition of a Sampled Signal

$$g(nT_s) = A\cos(\boxed{2\pi f_0 T_s} n + \theta)$$

$$F_0 = f_0 T_s = f_0 / f_s$$

$$g[n] = A\cos(2\pi F_0 n + \theta)$$

$$\boxed{2\pi F_0} n = 2\pi m \qquad F_0 n = m$$

$$F_0 = \frac{m}{n}$$

integers n, m

Rational Number $F_0 = \frac{m}{n}$

integers n, m

The Smallest Integer n

$$N_0 = min(n) \qquad F_0 = \frac{m}{N_0}$$

M.J. Roberts, Fundamentals of Signals and Systems

F_0 and N_0 of a Sampled Signal

Rational Number F_0

$$F_0 = \frac{m}{n} = \frac{p}{q}$$

integer n, m, p, q

$$F_0 = \frac{f_0}{f_s} = \frac{T_s}{T_0}$$

real f_0, f_s, T_s, T_0

Integer N_0

$$N_0 F_0 = m$$

$$N_0 = \frac{m}{F_0} = m \cdot \frac{T_0}{T_s} = m \cdot \frac{f_s}{f_0} = m \cdot \frac{q}{p}$$

$$2\pi F_0 n$$

$$2\pi f_0 T_s n$$

M.J. Roberts, Fundamentals of Signals and Systems

A cosine waveform example

```
n= [0:19];
x= cos(2*pi*1*(n/10));
```

$$= 2\pi F_0 n = 2\pi f_0 T_s n =$$

```
n= [0:19];
x= cos(2*pi*(1/10)*n);
```

$$n T_s = n \cdot \frac{1}{10}$$

$$F_0 = f_0 T_s = \frac{f_0}{f_s} = \frac{T_s}{T_0}$$

$$n T_s = n \cdot 1$$

$$2\pi f_0 n T_s$$

$$= 2\pi \cdot 1 \cdot n \cdot \frac{1}{10}$$

$$T_s = 0.1$$

$$f_0 = 1 \quad (T_0 = 1)$$

$$F_0 = f_0 T_s = 0.1$$

$$2\pi f_0 n T_s$$

$$= 2\pi \cdot \frac{1}{10} \cdot n \cdot 1$$

$$T_s = 1$$

$$f_0 = 0.1 \quad (T_0 = 10)$$

$$F_0 = f_0 T_s = 0.1$$

U of Rhode Island, ELE 436, FFT Tutorial

Two cases of the same $F_0 = f_0 \, T_s$

$\cos(0.2\pi n)$	$\cos(0.2\pi n)$
$\cos(2\pi \cdot f_0 \cdot n \cdot T_s)$	$\cos(2\pi \cdot f_0 \cdot n \cdot T_s)$
$\cos(2\pi \cdot 1 \cdot 0.1 \cdot n)$	$\cos(2\pi \cdot 0.1 \cdot 1 \cdot n)$
$T_s = 0.1$, $f_0 = 1$	$T_s = 1$, $f_0 = 0.1$
$F_0 = 0.1$	$F_0 = 0.1$

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The same sampled waveform examples

$\cos(0.2\pi n)$ $\cos(0.2\pi n)$

$2\pi f_0 n T_s$

$2\pi n/10$

$0.1 = f_0 T_s$

$0.1 = F_0$

```
n= [0:19];
x= cos(2*pi*1*0.1*n);
```

$2\pi F_0 n = 2\pi f_0 T_s n$

```
n= [0:19];
x= cos(2*pi*0.1*1*n);
```

$\cdots$

$T_s = 0.1$, $f_0 = 1$, $F_0 = 0.1$

$\cdots$

$T_s = 0.2$, $f_0 = 0.5$, $F_0 = 0.1$

$\cdots$

$T_s = 0.5$, $f_0 = 0.2$, $F_0 = 0.1$

$\cdots$

$T_s = 1$, $f_0 = 0.1$, $F_0 = 0.1$

$\cdots$

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Many waveforms share the same sampled data

The same sampled data

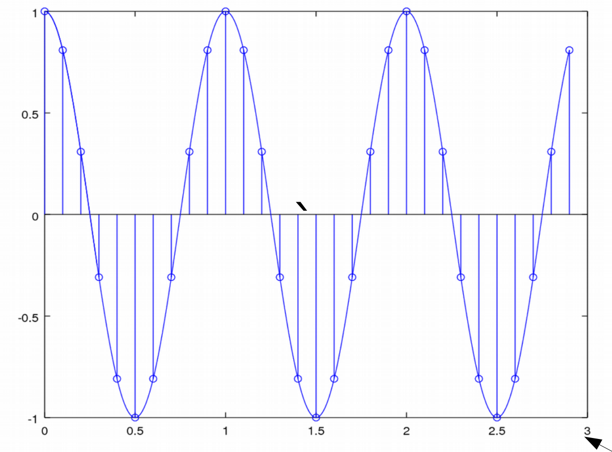
1.00000
0.80902
0.30902
-0.30902
-0.80902
-1.00000
-0.80902
-0.30902
0.30902
0.80902
1.00000
0.80902
0.30902
-0.30902
-0.80902
-1.00000
-0.80902
-0.30902
0.30902
0.80902
1.00000
0.80902
0.30902
-0.30902
-0.80902
-1.00000
-0.80902
-0.30902
0.30902
0.80902

$2\pi n/10$

$2\pi n f_0 T_s$

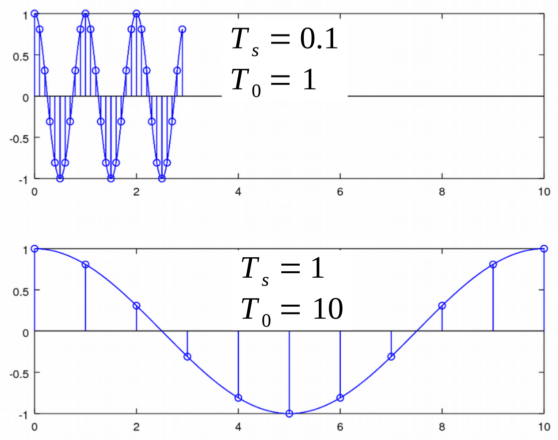
$0.1 = f_0 T_s$

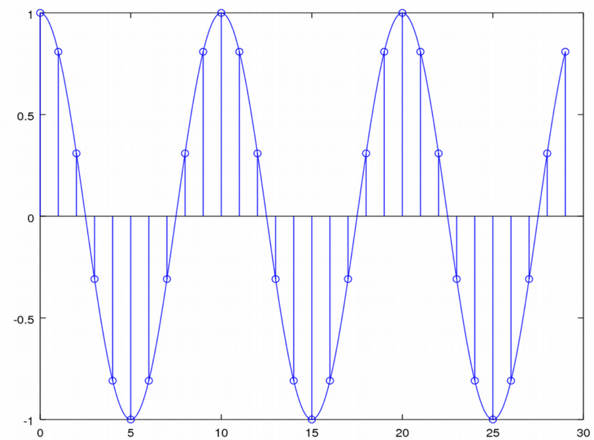
$0.1 = F_0$



$T_s = 0.1$
$T_0 = 1$

3





$T_s = 1$
$T_0 = 10$

30

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Different number of data points

x= cos(2*pi*n/10);

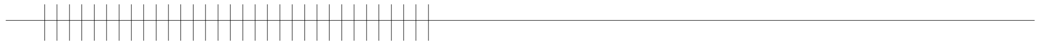
```
t = [0:19]/10;
y = cos(2*pi*t);
stem(t, y)
hold on
t2 = [0:199]/100;
y2 = cos(2*pi*t2);
plot(t2, y2)
```

[0:19]; $[0,\cdots,19]$ 20 *data points*

size([0:19], 2) = 20

[0:199]; $[0,\cdots,199]$ 200 *data points*

size([0:199], 2) = 200



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Normalized data points

```
x= cos(2*pi*n/10);
```

```
t = [0:19]/10;
y = cos(2*pi*t);
stem(t, y)
hold on
t2 = [0:199]/100;
y2 = cos(2*pi*t2);
plot(t2, y2)
```

t = [0:19]/10; $[0.0, \cdots, 1.90]$ 20 *data points*

coarse resolution

$[0.0, \cdots, 1.90] \rightarrow 2\ cycles$ $[0, \cdots, 4\pi]$

t2 = [0:199]/100; $[0.0, \cdots, 1.99]$ 200 *data points*

fine resolution

$[0.0, \cdots, 1.99] \rightarrow 2\ cycles$ $[0, \cdots, 4\pi]$

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Different number of data points

x= cos(0.2*pi*n);

```
t = [0:19];
y = cos(0.2*pi*t);
stem(t, y)
hold on
t2 = [0:199]/10;
y2 = cos(0.2*pi*t2);
plot(t2, y2)
```

[0:19]; $[0, \cdots, 19]$ 20 *data points*

size([0:19], 2) = 20

[0:199]; $[0, \cdots, 199]$ 200 *data points*

size([0:199], 2) = 200

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Normalized data points

t = [0:19]; $[0.0, \cdots, 19.0]$ 20 *data points*

coarse resolution

$[0.0, \cdots, 19.0] \rightarrow 2 \; cycles \qquad [0, \cdots, 4\pi]$

x= cos(0.2*pi*n);

```
t = [0:19];
y = cos(0.2*pi*t);
stem(t, y)
hold on
t2 = [0:190]/10;
y2 = cos(0.2*pi*t2);
plot(t2, y2)
```

t2 = [0:199]/10; $[0.0, \cdots, 19.9]$ 200 *data points*

fine resolution

$[0.0, \cdots, 19.9] \rightarrow 2 \; cycles \qquad [0, \cdots, 4\pi]$

Plotting sampled cosine waves

x= cos(2*pi*n/10);

```
t = [0:19]/10;
y = cos(2*pi*t);
stem(t, y)
hold on
t2 = [0:199]/100;
y2 = cos(2*pi*t2);
plot(t2, y2)
```

t = [0:19]/10;	$[0.0, \cdots, 1.9]$ 20 $data\ points$	
y = cos(2*pi*t);	stem(t, y)	coarse resolution
t2 = [0:199]/100;	$[0.0, \cdots, 1.99]$ 200 $data\ points$	
y = cos(2*pi*t2);	plot(t2, y)	fine resolution

x= cos(0.2*pi*n);

```
t = [0:19];
y = cos(0.2*pi*t);
stem(t, y)
hold on
t2 = [0:190]/10;
y2 = cos(0.2*pi*t2);
plot(t2, y2)
```

t = [0:19];	$[0.0, \cdots, 1.9]$ 20 $data\ points$	
y = cos(0.2*pi*t);	stem(t, y)	coarse resolution
t2 = [0:199]/00;	$[0.0, \cdots, 1.99]$ 200 $data\ points$	
y = cos(0.2*pi*t2);	plot(t2, y)	fine resolution

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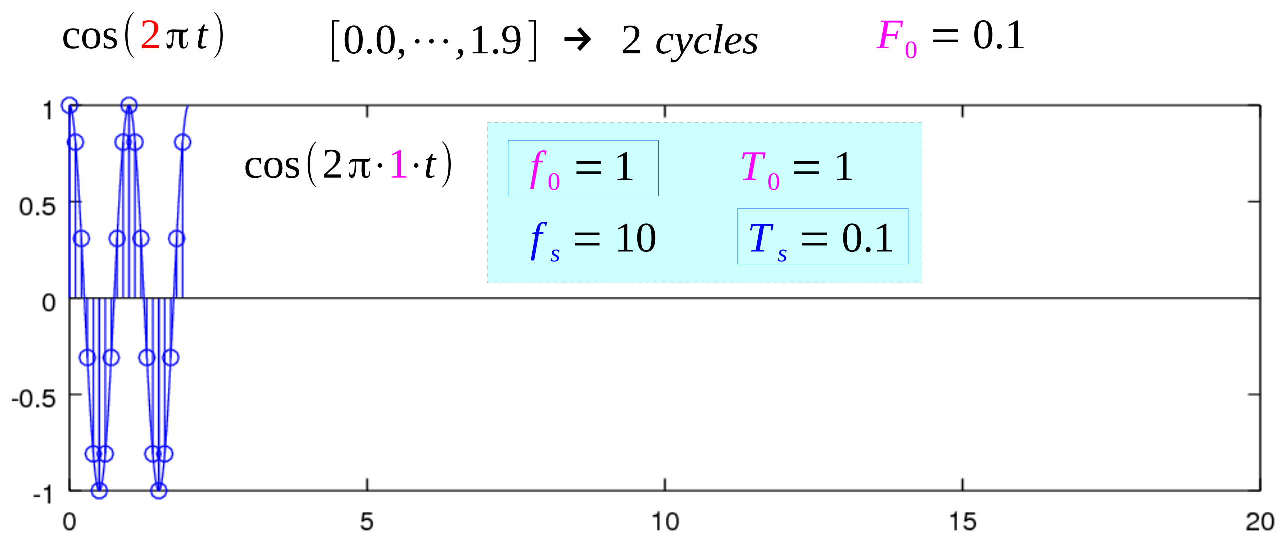
Two waveforms with the same normalized frequency

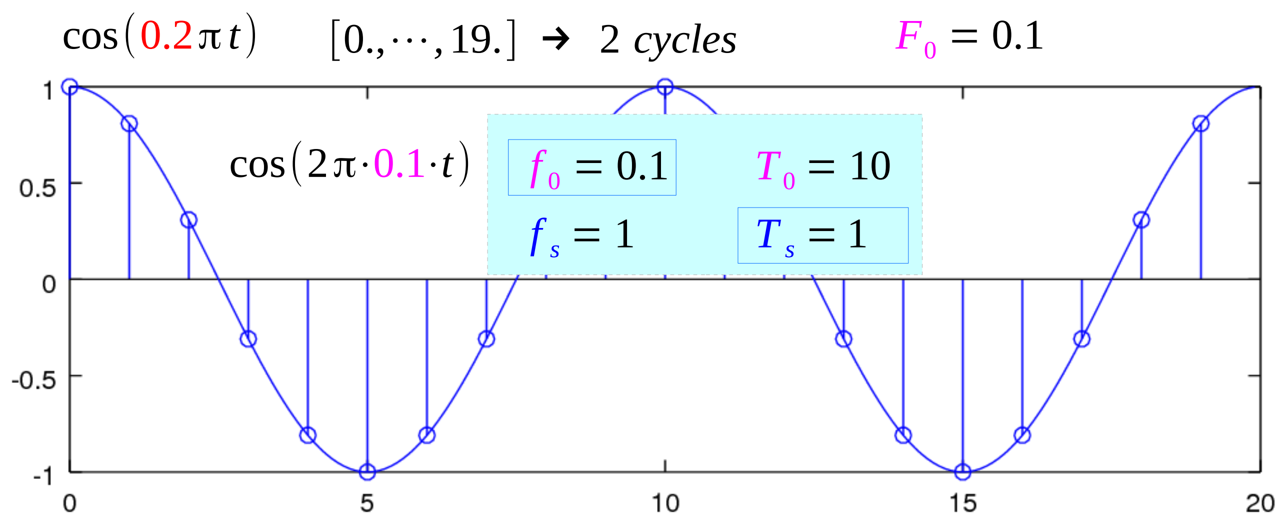
x= cos(2*pi*n/10);

```
t = [0:19]/10;
y = cos(2*pi*t);
stem(t, y)
hold on
t2 = [0:199]/100;
y2 = cos(2*pi*t2);
plot(t2, y2)
```



x= cos(0.2*pi*n);

```
t = [0:19];
y = cos(0.2*pi*t);
stem(t, y)
hold on
t2 = [0:190]/10;
y2 = cos(0.2*pi*t2);
plot(t2, y2)
```



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Cosine Wave 1

x= cos(2*pi***n**/10);

```
t = [0:29]/10;
y = cos(2*pi*t);
stem(t, y)
hold on
t2 = [0:299]/100;
y2 = cos(2*pi*t2);
plot(t2, y2)
```

$f_0 = 1$

$T_s = 0.1$

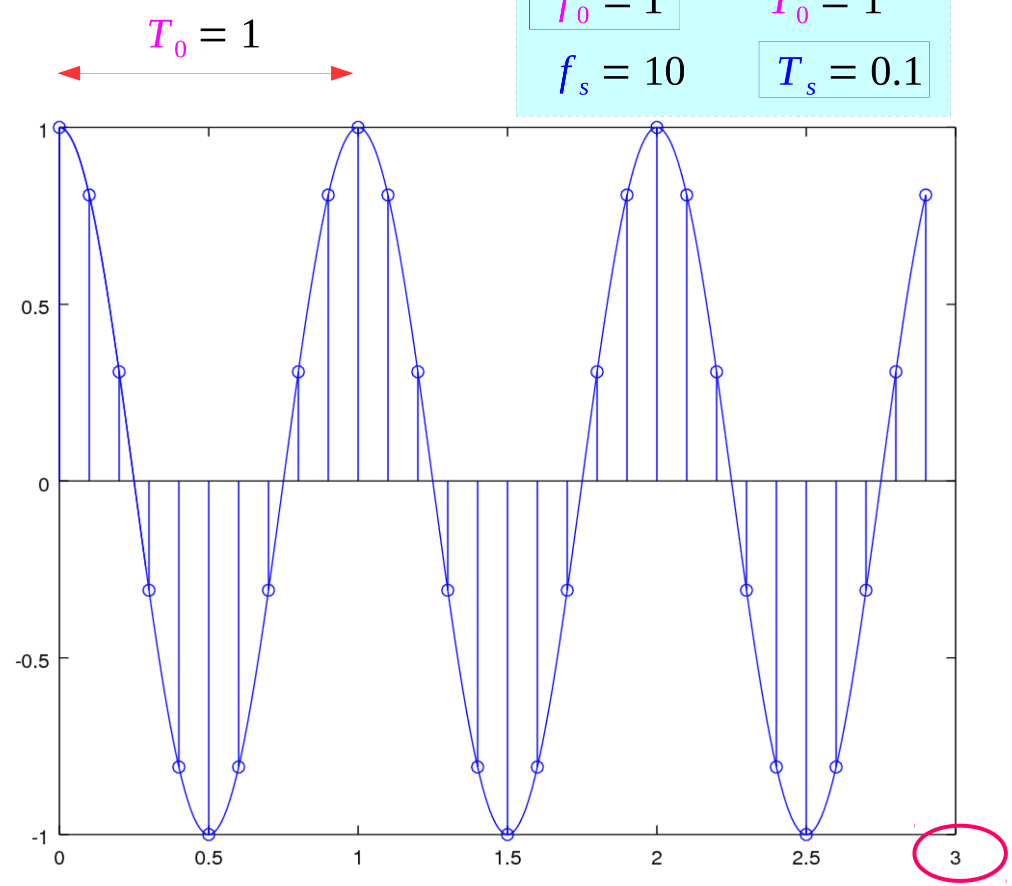
$F_0 = f_0 T_s = 0.1$

$\cos(2\pi t)$

$\cos(2\pi \cdot 1 \cdot t)$

$f_0 = 1$ $T_0 = 1$

$f_s = 10$ $T_s = 0.1$



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Cosine Wave 2

x= cos(0.2*pi*n);

```
t = [0:29];
y = cos(0.2*pi*t);
stem(t, y)
hold on
t2 = [0:299]/10;
y2 = cos(0.2*pi*t2);
plot(t2, y2)
```

$f_0 = 0.1$

$T_s = 1$

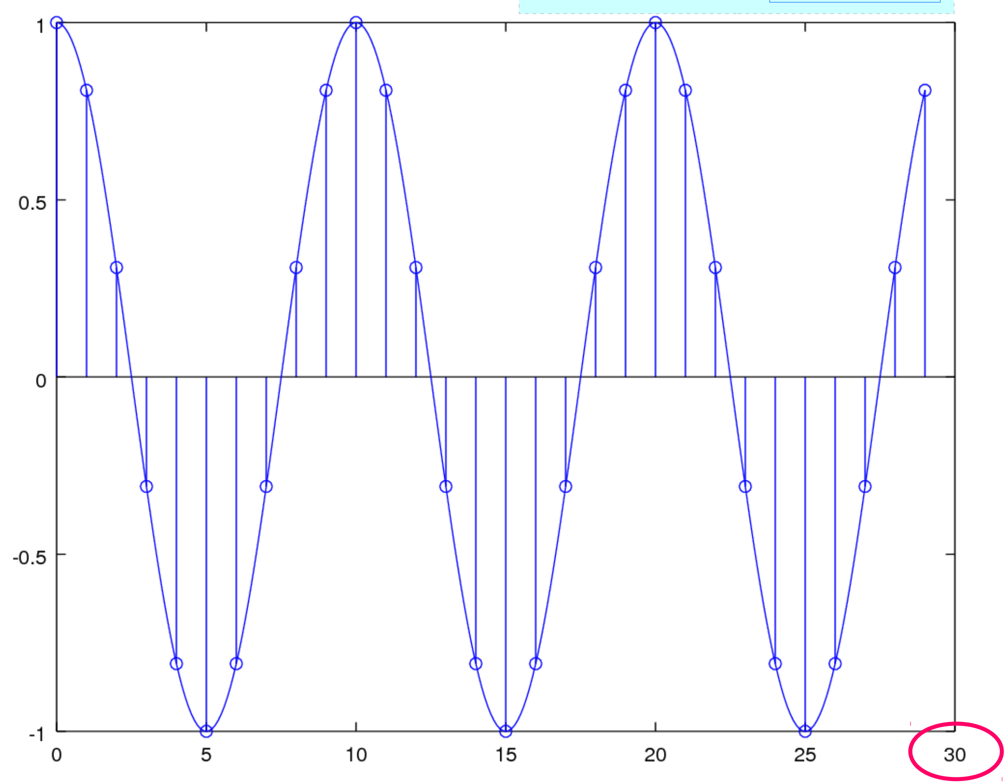
$F_0 = f_0 T_s = 0.1$

$\cos(0.2\pi t)$ $\cos(2\pi \cdot 0.1 \cdot t)$

$\boxed{f_0 = 0.1}$ $T_0 = 10$

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

$T_0 = 10$



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Sampled Sinusoids

$$g[n] = A\cos(2\pi n m/N_0 + \theta)$$

$$g[n] = A\cos(2\pi F_0 n + \theta)$$

$$g[n] = A\cos(\Omega_0 n + \theta)$$

m/N_0

$= F_0$

$= \Omega_0/2\pi$

$2\pi m/N_0$

$= 2\pi F_0$

$= \Omega_0$

$$N_0 = \frac{m}{F_0} \qquad N_0 \neq \frac{1}{F_0}$$

$$g[n] = A e^{\beta n}$$

$$g[n] = A z^n \qquad z = e^{\beta}$$

M.J. Roberts, Fundamentals of Signals and Systems

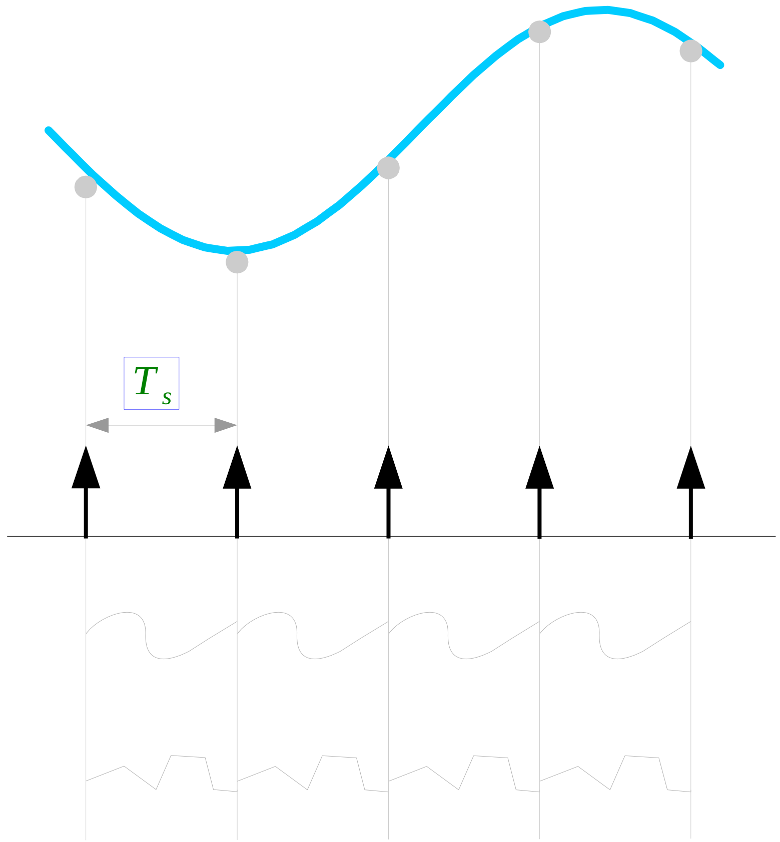
Sampling Period and Frequency

$$g(t) = A\cos(2\pi f_0 t + \theta)$$

$F_0 \leftarrow f_0 \cdot T_s$

$f_0 \leftarrow F_0 \cdot f_s$

$$g[n] = A\cos(2\pi F_0 n + \theta)$$



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

$\frac{1}{T_s} = f_s$ sampling frequency
sampling rate

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Periodic Condition of a Sampled Signal

$$2\pi F_0 n = 2\pi m$$

$$F_0 n = m$$ Integers $n, \; m$

$$F_0 = \frac{m}{n}$$

$$\boxed{F_0 = \frac{m}{n} = \frac{f_0}{f_s}}$$

Fundamental Frequency

Sampling Frequency

Rational Number $F_0 = \dfrac{m}{n}$

$$g(nT_s) = A\cos(2\pi f_0 T_s n + \theta)$$

$$F_0 = f_0 T_s = f_0 / f_s$$

$$g[n] = A\cos(2\pi F_0 n + \theta)$$

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Periodic Condition Examples

$$g(t) = A\cos(2\pi f_0 t + \theta)$$

$$g[n] = A\cos(2\pi F_0 n + \theta)$$

$$g[t] = 4\cos\left(\frac{72\pi t}{19}\right) = 4\cos\left(2\pi\cdot\frac{36}{19}\cdot t\right)$$

$$g[n] = 4\cos\left(\frac{72\pi n}{19}\right) = 4\cos\left(2\pi\cdot\frac{36}{19}\cdot n\right) \qquad T_s = 1$$

$$g(t) = 4\cos\left(2\pi\cdot\frac{36}{19}\cdot(t + T_0)\right) \qquad T_0 = \frac{19}{36}$$

Fundamental Period of $g(t)$

$$g[n] = 4\cos\left(2\pi\cdot\frac{36}{19}\cdot(n + N_0)\right) \qquad N_0 = 19$$

Fundamental Period of $g[n]$

$$N_0 \neq \frac{1}{F_0} \qquad N_0 = \frac{q}{F_0} \qquad \frac{q}{N_0} = F_0$$

M.J. Roberts, Fundamentals of Signals and Systems

Periodic Condition Examples

$$g(t) = 4\cos\left(2\pi \cdot \frac{36}{19} \cdot (t + T_0)\right) \qquad T_0 = \frac{19}{36}$$ Fundamental Period of $g(t)$

$$g[n] = 4\cos\left(2\pi \cdot \frac{36}{19} \cdot (n + N_0)\right) \qquad N_0 = 19$$ Fundamental Period of $g[n]$

$$F_0 = \frac{36}{19} = \frac{q}{N_0}$$

the number of cycles in N_0 samples

the smallest integer : fundamental period

$$N_0 \neq \frac{1}{F_0} \qquad N_0 = \frac{q}{F_0} \qquad \frac{q}{N_0} = F_0$$

M.J. Roberts, Fundamentals of Signals and Systems

Periodic Condition Examples

$$F_0 = \frac{36}{19} = \frac{q}{N_0}$$

the number of cycles in N_0 samples

the smallest integer : fundamental period

“When F_0 is not the reciprocal of an integer (q=1),
a discrete-time sinusoid may not be
immediately recognizable from its graph as a sinusoid.”

M.J. Roberts, Fundamentals of Signals and Systems

Periodic Condition Examples

$$g[n] = 4\cos\left(2\pi \cdot \frac{36}{19} \cdot (n + N_0)\right)$$

$\boxed{\frac{36}{19} \cdot (n + N_0)}$ integer

$\boxed{\frac{1}{19} \cdot N_0 = k}$ integer

$\boxed{N_0}$ integer

$N_0 = 19$ Fundamental period of $g[n]$

$$g(t) = 4\cos\left(2\pi \cdot \frac{36}{19} \cdot (t + T_0)\right)$$

$\boxed{\frac{36}{19} \cdot (t + T_0)}$ integer

$\boxed{\frac{36}{19} \cdot T_0 = k}$ integer

$\boxed{T_0}$ ~~integer~~

$T_0 = \frac{19}{36}$ Fundamental period of $g(t)$

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Periodic Condition Examples

$$g[n] = 4\cos\left(2\pi\cdot\frac{1}{19}\cdot n\right)$$

$$g[n] = 4\cos\left(2\pi\cdot\frac{2}{19}\cdot n\right)$$

$$g[n] = 4\cos\left(2\pi\cdot\frac{3}{19}\cdot n\right)$$

$$g[n] = 4\cos\left(2\pi\cdot\frac{36}{19}\cdot n\right)$$

```
clf
n = [0:36]; t = [0:3600]/100;
y1 = 4*cos(2*pi*(1/19)*n);
y2 = 4*cos(2*pi*(2/19)*n);
y3 = 4*cos(2*pi*(3/19)*n);
y4 = 4*cos(2*pi*(36/19)*n);
yt1 = 4*cos(2*pi*(1/19)*t);
yt2 = 4*cos(2*pi*(2/19)*t);
yt3 = 4*cos(2*pi*(3/19)*t);
yt4 = 4*cos(2*pi*(36/19)*t);

subplot(4,1,1);
stem(n, y1); hold on;
plot(t, yt1);
subplot(4,1,2);
stem(n, y2); hold on;
plot(t, yt2);
subplot(4,1,3);
stem(n, y3); hold on;
plot(t, yt3);
subplot(4,1,4);
stem(n, y4); hold on;
plot(t, yt4);
```

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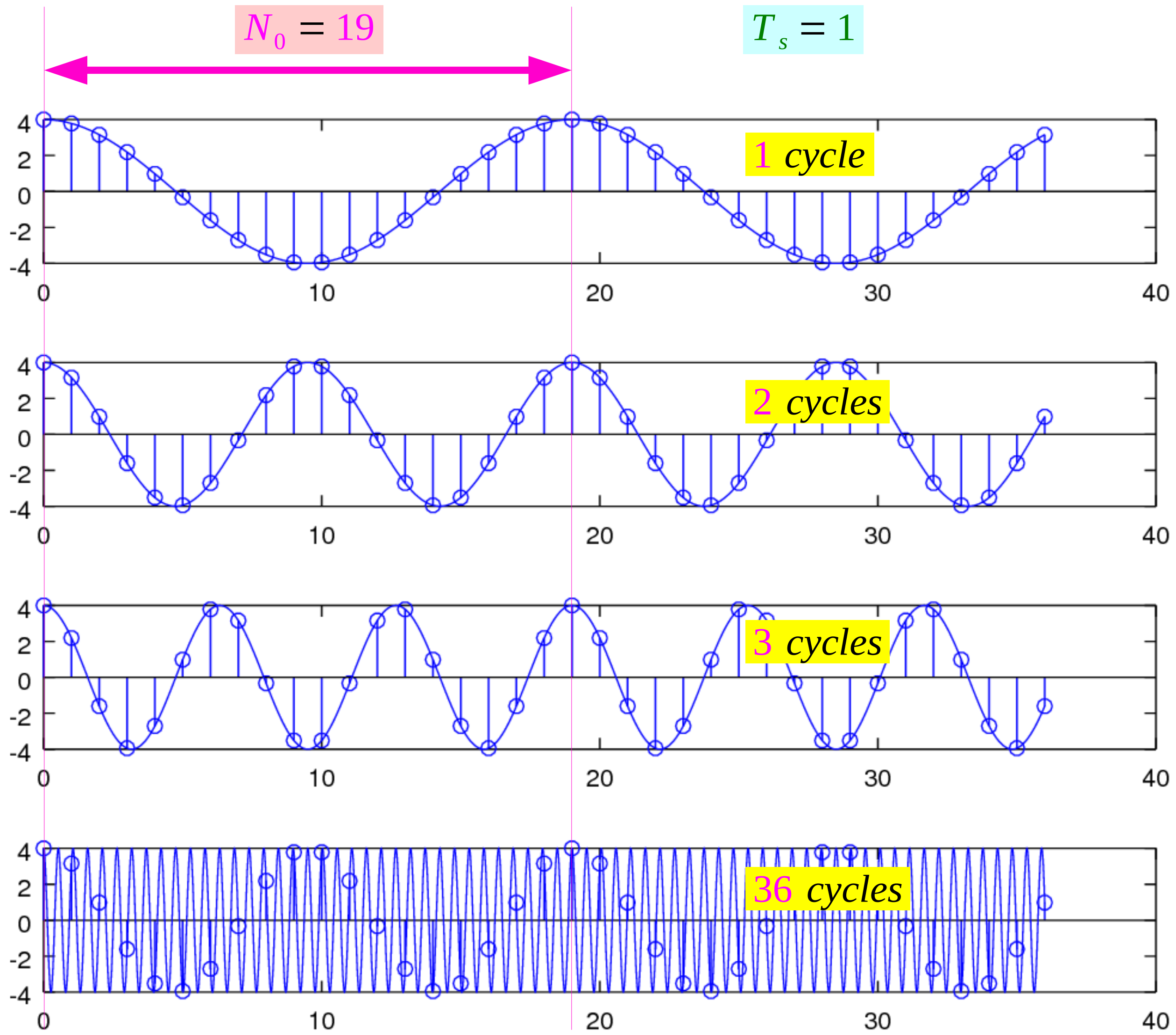
Periodic Condition Examples

$$g[n] = 4\cos\left(2\pi\cdot\frac{1}{19}\cdot n\right)$$

$$g[n] = 4\cos\left(2\pi\cdot\frac{2}{19}\cdot n\right)$$

$$g[n] = 4\cos\left(2\pi\cdot\frac{3}{19}\cdot n\right)$$

$$g[n] = 4\cos\left(2\pi\cdot\frac{36}{19}\cdot n\right)$$



Periodic Condition Examples

$$g(t) = A\cos(2\pi f_0 t + \theta)$$

$$g[n] = A\cos(2\pi F_0 n + \theta)$$

$$g_1(t) = 4\cos(2\pi\cdot 1\cdot t) \qquad t \leftarrow nT_1 \qquad g_1[n] = 4\cos(2\pi n T_{s1})$$

$$g_2(t) = 4\cos(2\pi\cdot 2\cdot t) \qquad t \leftarrow nT_2 \qquad g_2[n] = 4\cos(2\pi n T_{s2})$$

$$g_3(t) = 4\cos(2\pi\cdot 3\cdot t) \qquad t \leftarrow nT_3 \qquad g_3[n] = 4\cos(2\pi n T_{s3})$$

$$t \leftarrow nT_1 \qquad T_1 = \tfrac{1}{10} \qquad n = 0, 1, 2, 3, \cdots \Rightarrow 1\cdot t = 0, 0.1, 0.2, 0.3, \cdots$$

$$t \leftarrow nT_2 \qquad T_2 = \tfrac{1}{20} \qquad n = 0, 1, 2, 3, \cdots \Rightarrow 2\cdot t = 0, 0.1, 0.2, 0.3, \cdots$$

$$t \leftarrow nT_3 \qquad T_3 = \tfrac{1}{30} \qquad n = 0, 1, 2, 3, \cdots \Rightarrow 3\cdot t = 0, 0.1, 0.2, 0.3, \cdots$$

$$\{\, g_1[n] \,\} \equiv \{\, g_2[n] \,\} \equiv \{\, g_2[n] \,\}$$

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Periodic Condition Examples

$$g(t) = A\cos(2\pi f_0 t + \theta)$$

$$g[n] = A\cos(2\pi F_0 n + \theta)$$

$$2\pi F_0 n = 2\pi m$$

$$\frac{36}{19} n = m$$

smallest n = 19

$$\frac{36}{19} = \frac{m}{n}$$

$$\frac{36}{19} = \frac{m}{n} = \frac{f_0}{f_s}$$

$$g[n] = 4\cos\left(\frac{72\pi n}{19}\right)$$

$$= 4\cos\left(2\pi\left(\frac{36}{19}\right)n\right)$$

$$= 4\cos\left(2\pi\left(\frac{36}{19}\cdot(n + N_0)\right)\right)$$

smallest $N_0 = 19$

$$F_0 = \frac{q}{N_0}$$

$$1/N_0$$

$$= F_0$$

$$= \Omega_0/2\pi$$

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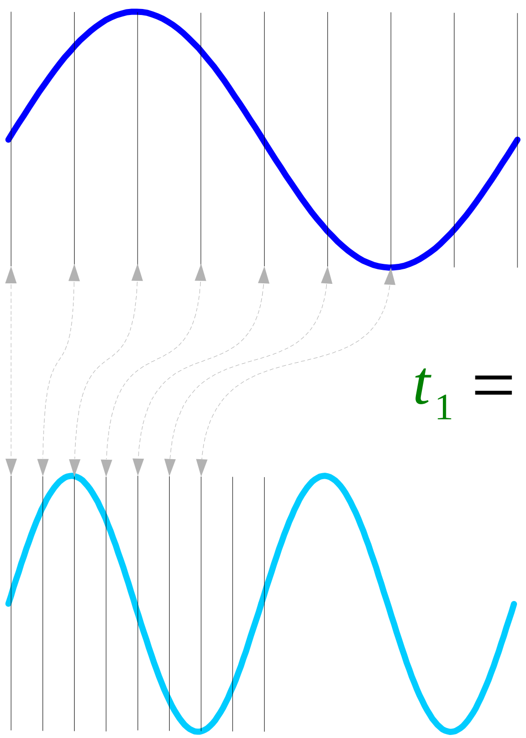
Periodic Condition Examples

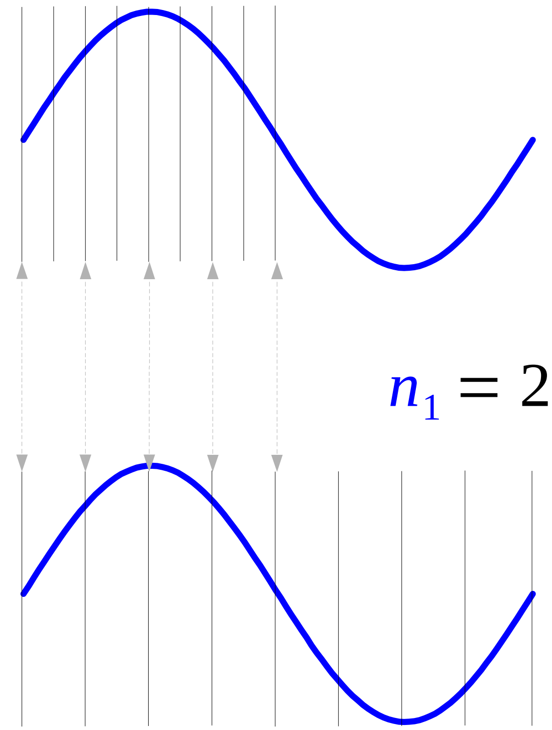
$4\cos(\omega t_1)$



$t_1 = 2t_2$

$4\cos(2\omega t_2)$

$4\cos(\omega n_1)$ $\quad n_1 \cdot 1 \quad T_s = 1$



$n_1 = 2n_2$

$4\cos(\omega 2 n_2)$ $\quad n_2 \cdot 2 \quad T_s = 2$

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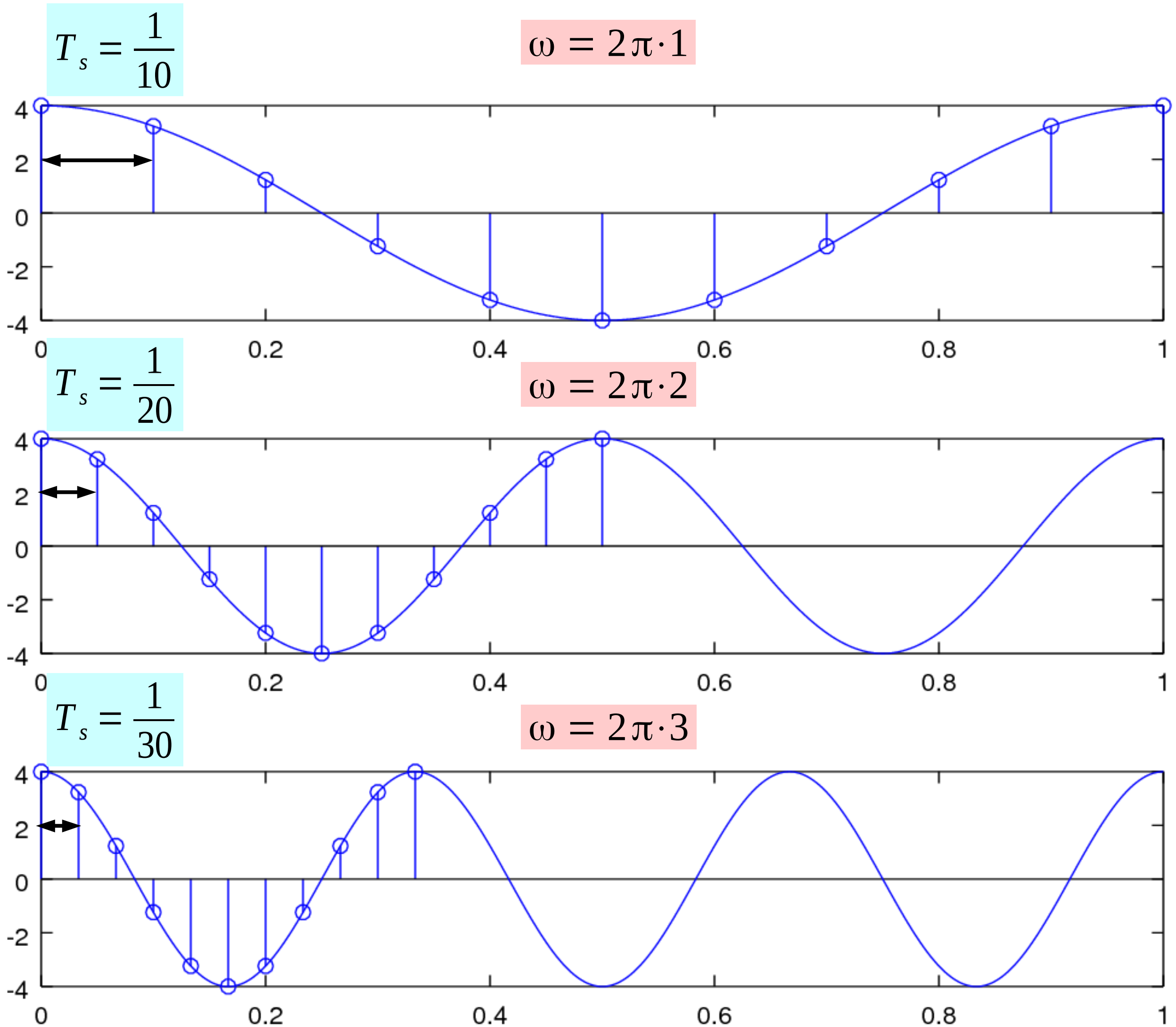
Periodic Condition Examples




```
clf
n = [0:10]; t = [0:1000]/1000;
y1 = 4*cos(2*pi*1*n/10);
y2 = 4*cos(2*pi*2*n/20);
y3 = 4*cos(2*pi*3*n/30);
yt1 = 4*cos(2*pi*t);
yt2 = 4*cos(2*pi*2*t);
yt3 = 4*cos(2*pi*3*t);

subplot(3,1,1);
stem(n, y1); hold on;
plot(t, yt1);
subplot(3,1,2);
stem(n/20, y2); hold on;
plot(t, yt2);
subplot(3,1,3);
stem(n/30, y3); hold on;
plot(t, yt3);
```

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References

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[5] K. Shin, et al., Fundamentals of Signal Processing for Sound and Vibration Engineerings

[6] A “graphical interpretation” of the DFT and FFT, by Steve Mann