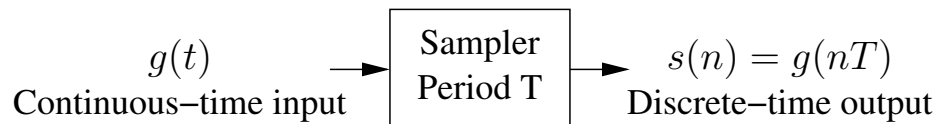


# 1-D Sampling



- Let  $f_s = 1/T$  be the sampling frequency.
- What is the relationship between  $S(e^{j\omega})$  and  $G(f)$ ?

$$S(e^{j\omega}) = \frac{1}{T} \sum_{k=-\infty}^{\infty} G\left(\frac{\omega - 2\pi k}{2\pi T}\right)$$

- Intuition
  - Scale frequencies

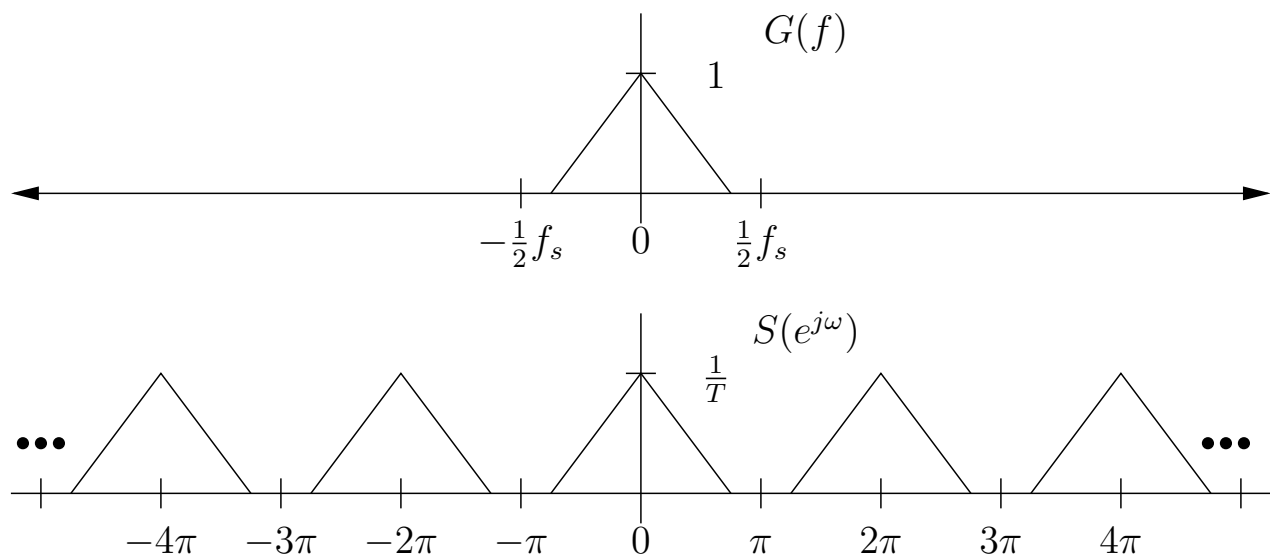
$$f = 0 \Leftrightarrow \omega = 0$$

$$f = \frac{1}{2T} = \frac{1}{2}f_s \Leftrightarrow \omega = \pi$$

$$f = \frac{1}{T} = f_s \Leftrightarrow \omega = 2\pi$$

- Replicate at period  $2\pi$
- Apply gain factor of  $\frac{1}{T}$ .

# 1-D Sampling

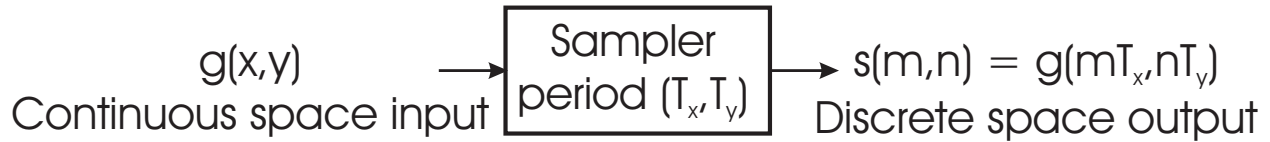


- Scale frequencies

| CT Frequency     | DT Frequency |
|------------------|--------------|
| $0$              | $0$          |
| $\frac{1}{2}f_s$ | $\pi$        |
| $f_s$            | $2\pi$       |

- Replicate at period  $2\pi$
- Apply gain factor of  $\frac{1}{T}$ .

## 2-D Sampling



- Let  $T_x$  and  $T_y$  be the sampling period in the  $x$  and  $y$  dimensions.

- Then

$$S(e^{j\mu}, e^{j\nu}) = \frac{1}{T_x T_y} \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} G \left( \frac{\mu - 2\pi k}{2\pi T_x}, \frac{\nu - 2\pi l}{2\pi T_y} \right)$$

- Intuition

- Scale frequencies

$$(u, v) = (0, 0) \Leftrightarrow (\mu, \nu) = (0, 0)$$

$$(u, v) = \left( \frac{1}{2T_x}, 0 \right) \Leftrightarrow (\mu, \nu) = (\pi, 0)$$

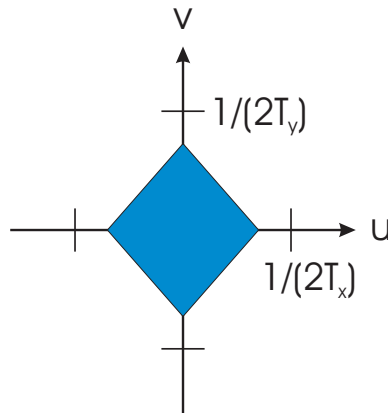
$$(u, v) = \left( 0, \frac{1}{2T_y} \right) \Leftrightarrow (\mu, \nu) = (0, \pi)$$

$$(u, v) = \left( \frac{1}{2T_x}, \frac{1}{2T_y} \right) \Leftrightarrow (\mu, \nu) = (\pi, \pi)$$

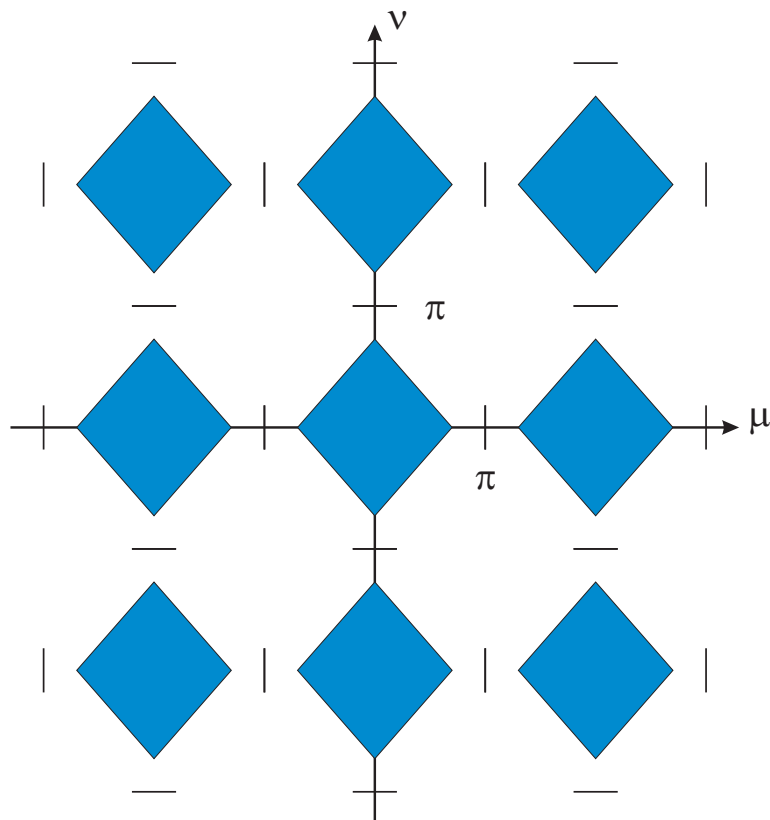
- Replicate along both  $\mu$  and  $\nu$  with period  $2\pi$
- Apply gain factor of  $\frac{1}{T_x T_y}$ .

## Example 1: 2-D Sampling Without Aliasing

$G(u, v)$  - Spectrum of continuous space image.

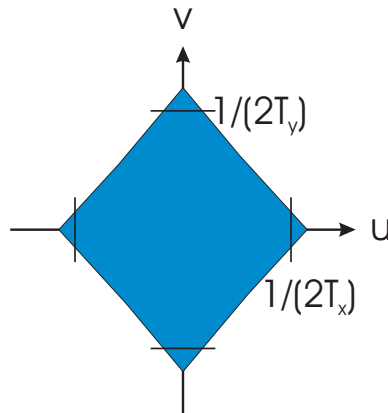


$S(e^{j\mu}, e^{j\nu})$  - Spectrum of sampled image.

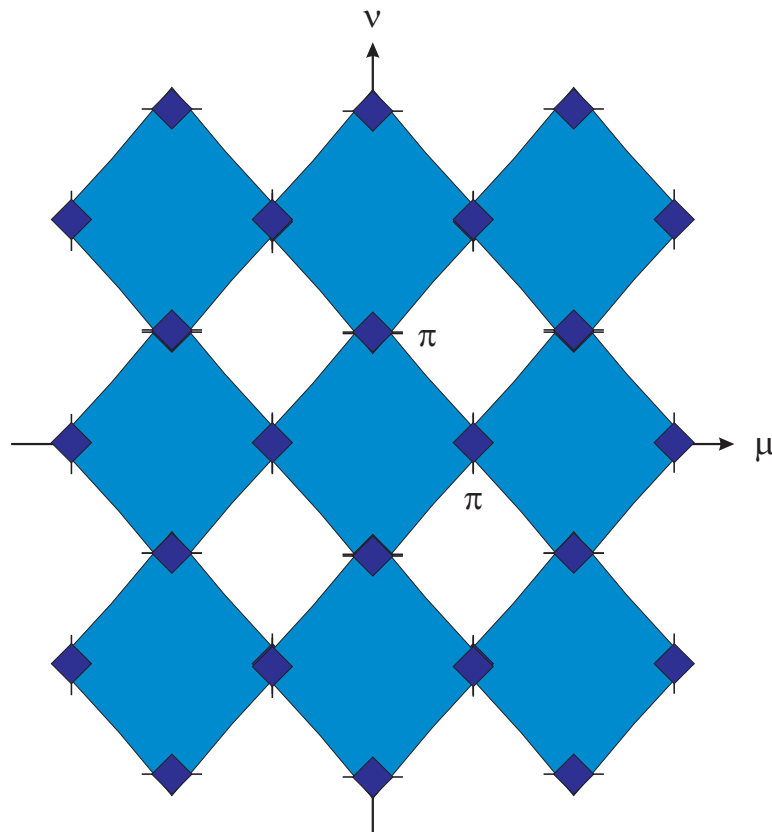


## Example 2: 2-D Sampling With Aliasing

$G(u, v)$  - Spectrum of continuous space image.



$S(e^{j\mu}, e^{j\nu})$  - Spectrum of sampled image.

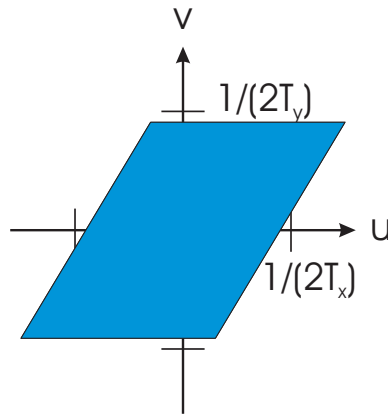


## Nyquist Condition

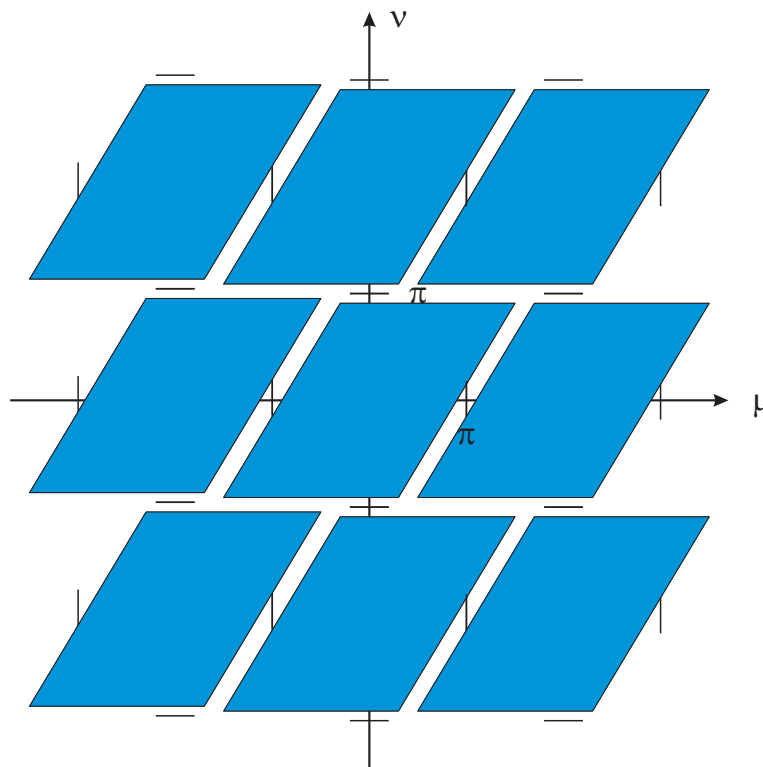
- A continuous-space signal,  $g(x, y)$ , may be uniquely reconstructed from its sampled version,  $s(m, n)$ , if  $G(u, v) = 0$  for all  $|u| > \frac{1}{2T_x}$  and  $|v| > \frac{1}{2T_y}$ .
- This condition is sufficient, but not necessary.

### Example 3: Nonrectangular Spectral Support

$G(u, v)$  - Spectrum of continuous space image.

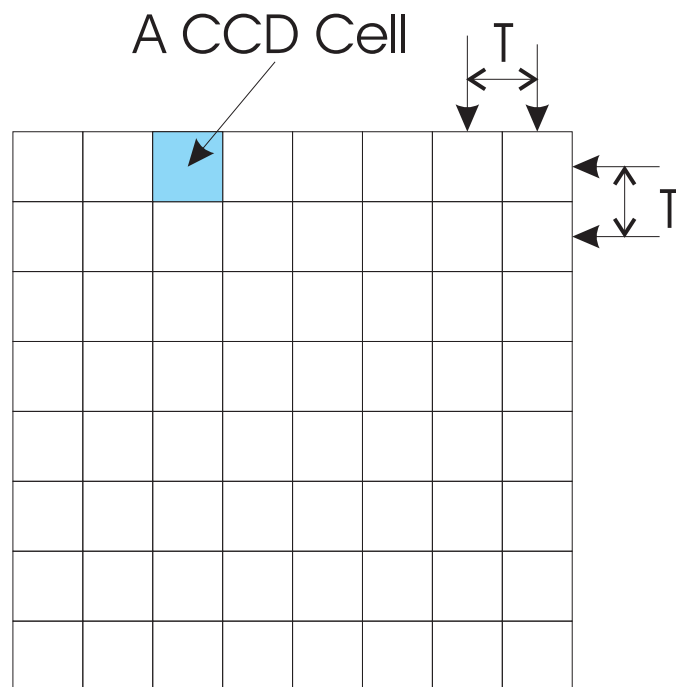


$S(e^{j\mu}, e^{j\nu})$  - Spectrum of sampled image.



## Focal Plain Arrays

- Typical Charged Coupled Devices (CCD) Imaging array



- Solid state device used in video and still cameras.
- Each cell collects photons in a square  $T \times T$  region.
- Response of each cell is linear with energy (photons).
- Signal is “shifted out” after capture.
- Cell should be large for best sensitivity.
- Finite cell size violates sampling assumptions.



## Mathematical Model for CCD

- Let  $s(m, n)$  be the output of cell  $(m, n)$ , then

$$s(m, n) = \int_{\mathbb{R}^2} h(x - mT, y - nT) g(x, y) dx dy$$

where  $h(x, y)$  is the rectangular window for each cell.

$$h(x, y) = \frac{1}{T^2} \text{rect}(x/T, y/T)$$

- Define  $\tilde{g}(x, y)$  so that

$$\begin{aligned} \tilde{g}(\xi, \eta) &= \int_{\mathbb{R}^2} h(x - \xi, y - \eta) g(x, y) dx dy \\ &= h(-x, -y) * g(x, y) \end{aligned}$$

and then we have that

$$s(m, n) = \tilde{g}(mT, nT)$$

## CCD Model in Space Domain

- Filter signal with space reversed cell profile

$$\begin{aligned}\tilde{g}(x, y) &= h(-x, -y) * g(x, y) \\ &= \frac{1}{T^2} \text{rect}(x/T, y/T) * g(x, y)\end{aligned}$$

- Sample filtered image

$$s(m, n) = \tilde{g}(mT, nT)$$

- Cell aperture blurs image.

## CCD Model in Frequency Domain

- Filter signal with cell profile

$$\begin{aligned}\tilde{G}(u, v) &= H^*(u, v)G(u, v) \\ &= \text{sinc}(uT, vT)G(u, v)\end{aligned}$$

- Sample filtered image

$$S(e^{j\mu}, e^{j\nu}) = \frac{1}{T^2} \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} \tilde{G}\left(\frac{\mu - 2\pi k}{2\pi T}, \frac{\nu - 2\pi l}{2\pi T}\right)$$

- Complete model

$$S(e^{j\mu}, e^{j\nu}) = \frac{1}{T^2} \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} \text{sinc}\left(\frac{\mu - 2\pi k}{2\pi}, \frac{\nu - 2\pi l}{2\pi}\right) \cdot G\left(\frac{\mu - 2\pi k}{2\pi T}, \frac{\nu - 2\pi l}{2\pi T}\right)$$

- Sinc function filters image.

## Sampled Image Display or Rendering (Reconstruction)

- CRT's and LCD displays convert discrete-space images to continuous-space images.

- Notation:

$s(m, n)$  - sampled image

$p(x, y)$  - point spread function (PSF) of display

$f(x, y)$  - displayed image

- Model:

- In space domain:

$$f(x, y) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} s(m, n) p(x - mT, y - nT)$$

- In frequency domain:

$$F(u, v) = P(u, v) S(e^{j2\pi Tu}, e^{j2\pi Tv})$$

$$\mu \rightarrow 2\pi Tu$$

$$\nu \rightarrow 2\pi Tv$$

- Monitor PSF further “softens” image.

## Model for Sampling and Reconstruction

- Combining models for sampling and reconstruction results in:

$$F(u, v) = \frac{P(u, v)}{T^2} \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} H^* \left( u - \frac{k}{T}, v - \frac{l}{T} \right) G \left( u - \frac{k}{T}, v - \frac{l}{T} \right)$$

- When no aliasing occurs, this reduces to

$$\begin{aligned} F(u, v) &= \frac{P(u, v) H^*(u, v)}{T^2} G(u, v) \\ &= \frac{P(u, v) \operatorname{sinc}(uT, vT)}{T^2} G(u, v) \end{aligned}$$

## Effect of Sampling and Reconstruction

- The image is effectively filtered by the transfer function

$$\frac{1}{T^2}P(u, v)H^*(u, v) = \frac{1}{T^2}P(u, v)\text{sinc}(uT, vT)$$

- Scanned image normally must be “sharpened” to remove the effect of softening produced in the scanning and display processes.

## Raster Scan Ordering

- Specific scan pattern for mapping 2-D images to 1-D.
- Order pixels from top to bottom and left to right.
- Example: Consider the discrete-space image  $f(m, n)$

$$\begin{bmatrix} f(0, 0) & \cdots & f(M-1, 0) \\ \vdots & \ddots & \vdots \\ f(0, N-1) & \cdots & f(M-1, N-1) \end{bmatrix}$$

- Raster ordering produces a 1-D signal  $x_n$

$$\begin{bmatrix} x_0 & x_1 & \cdots & x_{M-1} \\ x_M & x_{M+1} & \cdots & x_{2M-1} \\ \vdots & \vdots & \ddots & \vdots \\ x_{(N-1)M} & x_{(N-1)M+1} & \cdots & x_{NM-1} \end{bmatrix}$$

## Vector Representation of Images

- An image is **not a matrix**. (A Matrix specifies a linear function.)
- Vectorizing images
  - Often image must be converted to a vector (data).
  - Vector looks like

$$x = \begin{bmatrix} f(0, 0) \\ \vdots \\ f(M - 1, 0) \\ \vdots \\ f(0, N - 1) \\ \vdots \\ f(M - 1, N - 1) \end{bmatrix}$$

- Mapping from vector to image is  $f(m, n) = x_{n*M+m}$ .