Sampling & Quantization

Dr. Tushar Sandhan

Introduction

Introduction

- Input

- Sampling

- Quantization

Sampling

- Sampling
  - determines spatial resolution
  - space digitization

- Image frequency
  - what are freq contents inside an image?
  - is the uniform sampling optimal?
  - is oversampling useful?
  - strive for efficient sampling
    - sampling density
    - data storage, data transmission

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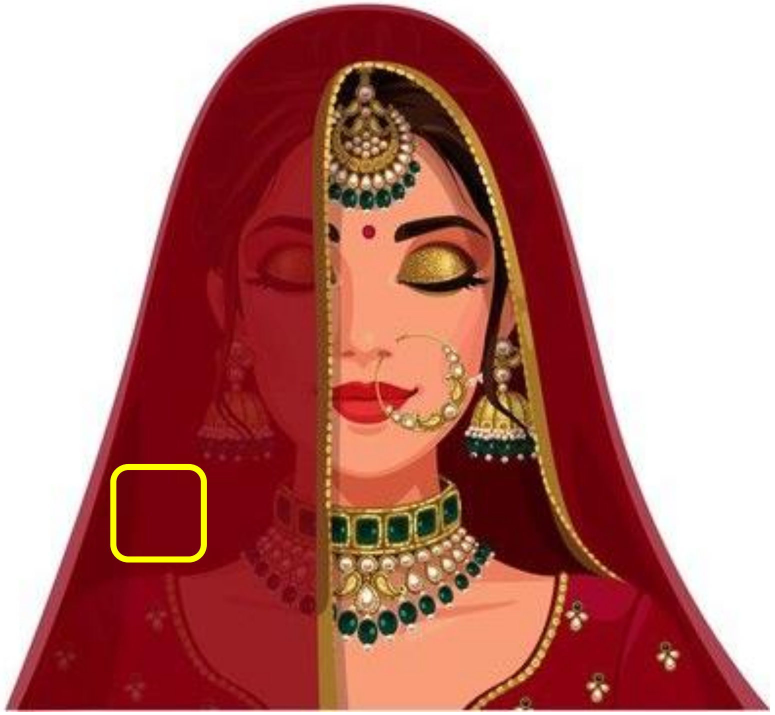

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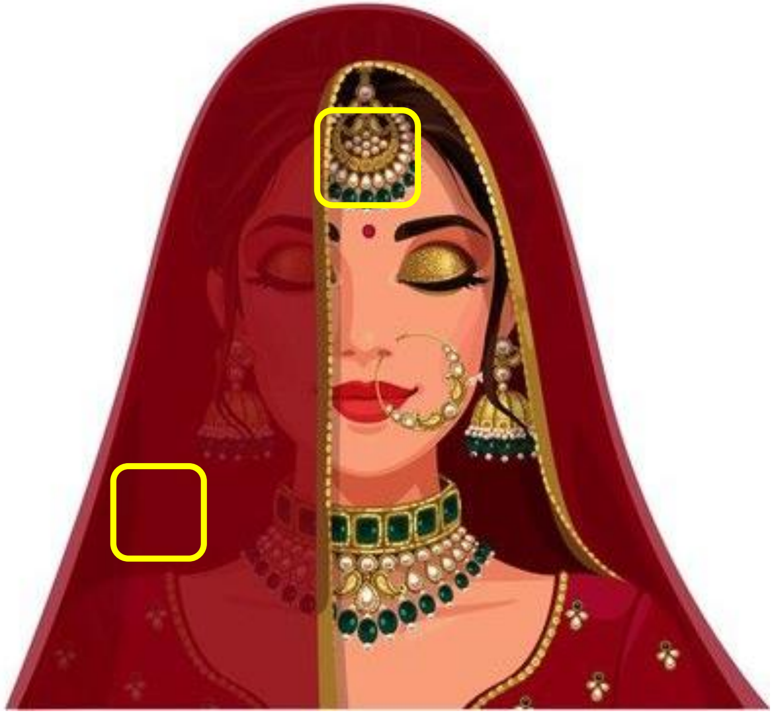

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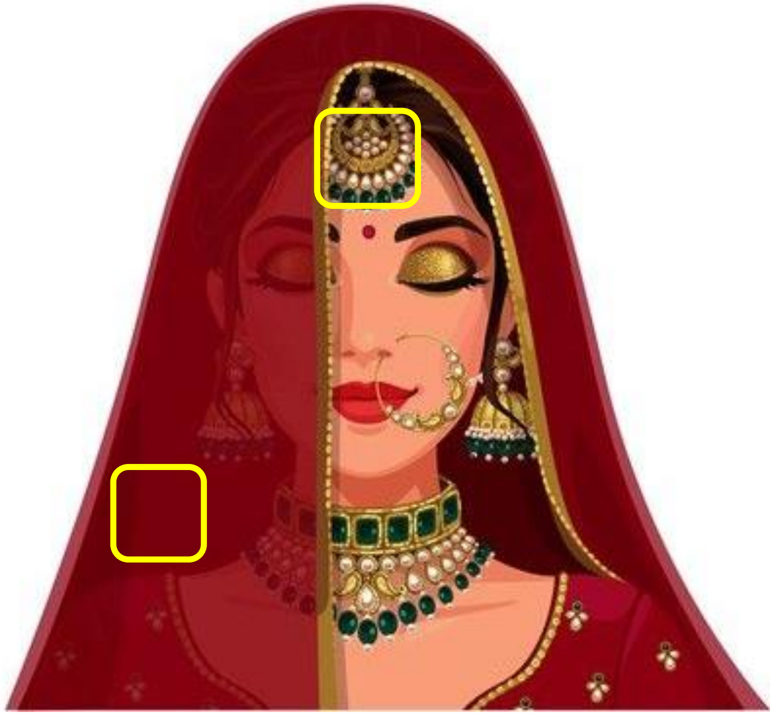
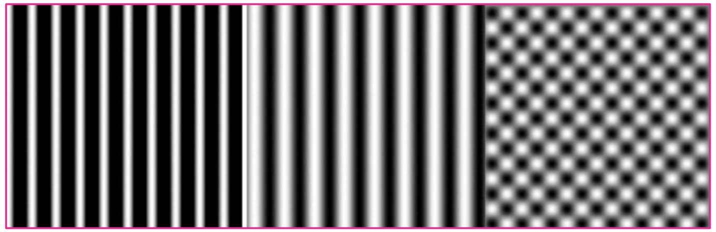
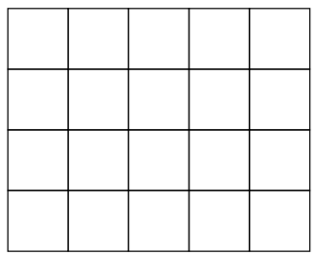
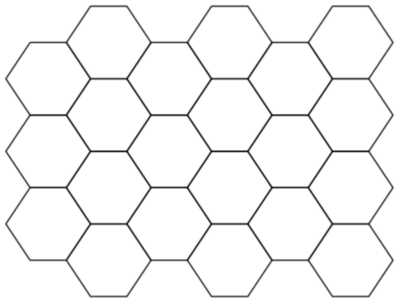


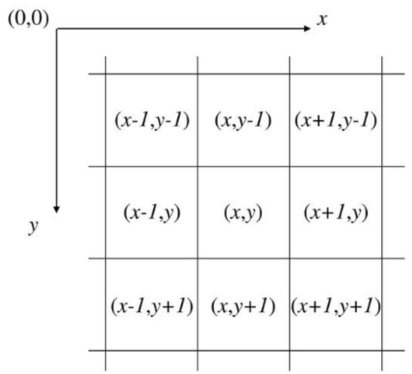


Sampling

- Grid
  - continuous image is digitized at sampling points
  - sampling points ordered in the plane
  - their geometric relation – grid
  - smallest grid point corresponds to – pixel (2D)
  - voxel (3D)







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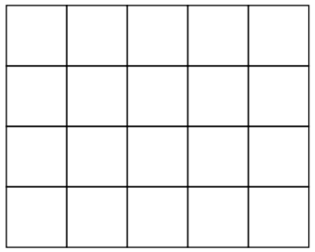
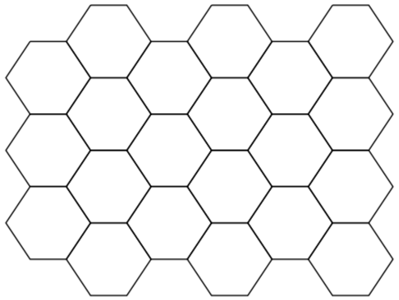
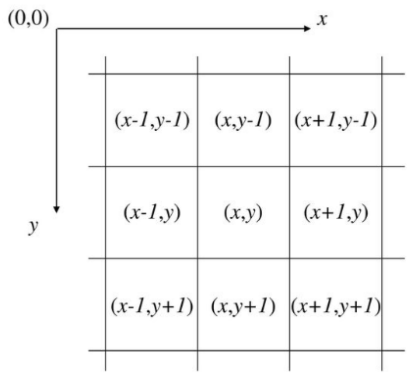




- Neighbourhood



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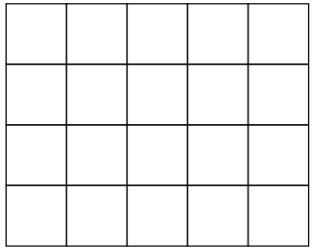

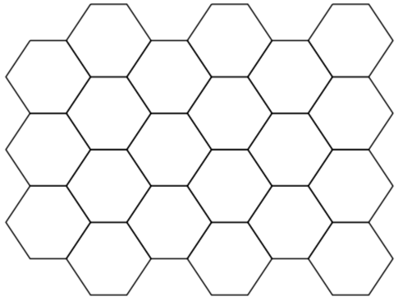

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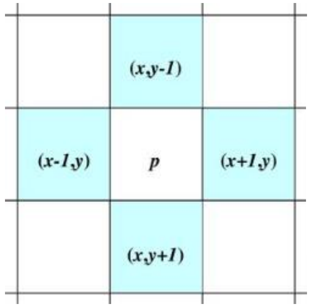
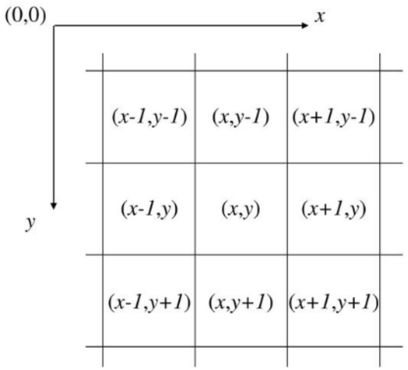


$$N_4(p) = \left\{ \begin{array}{c} (x-1,y) \\ (x+1,y) \\ (x,y-1) \\ (x,y+1) \end{array} \right\}$$



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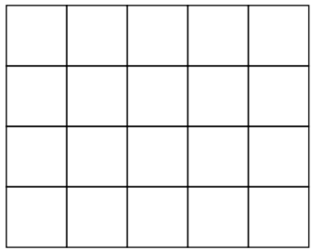

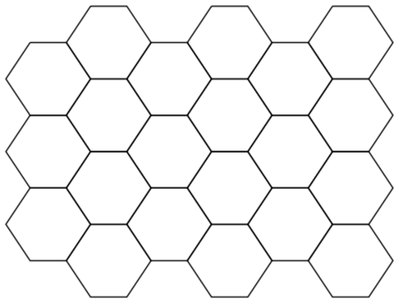

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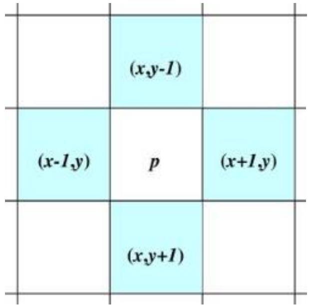
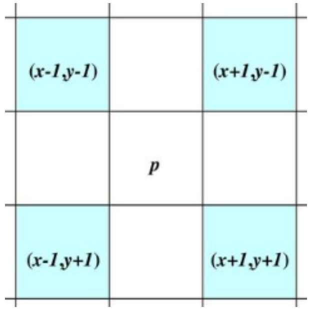
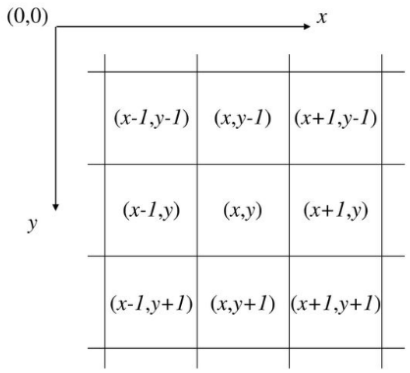


$$N_4(p) = \begin{Bmatrix} (x-1,y) \\ (x+1,y) \\ (x,y-1) \\ (x,y+1) \end{Bmatrix}$$



$N_D(p)$



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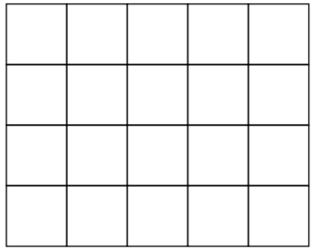

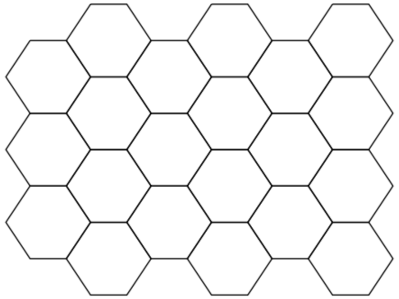

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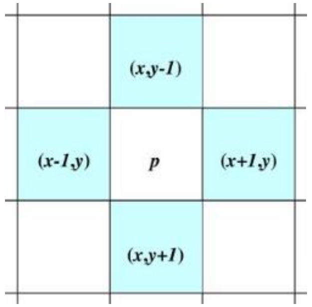

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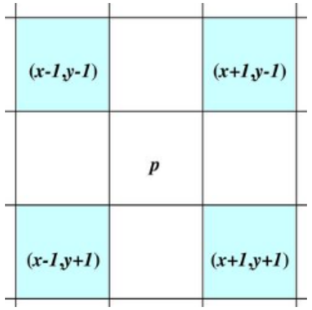

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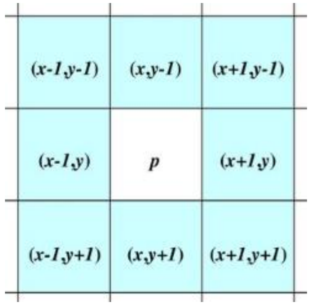
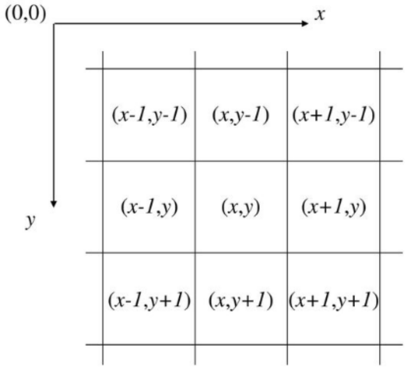
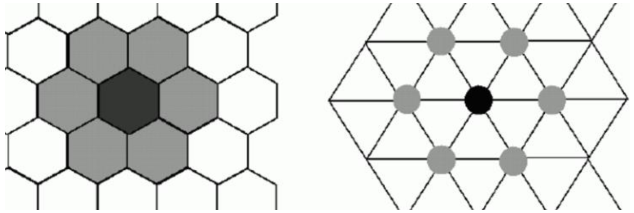


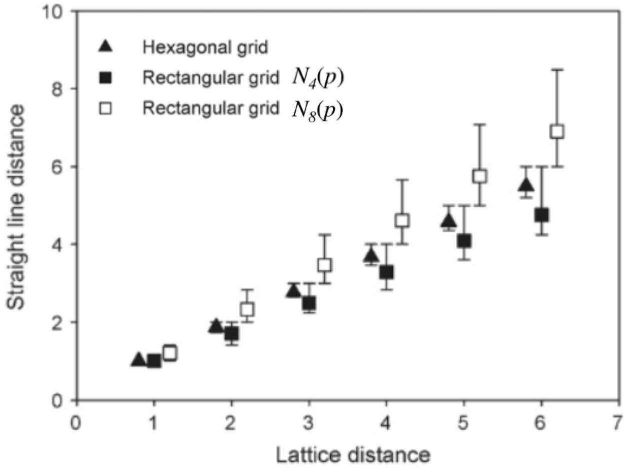
$N_8(p)$



Sampling

- Neighbourhood
  - hexagonal grid
  - neighbour interaction





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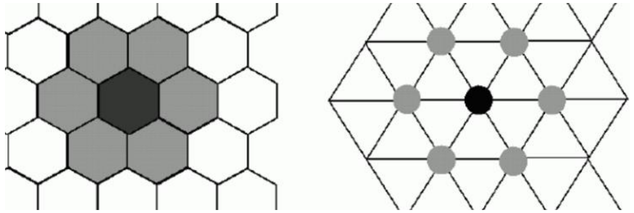

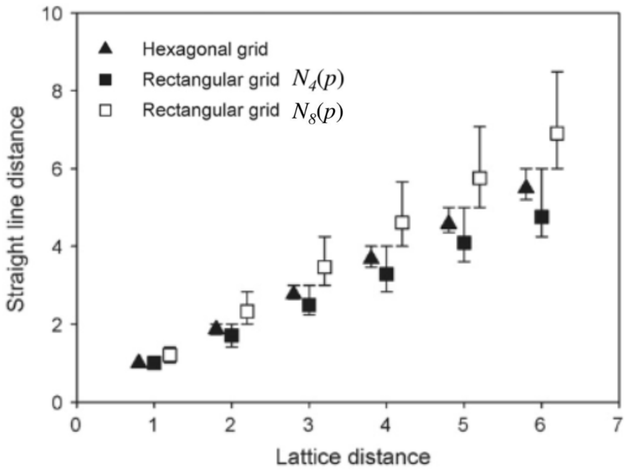

- Neighbour interactions
  - distance, energy, edges, features
  - sq. grid neighbourhood paradox
    - N_4: broken ring encloses
    - N_8: complete ring without enclosure

Sampling

- Neighbourhood
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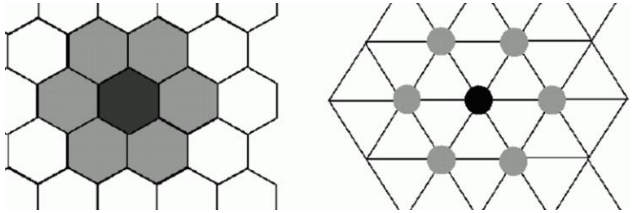

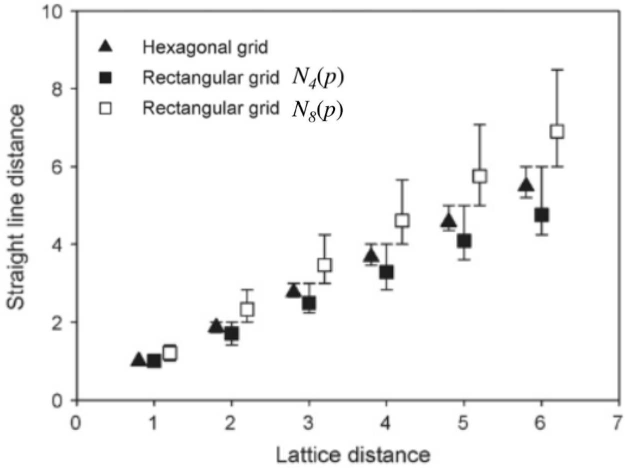

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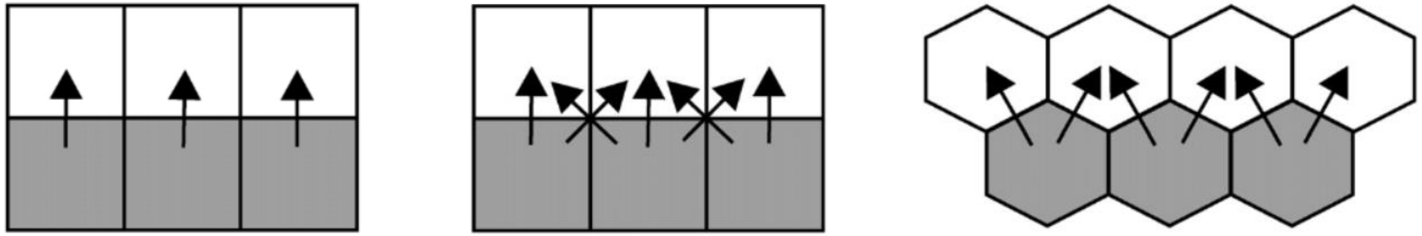

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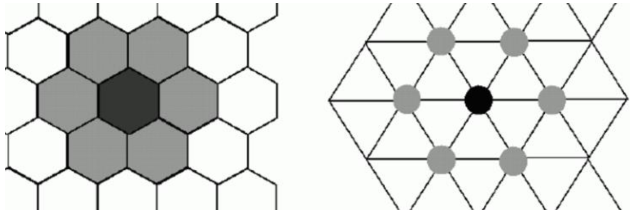

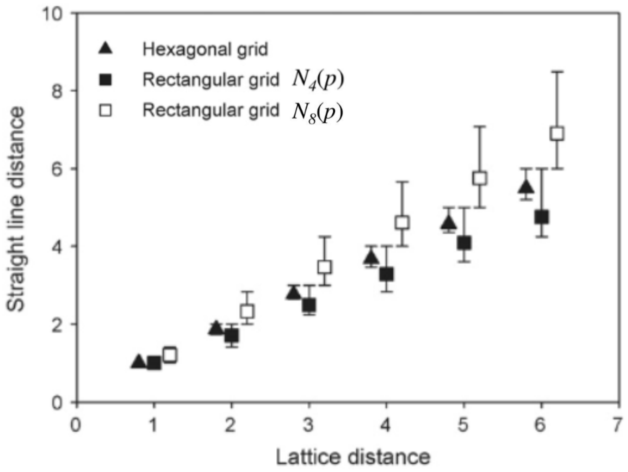

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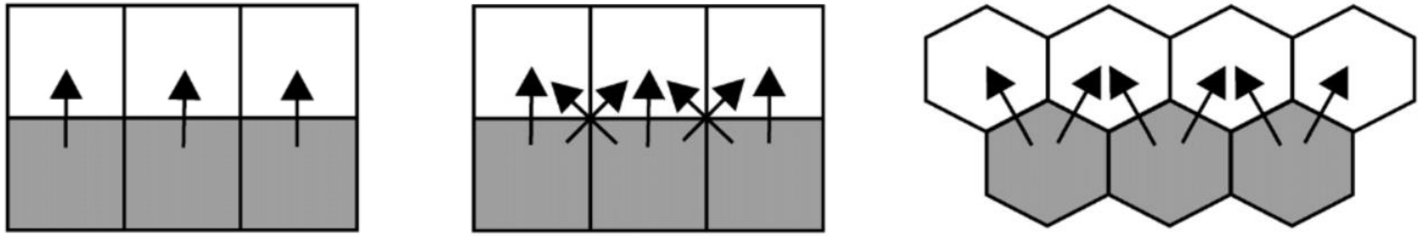
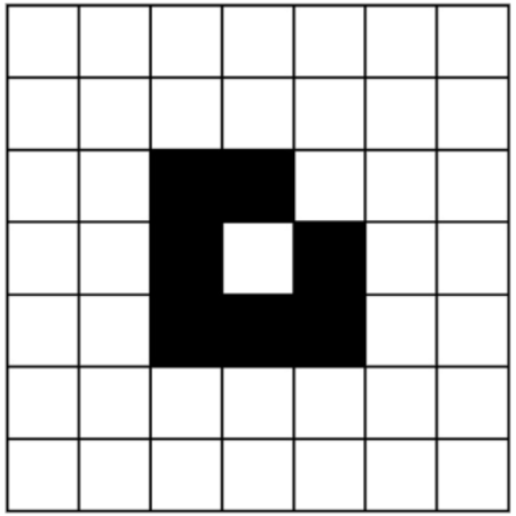
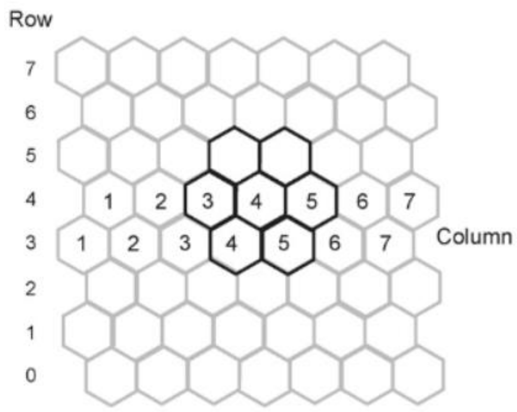




Sampling

- Coordinate system
  - hexagonal grid
  - SHCS: symmetrical hexagonal coordinate system in (C)



(a)

Sampling

- Coordinate system
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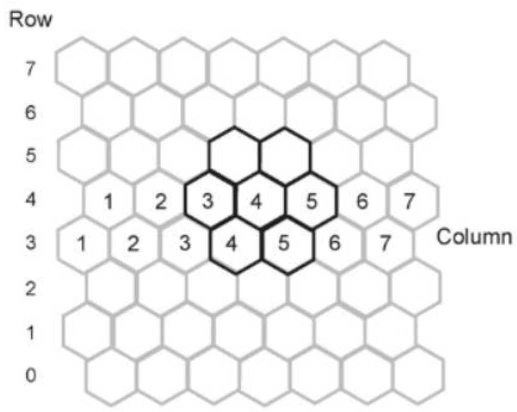

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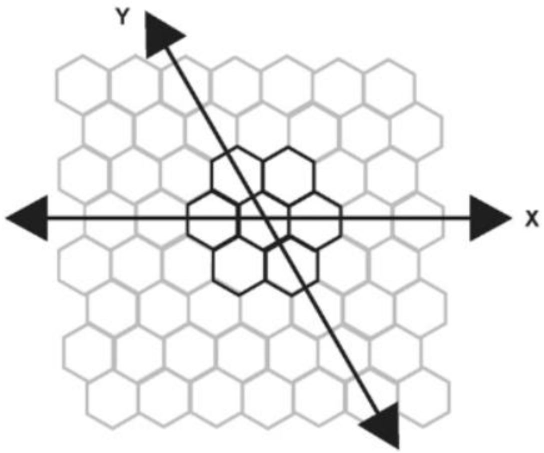

(b)

Sampling

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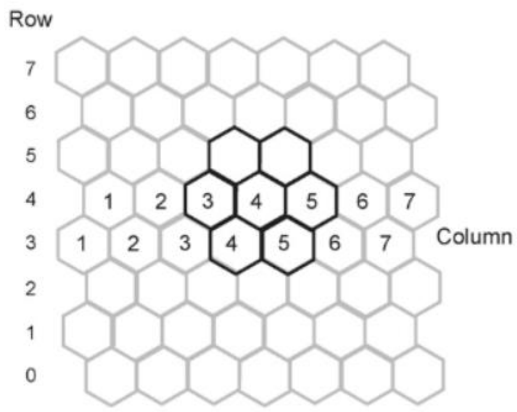

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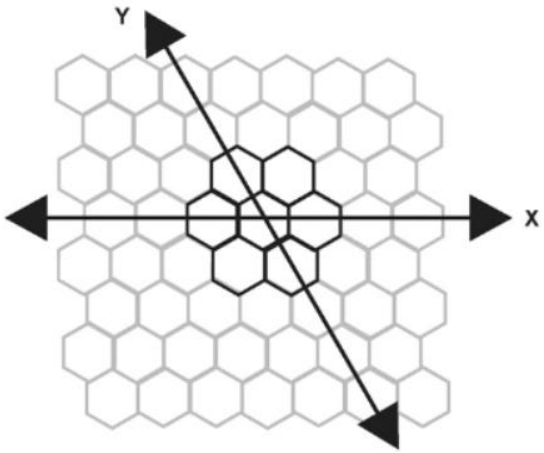
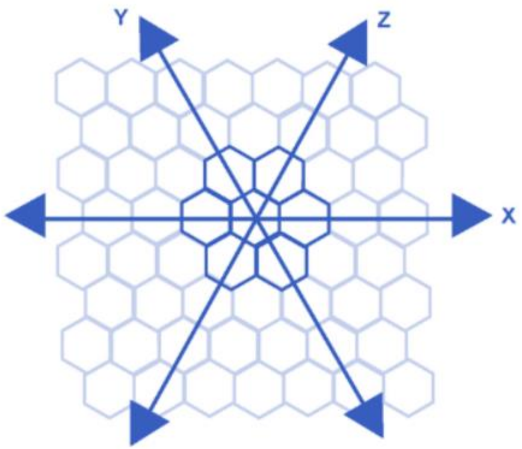


(b)



(C)

Sampling

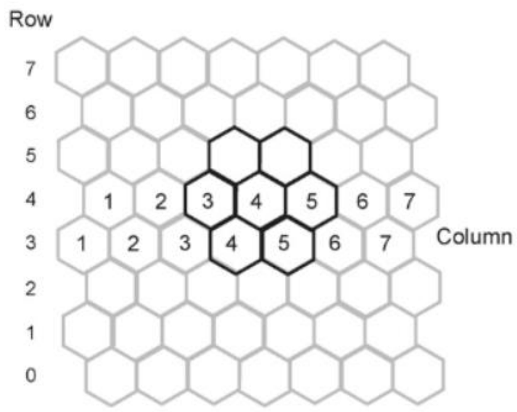
- Coordinate system
  - hexagonal grid
  - SHCS: symmetrical hexagonal coordinate system in (C)

$\forall(x, y, z) : x + y + z = 0$

(x_1, y_1, z_1) and (x_2, y_2, z_2) are the co-ordinates of the two hexagons.

$$D_{Eucl.}[(x_1, y_1, x_1), (x_2, y_2, x_2)]$$
$$= \sqrt{\tfrac{1}{2}[(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2]}$$

$$D_{Grid}[(x_1, y_1, x_1), (x_2, y_2, x_2)] = \max(|x_1 - x_2|, |y_1 - y_2|, |z_1 - z_2|)$$



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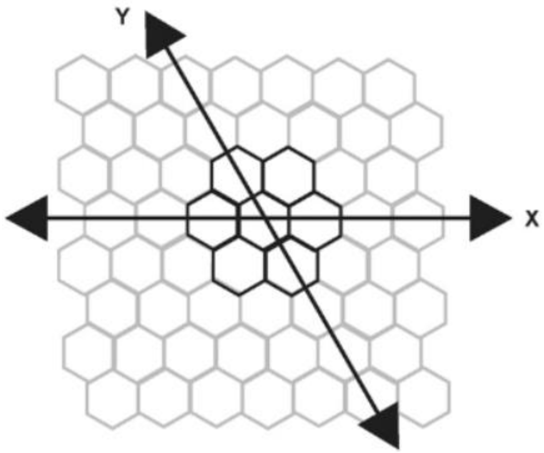

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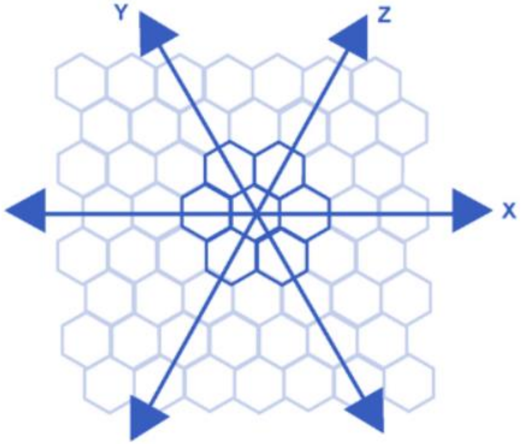
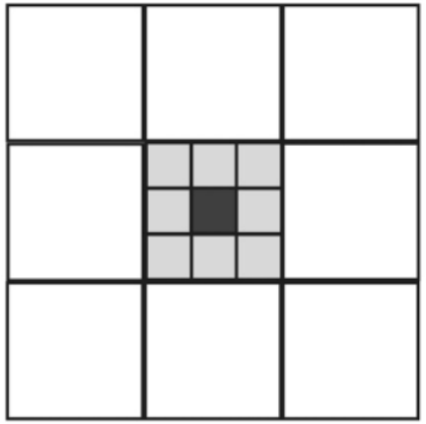


(C)

Sampling

- Hierarchical grids
  - neighbours at finer scale become
    focal cell or centroids for coarser scale
  - smooth out or simplify some grids
    - dynamic grid resolution
  - θ, r can be used to find out current resolution scale



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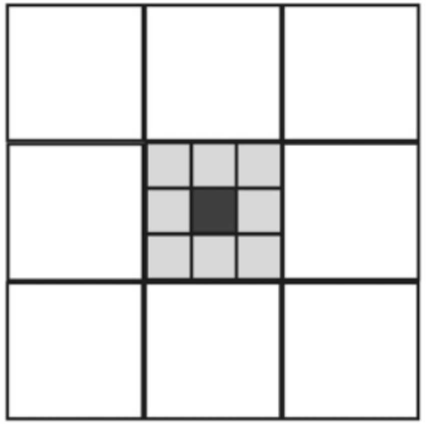

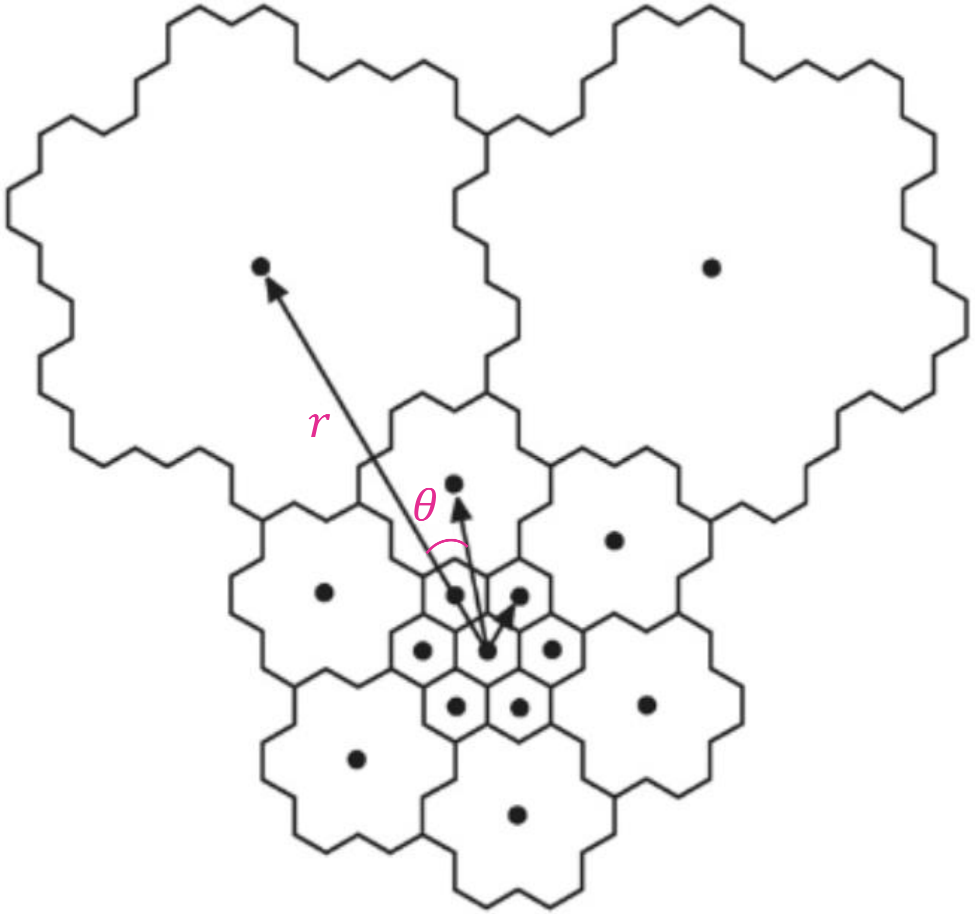

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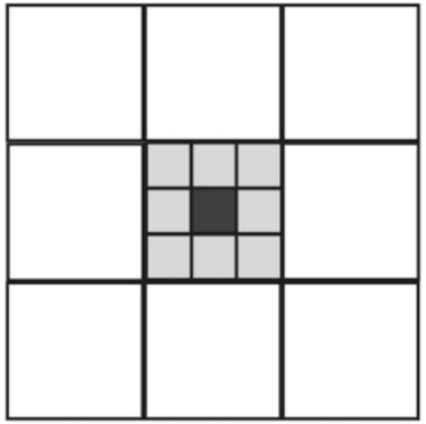
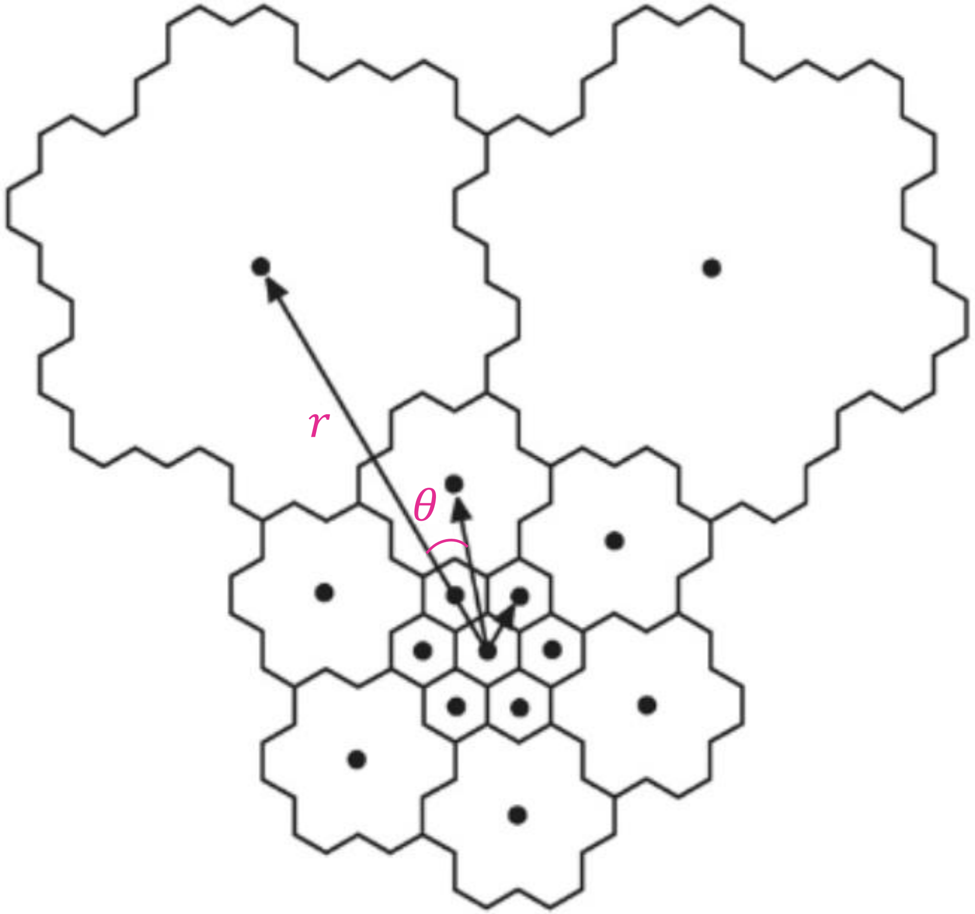




Sampling

- Checkerboard effect
  - due to uniform non-optimal square grid sampling

Sampling

- Checkerboard effect
  - due to uniform non-optimal square grid sampling

128x128

64x64

32x32

Sampling

- Aliasing

continuous bandlimited function

$$f(x, y)$$

$$\delta(x, y) = \begin{cases} 1 & \text{if } x = y = 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\sum_{x=-\infty}^{\infty} \sum_{y=-\infty}^{\infty} f(x, y)\, \delta(x - x_0, y - y_0) = f(x_0, y_0)$$

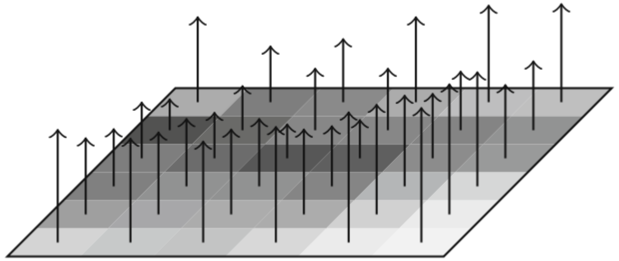
$f(x, y)$ is a func of discrete vars x, y

Sampling

- Aliasing

continuous bandlimited function

$f(x, y)$



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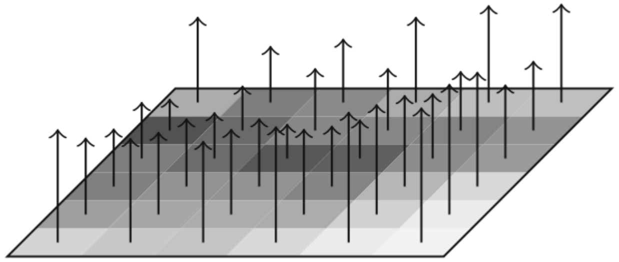
$f(x,y)$



$$comb(x, y, \Delta x, \Delta y) = \sum_m \sum_n \delta(x - m\Delta x, y - n\Delta y)$$

$$\delta(x, y) = \begin{cases} 1 & \text{if } x = y = 0 \\ 0 & \text{otherwise} \end{cases}$$

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$f(x, y)$ is a func of discrete vars x, y

Sampling

- Aliasing

$$f_s(x,y) = f(x,y)\, comb(x,y,\Delta x,\Delta y)$$

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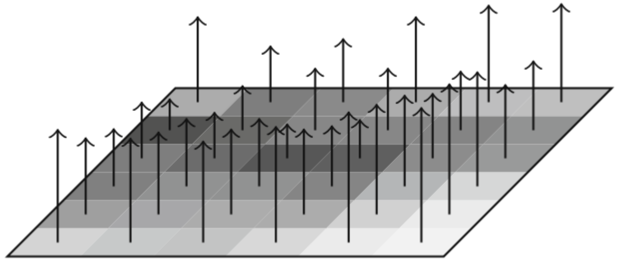
continuous bandlimited function

$f(x,y)$



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Sampling

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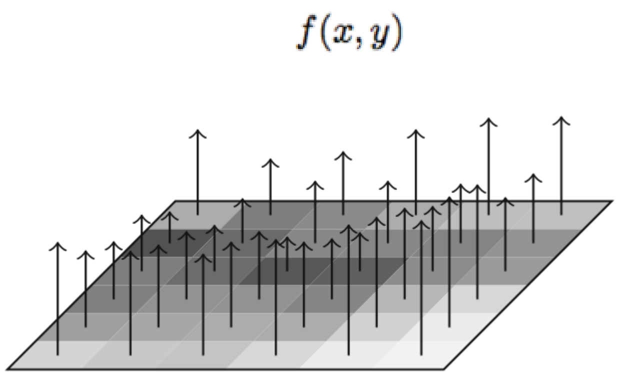
$$f_s(x,y) = f(x,y)\, comb(x,y,\Delta x,\Delta y)$$

$$comb(x,y,\Delta x,\Delta y) = \sum_m \sum_n \delta(x - m\Delta x, y - n\Delta y)$$

$$F_s(\omega_x,\omega_y) = F(\omega_x,\omega_y) * \omega_{x_s}\omega_{y_s} \sum_p \sum_q \delta(\omega_x - p\omega_{x_s}, \omega_y - q\omega_{y_s})$$
$$= \omega_{x_s}\omega_{y_s} \sum_p \sum_q F(\omega_x - p\omega_{x_s}, \omega_y - q\omega_{y_s})$$

where $\omega_{xs} = \frac{2\pi}{\Delta x}$, and $\omega_{ys} = \frac{2\pi}{\Delta y}$

continuous bandlimited function



$$\delta(x,y) = \begin{cases} 1 & \text{if } x = y = 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\sum_{x=-\infty}^{\infty} \sum_{y=-\infty}^{\infty} f(x,y)\,\delta(x - x_0, y - y_0) = f(x_0, y_0)$$

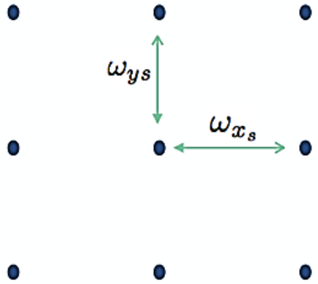
$f(x,y)$ is a func of discrete vars x, y

Sampling

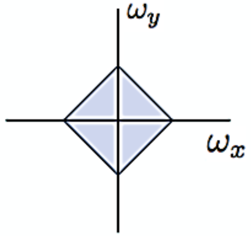
- Aliasing

$$f_s(x,y) = f(x,y)\, comb(x,y,\Delta x,\Delta y)$$

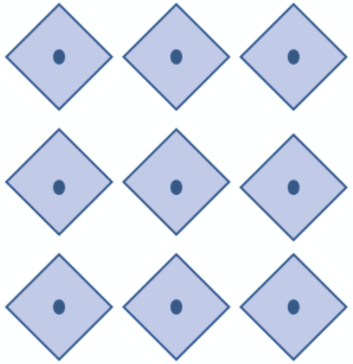
$$F_s(\omega_x,\omega_y) = \omega_{x_s}\omega_{y_s}\sum_p\sum_q F(\omega_x - p\omega_{x_s}, \omega_y - q\omega_{y_s})$$



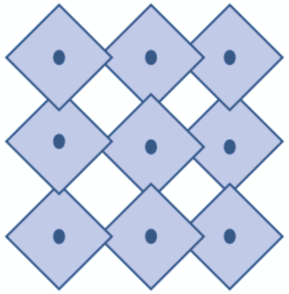
$comb(\omega_x,\omega_y)$



$F(\omega_x,\omega_y)$



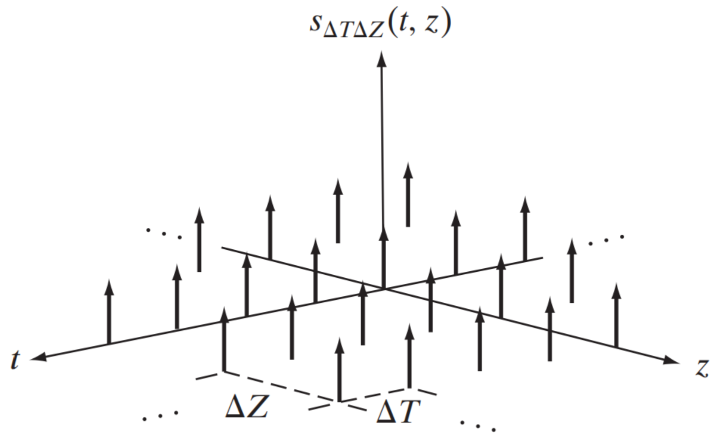
$F_s(\omega_x,\omega_y)$



$F_s(\omega_x,\omega_y)$

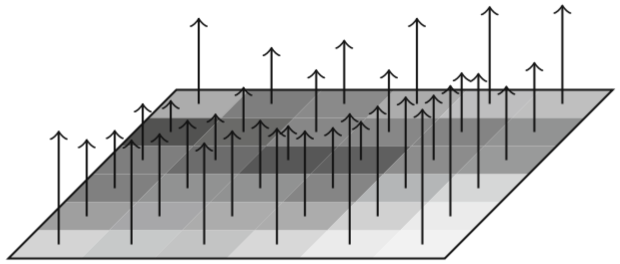
Sampling

- Sampling theorem
  - $f(t,z)$ can be recovered fully with zero error from its samples
  - iff grid is 'sufficiently' dense
  - just change of variables to simplify notations



continuous bandlimited function

$f(t, z)$



$$s_{\Delta T \Delta Z}(t, z) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \delta(t - m\Delta T, z - n\Delta Z)$$

$$F(\mu, \nu) = 0 \quad \text{for } |\mu| \geq \mu_{\max} \text{ and } |\nu| \geq \nu_{\max}$$

... band limits

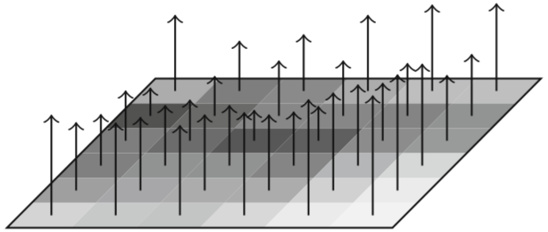
Sampling

- Sampling theorem
  - $f(t,z)$ can be recovered fully with zero error from its samples
  - No info is lost in the image if it is obtained via sampling at rates greater than twice the max freq content of $f(t,z)$ in both μ, v directions.

continuous bandlimited function

Image $\longleftarrow$ $f(t, z)$

$$s_{\Delta T \Delta Z}(t, z) = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \delta(t - m\Delta T, z - n\Delta Z)$$

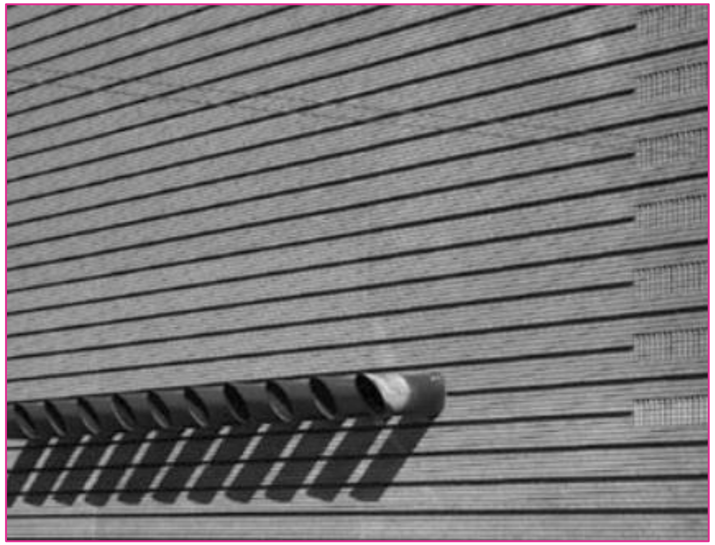


$$F(\mu, \nu) = 0 \quad \text{for } |\mu| \geq \mu_{\max} \text{ and } |\nu| \geq \nu_{\max}$$ ... band limits

$$\boxed{\frac{1}{\Delta T} > 2\mu_{\max} \qquad \frac{1}{\Delta Z} > 2\nu_{\max}}$$

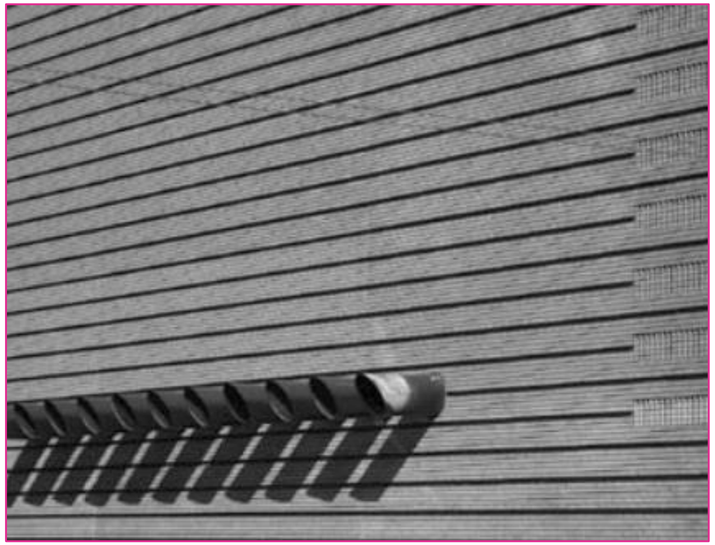
Sampling

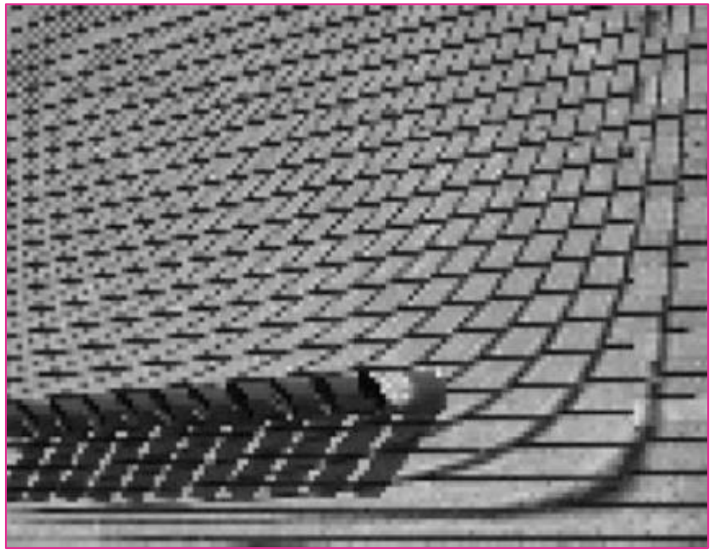
- Erroneous effects
  - square grid sampling



Sampling

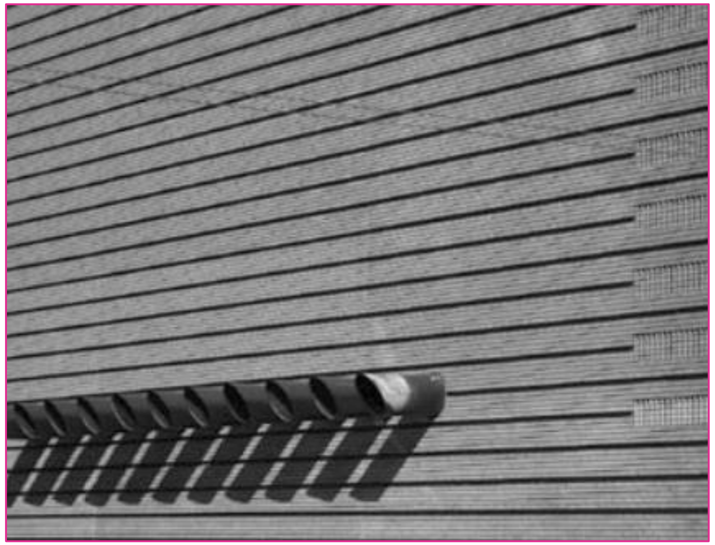
- Erroneous effects
  - square grid sampling

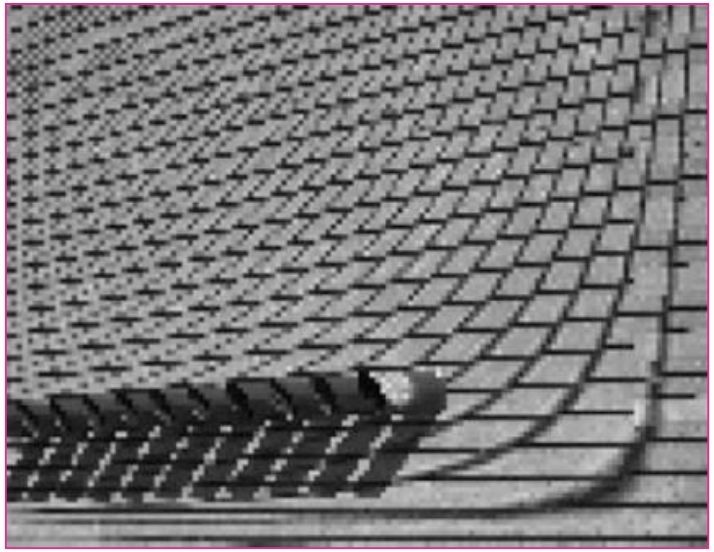


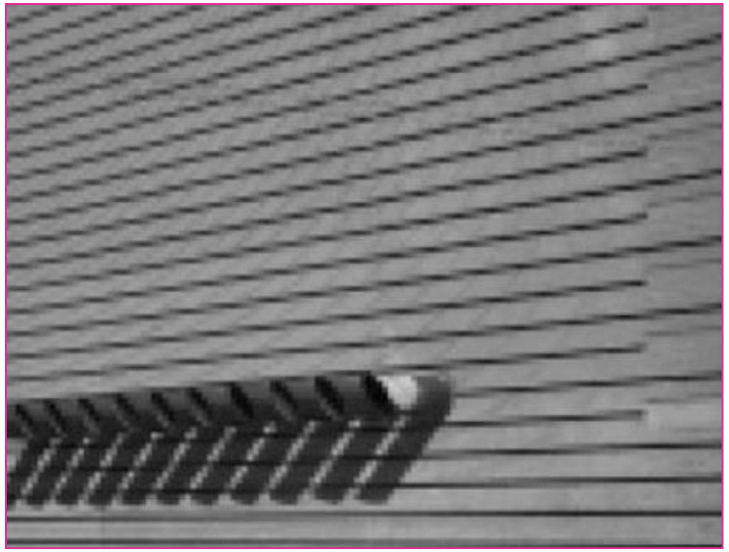


Sampling

- Erroneous effects
  - square grid sampling



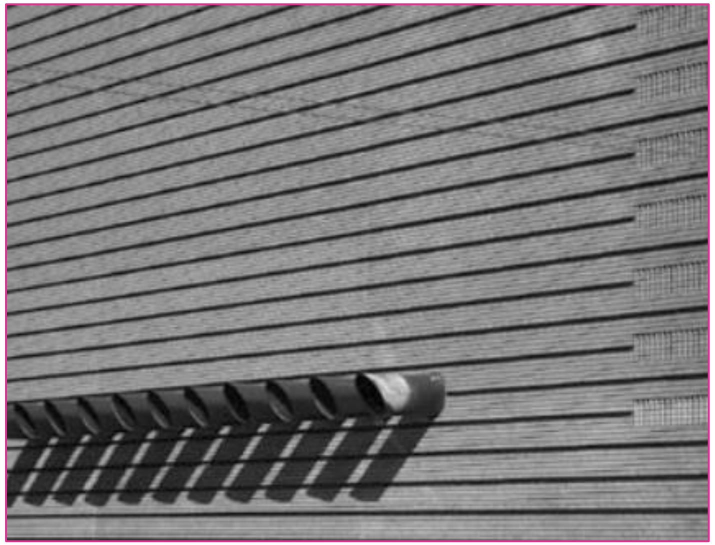




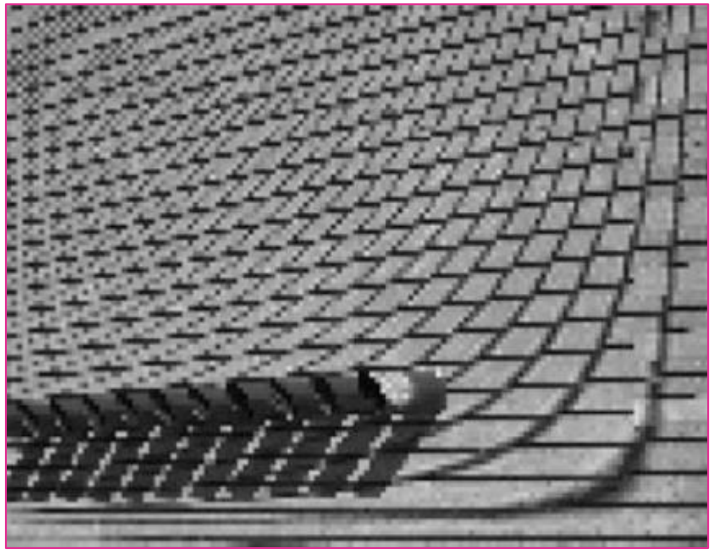
Sampling

- Erroneous effects
  - square grid sampling

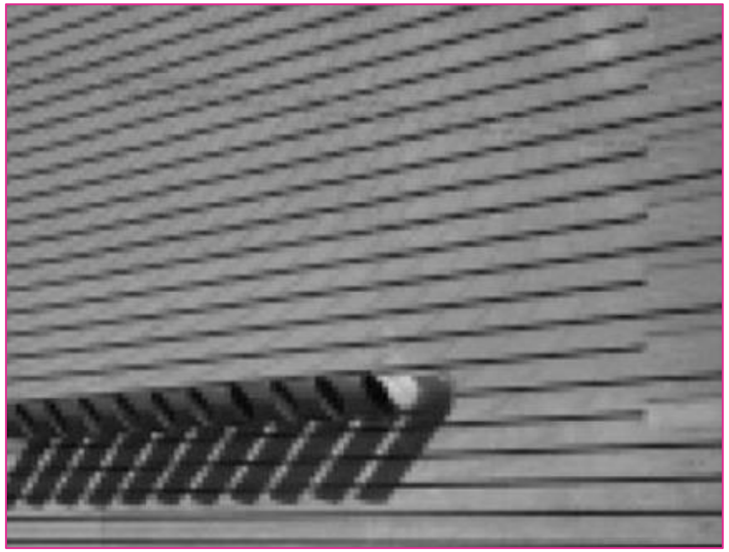
input



8x8 sq grid



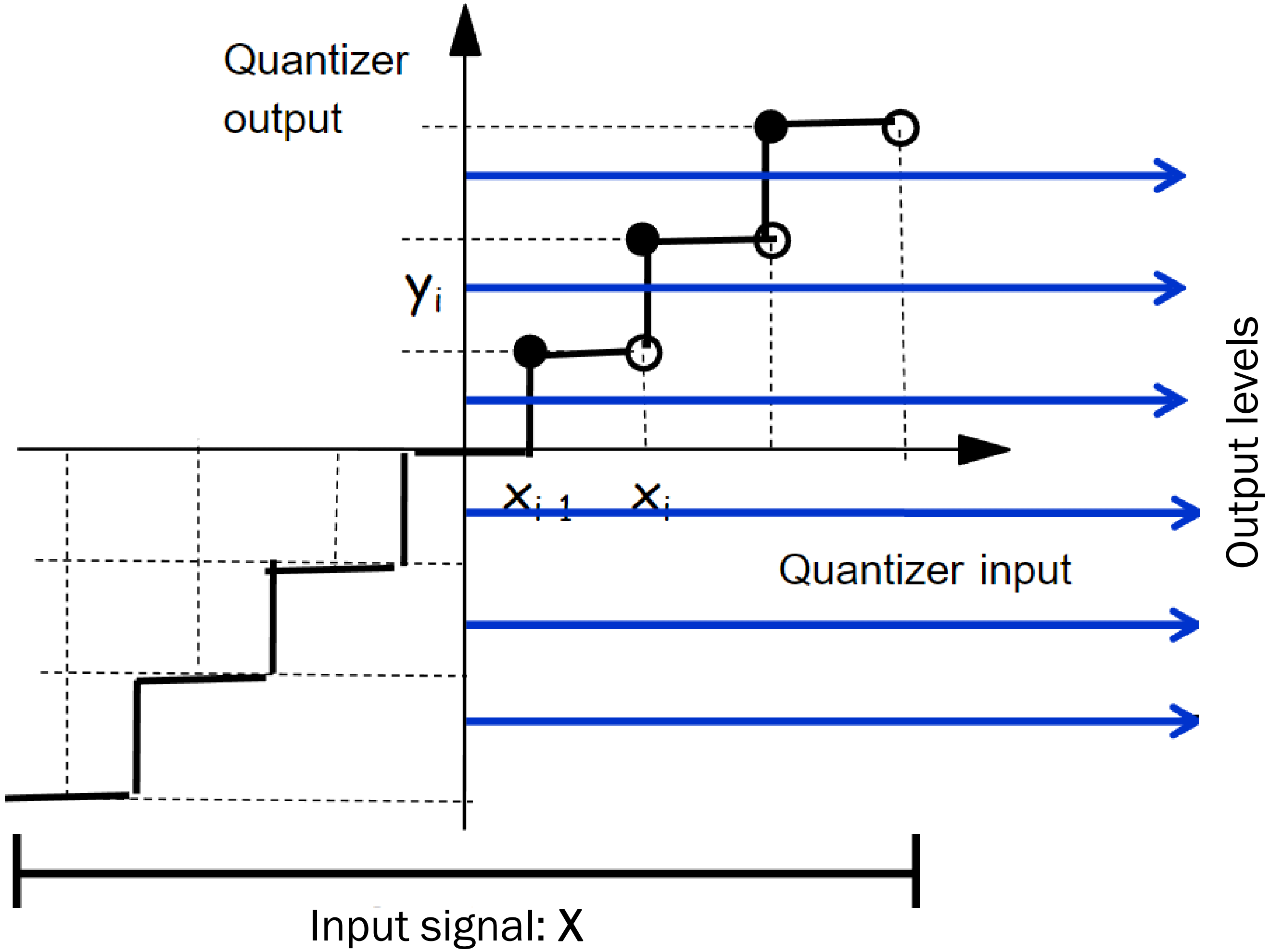
8x8 mean



Quantization

- Quantizer
  - SISO – scalar quantizer
  - mappings $[x_{i-1}, x_i) \rightarrow y_i$
  - what are the unknowns?

$$x \in [t_k, t_{k+1}) \Rightarrow Q(x) = r_k$$

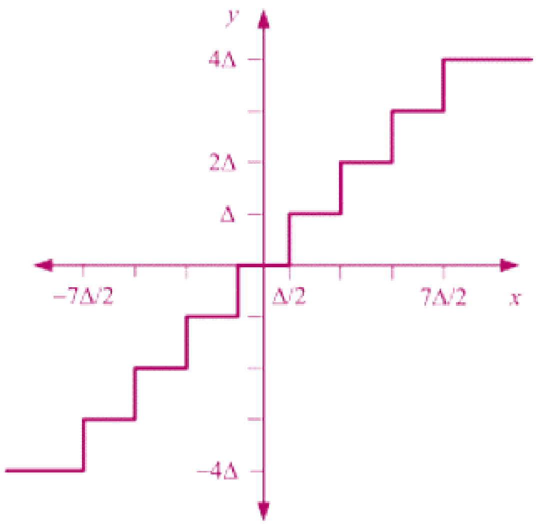


sandhan@iitk.ac.in

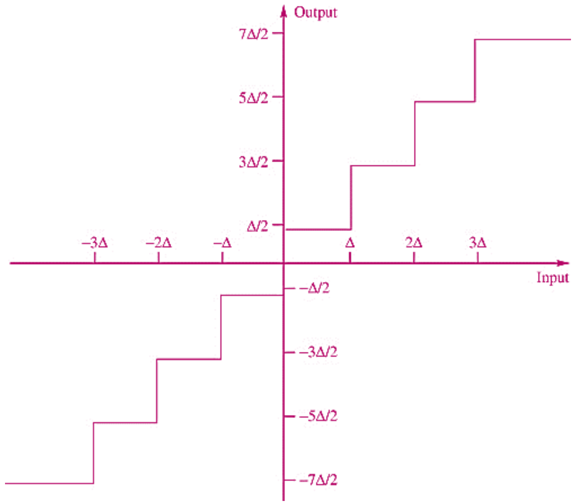
Quantization

- Uniform quantizers
  - all ranges divided equally with $\Delta = [t_k, t_{k+1})$ intervals
  - deadzone

Midtread quantizer



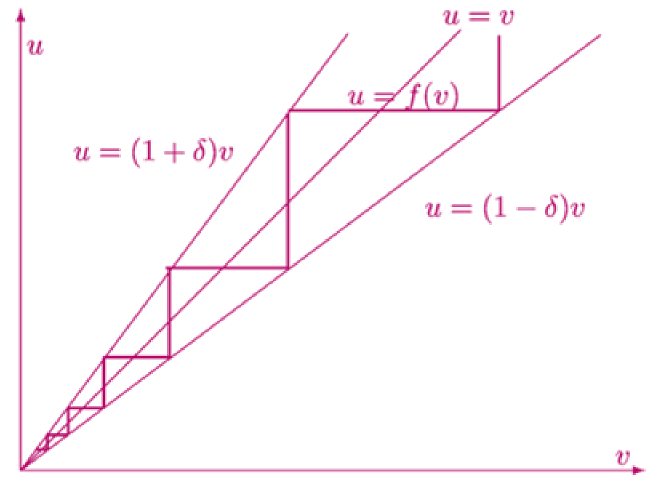
Midrise quantizer



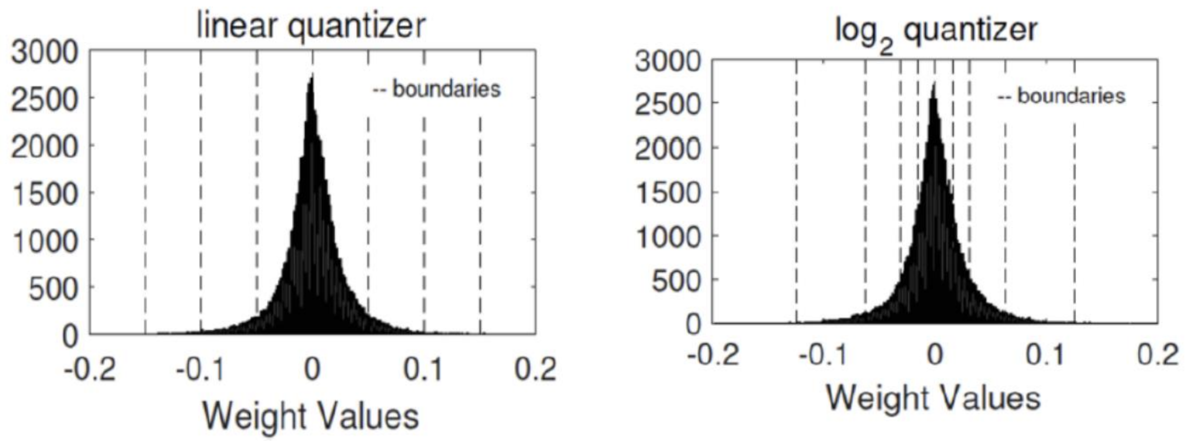
Quantization

- Non-uniform quantizers
  - ranges divided via predefined function which gives Δ intervals

Logarithmic quantizer



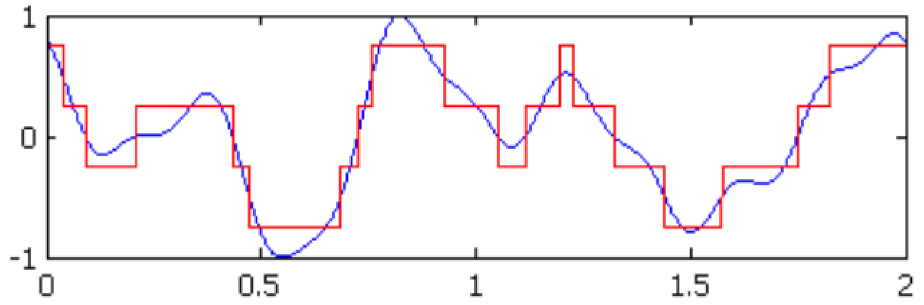
Logarithmic quantizer for image filter weights



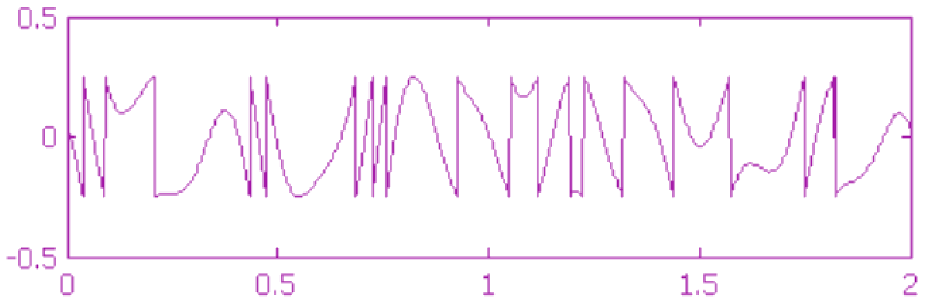
Quantization

- Non-uniform quantizers
  - can we design optimal quantizer?
  - optimal in the sense to minimize error (which error?)
  - input: $x_i \approx t_i$:thresholds
  - output: $y_i \approx r_i$:reconstructions
  - signal distribution is known: $p(x)$

Original and quantized signal



Quantization error



Quantization

- Non-uniform quantizers
  - can we design optimal quantizer?
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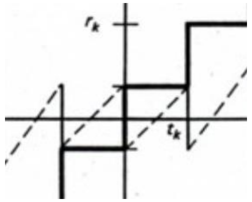
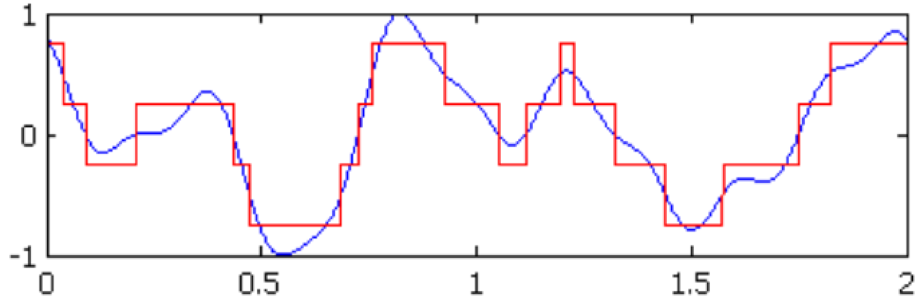
  - input: $x_i \approx t_i$:thresholds
  - output: $y_i \approx r_i$:reconstructions
  - signal distribution is known: $p(x)$
- MSE

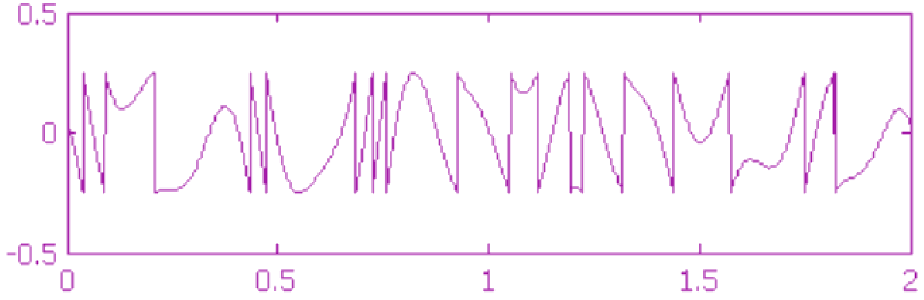
$$D = \int_a^b (x - Q(x))^2 p(x) dx$$



Original and quantized signal



Quantization error



Quantization

$$\begin{aligned} \min_{t_k, r_k} D &= \sum_{k=1}^{L} \int_{t_k}^{t_{k+1}} (x - r_k)^2 p(x) dx \\ \text{sub. to} \quad & t_1 = a, t_{L+1} = b \\ & t_k \leq r_k \leq t_{k+1}, k = 0, \ldots, L \end{aligned}$$

Quantization

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\min_{t_k, r_k} D &= \sum_{k=1}^{L} \int_{t_k}^{t_{k+1}} (x - r_k)^2 p(x) dx \\
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& t_k \le r_k \le t_{k+1}, k = 0, \ldots, L
\end{aligned}$$

$$\begin{aligned}
\frac{\partial D}{\partial r_k} &= \frac{\partial}{\partial r_k} \sum_{j=1}^{L} \int_{t_j}^{t_{j+1}} (x - r_j)^2 p(x) dx \\
&= -2 \int_{t_k}^{t_{k+1}} (x - r_k) p(x) dx, \;\; k = 1, \ldots, L
\end{aligned}$$

Quantization

$$
\begin{aligned}
\min_{t_k, r_k} D \quad &= \quad \sum_{k=1}^{L} \int_{t_k}^{t_{k+1}} (x - r_k)^2 p(x) dx \\
\text{sub. to} \quad & \quad t_1 = a, t_{L+1} = b \\
& \quad t_k \leq r_k \leq t_{k+1}, k = 0, \ldots, L
\end{aligned}
$$

$$
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$$

Quantization

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Fundamental theorem of calculus:
derivative with accumulation function
(c initial const., $f(t)$ is cts in open interval)

$$A(t) = \int_c^t f(x) dx$$

$$A'(t) = f(t)$$

Quantization

$$\min_{t_k, r_k} D = \sum_{k=1}^{L} \int_{t_k}^{t_{k+1}} (x - r_k)^2 p(x) dx$$

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$$= -(t_k - r_k)^2 p(t_k) + (t_k - r_{k-1})^2 p(t_k), \;\; k = 2, \ldots, I$$

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Quantization

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$$\begin{aligned} \frac{\partial D}{\partial r_k} &= \frac{\partial}{\partial r_k} \sum_{j=1}^{L} \int_{t_j}^{t_{j+1}} (x - r_j)^2 p(x) dx \\ &= -2 \int_{t_k}^{t_{k+1}} (x - r_k) p(x) dx, \ k = 1, \ldots, L \end{aligned}$$

$$\begin{aligned} \frac{\partial D}{\partial t_k} &= \frac{\partial}{\partial t_k} \sum_{j=1}^{L} \int_{t_j}^{t_{j+1}} (x - r_j)^2 p(x) dx \\ &= -(t_k - r_k)^2 p(t_k) + (t_k - r_{k-1})^2 p(t_k), \ k = 2, \ldots, L \end{aligned}$$

Assuming $p(x) > 0$ for each $x \in [a, b]$:

$$r_k = \frac{\int_{t_k}^{t_{k+1}} x p(x) dx}{\int_{t_k}^{t_{k+1}} p(x) dx}, \ k = 1, \ldots, L$$

$$t_k = \frac{r_{k-1} + r_k}{2}, \ k = 2, \ldots, L$$

Fundamental theorem of calculus:
derivative with accumulation function
(c initial const., $f(t)$ is cts in open interval)

$$A(t) = \int_c^t f(x) dx$$

$$A'(t) = f(t)$$

Quantization

- Lloyd-Max Quantizer
  - optimal MSE quantizer

$$r_k = \bar{x}_k = \frac{\int_{t_k}^{t_{k+1}} x p(x) dx}{\int_{t_k}^{t_{k+1}} p(x) dx}, \quad k = 1, \ldots, L \qquad \ldots (1)$$

$$t_k = \frac{r_{k-1} + r_k}{2} = \frac{\bar{x}_{k-1} + \bar{x}_k}{2}, \quad k = 2, \ldots, L \qquad \ldots (2)$$

Quantization

- Lloyd-Max Quantizer
  - optimal MSE quantizer

$$r_k = \bar{x}_k = \frac{\int_{t_k}^{t_{k+1}} x p(x) dx}{\int_{t_k}^{t_{k+1}} p(x) dx}, \quad k = 1, \ldots, L \quad \ldots (1)$$

$$t_k = \frac{r_{k-1} + r_k}{2} = \frac{\bar{x}_{k-1} + \bar{x}_k}{2}, \quad k = 2, \ldots, L \quad \ldots (2)$$

- Pseudo-code

: pick initial values for t (uniform grid)
: find r values using (1)
: find new t values using (2)
: repeat till both t, r converge

Quantization

- Properties of optimal quantizer
  - $E[Q(x)] = \sum_k r_k p_k$

    $= E[x]$

$$r_k = \frac{\int_{t_k}^{t_{k+1}} xp(x)dx}{\int_{t_k}^{t_{k+1}} p(x)dx}$$

$$p_k = \int_{t_k}^{t_{k+1}} p(x)dx$$

  - $E[x - Q(x)] = 0$

Quantization

- Properties of optimal quantizer
  - $$E[(x - Q(x))Q(x)] = \sum_k \int_{t_k}^{t_{k+1}} (x - r_k) r_k p(x) dx$$

$$r_k = \frac{\int_{t_k}^{t_{k+1}} x p(x) dx}{\int_{t_k}^{t_{k+1}} p(x) dx}$$

$$p_k = \int_{t_k}^{t_{k+1}} p(x) dx$$

Quantization

- Properties of optimal quantizer
  - $$E[(x-Q(x))Q(x)] = \sum_k \int_{t_k}^{t_{k+1}} (x-r_k) r_k p(x) dx$$

    $$= 0$$

$$r_k = \frac{\int_{t_k}^{t_k+1} x p(x) dx}{\int_{t_k}^{t_k+1} p(x) dx}$$

$$p_k = \int_{t_k}^{t_k+1} p(x) dx$$

Quantization

- Properties of optimal quantizer
  - $$E[(x - Q(x))Q(x)] = \sum_k \int_{t_k}^{t_{k+1}} (x - r_k) r_k p(x) dx$$ $$r_k = \frac{\int_{t_k}^{t_{k+1}} xp(x)dx}{\int_{t_k}^{t_{k+1}} p(x)dx}$$

    $$= 0$$ $$p_k = \int_{t_k}^{t_{k+1}} p(x)dx$$

  - error is uncorrelated with the quantizer's output

Quantization

- Lloyd-Max example

8 bpp

Quantization

- Lloyd-Max example

8 bpp

6 bpp

Quantization

- Lloyd-Max example

8 bpp

6 bpp

4 bpp

Conclusion

- Sampling
- Quantization

32x32

Conclusion

- Sampling
- Quantization

❑ Sampling

- Squares
- Hexagonal
- Aliasing

❑ Quantization

- Uniform
- Non-uniform
- Optimal

32x32