Module - 3

Image Transform

Image Transformation

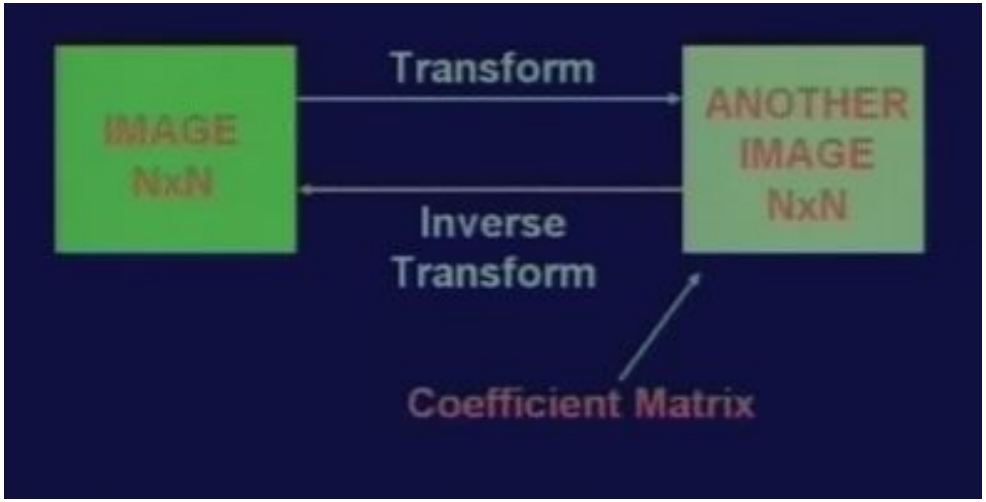


Image Transforms

Orthogonal Sinusoidal Basis Functions

1. DFT
2. DCT
3. DST

Non Sinusoidal Orthogonal Basis Functions

1. Haar
2. Hadamard
3. Slant

Basis Functions depending on statistics of i/p

1. KL (PCA)
2. SVD

Directional Transformation

1. Hough Tx
2. Radon Tx
3. Ridgelet Tx
4. Contourlet TX

Applications

- Preprocessing
  - Filtering
  - Enhancement etc.
- Data Compression
- Feature Extraction
  - Edge detection
  - Corner detection etc.

What it actually does?

It represents a given image as a series summation of a set of Unitary Matrices

What is a Unitary matrix?

A matrix A is a Unitary matrix if

$$A^{-1} = A^{*T} \qquad A^{*} \longrightarrow \text{Conjugate of } A$$

Unitary Matrices $\longrightarrow$ Basis Images

Introduction

What does the Image Transform do?

It represents the given image as a series summation of a set of Unitary Matrices.

What is a Unitary Matrix?

A Matrix 'A' is a unitary matrix if

$A^{-1} = A^{*T}$ where A^* is conjugate of A

Unitary Matrix --------> Basis Functions

Introduction

An arbitrary continuous signal x(t) can be represented by a series summation of set of orthogonal basis functions.

The series expansion is given as:

$$x(t) = \sum_{n=0}^{\infty} c_n a_n(t)$$ infinite series expansion

$$\hat{x}(t) = \sum_{n=0}^{N-1} c_n a_n(t)$$ finite series expansion

It gives an approximate representation of x(t).

Introduction

In discrete signals
We have a series of 1D sequence of samples represented by:
$\{u(n) ; 0 \leq n \leq N-1\}$

We have N number of samples, so we represent this set by a vector 'u' of dimension 'N'.

For transformation:
We pre-multiply this matrix u by unitary matrix of dimension NxN.

$$v = A \cdot u$$

Where, v -> transformed vector
A -> Transformed matrix

Introduction

Clip slide

After expansion:

$$v(k) = \sum_{n=0}^{N-1} a(k, n)\, u(n) \qquad ; k = 0, 1, \ldots\ldots N-1$$

If vector 'A' is an unitary matrix we can get back our original vector 'u'

So pre-multiplying v by A-1

$u = A^{-1}v = A^{*T}v$

Representing above equation in the form of a series summation,

$$u(n) = \sum_{n=0}^{N-1} a^*(k, n)\, v(k) \qquad ; n = 0, 1, \ldots\ldots N-1$$

Introduction

Expanding matrix a(k, n), it is of the form,

$$a(k, n) = \begin{bmatrix} a(0, 0) & a(0, 1) & a(0, 2) & \ldots a(0, n) \\ a(1, 0) & a(1, 1) & a(1, 2) & \ldots \\ a(2, 0) & a(2, 1) & a(2, 2) & \ldots \\ \ldots & & & \\ a(k, 0) & & & a(k, n) \end{bmatrix}$$

a*(k, n) is the column vector of matrix A^{*T}

These column vectors are usually called the basis vectors of A.

$$u(n) = \sum_{n=0}^{N-1} a^*(k, n)\, v(k) \qquad ; n = 0, 1, \ldots\ldots N-1$$

Where, u(n) is series summation of basis vectors

Introduction

The concept of representing the vector as a series summation of basis vectors can be expanded to 2D signals(image) as well

Consider any image $u(m, n)$; $0 \le m, n \le N-1$ of dimension N x N.
Transformation on this image is given by:

$$v(k, l) = \sum_{m, n = 0}^{N-1} a_{k, l}(m, n)\, u(m, n) \qquad 0 \le k, l \le N-1$$

Thus, we have N^2 number of unitary matrices.

$$u(m, n) = \sum_{k, l = 0}^{N-1} a^*_{k, l}(m, n)\, v(k, l) \qquad 0 \le m, n \le N-1$$

$V = \{v(k, l)\}$ is the transform coefficient.

Introduction

During Inverse Transformation if all coefficients are not considered then an approximate reconstructed image will be generated.

$$\hat{u} = \sum_{k=0}^{P-1} \sum_{l=0}^{Q-1} v(k, l)\, a^*_{k,l}(m, n)$$

So, we are considering only P x Q coefficients instead of N^2.
The sum of squared error will be given by:

$$€^2 = \sum_{m,n=0}^{N-1} \sum [u(m, n) - \hat{u}(m, n)]^2$$

This error will be minimized if the set of basis images $a_{k,l}(m, n)$ is complete.
Computations required : $O(N^4)$

Introduction

To reduce Computational Complexity:

We have to make use of separable unitary transforms

$a_{k,l}(m, n)$ is separable if it can be represented in the form

$$a_{k,l}(m, n) = a_k(m) \,.\, b_l(n) \approx a(k, m)\, b(l, n)$$

where, $\{ a_k(m), k=0, 1, \ldots.N-1\}$

$\{ b_l(n), l = 0, 1, \ldots..N-1\}$

they are set of complete orthogonal set of basis vectors.

If we represent $A \approx \{a(k, m)\}$ & $B \approx \{b(l, n)\}$ in the form of matrices then both should be unitary so that

$$AA^{*T} = A^T A^* = I$$

If this is correct then we say that the transformation is a separable transformation.

Introduction

Usually we assume both the matrices A & B to be same.
Then the transformation equation changes to

$$v(k, l) = \sum_{m,n=0}^{N-1} \sum a(k, m)\, u(m, n)\, a(l, n)$$

In terms of matrices it is given by:

$V = AUA^T$ where all the matrices are f the order of N x N

By applying inverse transformation we will have he original matrix from the coefficient matrix.
Similarly, inverse transformation can now be written as:

$$u(m, n) = \sum_{k,l=0}^{N-1} \sum a^*(k, m)\, v(k, l)\, a^*(l, n)$$

$U = A^{*T}VA^*$
They are 2D separable transformations.

Introduction

$V = AUA^T$

$V^T = A[AU]^T$

By general matrix arithmetic, we know
if two matrices A & U of order N x N when multiplied requires $O(N^3)$ computations.
Thus it takes $O(2N^3)$ computations over all instead of $O(N^4)$ when separable transform are not considered.

Basis Images

Suppose if a^*_k denotes k^{th} column of A^{*T}.

If the matrix is defined as

$$A^*_{k,l} = a^*_k a^{*T}_l$$

where, a^*_l is k^{th} column of A^{*T}

We can have

$$u(m, n) = \sum_{k,l=0}^{N-1}\sum v(k,l)\, a^*_{k,l}(m, n)$$

Basis Images

In matrix form,

$$U = \sum_{k,l=0}^{N-1}\sum v(k,l)\, A^*_{k,l}$$

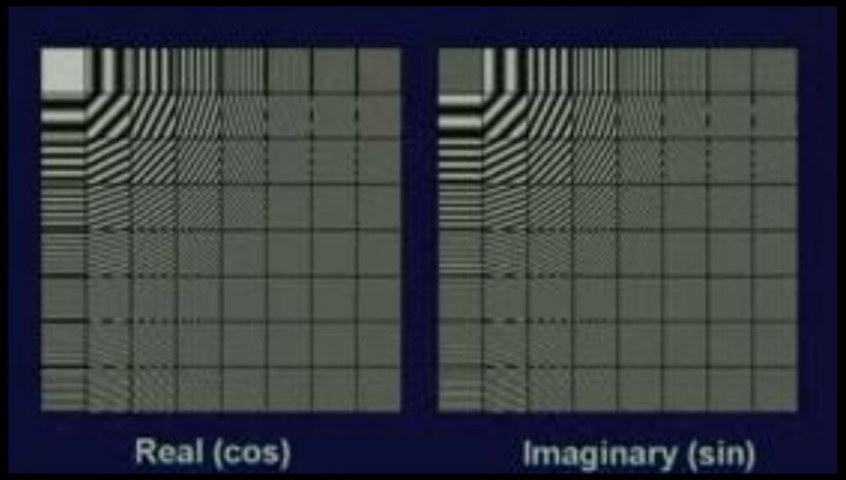
It can be observed that our original image matrix now is represented by a linear combination of N square matrices $A^*_{k,l}$ with each having dimension of N x N.

The matrices $A^*_{k,l}$ is known as the basis images.

The aim of transform is to represent the input image in the form of linear combination of a set of basis images.

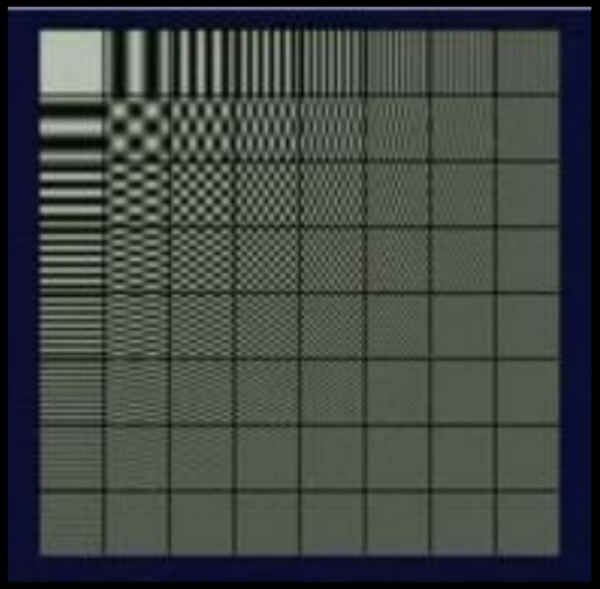
Basis Images

DFT basis function:



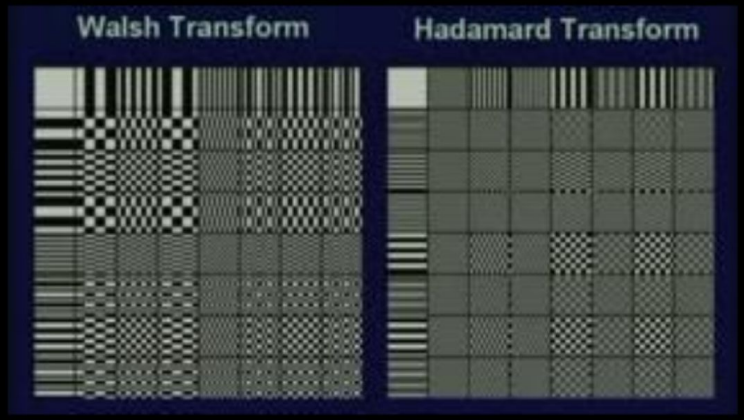
Basis Images

DCT Basis images



Basis Images

Basis images



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Ex. 1) $A = (1/\sqrt{2})\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$ $\quad U = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$

$$V = (½)\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$= (½)\begin{bmatrix} 4 & 6 \\ -2 & -2 \end{bmatrix}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$= \begin{bmatrix} 5 & -1 \\ -2 & 0 \end{bmatrix}$$

Basis Images: $A^*_{k,l} = a^*k \,.\, a^*l$

$A^*_{00} = (½)[1][1\ 1] = (½)[1\ 1;\ 1\ 1]$

$[1]$

$A^*_{01} = A^*_{10} = (½)[1\ -1;\ 1\ -1]$

$A^*_{11} = (½)[1\ -1;\ -1\ 1]$

Discrete Fourier Transform

Assume f(x) to be a continuous function of some variable x.

Then FT of the variable f(x) is given by

$$F\{f(x)\} = F(u) = \int_{-\infty}^{\infty} f(x)\, e^{-j2\pi ux}\, dx$$

where, u is the frequency term.

Requirement of the function:

(i) Function must be continuous.

(ii) Function must be integrable.

Similarly, IFT is found by

$$F^{-1}\{F(u)\} = f(x) = \int_{-\infty}^{\infty} F(u)\, e^{j2\pi ux}\, du$$

But F(u) must be integrable.

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Discrete Fourier Transform

Clip slide

F(u) is in general a complex function

It can therefore be broken down into real & imaginary parts.

$F(u) = R(u) + jI(u) \Rightarrow |F(u)|\, e^{j\phi(u)}$

where, $|F(u)| = [R^2(u) + I^2(u)]^{1/2}$ is Fourier spectrum of f(x);

$\phi = \tan^{-1}\{I(u)/R(u)\}$ is the phase angle &

$P(u) = |F(u)|^2 = R^2(u) + I^2(u)$ is the power spectrum.

Discrete Fourier Transform

Clip slide

2D Fourier Transform of a continuous signal f(x, y) is given by:

$$F(u, v) = \int_{-\infty}^{\infty}\int f(x, y)\, e^{-j2\pi(ux + vy)}\, dx\, dy$$

2D IFT is given below:

$$f(x, y) = \int_{-\infty}^{\infty}\int F(u, v)\, e^{j2\pi(ux + vy)}\, dx\, dy$$

Where,

$|F(u, v)| = [R^2(u, v) + I^2(u, v)]^{1/2}$ is Fourier spectrum of f(x, y);

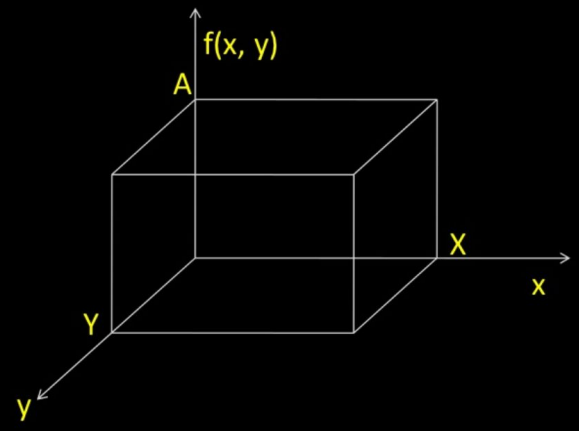
$\phi = \tan^{-1}(I(u, v)/R(u, v))$ is the phase angle &

$P(u) = |F(u, v)|^2 = R^2(u, v) + I^2(u, v)$ is the power spectrum.

Discrete Fourier Transform

Clip slide

f(x, y) is a 2D signal with magnitude A, then its Fourier Transform is found out.



Discrete Fourier Transform

$$F(u, v) = \int_{-\infty}^{\infty}\int f(x, y)\, e^{-j2\pi(ux + vy)}\, dx\, dy$$

$$= A \int_{0}^{X} e^{-j2\pi ux}\, dx \,.\, \int_{0}^{Y} e^{-j2\pi vy}\, dy$$

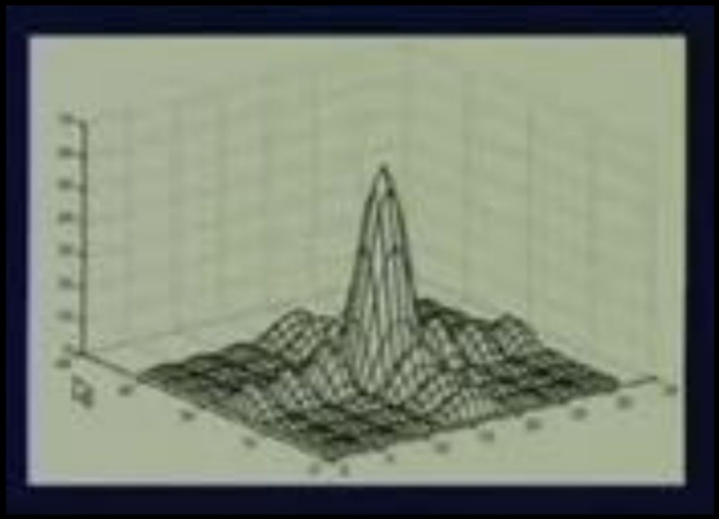
$$= A\, [(e^{-j2\pi ux})/(-j2\pi u)]_{0}^{X} .\, [(e^{-j2\pi vy})/(-j2\pi v)]_{0}^{Y}$$

$$= AXY\, [(\sin(\pi ux)\, e^{-j2\pi ux})/(\pi ux)]\, [(\sin(\pi vy)\, e^{-j2\pi vy})/(\pi vy)]$$

Fourier Spectrum of FT:

$$|F(u, v)| = Axy\, |(\sin(\pi ux))/(\pi ux)|\, |(\sin(\pi vy))/(\pi vy)|$$

Discrete Fourier Transform



Discrete Fourier Transform

Clip slide

2D DFT of the function g(x, y) of size M x N is expressed as:

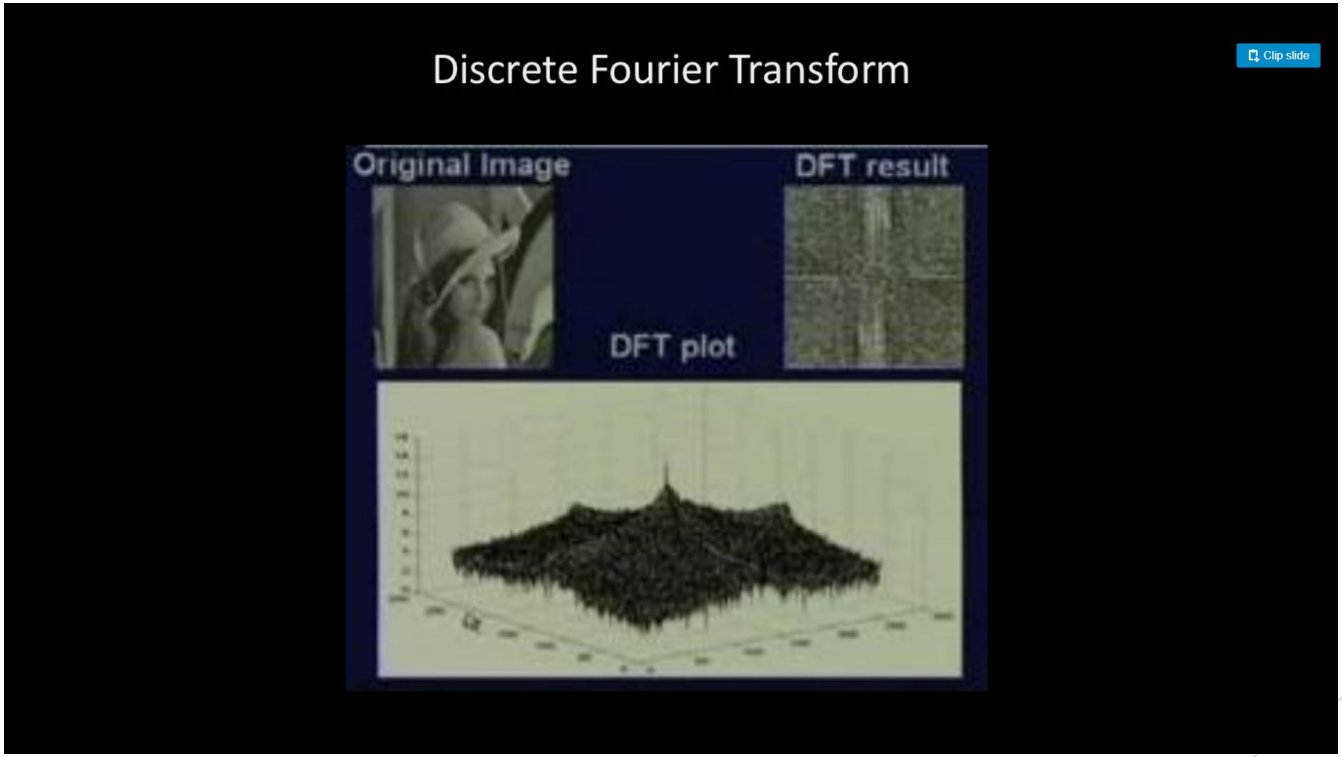
$$F(u, v) = (1/MN) \sum_{x=y=0}^{M-1\ N-1} \sum f(x, y)\, e^{-j2\pi((ux/M)+(vy/N))} \quad \text{--------(1)}$$

for, u = 0, 1, 2, ……M-1
v = 0, 1, 2, ……N-1

If F(u, v) is given then f(x, y) can be obtained by IDFT

$$f(x, y) = \sum_{u=v=0}^{M-1\ N-1} \sum F(u, v)\, e^{j2\pi((ux/M)+(vy/N))} \quad \text{----------(2)}$$

for, x = 0, 1, ……M-1
y = 0, 1, ……N-1


Discrete Fourier Transform
Clip slide
Original Image
DFT result
DFT plot

Discrete Fourier Transform

Clip slide

Properties of Fourier Transform:

1) <u>Separability:</u>

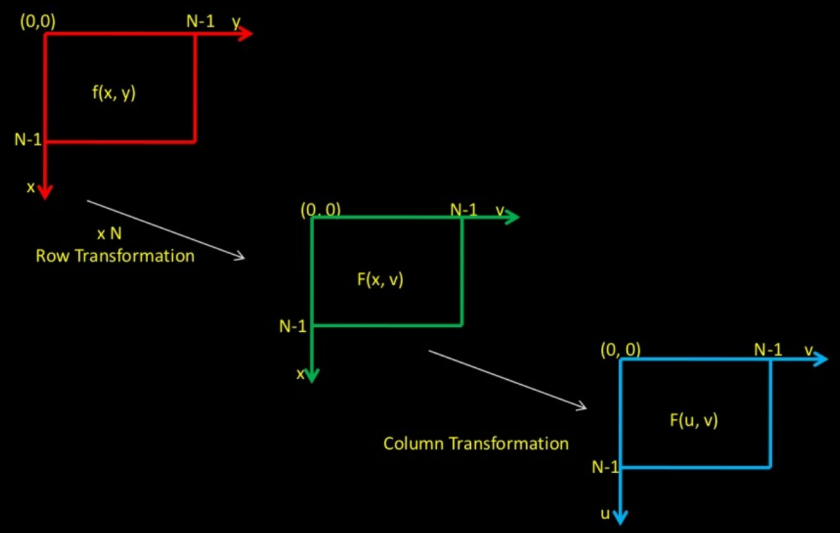
$$F(u, v) = (1/N) \sum_{x=y=0}^{N-1} \sum f(x, y)\, e^{-j(2\pi/N)(ux+vy)} \quad \text{--------(1)}$$

$$= (1/N) \sum_{x=0}^{N-1} e^{-j(2\pi ux/N)} .N.(1/N) \sum_{y=0}^{N-1} f(x, y)\, e^{-j(2\pi vy/N)}$$

$$= (1/N) \sum_{x=0}^{N-1} e^{-j(2\pi ux/N)} .N.F(x, v)$$

$$= (1/N) \sum F(x, v)\, e^{-j(2\pi ux/N)}$$

Discrete Fourier Transform



Discrete Fourier Transform

Clip slide

For Inverse DFT

$$f(x, y) = (1/N) \sum_{u=v=0}^{N-1} \sum F(u, v)\, e^{j(2\pi/N)(ux+vy)}$$

$$= (1/N) \sum_{u=0}^{N-1} e^{j(2\pi ux/N)}\, N.\, (1/N) \sum_{v=0}^{N-1} F(u, v)\, e^{j(2\pi vy/N)}$$

$$= (1/N) \sum_{u=0}^{N-1} N\, f(u, y)\, e^{j(2\pi ux/N)}$$

Column Transformation

Row Transformation

Discrete Fourier Transform

Clip slide

2) <u>Translation Property:</u>

For any image $f(x, y)$ if translated by (x_0, y_0)becomes $f(x-x_0, y-y_0)$

The translated Fourier Transform is given by:

$$F_t(u, v) = (1/N) \Sigma \Sigma f(x-x_0, y-y_0)\, e^{-j(2\pi/N)(u(x-x_0)+v(y-y_0))}$$

$$= (1/N) \Sigma \Sigma f(x-x_0, y-y_0)\, e^{-j(2\pi/N)(ux + vy)}\, e^{j(2\pi/N)(ux_0 + vy_0)}$$

$$= F(u, v)\, e^{j(2\pi/N)(ux_0 + vy_0)}$$

After Translation, the magnitude does not change, it just includes some additional phase difference.

Similarly, in IDFT, $F(u-u_0, v-v_0) = f(x, y)\, e^{j(2\pi/N)(u_0 x + v_0 y)}$

Discrete Fourier Transform

Clip slide

Basics of filtering in Frequency domain:

Frequency domain describes the space defined by values of the FT and the frequency variable (u & v).

Depending on equation (1) we observe the following salient features:

(i) Each term of G(u, v) consists of all values of g(x, y) modified by exponential terms.

(ii) We can establish a general connection between frequency component of FT & spatial characteristics of an image.

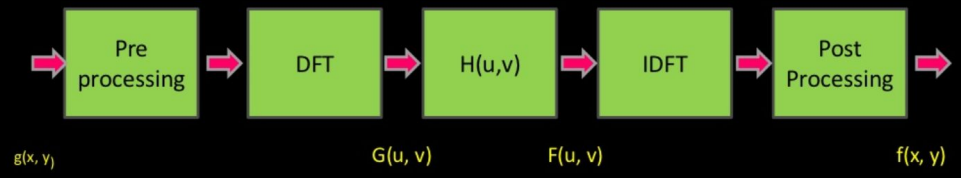
(iii) Slowest varying frequency components (u=v=0) corresponds to the average gray level of the image.

Discrete Fourier Transform

(iv) As we move away from origin of transform, LF correspond to slowly varying component of an image.

(v) As we move further away from origin, the higher frequency begin to correspond to faster & faster gray level changes in image. These are the edges of objects & other components of the images characterized by abrupt changes in gray levels (noise).

Filtering in Frequency Domain:



Discrete Fourier Transform

Ex. 2) Compute 2D DFT and amplitude spectrum of the following image

$$U = \begin{matrix} 5 & 3 & 0 & 2 \\ 1 & 7 & 8 & 3 \\ 4 & 2 & 2 & 2 \\ 8 & 5 & 2 & 1 \end{matrix} \qquad F = \begin{matrix} 1 & 1 & 1 & 1 \\ 1 & -j & -1 & j \\ 1 & -1 & 1 & -1 \\ 1 & j & -1 & -j \end{matrix} = F^T$$

Discrete Fourier Transform

Clip slide

3) Periodicity & Conjugate:

$F(u, v) = F(u, v+N) = F(u+N, v) = F(u+N, v+N)$

$$F(u, v) = (1/N) \sum_{x=y=0}^{N-1} \sum f(x, y)\, e^{-j(2\pi/N)(ux+vy)}$$

$$F(u+N, v+N) = (1/N) \sum_{x=y=0}^{N-1} \sum f(x, y)\, e^{-j(2\pi/N)(ux+vy+Nx+Ny)}$$

$$= (1/N) \sum_{x=y=0}^{N-1} \sum f(x, y)\, e^{-j(2\pi/N)(ux+vy)}\, e^{-j(2\pi)(x+y)}$$

$$= (1/N) \sum \sum f(x, y)\, e^{-j(2\pi/N)(ux+vy)} \cdot 1$$

$$= F(u, v)$$

Discrete Fourier Transform

Clip slide

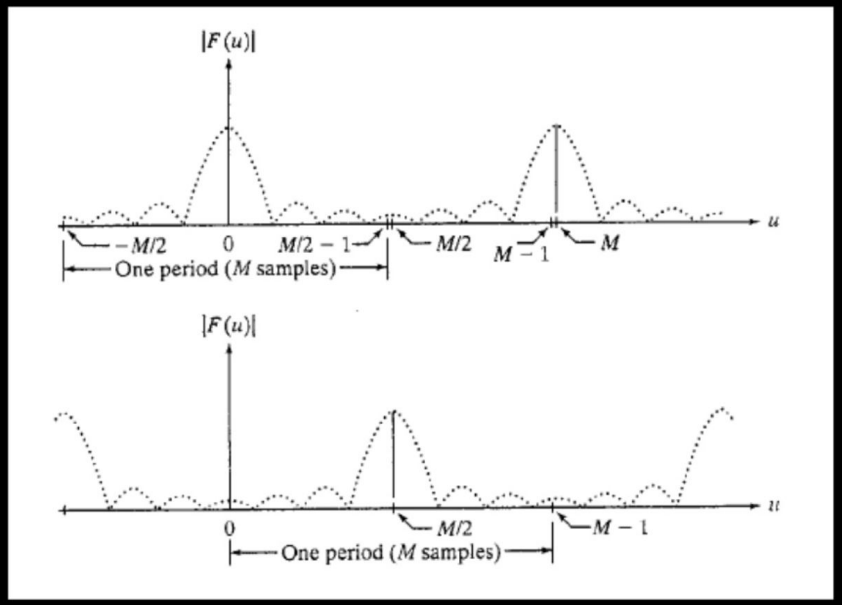
Conjugate:

f(x, y) is real

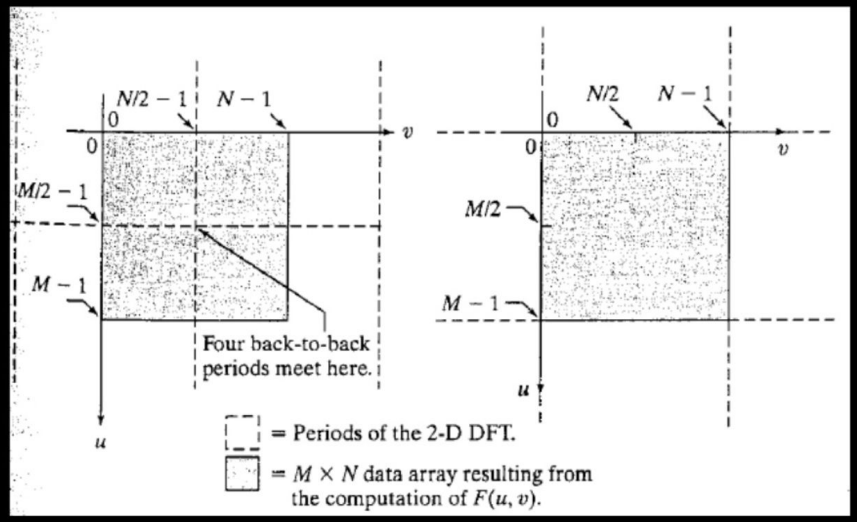
$F(u, v) = F^*(-u, -v)$

$|F(u, v)| = |F(-u, -v)|$

Discrete Fourier Transform



Discrete Fourier Transform



Spectrum obtained by multiplying f(x, y) by $(-1)^{x+y}$

Image transforms

Discrete Fourier Transform

4) Rotation:

$x = r \cos \theta$; $y = r \sin \theta$;

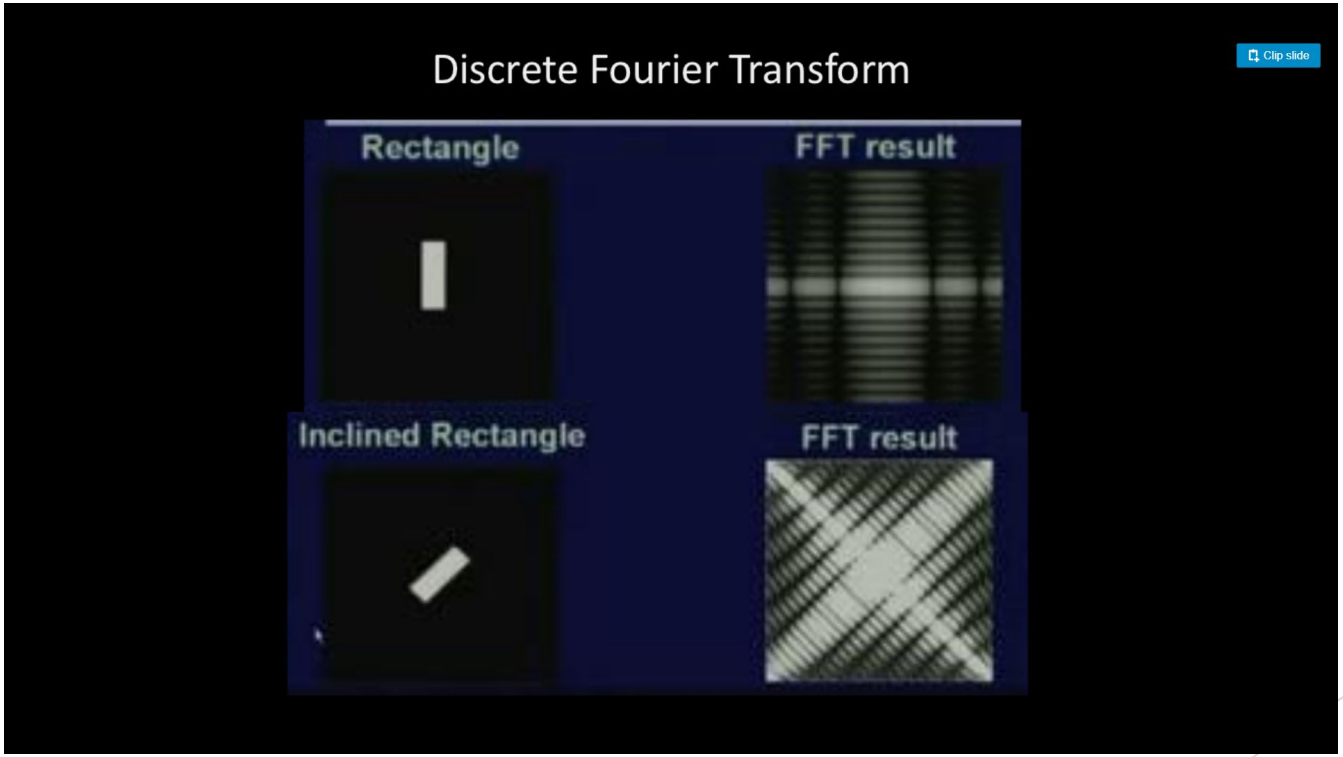
$u = \omega \cos \phi$; $y = \omega \sin \phi$;

$f(x, y) \Rightarrow f(r, \theta)$;

$F(u, v) \Rightarrow F(\omega, \phi)$;

$f(r, \theta + \theta_0) \Leftrightarrow F(\omega, \phi + \theta_0)$;

40 of 78


Discrete Fourier Transform
Clip slide
Rectangle
FFT result
Inclined Rectangle
FFT result

Discrete Fourier Transform

Clip slide

5) Distributivity & Scaling:

Distributivity:

$F\{f_1(x, y) + f_2(x, y)\} = F\{f_1(x, y)\} + F\{f_2(x, y)\}$

$F\{f_1(x, y) . f_2(x, y)\} \neq F\{f_1(x, y)\} . F\{f_2(x, y)\}$

True for IDFT also.

Scaling: If a & b are scalar quantities.

$a . f(x, y) \Leftrightarrow a . F(u, v)$

$f(ax, by) \Leftrightarrow (1/|ab|) F(u/a , v/b);$

Discrete Fourier Transform

Average:

$$\bar{f}(x, y) = (1/N^2) \sum_{x,y=0}^{N-1}\sum f(x, y)$$

$$F(0, 0) = (1/N) \sum_{x,y=0}^{N-1}\sum f(x, y)$$

$$\bar{f}(x, y) = (1/N) F(0, 0)$$

Discrete Fourier Transform

Clip slide

6) Convolution:

$f(x) \,.\, g(x) \Leftrightarrow F(u) * G(u)$

$f(x) * g(x) \Leftrightarrow F(u) \,.\, G(u)$

7) Correlation:

$f(x, y) \circ g(x, y) \Leftrightarrow F^*(u, v) \,.\, G(u, v)$

$f^*(x, y) \,.\, g(x, y) \Leftrightarrow F(u, v) \circ G(u, v)$

Discrete Fourier Transform

Clip slide

Few other properties of DFT:

8) It is symmetric.

9) It is a fast Transform.

10) Its computational capacity is given by $N.\log_2 N$.

11) It has very good compaction for the image.

Discrete Cosine Transform

In DCT the forward transformation channel is given by:

$$g(x, y, u, v) = \alpha(u).\alpha(v).\cos[(2x+1)u\pi/2N].\cos[(2y+1)v\pi/2N]$$
$$= f(x, y, u, v)$$

inverse and forward transformation channel are identical.

They are separable as well.

Here, $\alpha(u) = \sqrt{(1/N)} \quad u = 0$

$\sqrt{(2/N)} \quad u = 1, 2, \ldots..N-1;$

Similarly the values of $\alpha(v)$ can be found.

Discrete Cosine Transform

Clip slide

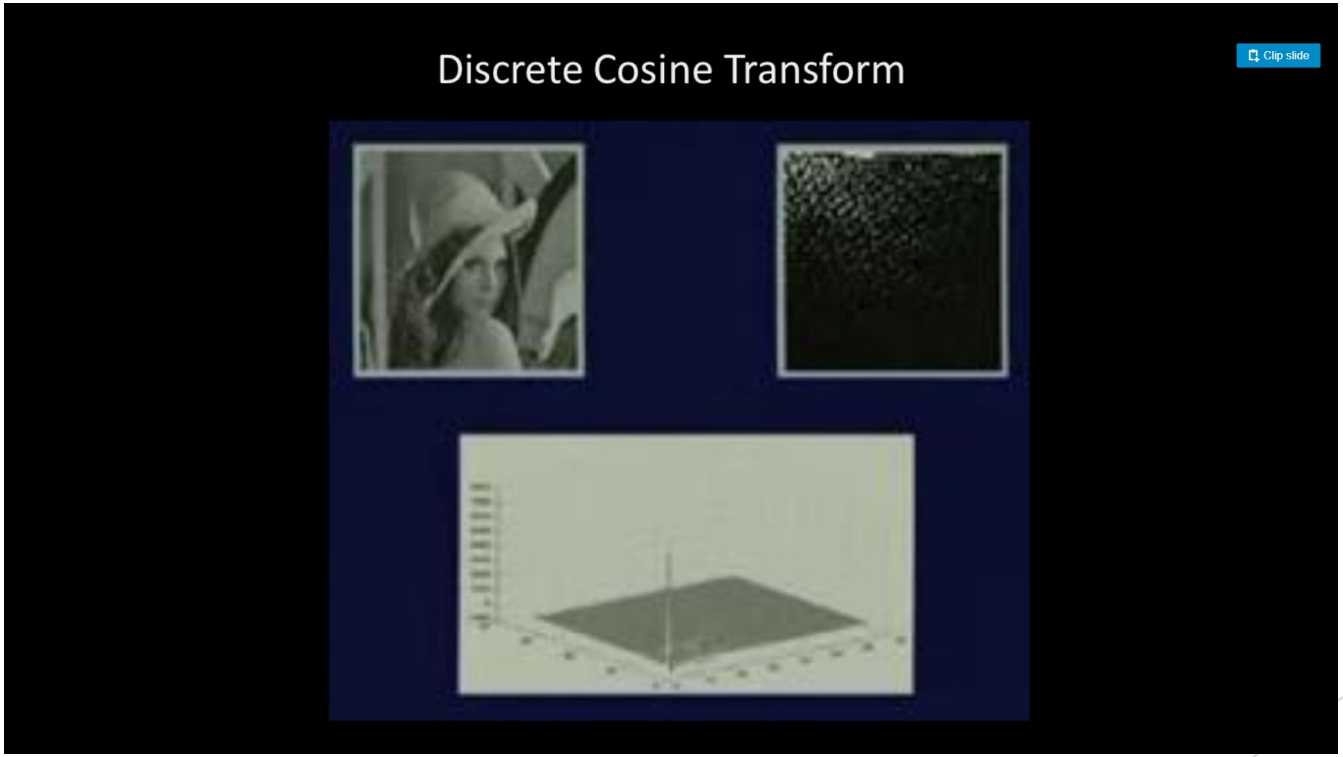
Forward DCT:

$$C(u, v) = \alpha(u).\alpha(v) \sum_{x, y = 0}^{N-1}\sum \{f(x, y) \cos[(2x+1)u\pi/2N]. \cos[(2y+1)v\pi/2N]\}$$

Reverse DCT:

$$f(x, y) = \sum_{u, v = 0}^{N-1}\sum \{\alpha(u).\alpha(v)\, C(u, v) \cos[(2x+1)u\pi/2N]. \cos[(2y+1)v\pi/2N]\}$$

In DCT, energy is concentrated in a small region.
It helps in image compression.


Discrete Cosine Transform
Clip slide

Discrete Cosine Transform

Clip slide

Properties of DCT:

(1) It is real orthogonal.

$C = C^* \Rightarrow C^{-1} = C^T$

(2) It is fast transform.

(3) It can be calculated in $N\log_2 N$ operations via N-point transform.

(4) It is good for energy compaction for highly correlated data.

(5) It can be used for designing transform code & wiener filter.

(6) It is near substitute for Hotelling & KL transform.

(7) It is used for JPEG compression.

Discrete Cosine Transform

The NxN cosine transform matrix C = {C(k, n)} also called the DCT is defined as

$$C(k, n) = 1/\sqrt{N}; \quad k = 0; \quad 0 \le n \le N-1$$

$$= \sqrt{(2/N)}.\cos((\pi(2n+1)k)/2N); \quad 1 \le k \le N-1; \quad 0 \le n \le N-1$$

Ex. 3) Find the 2D DCT matrix for N = 4.

Discrete Cosine Transform

Sol: C =

k\n	0	1	2	3
0	0.5	0.5	0.5	0.5
1	0.65	0.27	-0.27	-0.65
2	0.5	-0.5	-0.5	0.5
3	0.27	-0.65	0.65	-0.27

Ex. 4) Compute 2D DCT of the following image for N = 4

$$U = \begin{matrix} 5 & 3 & 0 & 2 \\ 1 & 7 & 8 & 3 \\ 4 & 2 & 2 & 2 \\ 8 & 5 & 2 & 1 \end{matrix} \qquad V = ?$$

Discrete Sine Transform

The N x N Discrete Sine Transform is given by matrix $\psi = \{\psi(k, n)\}$

$\psi(k, n) = \sqrt{(2/(N+1))} \sin(\pi\{(k+1)(n+1)/(N+1)\})$, for $0 \le k;\ n \le N - 1$

Properties:

(1) It is symmetrical, real & orthogonal.

$$\psi = \psi^T, \quad \psi = \psi^*, \quad \psi^T = \psi^{-1}.$$

(2) It is faster than DCT.

(3) It is calculated by $N \log_2 N$ via 2(N+1) point FFT.

(4) It has very good energy compression property for images.

(5) It is used for estimating performances in digital image processing problems.

Discrete Sine Transform

For N = 4 the Discrete Sine Transform matrix is given by:

$\Psi =$

k \ n	0	1	2	3
0	0.37	0.6	0.6	0.37
1	0.6	0.37	-0.37	-0.6
2	0.6	-0.37	-0.37	0.6
3	0.37	-0.6	0.6	-0.37

PCA v/s SVD

1. SVD is needed in abstract mathematics, matrix decomposition and quantum physics .
2. PCA is useful in statistics, specifically in analyzing exploratory data.
3. Both SVD and PCA are helpful in their respective branches of mathematics.

Image Compression using SVD

- When an image is compressed using SVD, it is not compressed ,but the data take a form of the first singular values having greater information.
- So, few singular values can be used to represent image with little differences from the original image.

Compression Ratio

$$=(m \times n)/ k(m+n+1)$$

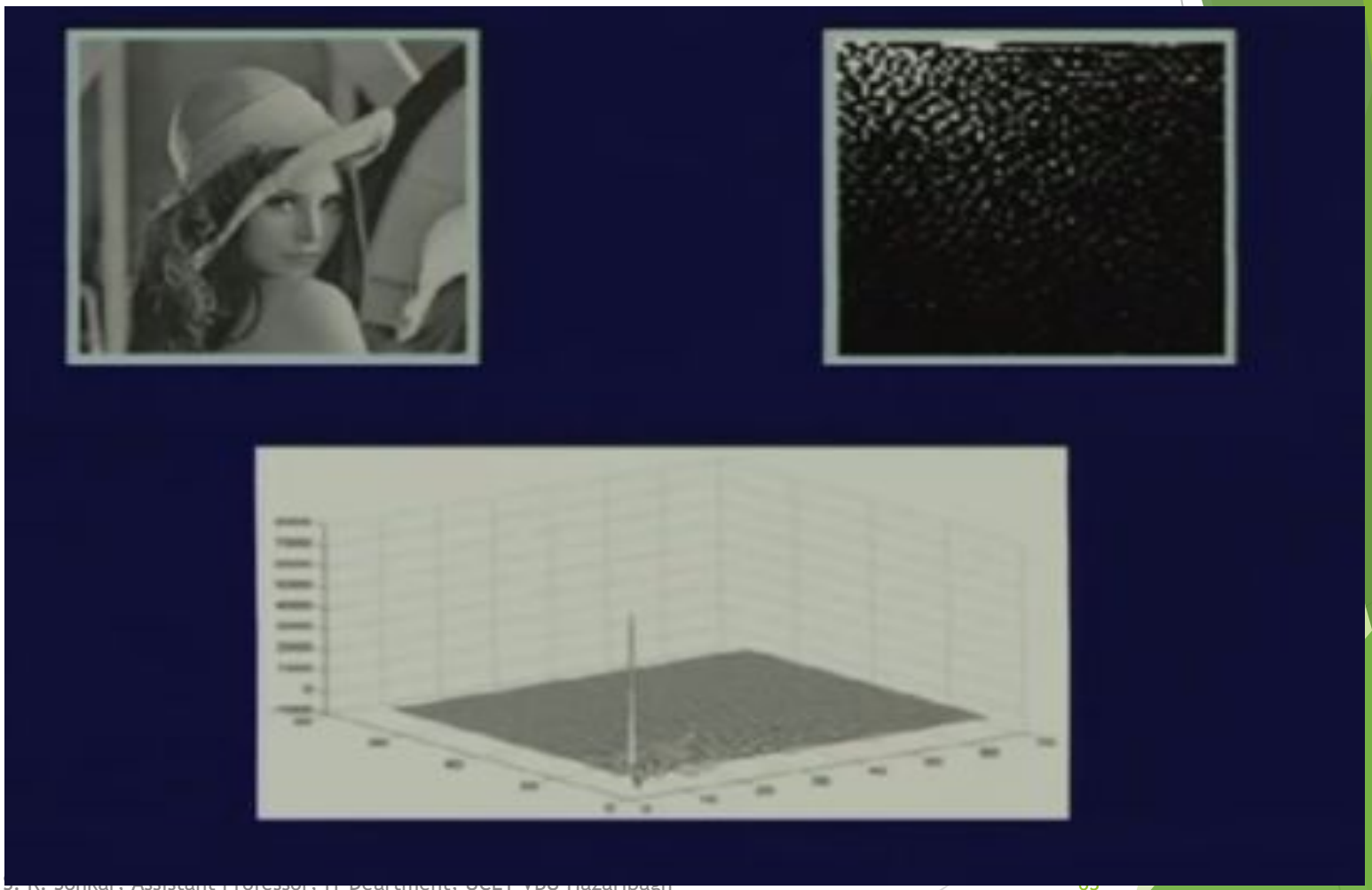
Discrete Cosine Transform

- Member of a family of real valued discrete sinusoidal unitary transform.
- Consists of a set of basis vectors that are sample cosine functions.
  DCT is a technique for converting a signal into elementary frequency components and it is widely used in image compression.

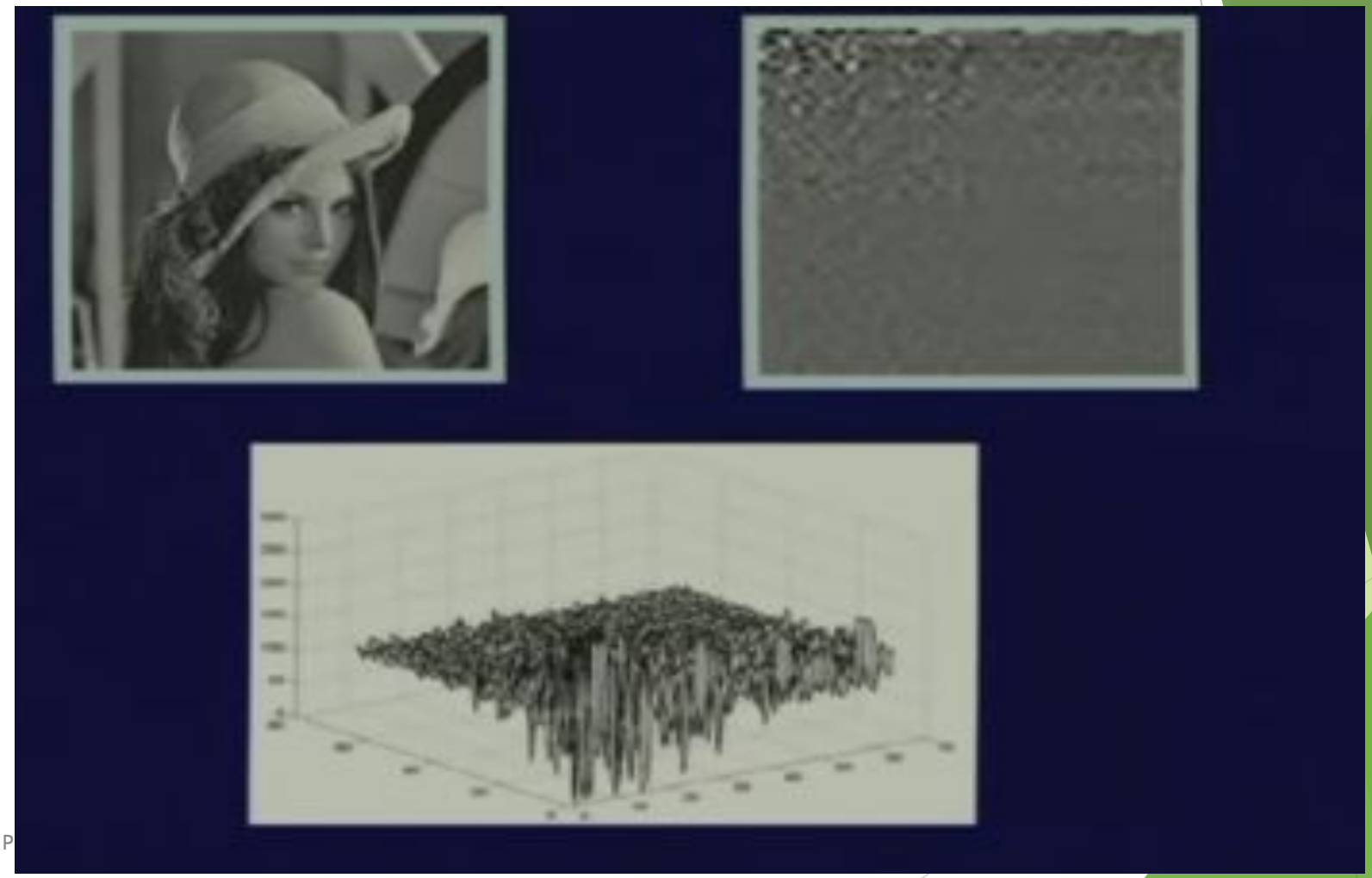
Properties of DCT

1. Unitary i.e $AA^T=I$
2. Excellent Energy compaction for highly correlated data.
3. Separable property i.e 2D DCT can be computed in 2-steps.

DCT Result



Walsh Transform Results



Hadamard Matrix

u →

x ↓

	0	1	2	3	4	5	6	7
0	+	+	+	+	+	+	+	+
1	+	-	+	-	+	-	+	-
2	+	+	-	-	+	+	-	-
3	+	-	-	+	+	-	-	+
4	+	+	+	+	-	-	-	-
5	+	-	+	-	-	+	-	+
6	+	+	-	-	-	-	+	+
7	+	-	-	+	-	+	+	-

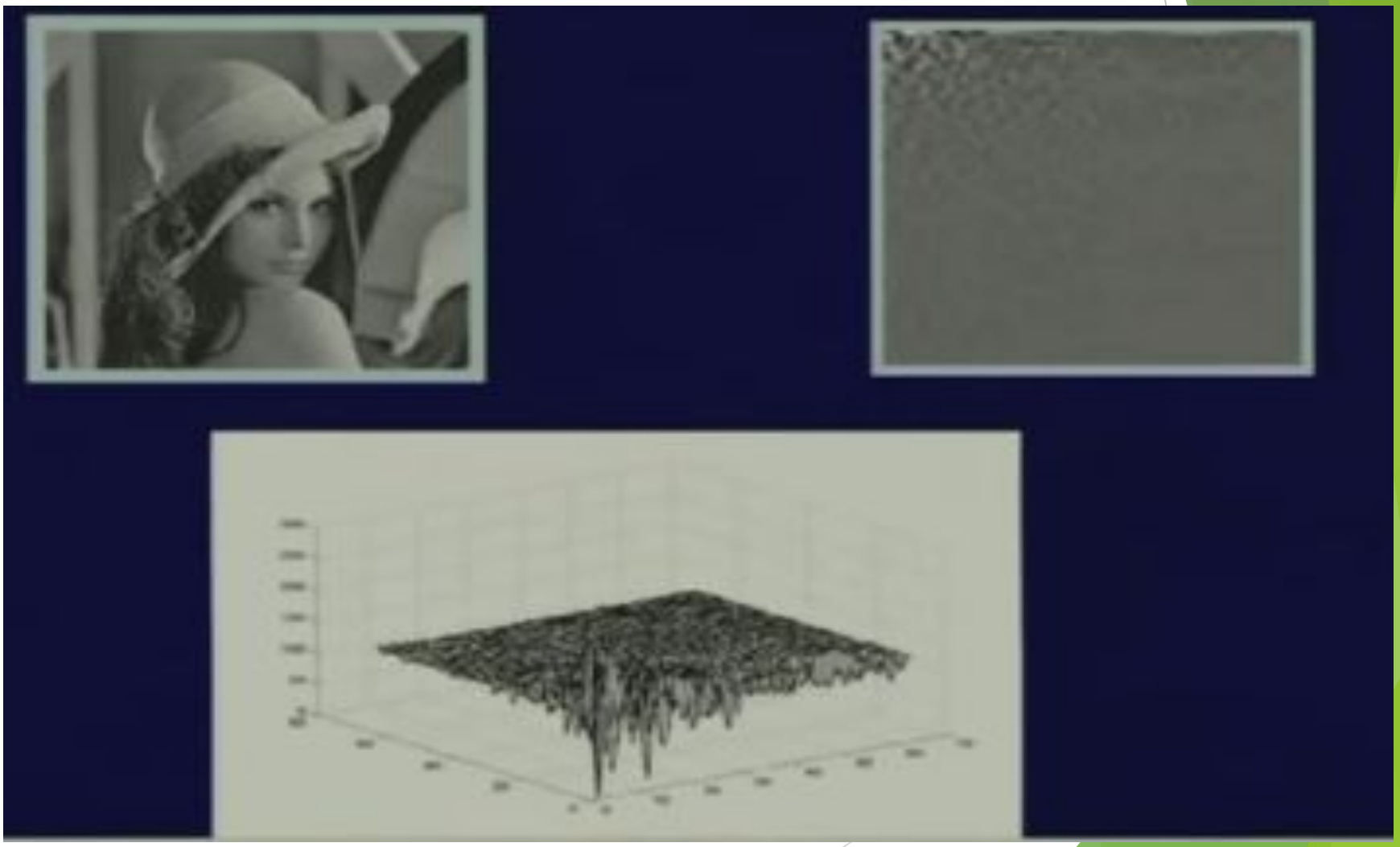
Modified Hadamard Matrix(N=8)

u →

x ↓

	0	1	2	3	4	5	6	7
0	+	+	+	+	+	+	+	+
1	+	+	+	+	-	-	-	-
2	+	+	-	-	-	-	+	+
3	+	+	-	-	+	+	-	-
4	+	-	-	+	+	-	-	+
5	+	-	-	+	-	+	+	-
6	+	-	+	-	-	+	-	+
7	+	-	+	-	+	-	+	-

Ordered Hadamard Result



Hadamard / Walsh Transform

- Basis function of Walsh Tx are same as that of Hadamard , the only difference is in its ordering.
- Energy compaction is better in the case of Walsh Transform.
- Best energy compaction is in DCT .