Lecture 5:

Recall:

Haar transformation

Definition: (Haar functions) The Haar functions are defined recursively as follows

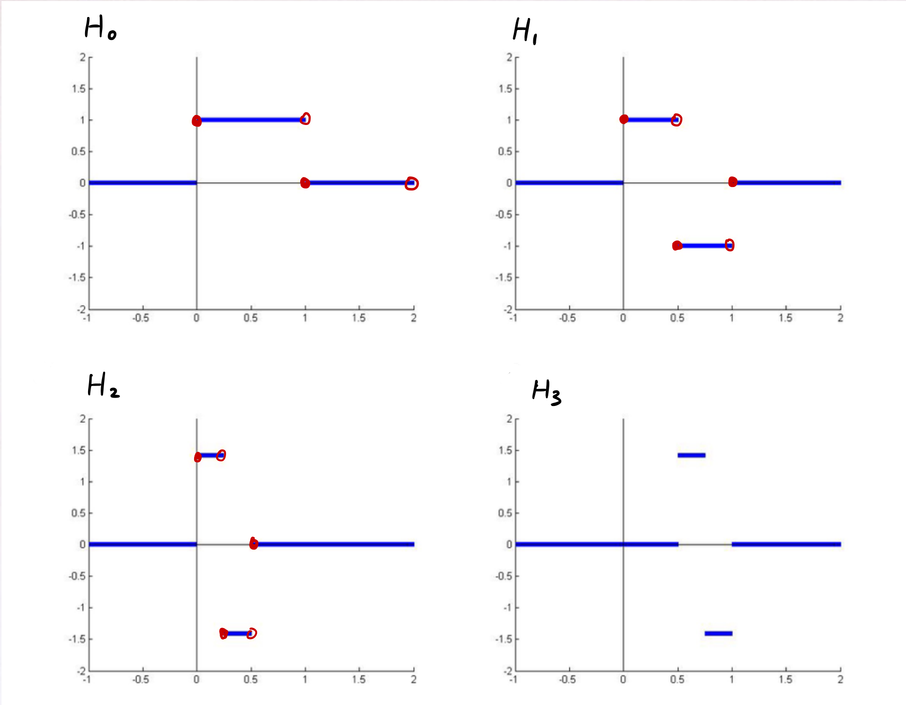
$$H_0(t) \equiv \begin{cases} 1 & \text{if } 0 \le t < 1 \\ 0 & \text{elsewhere.} \end{cases}$$

$$H_1(t) \equiv \begin{cases} 1 & \text{if } 0 \le t < 1/2 \\ -1 & \text{if } 1/2 \le t < 1 \\ 0 & \text{elsewhere} \end{cases}$$

$$H_{2^p+n} \equiv \begin{cases} \sqrt{2}^p & \text{if } \frac{n}{2^p} \le t < \frac{n+0.5}{2^p} \\ -\sqrt{2}^p & \text{if } \frac{n+0.5}{2^p} \le t < \frac{n+1}{2^p} \\ 0 & \text{elsewhere} \end{cases}$$

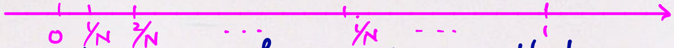
where $p = 1, 2, \dots ; \; n = 0, 1, 2, \dots, 2^p - 1$

Examples of Haar functions:



Definition (Discrete Haar Transform)

The Haar Transform of a $N \times N$ image is done by dividing $[0,1]$ into partitions.



Let $H(k,i) \equiv H_k\left(\frac{i}{N}\right)$ where $k, i = 0, 1, 2, \ldots, N-1$.

We obtain the Haar Transform matrix: $\tilde{H} \equiv \frac{1}{\sqrt{N}} H$ where $H \equiv \left(H(k,i)\right)_{0 \le k, i \le N-1}$

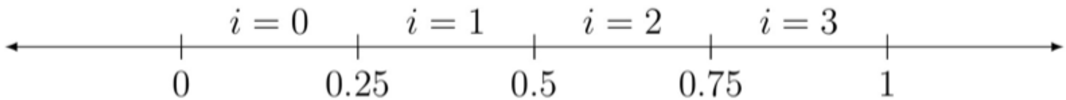
The Haar Transform of $f \in M_{n \times n}$ is defined as:

$$g = \tilde{H} f \tilde{H}^T.$$

$$\tilde{H}^T \tilde{H} = \tilde{H} \tilde{H}^T = I$$

Example Compute the Haar Transform matrix for a 4×4 image.

Solution: Divide $[0,1]$ into 4 portions:



Elementary images under Haar transform:

Using Haar transform, f can be written as:

$$f = \tilde{H}^T g \tilde{H}$$

g ← transformed image

Let $\tilde{H} = \begin{pmatrix} - & \vec{h}_1^T & - \\ - & \vec{h}_2^T & - \\ & \vdots & \\ - & \vec{h}_N^T & - \end{pmatrix}$. Then: $f = \sum_{i=1}^{N} \sum_{j=1}^{N} g_{ij} \vec{h}_i \vec{h}_j^T$

$\vec{h}_i \vec{h}_j^T = I_{ij}^H$

I_{ij}^T = elementary images under Haar Transform.

Recall:

Elementary images under Haar transform:

Using Haar transform, f can be written as:

$$f = \tilde{H}^T \underset{\uparrow}{g} \tilde{H}$$

transformed image

Let $\tilde{H} = \begin{pmatrix} - & \vec{h}_1^{\,T} & - \\ - & \vec{h}_2^{\,T} & - \\ & \vdots & \\ - & \vec{h}_N^{\,T} & - \end{pmatrix}$. Then: $f = \sum_{i=1}^{N} \sum_{j=1}^{N} g_{ij} \underbrace{\vec{h}_i \vec{h}_j^{\,T}}_{= I_{ij}^H}$

I_{ij}^T = elementary images under Haar Transform.

Definition: (Walsh function) The Walsh functions are defined recursively by:

$$W_{2j+q}(t) \equiv (-1)^{\lfloor \frac{j}{2} \rfloor + q} \left\{ W_j(2t) + (-1)^{j+q} W_j(2t-1) \right\}$$

where $\lfloor \frac{j}{2} \rfloor$ = biggest integer smaller than or equal to $\frac{j}{2}$.

$q = 0$ or 1, $j = 0, 1, 2, \dots$ and

$$W_0(t) \equiv \begin{cases} 1 & 0 \le t < 1 \\ 0 & \text{elsewhere} \end{cases}$$

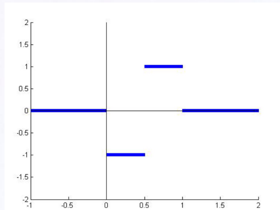
Example: Compute $W_1(t)$.

Put $j = 0$, $q = 1$. Then:

$$W_1(t) = (-1)^{\lfloor 0 \rfloor + 1} \left\{ W_0(2t) + (-1)^1 W_0(2t-1) \right\} = (-1) \left\{ W_0(2t) + (-1)^1 W_0(2t-1) \right\}$$

For $0 \le t < \frac{1}{2}$, $W_0(2t) = 1$, $W_0(2t-1) = 0 \Rightarrow W_1(t) = -1$.

For $\frac{1}{2} \le t < 1$, $W_0(2t) = 0$, $W_0(2t-1) = 1 \Rightarrow W_1(t) = 1$.



Definition: (Discrete Walsh transform)

The Walsh Transform of a $N \times N$ image is defined as follows.

Define $W(k, i) \equiv W_k\left(\frac{i}{N}\right)$ where $k, i = 0, 1, 2, \ldots, N-1$.

The Walsh transform matrix is: $\tilde{W} \equiv \frac{1}{\sqrt{N}} W$ where $W \equiv \left(W(k,i)\right)_{0 \le k, i \le N-1}$

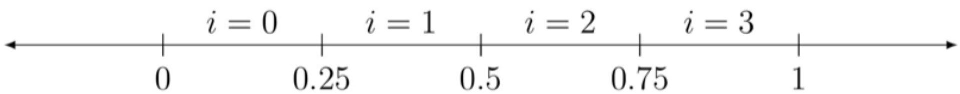
The Walsh transform of $f \in M_{n \times n}$ is defined as:

$$g = \tilde{W} f \tilde{W}^T$$

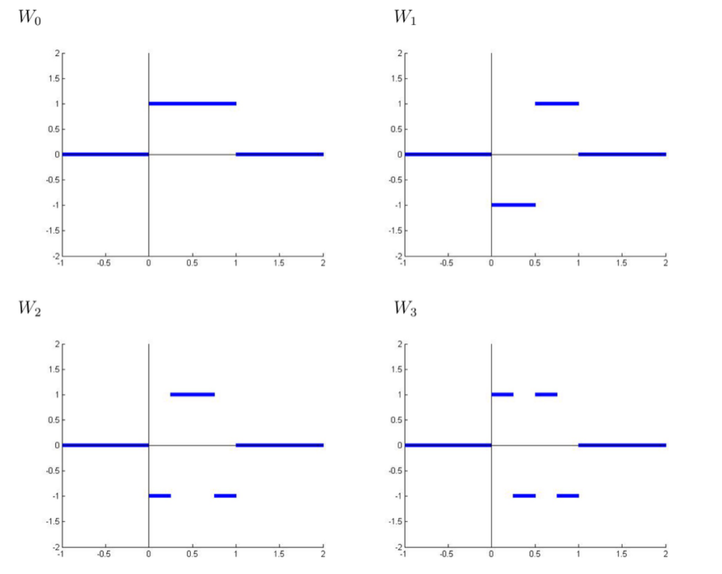
$$\tilde{W}^T \tilde{W} = I = \tilde{W} \tilde{W}^T$$

Example Compute the Walsh Transform matrix for a 4×4 image.

Solution: Again, divide $[0, 1]$ into 4 portions:



We can check that:



So,

$$W = \begin{pmatrix} 1 & 1 & 1 & 1 \\ -1 & -1 & 1 & 1 \\ -1 & 1 & 1 & -1 \\ 1 & -1 & 1 & -1 \end{pmatrix} \quad \text{and} \quad \tilde{W} = \frac{1}{\sqrt{4}} W = \frac{1}{2} W$$

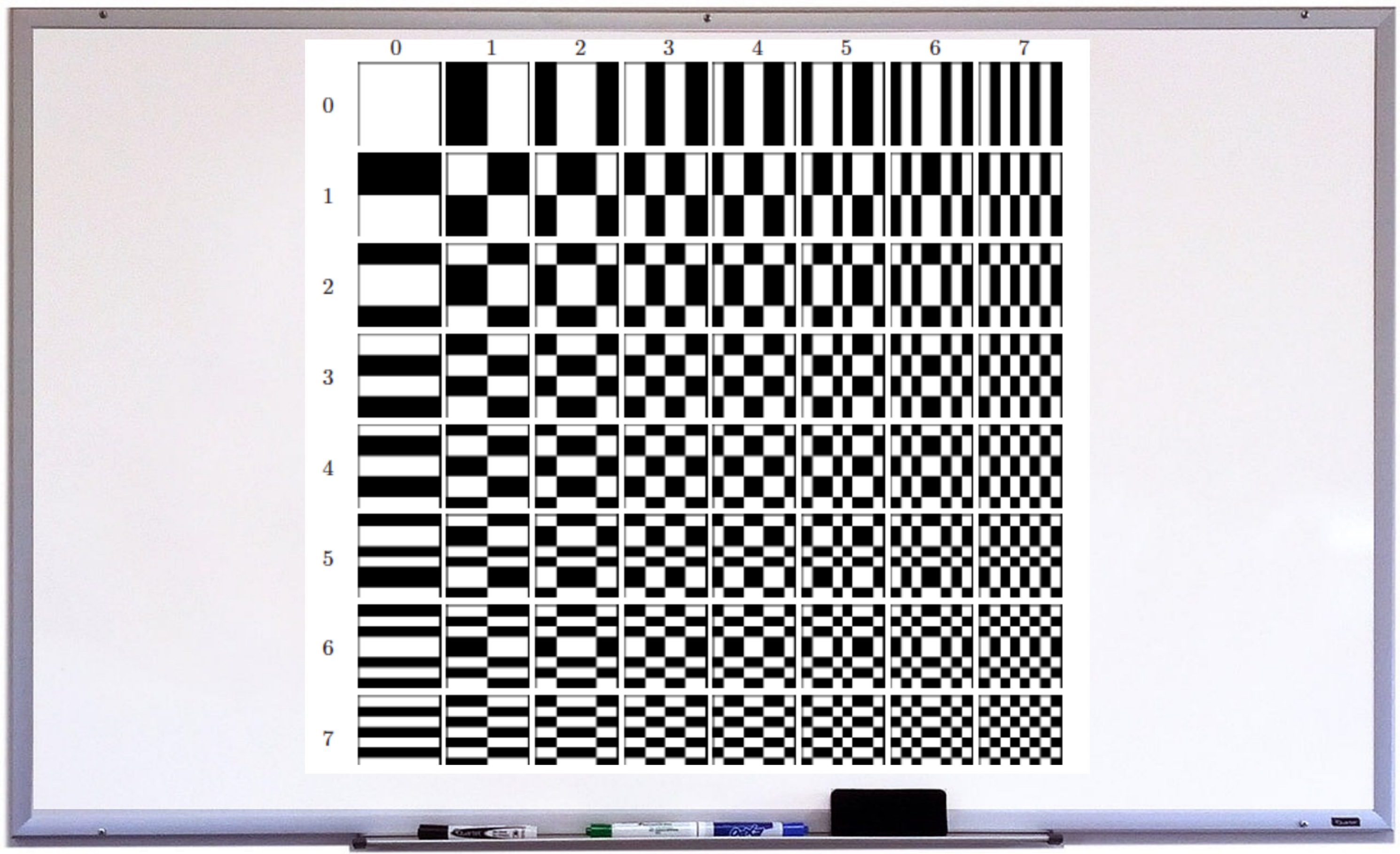
$(\tilde{W}^T \tilde{W} = I)$

Elementary images under Walsh transform:

Under Walsh Transform, $f = \tilde{W}^T g \tilde{W}$.

Then: $f = \sum_{i=1}^{N} \sum_{j=1}^{N} g_{ij} \underbrace{\vec{w}_i \vec{w}_j^T}_{I_{ij}^W}$ where $\tilde{W} = \begin{pmatrix} - \vec{w}_1^T - \\ - \vec{w}_2^T - \\ \vdots \\ - \vec{w}_N^T - \end{pmatrix}$

I_{ij}^W = elementary images under Walsh transform.


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

Walsh functions and sine function

Definition: (Rademacher function)

A Rademacher function of order n $(n \neq 0)$ is defined as:

$$R_n(t) \equiv \text{sign}[\sin(2^n \pi t)] \text{ for } 0 \leq t \leq 1.$$

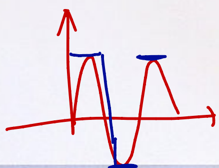
where $\text{sign}(x) = 1$ if $x > 0$, $\text{sign}(x) = -1$ if $x < 0$ and $\text{sign}(x) = 0$ if $x = 0$.

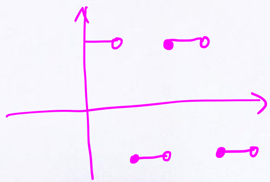
For $n = 0$, $R_0(t) \equiv 1$ for $0 \leq x \leq 1$.

Let $N = b_{m+1} 2^m + b_m 2^{m-1} + \dots + b_1 2^0$. Then, the R-Walsh function $\tilde{W}_N$ is given by:

$$\tilde{W}_N = \prod_{i=1,\, b_i \neq 0}^{m+1} R_i(t)$$

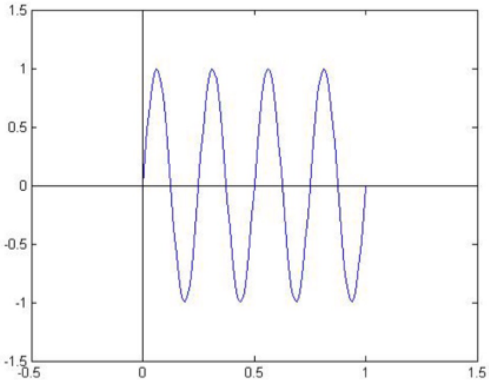
(where the values at the jumps are defined such that the function is continuous from the right)



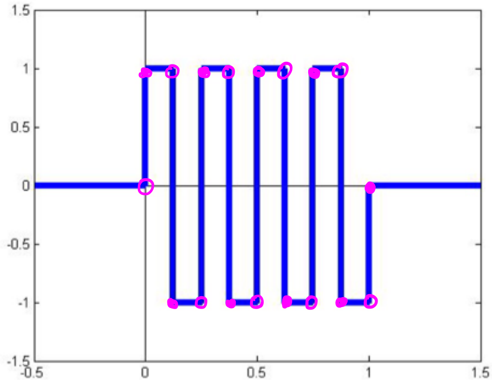


Example : Compute R-Walsh function $\tilde{W}_4$ using Rademacher function.

Consider $\sin(8\pi t)$:



Therefore, $R_3(t) =$



As $4 = \underbrace{1}_{b_3} \cdot 2^2 + \underbrace{0}_{b_2} \cdot 2^1 + \underbrace{0}_{b_1} \cdot 2^0$, we have

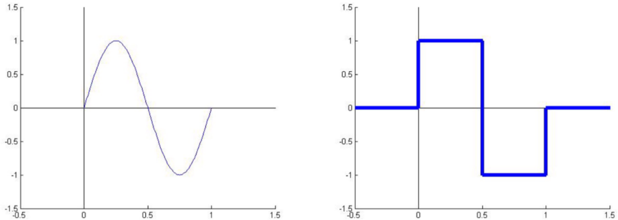
$$\tilde{W}_4 = \prod_{i=1, b_i \neq 0}^{3} R_i(t) = R_3(t)$$

$$(W_{2j+q}(t) \equiv (-1)^{\lfloor j/2 \rfloor + q}\{W_j(2t) + (-1)^{j+q} W_j(2t-1)\})$$

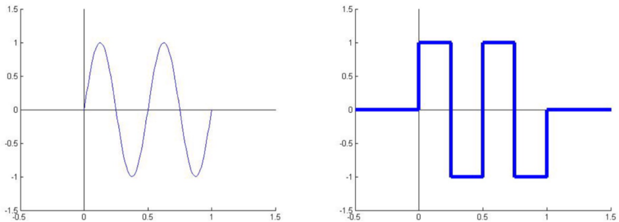
For $W_3(t)$: As $3 = \underbrace{1}_{b_2} \cdot 2^1 + \underbrace{1}_{b_1} \cdot 2^0$, we have

$$\tilde{W}_3(t) = \prod_{i=1, b_i \neq 0}^{2} R_i(t) = R_1(t) R_2(t)$$

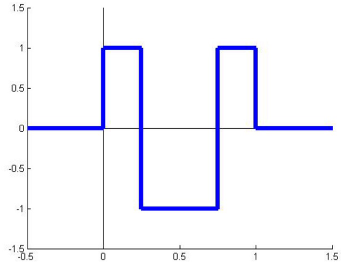
$R_1(t)$:



$R_2(t)$:



Therefore, $\tilde{W}_3(t)$:



Discrete Fourier Transform:

Definition: The 1D discrete Fourier Transform (DFT) of a function $f(k)$, defined at discrete points $k = 0, 1, 2, \ldots, N-1$ is defined as:

$$\hat{f}(m) = \frac{1}{N} \sum_{k=0}^{N-1} f(k)\, e^{-j\, 2\pi m k}$$

(where $j = \sqrt{-1}$, $e^{j\theta} = \cos\theta + j \sin\theta$)

The 2D DFT of a $M \times N$ image $g = (g(k,l))_{k,l}$, where $0 \le k \le M-1$, $0 \le l \le N-1$ is defined as:

$$\hat{g}(m,n) = \frac{1}{MN} \sum_{k=0}^{M-1} \sum_{l=0}^{N-1} g(k,l)\, e^{-j 2\pi \left(\frac{km}{M} + \frac{ln}{N}\right)}$$

Remark: The inverse of DFT is given by:

$$g(p,q) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \hat{g}(m,n)\, e^{j 2\pi \left(\frac{pm}{M} + \frac{qn}{N}\right)}$$

DFT of g

(no $\frac{1}{Mn}$!)

(no -ve sign)

Proof of Inverse DFT:

$$\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} e^{j2\pi\left(\frac{pm}{M}+\frac{qn}{N}\right)}\,\hat{g}(m,n) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} e^{j2\pi\left(\frac{pm}{M}+\frac{qn}{N}\right)} \frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1} g(k,l)\, e^{-j2\pi\left(\frac{km}{M}+\frac{ln}{N}\right)}$$

$$= \frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1}\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} g(k,l)\, e^{j2\pi\left(\frac{(p-k)m}{M}+\frac{(q-l)n}{N}\right)}$$

$$= \underbrace{\frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1} g(k,l) \sum_{m=0}^{M-1} e^{j2\pi\left(\frac{(p-k)m}{M}\right)} \sum_{n=0}^{N-1} e^{j2\pi\left(\frac{(q-l)n}{N}\right)}}_{(*)}$$

Note that: $$\sum_{m=0}^{M-1} e^{j2\pi\left(\frac{mt}{M}\right)} = \underbrace{\frac{\left[e^{j2\pi\left(\frac{t}{M}\right)}\right]^M - 1}{e^{j2\pi\left(\frac{t}{M}\right)} - 1}}_{\text{if } t\neq 0} = M\,\delta(t) := \begin{cases} M & t=0 \\ 0 & t\neq 0 \end{cases}$$

$\therefore$ (*) becomes: $$\frac{1}{MN}\sum_{k=0}^{M-1}\sum_{l=0}^{N-1} g(k,l)\, M\,\delta(p-k)\, N\,\delta(q-l) = g(p,q).$$

Image decomposition under DFT:

Consider a $N \times N$ image g, the DFT of g:

$$\hat{g}(m,n) = \frac{1}{N^2} \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} g(k,l)\, e^{-j2\pi\left(\frac{km+ln}{N}\right)}$$

Define $U_{kl} = \frac{1}{N} e^{-j\frac{2\pi kl}{N}}$ where $0 \le k, l \le N-1$ and $U = (U_{kl})_{0 \le k,l \le N-1} \in M_{N\times N}$

U is clearly symmetric and also:

$$\hat{g} = U g U \quad \text{(DFT in matrix form)}$$

Note that: $\frac{1}{N^2} \sum_{\alpha=0}^{N-1} e^{-j\left(\frac{2\pi x_1 \alpha}{N}\right)} e^{+j\left(\frac{2\pi x_2 \alpha}{N}\right)} = \frac{1}{N^2} \sum_{\alpha=0}^{N-1} e^{-j\frac{2\pi(x_2 - x_1)\alpha}{N}}$

$$= \frac{1}{N^2} N \,\delta(x_2 - x_1)$$

$$= \frac{1}{N} \delta(x_2 - x_1)$$

Let $U = \begin{pmatrix} | & | & & | \\ \vec{u}_1 & \vec{u}_2 & \cdots & \vec{u}_N \\ | & | & & | \end{pmatrix}$. Then: $\langle \vec{u}_i, \vec{u}_j \rangle = \vec{u}_i^{\,T} \overline{\vec{u}_j} = \begin{cases} \frac{1}{N} & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$

$\therefore \{\vec{u}_i\}_{i=1}^{N}$ is orthogonal but NOT orthonormal!

$$\hat{g}(m,n) = \frac{1}{N^2}\sum_{k=0}^{N-1}\sum_{l=0}^{N-1} g(k,l)\, e^{-j2\pi\left(\frac{km+ln}{N}\right)}$$

$$\sum_{k=0}^{N-1} \underbrace{\frac{e^{-j2\pi\frac{km}{N}}}{N}}_{U_{mk}} \underbrace{\sum_{l=0}^{N-1} g(k,l) \underbrace{\left(\frac{e^{-j\frac{2\pi ln}{N}}}{N}\right)}_{U_{ln}}}_{gU(k,n)}$$

$$= U(gU)(m,n)$$

$$\therefore \boxed{\hat{g} = UgU}$$

$\therefore \quad \mathcal{U}\mathcal{U}^* = \frac{1}{N} I = \mathcal{U}^*\mathcal{U}$

$\therefore \quad g = (N\mathcal{U})^* \hat{g} (N\mathcal{U})^*$

$\therefore \quad g = \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} \hat{g}_{kl} \vec{w}_k \vec{w}_l^T$ ← Elementary image of DFT

where $\vec{w}_k = k^{th}$ col of $(N\mathcal{U})^*$

$\hat{g} = \mathcal{U} g \mathcal{U}$

$\Rightarrow \quad \mathcal{U}^* \hat{g} \mathcal{U}^* = (\mathcal{U}^*\mathcal{U}) g (\mathcal{U}\mathcal{U}^*)$

$= \left(\frac{1}{N}\right) g \left(\frac{1}{N}\right)$

$\therefore \quad (N\mathcal{U})^* \hat{g} (N\mathcal{U})^* = g \quad //$

Example Find the DFT of the following 4×4 image

$$g = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Solution

The matrix U is given by:

$$U = \frac{1}{4} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -j & -1 & j \\ 1 & -1 & 1 & -1 \\ 1 & j & -1 & -j \end{pmatrix}$$

$$U = \left(U_{kl} \right)_{k,l}$$

$$= \frac{1}{4} \left(e^{-j2\pi\left(\frac{kl}{4}\right)} \right)$$

$$\therefore \text{DFT of } g = \hat{g} = UgU = \begin{pmatrix} \frac{1}{4} & -\frac{1}{4} & \frac{1}{4} & -\frac{1}{4} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

How to compute DFT fast?

Goal: Convert image I to $\underbrace{\hat{I}}_{\text{DFT}}$ ⟶ Manipulate / adjust $\hat{I}$ (Fourier coefficients)
(Fast ?)

to get a new $\hat{I}^{new}$
↓
Convert $\hat{I}^{new}$ into the spatial domain
(Fast ?)

Fast Fourier Transform

Recall: DFT is separable ⇒ 2D DFT = Two 1D DFT!

$$\hat{I}(m,n) = \underbrace{\frac{1}{N}\sum_{k=0}^{N-1}\underbrace{\left(\frac{1}{N}\sum_{l=0}^{N-1} I(k,l)\, e^{-j2\pi\left(\frac{ln}{N}\right)}\right)}_{\text{1D DFT}} e^{-j2\pi\left(\frac{km}{N}\right)}}_{\text{1D DFT}}$$

Suffices to consider how to compute 1D DFT fast!!

1D DFT is: $\hat{f}(u) = \frac{1}{N}\sum_{x=0}^{N-1} f(x)\underbrace{e^{-j2\pi\left(\frac{ux}{N}\right)}}_{\omega_N^{ux}}$ where $\omega_N = e^{-j\frac{2\pi}{N}}$

Assume $N = 2^n = 2M$ $(\therefore M = 2^{n-1})$.

Then: $\hat{f}(u) = \frac{1}{2M}\sum_{x=0}^{2M-1} f(x)\,\omega_{2M}^{ux}$ $\left(\hat{f} = F_{2M}\vec{f}\right.$, where $F_{2M} = \left(\omega_N^{kl}\right)_{0\le k,l\le N-1}\Big)$

Separate the summation into odd and even parts:

$$\hat{f}(u) = \frac{1}{2}\left\{\frac{1}{M}\sum_{y=0}^{M-1}\underbrace{f(2y)}_{=f_{even}(y)}\,\underbrace{\omega_{2M}^{u(2y)}}_{=\omega_N^{uy}} + \frac{1}{M}\sum_{y=0}^{M-1}\underbrace{f(2y+1)}_{=f_{odd}(y)}\,\underbrace{\omega_{2M}^{u(2y+1)}}_{\omega_{2M}^{u(2y)}\,\omega_{2M}^{u}}\right\}$$

$$\omega_{2M}^{u(2y)} = \omega_M^{uy}$$

Let $f_{even} = (f(0), f(2), \ldots, f(2M-2))^T$ — even part of f

$f_{odd} = (f(1), f(3), \ldots, f(2M-1))^T$ — odd part of f

Then: $\hat{f}(u) = \frac{1}{2}\left\{\hat{f}_{even}(u) + \hat{f}_{odd}(u)\,\omega_{2M}^{u}\right\}$ for $u = 0, 1, 2, \ldots, M-1$

DFT on f_{even} of size $\frac{N}{2}$

DFT on f_{odd} of size $\frac{N}{2}$.

Remark: DFT on signal of size N is reduced to two DFT on signal of size $\frac{N}{2}$
If $\frac{N}{2}$ is even, we can repeat the process so that we just need to compute DFTs on signal of size $\frac{N}{4}$ etc...