

## Cooley-Tukey FFT Algorithms

- Consider a length- $N$  sequence  $x[n]$  with an  $N$ -point DFT  $X[k]$  where  $N = N_1 N_2$
- Represent the indices  $n$  and  $k$  as

$$n = N_2 n_1 + n_2, \quad \begin{cases} 0 \leq n_1 \leq N_1 - 1 \\ 0 \leq n_2 \leq N_2 - 1 \end{cases}$$

$$k = k_1 + N_1 k_2, \quad \begin{cases} 0 \leq k_1 \leq N_1 - 1 \\ 0 \leq k_2 \leq N_2 - 1 \end{cases}$$

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## Cooley-Tukey FFT Algorithms

- Using these index mappings we can write

$$\begin{aligned} X[k] &= \sum_{n=0}^{N-1} x[n] W_N^{nk} \\ \text{as} \\ X[k] &= X[k_1 + N_1 k_2] \\ &= \sum_{n_2=0}^{N_2-1} \sum_{n_1=0}^{N_1-1} x[N_2 n_1 + n_2] W_N^{(N_2 n_1 + n_2)(k_1 + N_1 k_2)} \\ &= \sum_{n_2=0}^{N_2-1} \sum_{n_1=0}^{N_1-1} x[N_2 n_1 + n_2] W_N^{N_2 n_1 k_1} W_N^{n_2 k_1} W_N^{N_1 n_2 k_2} W_N^{N_1 N_2 n_1 k_2} \end{aligned}$$

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## Cooley-Tukey FFT Algorithms

- Since  $W_N^{N_2 n_1 k_1} = W_{N_1}^{n_1 k_1}$ ,  $W_N^{N_1 n_2 k_2} = W_{N_2}^{n_2 k_2}$ , and  $W_N^{N_1 N_2 n_1 k_2} = 1$ , we have

$$\begin{aligned} &X[k_1 + N_1 k_2] \\ &= \sum_{n_2=0}^{N_2-1} \left[ \sum_{n_1=0}^{N_1-1} x[N_2 n_1 + n_2] W_{N_1}^{n_1 k_1} \right] W_{N_2}^{n_2 k_1} W_{N_2}^{n_2 k_2} \end{aligned}$$

where  $0 \leq k_1 \leq N_1 - 1$  and  $0 \leq k_2 \leq N_2 - 1$

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## Cooley-Tukey FFT Algorithms

- The effect of the index mapping is to map the 1-D sequence  $x[n]$  into a 2-D sequence that can be represented as a 2-D array with  $n_1$  specifying the rows and  $n_2$  specifying the columns of the array
- Inner parentheses of the last equation is seen to be the set of  $N_1$ -point DFTs of the  $N_2$ -columns:

$$G[k_1, n_2] = \sum_{n_1=0}^{N_1-1} x[N_2 n_1 + n_2] W_{N_1}^{n_1 k_1}, \quad \begin{cases} 0 \leq k_1 \leq N_1 - 1 \\ 0 \leq n_2 \leq N_2 - 1 \end{cases}$$

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## Cooley-Tukey FFT Algorithms

- Note:** The column DFTs can be done in place
- Next, these row DFTs are multiplied in place by the twiddle factors  $W_{N_2}^{n_2 k_1}$  yielding

$$\tilde{G}[k_1, n_2] = W_{N_2}^{n_2 k_1} G[k_1, n_2], \quad \begin{cases} 0 \leq k_1 \leq N_1 - 1 \\ 0 \leq n_2 \leq N_2 - 1 \end{cases}$$

- Finally, the outer sum is the set of  $N_2$ -point DFTs of the columns of the array:

$$X[k_1 + N_1 k_2] = \sum_{n_2=0}^{N_2-1} \tilde{G}[k_1, n_2] W_{N_2}^{n_2 k_2}, \quad \begin{cases} 0 \leq k_1 \leq N_1 - 1 \\ 0 \leq k_2 \leq N_2 - 1 \end{cases}$$

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## Cooley-Tukey FFT Algorithms

- The row DFTs,  $X[k_1 + N_1 k_2]$ , can again be computed in place
- The input  $x[n]$  is entered into an array according to the index map:

$$n = N_2 n_1 + n_2, \quad \begin{cases} 0 \leq n_1 \leq N_1 - 1 \\ 0 \leq n_2 \leq N_2 - 1 \end{cases}$$

- Likewise, the output DFT samples  $X[k]$  need to be extracted from the array according to the index map:

$$k = k_1 + N_1 k_2, \quad \begin{cases} 0 \leq k_1 \leq N_1 - 1 \\ 0 \leq k_2 \leq N_2 - 1 \end{cases}$$

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## Cooley-Tukey FFT Algorithms

- **Example** - Let  $N = 8$ . Choose  $N_1 = 2$  and  $N_2 = 4$

- Then

$$X[k_1 + 2k_2] = \sum_{n_2=0}^3 \left[ \left( \sum_{n_1=0}^1 x[4n_1 + n_2] W_2^{k_1 n_1} \right) W_8^{k_1 n_2} \right] W_4^{k_2 n_2}$$

for  $0 \leq k_1 \leq 1$  and  $0 \leq k_2 \leq 3$

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## Cooley-Tukey FFT Algorithms

- 2-D array representation of the input is

$\begin{smallmatrix} n_2 \\ \backslash n_1 \end{smallmatrix}$	0	1	2	3
0	$x[0]$	$x[1]$	$x[2]$	$x[3]$
1	$x[4]$	$x[5]$	$x[6]$	$x[7]$

- The column DFTs are 2-point DFTs given by

$$G[k_1, n_2] = x[n_2] + (-1)^{k_1} x[4 + n_2], \quad \begin{cases} 0 \leq k_1 \leq 1 \\ 0 \leq n_2 \leq 3 \end{cases}$$

- These DFTs require no multiplications

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## Cooley-Tukey FFT Algorithms

- 2-D array of row transforms is

$\begin{smallmatrix} n_2 \\ \backslash k_1 \end{smallmatrix}$	0	1	2	3
0	$G[0,0]$	$G[0,1]$	$G[0,2]$	$G[0,3]$
1	$G[1,0]$	$G[1,1]$	$G[1,2]$	$G[1,3]$

- After multiplying by the twiddle factors  $W_8^{n_2 k_1}$  array becomes

$\begin{smallmatrix} n_2 \\ \backslash k_1 \end{smallmatrix}$	0	1	2	3
0	$\tilde{G}[0,0]$	$\tilde{G}[0,1]$	$\tilde{G}[0,2]$	$\tilde{G}[0,3]$
1	$\tilde{G}[1,0]$	$\tilde{G}[1,1]$	$\tilde{G}[1,2]$	$\tilde{G}[1,3]$

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## Cooley-Tukey FFT Algorithms

- Note:  $\tilde{G}[k_1, n_2] = W_8^{n_2 k_1} G[k_1, n_2]$

- Finally, the 4-point DFTs of the rows are computed:

$$X[k_1 + 2k_2] = \sum_{n_2=0}^3 \tilde{G}[k_1, n_2] W_4^{n_2 k_2}, \quad \begin{cases} 0 \leq k_1 \leq 1 \\ 0 \leq k_2 \leq 3 \end{cases}$$

- Output 2-D array is given by

$\begin{smallmatrix} k_2 \\ \backslash k_1 \end{smallmatrix}$	0	1	2	3
0	$X[0]$	$X[2]$	$X[4]$	$X[6]$
1	$X[1]$	$X[3]$	$X[5]$	$X[7]$

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## Cooley-Tukey FFT Algorithms

- The process illustrated is precisely the first stage of the DIF FFT algorithm
- By choosing  $N_1 = 4$  and  $N_2 = 2$ , we get the first stage of the DIT FFT algorithm
- Alternate index mappings are given by

$$n = n_1 + N_1 n_2, \quad \begin{cases} 0 \leq n_1 \leq N_1 - 1 \\ 0 \leq n_2 \leq N_2 - 1 \end{cases}$$

$$k = N_2 k_1 + k_2, \quad \begin{cases} 0 \leq k_1 \leq N_1 - 1 \\ 0 \leq k_2 \leq N_2 - 1 \end{cases}$$

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## Prime Factor Algorithms

- Twiddle factors can be eliminated by defining the index mappings as

$$n = \langle An_1 + Bn_2 \rangle_N, \quad \begin{cases} 0 \leq n_1 \leq N_1 - 1 \\ 0 \leq n_2 \leq N_2 - 1 \end{cases}$$

$$k = \langle Ck_1 + Dk_2 \rangle_N, \quad \begin{cases} 0 \leq k_1 \leq N_1 - 1 \\ 0 \leq k_2 \leq N_2 - 1 \end{cases}$$

- To eliminate the twiddle factors we need to express

$$W_N^{(An_1 + Bn_2)(Ck_1 + Dk_2)} = W_{N_1}^{k_1 n_1} W_{N_2}^{k_2 n_2}$$

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## Prime Factor Algorithms

- Now  $W_N^{(An_1+Bn_2)(Ck_1+Dk_2)}$   

$$= W_N^{ACn_1k_1} W_N^{ADn_1k_2} W_N^{BCn_2k_1} W_N^{BDn_2k_2}$$
- It follows from above that if  

$$\langle AC \rangle_N = N_2, \langle BD \rangle_N = N_1,$$

$$\langle AD \rangle_N = \langle BC \rangle_N = 0$$
then  

$$W_N^{(An_1+Bn_2)(Ck_1+Dk_2)} = W_{N_1}^{n_1k_1} W_{N_2}^{n_2k_2}$$

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## Prime Factor Algorithms

- One set of coefficients that eliminates the twiddle factors is given by  

$$A = N_2, B = N_1,$$

$$C = N_2 \langle N_2^{-1} \rangle_{N_1}, \quad D = N_1 \langle N_1^{-1} \rangle_{N_2}$$
- Here  $\langle N_1^{-1} \rangle_{N_2}$  denotes the **multiplicative inverse** of  $N_1$  reduced modulo  $N_2$
- $\Rightarrow$  If  $\langle N_1^{-1} \rangle_{N_2} = \alpha$  then  $\langle N_1 \alpha \rangle_{N_2} = 1$   
or, in other words  $N_1 \alpha = N_2 \beta + 1$  where  $\beta$  is any integer

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## Prime Factor Algorithms

- For example, if  $N_1 = 4$  and  $N_2 = 3$ , then  
 $\langle 3^{-1} \rangle_4 = 3$  since  $\langle 3 \cdot 3 \rangle_4 = 1$
- Likewise, if  $\langle N_2^{-1} \rangle_{N_1} = \gamma$ , then  $N_2 \gamma = N_1 \delta + 1$   
where  $\delta$  is any integer
- Now,  $\langle AC \rangle_N = \langle N_2 \cdot (N_2 \langle N_2^{-1} \rangle_{N_1}) \rangle_N$   

$$= \langle N_2 (N_1 \delta + 1) \rangle_N = \langle N_2 N_1 \delta + N_2 \rangle_N = N_2$$
- Similarly,  $\langle BD \rangle_N = \langle N_1 \cdot (N_1 \langle N_1^{-1} \rangle_{N_2}) \rangle_N$   

$$= \langle N_1 (N_2 \beta + 1) \rangle_N = \langle N_1 N_2 \beta + N_1 \rangle_N = N_1$$

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## Prime Factor Algorithms

- Next,  

$$\langle AD \rangle_N = \langle N_2 \cdot (N_1 \langle N_1^{-1} \rangle_{N_2}) \rangle_N = \langle N \alpha \rangle_N = 0$$
- Likewise,  

$$\langle BC \rangle_N = \langle N_1 \cdot (N_2 \langle N_2^{-1} \rangle_{N_1}) \rangle_N = \langle N \gamma \rangle_N = 0$$
- Hence,  

$$X[k] = X[C_1 k + D k_2]_N$$

$$= \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} x[\langle An_1 + Bn_2 \rangle_N] W_N^{N_2 n_1 k_1} W_N^{N_1 n_2 k_2}$$

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## Prime Factor Algorithms

- Thus,  $X[\langle Ck_1 + Dk_2 \rangle_N]$   

$$= \sum_{n_1=0}^{N_1-1} \sum_{n_2=0}^{N_2-1} x[\langle An_1 + Bn_2 \rangle_N] W_{N_1}^{n_1 k_1} W_{N_2}^{n_2 k_2}$$

$$= \sum_{n_2=0}^{N_2-1} G[n_2, k_1] W_{N_2}^{n_2 k_2}$$
where  

$$G[n_2, k_1] = \sum_{n_1=0}^{N_1-1} x[\langle An_1 + Bn_2 \rangle_N] W_{N_1}^{n_1 k_1}$$
and  $0 \leq k_1 \leq N_1 - 1, 0 \leq k_2 \leq N_2 - 1$

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## Prime Factor Algorithms

- Example - Let  $N = 12$ . Choose  $N_1 = 4$  and  $N_2 = 3$
- Then,  $A = 3, B = 4, C = 3 \langle 3^{-1} \rangle_4 = 9$  and  $D = 4 \langle 4^{-1} \rangle_3 = 4$
- The index mappings are  

$$n = \langle 3n_1 + 4n_2 \rangle_{12}, \quad \begin{cases} 0 \leq n_1 \leq 3 \\ 0 \leq n_2 \leq 2 \end{cases}$$

$$k = \langle 9k_1 + 4k_2 \rangle_{12}, \quad \begin{cases} 0 \leq k_1 \leq 3 \\ 0 \leq k_2 \leq 2 \end{cases}$$

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## Prime Factor Algorithms

- 2-D array representation of input is

$\frac{n_2}{n_1} \backslash$	0	1	2
0	$x[0]$	$x[4]$	$x[8]$
1	$x[3]$	$x[7]$	$x[11]$
2	$x[6]$	$x[10]$	$x[2]$
3	$x[9]$	$x[1]$	$x[5]$

- 4-point transforms of the columns lead to

$\frac{n_2}{k_1} \backslash$	0	1	2
0	$G[0,0]$	$G[0,1]$	$G[0,2]$
1	$G[1,0]$	$G[1,1]$	$G[1,2]$
2	$G[2,0]$	$G[2,1]$	$G[2,2]$
3	$G[3,0]$	$G[3,1]$	$G[3,2]$

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## Prime Factor Algorithms

- Final DFT array is

$\frac{k_2}{k_1} \backslash$	0	1	2
0	$X[0]$	$X[4]$	$X[8]$
1	$X[9]$	$X[1]$	$X[5]$
2	$X[6]$	$X[10]$	$X[2]$
3	$X[3]$	$X[7]$	$X[11]$

- 4-point DFTs require no multiplications, whereas the 3-point DFTs require 4 complex multiplications
- Thus, the algorithm requires 16 complex multiplications

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## Chirp z-Transform Algorithm

- Let  $x[n]$  be a length- $N$  sequence with a Fourier transform
- We consider evaluation of  $M$  samples of that are equally spaced in angle on the unit circle at frequencies

$$\omega_k = \omega_o + k\Delta\omega, \quad 0 \leq k \leq M-1$$

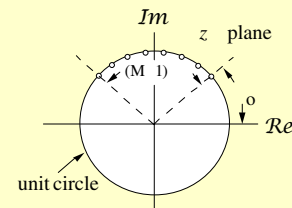
where the starting frequency  $\omega_o$  and the frequency increment  $\Delta\omega$  can be chosen arbitrarily

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## Chirp z-Transform Algorithm

- Figure below illustrates the problem



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## Chirp z-Transform Algorithm

- The problem is thus to evaluate

$$X(e^{j\omega_k}) = \sum_{n=0}^{N-1} x[n]e^{-j\omega_k n}, \quad 0 \leq k \leq M-1$$

or, with  $W$  defined as

$$W = e^{-j\Delta\omega}$$

to evaluate

$$X(e^{j\omega_k}) = \sum_{n=0}^{N-1} x[n]e^{-j\omega_o n} W^{nk}$$

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## Chirp z-Transform Algorithm

- Using the identity  $nk = \frac{1}{2}[n^2 + k^2 - (k-n)^2]$  we can write

$$X(e^{j\omega_k}) = \sum_{n=0}^{N-1} x[n]e^{j\omega_o n} W^{n^2/2} W^{k^2/2} W^{-(k-n)^2/2}$$

- Letting  $g[n] = x[n]e^{-j\omega_o n} W^{n^2/2}$  we arrive at

$$X(e^{j\omega_k}) = W^{k^2/2} \left( \sum_{n=0}^{N-1} g[n]W^{-(k-n)^2/2} \right), \quad 0 \leq k \leq M-1$$

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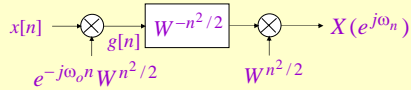
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## Chirp z-Transform Algorithm

- Interchanging  $k$  and  $n$  we get

$$X(e^{j\omega_n}) = W^{n^2/2} \left( \sum_{k=0}^{N-1} g[k] W^{-(n-k)^2/2} \right),$$

- Thus,  $X(e^{j\omega_n})$  corresponds to the convolution of the sequence  $g[n]$  with the sequence  $W^{-n^2/2}$  followed by multiplication by the sequence  $W^{n^2/2}$  as indicated below



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## Chirp z-Transform Algorithm

- The sequence  $W^{-n^2/2}$  can be thought of as a complex exponential sequence with linearly increasing frequency
- Such signals, in radar systems, are called chirp signals
- Hence, the name **chirp transform**

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## Chirp z-Transform Algorithm

- For the evaluation of

$$X(e^{j\omega_n}) = W^{n^2/2} \left( \sum_{k=0}^{N-1} g[k] W^{-(n-k)^2/2} \right),$$

the output of the system depicted earlier need to be computed over a finite interval

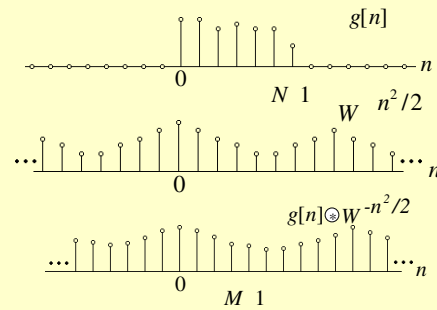
- Since  $g[n]$  is a length- $N$  sequence, only a finite portion of the infinite length sequence  $W^{-n^2/2}$  is used in obtaining the convolution sum over the interval  $0 \leq n \leq M-1$

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## Chirp z-Transform Algorithm

- Typical signals



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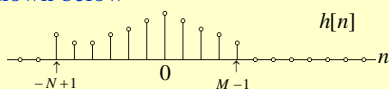
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## Chirp z-Transform Algorithm

- The portion of the sequence  $W^{-n^2/2}$  used in obtaining the convolution sum is from the interval  $-N+1 \leq n \leq M-1$

- Let  $h[n] = \begin{cases} W^{-n^2/2}, & -(N-1) \leq n \leq (M-1) \\ 0, & \text{otherwise} \end{cases}$

as shown below

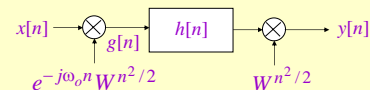


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## Chirp z-Transform Algorithm

- It can be seen that  $g[n] \odot W^{-n^2/2} = g[n] \odot h[n], 0 \leq n \leq M-1$
- Hence, the computation of the frequency samples  $X(e^{j\omega_n})$  can be carried out using an FIR filter as indicated below



where  $y[n] = X(e^{j\omega_n}), 0 \leq n \leq M-1$

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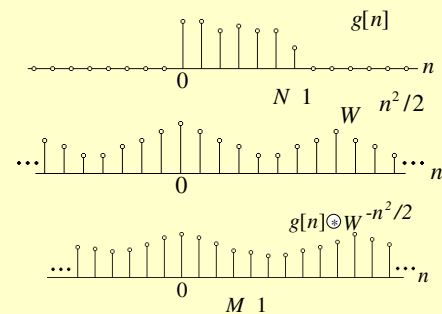
## Chirp z-Transform Algorithm

- Advantages -
- (1)  $N = M$  is not required as in FFT algorithms
- (2) Neither  $N$  nor  $M$  do not have to be composite numbers
- (3) Parameters  $\omega_o$  and  $\Delta\omega$  are arbitrary
- (4) Convolution with  $h[n]$  can be implemented using FFT techniques

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## Chirp z-Transform Algorithm



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