

DFT Analysis (5B)

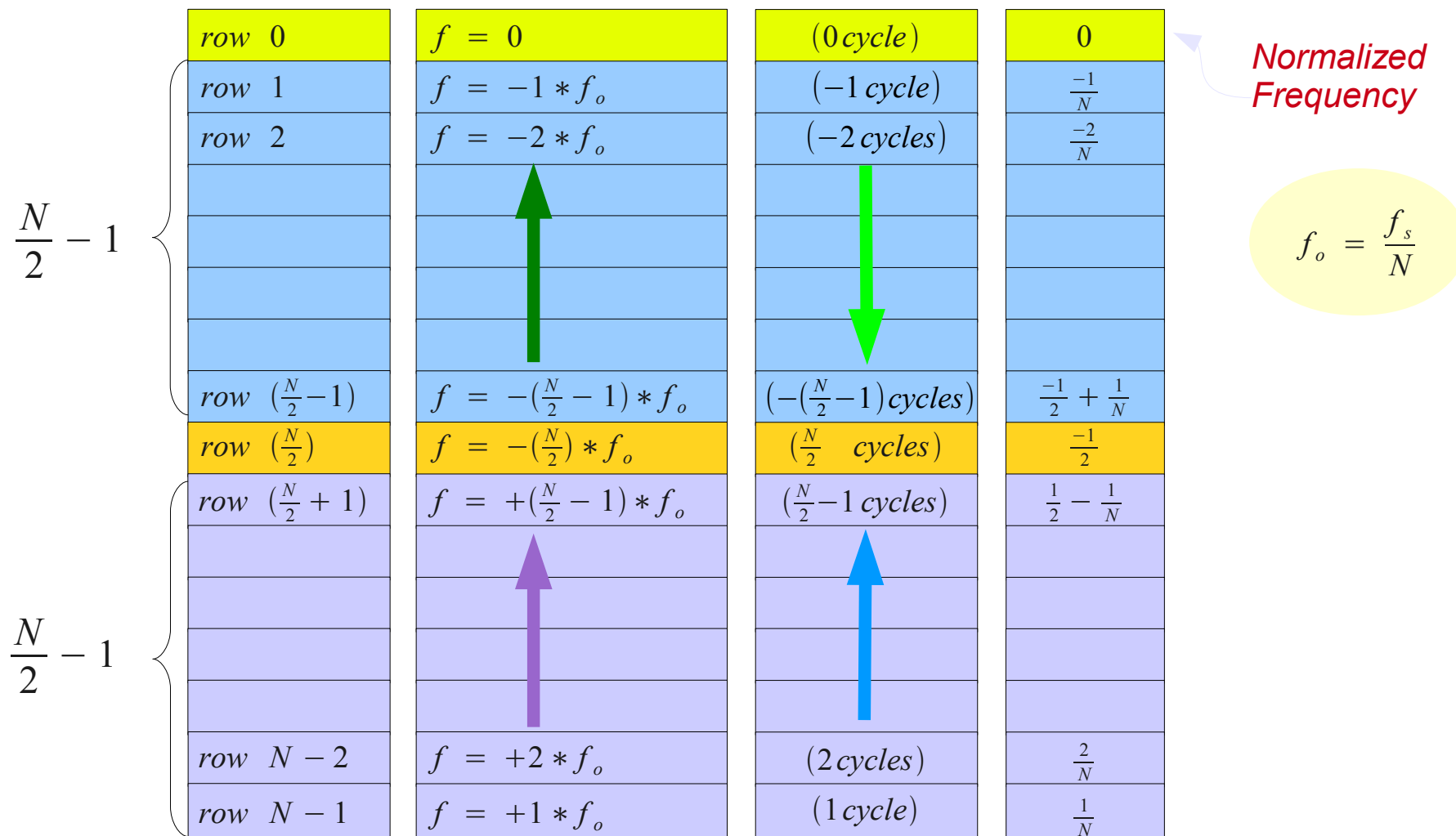
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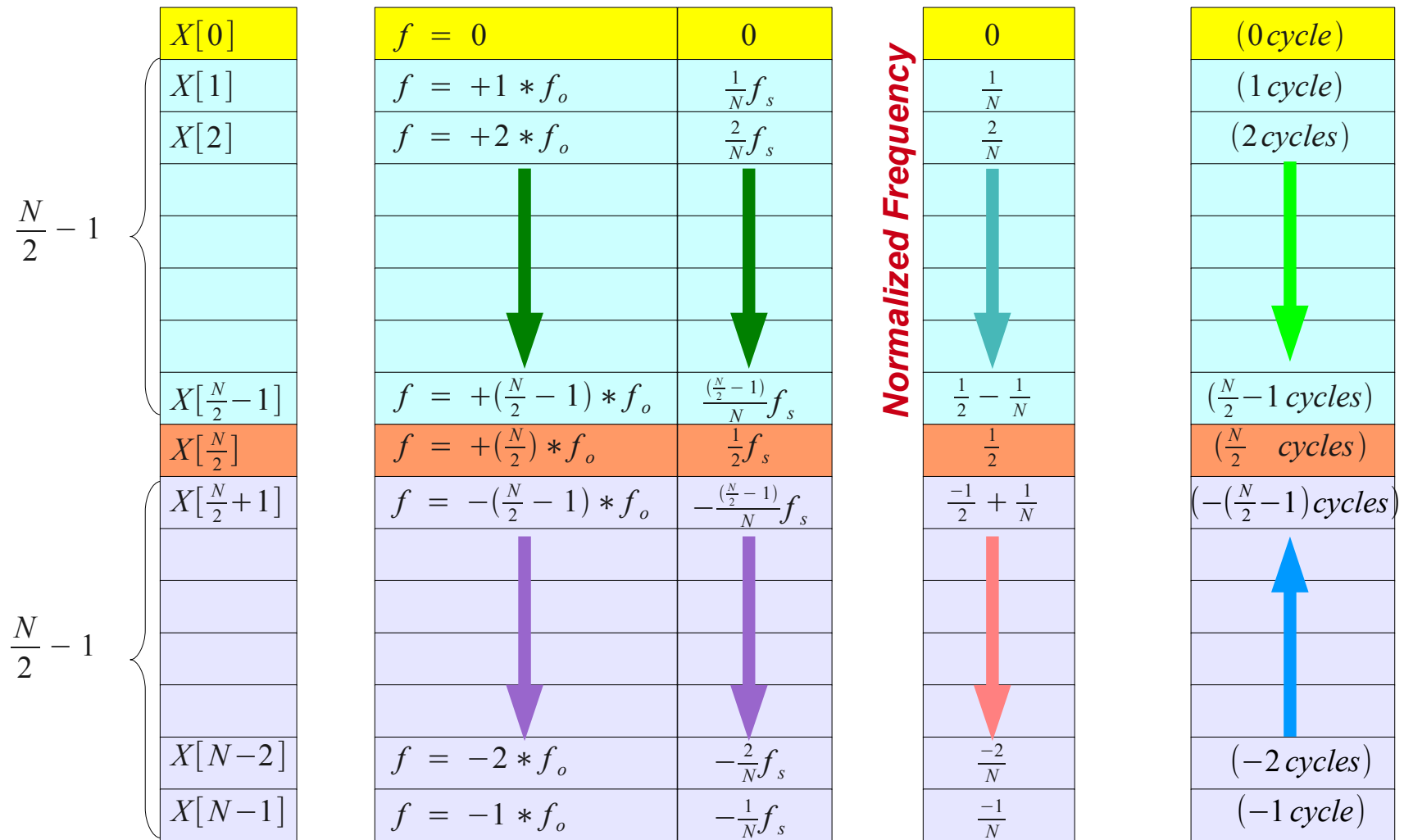
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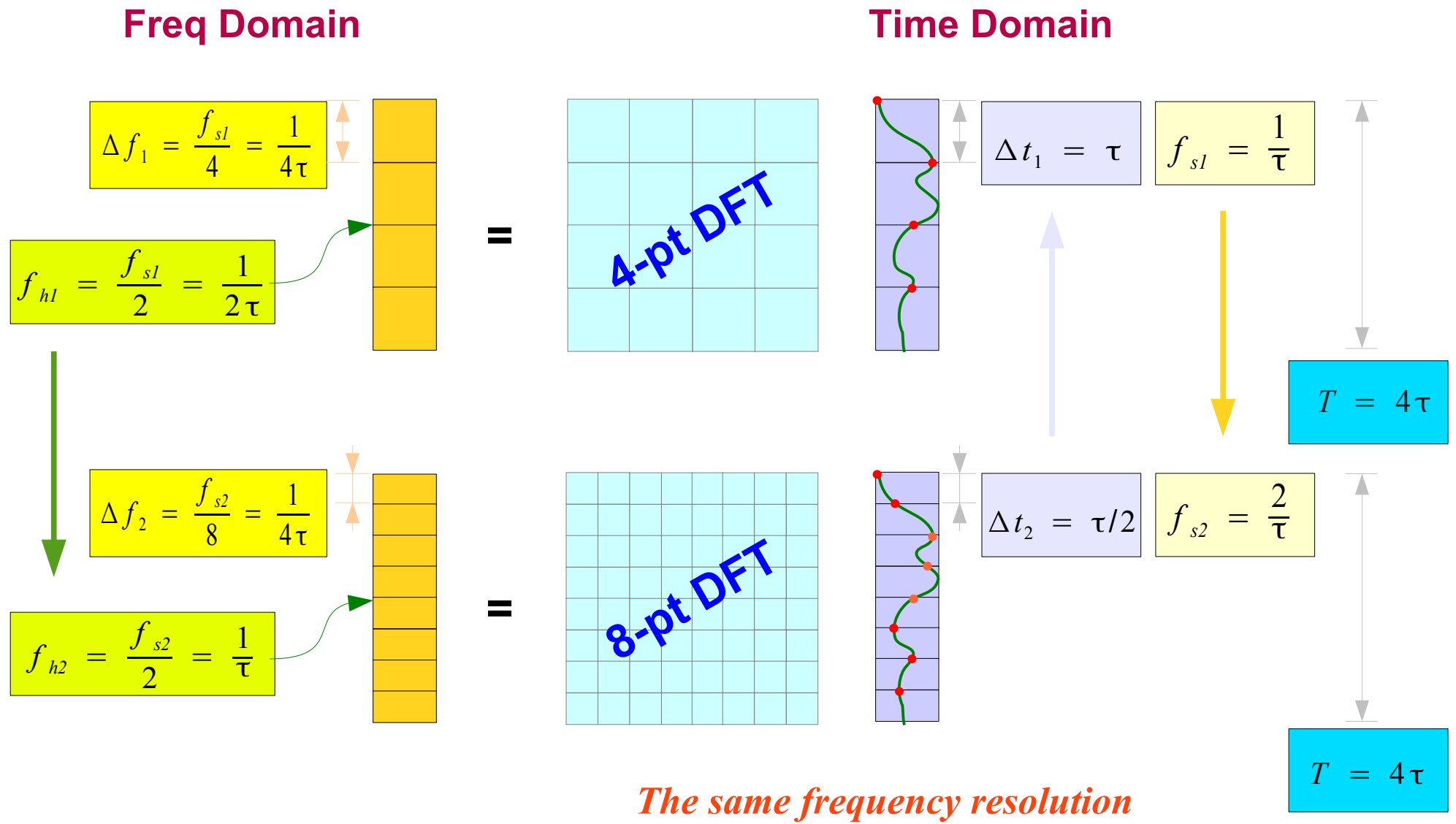
Frequency View of a DFT Matrix



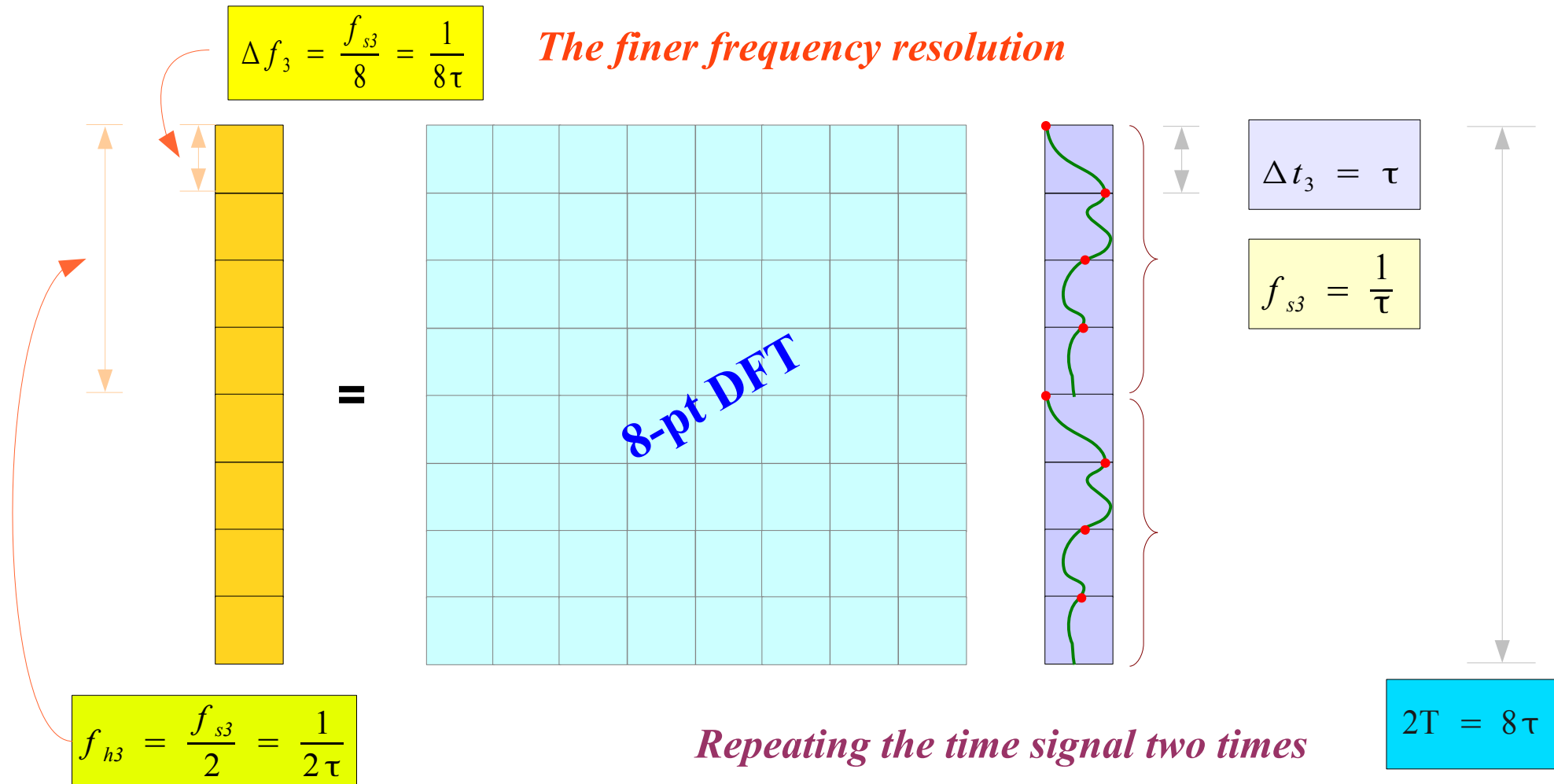
Frequency View of a X[i] Vector



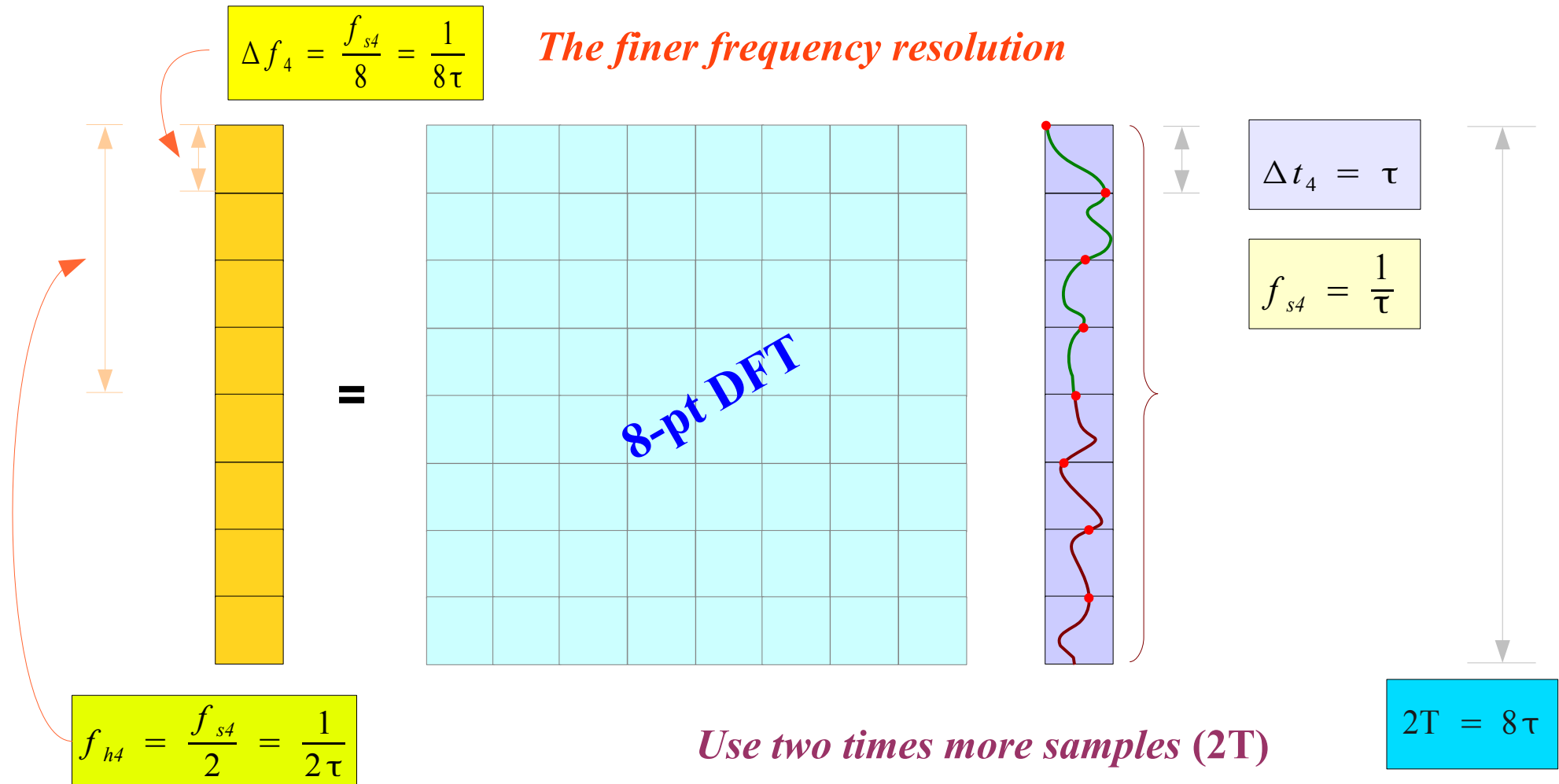
Frequency and Time Interval (1)



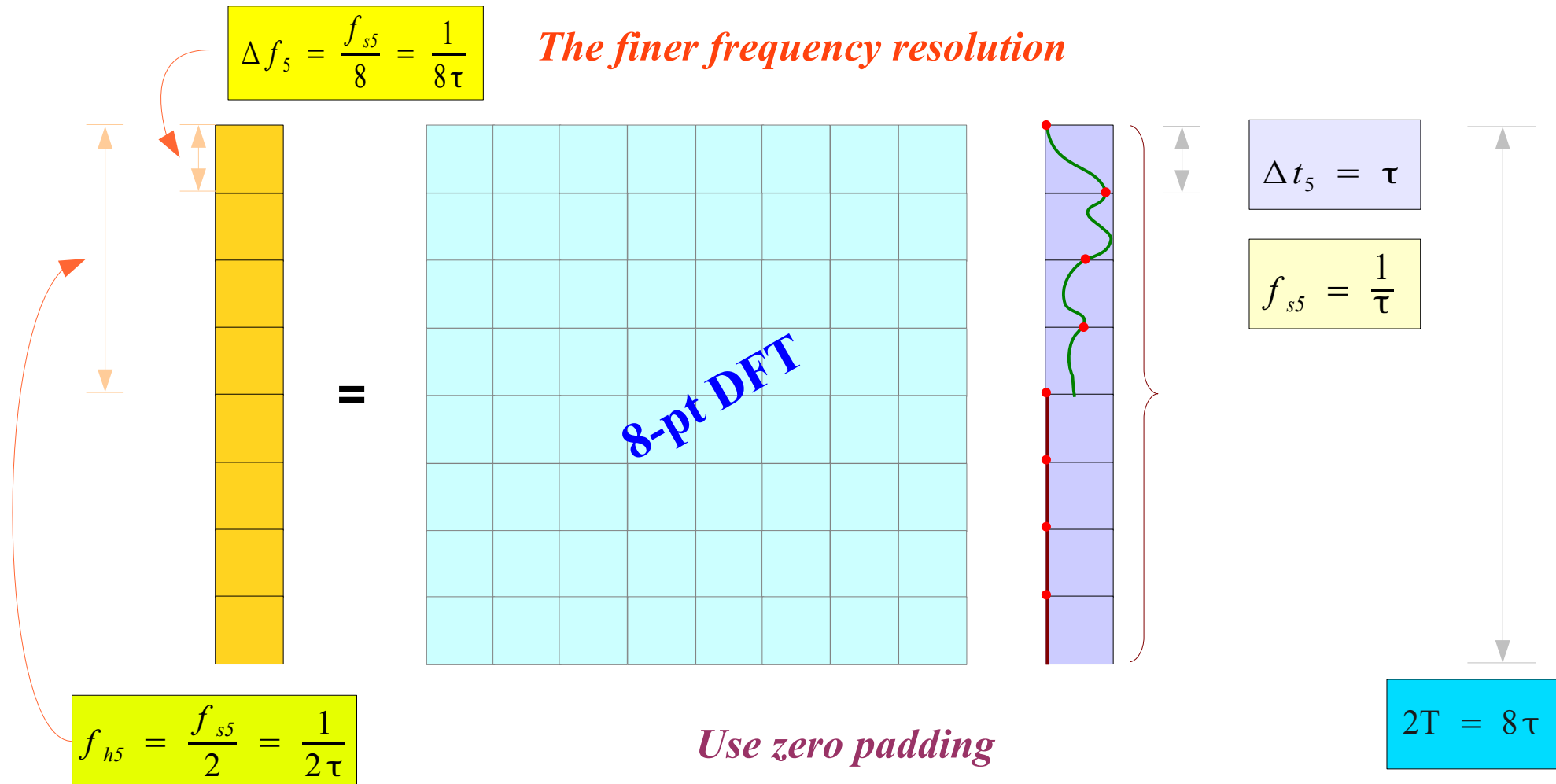
Frequency and Time Interval (2)



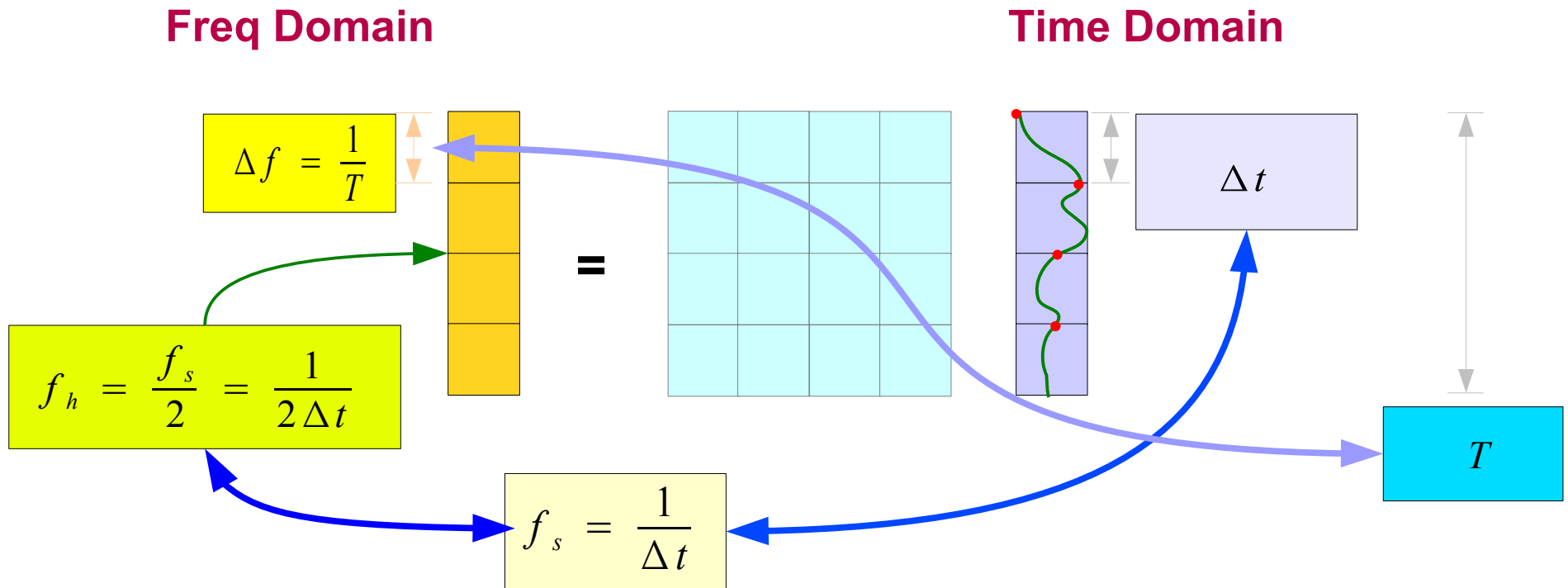
Frequency and Time Interval (3)



Frequency and Time Interval (4)



Frequency and Time Interval (5)



CTFS with Complex Coefficients

$$x(t) = a_0 + \sum_{k=1}^{\infty} (a_k \cos(k\omega_0 t) + b_k \sin(k\omega_0 t))$$

$$a_0 = \frac{1}{T} \int_0^T x(t) dt$$

$$a_k = \frac{2}{T} \int_0^T x(t) \cos(k\omega_0 t) dt$$

$$b_k = \frac{2}{T} \int_0^T x(t) \sin(k\omega_0 t) dt$$
$$k = 1, 2, \dots$$

$$x(t) = A_0 + \sum_{k=1}^{\infty} (A_k e^{jk\omega_0 t} + B_k e^{-jk\omega_0 t})$$

$$A_0 = a_0$$

$$A_k = \frac{1}{2} (a_k - jb_k)$$

$$B_k = \frac{1}{2} (a_k + jb_k)$$

$$k = 1, 2, \dots$$

$$x(t) = \sum_{k=0}^{\infty} (A_k e^{+jk\omega_0 t} + B_k e^{-jk\omega_0 t})$$

$$A_k = \frac{1}{T} \int_0^T x(t) e^{-jk\omega_0 t} dt$$
$$k = 0, 1, 2, \dots$$

$$B_k = \frac{1}{T} \int_0^T x(t) e^{+jk\omega_0 t} dt$$
$$k = 1, 2, \dots$$

$$x(t) = \sum_{k=-\infty}^{+\infty} C_k e^{+jk\omega_0 t}$$

$$C_k = \frac{1}{T} \int_0^T x(t) e^{-jk\omega_0 t} dt$$
$$k = -2, -1, 0, +1, +2, \dots$$

$$C_k = \begin{cases} A_0 = a_0 & (k = 0) \\ A_k = \frac{1}{2} (a_k - jb_k) & (k > 0) \\ B_k = \frac{1}{2} (a_k + jb_k) & (k < 0) \end{cases}$$

CTFS and Power Spectrum

$$x(t) = a_0 + \sum_{k=1}^{\infty} (a_k \cos(k\omega_0 t) + b_k \sin(k\omega_0 t))$$

$$a_0 = \frac{1}{T} \int_0^T x(t) dt$$

$$a_k = \frac{2}{T} \int_0^T x(t) \cos(k\omega_0 t) dt$$

$$b_k = \frac{2}{T} \int_0^T x(t) \sin(k\omega_0 t) dt$$

$k = 1, 2, \dots$

$$P = \frac{1}{T} \int_0^T |f(t)|^2 dt$$

$$P = |a_0|^2 + \frac{1}{2} (|a_k|^2 + |b_k|^2)$$

$$x(t) = \sum_{k=-\infty}^{+\infty} C_k e^{+jk\omega_0 t}$$

$$C_k = \frac{1}{T} \int_0^T x(t) e^{-jk\omega_0 t} dt$$

$$k = -2, -1, 0, +1, +2, \dots$$

$$C_k = \begin{cases} A_0 = a_0 & (k = 0) \\ A_k = \frac{1}{2}(a_k - jb_k) & (k > 0) \\ B_k = \frac{1}{2}(a_k + jb_k) & (k < 0) \end{cases}$$

$$P = \frac{1}{T} \int_0^T |f(t)|^2 dt$$

$$P = |c_0|^2 + (|c_k|^2 + |c_{-k}|^2)$$

CTFS and DTFS

$$x(t) = \sum_{k=-\infty}^{+\infty} C_k e^{+jk\omega_0 t} \quad \text{CTFS}$$

$$C_k = \frac{1}{T} \int_0^T x(t) e^{-jk\omega_0 t} dt$$

$$k = -2, -1, 0, +1, +2, \dots$$

$$x(t) \approx \sum_{k=-M}^{+M} C_k e^{+jk\omega_0 t} \quad N = 2M + 1$$

$$jk\omega_0 t \rightarrow k \left(\frac{2\pi}{T} \right) n \left(\frac{T}{N} \right) = \left(\frac{2\pi}{T} \right) nk$$

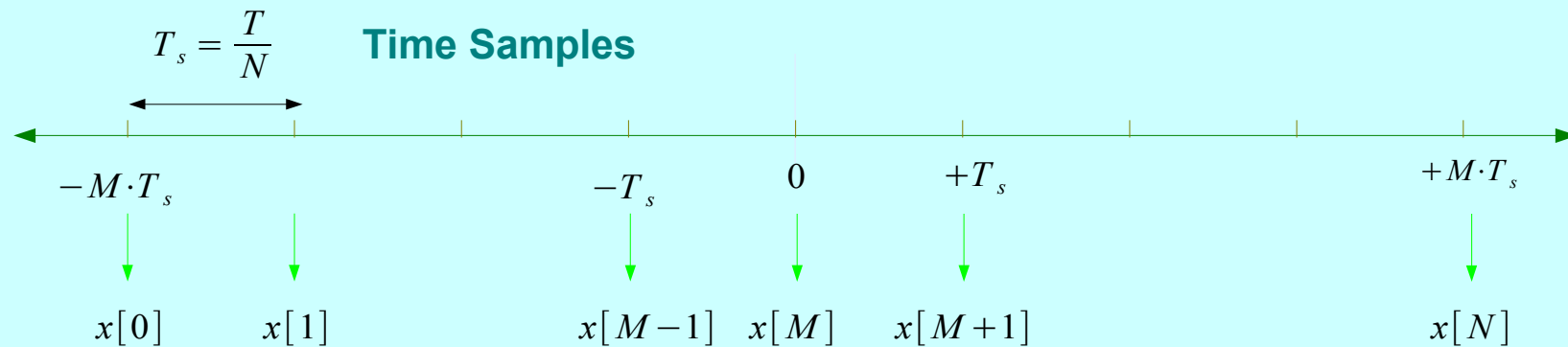
$$x[n] = \sum_{k=-M}^{+M} \gamma_k e^{+j \left(\frac{2\pi}{N} \right) nk}$$

$$n = 0, 1, 2, \dots, N-1,$$

$$\gamma_k = \frac{1}{N} \sum_{n=0}^{N-1} x[n] e^{-j \left(\frac{2\pi}{N} \right) nk}$$

$$k = -M, \dots, 0, \dots, +M$$

$$x_{FS}(t) = \sum_{k=-M}^{+M} \gamma_k e^{+jk\omega_0 t} \quad \text{DTFS}$$



fft and ifft

Discrete Fourier Transform

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

$$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} X[k] e^{+j(2\pi/N)kn}$$

$$X = \text{fft}(x)$$

$$x = \text{ifft}(X)$$

$$x(t) = \sum_{k=-\infty}^{+\infty} C_k e^{+jk\omega_0 t} \quad \text{CTFS}$$

$$x_{FS}(t) = \sum_{k=-M}^{+M} y_k e^{+jk\omega_0 t} \quad \text{DTFS}$$

$$C_k \approx y_k = \frac{X[k]}{N} \quad \text{Approximated Fourier Coefficients}$$

$$|C_k|^2 \approx \frac{|X[k]|^2}{N} \quad \text{Approximated Periodogram}$$

Approximated
Fourier Series Coefficients

$$fc = \text{fft}(x)/N = X/N$$

$$x = \text{ifft}(fc)*N$$

Periodic Signals

Aperiodic Signals

Random Signals

Frequency Spacing

$$\Delta f = \frac{1}{N\Delta t}$$

$$\Delta f = \frac{1}{N\Delta t}$$

$$\sum S \Delta f = \frac{1}{N\Delta t} \sum S \quad \frac{1}{N\Delta t} \sum x^2 \Delta t$$

Two Sided

$$\frac{1}{N} X(k)$$

$$\frac{\Delta t}{N} X(k)$$

$$S(k) = \frac{\Delta t}{N} |X(k)|^2 \quad P = \sum_{k=0}^{N-1} S(k) \Delta f$$

One Sided

$$k=0, \frac{N}{2}$$

$$\frac{1}{N} X(k)$$

$$\frac{\Delta t}{N} X(k)$$

$$S_1(k) = 2S(k) \quad P = \sum_{k=0}^{N/2} S_1(k) \Delta f$$

$$k=1, \dots, \frac{N}{2}-1$$

$$\frac{2}{N} X(k)$$

$$\frac{2\Delta t}{N} X(k)$$

$$S_1(k) = S(k)$$

Frequency Scale

$$k \Delta f$$

$$k \Delta f$$

$$k \Delta f$$

Periodic Signals

Frequency Spacing

$$\Delta f = \frac{1}{N\Delta t}$$

Two Sided Fourier Series Coefficient

$$\frac{1}{N} X(k)$$

One Sided Fourier Series Coefficient

$$\frac{1}{N} X(k) \quad k=0, \frac{N}{2}$$

$$\frac{2}{N} X(k) \quad k=1, \dots, \frac{N}{2}-1$$

Frequency Scale

$$k \Delta f$$

Aperiodic Signals

$$\Delta f = \frac{1}{N\Delta t}$$

Two Sided Fourier Series Coefficient

$$\frac{\Delta t}{N} X(k)$$

One Sided Fourier Series Coefficient

$$\frac{\Delta t}{N} X(k) \quad k=0, \frac{N}{2}$$

$$\frac{2\Delta t}{N} X(k) \quad k=1, \dots, \frac{N}{2}-1$$

$$k \Delta f$$

Random Signals

One-sided Power Spectral Density

$$P = \sum_{k=0}^{N-1} S(k) \Delta f$$

One-sided Power Spectral Density

$$P = \sum_{k=0}^{N/2} S_1(k) \Delta f$$

$$S_1(k) = 2S(k) \quad k = 1, \dots, \frac{N}{2} - 1$$

$$S_1(k) = S(k) \quad k = 0, \frac{N}{2}$$

Two Sided Fourier Series Coefficient

$$\frac{1}{N \Delta t} \sum x^2 \Delta t$$

$$\sum S \Delta f = \frac{1}{N \Delta t} \sum S$$

$$S(k) = \frac{\Delta t}{N} |X(k)|^2$$

$$k \Delta f$$

Amplitude Spectrum

$$A_k = \frac{1}{N}|X(k)| = \frac{1}{N}\sqrt{\Re^2(X(k)) + \Im^2(X(k))}$$

$$k = 0, 1, 2, \dots, N-1$$

Power Spectrum

$$P_k = \frac{1}{N^2}|X(k)|^2 = \frac{1}{N^2}\{\Re^2(X(k)) + \Im^2(X(k))\}$$

$$k = 0, 1, 2, \dots, N-1$$

One Sided Amplitude Spectrum

$$\bar{A}_k = \frac{1}{N}|X(0)| \quad k=0$$

$$\bar{A}_k = \frac{2}{N}|X(0)| \quad k=1, 2, \dots, N/2$$

One Sided Power Spectrum

$$\bar{P}_k = \frac{1}{N^2}|X(0)|^2 \quad k=0$$

$$\bar{P}_k = \frac{2}{N^2}|X(0)|^2 \quad k=1, 2, \dots, N/2$$

Frequency Bin

$$f = \frac{k f_s}{N}$$

Frequency Bin

$$f = \frac{k f_s}{N}$$

Phase Spectrum

$$\phi_k = \tan^{-1}\left(\frac{\Im(X(k))}{\Re(X(k))}\right) \quad k=0, 1, 2, \dots, N-1$$

Data Truncation
Frequency Resolution
Zero Padding
Periodogram
Spectral Plot

Amplitude spectrum in quantity peak

Phase spectrum in radians

Amplitude spectrum in volts rms

Phase spectrum in degrees

Power spectrum

Signals without discontinuity

Signals with discontinuity

Sampling frequency is not an integer multiple
of the FFT length

Leakage

$$\left[0, \frac{f_s}{2}\right]$$

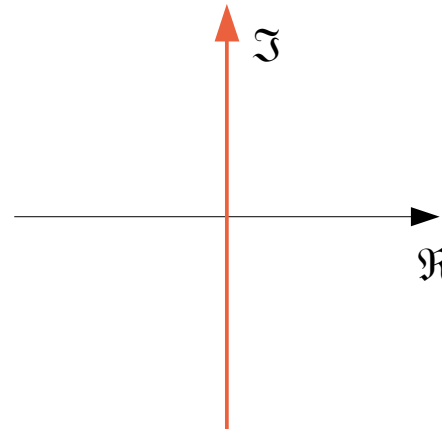
Fourier Transform

$f(t)$ A continuous sum of weighted exponential functions :

$$f(t) e^{-j\omega t}$$

$$-\infty < \omega < +\infty$$

Not so useful in transient analysis

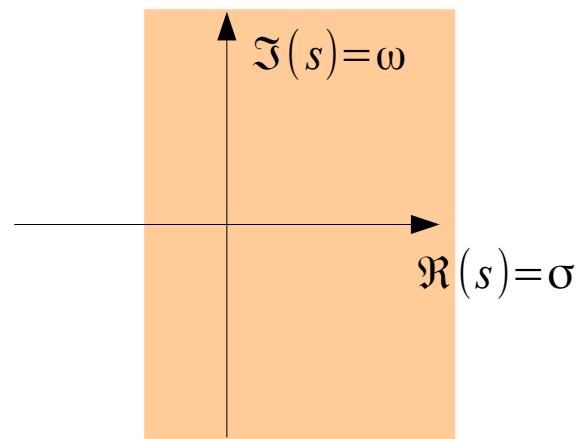


Laplace Transform

$$f(t) e^{-st} = f(t) e^{-(\sigma + j\omega)t}$$

Linear Time Domain Analysis

Initial Condition



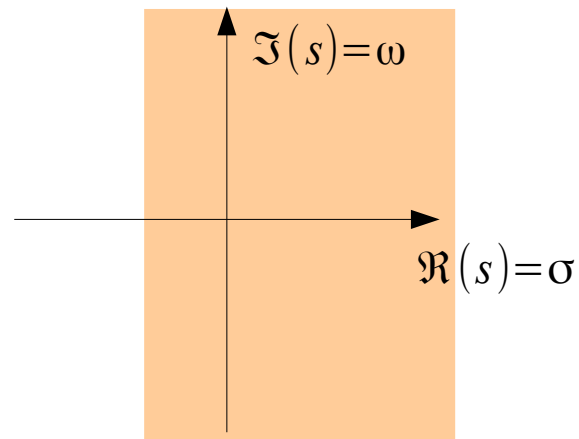
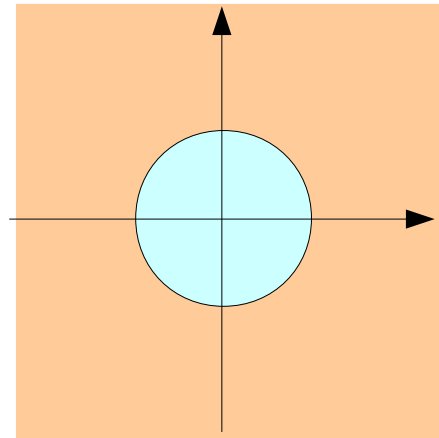
z Transform

$$f[n] z^{-n}$$

Discrete Time System

Difference Equation

$$z = e^{sT} = e^{\sigma T} e^{j\omega T}$$



References

- [1] <http://en.wikipedia.org/>
- [2] J.H. McClellan, et al., Signal Processing First, Pearson Prentice Hall, 2003
- [3] A “graphical interpretation” of the DFT and FFT, by Steve Mann