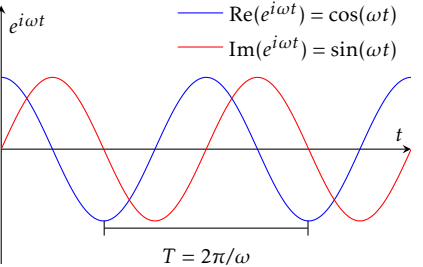


Frequencies
 Continuous-time: ω (rad/s), f (Hz or 1/s), $\omega = 2\pi f$, period: $T = 1/f$ (s)
 Discrete-time: $\hat{\omega}$ (rad/sample), ω (rad/s), f_s sample-rate (sample/s), $\hat{\omega} = \omega/f_s$.



Sampling
 Aliases of a discretized complex sinusoid:

$$x[n] = e^{i(\hat{\omega}_0 + 2\pi k)n} = e^{i\hat{\omega}_0 n}$$

Frequency aliases:

$$\hat{\omega}_k = \hat{\omega}_0 + 2\pi k$$
 Principal spectrum

$$-\pi \leq \hat{\omega} < \pi$$
 Dirac comb:

$$s(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_s)$$

$$= T_s^{-1} \sum_{k=-\infty}^{\infty} e^{i \frac{2\pi}{T_s} kt}.$$

Idealized sampled signal $\omega_s = 2\pi f_s$:

$$x_s(t) = x(t)s(t)$$

$$\hat{x}_s(\omega) = (2\pi)^{-1} \hat{x}(\omega) * \hat{s}(\omega)$$

$$= T_s^{-1} \sum_{k=-\infty}^{\infty} \hat{x}(\omega + k\omega_s)$$
 Nyquist oversampling criterion ($x(t) \in \mathbb{R}$):

$$f_s > 2f_{\max}$$
 Nyquist undersampling criterion ($x(t) \in \mathbb{R}$):

$$f_{\max} - f_{\min} < f_s/2$$

$$kf_s/2 < f_{\min} < (k+1)f_s/2$$

$$kf_s/2 < f_{\max} < (k+1)f_s/2$$

f_{\max} , and f_{\min} are the largest and smallest positive frequencies in signal, and $k \in \mathbb{N}_{>0}$ is Nyquist zone.

Nyquist sampling criterion ($x(t) \in \mathbb{C}$):

$$f_{\max} - f_{\min} < f_s$$
 f_{\max} , and f_{\min} are the largest and smallest frequencies in signal (can be negative).

Convolution

$$x_1(t) * x_2(t) := \int_{-\infty}^{\infty} x_1(\tau) x_2(t - \tau) d\tau$$

$$x_1[n] * x_2[n] := \sum_{k=-\infty}^{\infty} x_1[k] x_2[n - k]$$
 Identity: $x[n] * \delta[n] = x[n]$
 Commutative: $a[n] * b[n] = b[n] * a[n]$
 Associative $(a[n] * b[n]) * c[n] = a[n] * (b[n] * c[n])$
 Distributive:

$$a[n] * (b[n] + c[n]) = a[n] * b[n] + a[n] * c[n]$$

Get this signal processing cheat sheet and the rest of the course material from: https://github.com/jvierine/signal_processing_course

Fourier Series
 Synthesis ($x_N(t) = x_N(t + T)$)

$$x_N(t) = \sum_{k=-N}^N c_k e^{i \frac{2\pi}{T} kt}$$
 Analysis (t_0 is an arbitrary constant):

$$c_k = T^{-1} \int_{t_0}^{t_0+T} x(t) e^{-i \frac{2\pi}{T} kt} dt$$

Test for periodicity: all frequencies in $\sum_k c_k e^{i\omega_k t}$ are commensurable, i.e. $\omega_k/\omega_\ell = n/m \in \mathbb{Q}$ with $k, \ell, m, n \in \mathbb{Z}$.

Fourier Transform
 Forward

$$x(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{x}(\omega) e^{i\hat{\omega} t} d\omega$$
 Reverse

$$\hat{x}(\omega) = \int_{-\infty}^{\infty} x(t) e^{-i\omega t} dt$$
 Important transforms:

$$x(t) \xleftrightarrow{\mathcal{F}} \hat{x}(\omega) \quad \delta(t + \tau) \xleftrightarrow{\mathcal{F}} e^{i\omega \tau}$$

$$e^{i\omega_0 t} \xleftrightarrow{\mathcal{F}} 2\pi \delta(\omega - \omega_0) \quad x(t - t_0) \xleftrightarrow{\mathcal{F}} e^{-i\omega t_0} \hat{x}(\omega)$$

$$u(t + T/2) - u(t - T/2) \xleftrightarrow{\mathcal{F}} 2 \sin(\omega T/2)/\omega$$

$$e^{-\alpha t^2} \xleftrightarrow{\mathcal{F}} \sqrt{\pi/\alpha} e^{-\frac{\omega^2}{4\alpha}} \quad e^{-\beta t} u(t) \xleftrightarrow{\mathcal{F}} 1/(\beta + i\omega)$$

$$x(at) \xleftrightarrow{\mathcal{F}} |a|^{-1} \hat{x}(\omega/a) \quad e^{i\omega_0 t} x(t) \xleftrightarrow{\mathcal{F}} \hat{x}(\omega - \omega_0)$$
 Convolution theorem:

$$x_1(t) * x_2(t) \xleftrightarrow{\mathcal{F}} \hat{x}_1(\omega) \hat{x}_2(\omega)$$

$$x_1(t) x_2(t) \xleftrightarrow{\mathcal{F}} (2\pi)^{-1} \hat{x}_1(\omega) * \hat{x}_2(\omega)$$
 Plancherel's theorem:

$$\int_{-\infty}^{\infty} f(t) g^*(t) dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{F}(\omega) \hat{G}^*(\omega) d\omega.$$
 Parseval's theorem:

$$\int_{-\infty}^{\infty} |x(t)|^2 dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |\hat{x}(\omega)|^2 d\omega$$

Z-transform
 Forward:

$$X(z) = \sum_{k=-\infty}^{\infty} x[k] z^{-k}$$
 Reverse:

$$x[n] = \mathcal{Z}^{-1}\{X(z)\} = \frac{1}{2\pi i} \oint_{\mathcal{C}} X(z) z^{n-1} dz$$
 Infinite impulse response system:

$$y[n] = \sum_{\ell=1}^N a_\ell y[n - \ell] + \sum_{k=0}^M b_k x[n - k]$$

$$\mathcal{H}(z) = \frac{\sum_{k=0}^M b_k z^{-k}}{1 - \sum_{\ell=1}^N a_\ell z^{-\ell}} = \frac{\prod_{k=1}^M (1 - \alpha_k z^{-1})}{\prod_{\ell=1}^N (1 - \beta_\ell z^{-1})}$$
 Poles: $\beta_\ell \in \mathbb{C}$, Zeros: $\alpha_k \in \mathbb{C}$.
 Z-transform pairs:

$$\mathcal{H}(\hat{\omega}) = \mathcal{H}(z)|_{z=e^{i\hat{\omega}}} \quad a\delta[n - n_0] \xleftrightarrow{\mathcal{Z}} az^{-n_0}$$

$$ba^n u[n] \xleftrightarrow{\mathcal{Z}} \frac{b}{1 - az^{-1}} \quad a[n] * b[n] \xleftrightarrow{\mathcal{Z}} A(z)B(z)$$
 Bounded Input Bounded Output stability:

$$\sum_{k=-\infty}^{\infty} |h[k]| \leq M < \infty$$

Discrete-time Fourier Transform
 Reverse

$$x[n] = \frac{1}{2\pi} \int_{-\pi}^{\pi} \hat{x}(\hat{\omega}) e^{i\hat{\omega} n} d\hat{\omega}$$
 Forward

$$\hat{x}(\hat{\omega}) = \sum_{n=-\infty}^{\infty} x[n] e^{-i\hat{\omega} n}$$
 Important transforms:

$$x[n] \xleftrightarrow{\mathcal{F}} \hat{x}(\hat{\omega}) \quad a\delta[n - n_0] \xleftrightarrow{\mathcal{F}} ae^{i\hat{\omega} n_0}$$

$$x[n] * y[n] \xleftrightarrow{\mathcal{F}} \hat{x}(\hat{\omega}) \hat{y}(\hat{\omega})$$

$$e^{i\hat{\omega}_0 n} x[n] \xleftrightarrow{\mathcal{F}} \hat{x}(\hat{\omega} - \hat{\omega}_0)$$

$$\sum_{k=-N}^N \delta[n - k] \xleftrightarrow{\mathcal{F}} \frac{\sin(\hat{\omega} M/2)}{\sin(\hat{\omega}/2)}$$

Discrete Fourier Transform
 Forward:

$$\hat{x}[k] = \sum_{n=0}^{N-1} x[n] e^{-i \frac{2\pi}{N} kn}$$
 Reverse:

$$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} \hat{x}[k] e^{i \frac{2\pi}{N} kn}$$

$$x[n] = x[n + N], \quad \hat{x}[k] = \hat{x}[k + N], \quad k \in \{0, 1, 2, \dots, N - 1\}, n \in \{0, 1, 2, \dots, N - 1\}$$
 Principal spectrum frequency:

$$\hat{\omega}_k = \begin{cases} 2\pi k/N & k \leq N/2 \\ 2\pi k/N - 2\pi & N/2 < k \leq N - 1 \end{cases}$$

Frequency step:
 $\Delta\hat{\omega} = 2\pi/N$ or $\Delta f = f_s/N$.
 Periodic convolution:

$$a[n] \otimes b[n] = \sum_{k=0}^{N-1} a[k] b[(n - k) \bmod N].$$

Periodic convolution theorem:

$$a[n] \otimes b[n] \xleftrightarrow{\mathcal{F}} \hat{a}[k] \hat{b}[k]$$

DFT matrix $\hat{\mathbf{x}} = \mathbf{F} \mathbf{x}$:

$$\begin{bmatrix} \phi^{0 \cdot 0} & \phi^{0 \cdot 1} & \dots & \phi^{0 \cdot (N-1)} \\ \phi^{1 \cdot 0} & \phi^{1 \cdot 1} & \dots & \phi^{1 \cdot (N-1)} \\ \phi^{2 \cdot 0} & \phi^{2 \cdot 1} & \dots & \phi^{2 \cdot (N-1)} \\ \vdots & & \ddots & \vdots \\ \phi^{(N-1) \cdot 0} & \phi^{(N-1) \cdot 1} & \dots & \phi^{(N-1) \cdot (N-1)} \end{bmatrix}.$$

here $\phi = e^{-i2\pi/N}$
Ideal discrete-time filters
 Low-pass filter:

$$\frac{\sin(\hat{\omega}_0 n)}{\pi n} \xleftrightarrow{\mathcal{F}} u(\hat{\omega} + \hat{\omega}_0) - u(\hat{\omega} - \hat{\omega}_0)$$
 High-pass:

$$\delta[n] - \frac{\sin(\hat{\omega}_0 n)}{\pi n} \xleftrightarrow{\mathcal{F}} 1 - [u(\hat{\omega} + \omega_0) - u(\hat{\omega} - \omega_0)]$$
 Point-frequency:

$$(2\pi)^{-1} e^{i\hat{\omega}_0 n} \xleftrightarrow{\mathcal{F}} \delta(\hat{\omega} - \hat{\omega}_0)$$

Tapering windows
 Hann window

$$w[n] = \begin{cases} \sin^2(\pi n/N) & 0 \leq n \leq N - 1 \\ 0 & \text{otherwise.} \end{cases}$$

Time-frequency uncertainty
 The width of a function in time domain (Δt) is inversely proportional to width in frequency domain (Δf):

$$\Delta f \Delta t = \gamma \quad x(at) \xleftrightarrow{\mathcal{F}} |a|^{-1} \hat{x}(\omega/a)$$

where γ is a constant that depends on definition of width. E.g. diffraction limit of an optical system: $\theta \propto \lambda/D$, or frequency resolution of a filter: $\Delta f \propto 1/\Delta t$.

Linear Time-Invariant Systems
 Linearity

$$\mathcal{T}\{c_1 x_1[n] + c_2 x_2[n]\} = c_1 \mathcal{T}\{x_1[n]\} + c_2 \mathcal{T}\{x_2[n]\}$$
 Time-invariance

$$\mathcal{D}\{\mathcal{T}\{x[n]\}\} = \mathcal{T}\{\mathcal{D}\{x[n]\}\}$$

Here \mathcal{D} is time-shift: $\mathcal{D}\{x(t)\} = x(t - \tau)$.
 LTI system eigenfunction:

$$\mathcal{T}\{Ae^{i\phi} e^{i\omega t}\} = A' e^{i\phi'} e^{i\omega t}$$

Impulse response fully characterizes:

$$h(t) = \mathcal{T}\{\delta(t)\} \quad h[n] = \mathcal{T}\{\delta[n]\}$$

$$y(t) = \mathcal{T}\{x(t)\} = h(t) * x(t)$$

$$y[n] = \mathcal{T}\{x[n]\} = h[n] * x[n]$$

Frequency response:

$$\mathcal{H}(\omega) = \int_{-\infty}^{\infty} h(\tau) e^{-i\omega \tau} d\tau$$

$$\mathcal{H}(\hat{\omega}) = \sum_{n=-\infty}^{\infty} h[n] e^{-i\hat{\omega} n}$$

$$y(t) = h(t) * x(t) \xleftrightarrow{\mathcal{F}} \hat{y}(\omega) = \mathcal{H}(\omega) \hat{x}(\omega)$$

$$y[n] = h[n] * x[n] \xleftrightarrow{\mathcal{F}} \hat{y}(\hat{\omega}) = \mathcal{H}(\hat{\omega}) \hat{x}(\hat{\omega})$$

Magnitude response: $|\mathcal{H}(\omega)|$, phase response: $\angle \mathcal{H}(\omega)$. Magnitude response often reported in decibel: $10 \log_{10}(|\mathcal{H}(\omega)|^2)$,

Decibel (dB)					
dB	linear	dB	linear	dB	linear
7	5.01	0.5	1.12	40	10 ⁴
6	3.98	1	1.26	30	10 ³
3	2.00	1.5	1.41	20	10 ²
0	1.00	2	1.58	10	10
-3	0.50	5	3.16	-10	10 ⁻¹
-6	0.25	8	6.31	-20	10 ⁻²
-7	0.20	9	7.94	-30	10 ⁻³

Logarithmic scale of power $P = |z|^2$:

$$10 \log_{10}(P/P_{\text{ref}}) \quad 20 \log_{10}(|z|/P_{\text{ref}})$$

Reference power often unity: $P_{\text{ref}} = 1$
 Signal power (dBm): $P_{\text{ref}} = 10^{-3}$ W
 Radar cross-section (dBsm): $P_{\text{ref}} = 1$ m²
 Sound intensity (L_p): $P_{\text{ref}} = 1$ pW/m²

Elementary signals
 Dirac-delta (unit impulse)

$$\int_{-\infty}^{\infty} x(t) \delta(t - \tau) d\tau = x(\tau)$$
 Unit impulse

$$\delta[n] = \begin{cases} 1 & n = 0 \\ 0 & n \neq 0 \end{cases} \quad \delta(t) = \begin{cases} \rightarrow \infty & t = 0 \\ 0 & t \neq 0 \end{cases}$$

Unit-step (Heaviside-function):

$$u[n] = \begin{cases} 0 & n < 0 \\ 1 & n \geq 0 \end{cases} \quad u(t) = \begin{cases} 0 & t < 0 \\ 1 & t \geq 0 \end{cases}$$
Misc
 L'Hôpital:

$$\lim_{n \rightarrow c} \frac{f(n)}{g(n)} = \lim_{n \rightarrow c} \frac{f'(n)}{g'(n)}$$

Geometric series:

$$\sum_{k=0}^n r^k = \frac{1 - r^{n+1}}{1 - r}$$

Complex number

$$i = \sqrt{-1} \quad z = x + iy \quad z^* = x - iy$$

$$|z|^2 = zz^* \quad \angle z = \tan^{-1}(y/x) \quad z = |z|e^{i\angle z}$$

$$e^0 = 1 \quad e^{\pm i\pi} = -1 \quad e^{\pm i\pi/2} = \pm i$$
 Euler's formula:

$$e^{i\theta} = \cos(\theta) + i \sin(\theta)$$

$$\cos(\theta) = 2^{-1}(e^{i\theta} + e^{-i\theta})$$

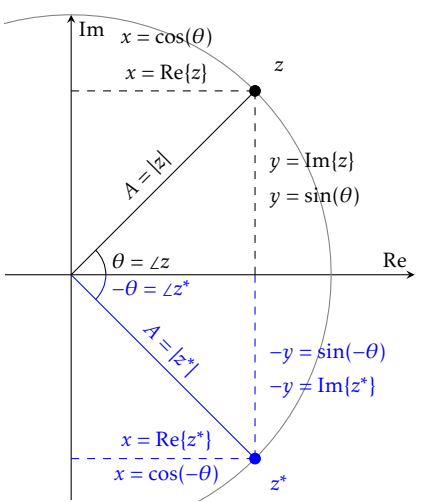
$$\sin(\theta) = (2i)^{-1}(e^{i\theta} - e^{-i\theta})$$

$$\text{Re}\{z\} = 2^{-1}(z + z^*)$$

$$\text{Im}\{z\} = (2i)^{-1}(z - z^*)$$

Nth root of unity ($z^N = 1$):

$$z = e^{i2\pi k/N} \quad k \in \{0, 1, 2, \dots, N - 1\}$$



Fast Fourier Transform

The most important signal processing algorithm. Efficient Discrete Fourier Transform implementation. $\mathcal{O}(N \log N)$ computational complexity.

Can be used for: convolution, deconvolution, differential equation solving, signal compression, spectral analysis, modulation and demodulation, interpolation and resampling, filtering, matrix diagonalization, calculating polynomial coefficients, estimating a Fourier transform or a discrete-time Fourier transform, channelizing signals (polyphase filterbank), etc.

Implementations

Python: `numpy.fft`, `scipy.fft`, `pyfftw`; C, Fortran, C++: `FFTW`, Intel MKL; `vDSP.FFT`; CUDA: `CuFFT`

Add your own notes here...