EE140 Introduction to Communication Systems

Lecture 2

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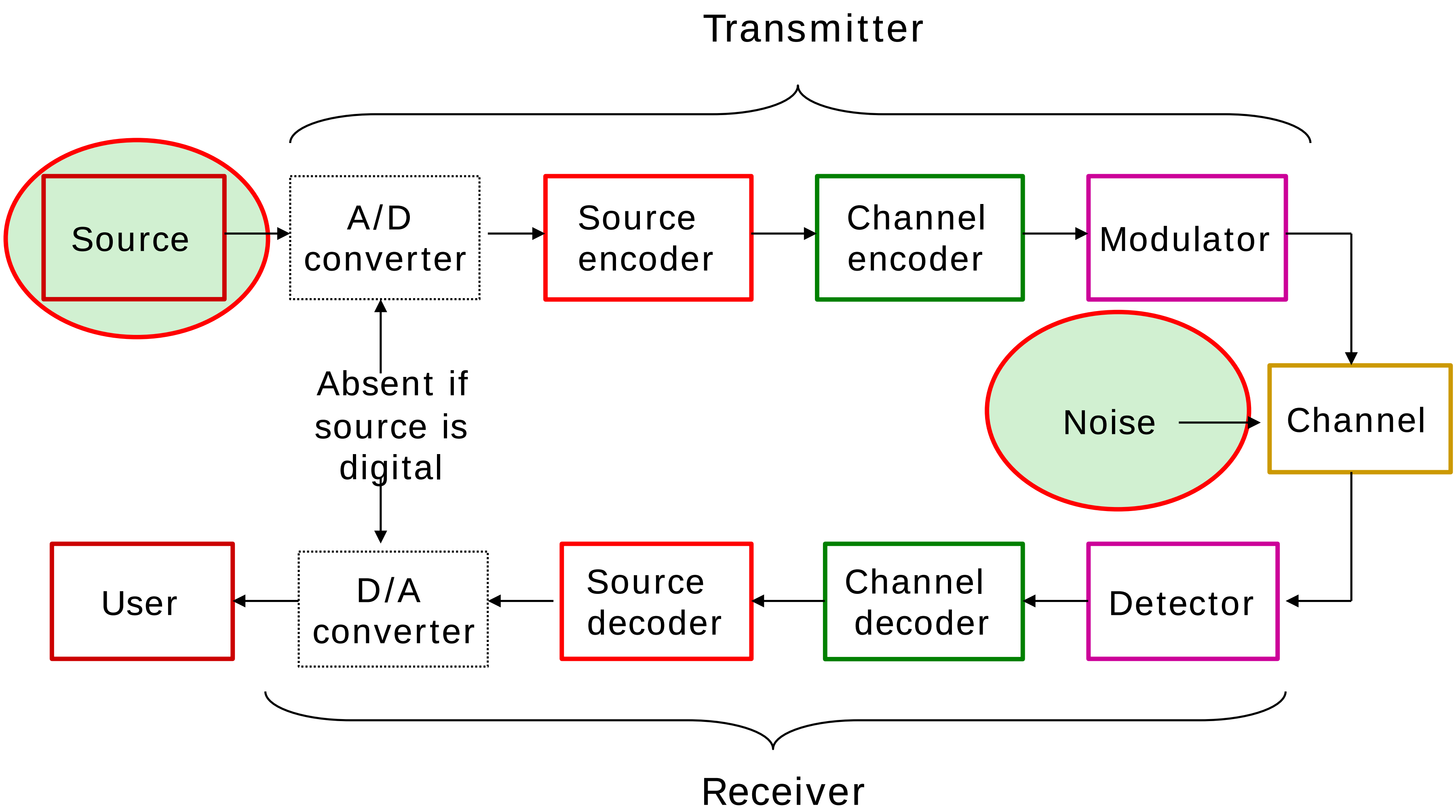
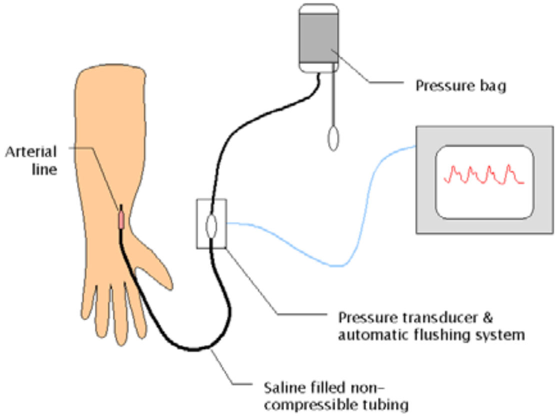
ShanghaiTech University, Fall 2022

Architecture of a Digital Communication System



Source Information

- *Message:* generated by source
- *Information:* the unpredictable part in a message
- *Signal:* a function that conveys information about the behavior or attributes of some phenomenon



Transducer: convert sensing signal to electric signal

Analog signal vs. digital signal

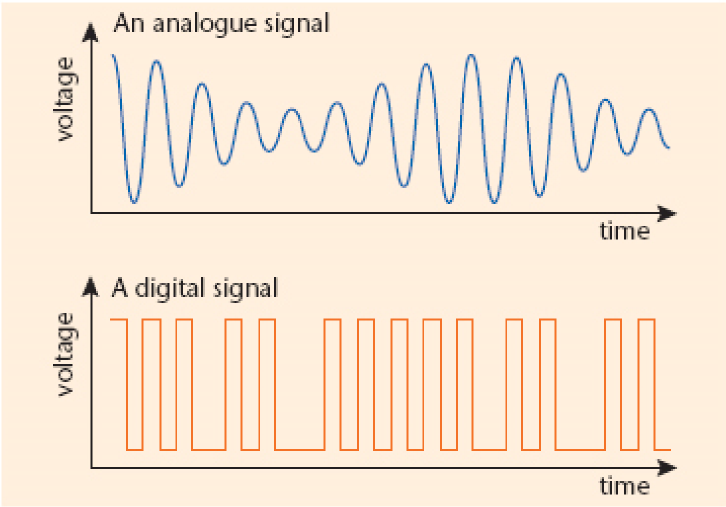


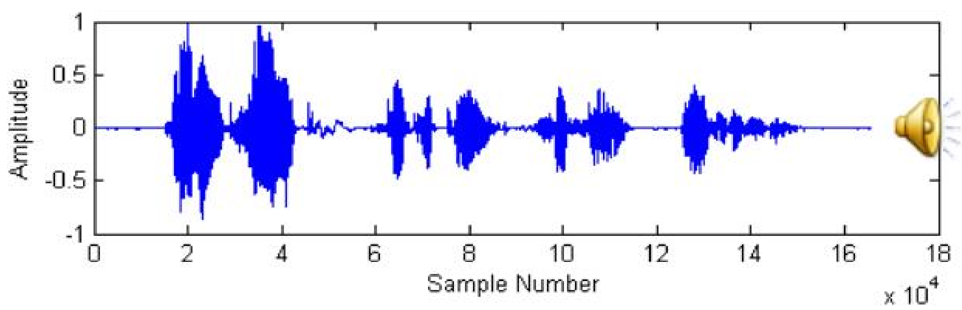
Fig. 12.4 How analogue and digital signals change with time.

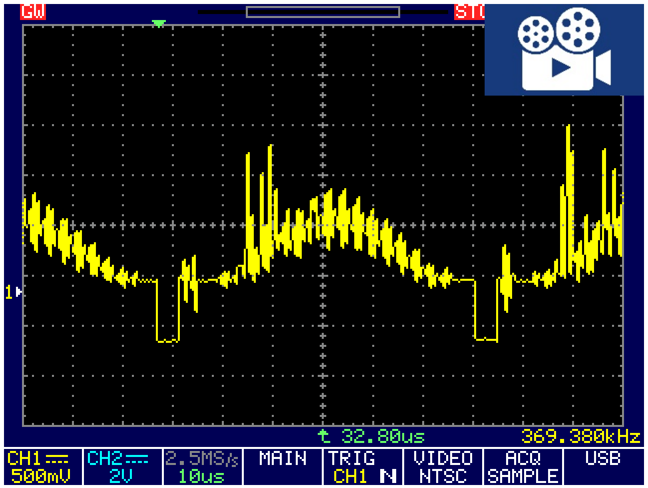
Contents

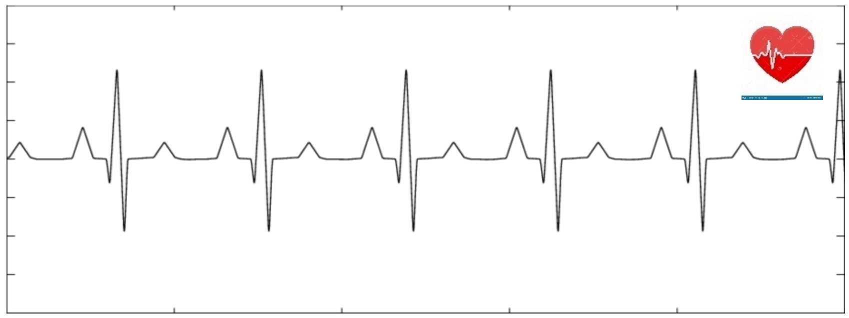
- Deterministic signals
  - Classification of signals
  - Review of Fourier Transform
  - Properties of the Fourier Transform
  - Fourier Transform of Periodic Signals
  - Sampling Theory
  - The Hilbert Transform

What is Signal?

- In communication systems, a signal is any function that carries information. Also called information bearing signal.

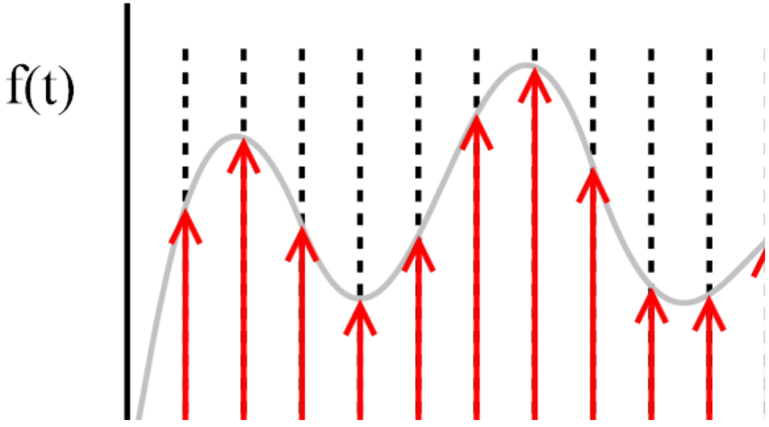




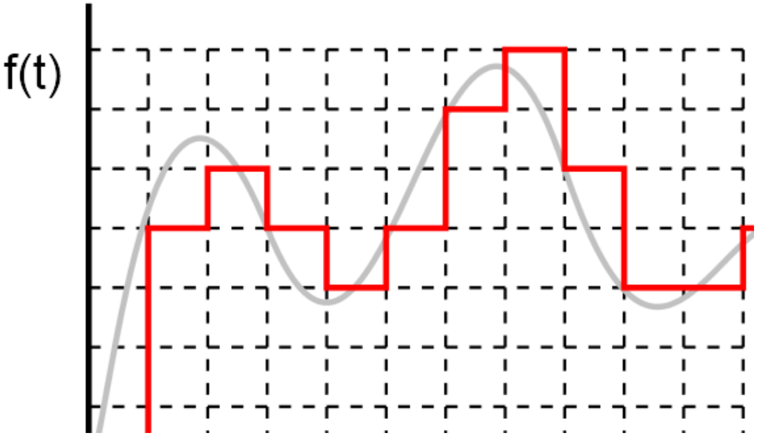


Classification of Signals

- Analog, discrete-time and digital signals
  - Analog signal: both time and value are continuous
  - Discrete-time signal: discrete time and continuous value
  - Digital signal: both time and value are discrete



Discrete-time signal

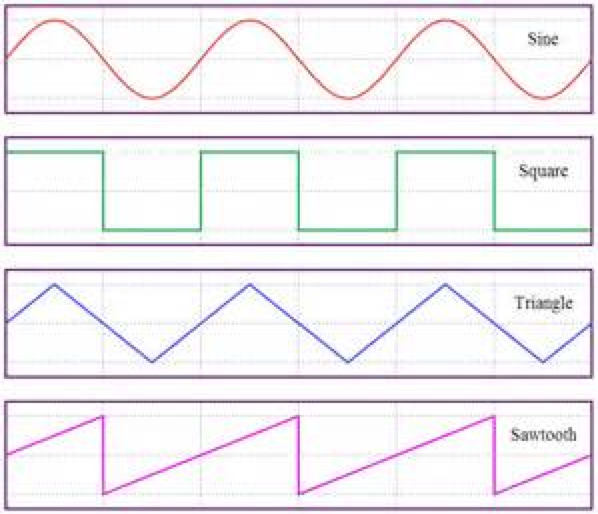


Digital signal

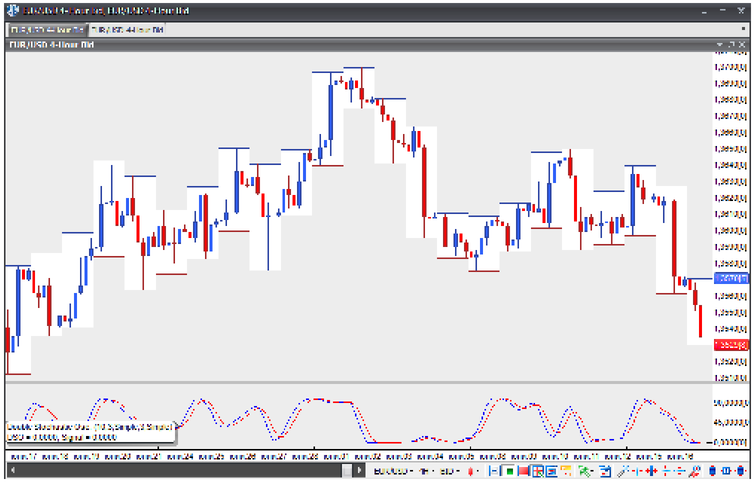
Classification of Signals

- Periodic and non-periodic signals

$$x(t + T_0) = x(t), \quad -\infty < t < \infty$$

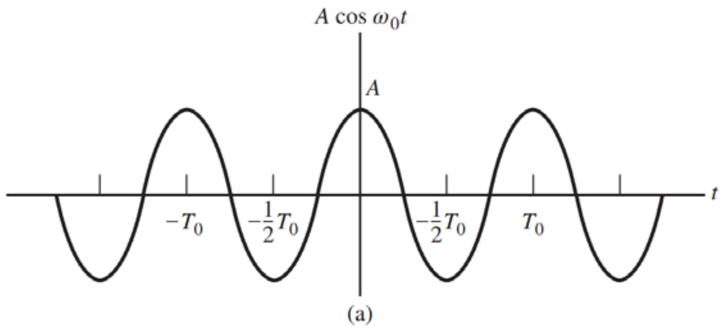


- Random and deterministic
  - Deterministic signal: no uncertainty in value. It can be modeled or expressed by an explicit mathematical function of time.
  - Random (stochastic) signal: its value is uncertain or unpredictable. Probability distribution MUST be used to model it.

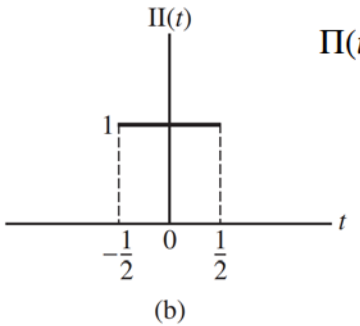


Classification of Signals

$$x(t) = A\cos\left(\omega_0 t\right), \quad -\infty < t < \infty$$

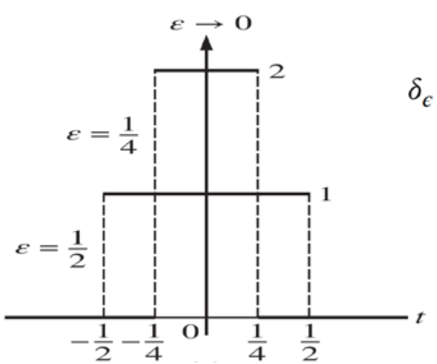


Deterministic (sinusoidal) signal



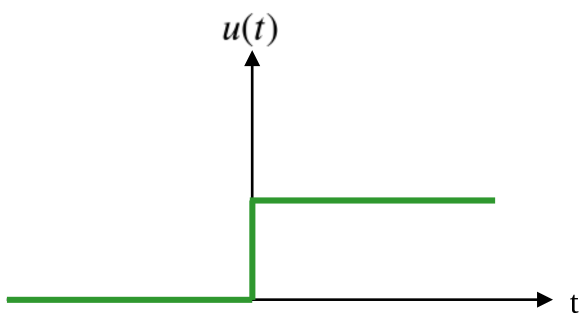
$$\Pi(t) = \begin{cases} 1, & |t| \le \frac{1}{2} \\ 0, & \text{otherwise} \end{cases}$$

Unit rectangular pulse signal



$$\delta_\epsilon(t) = \frac{1}{2\epsilon}\Pi\left(\frac{t}{2\epsilon}\right) = \begin{cases} \frac{1}{2\epsilon}, & |t| < \epsilon \\ 0, & \text{otherwise} \end{cases}$$

Unit impulse function (delta function)



Unit step function

Dirac Delta Function (cont'd)

- Sifting property: $x(t_0) = \int_{-\infty}^{\infty} x(t)\delta(t-t_0)dt$

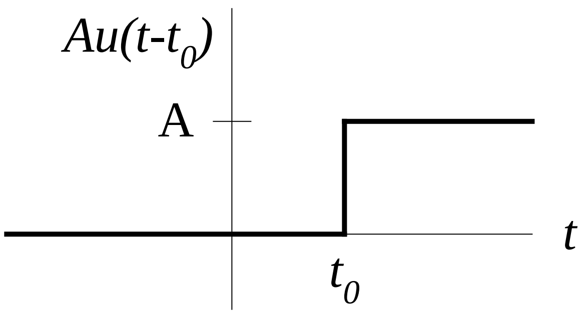
  because

  $$\int_{-\infty}^{\infty} x(t)\delta(t-t_0)dt = x(t_0)\int_{-\infty}^{\infty} \delta(t-t_0)dt = x(t_0)$$

  – The impulse function selects a particular value of the function $x(t)$ in the integration process

- Unit step function

$$u(t-t_0) = \begin{cases} 1 & t > t_0 \\ 0 & t < t_0 \end{cases}$$



- Relationship between $\delta(t)$ and $u(t)$

$$\delta(t-t_0) = \frac{d}{dt}u(t-t_0) \quad \Longleftrightarrow \quad u(t-t_0) = \int_{-\infty}^{t} \delta(\tau - t_0)\, d\tau$$

Classification of Signals

- Energy and power signals
  - Total Energy of a signal: $E = \int_{-\infty}^{\infty} |x(t)|^2 \, dt \quad \text{joules}$
  - Signal $x(t)$ is an energy signal if $\int_{-\infty}^{\infty} |x(t)|^2 \, dt < \infty$
  - Average Power of a signal: $P = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} |x(t)|^2 \, dt$ watts
  - Signal $x(t)$ is a power signal $0 < \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} |x(t)|^2 \, dt < \infty$

Exercise: Question

Classify the following signals as energy signals or power signals. Find the normalized energy or normalized power of each.

(1)

$$x(t) = \begin{cases} A\cos(2\pi f_0 t) & \text{for } -\mathrm{T}_0/2 \leq \mathrm{t} \leq \mathrm{T}_0/2, \text{where } \mathrm{T}_0 = 1/\mathrm{f}_0 \\ 0 & \text{elsewhere} \end{cases}$$

(2)

$$x(t) = \begin{cases} A\exp(-at) & \text{for t} > 0, \mathrm{a} > 0 \\ 0 & \text{elsewhere} \end{cases}$$

Exercise: Solution

Classify the following signals as energy signals or power signals. Find the normalized energy or normalized power of each.

(1)

$$x(t) = \begin{cases} A\cos(2\pi f_0 t) & \text{for } -\mathrm{T_0/2} \le \mathrm{t} \le \mathrm{T_0/2}, \text{where } \mathrm{T_0} = 1/\mathrm{f_0} \\ 0 & \text{elsewhere} \end{cases}$$

(2)

$$x(t) = \begin{cases} A\exp(-at) & \text{for } \mathrm{t} > 0, \mathrm{a} > 0 \\ 0 & \text{elsewhere} \end{cases}$$

Solution 1

(1) Energy signal. $E_x = \int_{-\infty}^{\infty} x^2(t)\,dt = \int_{-T_0/2}^{T_0/2} A^2\cos^2(2\pi f_0 t)\,dt = \frac{A^2 T_0}{2}$.

(2) Energy signal. $E_x = \int_{-\infty}^{\infty} x^2(t)\,dt = \int_0^{\infty} A^2\exp(-2at)\,dt = \frac{A^2\exp(-2at)}{-2a}\Big|_0^{\infty} = \frac{A^2}{2a}$.

Contents

- Deterministic signals
  - Classification of signals
  - Review of Fourier Transform
    - Fourier Transform
    - Discrete-time Fourier Transform (skip)
    - Discrete Fourier Series (skip)
    - Discrete Fourier Transform (skip)
    - Fast Fourier Transform (skip)
  - Properties of the Fourier Transform
  - Fourier Transform of Periodic Signals
  - Sampling Theory
  - The Hilbert Transform

Fourier Series

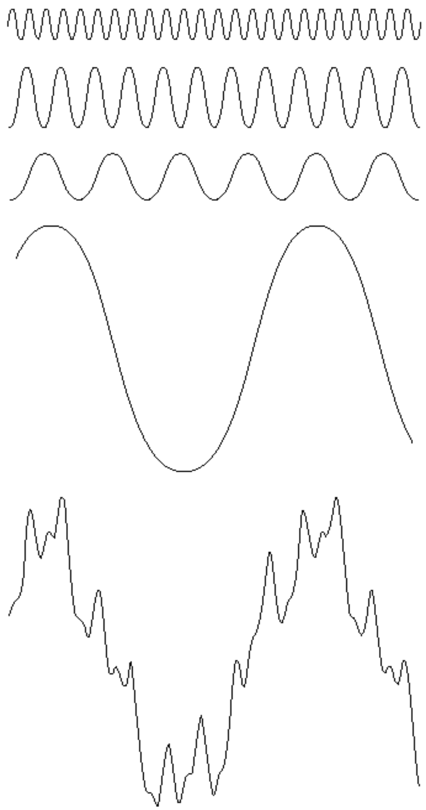


FIGURE 4.1 The function at the bottom is the sum of the four functions above it. Fourier's idea in 1807 that periodic functions could be represented as a weighted sum of sines and cosines was met with skepticism.

A periodic function = superposition or linear combination of simple sine and cosine functions

- Jean-Baptiste Joseph Fourier: 1768-1830
- Student of Laplace and Lagrange
- 1807: introduced the Fourier series expansion

Fourier Transform

- Fourier Transform of a continuous-time signal

$$\boxed{X(f) = \mathfrak{F}[x(t)] \Longleftrightarrow X(f) = \int_{-\infty}^{\infty} x(\lambda)\, e^{-j2\pi f \lambda}\, d\lambda}$$

if x(t) is absolutely integrable $\int_{-\infty}^{\infty} |x(t)|\, dt < \infty$

- Inverse Fourier Transform

$$\boxed{x(t) = \mathfrak{F}^{-1}[X(f)] \Longleftrightarrow x(t) = \int_{-\infty}^{\infty} X(f)\, e^{j2\pi f t}\, df}$$

- Spectrum
  - The Fourier transform of a continuous-time signal is a complex signal

$$X(f) = |X(f)| e^{j\angle X(f)}$$

Parseval's Theorem

- Parseval's Theorem

$$\int_{-\infty}^{\infty} x_1(t)x_2^*(t)dt = \int_{-\infty}^{\infty} X_1(f)X_2^*(f)df$$

  – When $x_1(t) = x_2(t)$, we have

$$E = \int_{-\infty}^{\infty} |x(t)|^2 dt = \int_{-\infty}^{\infty} |X(f)|^2 df$$

Energy

Energy Spectral Density

- Energy Spectral Density

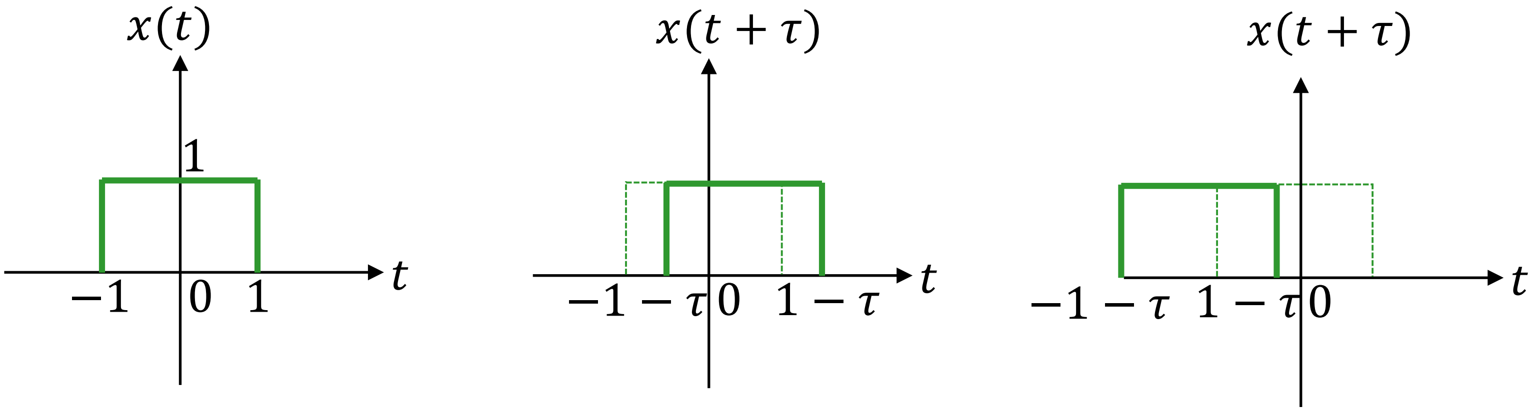
$$G(f) = |X(f)|^2 \text{ Joules/Hz}$$

Power Spectral Density and Correlation

	Energy Signal	Power Signal
Spectral density	Energy Spectral Density $E = \int_{-\infty}^{\infty} \lvert x(t)\rvert^2 \, dt = \int_{-\infty}^{\infty} \lvert X(f)\rvert^2 df$ $G(f) = \lvert X(f)\rvert^2$	$P = \int_{-\infty}^{\infty} S(f) df = \langle x^2(t) \rangle$
Time-average autocorrelation function	$\phi(\tau) = x(\tau) * x(-\tau) = \int_{-\infty}^{\infty} x(\lambda)x(\lambda+\tau)\, d\lambda$ $= \lim_{T\to\infty} \int_{-T}^{T} x(\lambda)x(\lambda+\tau)\, d\lambda$ (energy sign	$R(\tau) = \langle x(t)x(t+\tau) \rangle$ $\triangleq \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t)x(t+\tau)\, dt$
Relationship	$\phi(t) = \mathfrak{F}^{-1}(G(f))$ $G(f) = \mathfrak{F}(\phi(t))$	$R(\tau) = \mathfrak{F}^{-1}[S(f)] = \int_{-\infty}^{\infty} S(f)e^{j2\pi f\tau}\, df$ $S(f) = \mathfrak{F}[R(\tau)] = \int_{-\infty}^{\infty} R(\tau)\, e^{-j2\pi f\tau}\, d\tau$

Example: Autocorrelation Function

- Energy Signal

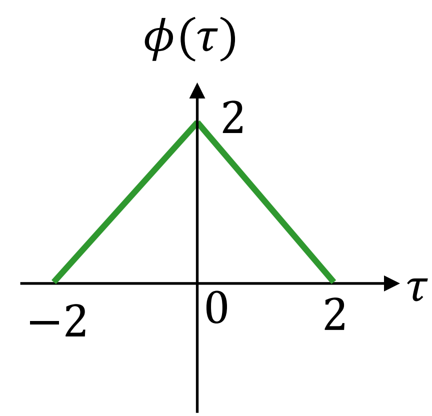


$$\tau = 0, \phi(0) = \int_{-1}^{1} x(t)x(t)dt = 2$$

$$-2 < \tau < 0, \phi(\tau) = \int_{-1-\tau}^{1} x(t)x(t+\tau)dt = 2 + \tau$$

$$0 < \tau < 2, \phi(\tau) = \int_{-1}^{1-\tau} x(t)x(t+\tau)dt = 2 - \tau$$

$$|\tau| \geq 2, \phi(\tau) = 0$$



1. $\phi(\tau)$ is even.
2. $\phi(0) \geq |\phi(\tau)|$.

Example: Rectangular Pulse

$$x(t) = A\Pi\left(\frac{t-t_0}{\tau}\right) \quad \Longrightarrow \quad X(f) = \int_{-\infty}^{\infty} A\Pi\left(\frac{t-t_0}{\tau}\right) e^{j2\pi ft}\,dt$$

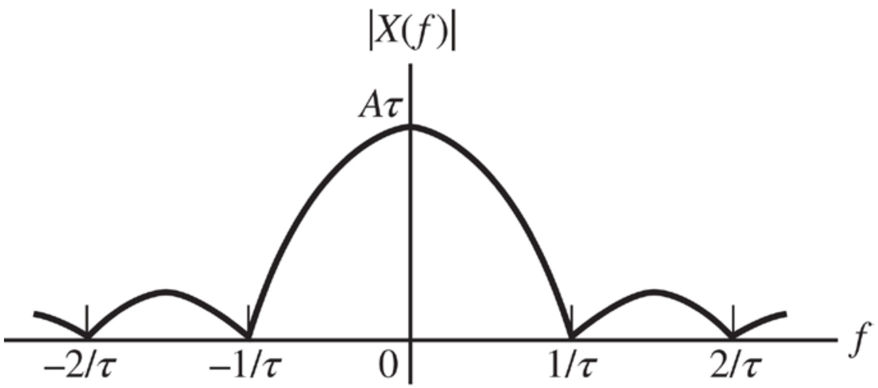
$$= A\int_{t_0-\tau/2}^{t_0+\tau/2} e^{-j2\pi ft}\,dt = A\tau\,\text{sinc}\,(f\tau)\,e^{-j2\pi f t_0}$$

Amplitude spectrum

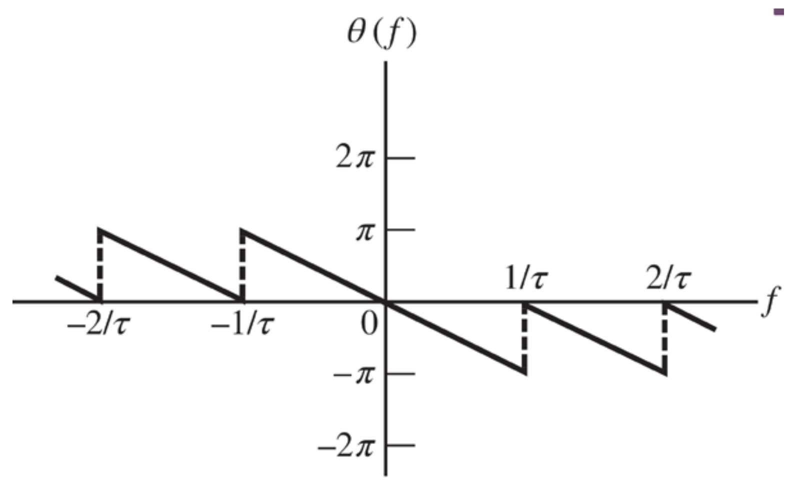
$$|X(f)| = A\tau\left|\text{sinc}\,(f\tau)\right|$$

Phase spectrum

$$\theta(f) = \begin{cases} -2\pi t_0 f & \text{if sinc}\,(f\tau) > 0 \\ -2\pi t_0 f \pm \pi & \text{if sinc}\,(f\tau) < 0 \end{cases}$$



(a)

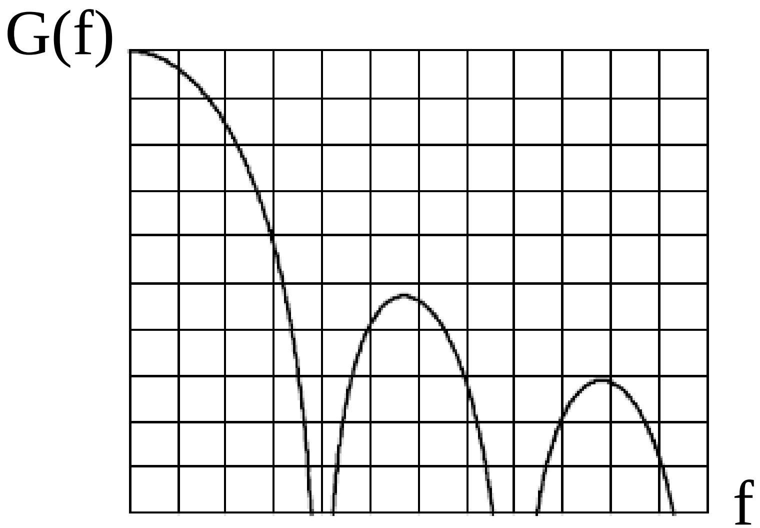


(b)

Example: Rectangular Pulse

- Energy spectral density

$$G(f) = |X(f)|^2 = A^2\tau^2 \mathrm{sinc}^2(f\tau)$$



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Properties of Fourier Transform

Operation	$x(t)$	$X(f)$
1. Superposition	$a_1x_1(t)+a_2x_2(t)$	$a_1X_1(f)+a_2X_2(f)$
2. Scaling	$x(at)$	$\frac{1}{\lvert a\rvert}X(\frac{f}{a})$
3. Time shifting	$x(t-t_0)$	$X(f)\exp(-j2\pi f t_0)$
4. Frequency shifting	$x(t)\exp(j2\pi f_0 t)$	$X(f-f_0)$
5. Duality theorem	$X(t)$	$x(-f)$
6. Modulation Theorem	$x(t)\cos(2\pi f_0 t)$	$\frac{1}{2}X(f-f_0)+\frac{1}{2}X(f+f_0)$
7. Time differentiation	$\frac{d^n x}{dt^n}$	$(j2\pi f)^n X(f)$
8. Frequency differentiation	$(-jt)^n x(t)$	$\frac{d^n X}{df^n}$
9. Time integration	$\int_{-\infty}^{t} x(\tau)d\tau$	$\frac{1}{j2\pi f}X(f)+\frac{1}{2}X(0)\delta(f)$
10. Time convolution	$x_1(t)*x_2(t)$	$X_1(f)X_2(f)$
11. Multiplication	$x_1(t)x_2(t)$	$X_1(f)*X_2\ (f)$

Example: Dirac Delta Function

- Dirac delta function

$$\delta(t) = \begin{cases} \infty & t = 0, \\ 0 & t \neq 0, \end{cases}$$

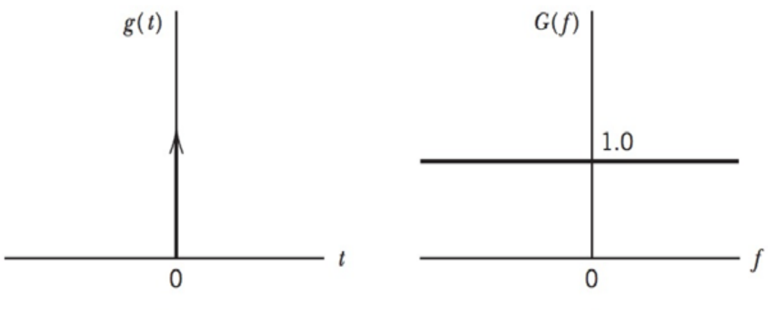
and

$$\int_{-\infty}^{\infty} \delta(t) dt = 1$$

- Fourier transform

$$G(f) = \mathrm{F}[\delta(t)] = \int_{-\infty}^{\infty} \delta(t)\, e^{-j2\pi f t} dt$$

$$= \int_{-\infty}^{\infty} \delta(t)\, e^{-j2\pi f 0} dt = e^{0} = 1$$



(a) (b)

Example: Dirac Delta Function

- Application of the delta function

1. $A\delta(t) \longleftrightarrow A$

2. $A\delta(t - t_0) \longleftrightarrow Ae^{-j2\pi f t_0}$

3. $A \longleftrightarrow A\delta(f)$

4. $Ae^{j2\pi f_0 t} \longleftrightarrow A\delta(f - f_0)$

$$\cos(2\pi f_c t) \rightleftharpoons \frac{1}{2}\left[\delta(f - f_c) + \delta(f + f_c)\right]$$

$$\sin(2\pi f_c t) \rightleftharpoons \frac{1}{2j}\left[\delta(f - f_c) - \delta(f + f_c)\right]$$

Definition of delta function

$$\int_{-\infty}^{\infty} \cos(2\pi f t)\, dt = \delta(f)$$

$$\int_{-\infty}^{\infty} \exp(-j2\pi f t)\, dt = \delta(f)$$

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Line Spectra for Periodic Signal

- Periodic signal $x(t)$ with period T_0

$$X(f) = \mathrm{F}[x(t)] = \int_{-\infty}^{\infty} x(t)\, e^{-j2\pi f t} dt$$

$$= \int_{-\infty}^{\infty} \left(\sum_{n=-\infty}^{\infty} X_n e^{j2\pi n f_0 t} \right) e^{-j2\pi f t} dt$$

$$= \sum_{n=-\infty}^{\infty} X_n \int_{-\infty}^{\infty} e^{-j2\pi(f-nf_0)t} dt$$

$$= \sum_{n=-\infty}^{\infty} X_n \delta(f - nf_0)$$

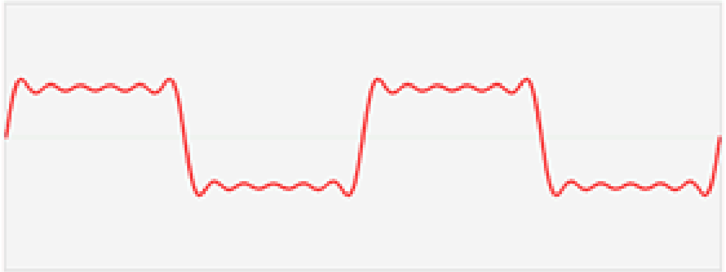
Fourier series

$$X_n = \frac{1}{T_0} \int_{t_0}^{t_0+T_0} x(t)\, e^{-jn\omega_0 t} dt$$

Continuous Periodic

FT

Discrete



Example: The “Comb” Function

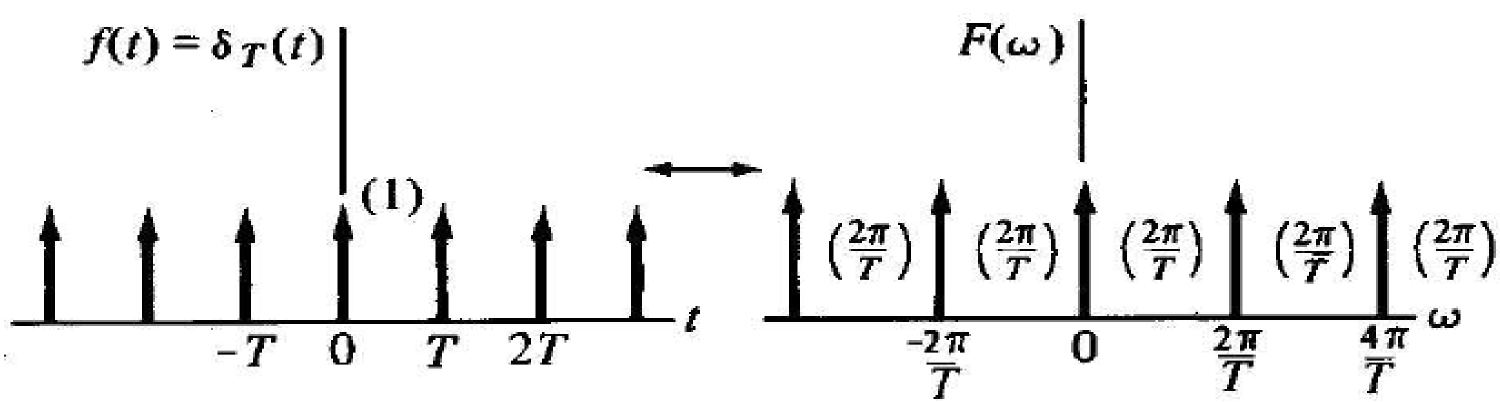
- The “comb” function:

$$\delta_T(t) = \sum_{m=-\infty}^{\infty} \delta(t - mT)$$

- FT 1: $$\delta_T(t) = \sum_{m=-\infty}^{\infty} \delta(t - mT) = \sum_{n=-\infty}^{\infty} X_n\, e^{jn2\pi f_0 t}, f_0 = \frac{1}{T}$$

$$X_n = \frac{1}{T}\int_T \delta(t)\, e^{-jn2\pi f_0 t} dt = f_0$$

$$\delta_T(t) = \sum_{n=-\infty}^{\infty} f_0\, e^{jn2\pi f_0 t} \Longleftrightarrow \mathfrak{F}[\delta_T(t)] = \sum_{n=-\infty}^{\infty} f_0\, \delta(f - nf_0)$$



Example: The “Comb” Function

- The “comb” function:

$$\delta_T(t) = \sum_{m=-\infty}^{\infty} \delta(t - mT)$$

- FT 2:

$$\Im\left[\sum_{m=-\infty}^{\infty} \delta(t - mT\ )\right] = \int_{-\infty}^{\infty}\left[\sum_{m=-\infty}^{\infty} \delta(t - mT_s)\right] e^{-j2\pi ft}\,dt$$

$$= \sum_{m=-\infty}^{\infty} \int_{-\infty}^{\infty} \delta(t - mT_s) e^{-j2\pi ft}\,dt$$

$$= \sum_{m=-\infty}^{\infty} e^{-j2\pi mT_s f}$$

$$\boxed{\sum_{m=-\infty}^{\infty} e^{j2\pi mTf} = f_0 \sum_{n=-\infty}^{\infty} \delta(f - nf_0)}$$

Fourier Series

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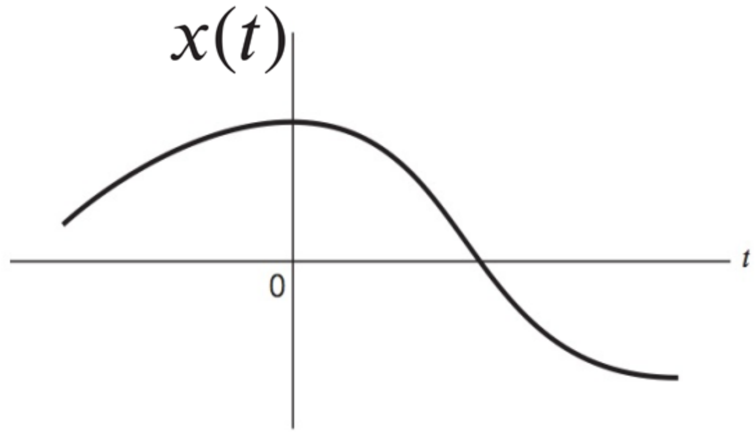
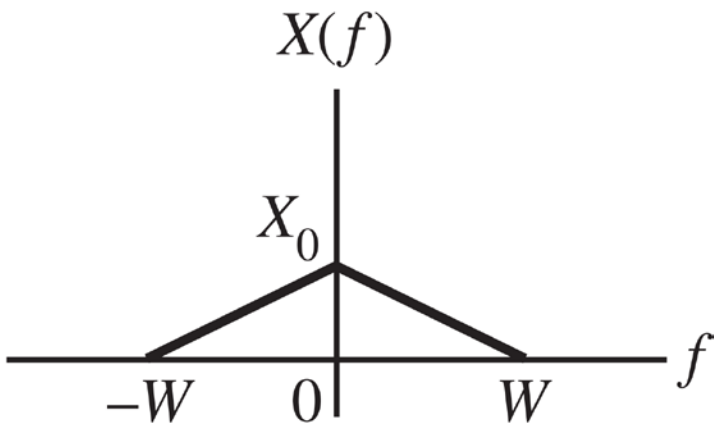
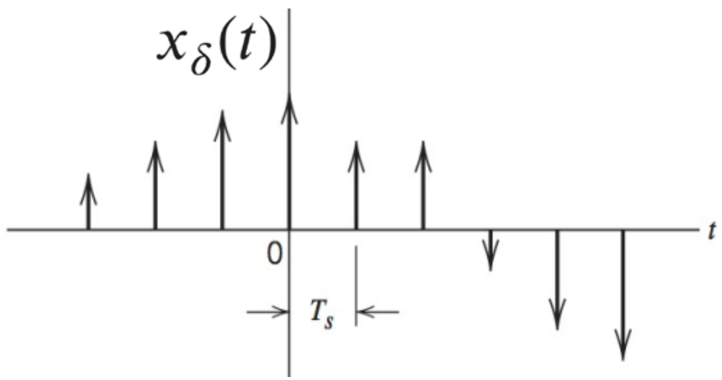
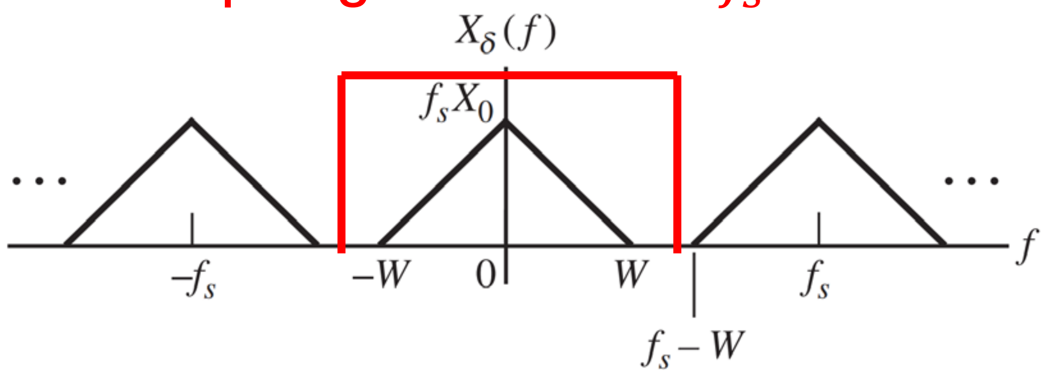
Sampling Theory





Sampling theorem: $f_s \geq 2W$





$$x_\delta(t) = \sum_{n=-\infty}^{\infty} x(nT_s)\delta(t - nT_s)$$

$$X_\delta(f) = f_s \sum_{n=-\infty}^{\infty} X(f - nf_s)$$

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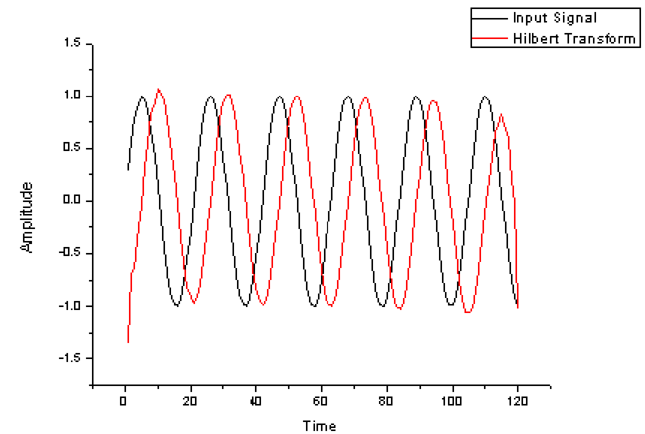
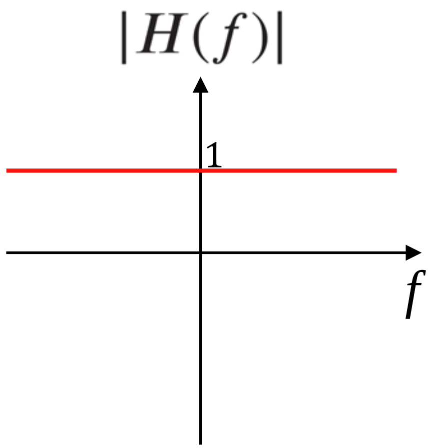
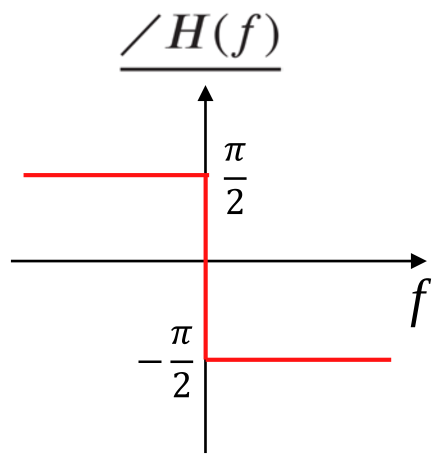
Hilbert Transform

- Frequency response function

$$H(f) = -j \operatorname{sgn} f \quad \operatorname{sgn}(f) = \begin{cases} 1, & f > 0 \\ 0, & f = 0 \\ -1, & f < 0 \end{cases}$$







$$\boxed{\frac{j}{\pi t} \longleftrightarrow \operatorname{sgn}(f)}$$

- Hilbert Transform of x(t): $\hat{x}(t) = \mathfrak{F}^{-1}[\boxed{-j \operatorname{sgn}(f)} X(f)]$

$$= h(t) * x(t)$$

Hilbert Transform

- Hilbert Transform of x(t):

$$\hat{x}(t) = \mathfrak{I}^{-1}[-j\ \mathrm{sgn}\,(f)X(f)]$$

$$= h(t) * x(t)$$

$$\hat{x}(t) = \int_{-\infty}^{\infty} \frac{x(\lambda)}{\pi(t-\lambda)} d\lambda = \int_{-\infty}^{\infty} \frac{x(t-\eta)}{\pi\eta} d\eta$$

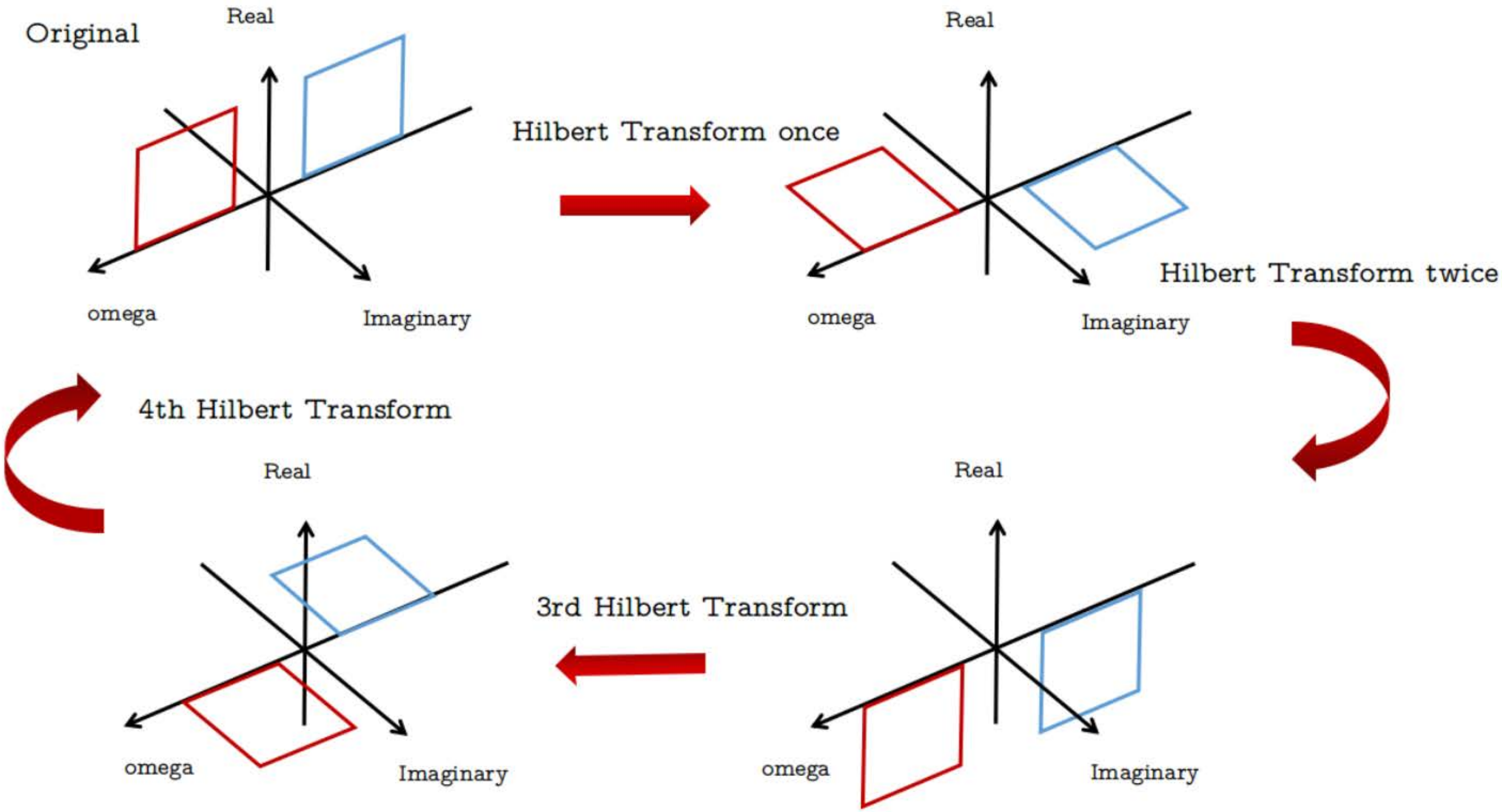
- Hilbert transform of Hilbert transform

$$(-j\ \mathrm{sgn}\ f)^2 = -1$$

$$\hat{\hat{x}}(t) = -x(t).$$

Hilbert Transform

- Hilbert Transform of x(t):



Example

- Calculate the Hilbert transform filter of

$$x(t) = \cos\left(2\pi f_0 t\right)$$

- Solution:

$$X(f) = \frac{1}{2}\delta(f - f_0) + \frac{1}{2}\delta(f + f_0)$$

$$\widehat{X}(f) = \frac{1}{2}\delta(f - f_0)e^{-j\pi/2} + \frac{1}{2}\delta(f + f_0)e^{j\pi/2}$$

$$\widehat{x}(t) = \frac{1}{2}e^{j2\pi f_0 t}e^{-j\pi/2} + \frac{1}{2}e^{-j2\pi f_0 t}e^{j\pi/2}$$

$$\widehat{\cos(2\pi f_0 t)} = \sin\left(2\pi f_0 t\right)$$

Properties (P84)

1. Energy in a signal and its Hilbert transform are equal.

$$\left|\widehat{X}(f)\right|^2 \triangleq \left|\mathfrak{F}\left[\widehat{x}(t)\right]\right| = |-j \text{ sgn } (f)|^2 \, |X(f)|^2 = |X(f)|^2$$

2. A signal and its Hilbert transform are orthogonal

$$\int_{-\infty}^{\infty} x(t)\widehat{x}(t)\, dt = 0 \text{ (energy signals)}$$

3. If c(t) and m(t) are signals with nonoverlapping spectra, where m(t) is lowpass and c(t) is highpass, then

$$\widehat{m(t)c(t)} = m(t)\widehat{c}(t)$$

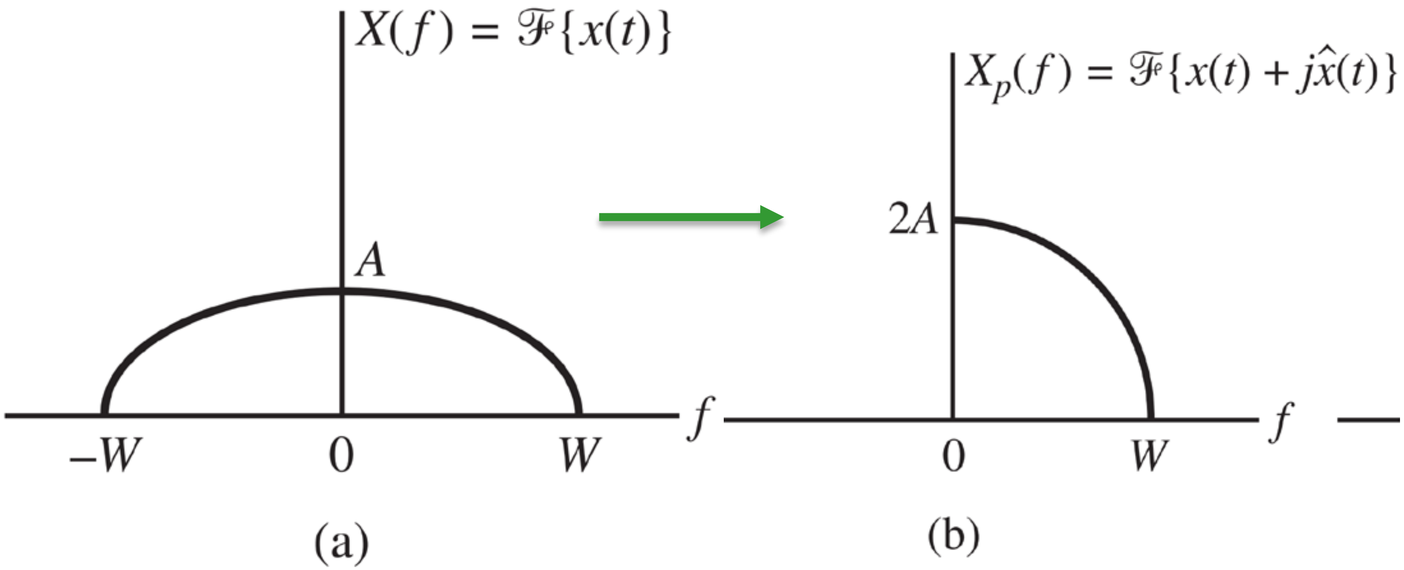
Analytic Signals

- The analytic signal of the real signal x(t) is

$$x_p(t) = x(t) + j\hat{x}(t)$$

- Envelope: $|x_p(t)| = \sqrt{x(t)^2 + \hat{x}(t)^2}$
- Spectrum:

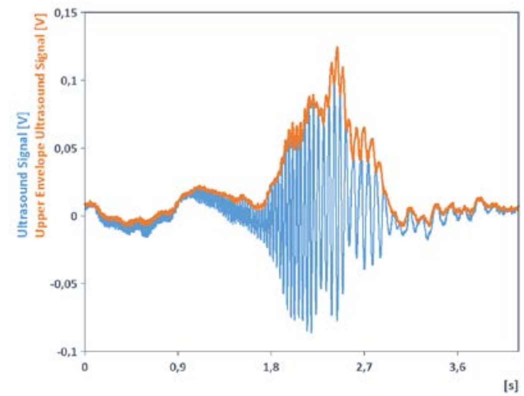
$$X_p(f) = X(f)\left[1 + \operatorname{sgn} f\right]$$



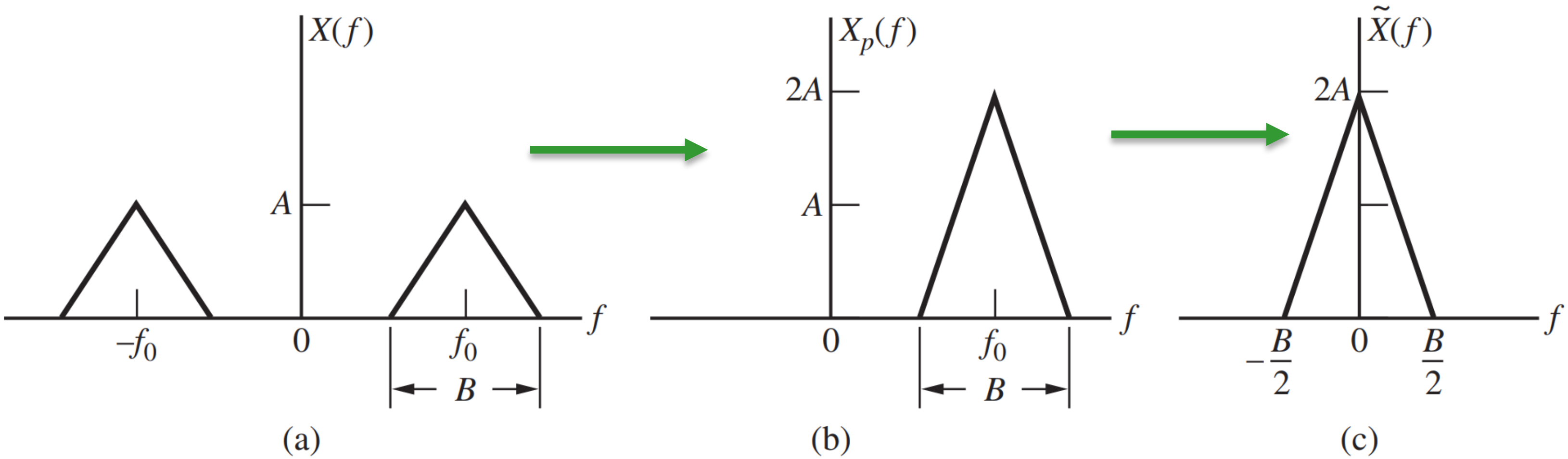
Complex Envelope

- The analytic signal can be written as

$$x_p(t) = \widetilde{x}(t)e^{j2\pi f_0 t}$$



- $\tilde{x}(t)$: complex envelope of x(t)
- f_0: reference frequency
- Spectrum:



Bandpass signal → lowpass signal

Inphase and Quadrature Components

- Since

$$x_p(t) = \widetilde{x}(t)e^{j2\pi f_0 t} \triangleq x(t) + j\widehat{x}(t)$$

- Thus

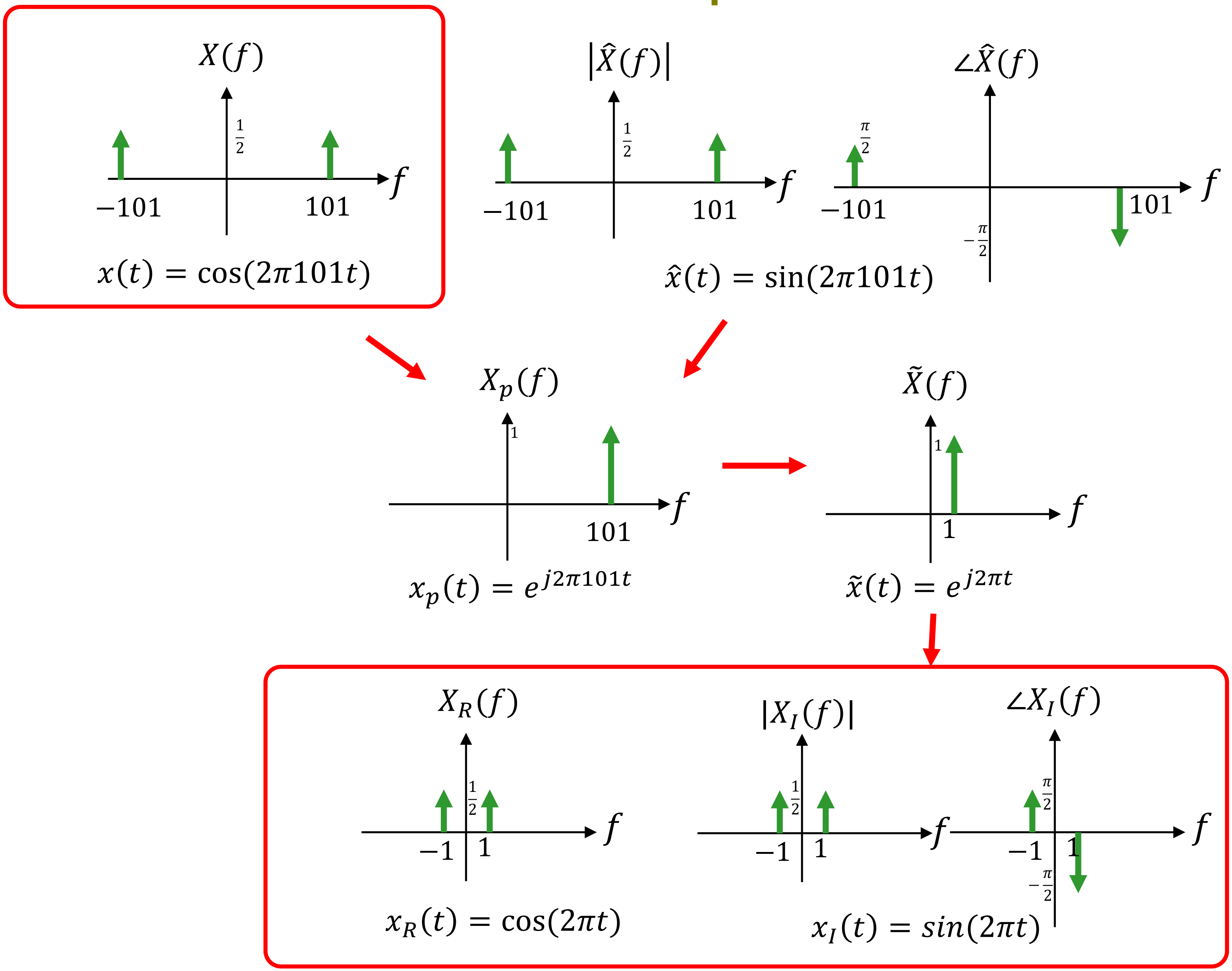
$$\begin{aligned} x(t) &= \text{Re}\left[\widetilde{x}(t)e^{j2\pi f_0 t}\right] \\ &= \underline{\text{Re}\left[\widetilde{x}(t)\right]} \cos\left(2\pi f_0 t\right) - \underline{\text{Im}\left[\widetilde{x}(t)\right]} \sin\left(2\pi f_0 t\right) \\ &= x_R(t)\cos(2\pi f_0 t) - x_I(t)\sin(2\pi f_0 t) \end{aligned}$$

Inphase component of x(t)

Quadrature component of x(t)

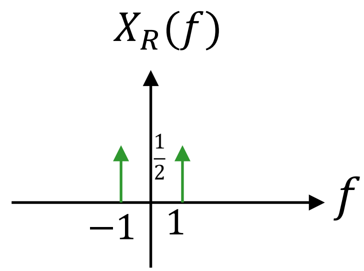
Example

$f_0 = 100Hz$

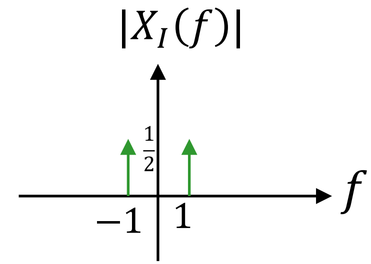


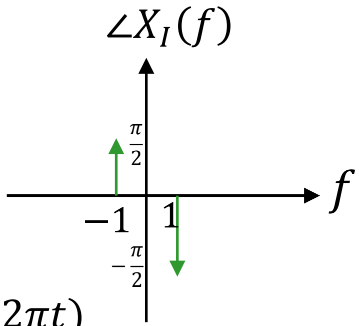
Example

$f_0 = 100Hz$

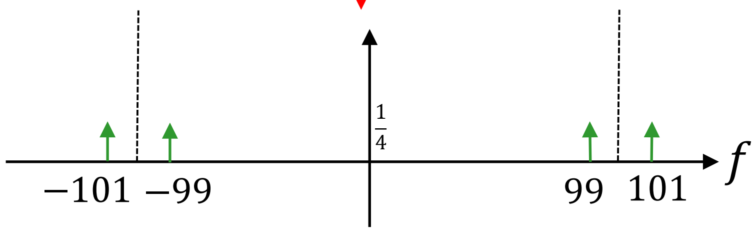


$x_R(t) = \cos(2\pi t)$

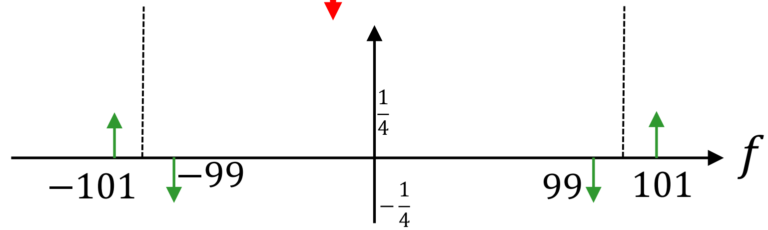




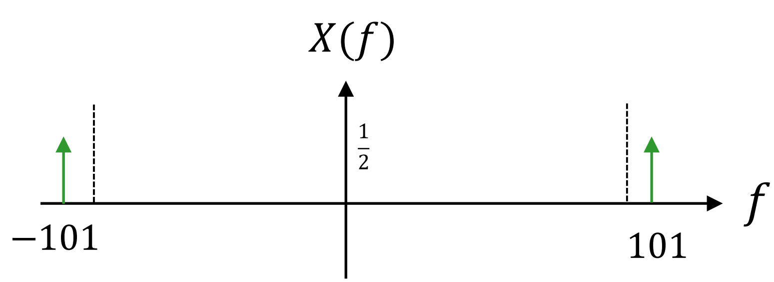
$x_I(t) = sin(2\pi t)$



$x_R(t)\cos(2\pi 100t)$



$-x_I(t)\sin(2\pi 100t)$



$x(t) = \cos(2\pi 101t)$

Thanks for your kind attention!

Questions?