Overview of Signal Processing

Chapter Intended Learning Outcomes:

(i) Understand basic terminology in signal processing

(ii) Differentiate digital signal processing and analog signal processing

(iii) Describe basic signal processing application areas

Signal:

- Anything that conveys information, e.g.,
  - Speech
  - Electrocardiogram (ECG)
  - Radar pulse
  - Medical image
  - Stock price
  - Orthogonal frequency division multiplexing waveform
  - Video
  - Smell

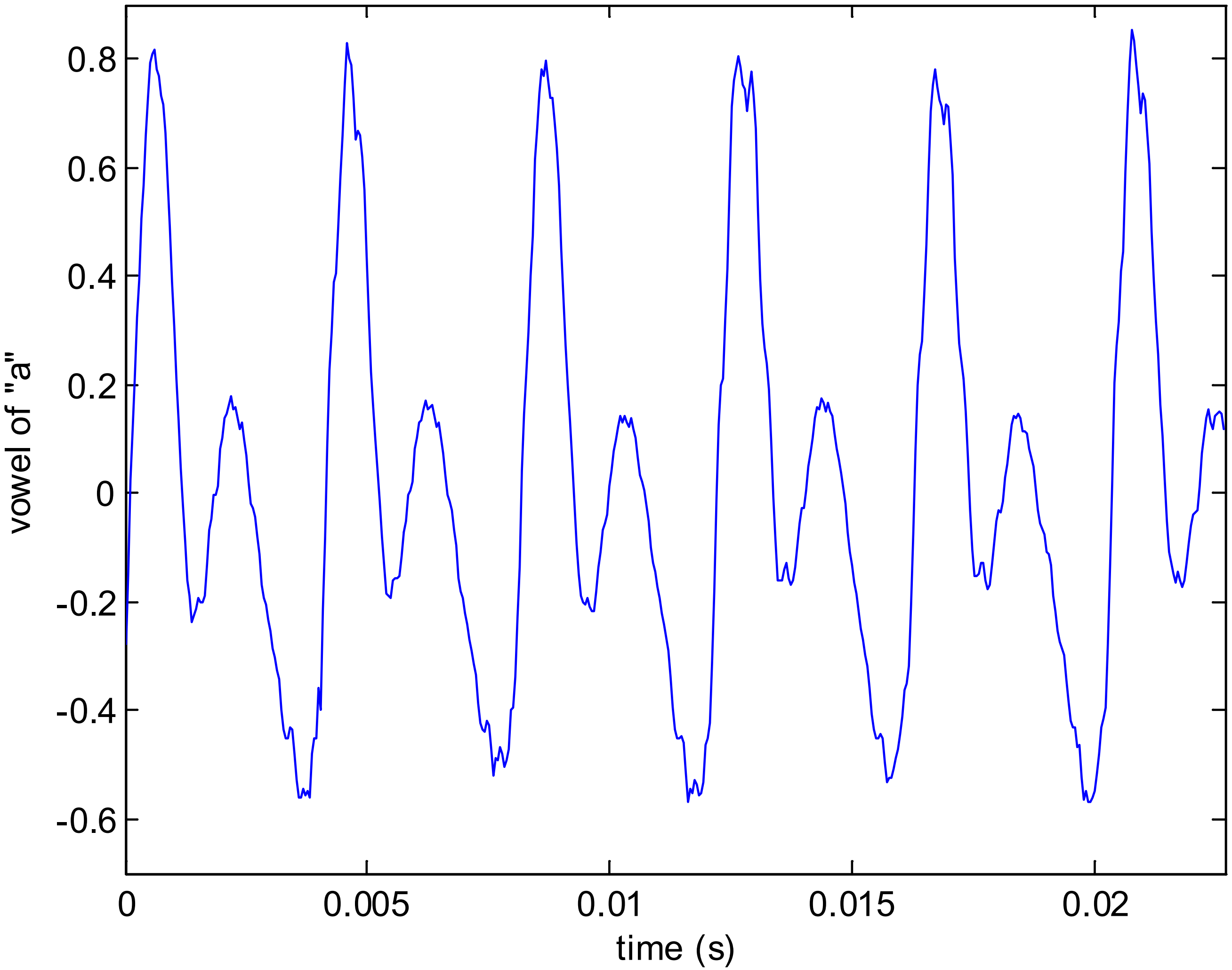


Fig.1.1: Speech

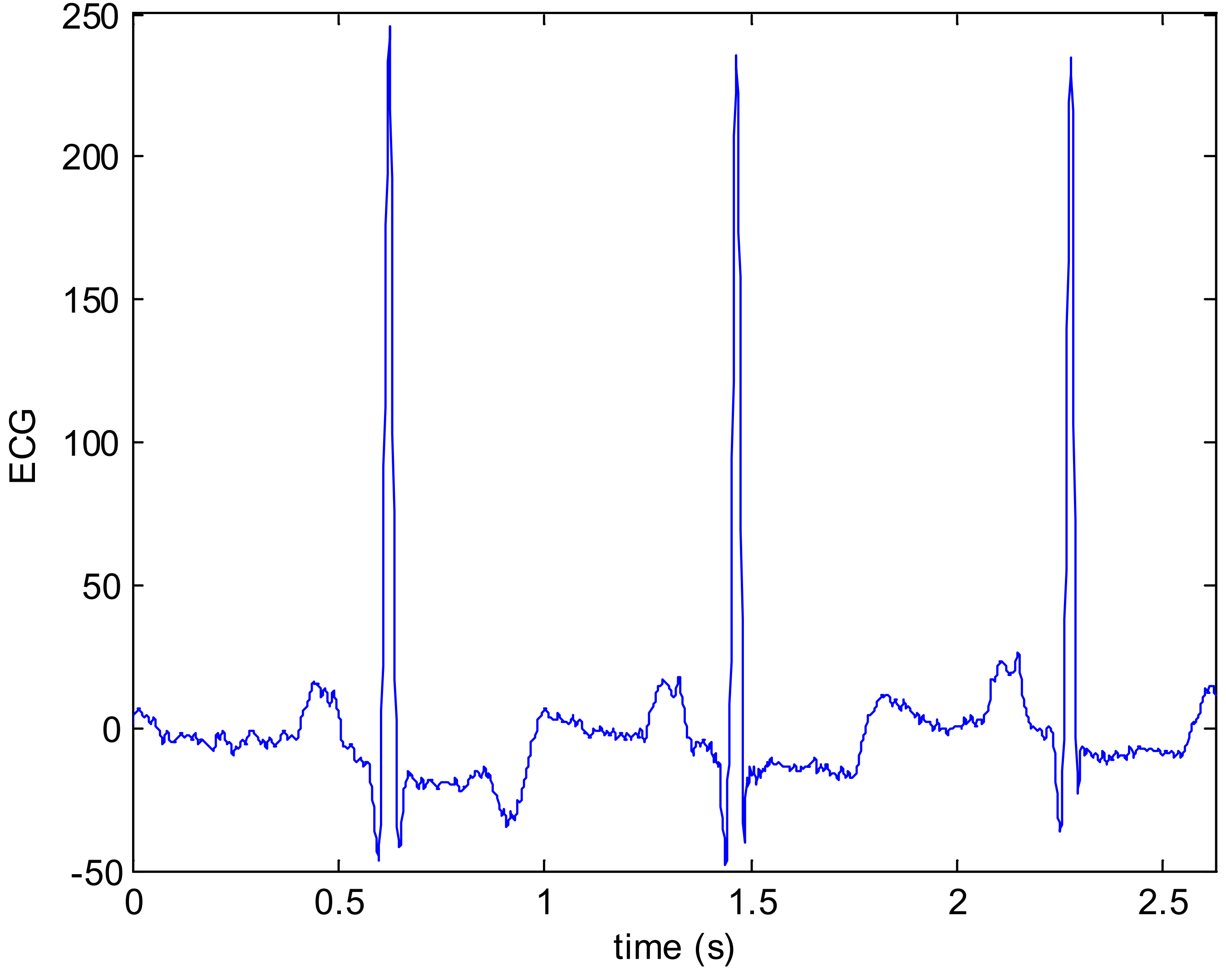


Fig.1.2: ECG

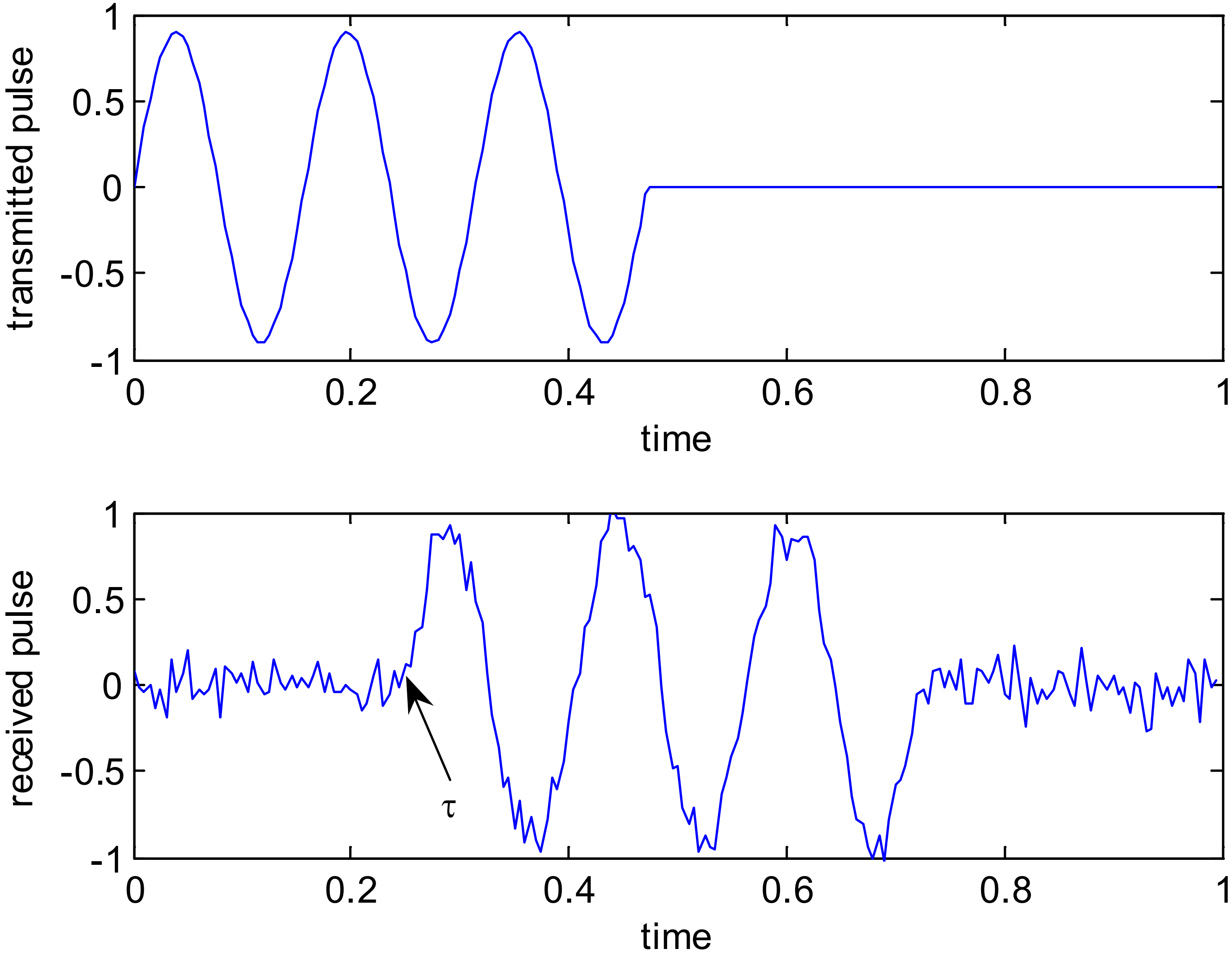
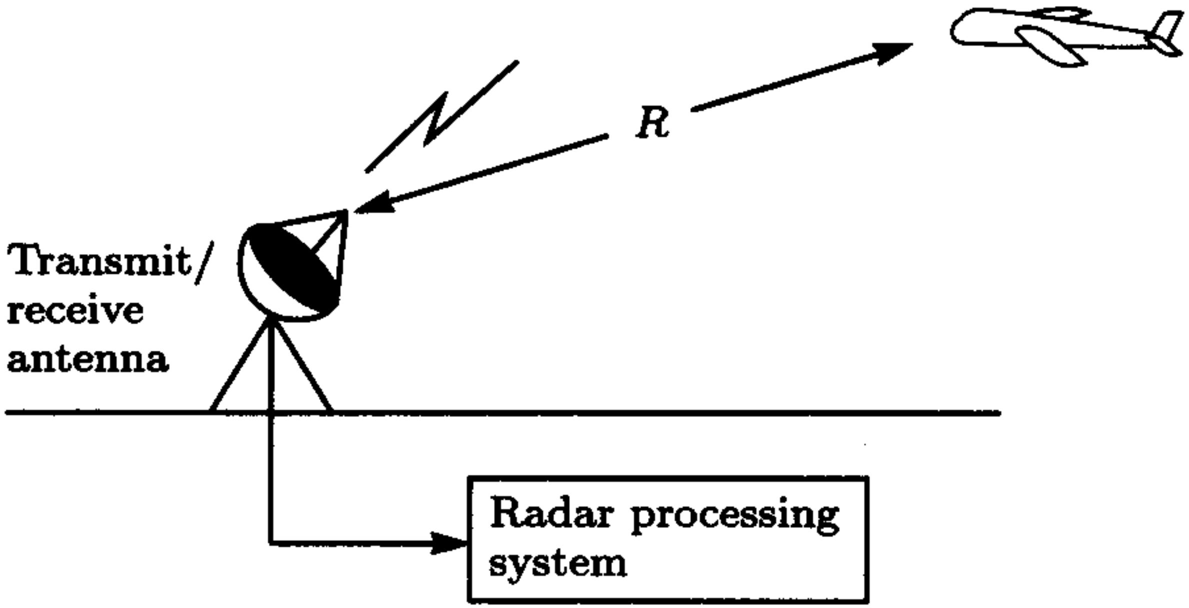


Fig.1.3: Transmitted & received radar waveforms: $s(t)$ & $r(t)$



$$r(t) = s(t-\tau) + w(t)$$

Fig.1.4: Radar ranging

Given the signal propagation speed, denoted by c, the time delay τ is related to R as:

$$\tau = \frac{2R}{c} \quad (1.1)$$

Hence the radar pulse contains the object range information

- Can be a function of one, two or three independent variables, e.g., speech is 1-D signal, function of time; image is 2-D, function of space; wind is 3-D, function of latitude, longitude and elevation

- 3 types of signals that are functions of time:
  - Continuous-time (analog) $x(t)$: defined on a continuous range of time t, amplitude can be any value
  - Discrete-time (sampled) $x(nT)$: defined only at discrete instants of time $t = \cdots - T, 0, T, 2T, \cdots$, amplitude can be any value
  - Digital (quantized) $x_Q(nT)$: both time and amplitude are discrete, i.e., it is defined only at $t = \cdots - T, 0, T, 2T, \cdots$ and amplitude is confined to a finite set of numbers

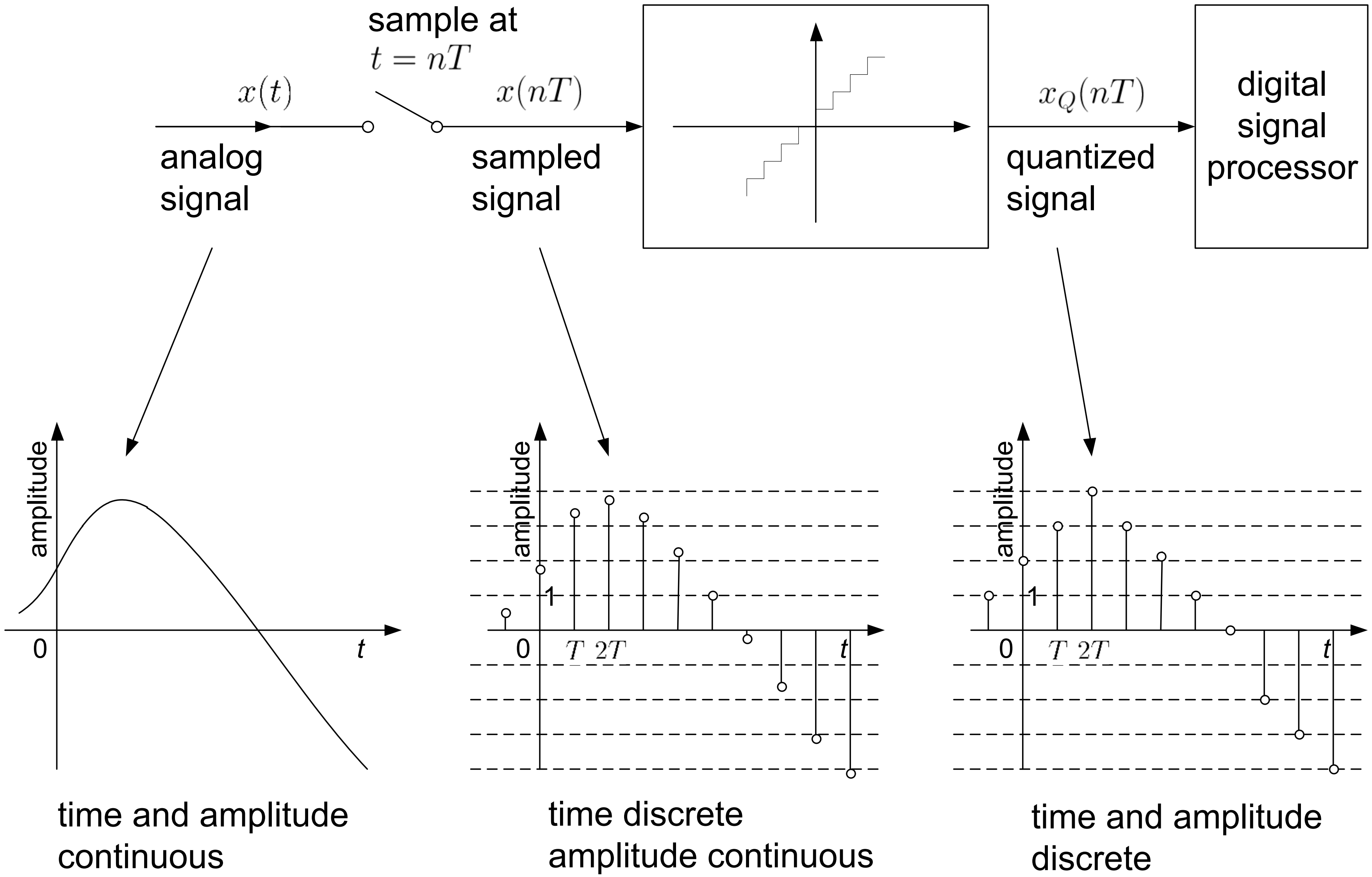


Fig. 1.5: Relationships between $x(t)$, $x(nT)$ and $x_Q(nT)$

$x(nT)$ at $n=0$ is close to 2 and $x_Q(0)=2$

$x(nT) \in (3,4)$ at $n=1$ and $x_Q(T)=3$

Using 4-bit representation, $x_Q(0)=0010$ and $x_Q(T)=0011$, and in general, the value of $x_Q(nT)$ is restricted to be an integer between -8 and 7 according to the two's complement representation.

In digital signal processing (DSP), we deal with $x_Q(nT)$ as it corresponds to computer-based processing. A digital signal will approach a discrete-time signal if the quantizer has very high resolution

Throughout the course, it is assumed that discrete-time signal = digital signal, or the quantizer has infinite resolution

System:

- Mathematical model or abstraction of a physical process that relates input to output

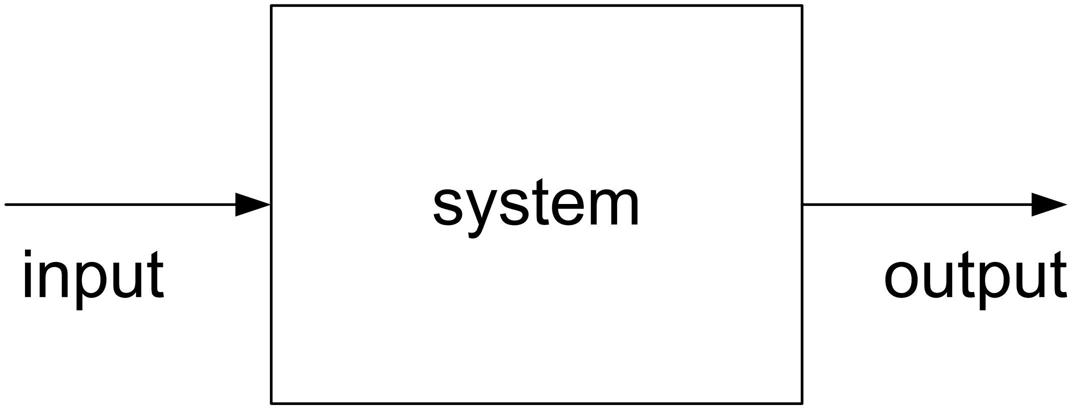


Fig.1.6: System with input and output

- It operates on an input to produce an output, e.g.:
  - Grading system: inputs are coursework and examination marks, output is grade

- Squaring system: input is 5, then the output is 25
- Amplifier: input is $\cos(\omega t)$, then output is $10\cos(\omega t)$
- Communication system: input to mobile phone is voice, output from mobile phone is 5G waveform
- Noise reduction system: input is a noisy speech, output is a noise-reduced speech
- Feature extraction system: input is $\cos(\omega t)$, output is ω

- A continuous-time (analog) system deals with continuous-time input and output while a discrete-time system deals discrete-time input and output

- A system can be realized in hardware or software via an algorithm

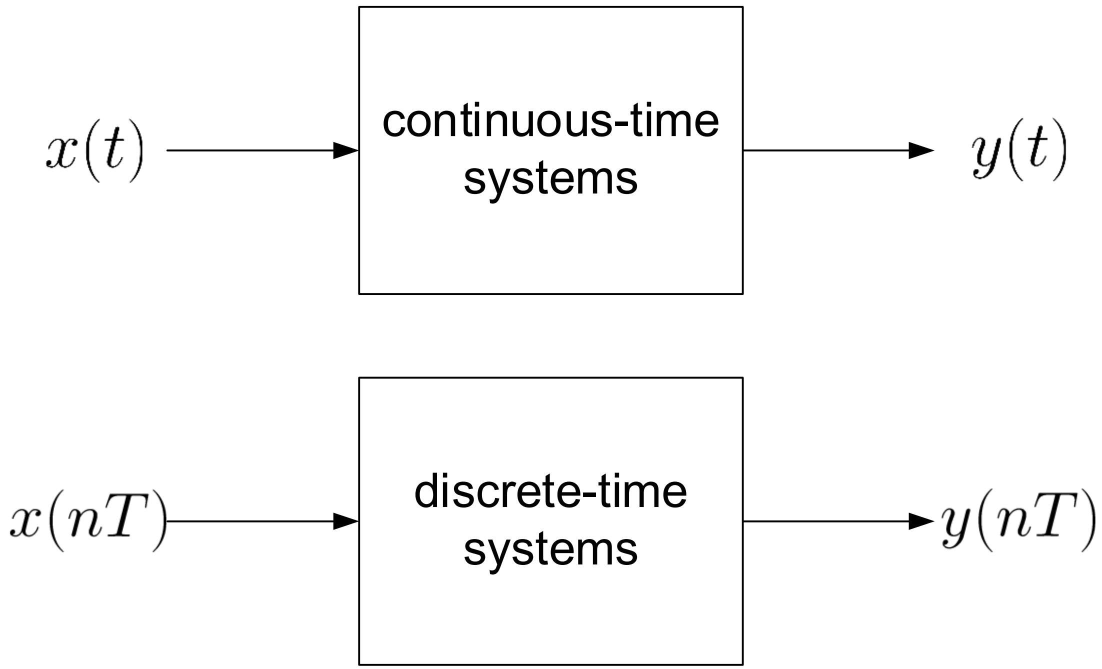


Fig. 1.7: Continuous-time and discrete-time systems

In a continuous-time (discrete-time) system, the input and output are continuous-time (discrete-time) signals

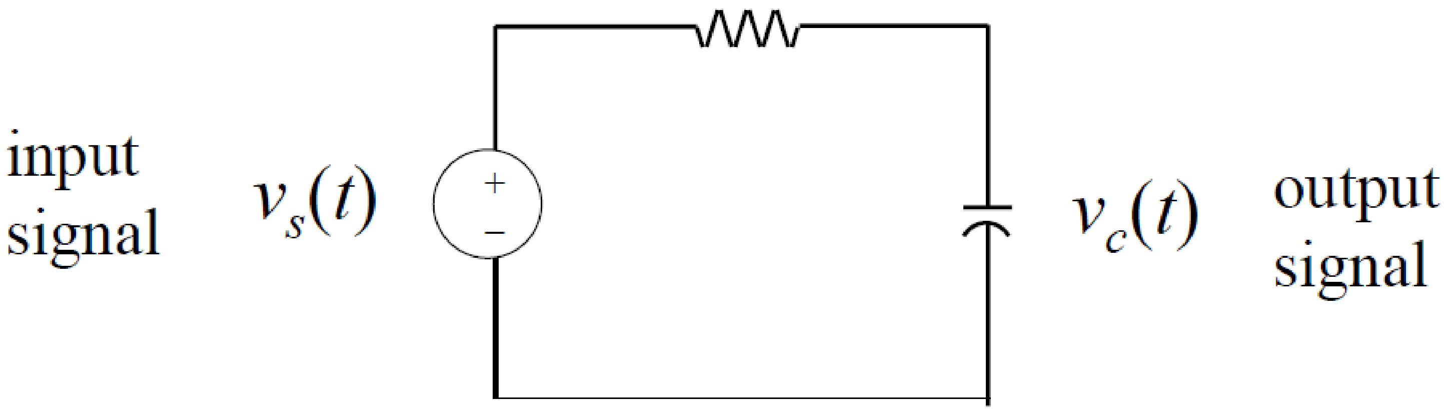


Fig.1.8: Hardware system of resistor-capacitor circuit

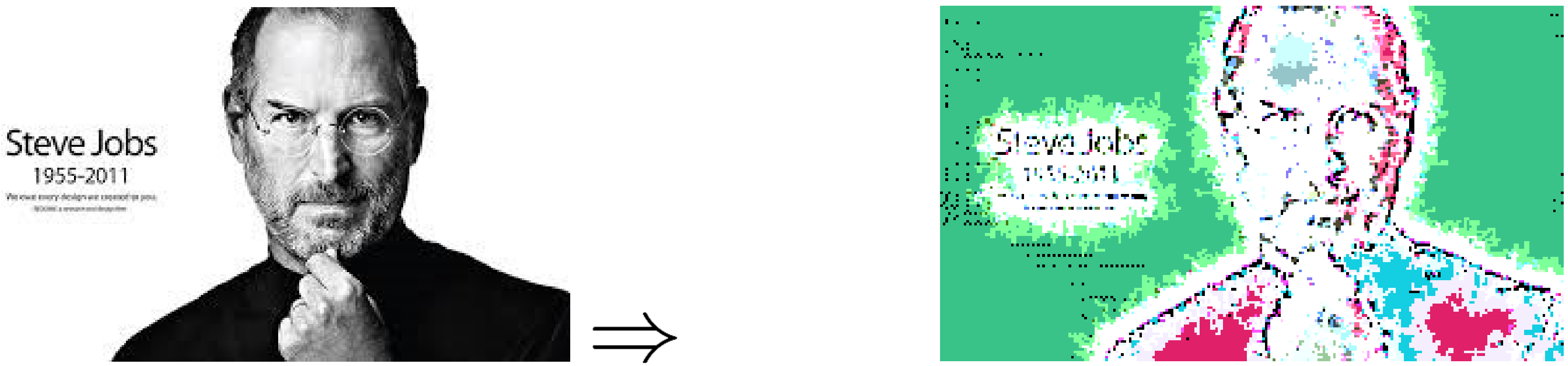


Fig.1.9: Algorithm for producing pop-art

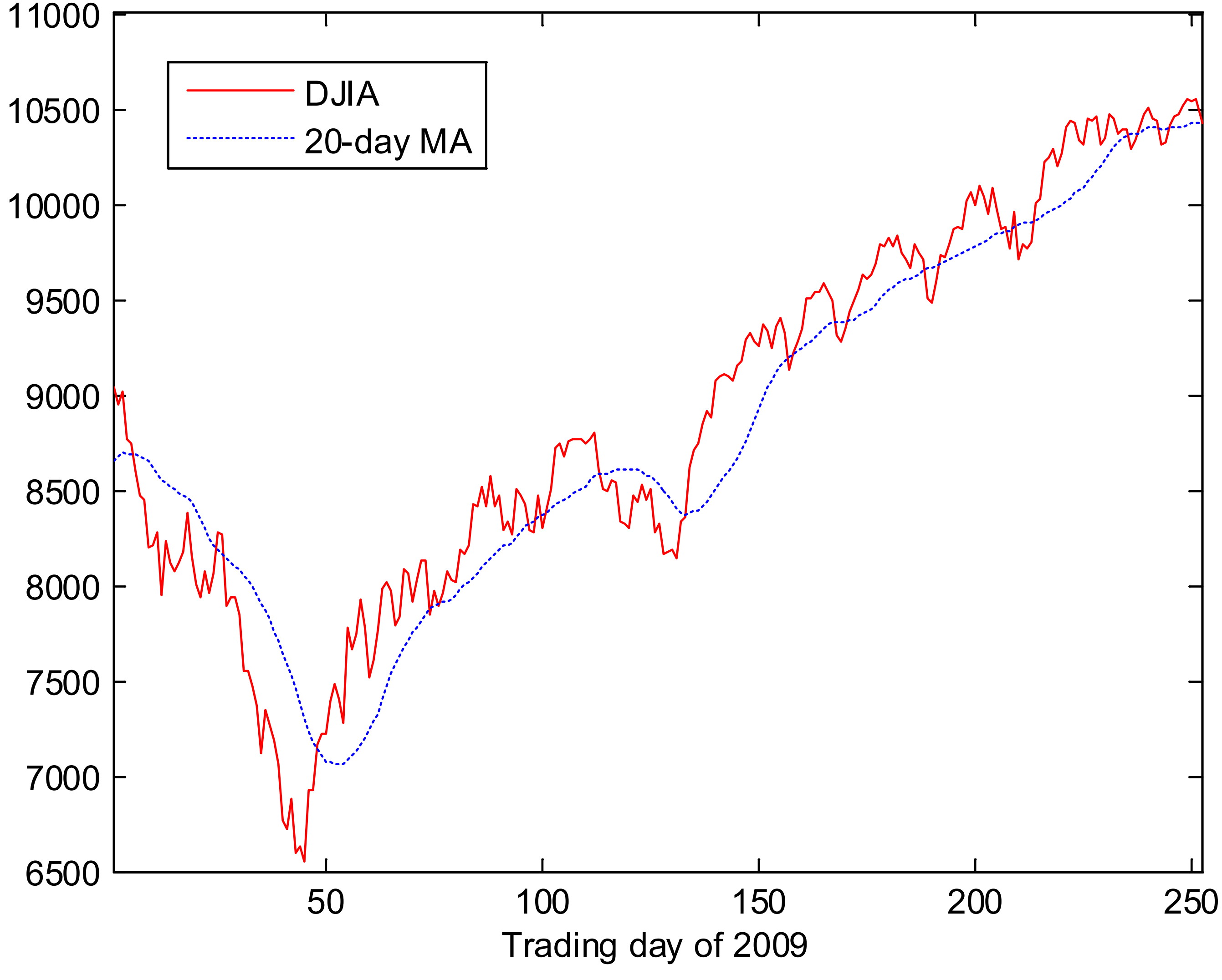


Fig.1.10: Software system for moving average of Dow Jones

Processing:

- Perform a particular function by passing an input signal through a system

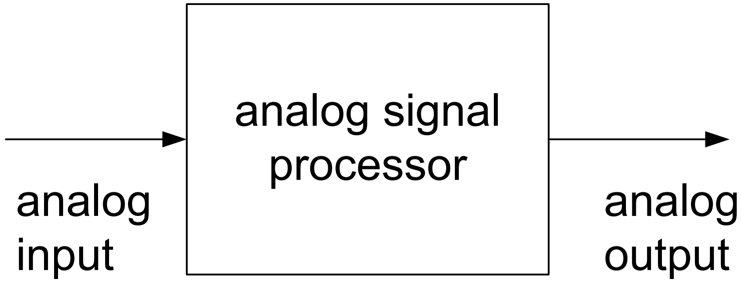


Fig.1.11: Analog processing of analog signal

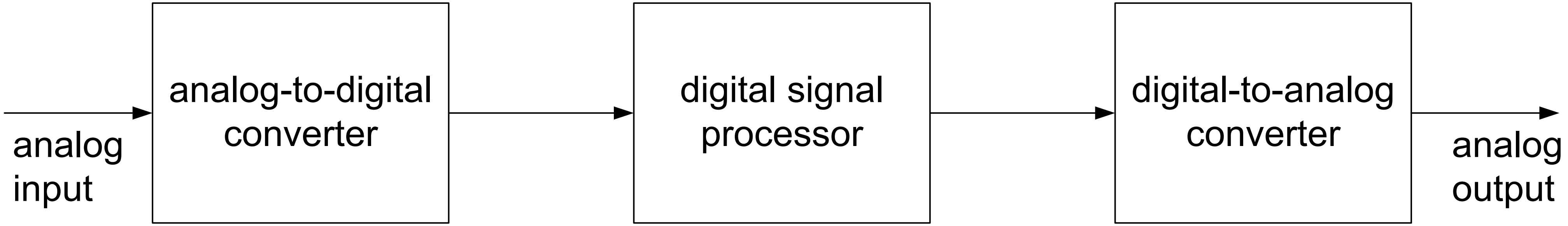


Fig.1.12: Digital processing of analog signal

Advantages of DSP over Analog Signal Processing

- Allow development with the use of PC, e.g., MATLAB
- Allow flexibility in reconfiguring the DSP operations by simply changing the program code
- Reliable: processing of 0 and 1 is almost immune to noise and data are easily stored without deterioration
- Lower cost due to advancement of VLSI technology
- Security can be introduced by encryption/scrambling
- Simple: additions and multiplications are main operations

DSP Application Areas

- Speech
  - Compression (e.g., linear predictive coding (LPC) is a coding standard for compression of speech data)
  - Synthesis (computer production of speech signals, e.g., text-to-speech app)
  - Recognition (e.g., speech-to-text app, emotion detection, speaker identification)
  - Enhancement (e.g., noise reduction for a noisy speech)

- Audio
  - Compression (e.g., MP3 is a coding standard for compression of audio data)
  - Generation of music by different musical instruments such as piano, cello, guitar and flute using computer
  - Song with low-cost electronic piano keyboard quality
  - Automatic music transcription (writing a piece of music down from a recording)
- Image and Video
  - Compression (e.g., JPEG and MPEG are coding standards for image and video compression, respectively)
  - Recognition such as face, palm and fingerprint

- Enhancement

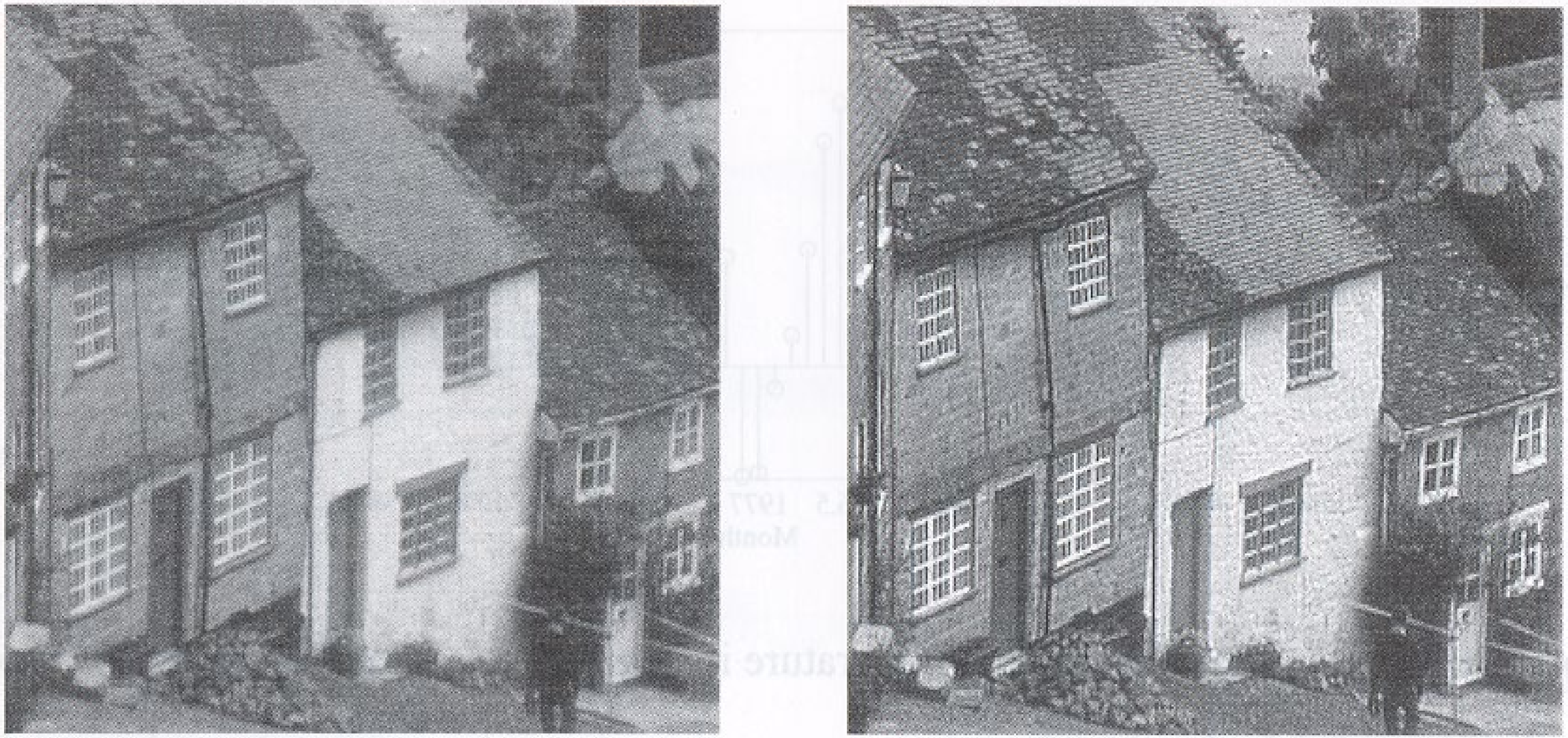


Fig.1.13: Photo enhancement

- Construction of 3-D objects from 2-D images
- Computer animation in film industry

- Communications: encoding and decoding of digital communication waveforms
- Astronomy: finding the periods of orbits
- Biomedical Engineering: medical care and diagnosis, analysis of ECG, electroencephalogram (EEG), nuclear magnetic resonance (NMR) data
- Bioinformatics: DNA sequence analysis, extracting, processing, and interpreting the information contained in genomic and proteomic data
- Finance: market risk management, trading algorithm design, investment portfolio analysis

What will You Learn?

- Signal representation and characterization, which includes generating signals, classifying signal types and properties, performing operations on signals

- System classification and analysis, which includes analysis of system stability and causality, understanding the importance of impulse response for linear time-invariant (LTI) systems

- Transform tools include Fourier series and Fourier transform, and their applications in signal representation and LTI system, e.g., a periodic continuous-time signal $x(t)$ can be expressed as sum of complex exponentials:

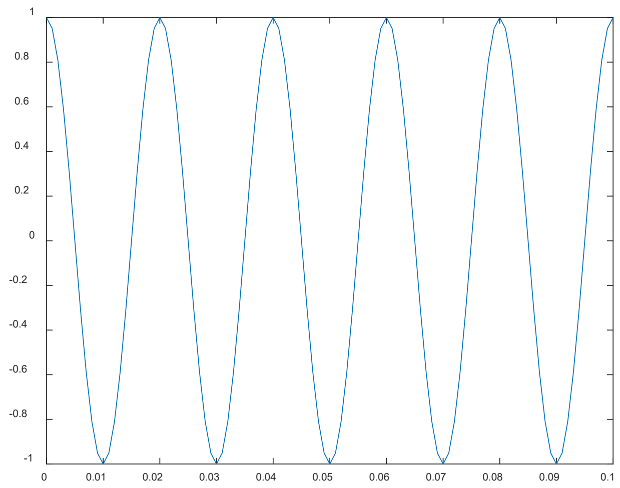
$$x(t) = \sum_{k=-\infty}^{\infty} a_k e^{jk\Omega_0 t}, \qquad t \in (-\infty, \infty) \tag{1.2}$$

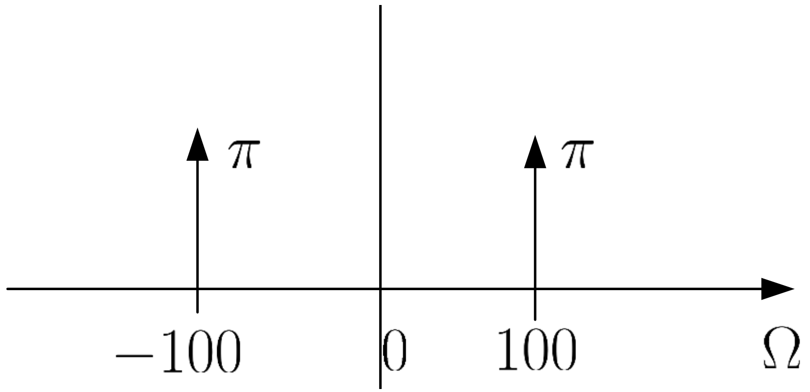
Why Important?

- Signal processing arises in our daily life, studying it will lay a good foundation for you in other relevant/higher-level courses and to solve real-world problems:
  - Generate signals which meet certain specifications
    e.g., synthesized speech and music
  - Design systems which produce desired outputs
    e.g., a system which suppresses noise in the observed data
  - New signal representation for efficient data processing, e.g., David Donoho proposed sparse representation and obtained the Shaw Prize 2013 (邵逸夫數學科學獎)
    https://www.youtube.com/watch?v=5wv4grOMgIU

e.g., a simple periodic signal of a cosine wave can yield a sparse representation in the frequency domain.

$$x(t) = \cos(100t) = \frac{e^{j100t} + e^{-j100t}}{2} \leftrightarrow X(j\Omega) = \pi\delta(\Omega + 100) + \pi\delta(\Omega - 100)$$





Sparse representation is useful in data compression and approximation particularly in big data era

How to Study?

Make sure you have a clear concept and then practice