Chapter 1

Signals and Signal Processing

Signals and Signal Processing

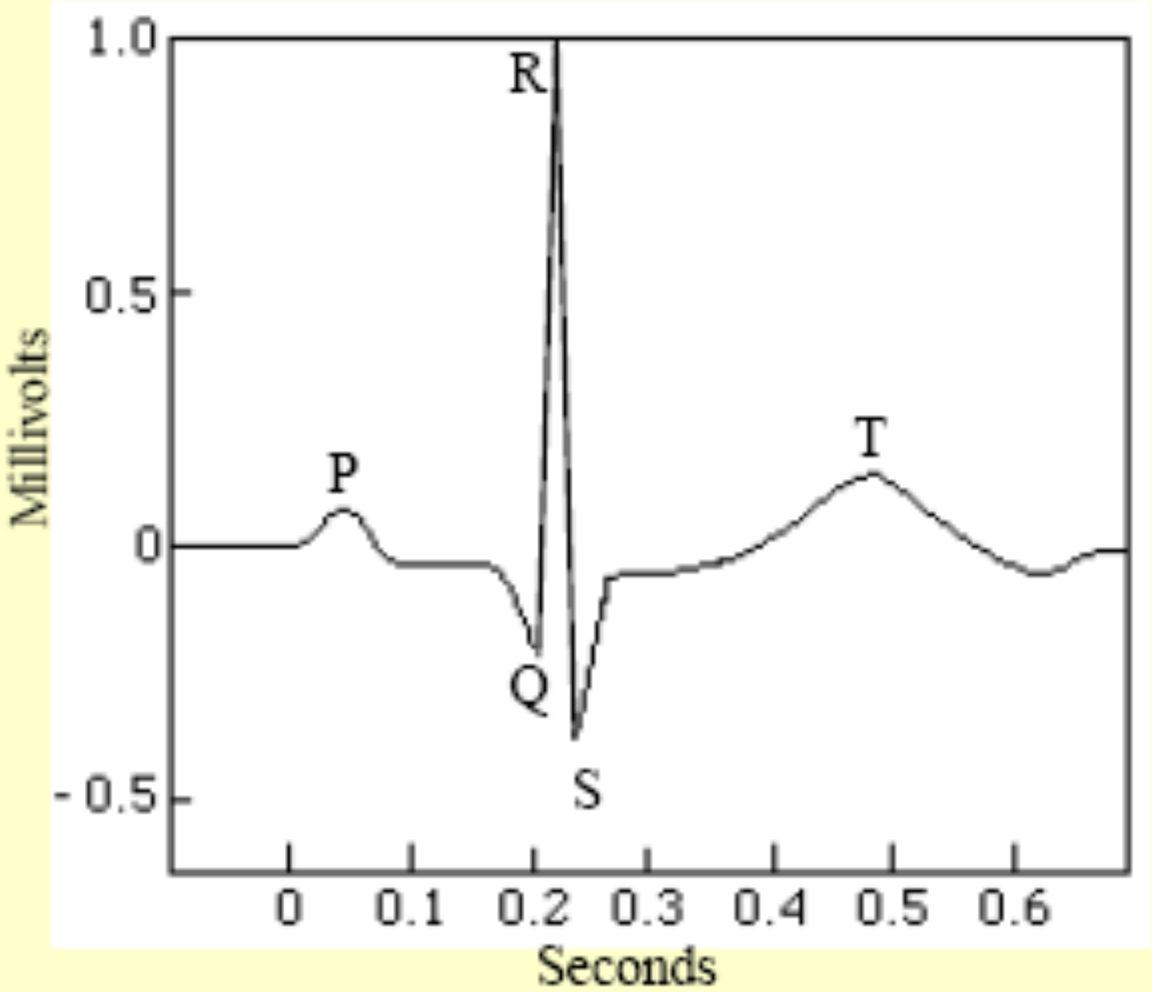
- Signals play an important role in our daily life
- A signal is a function(函数) of independent variables(自变量) such as time, distance, position, temperature, and pressure
- Some examples of typical signals are shown next

Examples of Typical Signals

- **Speech and music signals-Represent air pressure as a function of time at a point in space**
- **Electrocardiography (ECG心电图) Signal-Represents the electrical activity of the heart**
- **A typical ECG signal is shown in Figure 1.12(a)**

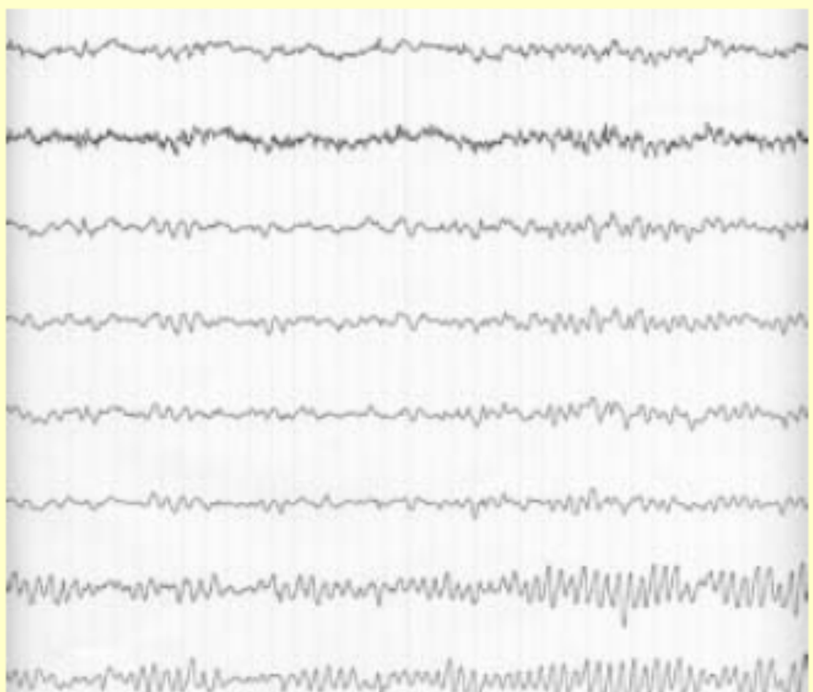
Examples of Typical Signals

- The ECG trace is periodic(周期的) waveform(波形)
- One period of the waveform shown in Figure 1.12(b) represents one cycle(循环) of the blood transfer(传输) process from the heart to the arteries(动脉)


1.0
0.5
0
- 0.5
Millivolts
R
P
T
Q
S
0
0.1
0.2
0.3
0.4
0.5
0.6
Seconds

Examples of Typical Signals

- **Electroencephalogram (EEG) Signals** - Represent the electrical activity caused by the random firings of billions of neurons in the brain



Examples of Typical Signals

- **Black-and-white picture – Represents light intensity as a function of two <u>spatial (空间的)coordinates(坐标)</u>**

Examples of Typical Signals

Examples of Typical Signals

- **Video(视频) signals – Consists of a sequence of images, called frames(帧), and is a function of 3 variables: 2 spatial coordinates and time**

Signals and Signal Processing

- **Most signals we encounter(遇到) are generated naturally**
- **However, a signal can also be generated synthetically(合成的) or by a computer**

Signals and Signal Processing

- A signal carries <u>information(信息)</u>
- <u>Objective(目标)</u> of signal processing: <u>Extract(提取)</u> the useful information carried by the signal
- Method of information extraction: Depends on the type of signal and the nature of the information being carried by the signal

Signals and Signal Processing

- Signals can be represented in the domain of the original independent variables or in a transformed domain
- Likewise, the information extraction process may be carried out in the original domain of the signal or in a transformed domain
- This course is concerned with(关于) the discrete-time(离散时间) representation(表示法) of signals and their discrete-time processing

特征，描述

Characterization and Classification of Signals

- Types of signal: Depends on the nature of the independent variables and the value of the function defining the signal
- For example, the independent variables can be continuous or discrete
- Likewise, the signal can be a continuous or discrete function of the independent variables

Characterization and Classification of Signals

- Continuous signals vs. discrete signals
- Real signals vs. complex signals
- Scalar(标量) signals vs. vector(矢量) signals
- One dimensional signals vs. multi-dimensional signals
- Deterministic signal vs. random signal

Characterization and Classification of Signals

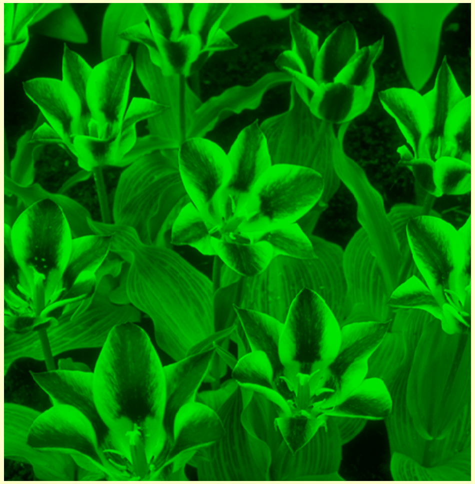
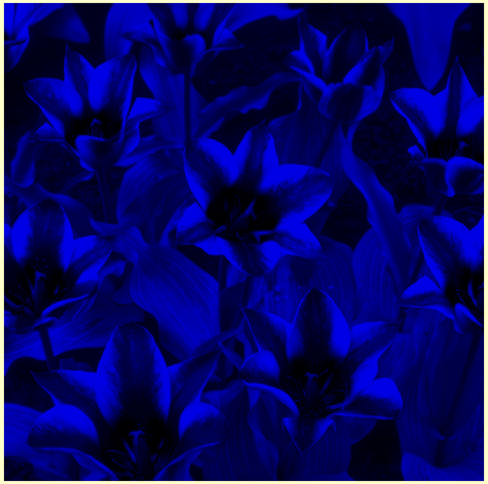
- A <u>one-dimensional</u>(1-D一维) signal is a function of a single independent variable
- A multidimensional(M-D) signal is a function of more than one independent variables
- The speech signal is an example of a 1-D signal where the independent variable is time

Characterization and Classification of Signals

- An image(图像) signal, such as a photograph(照片), is an example of a 2-D signal where the 2 independent variables are the 2 spatial variables
- A color image signal is composed of three 2-D signals representing the three primary colors: red, green and blue (RGB)

Characterization and Classification of Signals

- The 3 color components of a color image are shown below

Characterization and Classification of Signals

- The full color image obtained by displaying the previous 3 color components is shown below

Characterization and Classification of Signals

- Each frame of a black-and-white digital video signal is a 2-D image signal that is a function of 2 discrete spatial variables, with each frame occurring(出现) at discrete instants(时刻) of time
- Hence, black-and-white digital video signal can be considered as an example of a 3-D signal where the 3 independent variables are the 2 spatial variables and time

Characterization and Classification of Signals

- **A color video signal is a 3-channel signal composed of three 3-D signals representing the three primary colors: red, green and blue (RGB)**
- **For transmission purposes, the RGB television signal is transformed into another type of 3-channel signal composed of a <u>luminance(亮度)</u> component and 2 <u>chrominance(色度)</u> components**

Characterization and Classification of Signals

- For a 1-D signal, the independent variable is usually labeled as time
- If the independent variable is continuous, the signal is called a continuous-time signal
- If the independent variable is discrete, the signal is called a discrete-time signal

Characterization and Classification of Signals

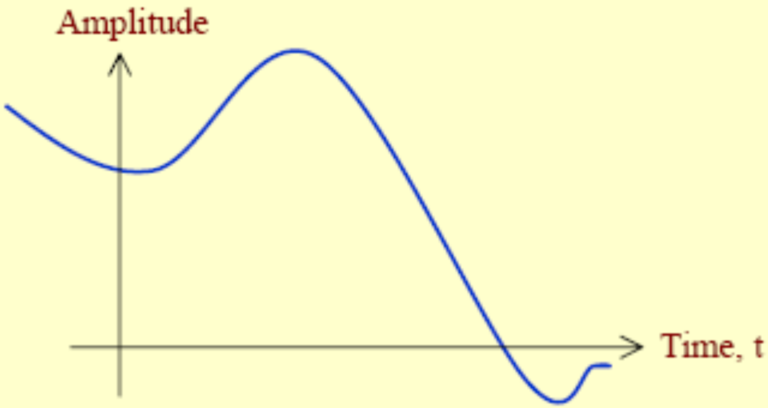
- A continuous-time signal is defined at every instant of time
- A discrete-time signal is defined at discrete instants of time, and hence, it is a sequence(序列) of numbers
- A continuous-time signal with a continuous amplitude(幅度) is usually called an analog(模拟) signal
- A speech(语音) signal is an example of an analog signal

Characterization and Classification of Signals

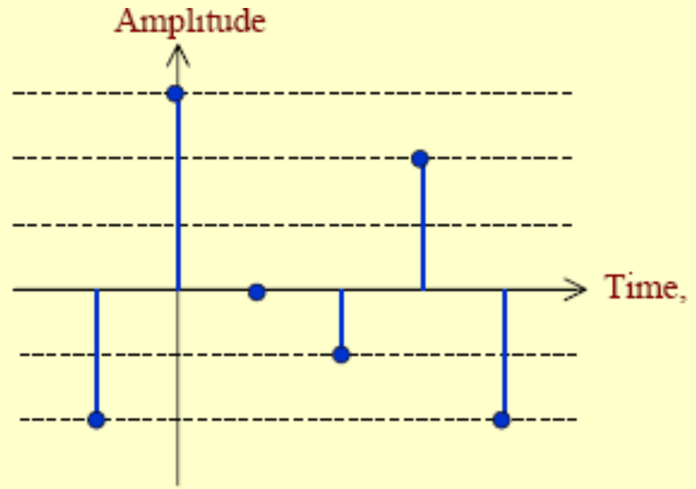
- A discrete-time signal with discrete-valued amplitudes represented by a finite(有限的) number of digits is referred to as the digital signal
- An example of a digital signal is the digitized(数字化) music signal stored in a CD-ROM disk
- A discrete-time signal with continuous-valued amplitudes is called a sampled-data(抽样数据) signal

Characterization and Classification of Signals

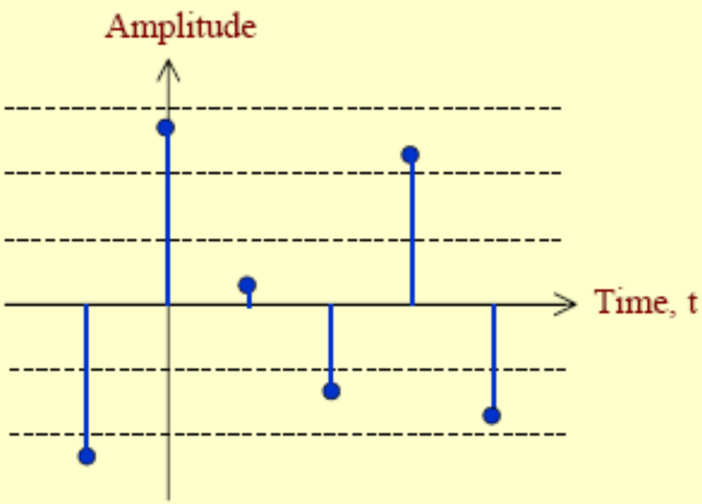
- A digital signal is thus a quantized(量化的) sampled-data signal
- A continuous-time signal with discrete-value amplitudes is usually called a quantized boxcar signal(量化矩形信号)
- Figure1.1 illustrates the 4 types of signals



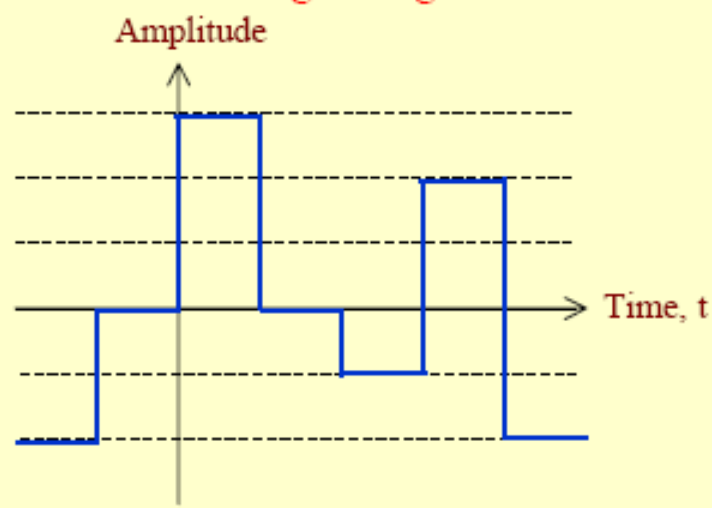
A continuous-time signal



A digital signal



A sampled - data signal



A quantized boxcar signal

Characterization and Classification of Signals

- The functional dependent(函数关系) of a signal in its mathematical representation is often explicitly(清楚的) shown
- For a continuous-time 1-D signal, the continuous independent variable is usually denoted by t
- For example, $u(t)$ represents a continuous-time 1-D signal

Characterization and Classification of Signals

- For a discrete-time 1-D signal, the discrete independent variable is usually denoted by n
- For example, $\{v[n]\}$ represents a discrete-time 1-D signal
- Each member, $v[n]$, of a discrete-time signal is called a sample(样本)

Characterization and Classification of Signals

- In many applications, a discrete-time signal is generated by sampling(采样) a parent(原始的) continuous-time signal at uniform(统一的) intervals(间隔) of time
- If the discrete instants of time at which a discrete-time signal is defined are uniformly spaced, the independent discrete variable n can be normalized(归一化) to assume integer(整数) values

Characterization and Classification of Signals

- In the case of a continuous-time 2-D signal, the 2 independent variables are the spatial coordinates, usually denoted by x and y
- For example, the intensity(强度) of a black-and-white image at location (x,y) can be expressed as $u(x,y)$

Characterization and Classification of Signals

- **On the other hand, a digitized image is a 2-D discrete-time signal, and its 2 independent variables are discretized spatial variables, often denoted by m and n**
- **Thus, a digitized image can be represented as $v[m,n]$**
- **A black-and-white video signal is a 3-D signal and can be represented as $u(x,y,t)$**

Characterization and Classification of Signals

- **A color video signal is a vector signal composed of 3 signals representing the 3 primary colors: red, green, and blue**

$$u(x,y,t)=\begin{bmatrix} r(x,y,t) \\ g(x,y,t) \\ b(x,y,t) \end{bmatrix}$$

Characterization and Classification of Signals

- A signal that can be uniquely(唯一的) determined by a well-defined(完全定义的) process, such as a mathematical expression or rule, or table look-up(查找表), is called a deterministic(确定的) signal
- A signal that is generated in a random(随机) fashion and cannot be predicted(预测) ahead of time is called a random signal

Typical Signal Processing Operations

- Most signal processing operations(运算) in the case of analog signals are carried out in the time-domain(时域)
- In the case of discrete-time signals, both time-domain or frequency-domain(频域) operations are usually employed

Simple Time-Domain Operations

- **Three most basic time-domain signal operations are scaling(标乘), delay, and addition**
- **Scaling is simply the multiplication(相乘) of a signal either by a positive(正的) or negative(负的) constant(常数)**
- **In the case of analog signals, the operation is usually called amplification(放大) if the magnitude of the multiplying constant, called gain(增益), is greater than 1**

Simple Time-Domain Operations

- If the magnitude of the multiplying constant is less than 1, the operation is called attenuation(衰减)
- If $x(t)$ is an analog signal that is scaled by a constant α , then the scaling operation generates a signal $y(t) = \alpha x(t)$
- Two other elementary operations are integration(积分) and differentiation(微分)

Simple Time-Domain Operations

- **The integration of an analog signal $x(t)$ generates a signal**

$$y(t) = \int_{-\infty}^{t} x(\tau)d\tau$$

- **The differentiation of an analog signal $x(t)$ generates a signal**

$$w(t) = \frac{dx(t)}{dt}$$

Simple Time-Domain Operations

- The delay(延时) operation generates a signal that is a delayed replica(复制品) of the original signal
- For an analog signal $x(t)$,

$$y(t)=x(t-t_0)$$

is the signal obtained by delaying $x(t)$ by the amount of time t_0 which is assumed(假定) to be a positive number

- If t_0 is negative, then it is an advance(超前) operation

Simple Time-Domain Operations

- Many applications require operations involving two or more signals to generate a new signal
- For example,

$$y(t) = x_1(t) + x_2(t) + x_3(t)$$

is the signal generated by the addition of the three analog signals, $x_1(t)$, $x_2(t)$, and $x_3(t)$

Simple Time-Domain Operations

- The product(乘积) of 2 signals, $x_1(t)$ and $x_2(t)$, generates a signal

$$y(t)=x_1(t)x_2(t)$$

- The elementary operations discussed so far are also carried out on discrete-time signals
- More complex operations are implemented by combining(组合) two or more elementary operations

Filtering

- Filtering(滤波) is one of the most widely used complex signal processing operations
- The system implementing(实现) this operation is called a filter(滤波器)
- A filter passes certain frequency components without any distortion and blocks(阻止) other frequency components

Filtering

- The range of frequencies that is allowed to pass through the filter is called the passband(通带), and the range of frequencies that is blocked by the filter is called the stopband(阻带)
- In most cases, the filtering operation for analog signals is linear(线性的)

Filtering

- A lowpass(低通) filter passes all low-frequency components below a certain specified frequency , called the cutoff frequency(截止频率), and blocks all high-frequency components above f_c
- A highpass filter passes all high-frequency components a certain cutoff frequency f_c

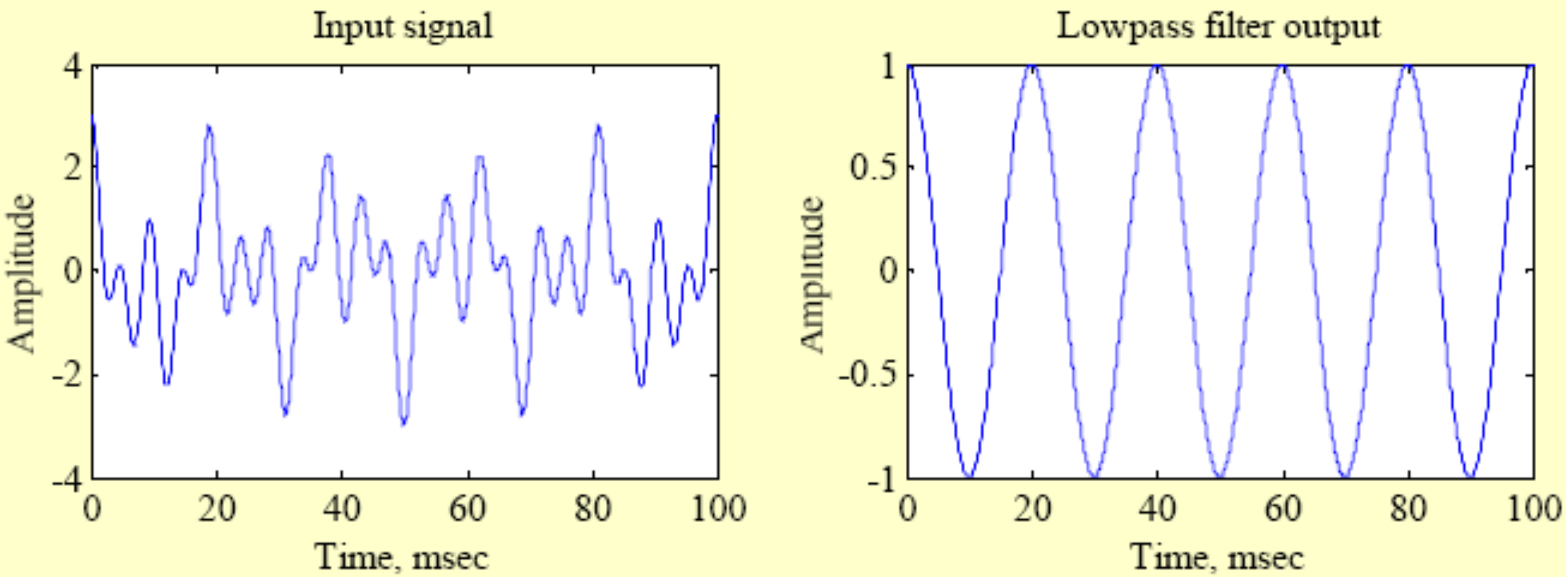
  and blocks all low-frequency components

  below f_c

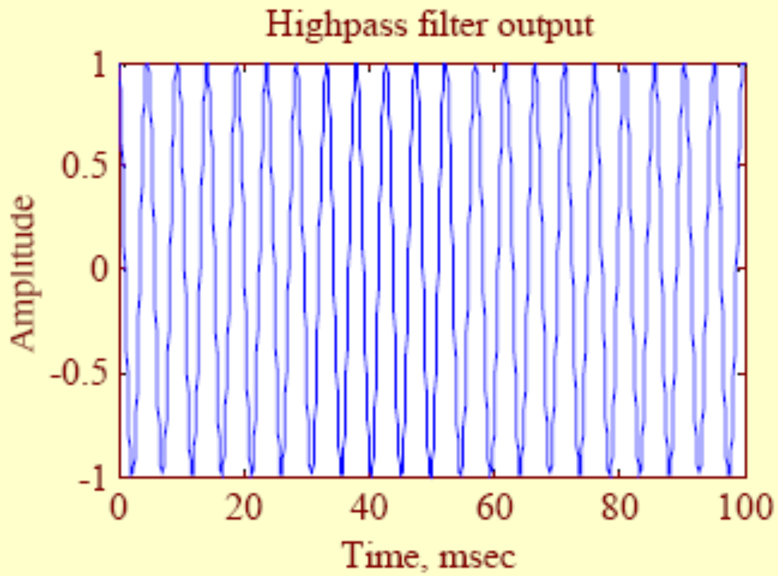
Filtering

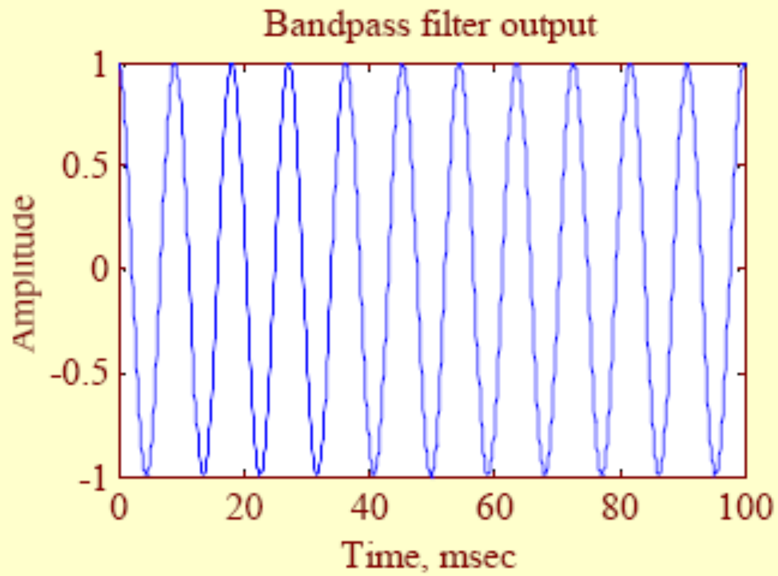
- A bandpass filter passes all frequency components between 2 cutoff frequencies, f_{c1} and f_{c2}, where $f_{c1} < f_{c2}$, and blocks all frequency components below the frequency f_{c1} and above the frequency f_{c2}
- A bandstop filter blocks all frequency components between 2 cutoff frequencies, f_{c1} and f_{c2}, where $f_{c1} < f_{c2}$, and passes all frequency components below the frequency f_{c1} and above the frequency f_{c2}

- Figures below illustrate the lowpass filtering of an input signal composed of 3 sinusoidal components of frequencies 50 Hz, 110 Hz, and 210 Hz



• Figures below illustrate highpass and bandpass filtering of the same input signal





Filtering

- There are various other types of filters
- A filter blocking a single(单个的) frequency component is called a notch filter(陷波器)
- A multiband(多频带) filter has more than one passband and more than one stopband
- A comb filter(梳状滤波器) blocks frequencies that are integral multiples(整数倍) of a low frequency

Filtering

- **In many applications the desired signal occupies a low-frequency band from dc to some frequency f_L Hz, and gets corrupted by a high-frequency noise with frequency components above f_H Hz with $f_H > f_L$**
- **In such cases, the desired signal can be recovered from the noise-corrupted signal by passing the latter through a lowpass filter with a cutoff frequency** f_c where $f_L < f_c < f_H$

Filtering

Example

- common source of noise is power lines(电力线) radiating(辐射) electric and magnetic fields(电磁场)
- The noise generated by power lines appears as a 60Hz sinusoidal signal corrupting the desired signal and can be removed by passing the corrupted signal through a notch filter with a notch frequency at 60 Hz

Multiplexing and Demultiplexing

- **For an efficient utilization of a wideband transmission channel, many narrow-bandwidth low-frequency signals are combined for a composite wideband signal that is transmitted as a single signal**
- **The process of combining the low-frequency signals is called <u>multiplexing(复用)</u>**

Multiplexing and Demultiplexing

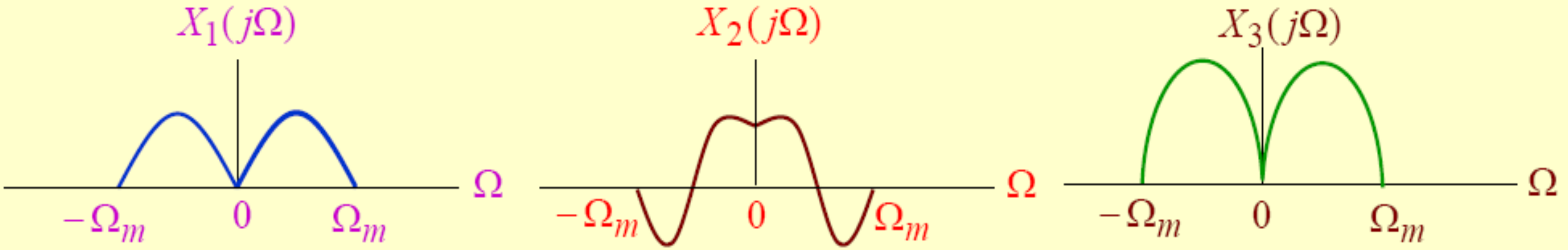
- Multiplexing is implemented to ensure that a replica of each of the original narrow-bandwidth low-frequency signal can be recovered at the receiving end
- The recovery process of the low-frequency signals is called demultiplexing(解复用)

Multiplexing and Demultiplexing

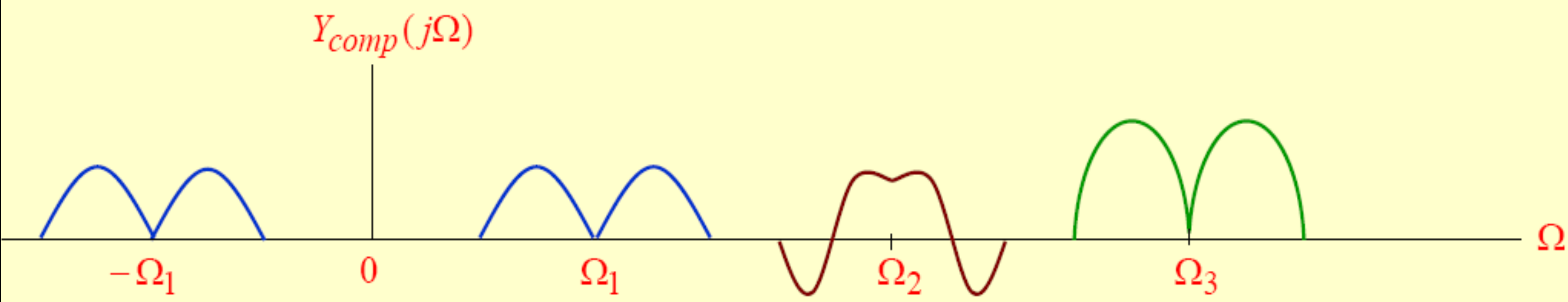
- **One method of combining different voice signals in a telephone communication system is the frequency-division multiplexing (FDM) scheme**
- **Here, each voice signal, typically bandlimited to a low-frequency band of width Ω_m , is frequency-translated into a higher frequency band using the amplitude modulation method**

Multiplexing and Demultiplexing

- The carrier frequency of adjacent amplitude-modulated signals is separated by Ω_0 , where $\Omega_0 > 2\Omega_m$ to ensure that there is no overlap in the spectra of the individual modulated signals after they are added to form the baseband composite signal
- The composite signal is then modulated onto the main carried developing the FDM signal and transmitted



Spectra of the low–frequency signals

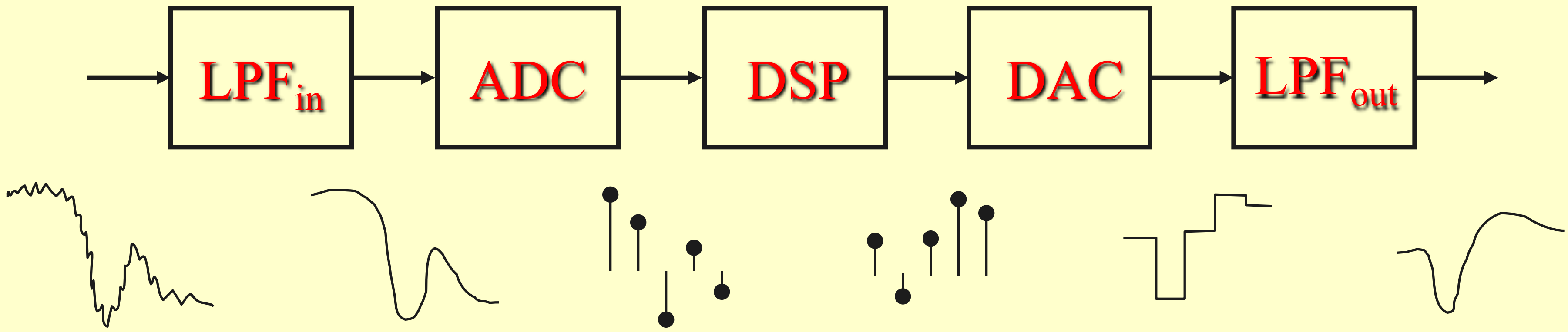


Spectra of the modulated composite signal

Multiplexing and Demultiplexing

- At the receiving end, the composite baseband signal is first recovered from the FDM signal by demodulation
- Then each individual frequency-translated signal is demultiplexed by passing the composite signal through a bank of bandpass filters

Digital Processing of Analog Signals

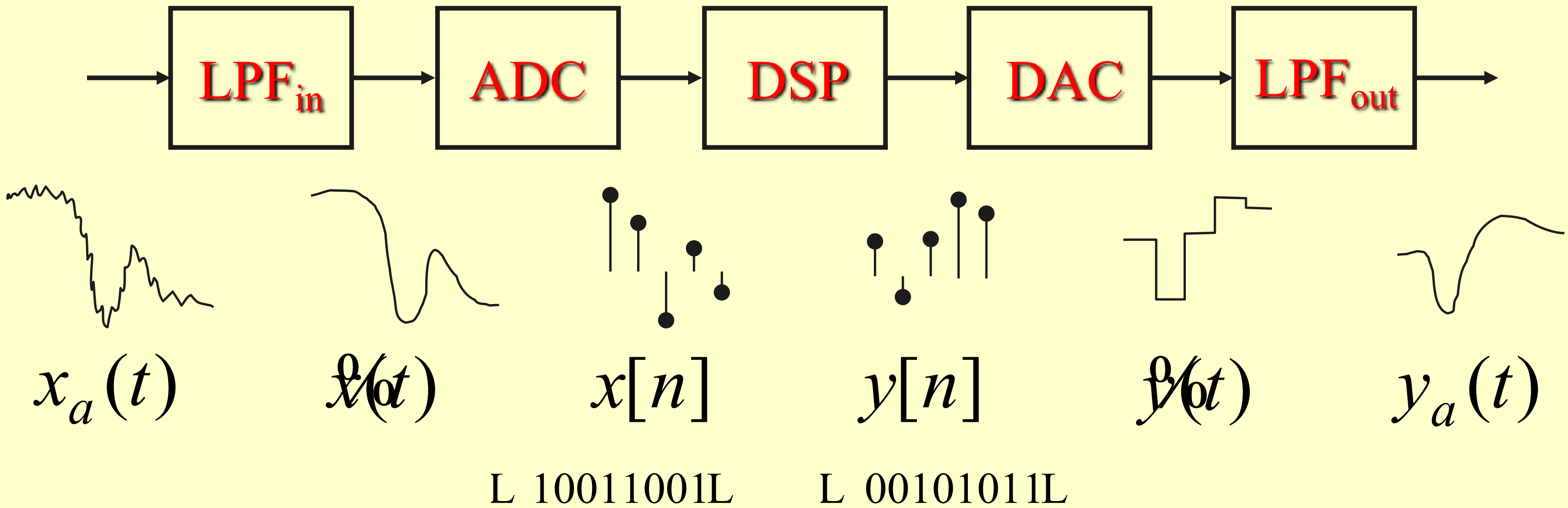


$x_a(t)$ $\tilde{x}_a(t)$ $x[n]$ $y[n]$ $\tilde{y}_a(t)$ $y_a(t)$

… 10011001 … … 00101011 …

- **LPF$_{in}$** is the **Prefilter or Antialiasing Filter**: it conditions the analog signal $x_a(t)$ to prevent aliasing (Sampling Theorem: $F_T \geq 2F_{\max}$)
- **ADC** is the **Analog-to-Digital Converter**: it consists of an ideal sampler followed by a quantizer and produces a stream of binary digits $x[n]$ encoding the samples of $\tilde{x}_a(t)$ taken at a rate $F_T = 1/T$, T being the sampling period

Digital Processing of Analog Signals



•**DSP** is the **Digital Signal Processor**: it's the heart of the DSP system and can represent a computer, special-purpose HW, a SW algorithm, etc.

•**DAC** is the **Digital-to-Analog Converter**: it consits of an interpolator and produces a staircase waveform $\tilde{y}(t)$ from the sequence of binary digits representing $y[n]$, the processed version of $x[n]$

•**LPF_{out}** is the **Postfilter**: it performs the smoothing of $\tilde{y}(t)$ into $y_a(t)$

Digital Processing of Analog Signals