ECE 3640 - Discrete-Time Signals and Systems
Applied DSP Chapter 1

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from the textbook

"Application of digital signal processing to the solution of real-world problems require more than knowledge of signal processing theory. Knowledge of hardware, including computers or digital signal processors, programming in C or Matlab, A/D and D/A converters, analog filters, and sensor technology are also very important." (page 16)

therefore ...

- we will be doing labs in C
- we will use our computers and sound-cards as a platform for prototyping real-time digital signal processing algorithms
- we will use Matlab in homework
- there is a difference between knowing about something and being able to do it (e.g. knowing about playing the piano is different from doing it)
- the labs are for practicing DSP on real signals
- the labs give meaning to classroom concepts

labs (2015)

1. basic Matlab - manipulate media files, multi-dimensional arrays, plot, image, FFT, spectral plots
2. basic C - multi-dimensional arrays, static and dynamic allocation, simple media manipulations
3. filtering in C - convolution and filtering in 1D, 2D, 3D
4. Hilbert transform - filtering, group delay, instantaneous frequency in audio
5. spectral processing - FFT and noise suppression in audio
6. amplitude modulation - Fourier transform properties, non-coherent demodulation
7. sample-rate conversion - upsampling, downsampling, fractional sample rate conversion
8. frequency modulation and stereo decoding - filter design

labs (2014)

- plotting in Matlab (self-study)
- wave files (required)
- port-audio (required)
- periodic signal generation (required)
- DTMF and music (optional)
- tremolo and amplitude modulation (AM) (required)
- time warping without pitch modification (overlap-add) (optional)
- Doppler (optional)
- reverberation (optional)
- FIR filtering (required)
- IIR filtering (required)
- non-coherent demodulation of AM and FM (required)

what is signal processing?

Signal processing is the enabling technology for the generation, transformation, and interpretation of information. It comprises the theory, algorithms, architecture, implementation, and applications related to processing information contained in many different formats broadly designated as signals. Signal refers to any abstract, symbolic, or physical manifestation of information with examples that include: audio, music, speech, language, text, image, graphics, video, multimedia, sensor, communication, geophysical, sonar, radar, biological, chemical, molecular, genomic, medical, data, or sequences of symbols, attributes, or numerical quantities.

Signal processing uses mathematical, statistical, computational, heuristic, and/or linguistic representations, formalisms, modeling techniques and algorithms for generating, transforming, transmitting, and learning from analog or digital signals, which may be performed in hardware or software. Signal generation includes sensing, acquisition, extraction, synthesis, rendering, reproduction and display. Signal transformations may involve filtering, recovery, enhancement, translation, detection, and decomposition. The transmission or transfer of information includes coding, compression, securing, detection, and authentication. Learning can involve analysis, estimation, recognition, inference, discovery and/or interpretation.

Signal processing is essential to integrating the contributions of other engineering and scientific disciplines in the design of complex systems that interact with humans and the environment, both as a fundamental tool due to the signals involved and as a driver of new design methodologies. As such, signal processing is a core technology for addressing critical societal challenges that include healthcare, energy systems, sustainability, transportation, entertainment, education, communication, collaboration, defense, and security. (IEEE Signal Processing Society)

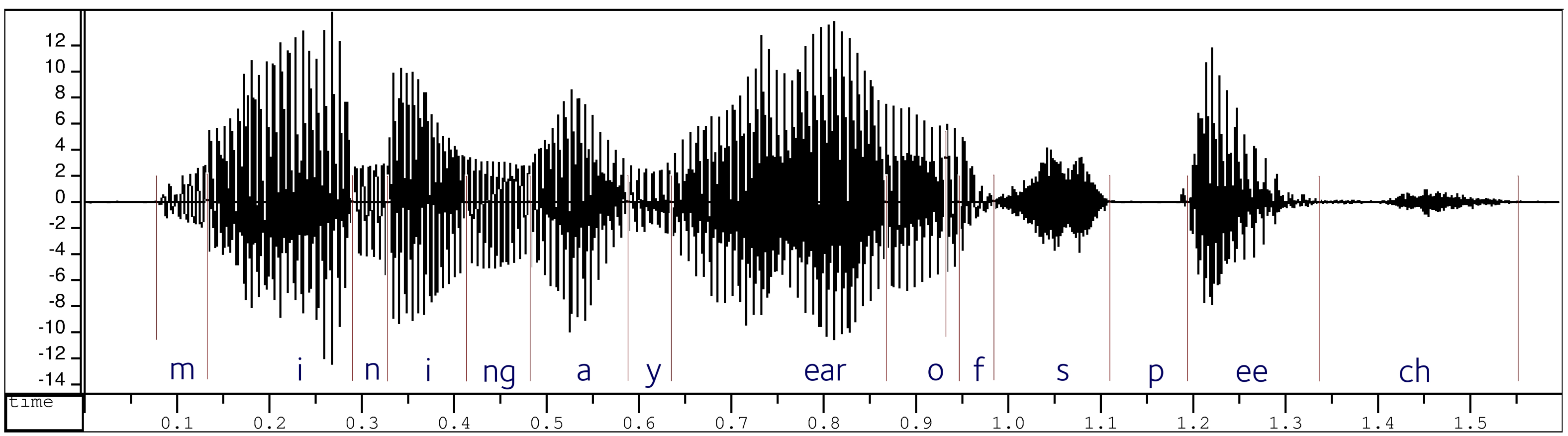
applications of DSP

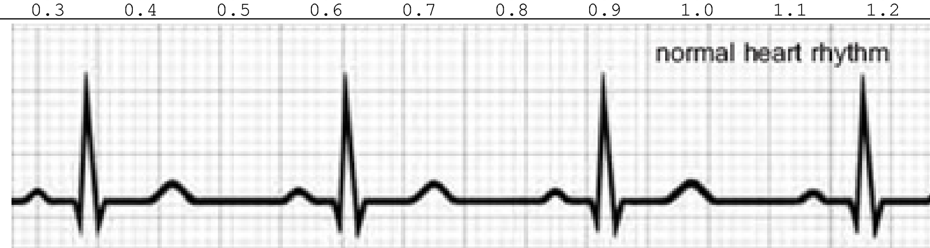
Table 1.1 Examples of digital signal processing applications and algorithms.

Application area	DSP algorithm
Key operations	convolution, correlation, filtering, finite discrete transforms, modulation, spectral analysis, adaptive filtering
Audio processing	compression and decompression, equalization, mixing and editing, artificial reverberation, sound synthesis, stereo and surround sound, and noise cancelation
Speech processing	speech synthesis, compression and decompression, speech recognition, speaker identification, and speech enhancement
Image and video processing	image compression and decompression, image enhancement, geometric transformations, feature extraction, video coding, motion detection, and tomographic image reconstruction
Telecommunications (transmission of audio, video, and data)	modulation and demodulation, error detection and correction coding, encryption and decryption, acoustic echo cancelation, multipath equalization, computer networks, radio and television, and cellular telephony
Computer systems	sound and video processing, disk control, printer control, modems, internet phone, radio, and television
Military systems	guidance and navigation, beamforming, radar and sonar processing, hyperspectral image processing, and software radio

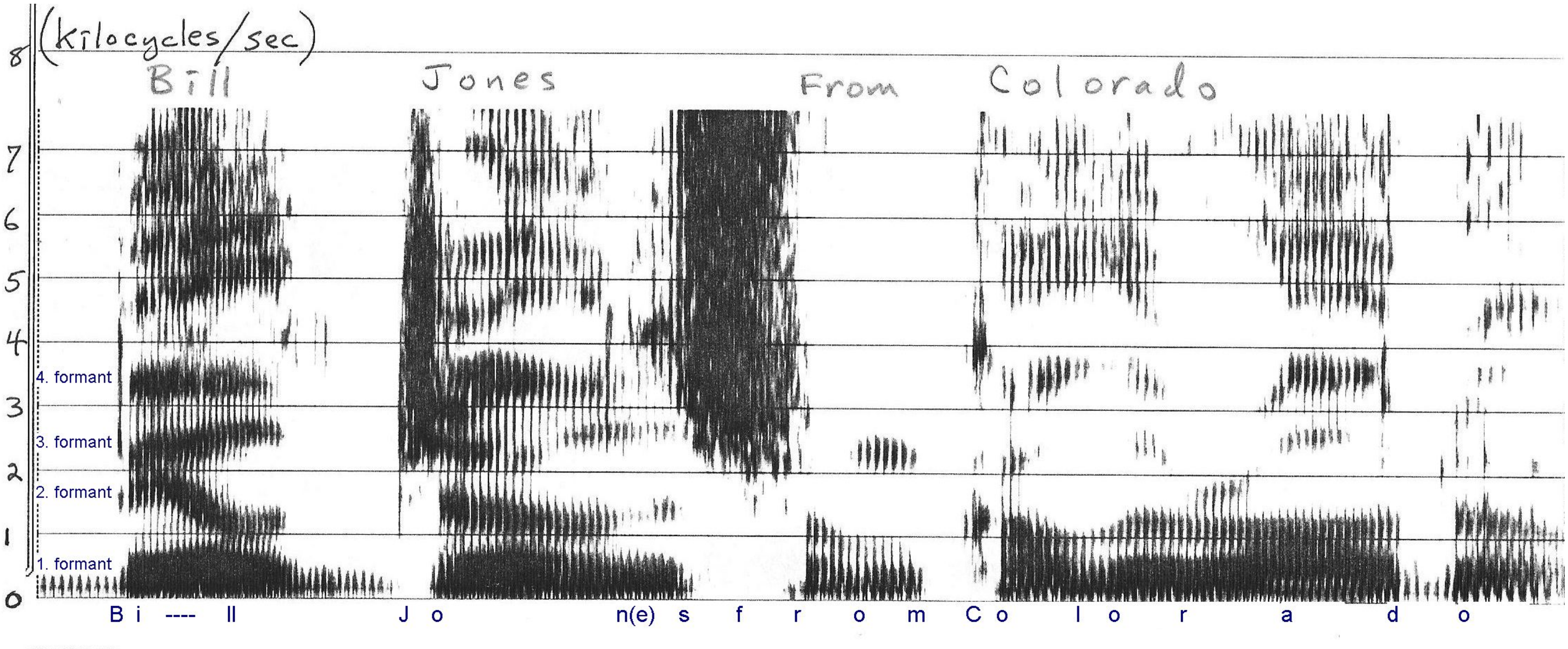
signals

- signal = physical quantity that varies as a function of time, space, or any other variable or variables
  - $x(t)$ - time t is independent variable
  - $f(x,y)$ - spatial coordinates (x,y) are independent variables
- signals convey information in their patterns of variation

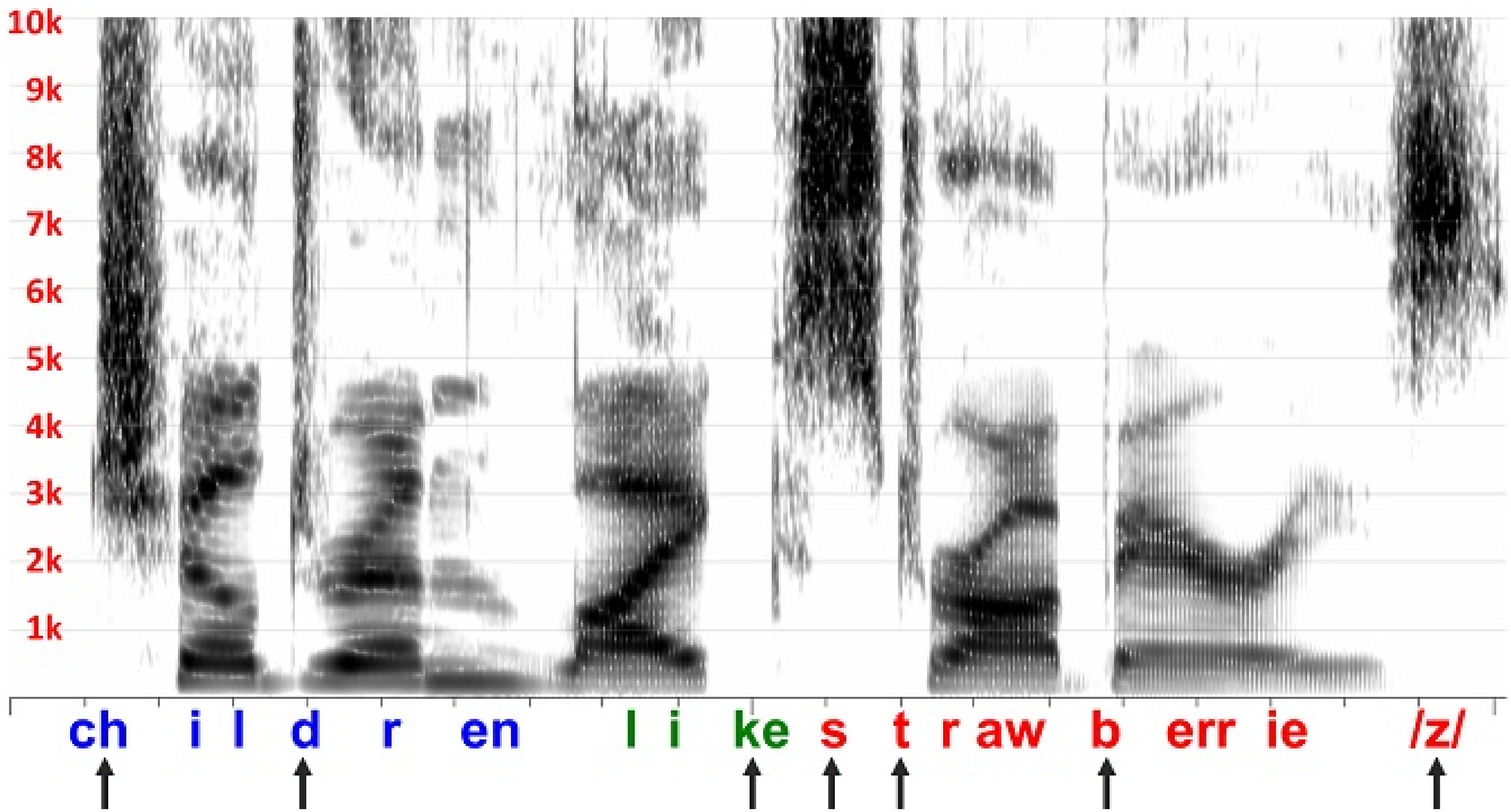




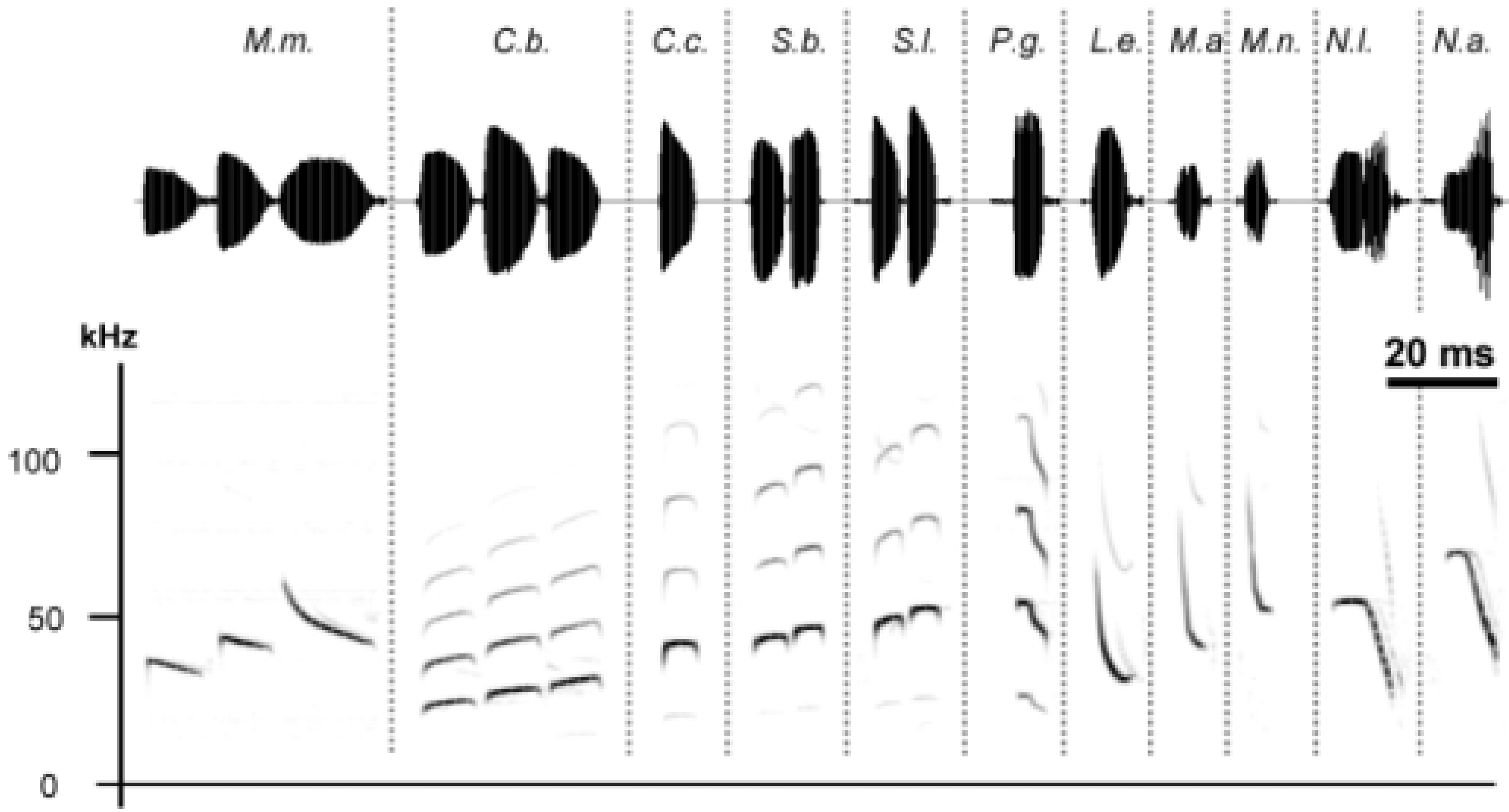
speech signals



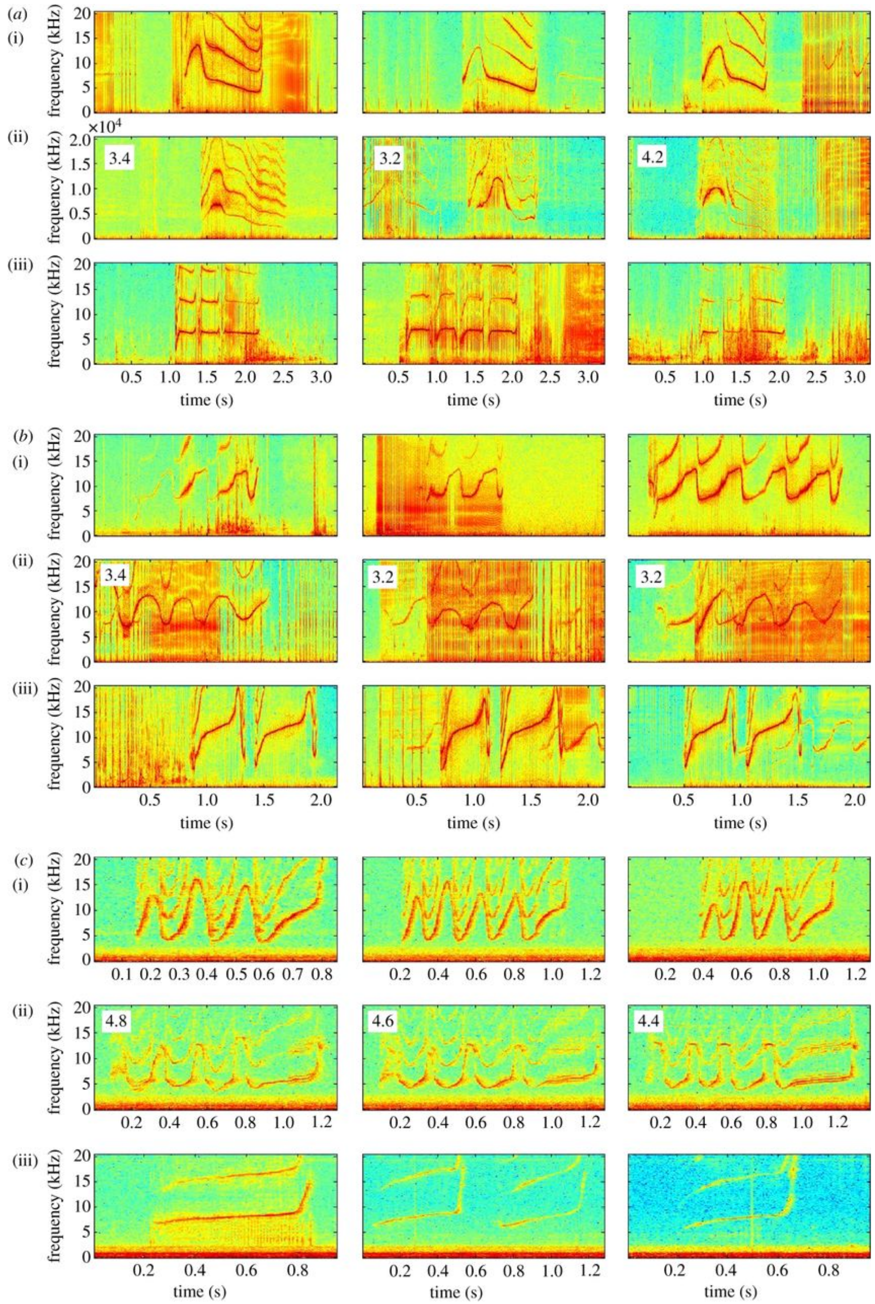
speech signals



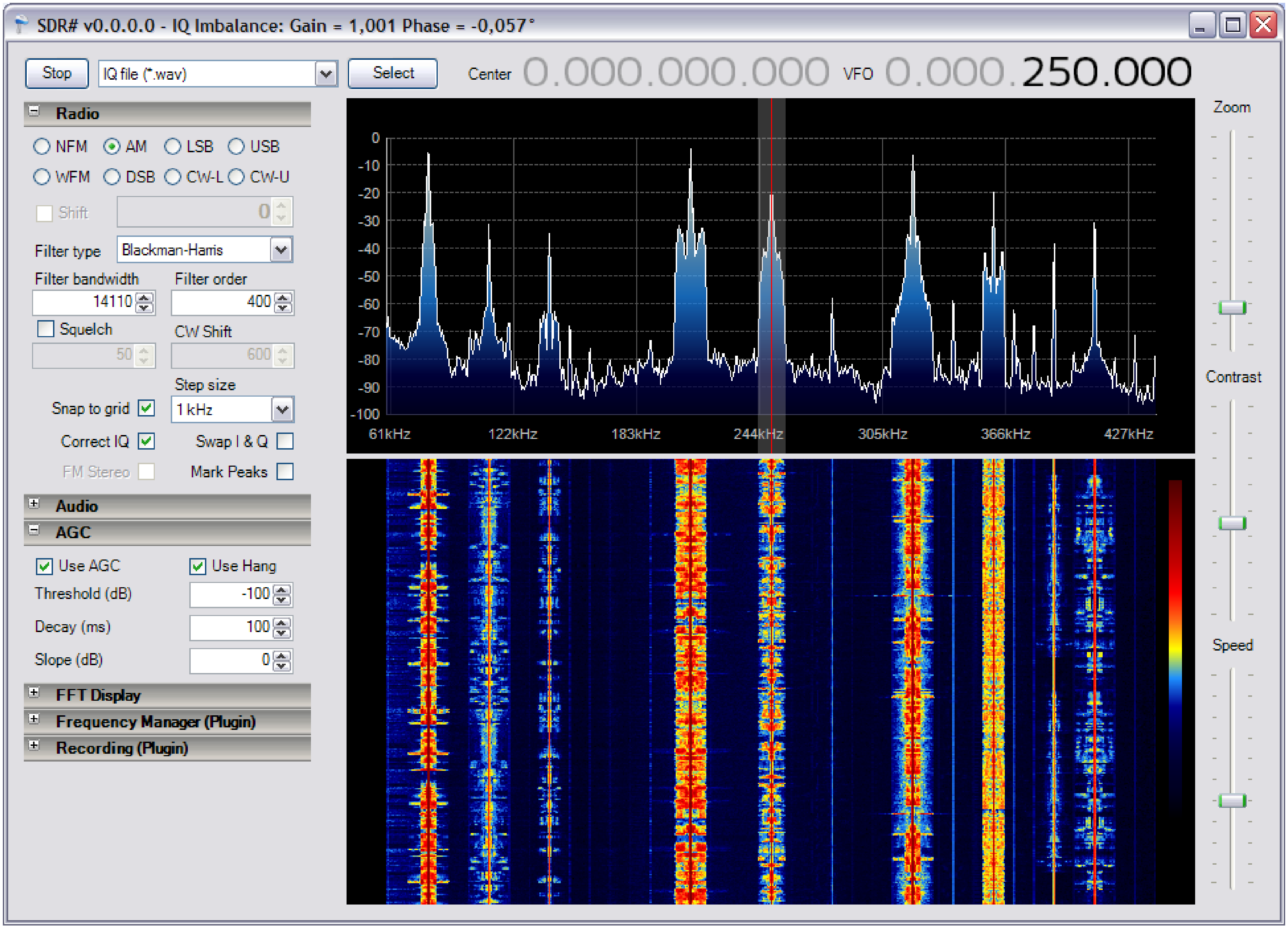
bat signals



dolphin signals

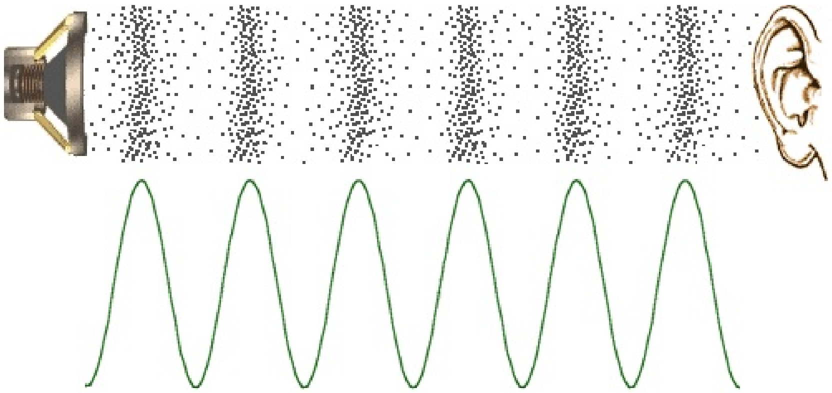


radio signals



signals

sound wave



radio wave

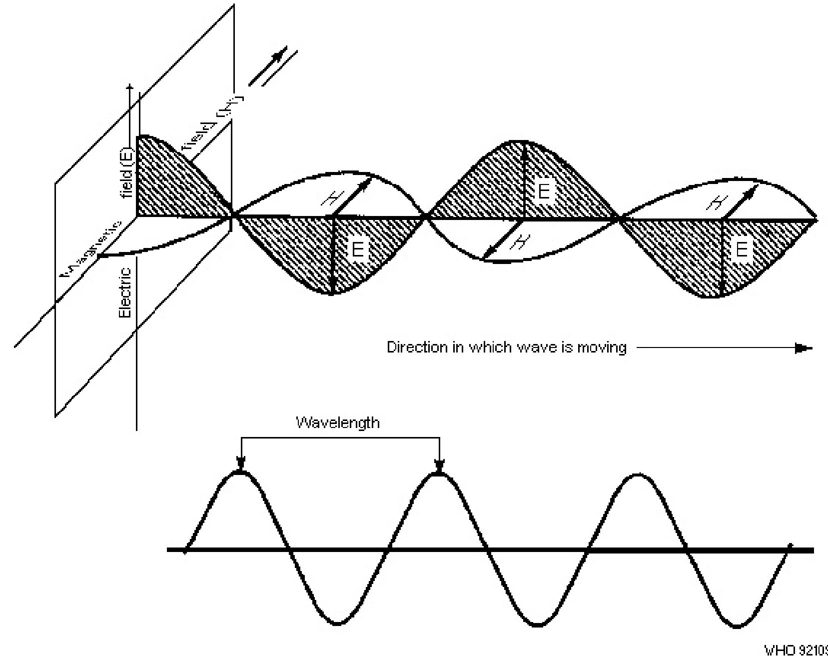


Fig. 1. An electromagnetic monochromatic wave. Electromagnetic waves consist of electrical and magnetic forces that move in consistent wave-like patterns at right angles to each other for far-field propagation, but at varying angles in the near-field.

sound wave
image/scene

physical representation of signals

storage, transmission, and processing of signals require their representation using physical media

analog physical representations

physical representation of signals

storage, transmission, and processing of signals require their representation using physical media

H.264
MPEG-4/AVC

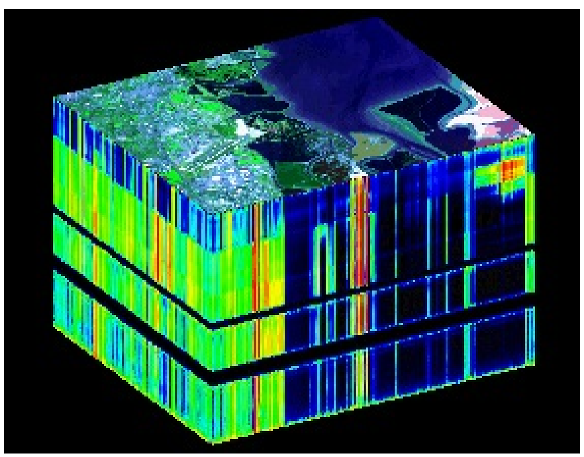
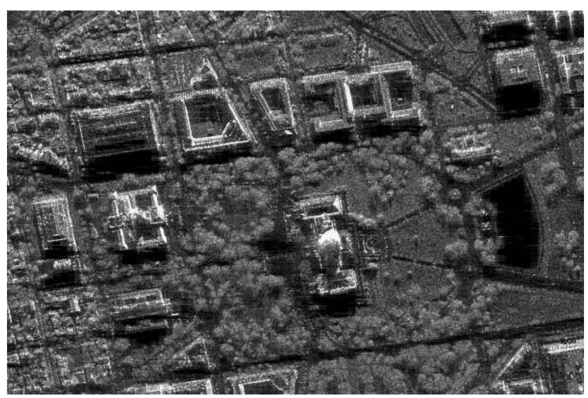
MP3
AUDIO

digital physical representations

mathematical representation of signals

- function of one or more independent variable
  - sound: $x(t)$
  - hight of a projectile: $h(t)$
  - brightness of a scene: $b(x, y)$
  - medical or radar image: $i(x, y)$
  - hyperspectral image: $i(x, y, \lambda)$

- representing signals as functions enables mathematical analysis to be applied

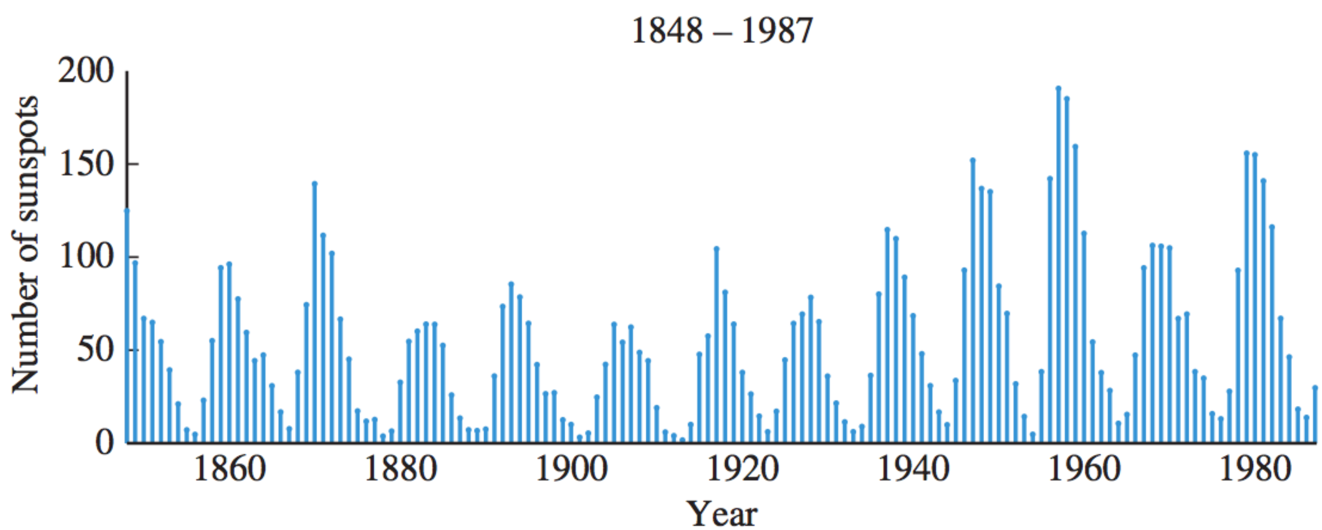




signal categories

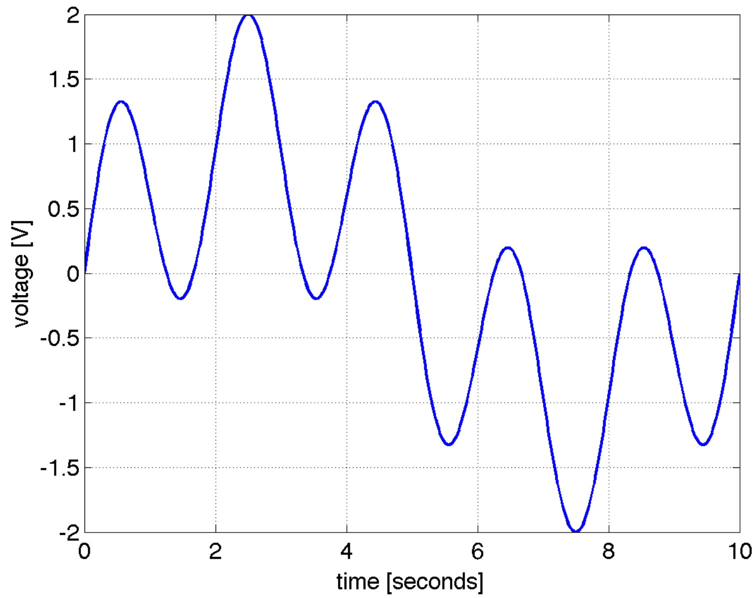
	continuous time t	discrete time n
continuous amplitude	analog, $x(t)$	discrete-time, $x[n]$, x_n
discrete amplitude		digital

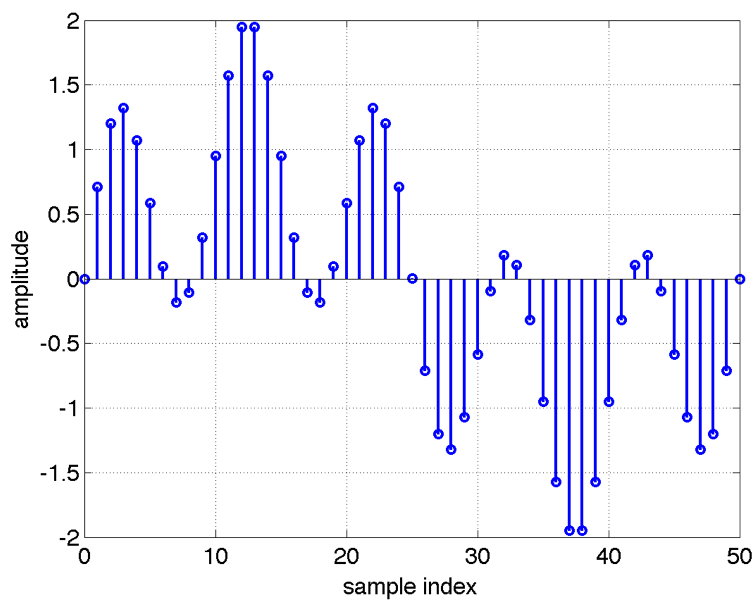
- focus of this class on continuous-time (analog) and discrete-time signals

- digital signals have amplitudes in discrete (usually finite) set
  - 8-bit grayscale image: $f[m, n] \in \{0, 1, 2, \cdots, 255\}$
  - heart rate: $x[n] \in \{30, 31, 32, 33, \cdots, 200\}$ beats/minute
  - number of sunspots per year:



CT and DT signals





$x[\ 0]$	=	0.00000	$x[25]$	=	0.00000
$x[\ 1]$	=	0.71312	$x[26]$	=	-0.71312
$x[\ 2]$	=	1.19975	$x[27]$	=	-1.19975
$x[\ 3]$	=	1.31918	$x[28]$	=	-1.31918
$x[\ 4]$	=	1.06954	$x[29]$	=	-1.06954
$x[\ 5]$	=	0.58779	$x[30]$	=	-0.58779
$x[\ 6]$	=	0.09676	$x[31]$	=	-0.09676
$x[\ 7]$	=	-0.18054	$x[32]$	=	0.18054
$x[\ 8]$	=	-0.10673	$x[33]$	=	0.10673
$x[\ 9]$	=	0.31704	$x[34]$	=	-0.31704
$x[10]$	=	0.95106	$x[35]$	=	-0.95106
$x[11]$	=	1.57007	$x[36]$	=	-1.57007
$x[12]$	=	1.94908	$x[37]$	=	-1.94908
$x[13]$	=	1.94908	$x[38]$	=	-1.94908
$x[14]$	=	1.57007	$x[39]$	=	-1.57007
$x[15]$	=	0.95106	$x[40]$	=	-0.95106
$x[16]$	=	0.31704	$x[41]$	=	-0.31704
$x[17]$	=	-0.10673	$x[42]$	=	0.10673
$x[18]$	=	-0.18054	$x[43]$	=	0.18054
$x[19]$	=	0.09676	$x[44]$	=	-0.09676
$x[20]$	=	0.58779	$x[45]$	=	-0.58779
$x[21]$	=	1.06954	$x[46]$	=	-1.06954
$x[22]$	=	1.31918	$x[47]$	=	-1.31918
$x[23]$	=	1.19975	$x[48]$	=	-1.19975
$x[24]$	=	0.71312	$x[49]$	=	-0.71312

- CT signal is a waveform
- DT signal is a sequence of numbers (concept of time encoded in sample rate)

digital signals

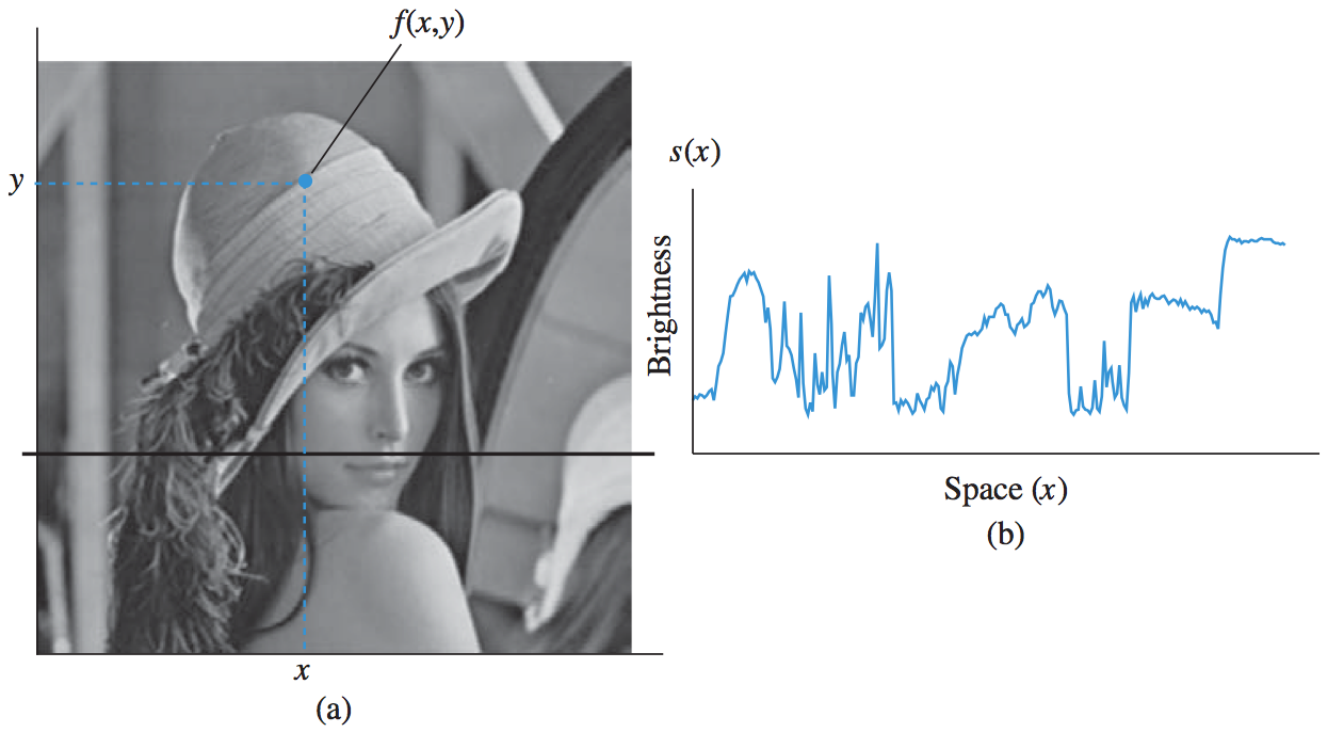
- DT and digital signals: concept of time is lost
- DT and digital signals are undefined between samples (not zero)
- need sample rate to interpret DT and digital signals
- DT signals have “amplitude”
- digitals signals are binary codes

$$x_d[n] = b_1 2^{-1} + b_2 2^{-2} + \cdots + b_B 2^{-B},$$
$$x[n] \approx R\, x_d[n],$$

where R is a reference voltage

x_d[0]	=	0011001000	x_d[25]	=	0011001000
x_d[1]	=	0100001111	x_d[26]	=	0010000001
x_d[2]	=	0101000000	x_d[27]	=	0001010000
x_d[3]	=	0101001100	x_d[28]	=	0001000100
x_d[4]	=	0100110011	x_d[29]	=	0001011101
x_d[5]	=	0100000011	x_d[30]	=	0010001101
x_d[6]	=	0011010010	x_d[31]	=	0010111110
x_d[7]	=	0010110110	x_d[32]	=	0011011010
x_d[8]	=	0010111101	x_d[33]	=	0011010011
x_d[9]	=	0011101000	x_d[34]	=	0010101000
x_d[10]	=	0100100111	x_d[35]	=	0001101001
x_d[11]	=	0101100101	x_d[36]	=	0000101011
x_d[12]	=	0110001011	x_d[37]	=	0000000101
x_d[13]	=	0110001011	x_d[38]	=	0000000101
x_d[14]	=	0101100101	x_d[39]	=	0000101011
x_d[15]	=	0100100111	x_d[40]	=	0001101001
x_d[16]	=	0011101000	x_d[41]	=	0010101000
x_d[17]	=	0010111101	x_d[42]	=	0011010011
x_d[18]	=	0010110110	x_d[43]	=	0011011010
x_d[19]	=	0011010010	x_d[44]	=	0010111110
x_d[20]	=	0100000011	x_d[45]	=	0010001101
x_d[21]	=	0100110011	x_d[46]	=	0001011101
x_d[22]	=	0101001100	x_d[47]	=	0001000100
x_d[23]	=	0101000000	x_d[48]	=	0001010000
x_d[24]	=	0100001111	x_d[49]	=	0010000001

what kind of signal is this?

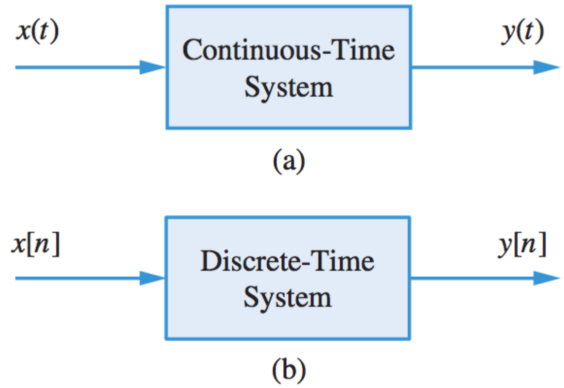


- brightness/intensity/amplitude $s(x, y)$ varies continuously with continuous spatial position (x, y)

- digital image is discretized both spatially and in brightness/intensity/amplitude

- picture element (pixel) $s[m, n] = s(m\Delta x, n\Delta y) \in \{0, 1, 2, \cdots, 255\}$

systems



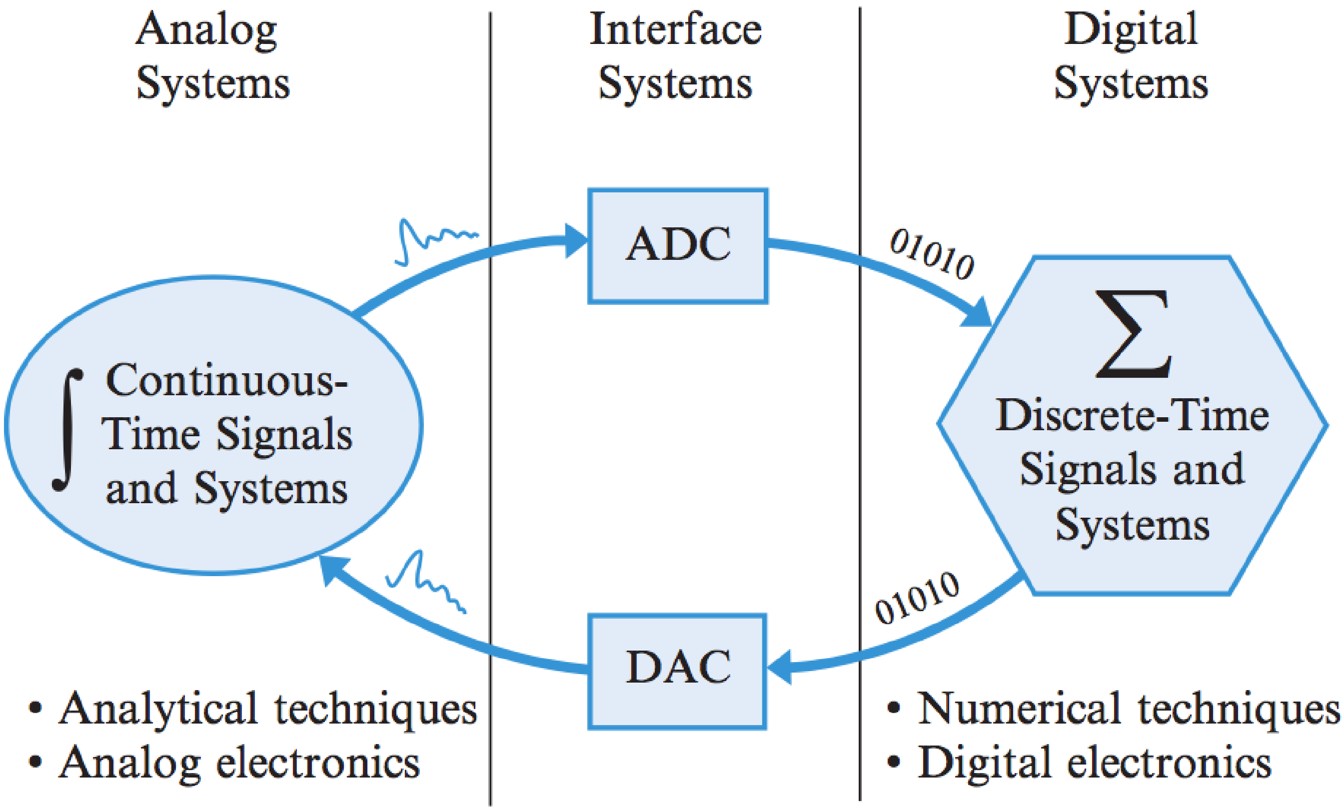
- CT systems: transform CT inputs to CT outputs
- CT systems implemented in analog electronics (analog systems)

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

- DT systems: transform DT inputs to DT outputs
- DT systems implemented in digital electronics that can manipulate binary encoded data (ex. ASIC or FPGA) or in software (ex. microprocessors, DSPs, ARM, 8051, etc.)

$$y[n] = \sum_{k=-\infty}^{n} x[k]$$

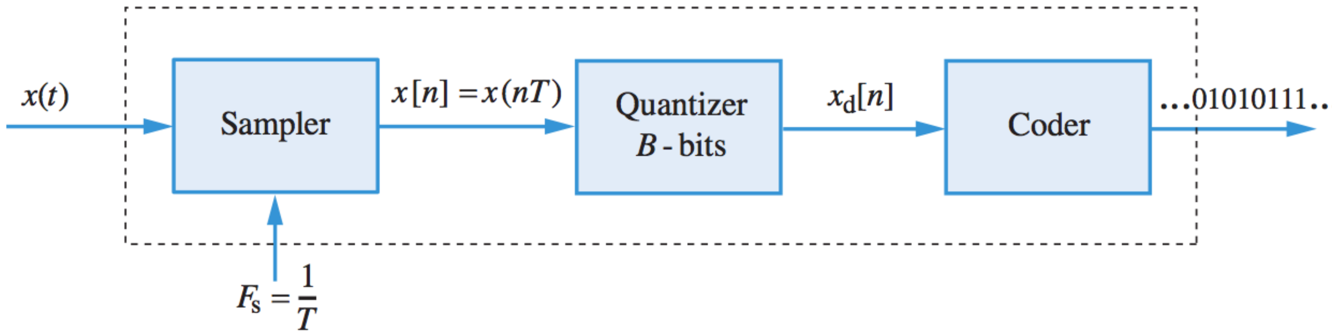
interface systems



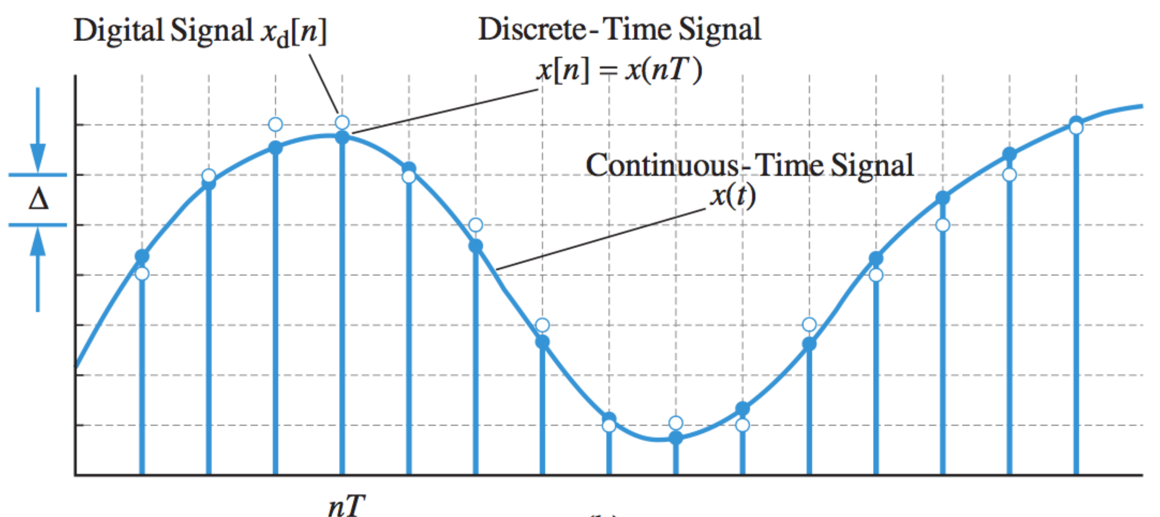
sampling and quantization: interface between continuous-time/analog and discrete-time/digital

(discrete-time) $x[n] = x(nT) = x(t)|_{t=nT}$ (continuous-time)

(digital) $x_d[n] = Q(x[n])$ (discrete-time)



(a)

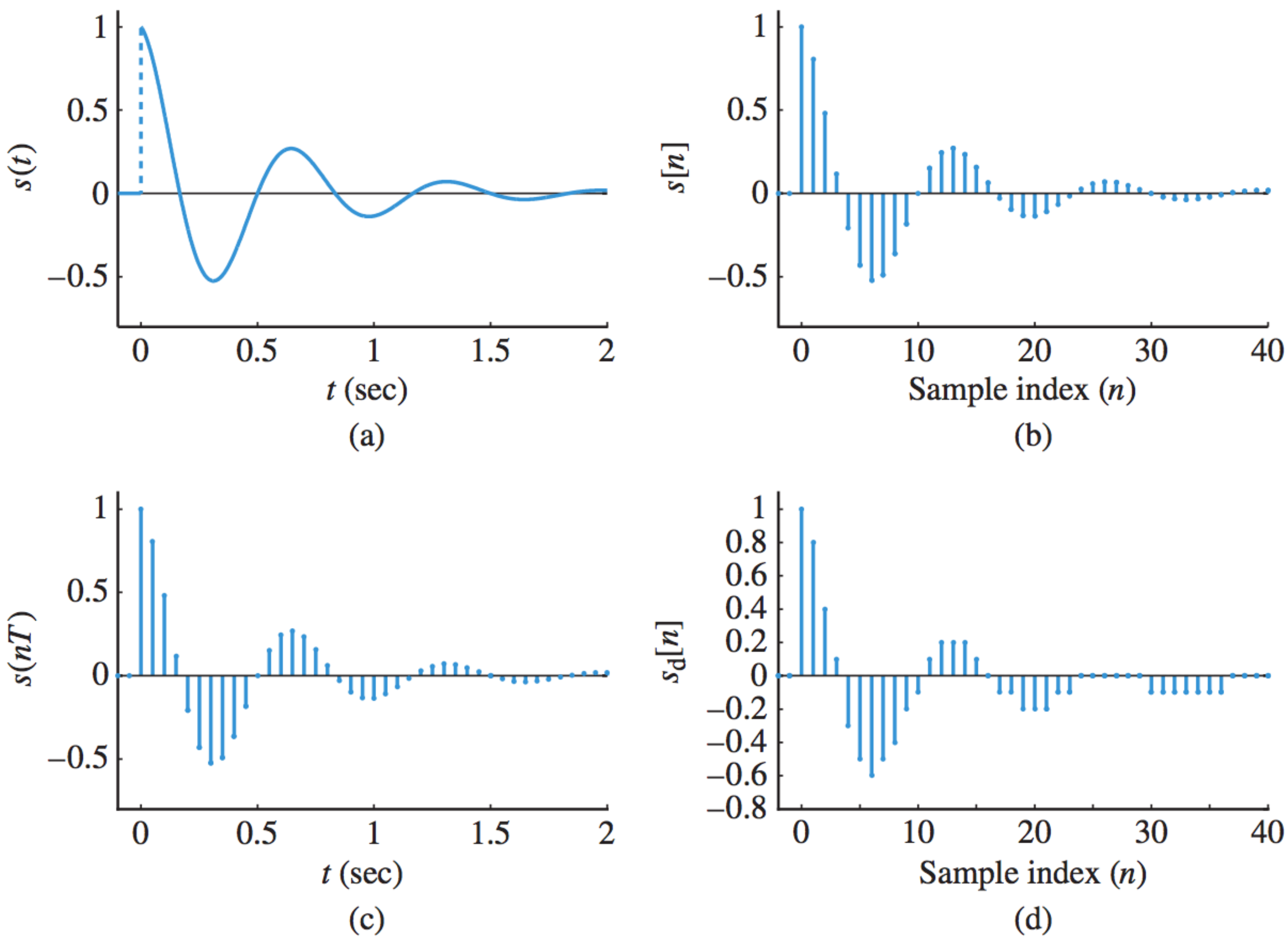


(b)

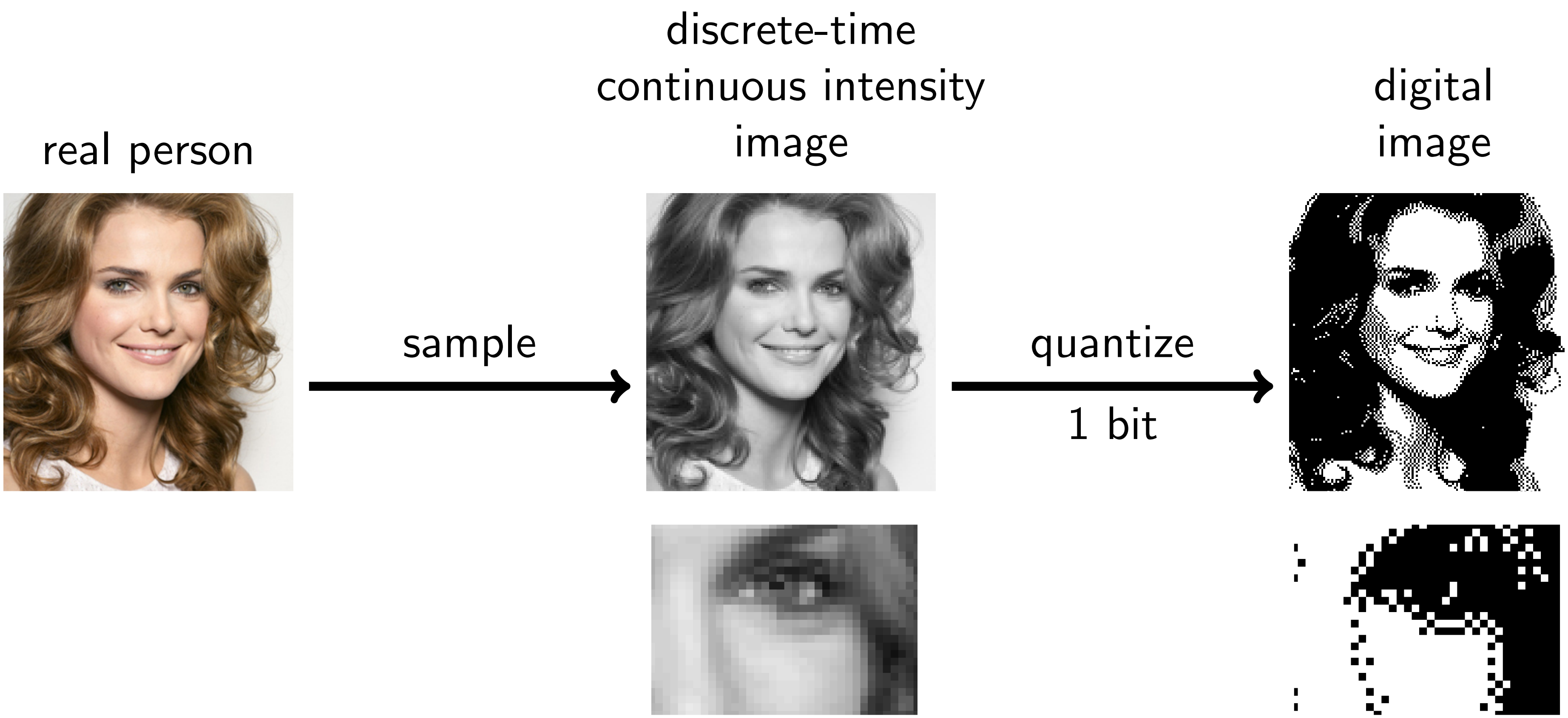
sampling and quantization

$$\text{(discrete-time)} \quad s[n] = s(nT) = s(t)|_{t=nT} \quad \text{(continuous-time)}$$

$$\text{(digital)} \quad s_d[n] = Q(s[n]) \quad \text{(discrete-time)}$$

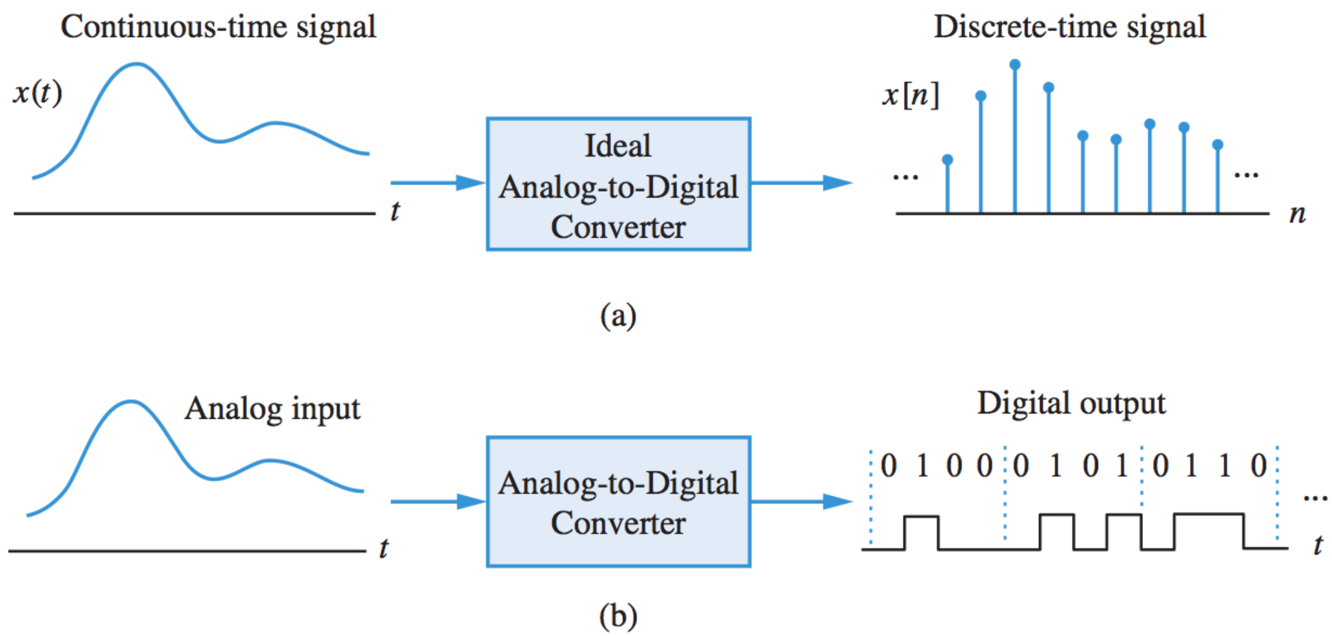


sampling and quantization



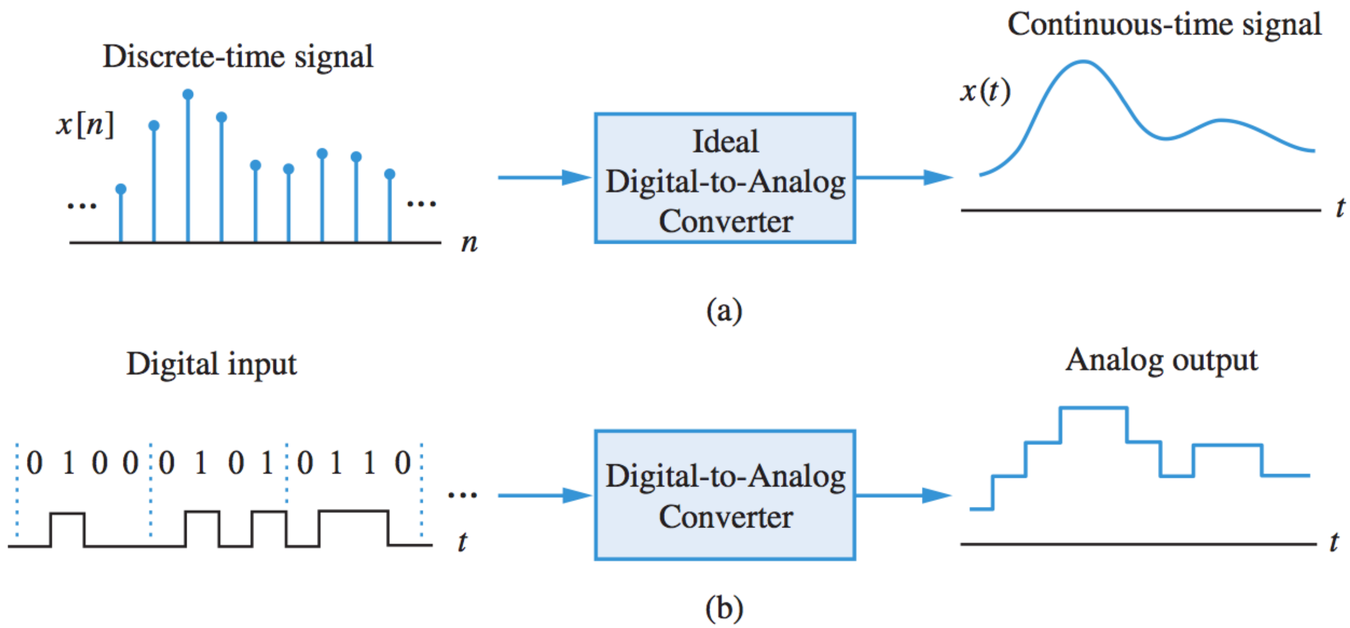
- errors are introduced when discretizing the independent variable
- errors are introduced when discretizing the dependent variable

analog to digital conversion



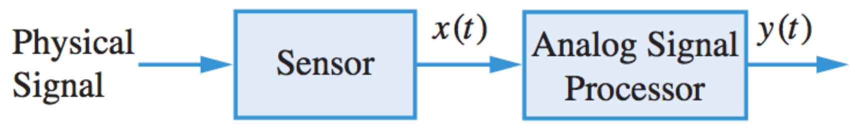
- in ECE 3640 we focus on ideal A/D conversion
- in ECE 3640 we focus on continuous-time and discrete-time signals and systems
- DT and digital signals are only defined at sample times

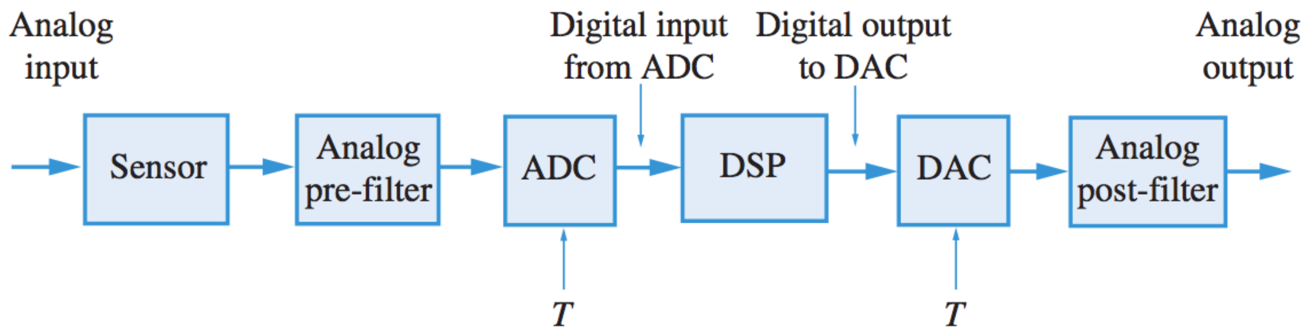
digital to analog conversion



- low pass filter follows D/A converter to smooth the signal
- D/A converter re-introduces the lost time-scale information

analog and digital signal processing



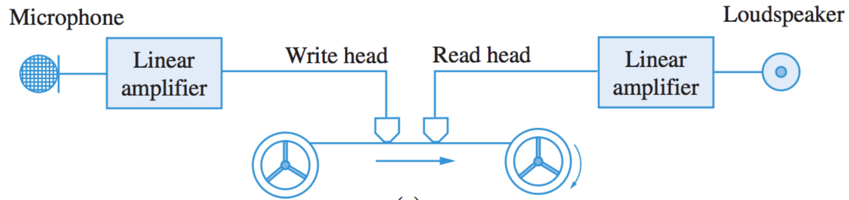


- sensor converts signal of interest (pressure, temperature, flow, EM wave, etc.) into electrical signal (voltage or current)

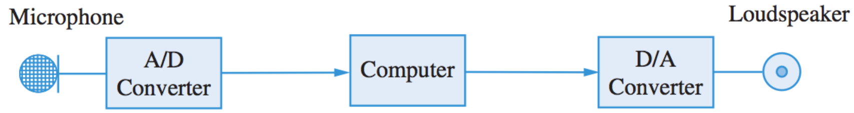
- (top) analog signal processing - have to do all processing using circuits

- (bottom) digital signal processing - accept quantization errors for greater flexibility in processing

merits of analog and digital signal processing



(a)

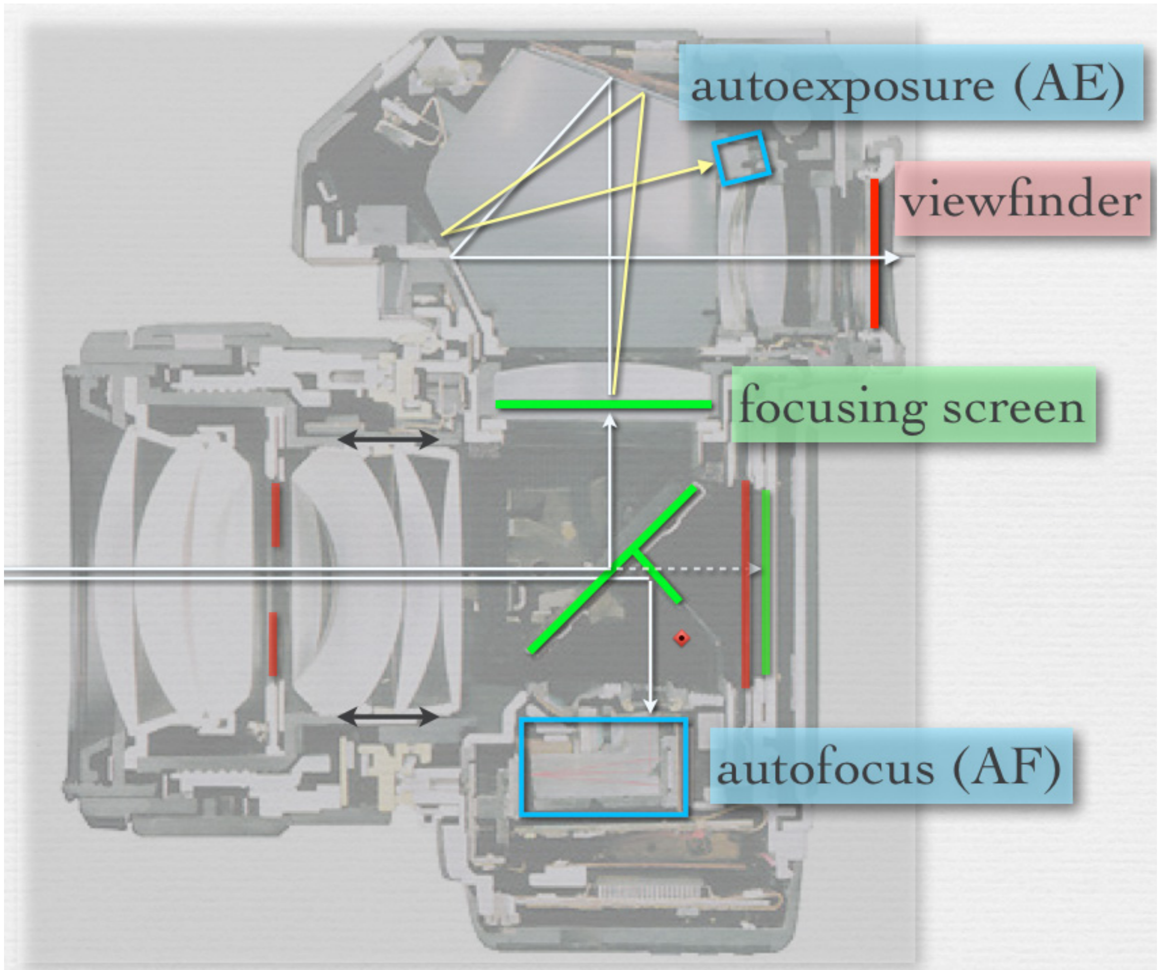


(b)

- analog tape recording system (top)
  - magnetic tape stretches and shrinks (time distortion)
  - speed of motor changes (time distortion)
  - changes in the strength of the magnetic field (amplitude distortion)
  - quality of playback diminishes overtime (amplitude distortion)

- digital recorder system (bottom)
  - quality of audio determined by stability of sample clock (time distortion)
  - quality of audio determined by number of bits in representation (amplitude distortion)
  - once audio is digitized, error free storage and transmission are possible
  - playback is consistent over time

merits of analog and digital signal processing



- front end optics = analog signal processing
- how much of this processing could be done in analog?

merits of analog and digital signal processing

- DSP makes sophisticated processing possible at low cost
- impossible to implement some functions using analog electronics, but can do it easily in DSP (eg. linear prediction for speech coding)
- DSP systems are more reliable, more compact, lower power, less sensitive to environmental conditions and component aging
- DSP allows time-sharing of a single processor among different processing functions
- DSP systems can re-use software in libraries or hardware designs in IP cores
- DSP systems limited by speed of A/D, D/A converters

questions

- What is a signal and how does it convey information?
- Describe various different ways a signal can be classified.
- What is the difference between a mathematical and physical representation of a signal?
- Explain the difference between continuous-time, discrete-time, and digital signals in terms of m mathematical and physical representations.
- What is a continuous-time system? A discrete-time system? Provide one example of each.
- Why do we need interface systems and where do we need them? Provide a block diagram description of such systems needed in signal processing?
- Describe an analog-to-digital (A/D) converter.
- Describe a digital-to-analog (D/A) converter.
- What is the difference between practical and ideal A/D converter? Between a practical and ideal D/A converter?
- Why is digital signal processing preferred over analog signal processing?