SI100B Introduction to Information Science and Technology

Signal Processing

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Week 1
Introduction to Signals and Signal Processing

Reference Books

- Richard G. Lyons, Understanding Digital Signal Processing
- Alan V. Oppenheim, Alan S. Willsky and S. Hanid Nawab, Signals and Systems, 2rd Edition
- Alan V. Oppenheim and Ronald W. Schafer, Discrete-Time Signal Processing, 3rd Edition

Why Learn Signal Processing?

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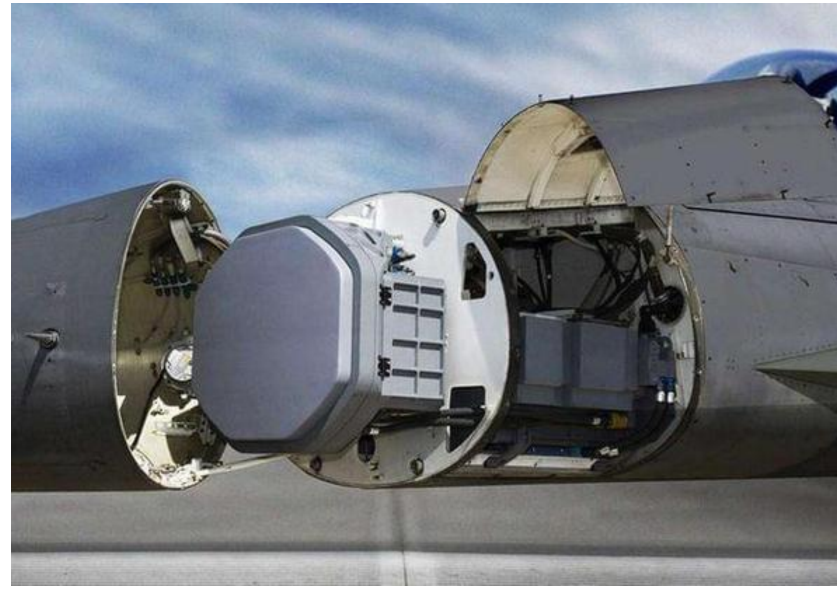


Why Learn Signal Processing?

- Swiss-Army-Knife of modern information science and technology
- Impacts all aspects of modern life
  - Speech/audio: speech recognition, digital audio, etc.
  - Image/video: enhancement, coding, robotic vision, etc.
  - Military/space: radar, sonar, missile guidance, etc.
  - Biomedical/health care: ECG, EEG analysis, X-ray, etc.
  - Communication: 5G, IoT, etc.

Application Examples

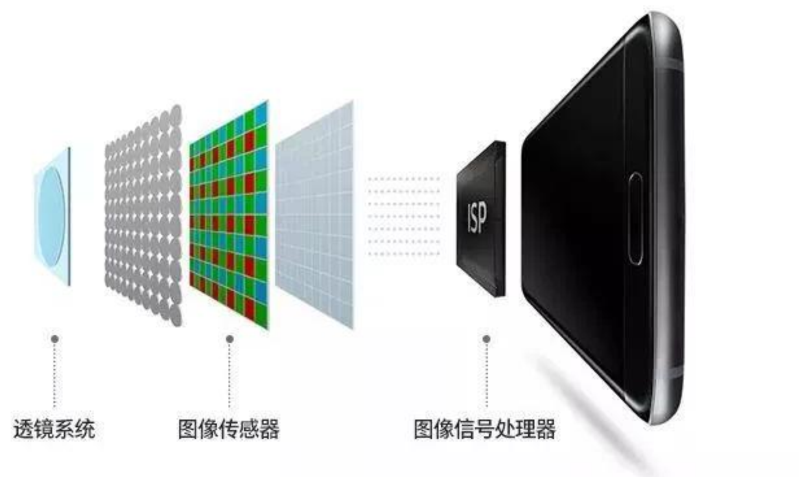
- Mobile Phone
  - Communication
  - Image/Video
  - Audio
  - Signal Coding & Compression

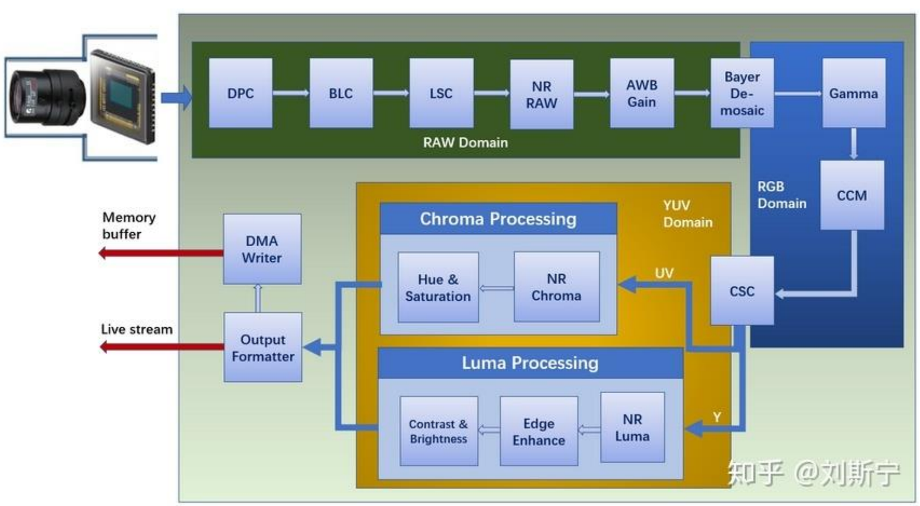
Mobile Phone

- Camera
  - ISP, Dual/Quad cameras
- Audio
  - Noise cancellation
- Baseband processing
  - 4G LTE, 5G, Wifi
- Storage

Digital Camera

❑ Image signal processor





DXOMARK

Rank	Device	Launch Price	Launch Date	CAMERA
1.	Huawei Mate 50 Pro	$1299	Sep 2022	149
2.	Google Pixel 7 Pro	$899	Oct 2022	147
=	Honor Magic4 Ultimate	$1211	Mar 2022	147
4.	Apple iPhone 14 Pro Max	$1099	Sep 2022	146
=	Apple iPhone 14 Pro	$999	Sep 2022	146
6.	Huawei P50 Pro	$907	Jul 2021	143
7.	Apple iPhone 13 Pro	$999	Sep 2021	141
=	Apple iPhone 13 Pro Max	$1099	Sep 2021	141
=	Xiaomi Mi 11 Ultra	$1200	Mar 2021	141
10.	Huawei Mate 40 Pro+	$1363	Oct 2020	139
11.	Xiaomi 12S Ultra	$908	Jul 2022	136
12.	Huawei Mate 40 Pro	$1199	Oct 2020	135
=	Samsung Galaxy S22 Ultra (Sna...	$1199	Feb 2022	135
14.	Google Pixel 6 Pro	$899	Oct 2021	134
=	Vivo X70 Pro+	$833	Sep 2021	134

Digital Camera

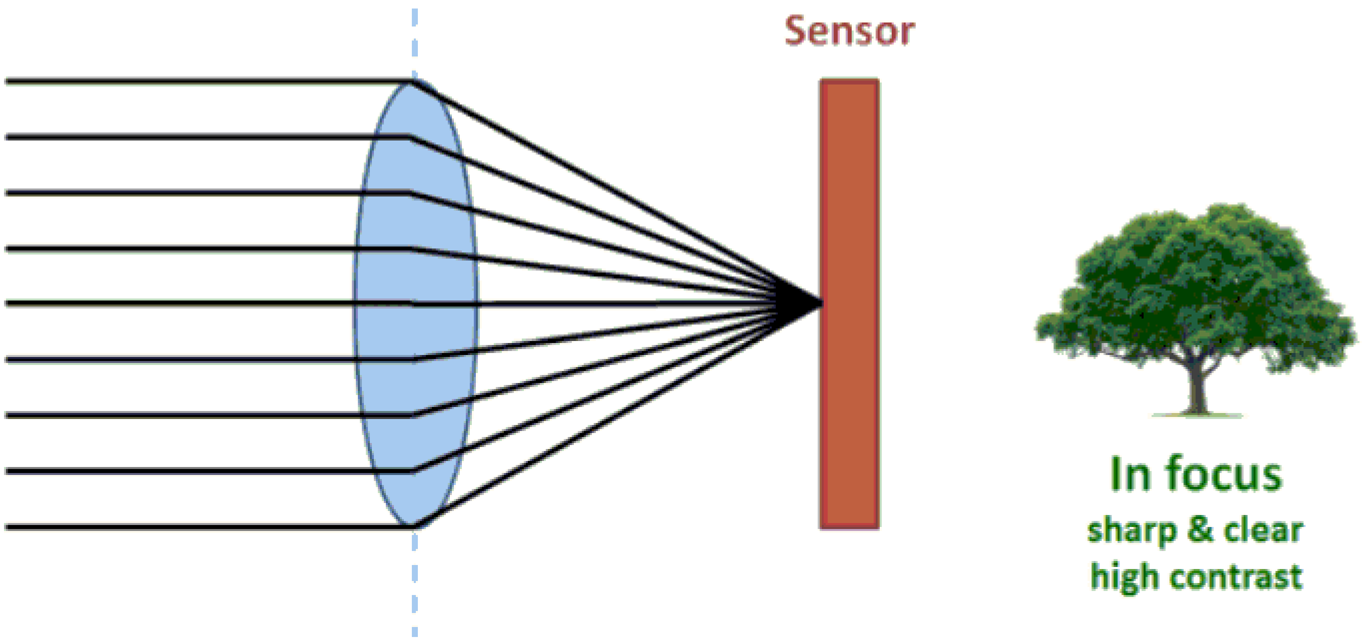
- Image Processing Algorithms
  - Auto focus
  - Auto exposure
  - Auto white balancing
  - Demosaicing
  - Denoise
  - Length correction
  - Dynamic range compression
  - Image compression
  - …

CAN be as many as a hundred steps !

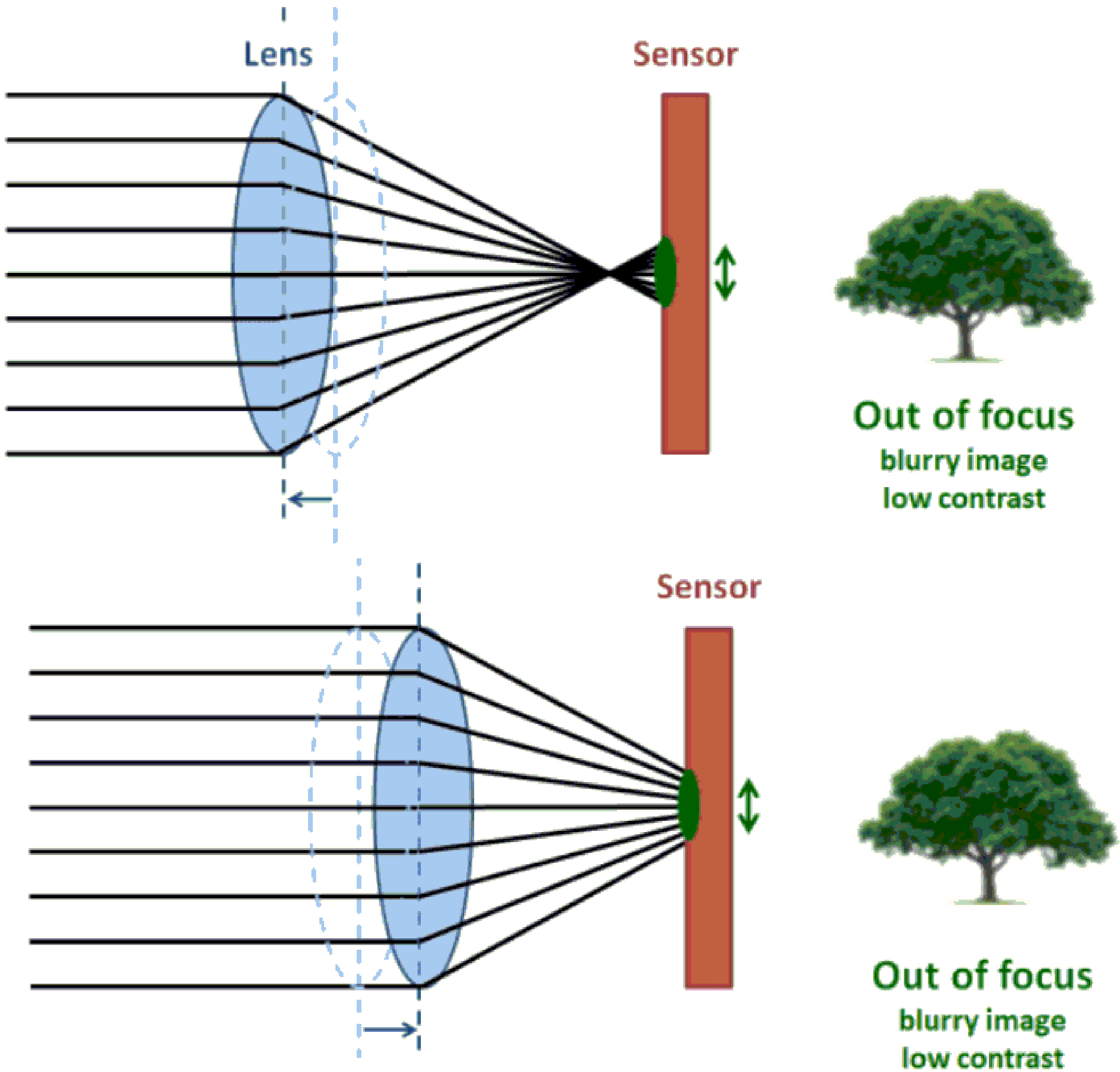
CS270 Digital Image processing
CS276 Computational Photography

Auto Focus (AF)

Auto Focus (AF)



Auto Focus (AF)



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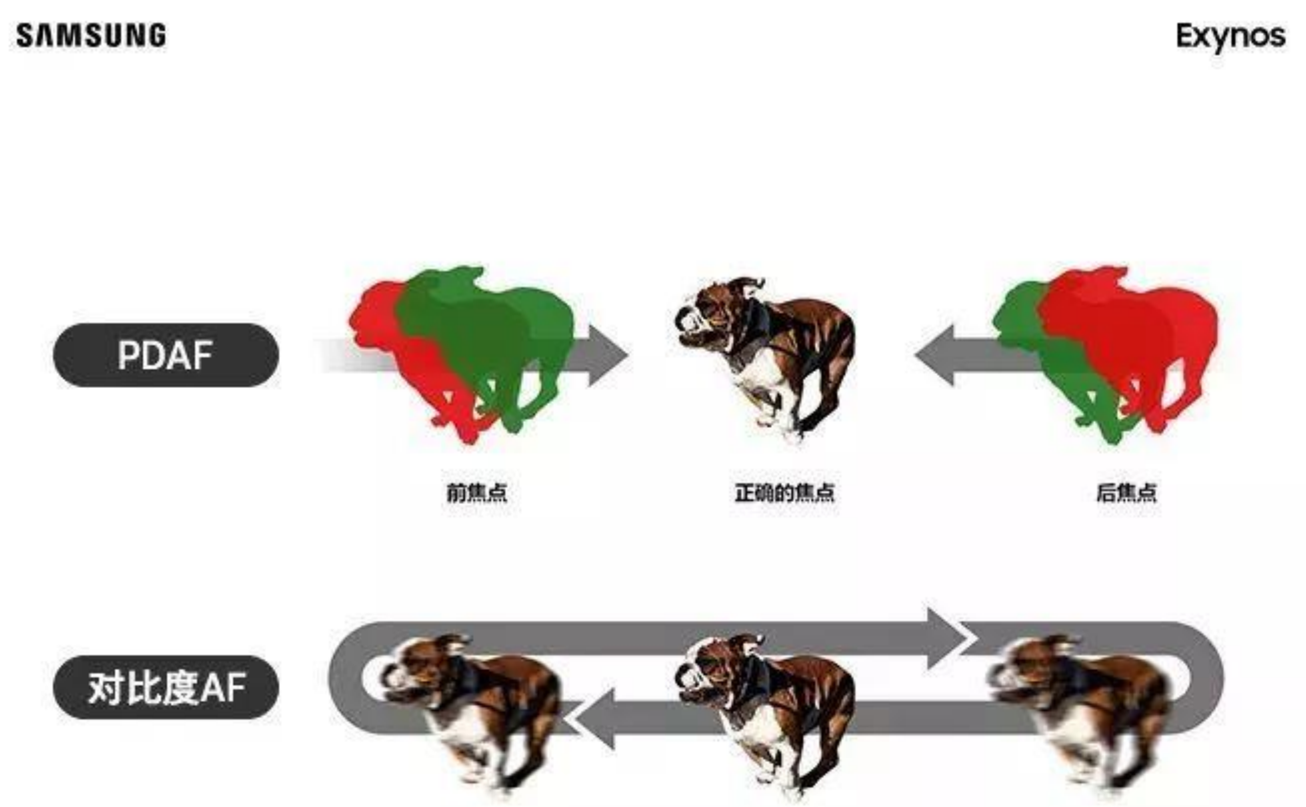
Auto Focus (AF)



To make photos (part of) clear!

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Auto Exposure (AE)

Auto Exposure (AE)

- Collection information to control
  - Aperture (f-number)
  - Sensor integration time
  - Sensor gain
  - ISO

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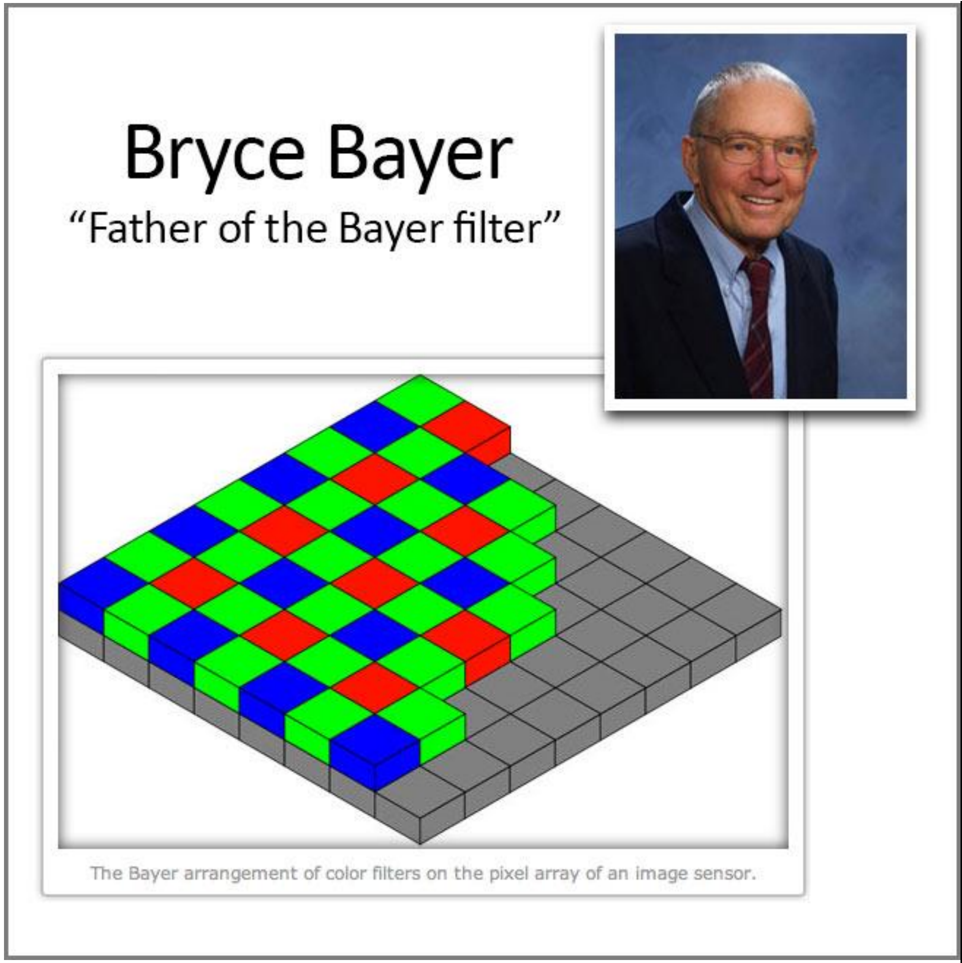
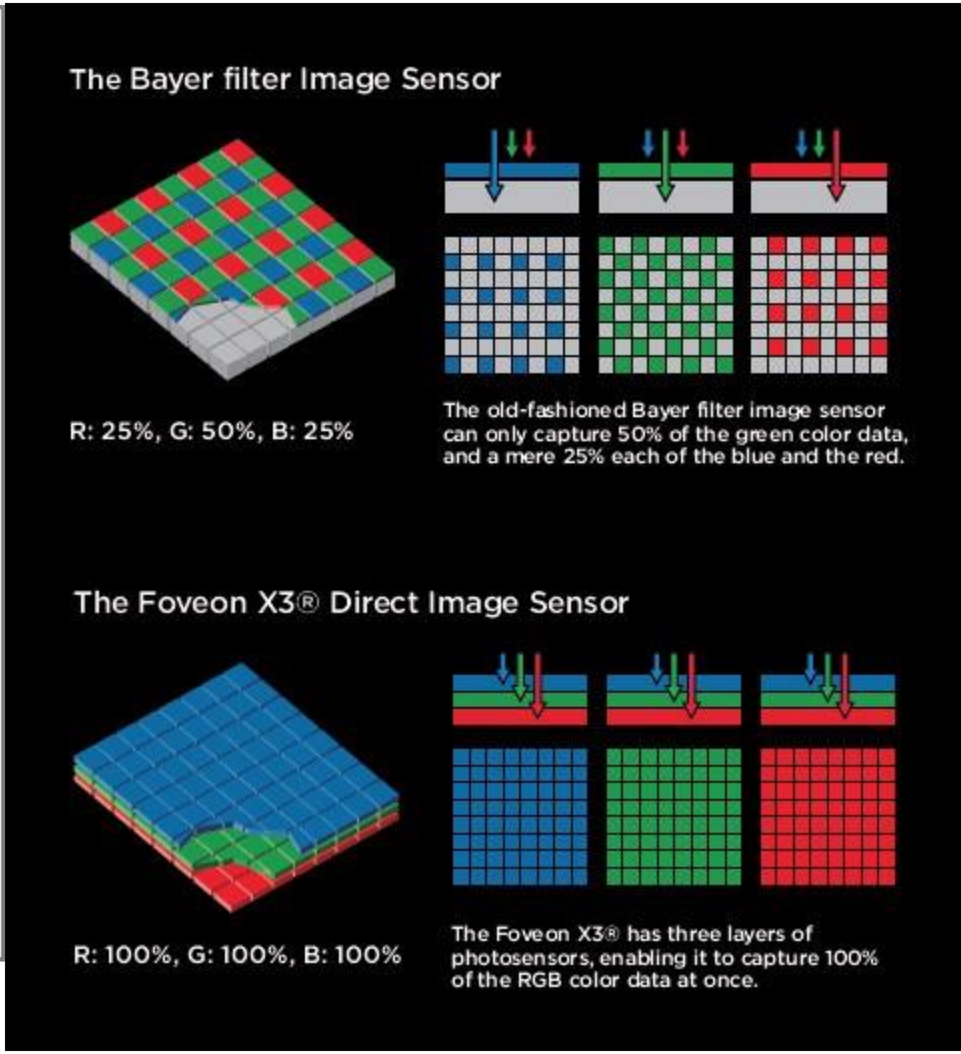
Auto White Balancing (AWB)

To make white objects rendered white!

Demosaicing



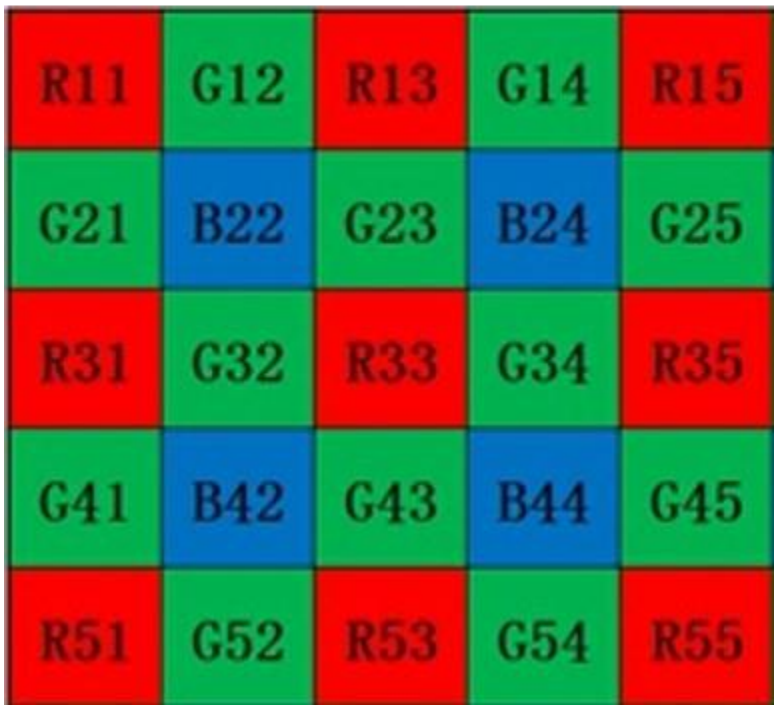
The Bayer arrangement of color filters on the pixel array of an image sensor.



To produce color photos!

Demosaicing

❑ Bilinear Interpolation



$$R_{23} = \frac{R_{13} + R_{33}}{2} \qquad B_{23} = \frac{B_{22} + B_{24}}{2}$$

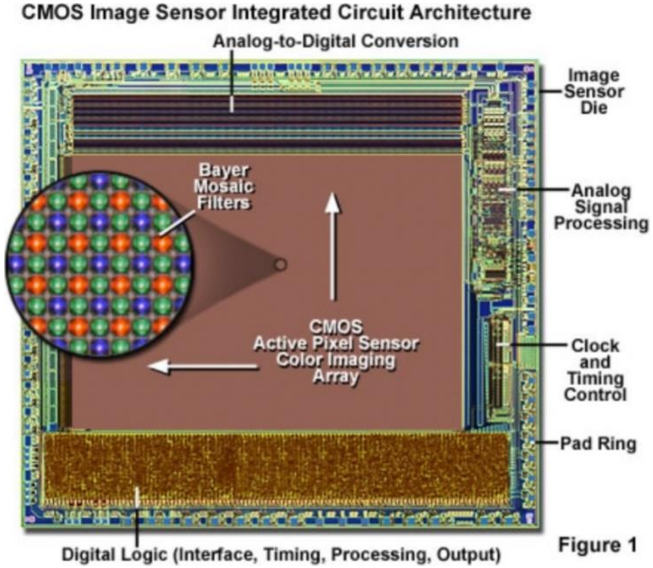
$$G_{33} = \frac{G_{23} + G_{43} + G_{32} + G_{34}}{4}$$

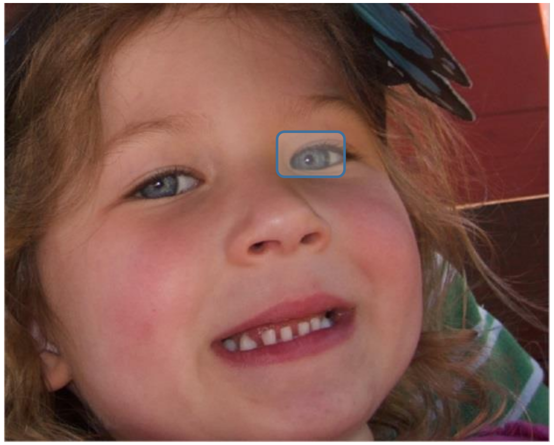
$$B_{33} = \frac{B_{22} + B_{24} + B_{42} + B_{44}}{4}$$

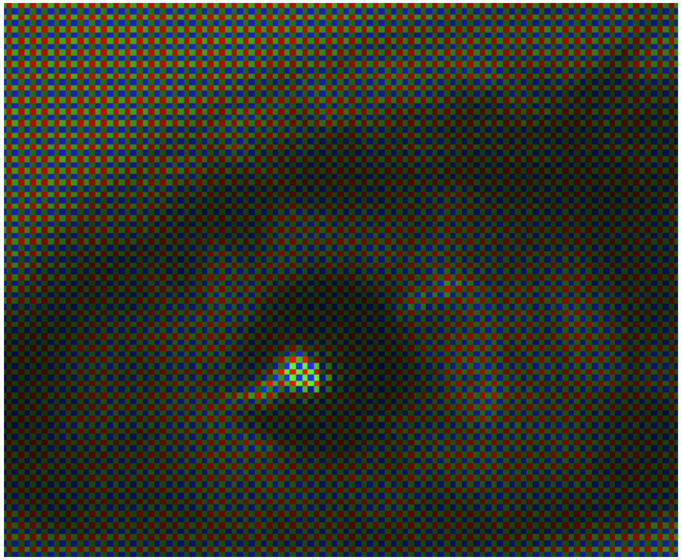
$$G_{44} = \frac{G_{34} + G_{54} + G_{43} + G_{45}}{4}$$

$$R_{44} = \frac{R_{33} + R_{35} + R_{53} + R_{55}}{4}$$

Demosaicing



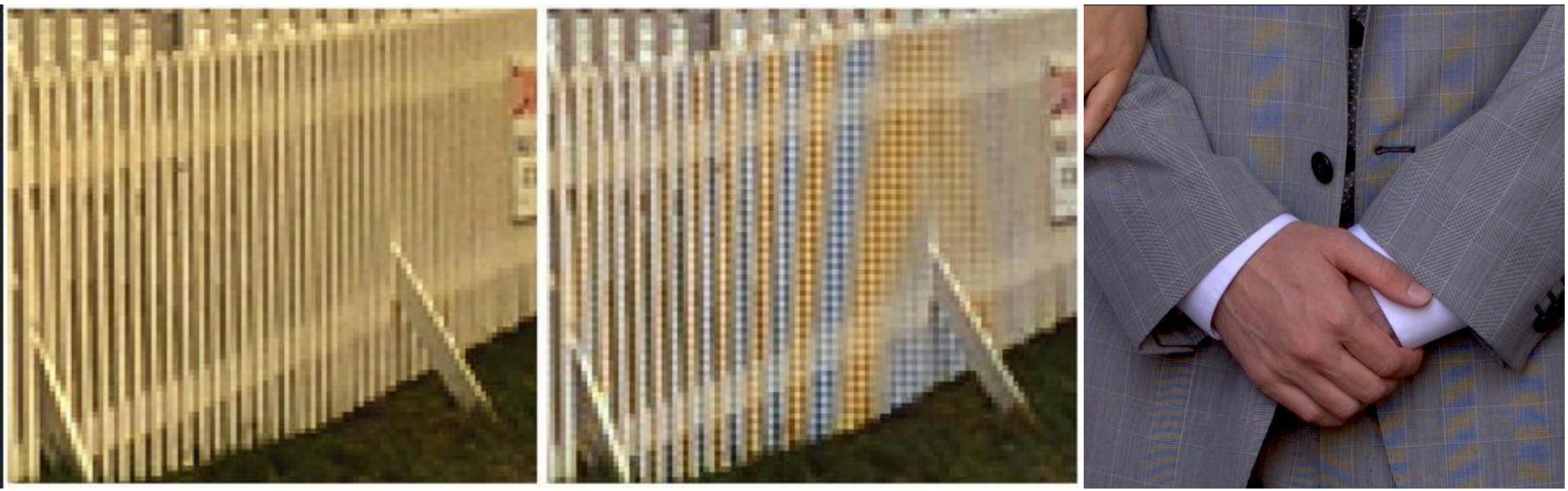




Demosaicing

Demosaicing

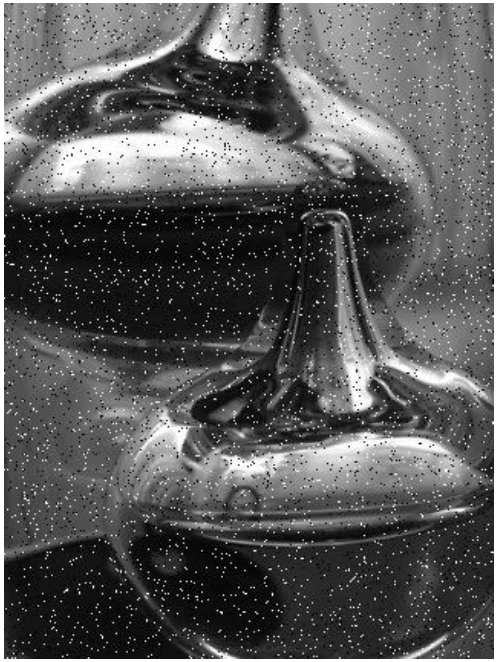
❑ Artifacts caused by demosaicing



Denoise

Denoise

Median filtering

Input: $x = (2, 3, 80, 6, 2, 3)$.

So, the median filtered output signal y will be:
$y_1 = \text{med}(2, 3, 80) = 3$, $y_2 = \text{med}(3, 80, 6) = 6$, $y_3 = \text{med}(80, 6, 2) = 6$, $y_4 = \text{med}(6, 2, 3) = 3$,

i.e. $y = (3, 6, 6, 3)$.

Denoise

Goyal B, Dogra A, Agrawal S, et al. Image denoising review: From classical to state-of-the-art approaches[J]. Information fusion, 2020, 55: 220-244.

Lens Correction

Gamma Correction

Dynamic Range Compression

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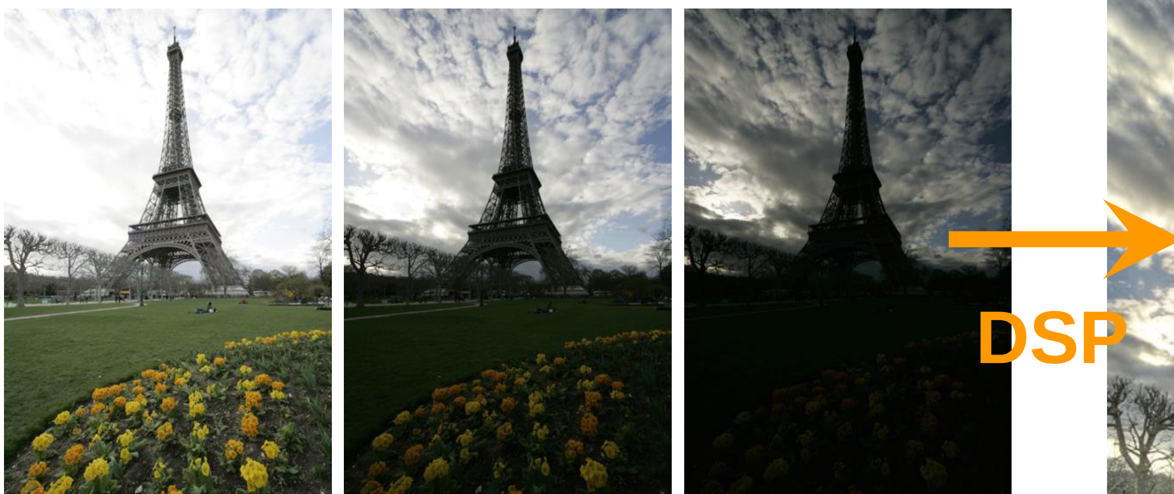
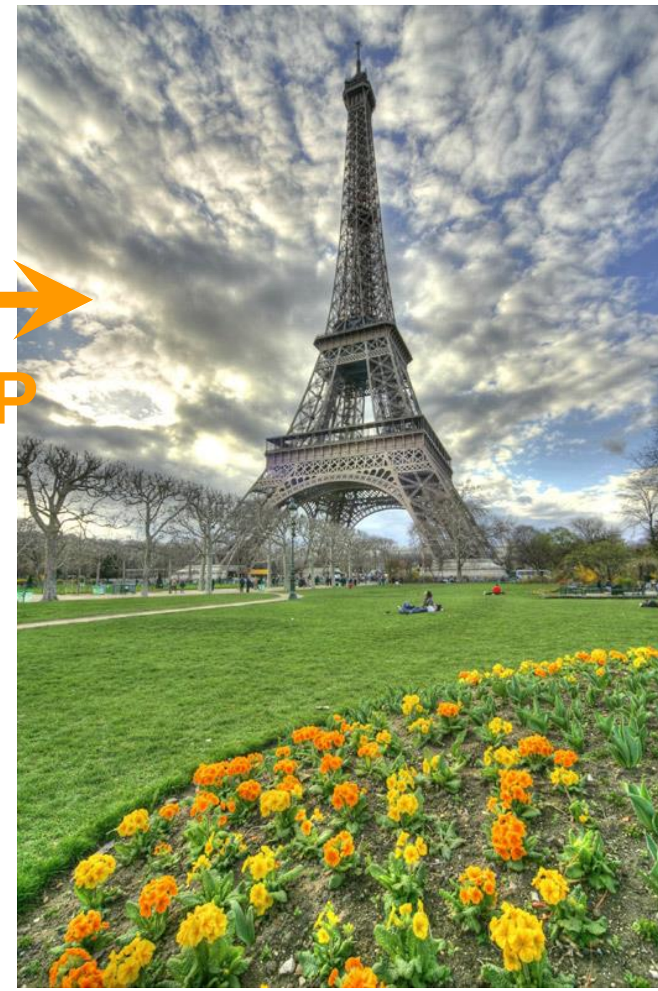
Computational Photography

- ❑ High Dynamic Range Imaging (HDR)





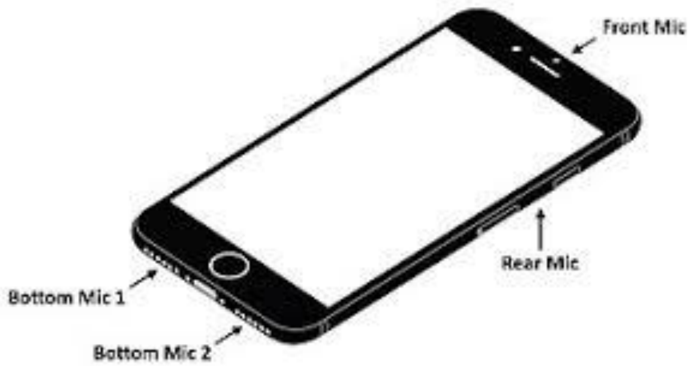
Now implemented in smart phones

- Compression of 40x without perceptual loss of quality.

- Example of slight over compression:
  - Difference enables 60x compression!

Audio

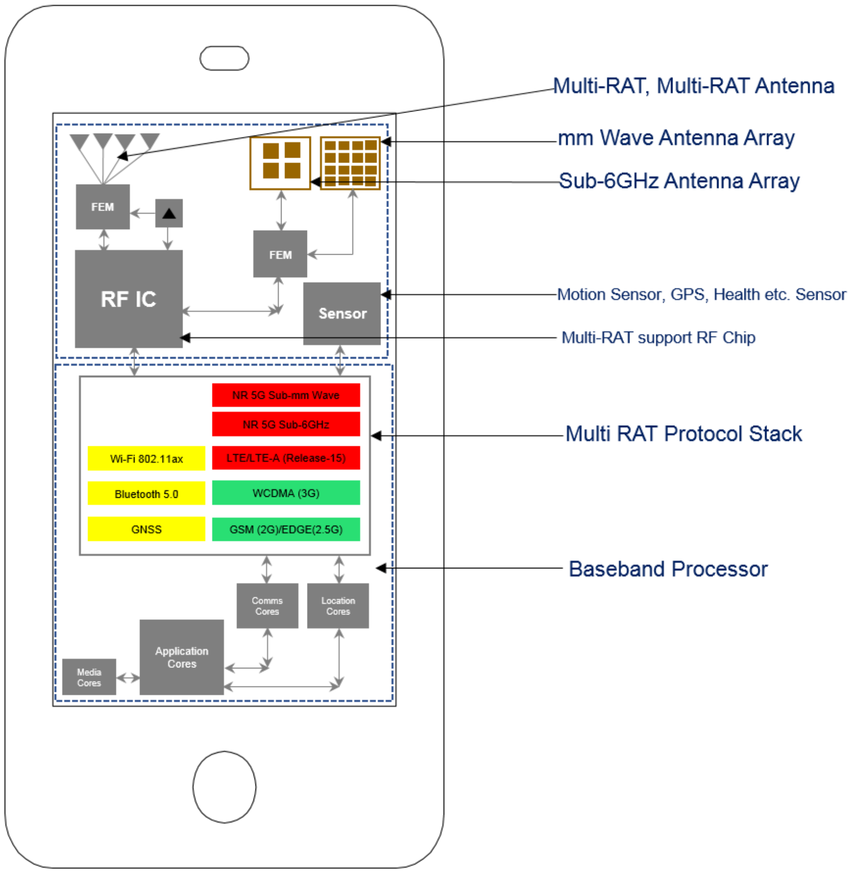
- Use multiple mics



EE152 Digital Signal Processing
EE254 Advanced Digital Signal Processing

Baseband Processing

- Support communication standards



EE140 Introduction to Communication Systems
EE240 Digital Communications
EE241 Fundamentals of Wireless Communications

Signal Coding & Compression

- For a PCM coded WAV file
  - 16-bit
  - 44.1KHz
  - 2 channel
- The data rate is 44.1K×16×2 =1411.2 Kbps
- For 1 second, we need1411.2 Kb, i.e.,176.4KB
- For 1 minute, we need 10.34MB
- MP3:128kbps
  - 3MB files instead of 30MB
  - Entire industry changed!

Signal Coding & Compression

- Concerned with efficient digital representation of audio/visual signal for storage and transmission to provide maximum quality to the listener or viewer

AI based compression are becoming popular!

Signal Coding & Compression

Original Lena
8 bits per pixel

Compressed Image
Average bit rate - 0.5 bits per pixel

AI based compression are becoming popular!

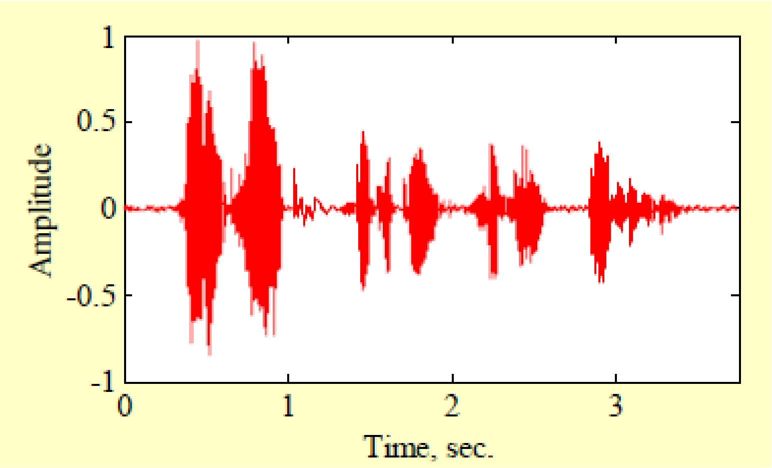
•[1] G Luo et al.,“DVC: An End-to-end Deep Video Compression Framework”, CVPR 2019
•[2] Z Liu et al., "CNN oriented fast HEVC intra CU mode decision", ISCAS, 2016
•[3] Y Li et al., "Convolutional Neural Network-Based Block Up-Sampling for Intra Frame Coding", IEEE T-CASVT, Sept. 2018
•[4] W Park, M Kim, "CNN-based in-loop filtering for coding efficiency improvement", IEEE IVMSP, 2016
•[5] Y Dai, D Liu, F Wu, "A Convolutional Neural Network Approach for Post-Processing in HEVC Intra Coding", arXiv 1608.06690, 2016 (accepted by MMM 2017)

Signal

- A signal is a function of independent variables such as time, distance, position, temperature, and pressure
- Example of typical signals
  - Sound
  - Image
  - Video

Examples of Typical Signals

- Sound represents air pressure as a function of time at a point in space
- Waveform of the speech signal "I like digital signal processing"



$f(t)$

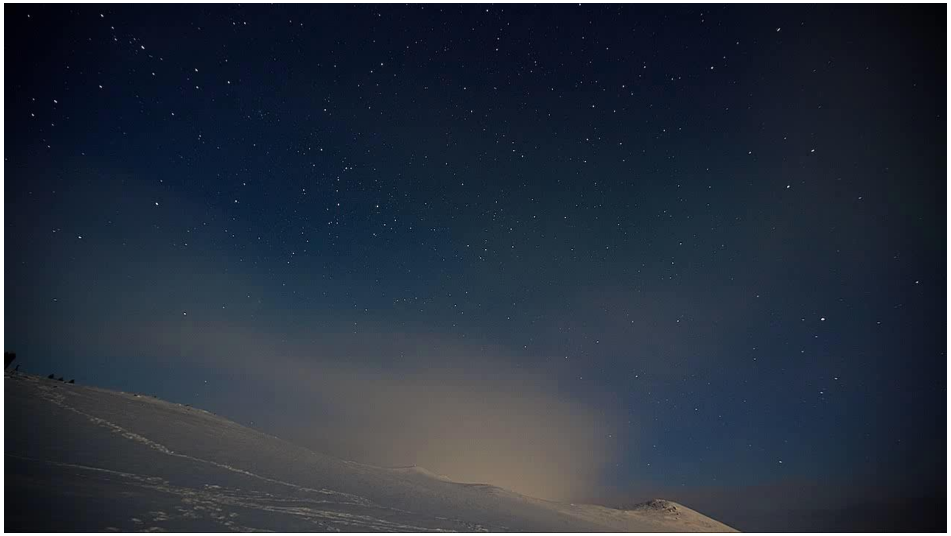
Examples of Typical Signals

- Gray-scale picture-represents light intensity as a function of two spatial coordinates

$f(x,y)$

Examples of Typical Signals

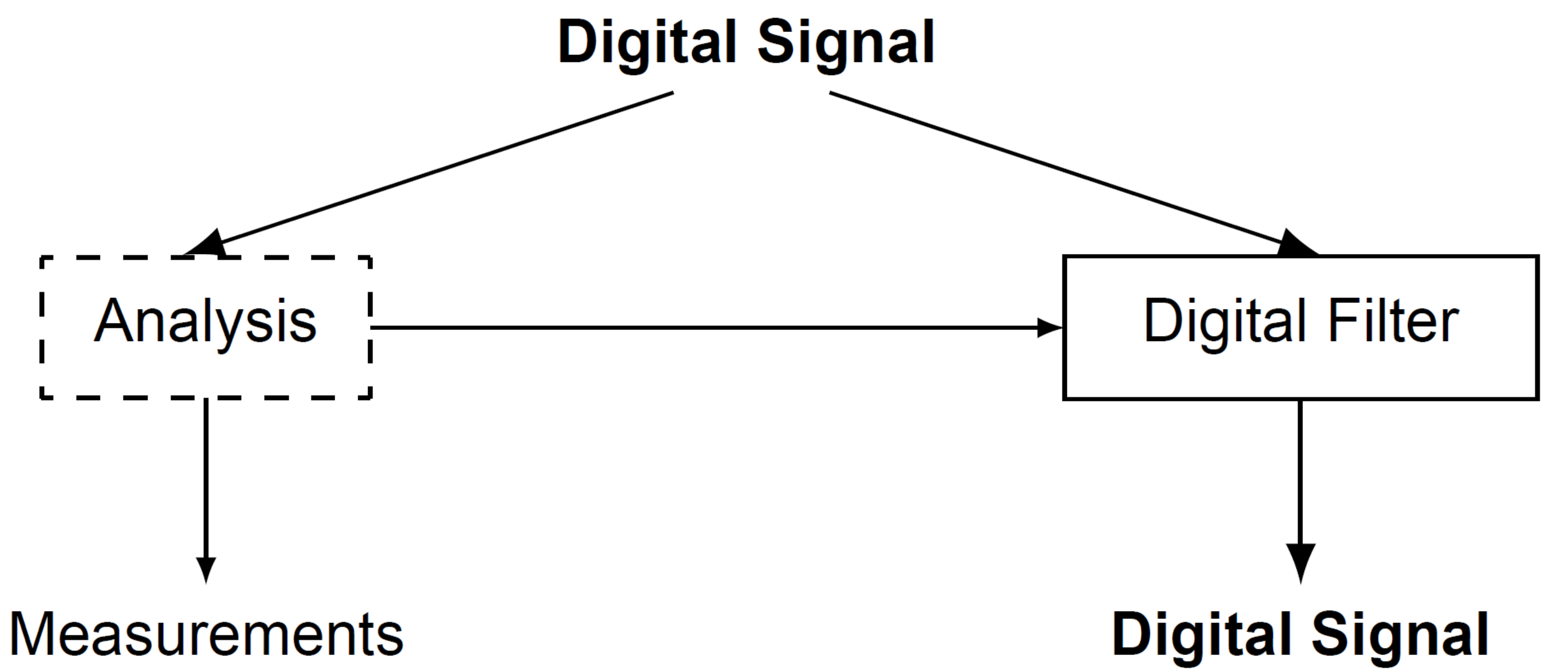
- Videos consist of a sequence of images, called frames, and is a function of 3 variables: 2 spatial coordinates and time



$$f\,(x, y, t)$$

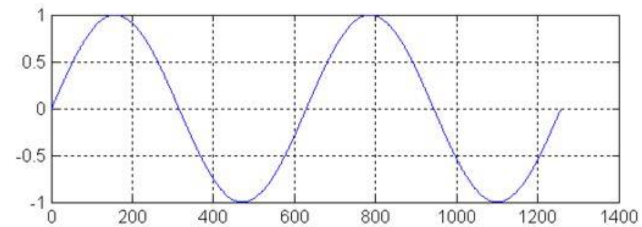
The Objective of Signal Processing

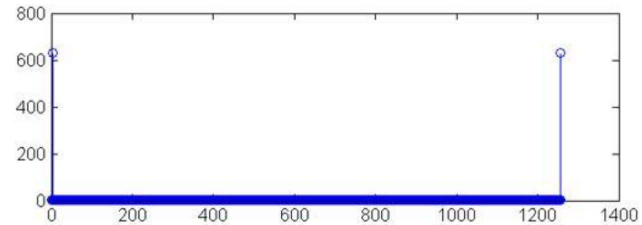
- The objective of signal processing

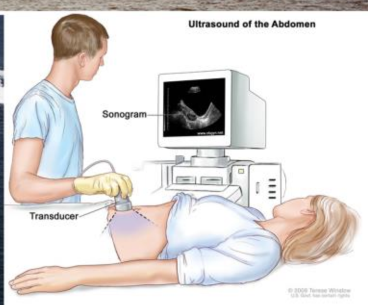


Signal Analysis

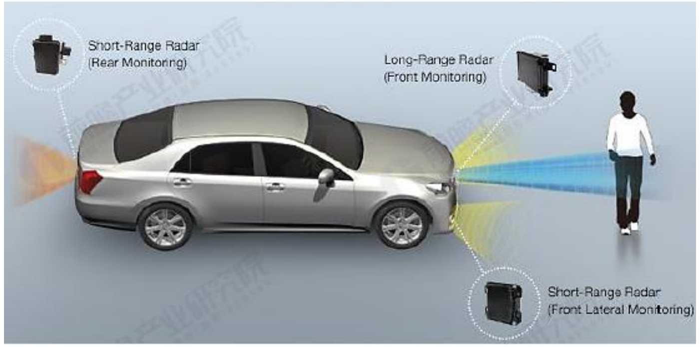
- This task deals with the measurement of signal properties
  - Spectrum analysis
    - frequency & phase
  - Target detection and tracking
    - Radar





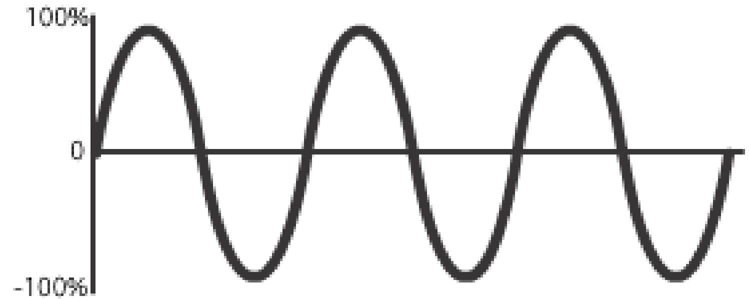


图表1：车载毫米波雷达应用

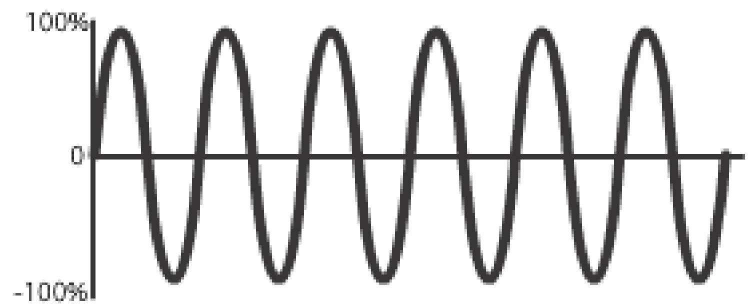


资料来源：前瞻产业研究院整理 @前瞻经济学人APP

Signal Analysis



基本正弦分量



Signal Filtering

- This task deals with the transformation of signals. The systems that perform this task are called filters
  - Removal of unwanted noise

Noise removal

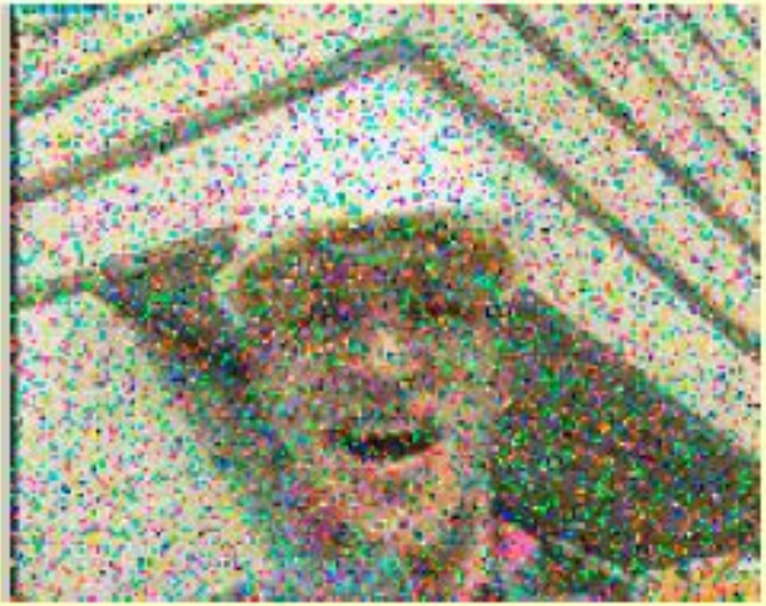
- Original uncorrupted speech signal
- Impulse-noise-corrupted speech signal
- Median filtered version of the noisy signal

Noise removal

Reduce Noise and Restore Audio in Adobe Audition

Noise removal

- Noise corrupted image and its noise-removed version



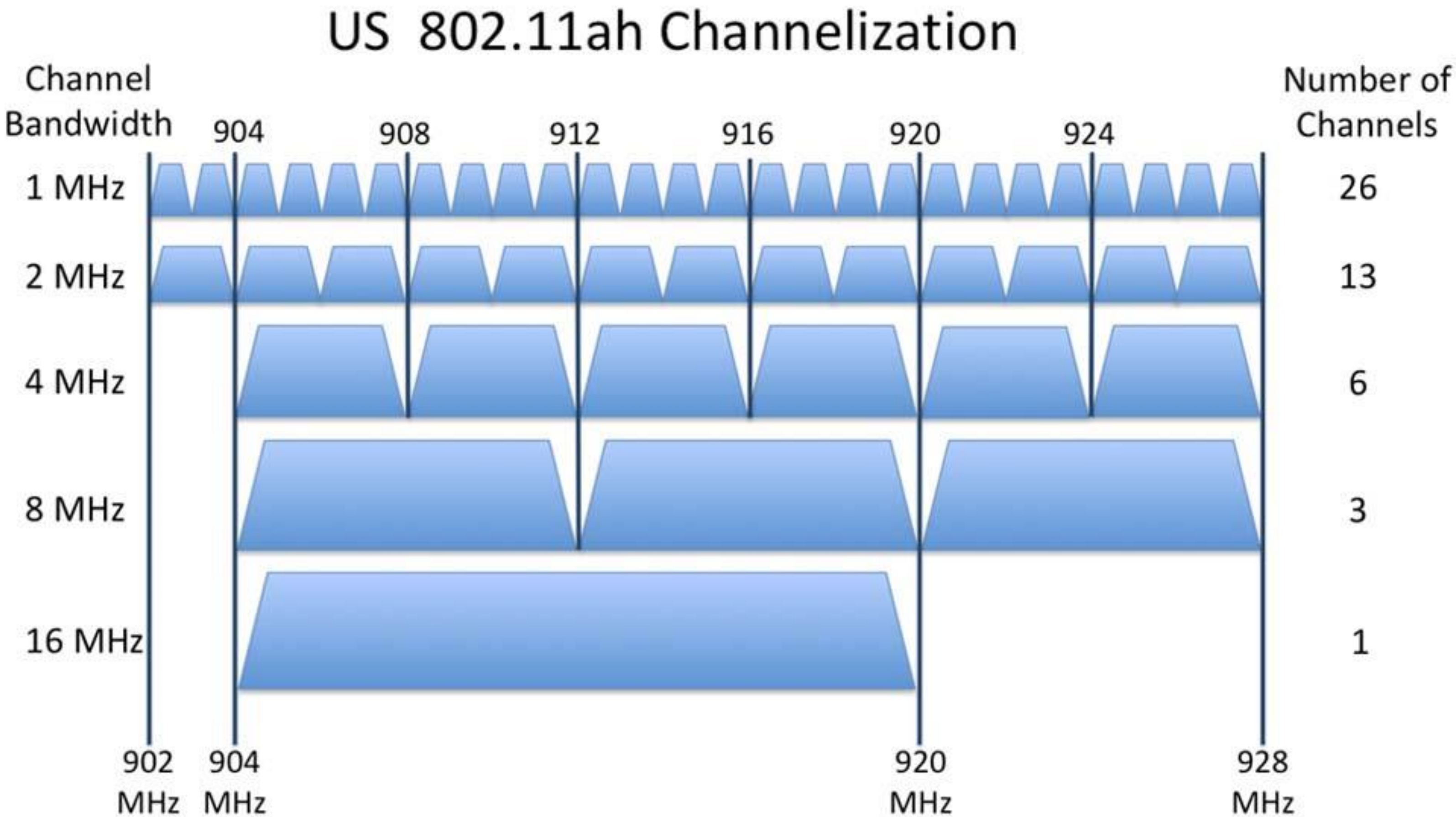
20% pixels corrupted with additive impulse noise

Noise-removed version

Signal Filtering

- This task deals with the transformation of signals. The systems that perform this task are called filters
  - Removal of unwanted noise
  - Separation of frequency bands

Separation of frequency bands



Separation of frequency bands

耳背式 耳内式 耳道式 完全耳道式

Separation of frequency bands

- Compensate each band individually

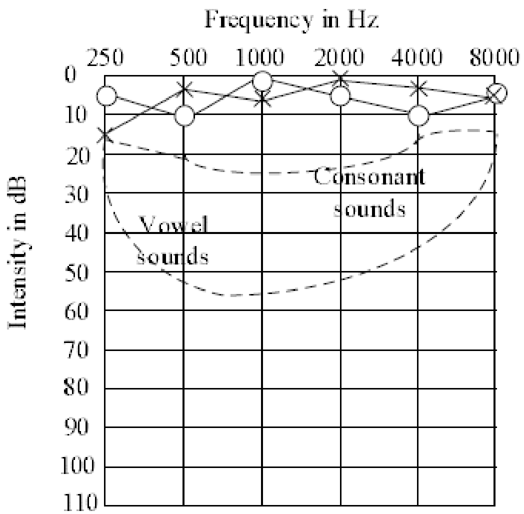


Figure 1. A typical audiogram for the normal hearing. O and X represent the thresholds of left and right ear respectively. The area in the dashed lines represents the intensities of normal voice.

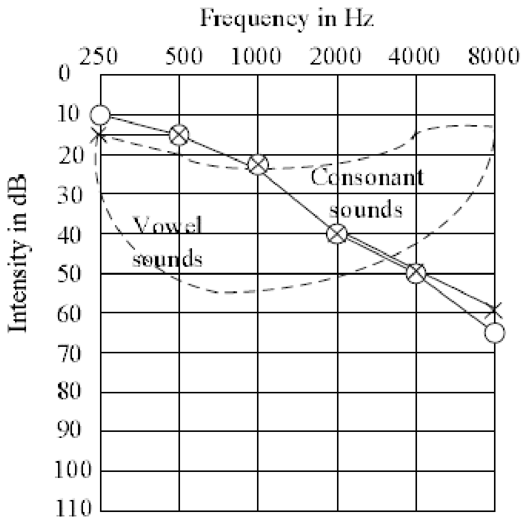


Figure 2. An audiogram for the hearing loss caused by aging.

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Signal Filtering

- This task deals with the transformation of signals. The systems that perform this task are called filters
  - Removal of unwanted background noise
  - Separation of frequency bands
  - Removal of interference
  - Shaping of the signal spectrum

Representation of Signals

- In terms of basis functions in the original domain,
  - Time
  - Spatial, etc.

- In terms of basis functions in a transform domain,
  - Fourier Transform
  - Z-transform, etc.

Classification of Signals

- Continuous vs. Discrete
  - Depends on the independent variable
- Real-valued vs. Complex-valued
  - Depends on the function defining the signal
- 1-D signal vs. *M*-D signal
  - 1 independent variable or *M* independent variables
- Stationary vs. Non-stationary
- etc.

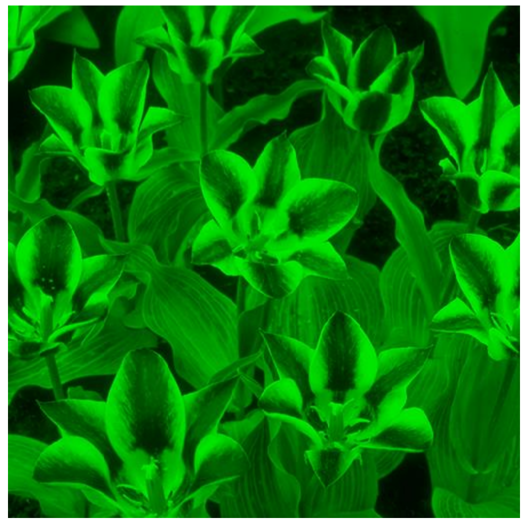
Classification of Signals

- The speech signal is an example of a 1-D signal where the independent variable is time
- The image signal 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)
  - 3-channel 2D signal

RGB Image

- The 3 color components of a color image

R



G

B

RGB Image

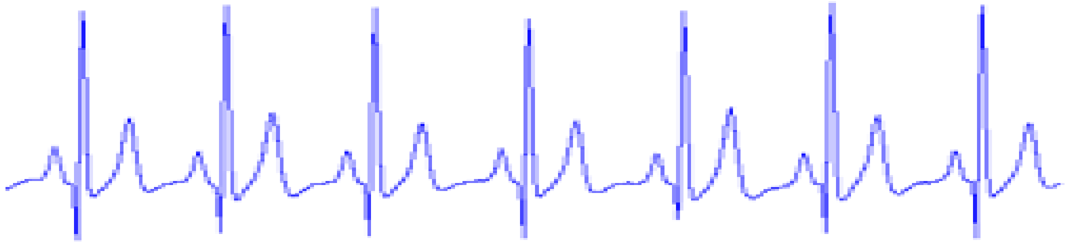
- The full color image obtained by displaying the previous 3 color components is shown below

Video Signals

- Black-and-white video signal is an example of a 3-D signal
  - 2 spatial variables and time
- Color video signal is a 3-channel 3-D signal
  - Red channel
  - Green channel
  - Blue channel

Characterization of Signals

- The value of a signal at a specific value of the independent variable is called amplitude
- The variation of the amplitude as a function of the independent variable is called waveform
- Let’s consider 1-D signal

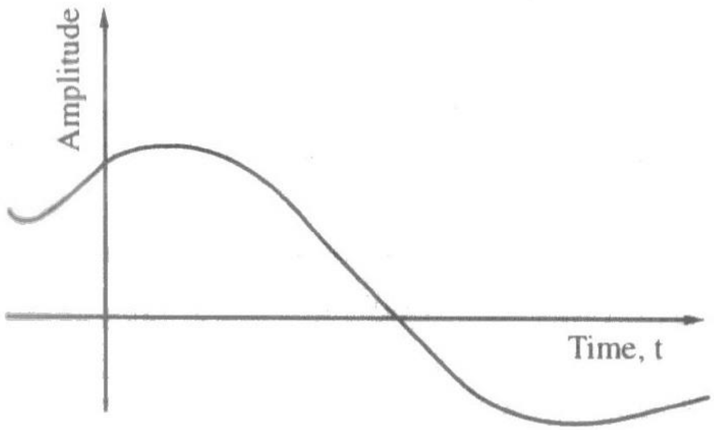


Continuous and Discrete Signals

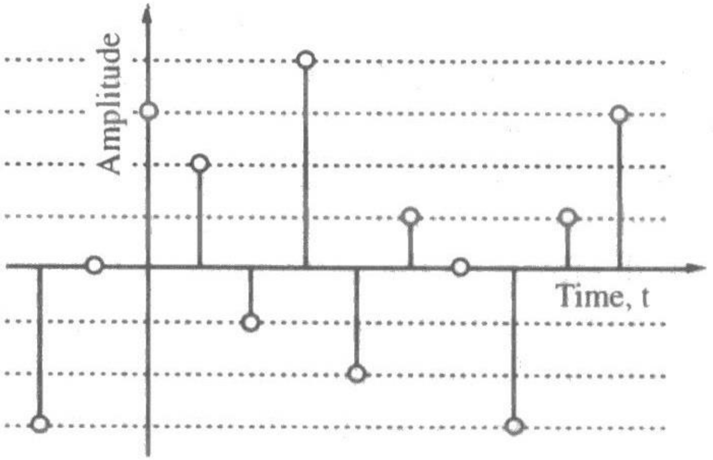
- If the independent variable is continuous, the signal is called a continuous-time signal
  - Is defined at every instant of time
- If the independent variable is discrete, the signal is called a discrete-time signal
  - Is defined at discrete instants of time
  - The signal is not defined in between the time instants

Analog Signal

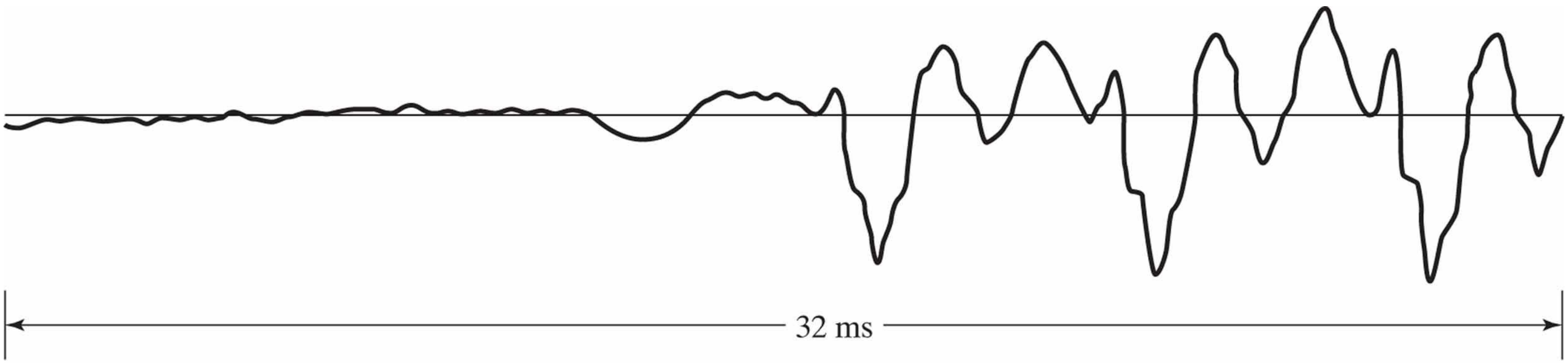
- Analog signal
  - Continuous-time signal with continuous-valued amplitude
  - Most of the natural signals are analog



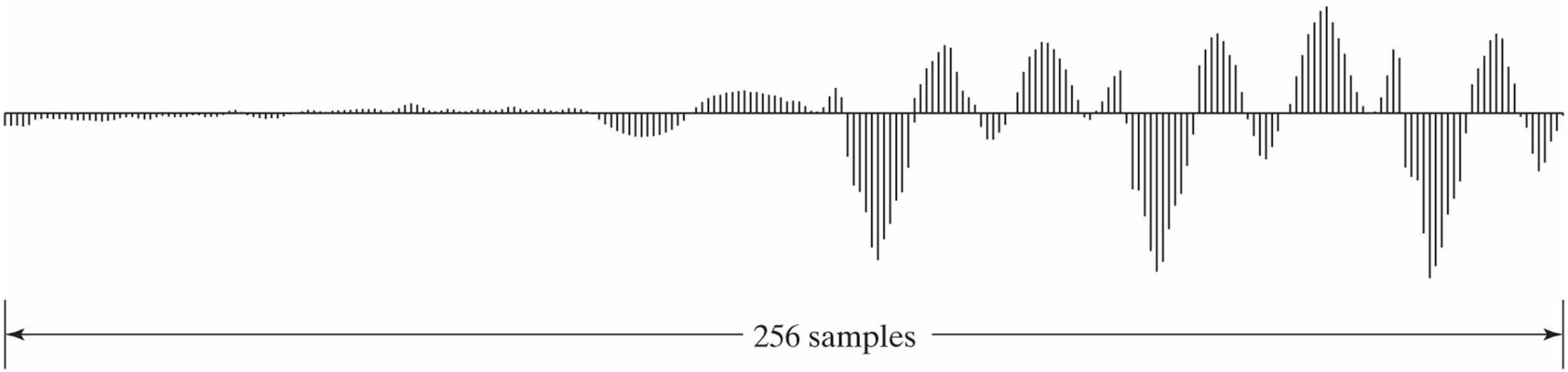
- Digital signal
  - Discrete-time signal with discrete-valued amplitude
  - A digital signal is a quantized sampled-data signal



Digital Signal



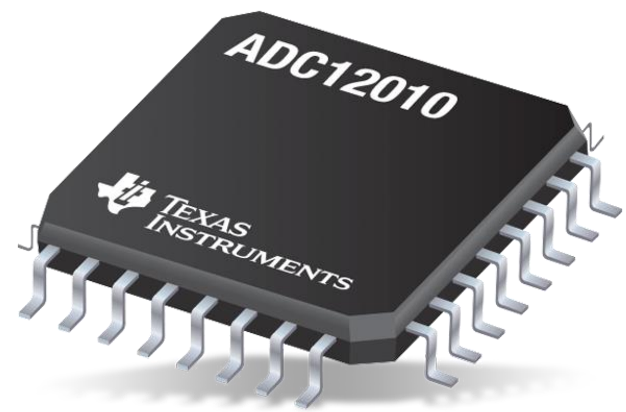
(a)



(b)

Analog-to-Digital Converter

- Analog-to-Digital Converter
  - Speed
  - Resolution



https://zh.wikipedia.org/wiki/%E9%A1%9E%E6%AF%94%E6%95%B8%E4%BD%8D%E8%BD%89%E6%8F%9B%E5%99%A8

https://pdf.dfcfw.com/pdf/H3_AP202107021501266402_1.pdf?1625213360000.pdf

Signal Processing

- Analog signal processing
  - Most operations are carried out in the time domain
- Discrete-time signal processing
  - Both time and frequency domain operations are employed
- The desired operations are implemented by a combination of elementary operations
  - Simple time domain operations
  - Filtering
  - Modulation and demodulation

Time-Domain Operations

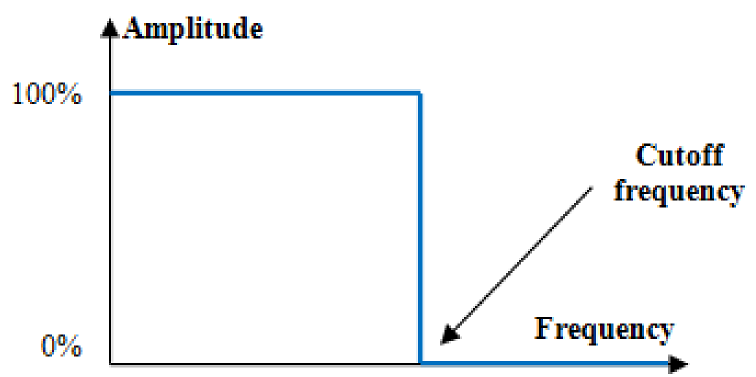
- Three most basic time-domain signal operations
  - Scaling
  - Delay
  - Addition

Time-Domain Operations

- More complex operations are implemented by combining two or more elementary operations
  - Filtering
  - Modulation and demodulation

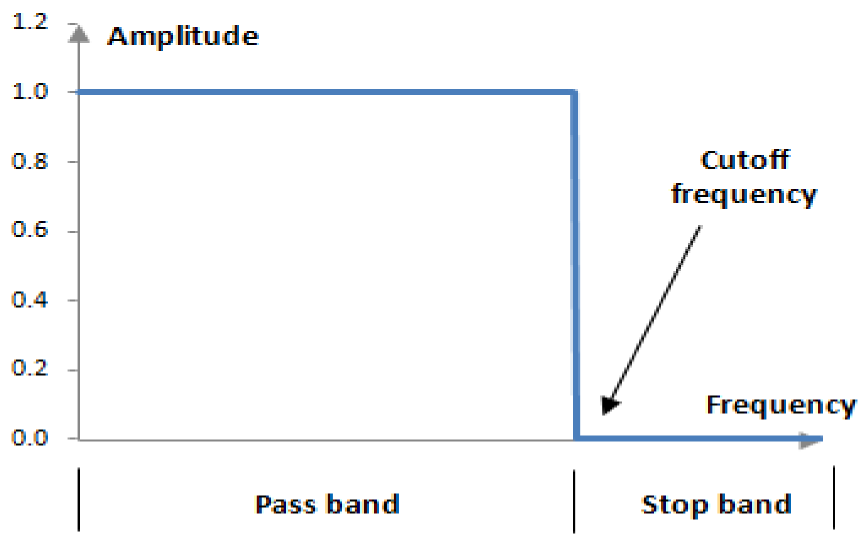
Filtering

- Filtering is one of the most widely used complex signal processing operations
  - The system implementing filtering is called filter
- A filter passes certain frequency components without any distortion and blocks other frequency components



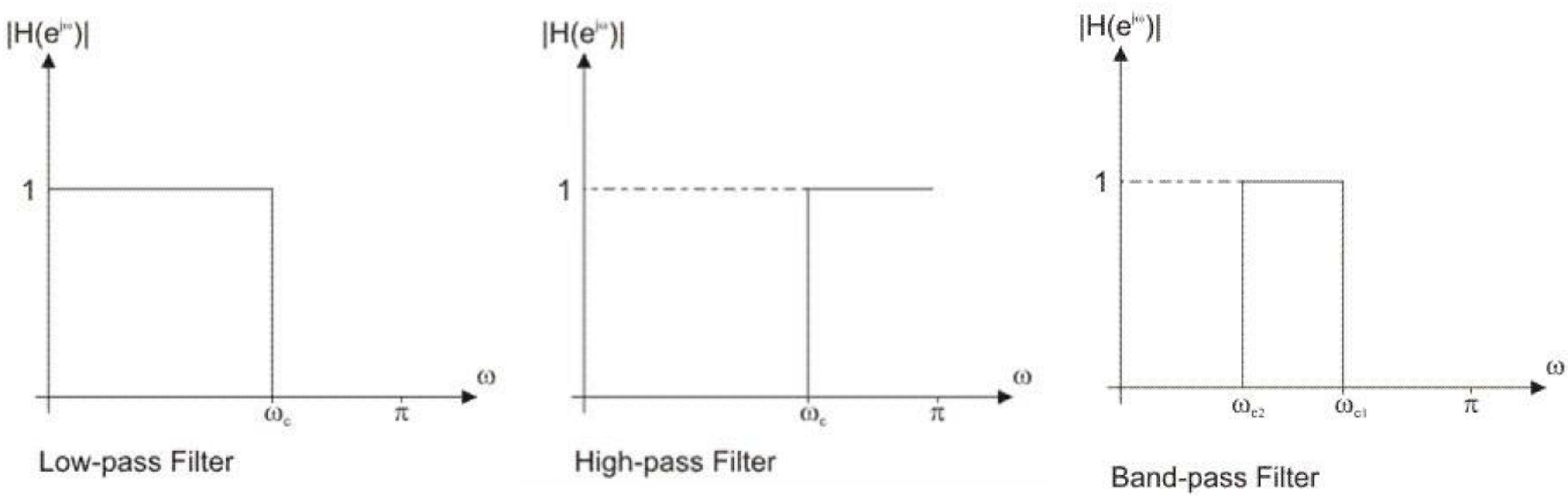
Passband and Stopband

- Passband
  - The range of frequencies that is allowed to pass through the filter
- Stopband
  - the range of frequencies that is blocked by the filter



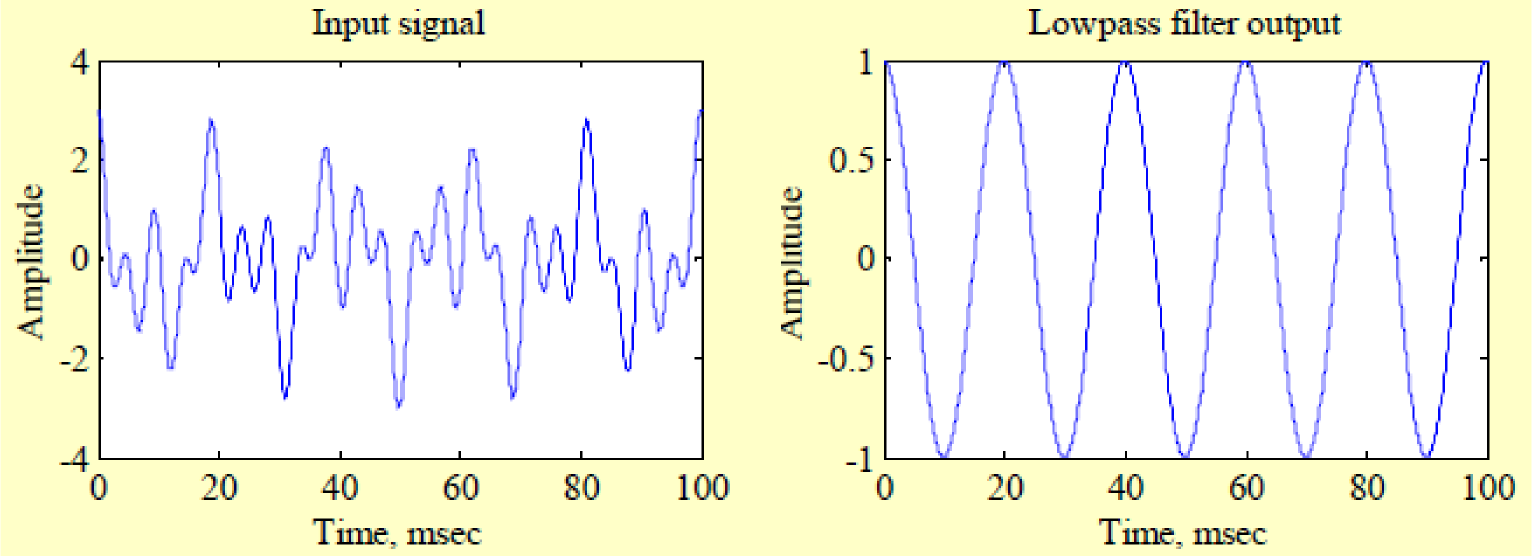
Types of Filters

- Low-pass, high-pass and band-pass filters



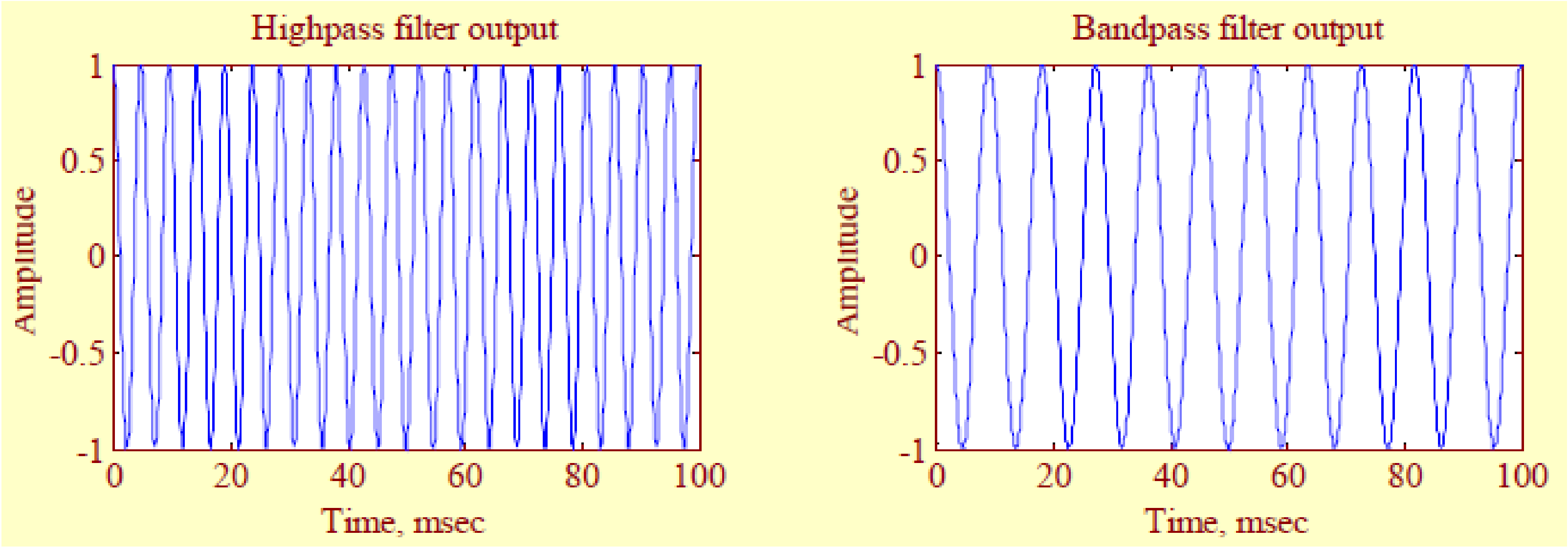
Filtering Example

- Low-pass filtering of an input signal composed of three sinusoidal components of frequencies 50 Hz, 100 Hz, and 200 Hz



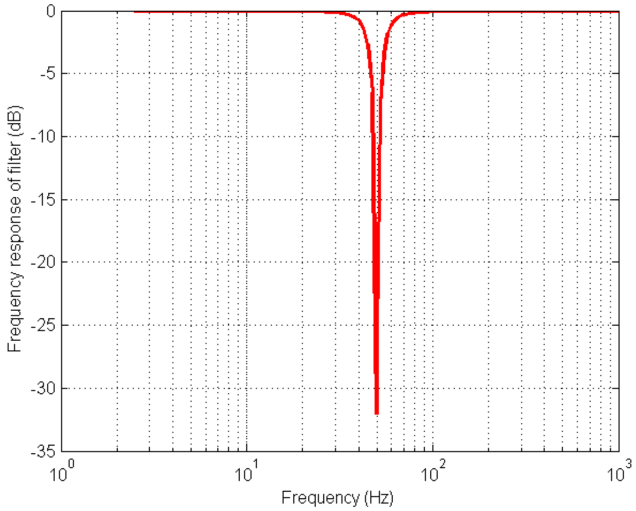
Filtering Example

- Figures below illustrate high-pass and band-pass filtering of the same input signal



Other Types of Filters

- Notch filter
  - A filter blocking a single frequency component



Modulation and Demodulation

- Modulation
  - Transform a low-frequency to a high-frequency signal
  - For efficient transmission
  - Transmitter
- Demodulation
  - Extract the desired low-frequency signal
  - Receiver

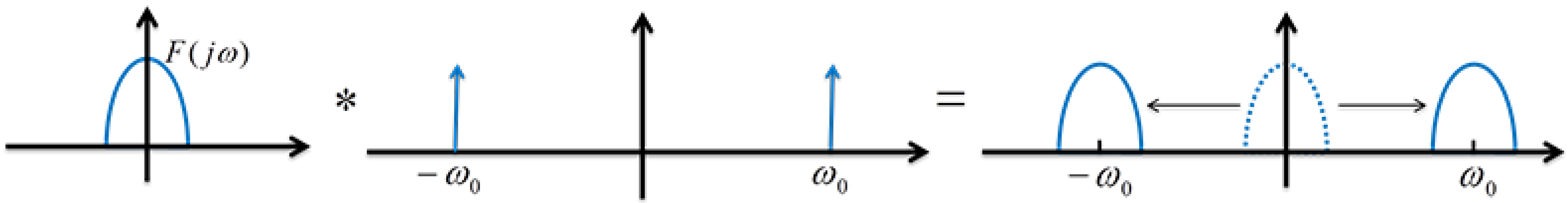
Modulation and Demodulation

- Four major types of modulation
  - Amplitude modulation
  - Frequency modulation
  - Phase modulation
  - Pulse amplitude modulation

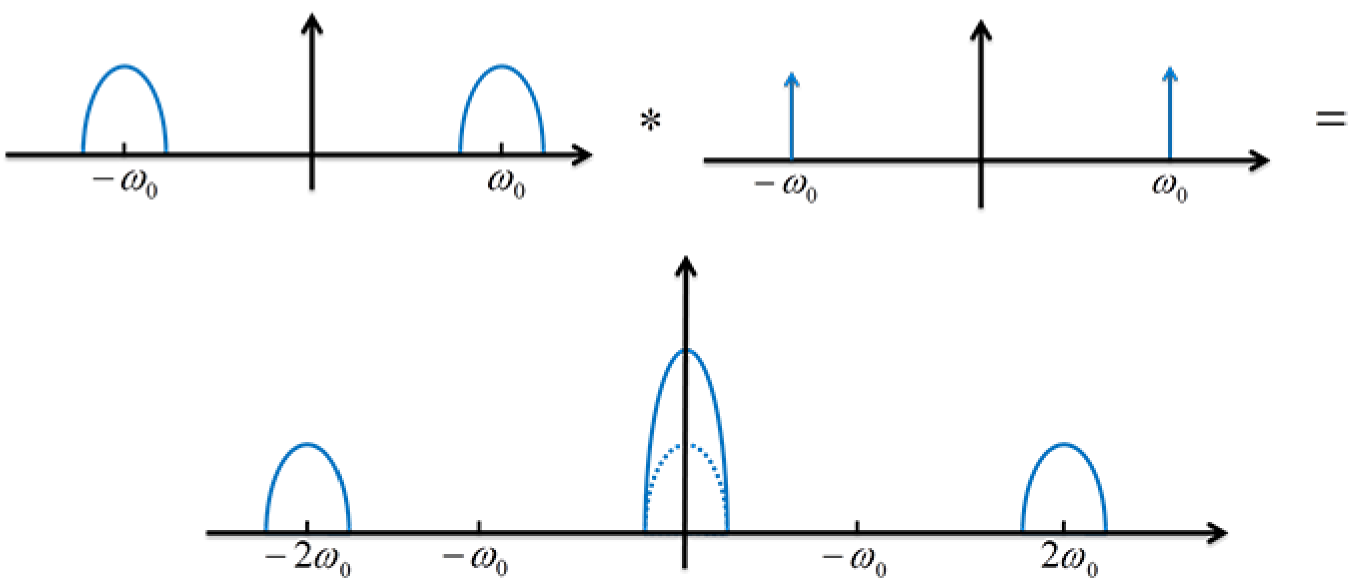
https://zh.wikipedia.org/wiki/%E8%AA%BF%E8%AE%8A

Modulation and Demodulation

❑ Amplitude modulation

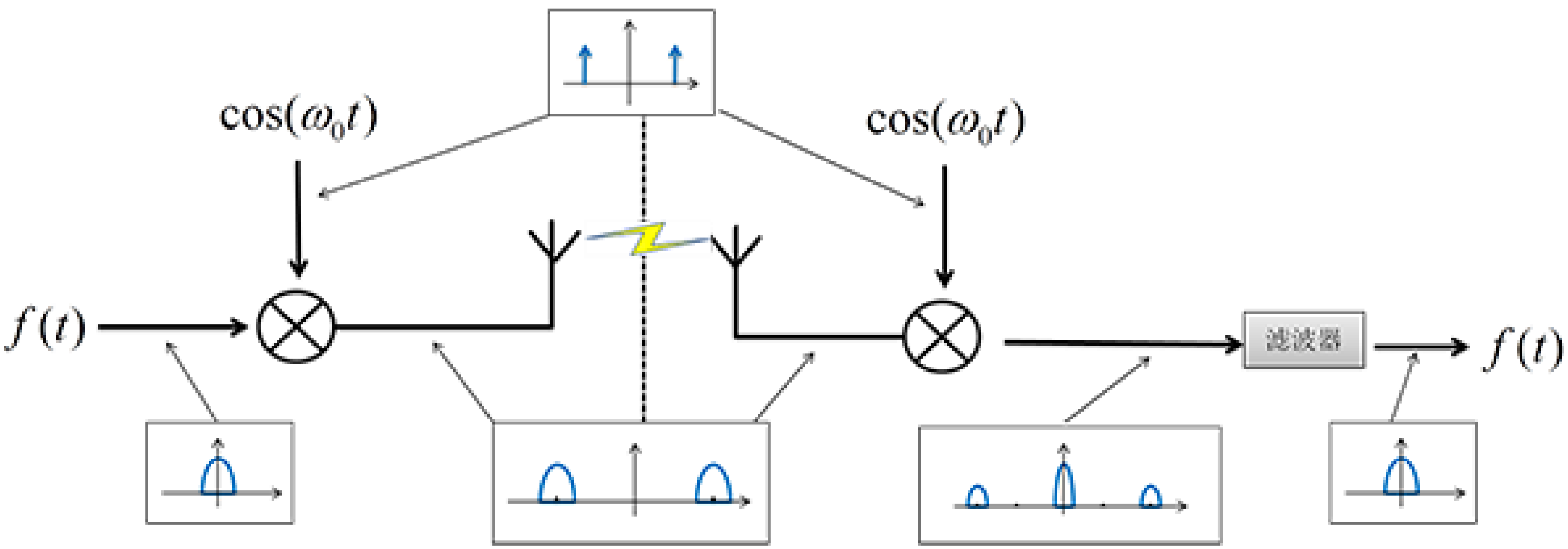


❑ Demodulation



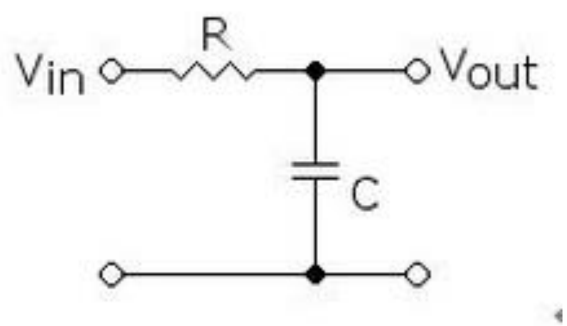
Modulation and Demodulation

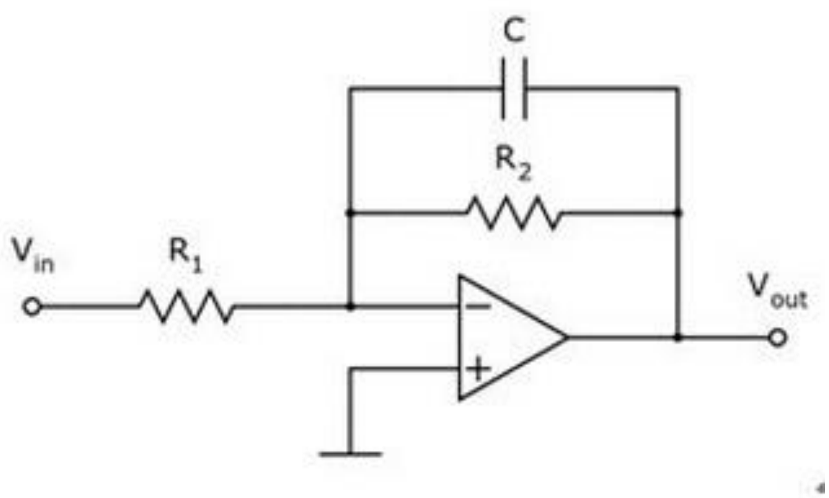
❑ Modulation and Demodulation



Analogue Signal Processing

- Process signals by using analogue components such as resistors, capacitors, inductors



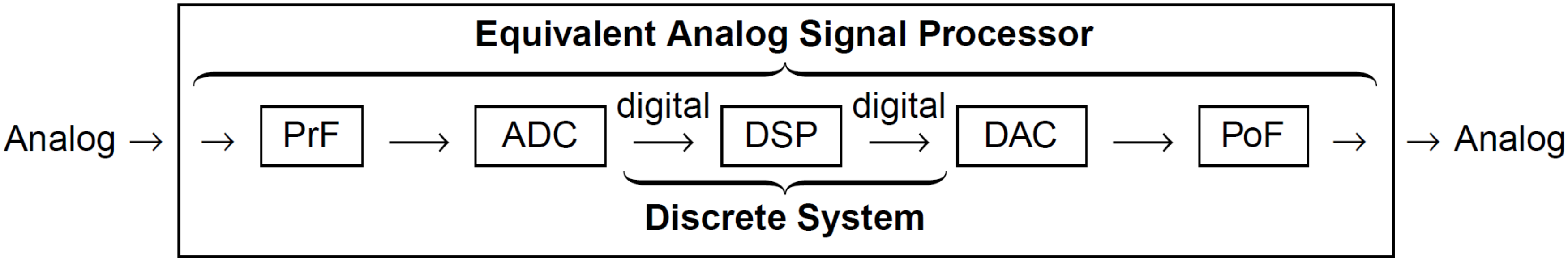


Analogue Signal Processing

- Pros:
  - linear over a large dynamic range and large bandwidths
  - circuits require less power
- Cons:
  - Sensitivity to electrical noise
  - Accuracy limitations due to component tolerances
  - Limited repeatability
  - Difficulty of storing information

Digital Signal Processing

- Digital signal processing requires



  - Analog-to-digital converter (ADC)
  - Computational device
    - CPU, DSP, ASIC, FPGA
  - Digital-to-analog converter (DAC) (optional)

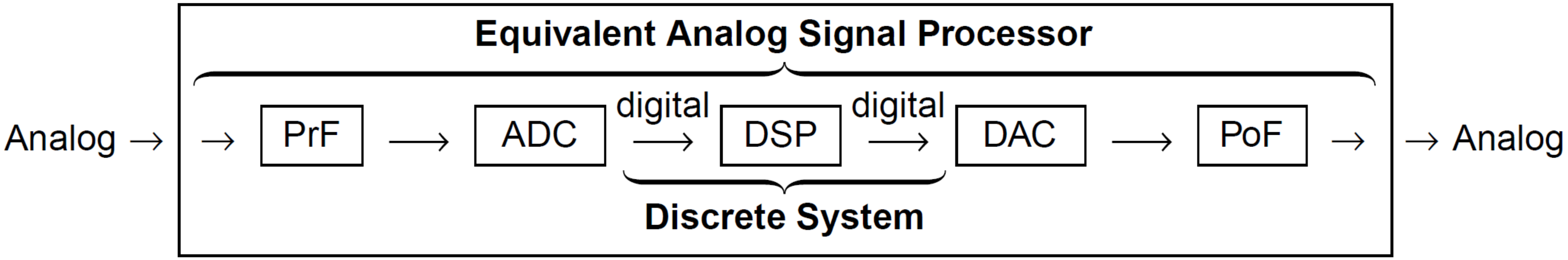
Advantages of DSP

- Noise is easy to control after initial quantization
- Complex algorithms fit into a single chip
- Flexibility in parameter change
- Insensitive to component tolerances, aging, environmental conditions, electromagnetic interference, et. al.
- Reproducibility, reusability
- Digital storage is easy and cheap
- Digital information can be encrypted for security
- Price/performance and reduced time-to-market

Limitations of DSP

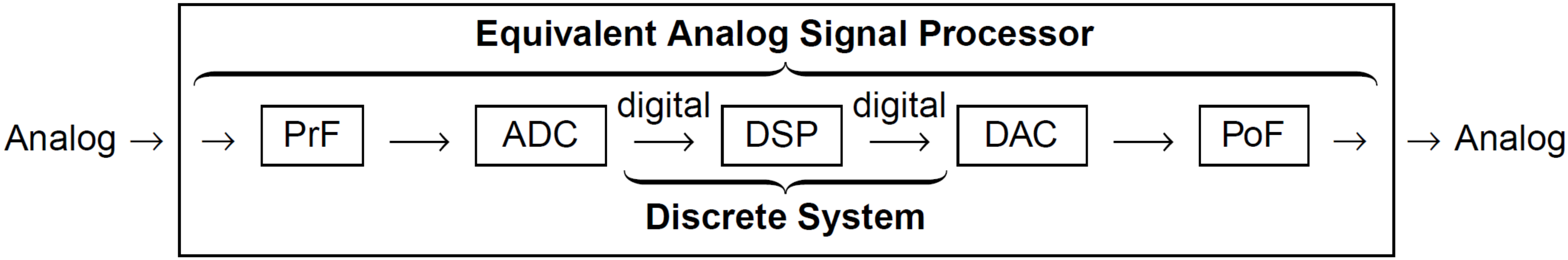
- Additional complexity in the processing of analog signals
  - A/D and D/A converters must be introduced, adding complexity to overall system
- Limited range of frequencies
  - A/D converters cannot work fast enough
  - Too complex to be performed in real-time

Typical DSP Systems



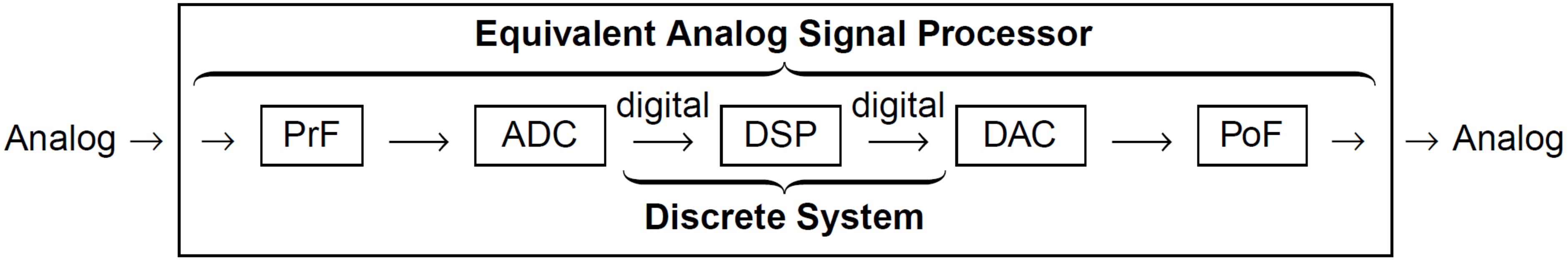
- PrF: A prefilter or an antialiasing filter which conditions the analog signal to prevent aliasing
- ADC: The device which convert analog signals to digital signals
- Computational device: to implement the DSP algorithms
  - CPU, DSP processor, FPGA, ASIC

Typical DSP Systems



- DAC: The device which convert digital signals to analog signals
- PoF: A postfilter to smooth out staircase waveform into the desired analog signal

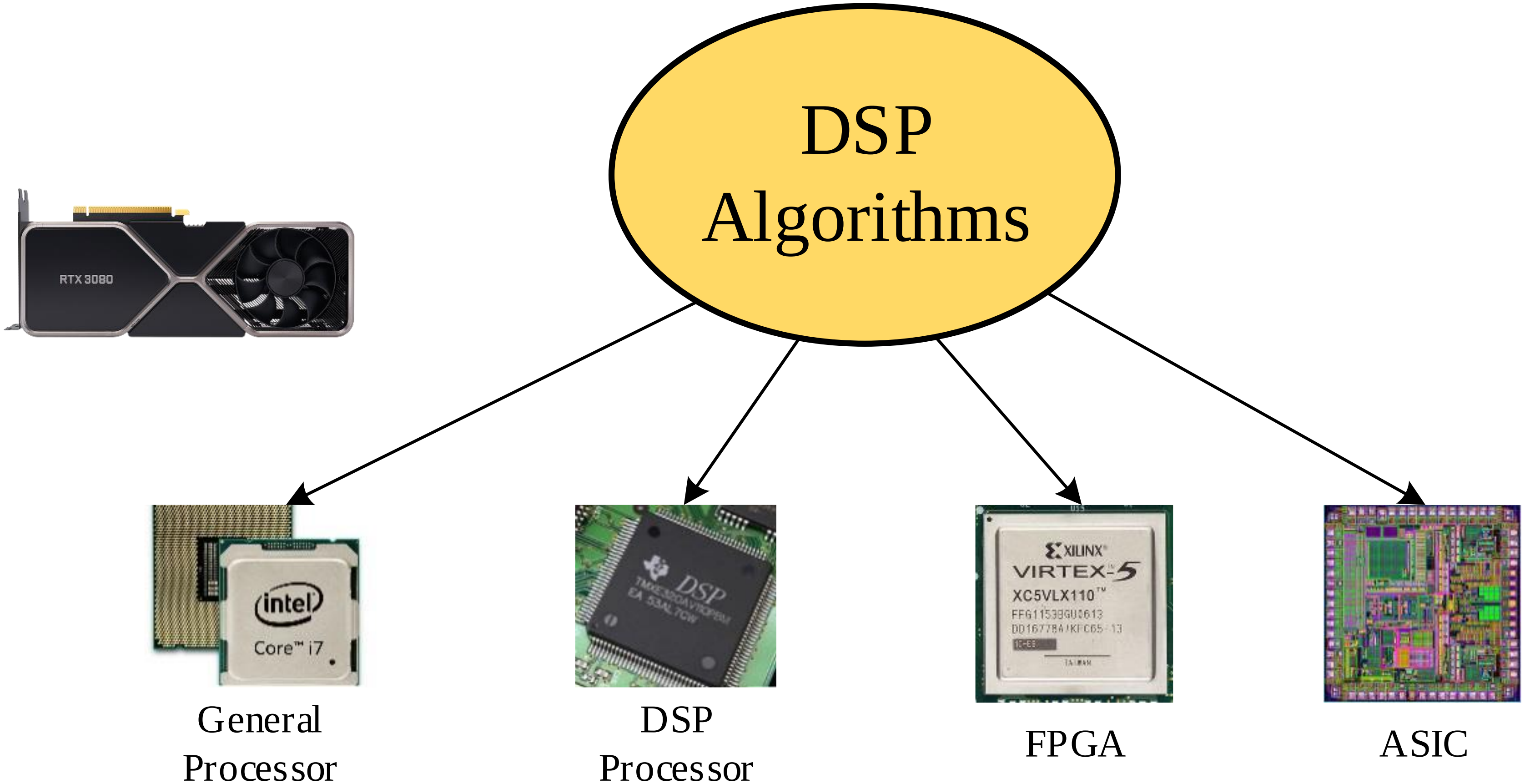
DSP Systems Design



- Usually highly real-time (speed)
  - Meet the speed constraint
- Battery powered (power consumption)
  - Battery life is important (reduce power)
- System complexity (area)
  - Cost

Implementation Alternatives

- A given DSP algorithm can be implemented in various ways

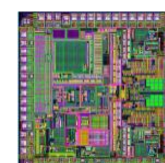


Implementation Alternatives

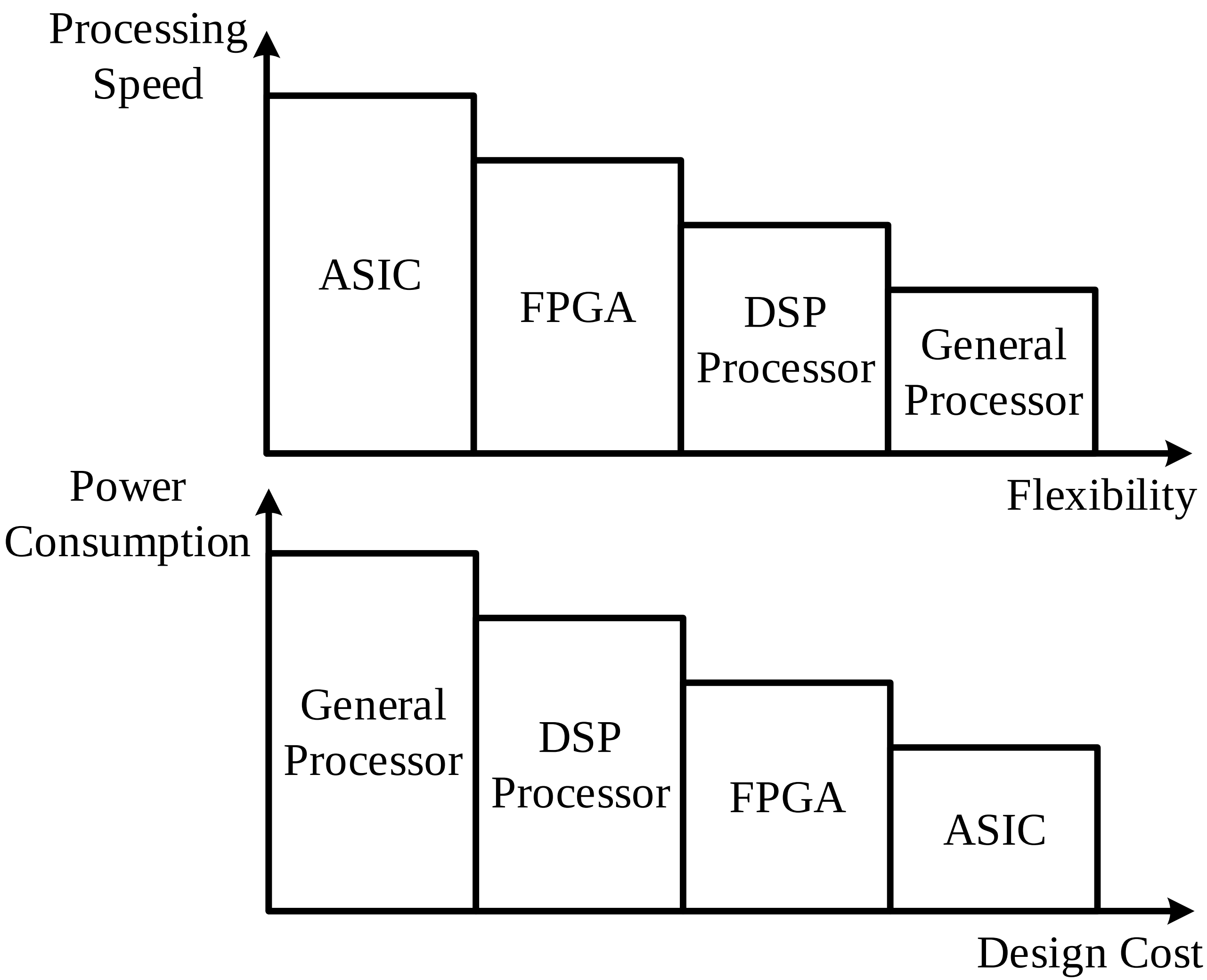
- General Processor


  - Pros: easy to implement, high flexibility, low cost
  - Cons: low throughput, high power
- DSP Processor (specialized processor)


  - Pros: easy to implement, high flexibility, low cost
  - Cons: limited speed, relatively high power
- FPGA (specific integrated circuit)


  - Pros : better speed and power, field re-programmability
  - Cons : expensive, limited resource
- ASIC

  - Pros : fully customizable, best speed and power, low unit cost
  - Cons : fixed (no flexibility), time-to-market, large NRE

Implementation Alternatives



For high speed, low power applications, ASIC is the only choice!

Example

Qualcomm
snapdragon
X55 5G modem

上海科技大学
ShanghaiTech University

Area-Speed-Power Tradeoffs

- 3-D optimization (area, speed, power)
  - Achieve required speed, area-power tradeoff
- Speed
  - T (clock period) × #cycles
  - $T \leftrightarrow$ critical path delay
  - #cycles $\leftrightarrow$ serial/parallel processing
  - Latency
- Power

$$P = C \cdot V^2 f$$

- Area
  - Cost! Cost! Cost!

Typical DSP Algorithms

- Combinations of multiplications and additions

Algorithm	Equation
Finite Impulse Response Filter	$y(n) = \sum_{k=0}^{M} b_k \, x(n-k)$
Infinite Impulse Response Filter	$y(n) = \sum_{k=0}^{M} b_k \, x(n-k) + \sum_{k=1}^{N} a_k y(n-k)$
Convolution	$y(n) = \sum_{k=0}^{N} x(k) h(n-k)$
Discrete Fourier Transform	$X(m) = \sum_{n=0}^{N-1} x(n) \exp[-j(2\pi / N) nm]$
Discrete Cosine Transform	$F(u) = \sum_{x=0}^{N-1} c(u).f(x).\cos\left[\frac{\pi}{2N} u(2x+1)\right]$

A Typical Example

- Example: $y(n) = b_0 \cdot x(n) + b_1 \cdot x(n-1) + b_2 \cdot x(n-2)$