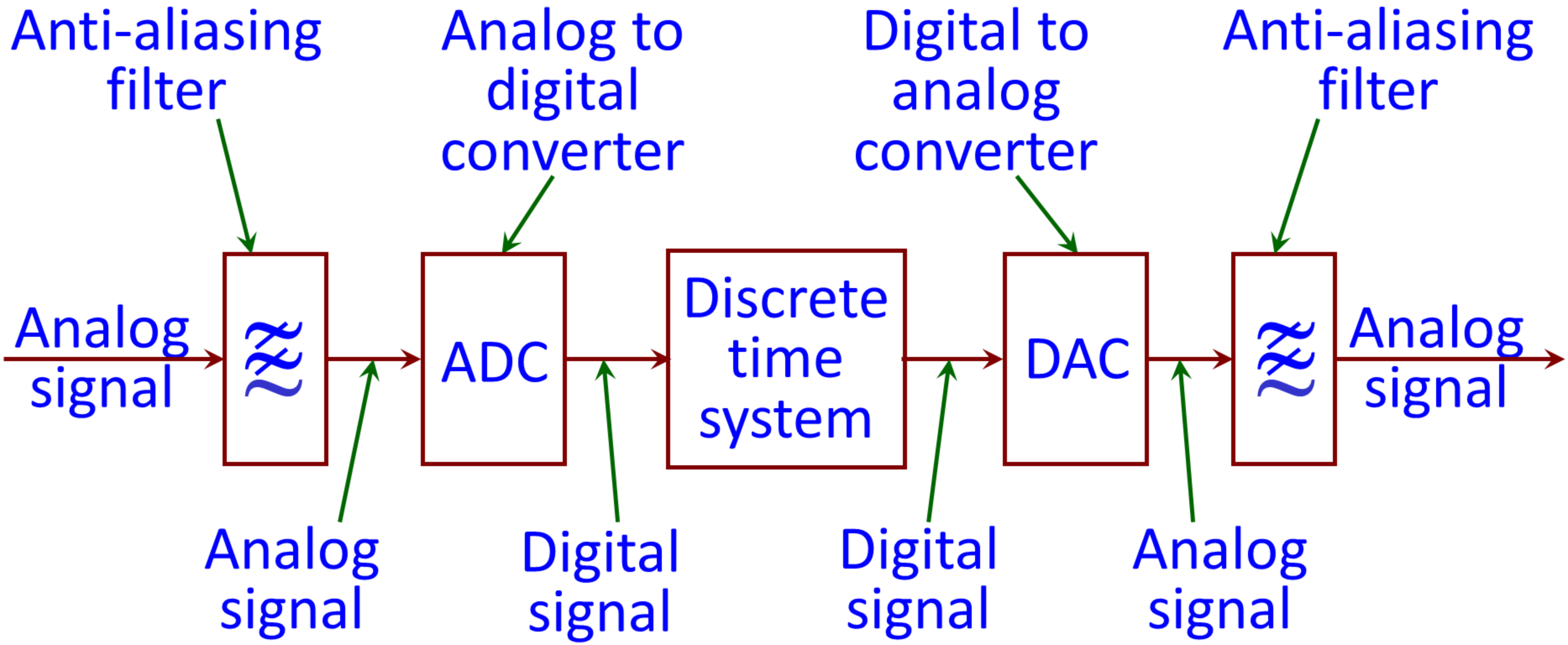
Week 4
Signal Processing Systems

Typical DSP Systems



Where Does the Signal Come From?

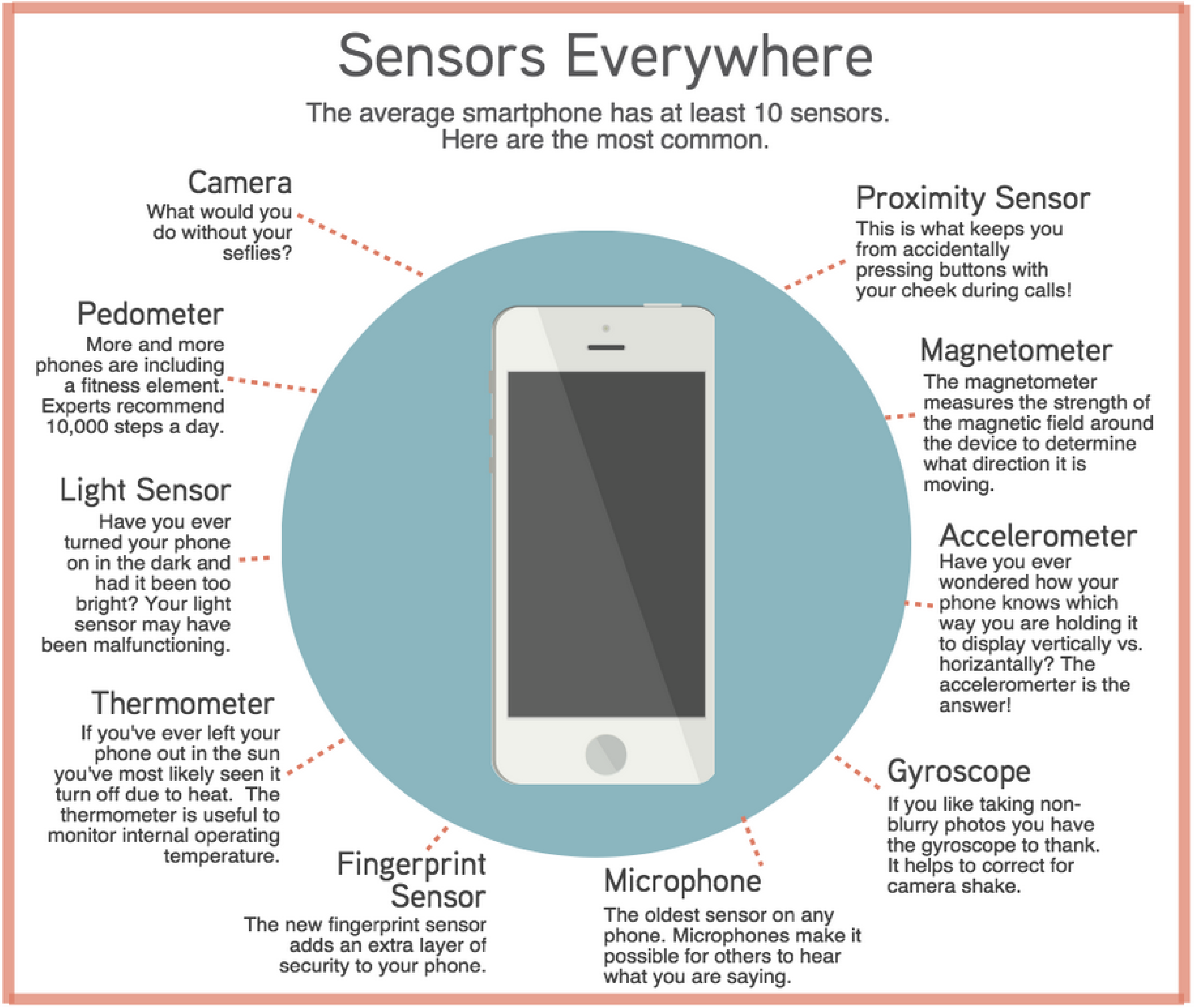
Where Does the Signal Come From?

- A sensor acquires a physical parameter and converts it into a signal suitable for processing

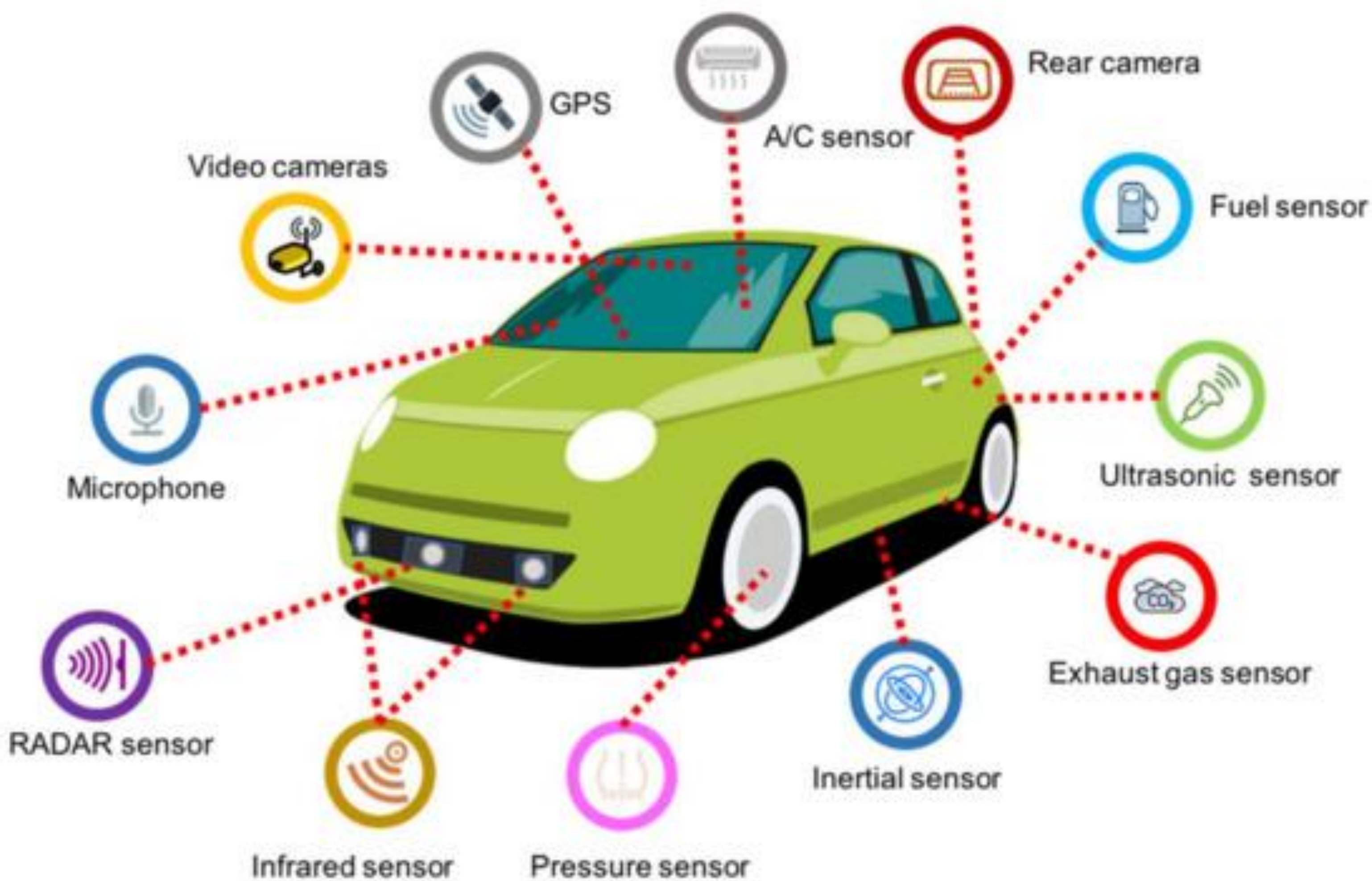
Where Does the Signal Come From?

- Sensors
  - Temperature Sensor
  - Light Sensor
  - Accelerometer
  - Magnetic Field Sensor
  - Ultrasonic Sensor
  - Photogate
  - CO2 Gas Sensor

Sensors In a Smart Phone

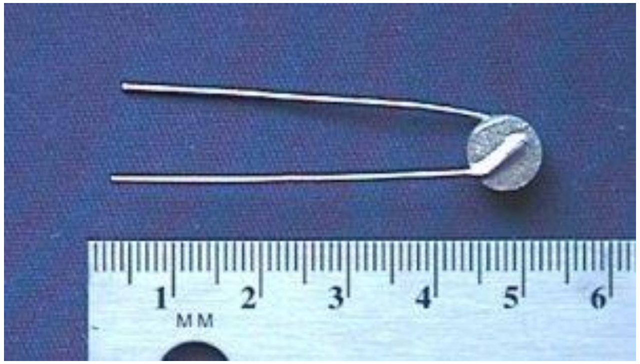


Sensors In a Car



Temperature Sensor

thermal resistor
“thermistor”



resistance changes with temperature

Light Sensor

photo-resistor

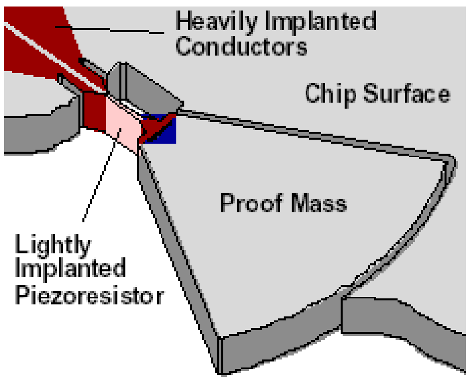
resistance changes with light intensity

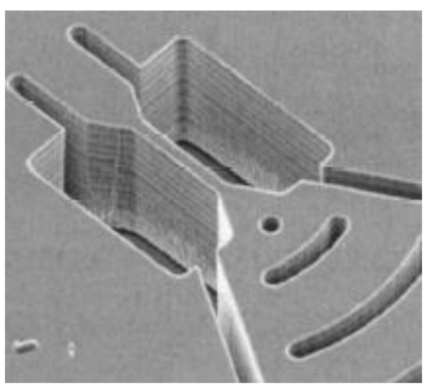
Physical Principles

- Ampere's Law
  - A current carrying conductor in a magnetic field experiences a force (e.g. galvanometer)
- Faraday's Law of Induction
  - A coil resist a change in magnetic field by generating an opposing voltage/current (e.g. transformer)
- Photoconductive Effect
  - When light strikes certain semiconductor materials, the resistance of the material decreases (e.g. photoresistor)

Different Sensing Techniques

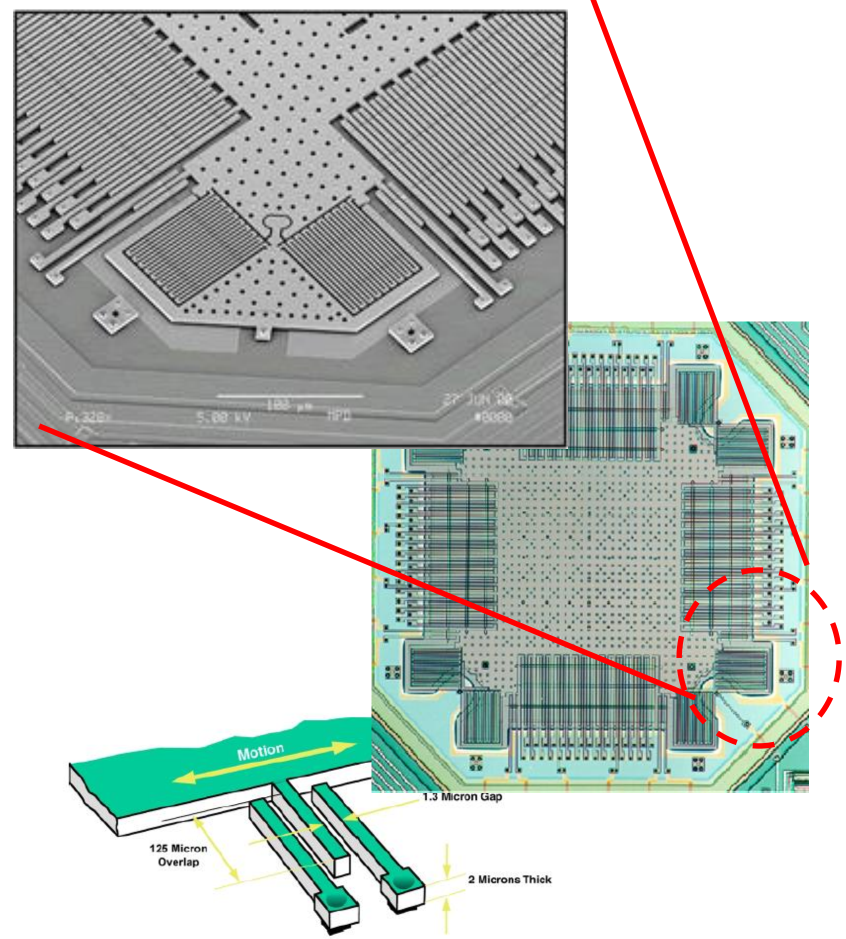
Piezoresistive MEMS accelerometer





Courtesy of JP Lynch, U Mich.

Capacitive MEMS accelerometer



Courtesy of Analog Devices, Inc.

Sensor Signal Conditioning

- Manipulation of an analog signal in such a way that it meets the requirements of the next stage for further processing
  - Amplification
  - Limiting
  - Linearization
  - Anti-aliasing filtering
  - …

EE111 Electric Circuits

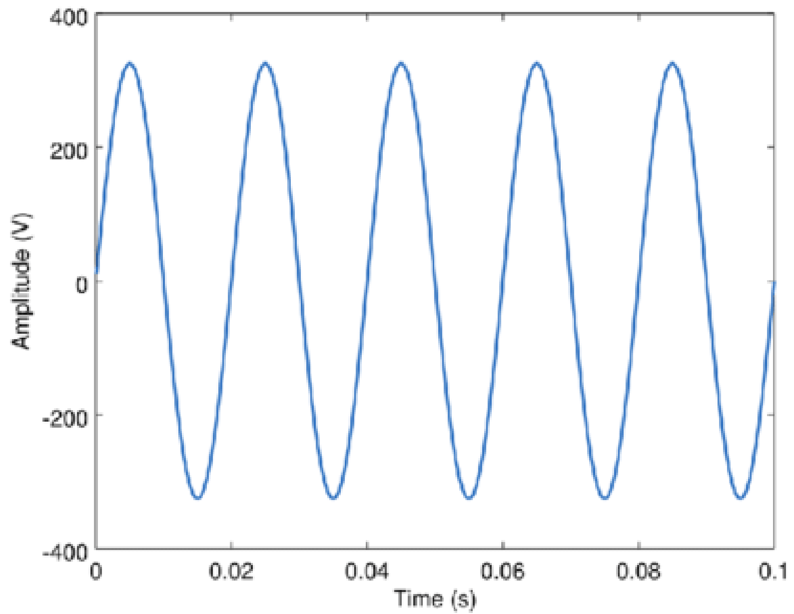
From Analog to Digital

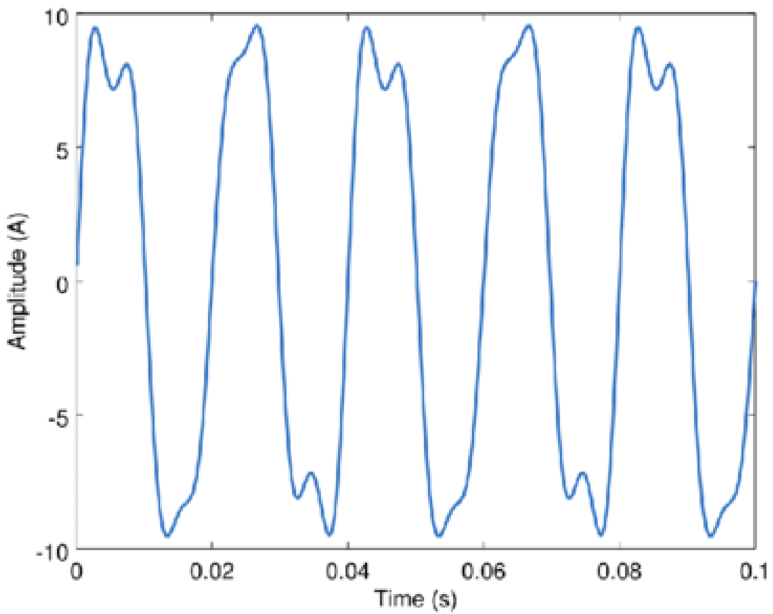
The World is Analog

- All the sensed signal is analog

The World is Analog

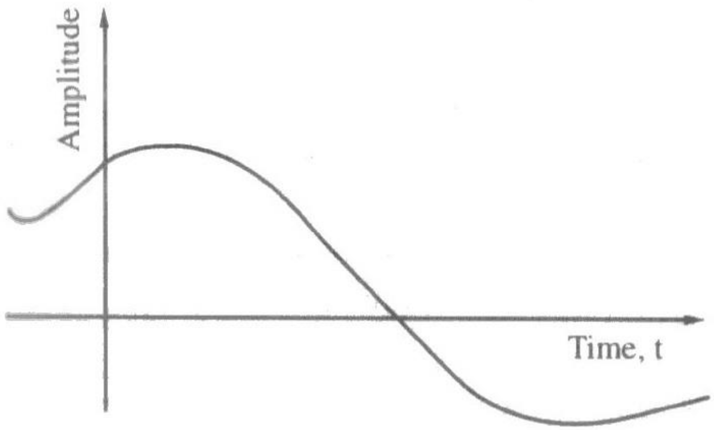
- Common sensor output: voltage and current



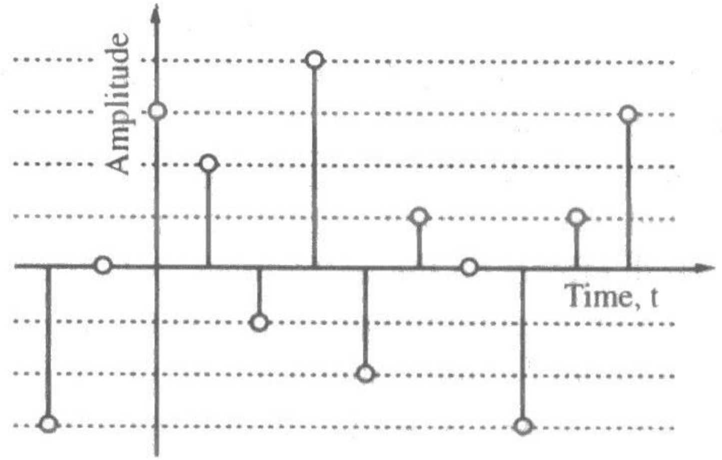


Analog & Digital Signal

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



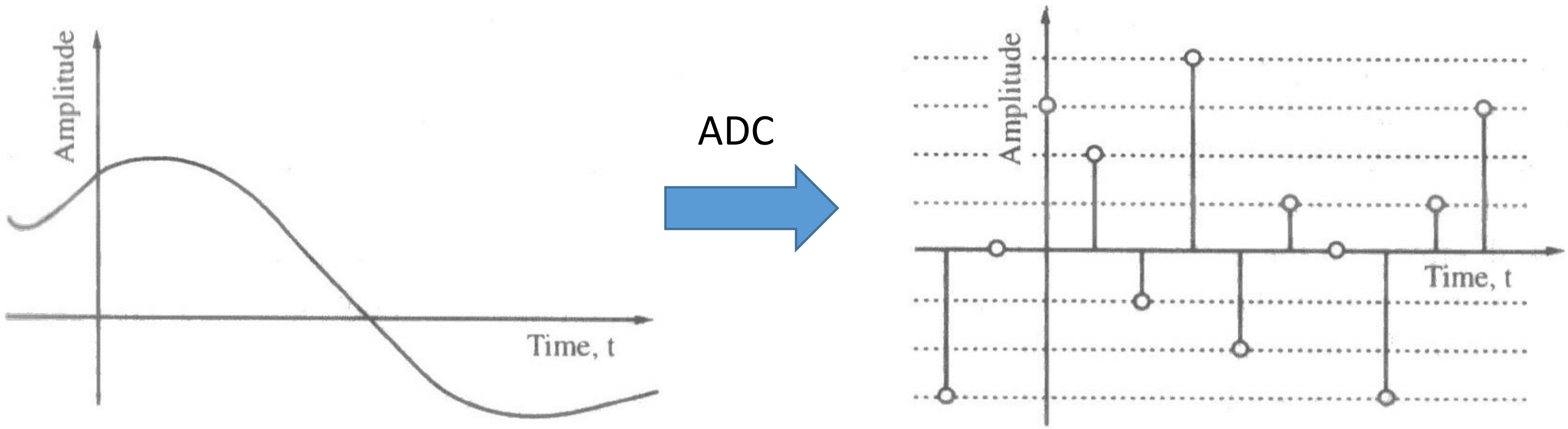
- Digital signal
  - Discrete-time signal with discrete-valued amplitude
  - A digital signal is a quantized sampled-data signal



Digital Processing Has Many Advantages

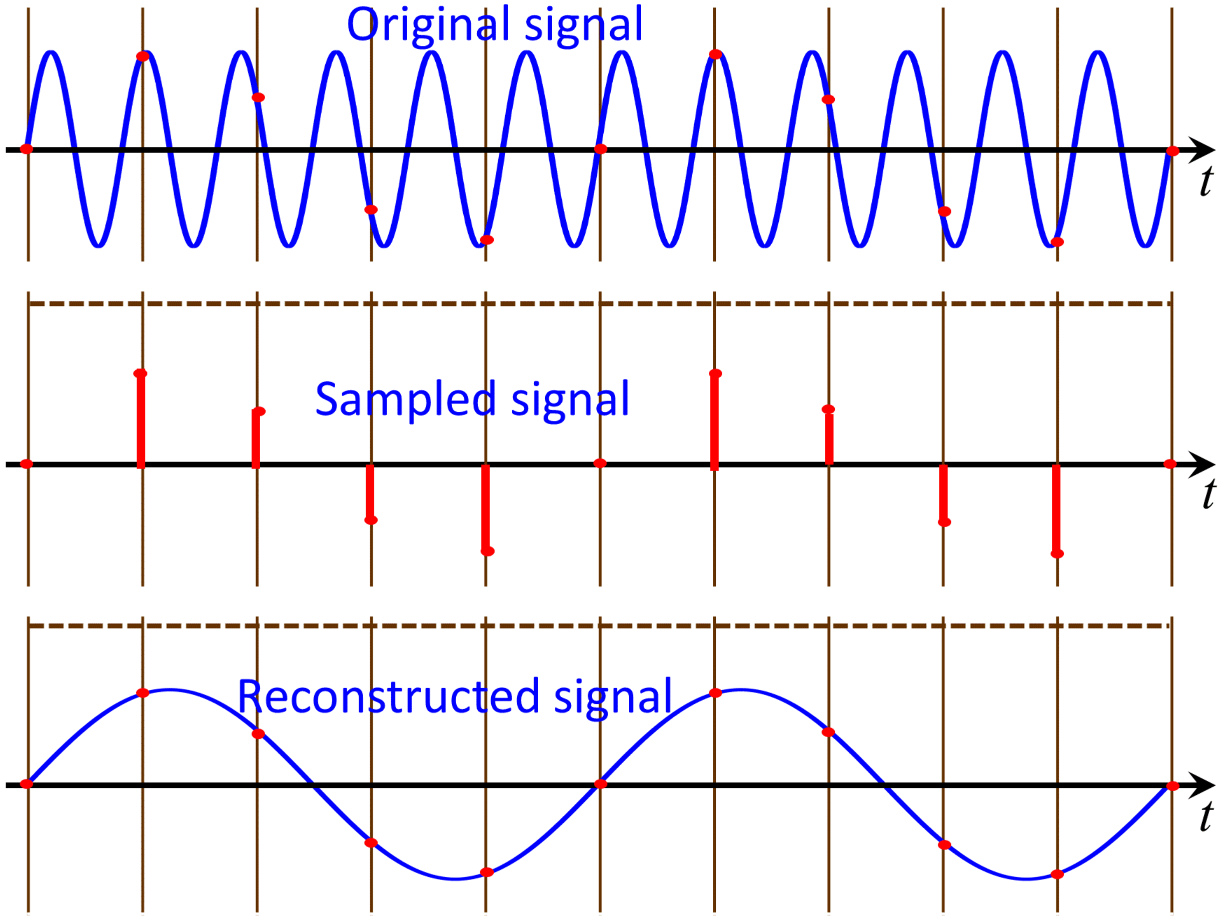
- Digital processing has many advantages
  - Refer to slides of week 1

The Bridge Between Analog and Digital



Analog-to-Digital Conversion

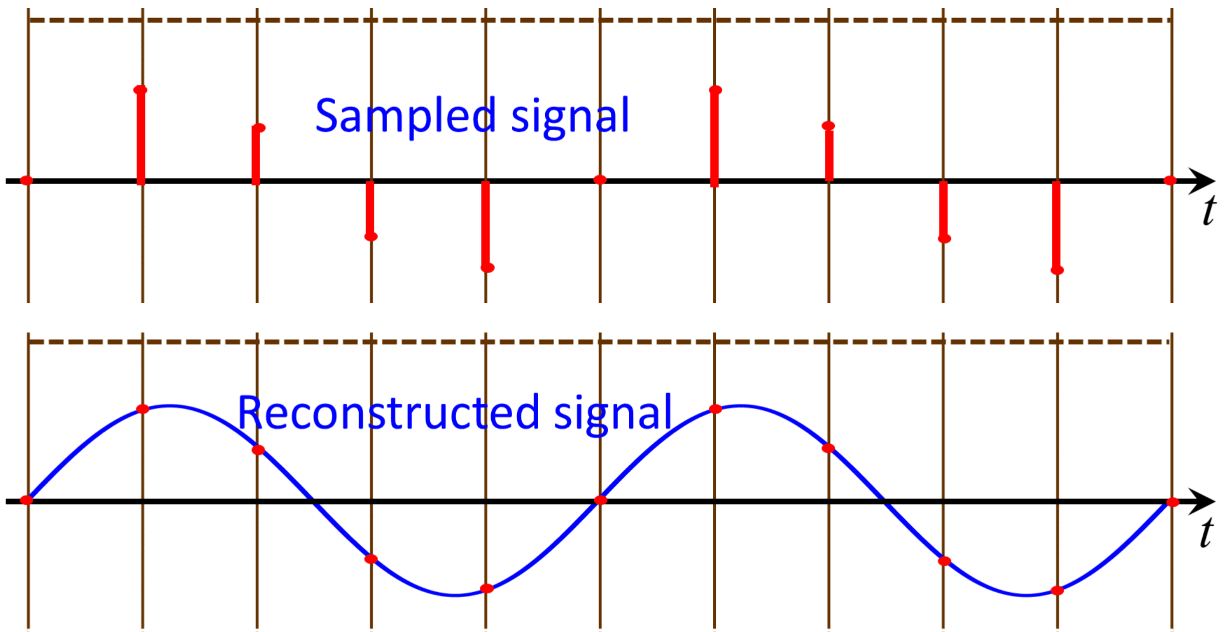
- Q1: can we recover the original continuous signal?



If the sampling rate is not sufficiently high, the reconstructed signal is different from the original signal.

Analog-to-Digital Conversion

- Q1: can we recover the original continuous signal?



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Analog-to-Digital Conversion

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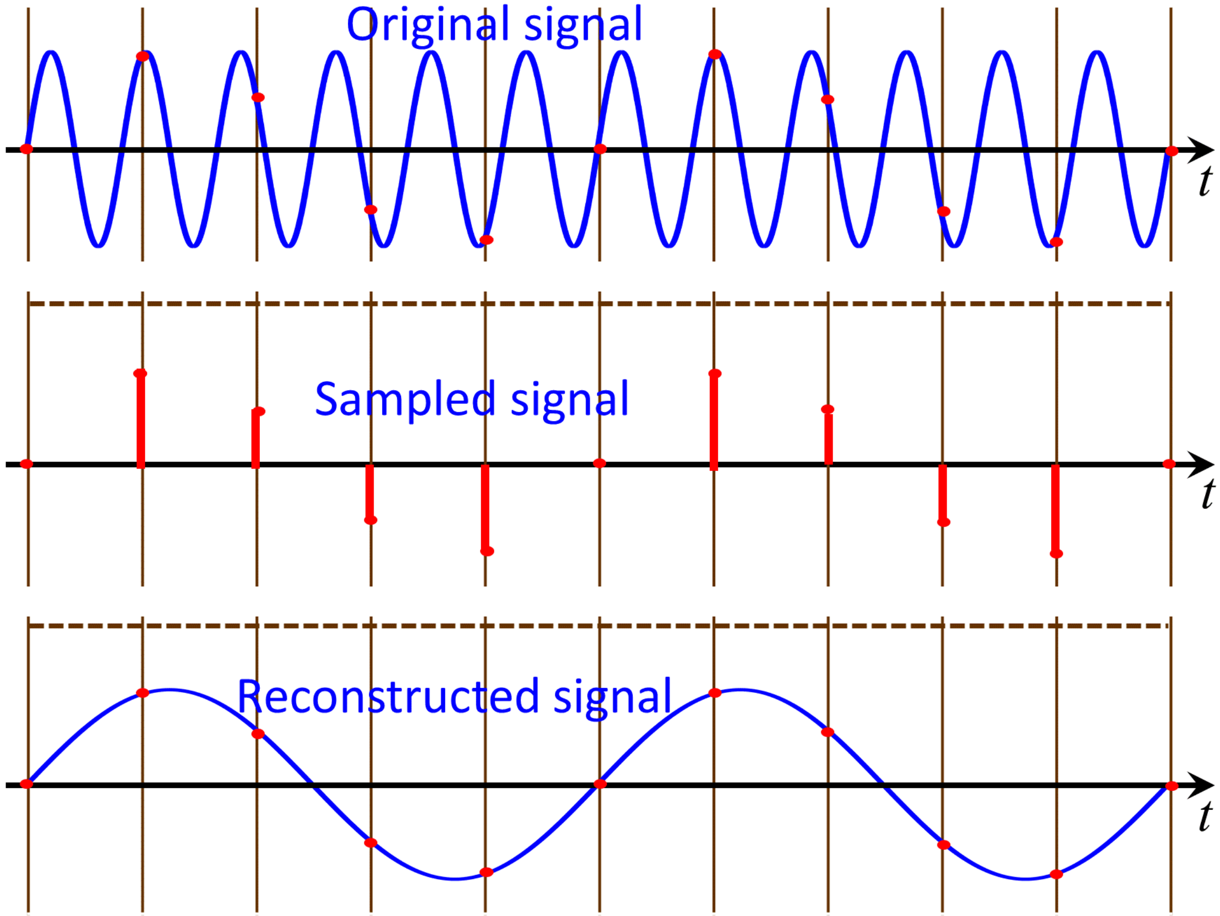


If the sampling rate is not sufficiently high, the reconstructed signal is different from the original signal.

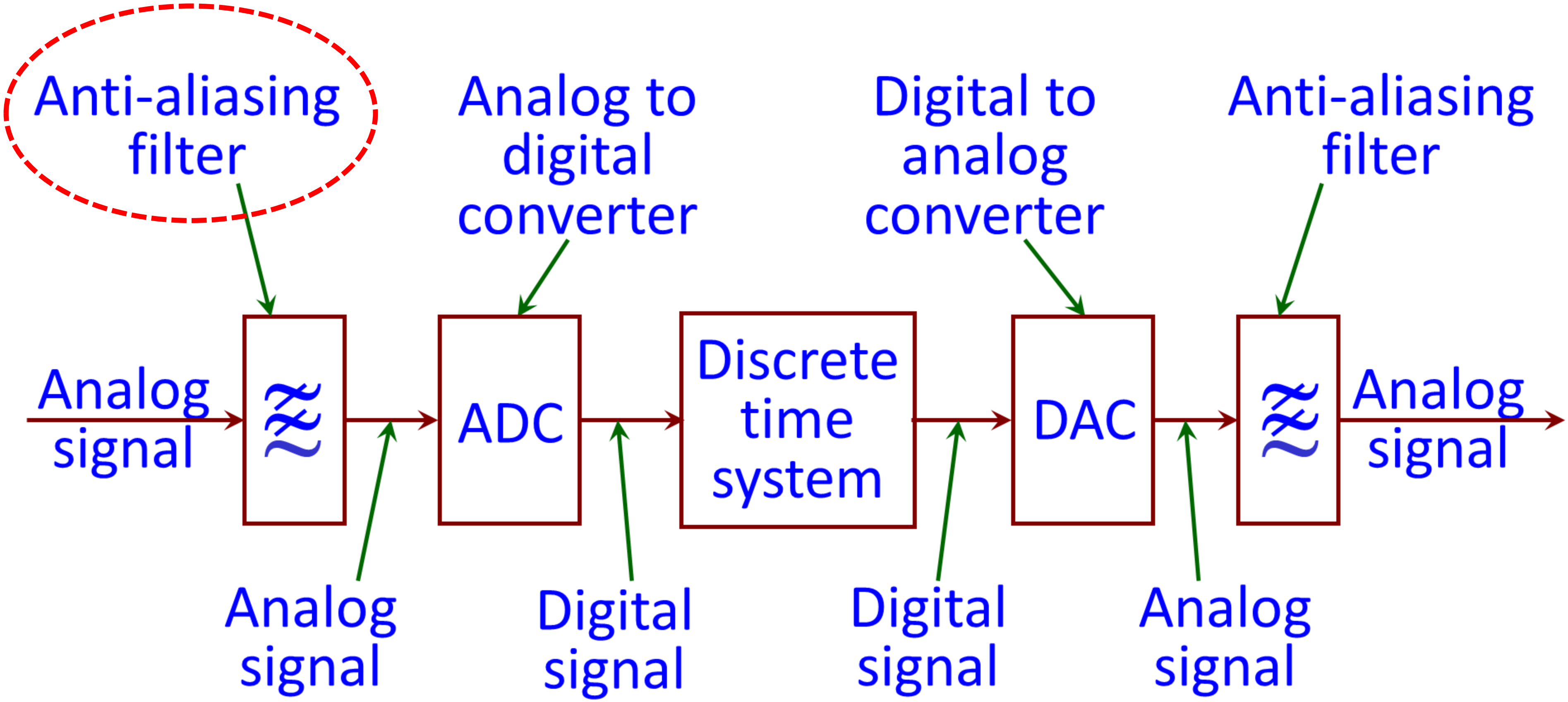
The Famous Nyquist Theorem

Birthdate
1889/02/07
Birthplace
Nilsby, Sweden
Death date
1976/04/04
Associated organizations
Bell Labs
Fields of study
Signal processing
Awards
IRE Medal of Honor, Stuart Ballantine Medal of the Franklin Institute, Mervin J. Kelly award

- The Nyquist Theorem states that in order to adequately reproduce the original signal it should be periodically sampled at a rate that is 2X the highest frequency you wish to record

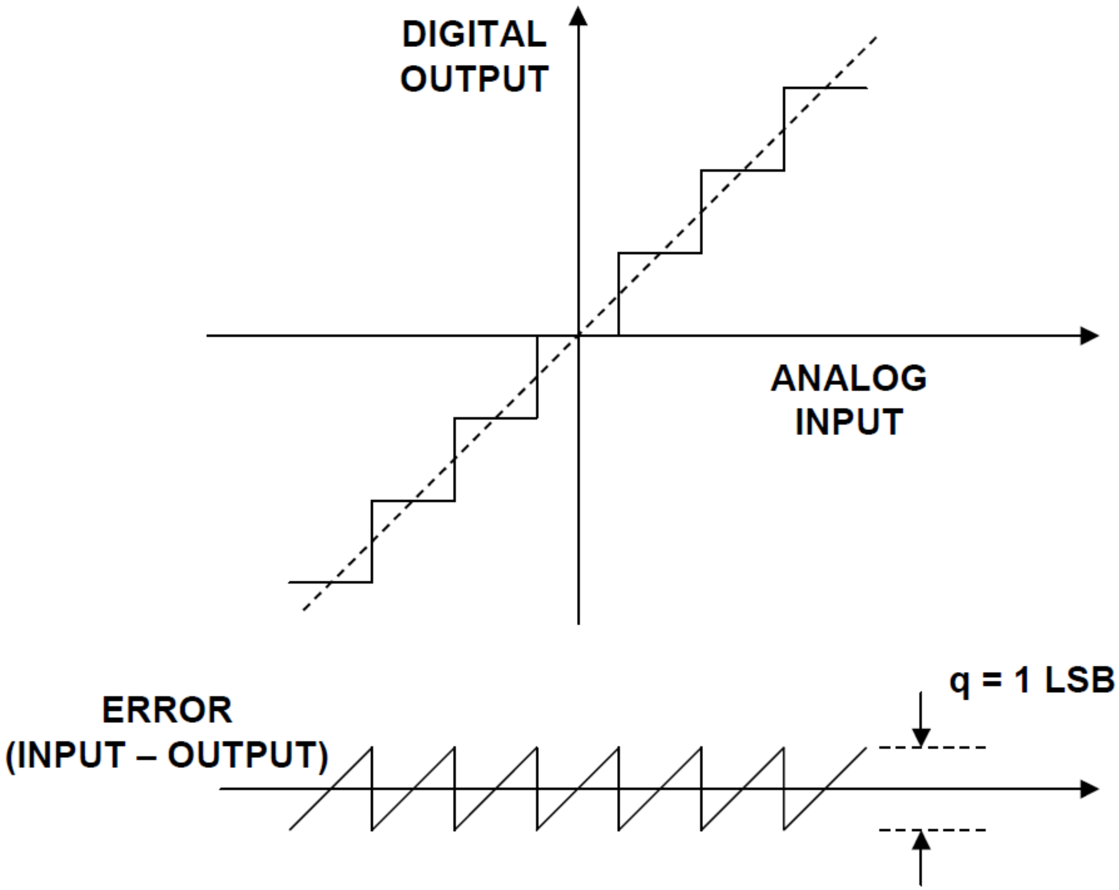
Typical DSP Systems

- Analog filter or digital filter?
- High-pass? Low-pass? Band-pass?



Analog-to-Digital Conversion

- Q2: how many bits we need to represent a sample?



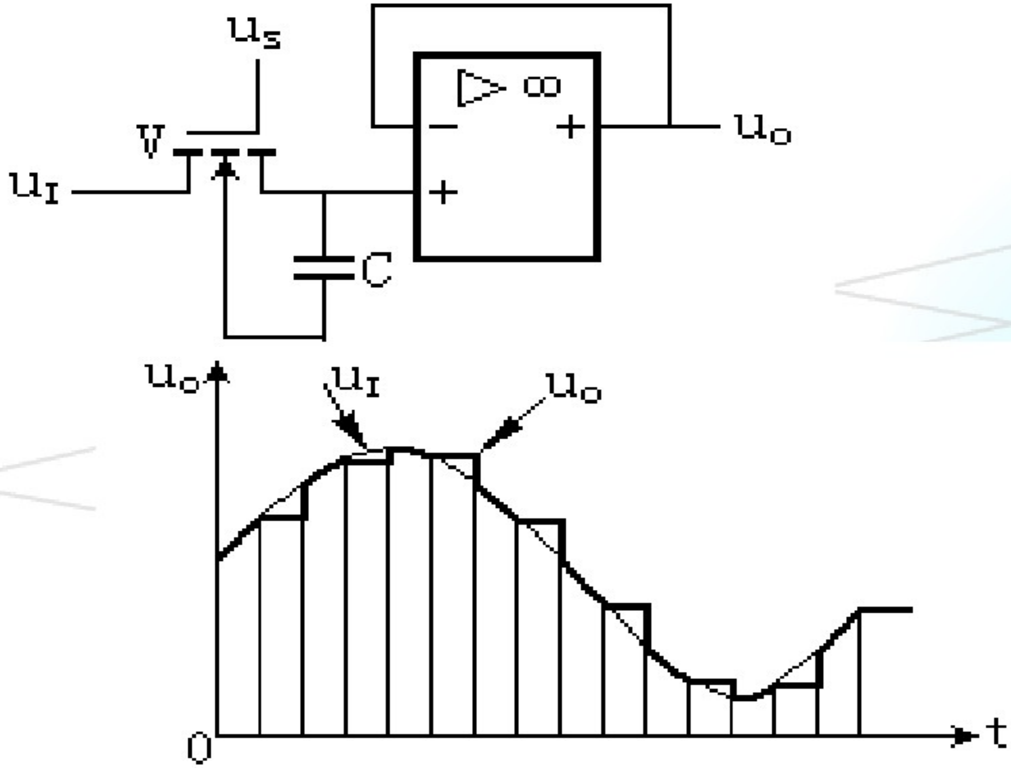
Analog-to-Digital Conversion

- Commonly used ADC
  - 8-bit, 10-bit, 12-bit, 14-bit, 16-bit, 24-bit

模拟电压U_i	量化结构	二进制码
0~1/8V	0V	0 0 0
1/8~2/8V	1/8V= Δ	0 0 1
2/8~3/8V	2/8V=2Δ	0 1 0
3/8~4/8V	3/8V=3Δ	0 1 1
4/8~5/8V	4/8V=4Δ	1 0 0
5/8~6/8V	5/8V=5Δ	1 0 1
6/8~7/8V	6/8V=6Δ	1 1 0
7/8~8/8V	7/8V=7Δ	1 1 1

How Does an ADC Work?

- Sample & hold



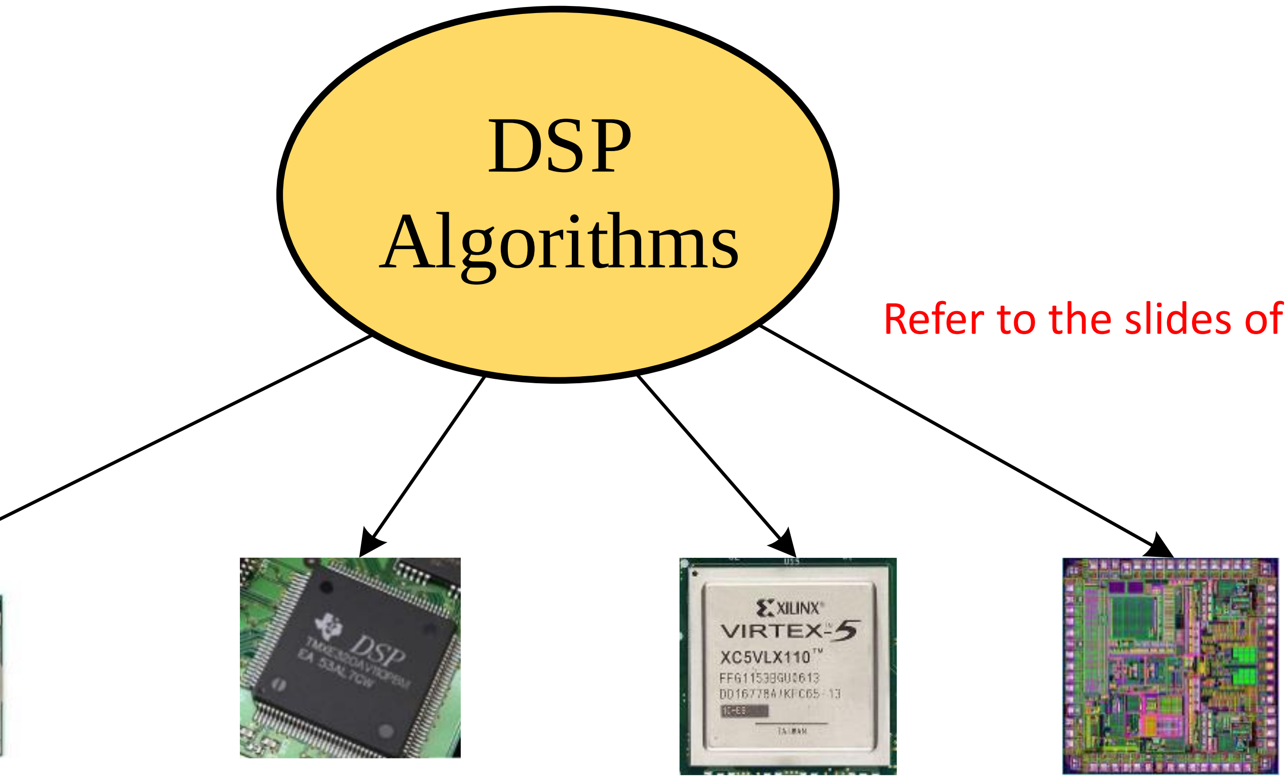
How Does an ADC Work?

- Quantize & coding

模拟电压U_i	量化结构	二进制码
0~1/8V	0V	0 0 0
1/8~2/8V	1/8V= Δ	0 0 1
2/8~3/8V	2/8V=2Δ	0 1 0
3/8~4/8V	3/8V=3Δ	0 1 1
4/8~5/8V	4/8V=4Δ	1 0 0
5/8~6/8V	5/8V=5Δ	1 0 1
6/8~7/8V	6/8V=6Δ	1 1 0
7/8~8/8V	7/8V=7Δ	1 1 1

The Discrete-time System

- A given DSP algorithm can be implemented in various ways



Refer to the slides of week 1

General Processor

DSP Processor

FPGA

ASIC

The Discrete-time System

- Fixed point VS Floating point

Fixed Point Number

- Fixed-point arithmetic
  - high speed
  - Low complexity
- Represented by an integer with a scaling factor

$$X = x_{W-1}x_{W-2}\ldots x_M \ . \ x_{M-1}\ldots x_0 = x_{W-1}x_{W-2}\ldots x_0 \times r^{-M}$$

Decimal Number System

- Decimal number system uses the 10 symbols (0, 1, 2, 3, 4, 5, 6, 7, 8, 9) to represent a number

- Example:

$$(456)_{10} = 4\times 10^2 + 5\times 10^1 + 6\times 10^0$$

$$(3705.86)_{10} = 3\times 10^3 + 7\times 10^2 + 0\times 10^1 + 5\times 10^0 + 8\times 10^{-1} + 6\times 10^{-2}$$

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Binary Number System

- In binary number system, 2 symbols (0 and 1) are used to represent a number
- Example:

$$(11001)_2 = (2^4)_{10} + (2^3)_{10} + (2^0)_{10}$$

$2^4 \quad 2^3 \quad 2^2 \quad 2^1 \quad 2^0$

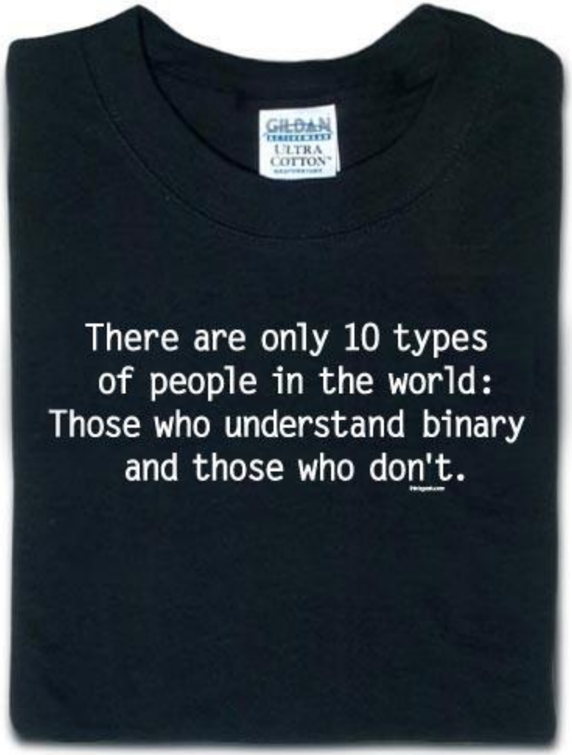
$$= (16)_{10} + (8)_{10} + (1)_{10}$$

$$= (25)_{10}$$

$$(101.01)_2 = (2^2)_{10} + (2^0)_{10} + (2^{-2})_{10}$$

$$= (4)_{10} + (1)_{10} + (0.25)_{10}$$

$$= (5.25)_{10}$$



Binary Number System (cont'd)

- Unsigned binary

$$X = x_{W-1}x_{W-2}\ldots x_0 = \sum_{k=0}^{W-1} x_k \cdot 2^k, \;\; x_k \in \{0, 1\}$$

- The range of an *N*-bit unsigned binary number is $[0, 2^N-1]$
  - The largest 4-bit number is $(1111)_2 = 16$
- Negative number is not represented. To represent negative numbers, an extra bit, called sign bit is needed

Negative Numbers

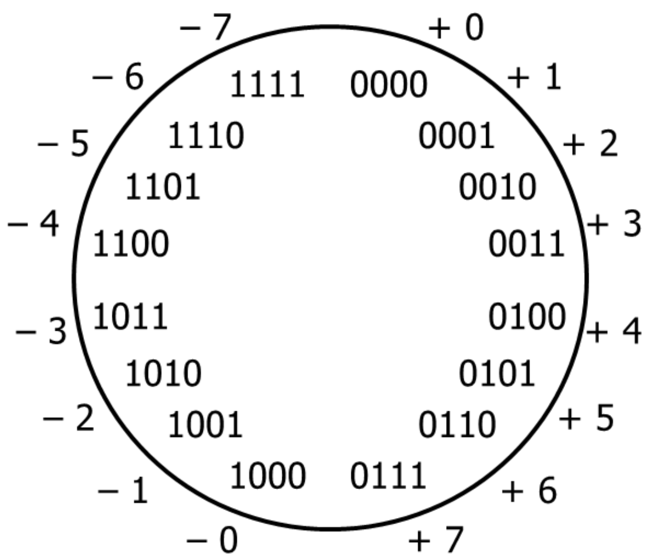
- Three approaches to represent negative numbers
  - Sign and magnitude
  - Two's-complement

- The two approaches represent positive numbers in the same way

Signed-Magnitude

- The most significant bit (MSB) is the sign bit
- Remaining bits are the number's magnitude

$$X = x_{W-1}x_{W-2}...x_0 = (-1)^{x_{W-1}} \sum_{k=0}^{W-2} x_k \cdot 2^k, \;\; x_k \in \{0,1\}.$$



Sign and Magnitude (cont'd)

- Problem 1: Two representations of for zero
  - +0 = 0000 and –0 = 1000

- Problem 2: Arithmetic is cumbersome
  - $4 - 3 \neq 4 + (-3)$

Add		Subtract			Compare and subtract		
4	0100	4	0100	0100	– 4	1100	1100
+ 3	+ 0011	– 3	+ 1011	– 0011	+ 3	+ 0011	– 0011
= 7	= 0111	= 1	≠ 1111	= 0001	– 1	≠ 1111	= 1001

Two's complement

- Negative number
  - $0111 \equiv 7_{10}$
  - $1001 \equiv -7_{10}$
- The value of a two's complement number is

$$X = x_{W-1}x_{W-2}...x_0 = -x_{W-1} \cdot 2^{W-1} + \sum_{k=0}^{W-2} x_k \cdot 2^k,\ x_k \in \{0,1\}.$$

- The MSB carries a negative weight

$$(1101)_{2's} = -2^3 + 2^2 + 2^0 = -8 + 4 + 1 = -3$$

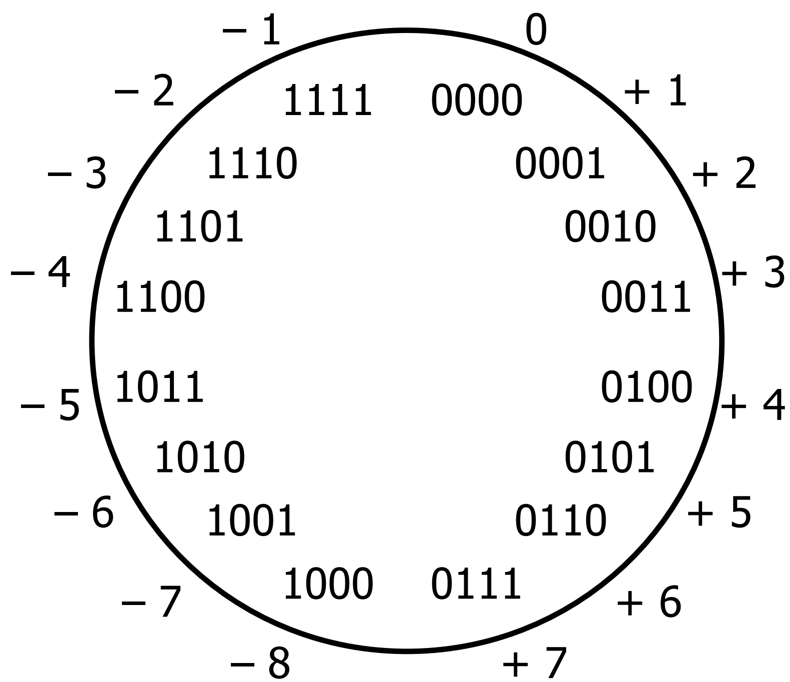
$$(1001)_{2's} = -2^3 + 2^0 = -8 + 1 = -7$$

$$(0110)_{2's} = 2^2 + 2^1 = 4 + 2 = 6$$

$$(110)_{2's} = -2^2 + 2^1 = -4 + 2 = -2$$

Two's complement (cont'd)

- The range of an N-bit two's complement number is $[-2^{N-1}, 2^{N-1}-1]$
- For a 4-bit two's complement number



Two's complement (cont'd)

EE115 Analog and Digital Circuits

- Benefits:
  - Simplified arithmetic
  - Only one zero!

Add		Invert and add		Invert and add	
4	0100	4	0100	– 4	1100
+ 3	+ 0011	– 3	+ 1101	+ 3	+ 0011
= 7	= 0111	= 1	1 0001	– 1	1111
		drop carry	= 0001		

- As long as the results can be represented (no overflow)!

Floating Point Number

exponent;
characteristic

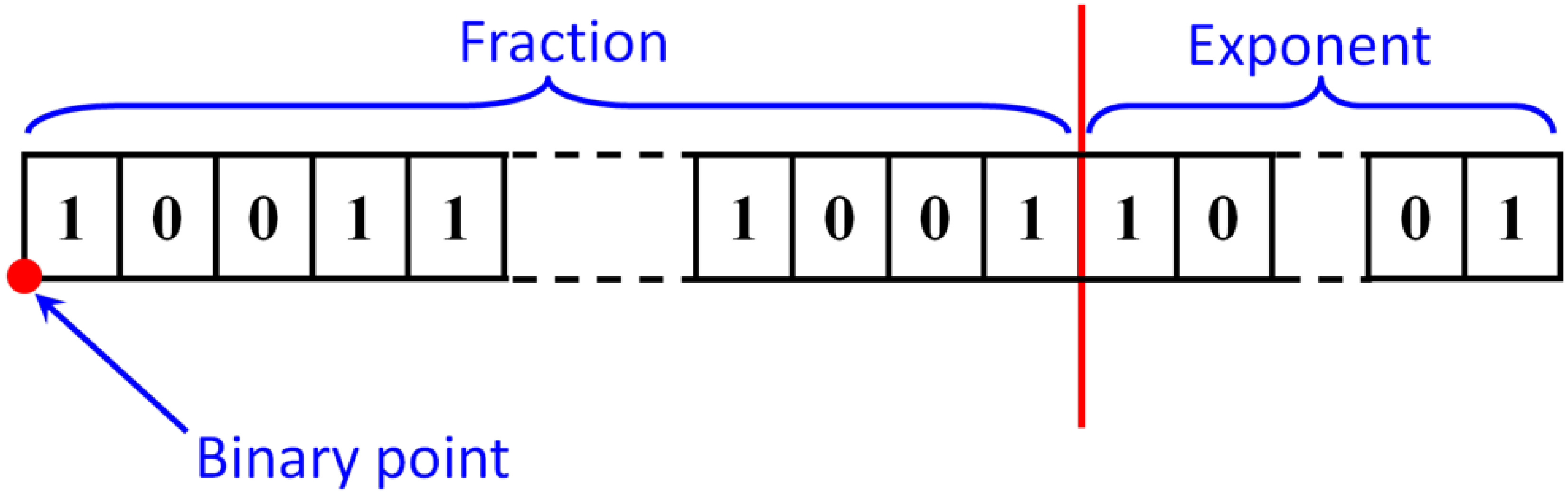
$$A = P \times Q^D$$

base; radix

fraction;
mantissa

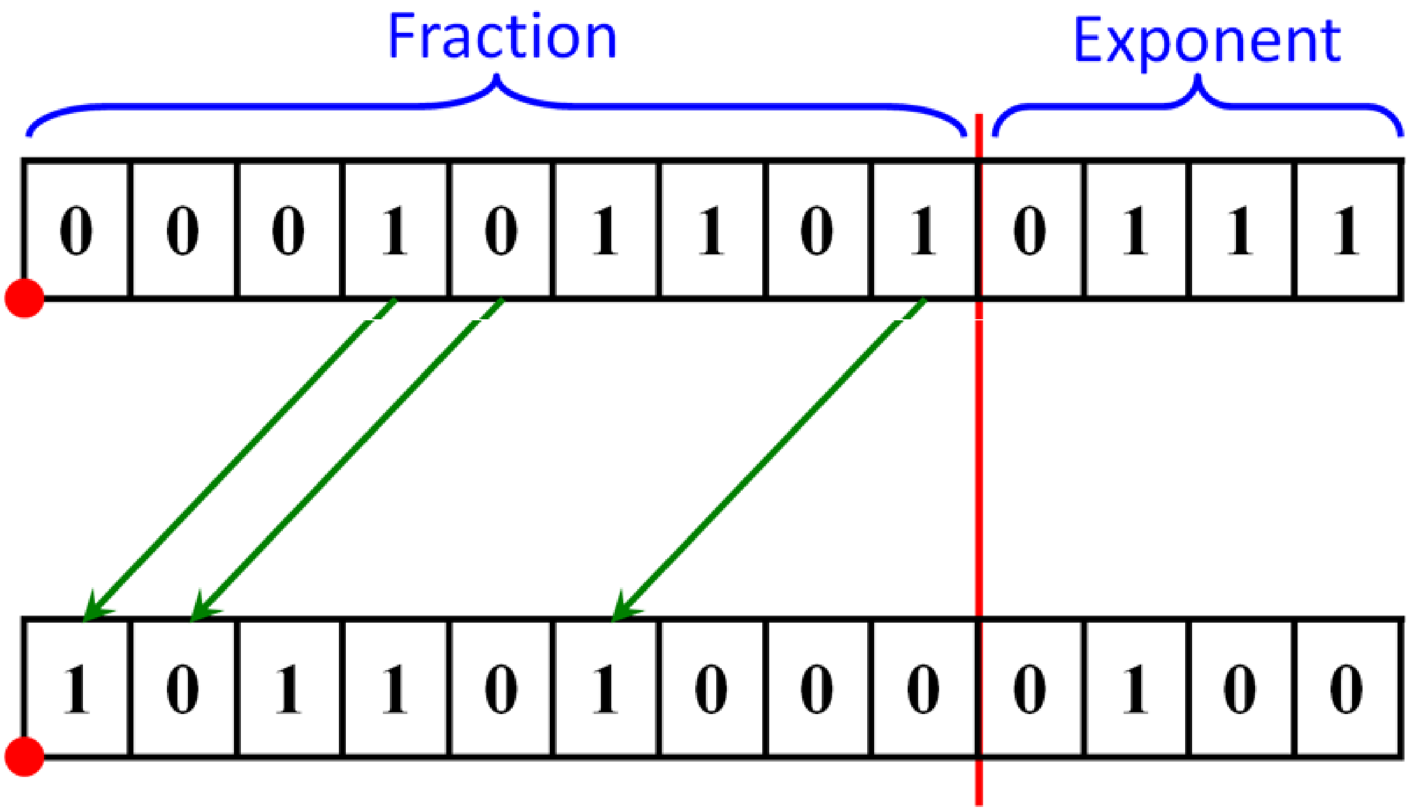
Example: 8934 can be written as 0.8934×10^4

Binary Representation of Floating Point Number



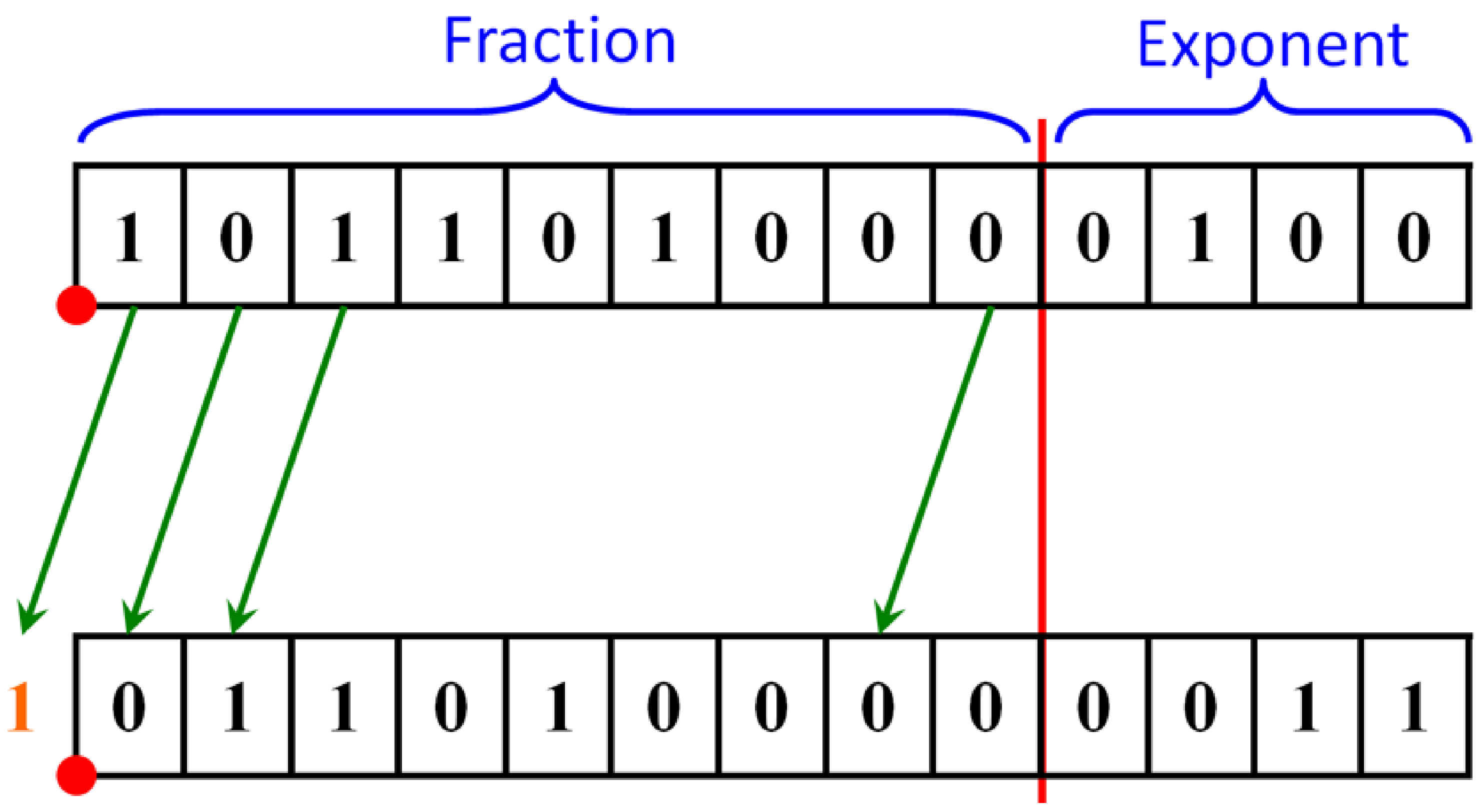
Binary Representation of Floating Point Number (cont'd)

- For maximum precision, the number can be normalized until the first digit is "1"



Binary Representation of Floating Point Number (cont'd)

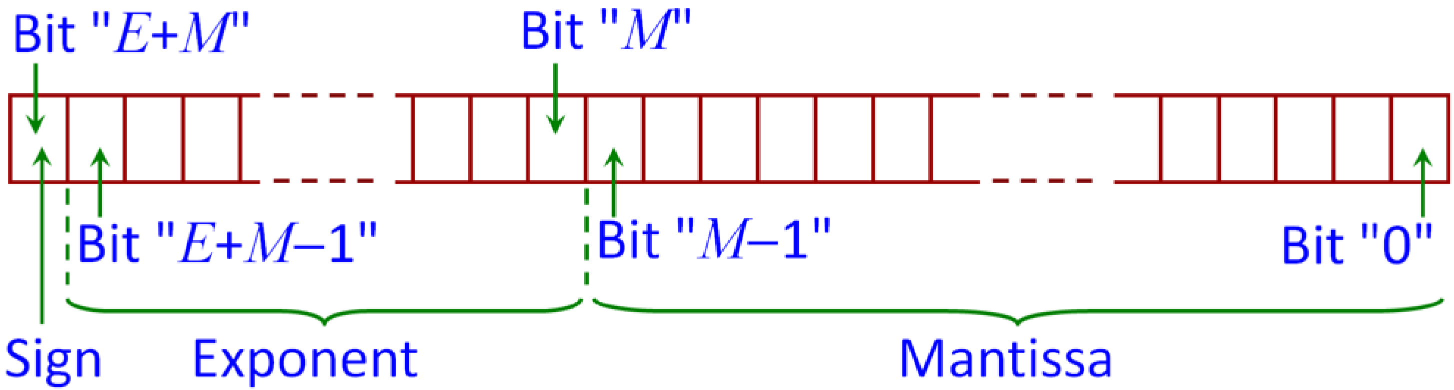
- Since the first digit is a "1", it is not necessary to record it



IEEE 754

- IEEE standard for binary floating-point arithmetic
- IEEE 754 specifies 4 formats
  - Single-precision (32-bit)
  - Double-precision (64-bit)
  - Signal-extended precision (≥43-bit, seldom used)
  - Double-extended precision (≥79-bit, usually 80-bit)

IEEE 754 Number Format



	Exponent	Mantissa
NaNs	$2^E - 1$, i.e. all 1s	non zero
Infinities	$2^E - 1$, i.e. all 1s	0
Zeroes	0, i.e. all 0s	0
Denormalized numbers	0, i.e. all 0s	non zero
Normalized numbers	1 to $2^E - 2$. Biased binary	Any number

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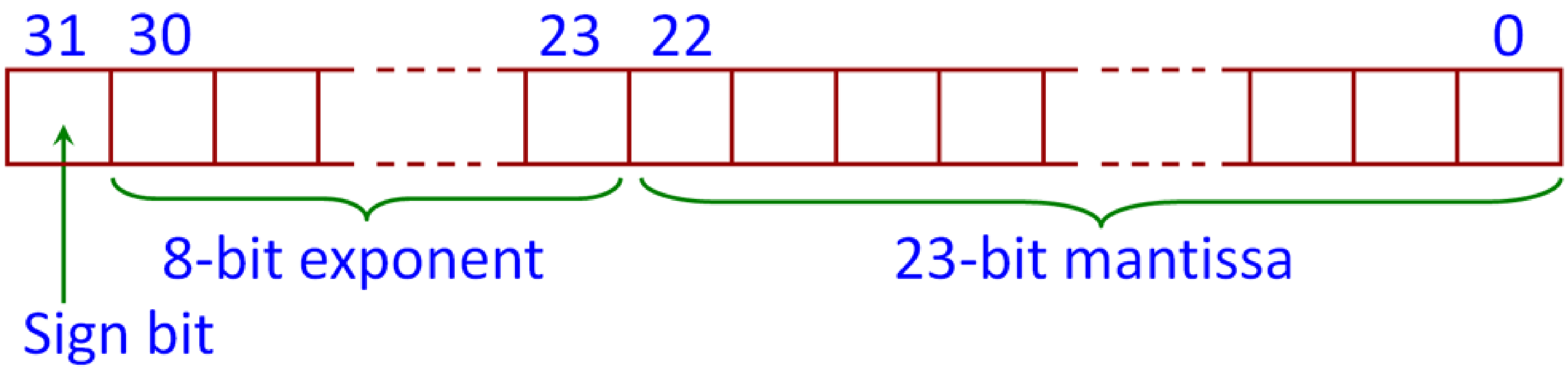
IEEE 754 Number Format (cont'd)

- Sign bit
  - Number is positive if sign bit is "0"
  - Number is negative if sign bit is "1"
- Biased exponent
  - The exponent is a signed value
    - for large and small magnitudes
  - Two's complement is not used
  - A constant $2^{E-1}-1$ is added to the exponent
    - E.g., for E=8, the exponent bias is $2^7-1=127$, if the exponent is -3, it will be recorded as $-3+127=124$, i.e., $(01111100)_2$

32-bit Single Precision Format



Value = $(-1)^{S} \times 2^{Exp-127} \times M$

Where

Exp = Recorded exponent.

M = 1.(value represented by fractional bit).

The Mantissa Value

Mantissa value = 1.(value represented by fractional bit).

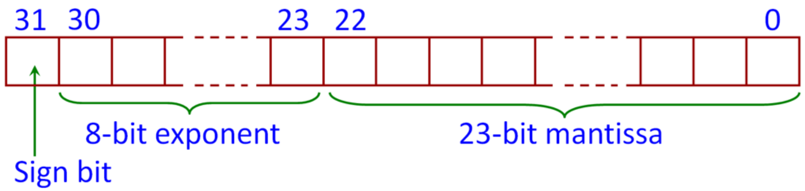
Example

	22																						0
	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

23-bit mantissa

Fixed point VS Floating point

- Example: 32bit
- For fixed point



Value = $(-1)^{S} \times 2^{Exp-127} \times M$

Where

Exp = Recorded exponent.

M = 1.(value represented by fractional bit).

The smallest 1×2^{-N}

The largest $(2^{32}-1) \times 2^{-N}$

Dynamic range $20\log(\frac{(2^{32}-1) \times 2^{-N}}{1 \times 2^{-N}}) \approx 192\text{dB}$

- For floating point

The smallest $1.00000000000000000000000 \times 2^{-126} \approx 1.175494 \times 10^{-38}$

The largest $1.11111111111111111111110 * 2^{128} \approx 3.402823 \times 10^{38}$

Dynamic range $20\log(\frac{3.402823 \times 10^{38}}{1.175494 \times 10^{-38}}) \approx 1667.6\text{dB}$

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Fixed point VS Floating point

- Fixed point
  - Limited dynamic range, fast, low-power
- Floating point
  - High dynamic range, complex, slow
- Example
  - Filter coefficient quantization

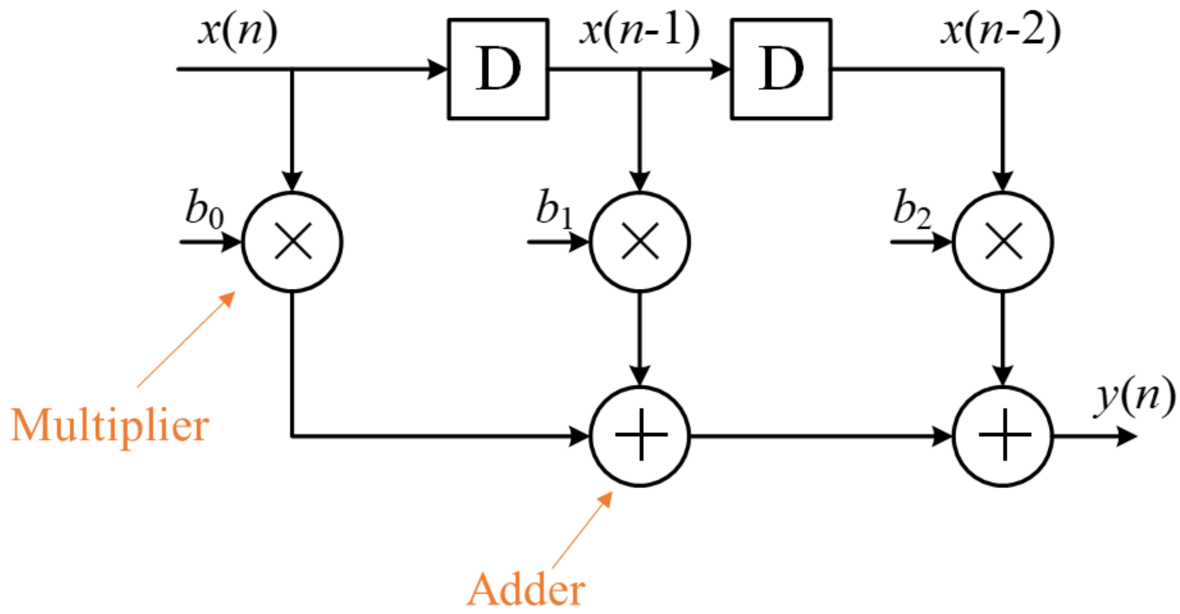
Question

- The word-length of commonly used ADCs are around 16 bit, why need such a large dynamic range?

- Answer
  - Multiplications

Typical DSP Operations

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



- Adders and multipliers are important components in DSP circuits

Other Number Systems

- Signed digit number system (SD)
- Residual number system (RNS)
- Logarithmic number system (LNS)

It Is Always a Tradeoff

- A number system with high dynamic range, high precision, low-complexity…

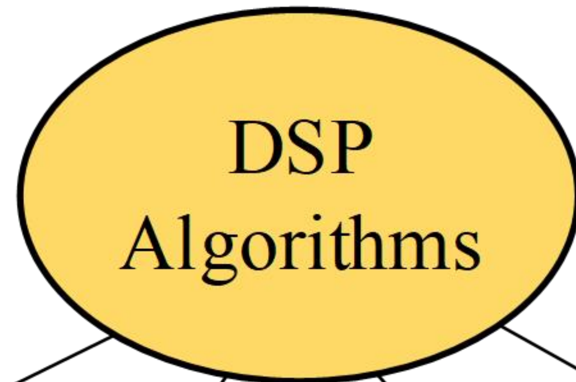
Does not exist !

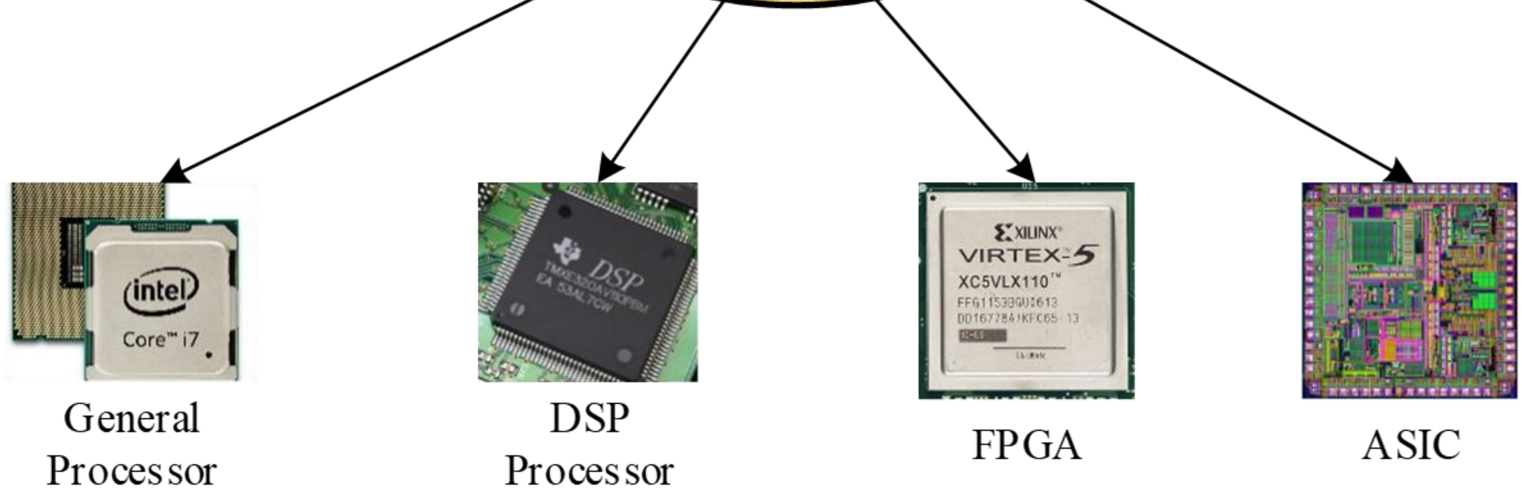
NVIDIA T4 SPECIFICATIONS

Performance	
	TURING TENSOR CORES 320
	NVIDIA CUDA® CORES 2,560
	SINGLE PRECISION PERFORMANCE (FP32) 8.1 TFLOPS
	MIXED PRECISION (FP16/FP32) 65 FP16 TFLOPS
	INT8 PRECISION 130 INT8 TOPS
	INT4 PRECISION 260 INT4 TOPS

Other Things

- Other things you need to think about when implementing a DSP system






头 戴 式 无 线 降 噪 耳 机
WH-1000XM4
SONY


业界盛名的降噪技术
智能体验 智慧聆听
SONY
HD Noise Cancelling Processor QN1
*示意图
Upgrade
新升级的
HD降噪处理器QN1
DIGITAL NC
20级环境声
可控降噪
NEW
智能免摘对话
AI自适应
Upgrade
声音控制


音频品质 实时提升
便捷操控 更懂你心
Upgrade
DSEE Extreme
数字声音增强引擎
进阶版
360 REALITY AUDIO
360临场音效
VAIO
升级降噪通话 NEW
支持佩戴感应 NEW
支持多点连接 * NEW