Elements of Measurement Systems

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Important Definitions

- Measurand
  - Measured quantity
    - This is what we measure (e.g., temperature, wind speed, pressure, etc.)
  - Any input to a sensor
  - We can never *exactly* determine a measurand because there are always errors associated with measurements

Important Definitions

- Sensor
  - Essential element that interacts with the variable to be measured (What was that called? Oh yeah, the measurand) and produces an output signal that is *proportional to the input*
  - Possible input:
    - Air temperature, wind speed, pressure, solar radiation
  - Possible output:
    - Resistance, voltage, mechanical deflection, rotation rate
  - Extracts energy from the measured medium and adds noise to the signal
    - Perfect measurement is impossible!

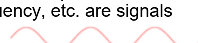
Important Definitions

- Data display
  - Any mechanism for displaying data to the user
- Transducer
  - Converts energy from one form to another

What is the difference between a sensor and an instrument?

- Instrument
  - Sensor + any other required *transducers* and a data display element
  - Example: Is a mercury-in-glass thermometer a sensor or an instrument?

Important Definitions

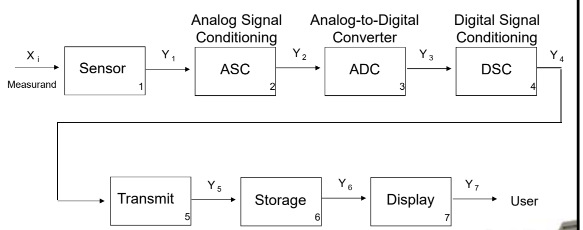
- Signal
  - An information-bearing quantity
    - Temperature, wind speed, shaft rotation rate, voltage, current, frequency, etc. are signals
  - Analog signal 
    - Information is *continuously* proportional to the measurand
    - Measurand (input) and most raw sensor outputs are analog signals
  - Digital signal
    - Information content varies in discrete steps
    - Smaller step sizes yield a digital signal that more closely resembles the analog signal
    - Output is discrete in both value and time

Important Definitions

- Signal conditioning
  - Operations that…
    - Convert a signal from one form to another
      - e.g., resistance to voltage
    - Increase the amplitude of the signal
      - e.g., an amplifier to provide gain and offset to raw output
      - e.g., large catch area to small funnel in rain gauges
    - Reduce high-frequency noise
      - e.g., filtering
    - Compensate for side effects
      - e.g., adjust for temperature sensitivity of a pressure sensor

Functional model of a measurement system

- A measurement system interacts with the atmosphere and delivers data to the user



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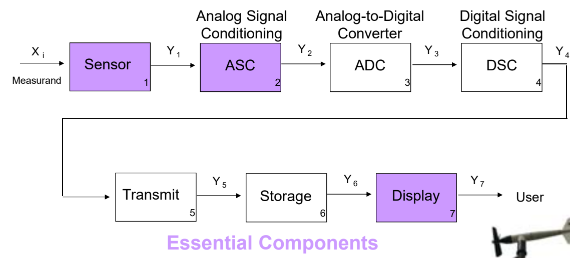
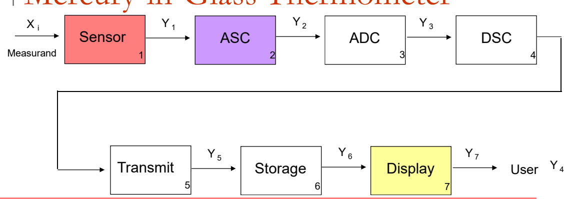


Mercury-in-Glass Thermometer



Heat energy converted into a change in volume of the mercury in the bulb

Amplification of the signal that is dependent upon the diameter of the column relative to the volume of the bulb

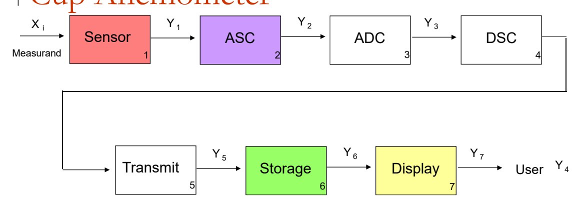
Scale etched into the glass provides calibration information and allows the user to translate raw height into temperature

X_i: Air temperature in K, °C, or °F

Y_1: Volume of the mercury

Y_2: Height of the mercury column

Cup Anemometer



Horizontal wind speed converted to angular rotation rate of a shaft connected to the cup wheel

X_i: Wind speed in m s^{-1}

Y_1: Shaft rotation rate in radians s^{-1}

Conversion of rotation rate to an electrical signal

Y_2 Option 1: DC signal with voltage proportional to wind speed → Y_2 = Voltage

Y_2 Option 2: AC signal with frequency proportional to wind speed → Y_2 = Frequency

Datalogger storage

Various options for display (meteorogram, map, numbers, etc.)

Analog-to-Digital Converter

- Present in most modern measurement systems
- Converts continuous analog signals to discrete, digital values (e.g., voltage to a digital number)
- Output of ADC: Stream of numbers representing value of input signal
- Conversions typically done at discrete time intervals (e.g., 3 seconds)
- Again, the digital signal output is discrete in both value and time
- Analog-to-digital conversion achieved by datalogger

Analog-to-Digital Conversion

- First, some definitions
  - A = Analog input (e.g., continuous voltage)
  - D = Digital output (generally binary)
  - A_L = Lower limit of the ADC input range
  - A_H = Upper limit of the ADC input range
  - S_p = Span

$$S_p = A_H - A_L$$

  - N_B = Number of bits used by the ADC
  - N_S = Number of binary states (quantization levels) available in the output *D*

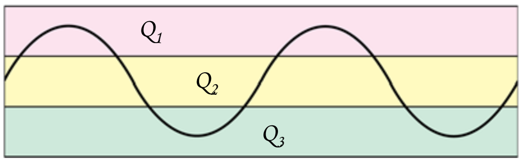
$$N_S = 2^{N_B}$$

  - Q = Quantum, uniformly distributed over the input range

$$Q = \frac{S_P}{N_S} = \frac{A_H - A_L}{2^{N_B}}$$

Analog-to-Digital Conversion: Binary Numbers

- The idea of analog-to-digital conversion:
  - Quantize
    - Partition an analog signal into a number of discrete quanta
    - Determine the quantum to which the input signal belongs



Analog-to-Digital Conversion: Binary Numbers

- The idea of analog-to-digital conversion:
  - Quantize
    - Partition an analog signal into a number of discrete quanta
    - Determine the quantum to which the input signal belongs
  - Encode
    - Assign a unique digital code to each quantum
    - Determine the code that corresponds to the input signal
    - Encode using a numbering system, usually binary
      - 2^{N_B} quanta with a set of N_B bits or "binary digits"
      - For a 3-bit binary representation of input signals:

Binary	000	001	010	011	100	101	110	111
Decimal	0	1	2	3	4	5	6	7

Analog-to-Digital Conversion

- An example of the number of binary states, N_S
  - $N_B = 1$ $N_S = 2^{N_B} = 2$ 0, 1
  - $N_B = 2$ $N_S = 2^{N_B} = 4$ 00, 01, 10, 11
  - $N_B = 3$ $N_S = 2^{N_B} = 8$ 000, 001, 010, etc.
- ADC Resolution
  - Indicates the number of discrete values produced by the ADC
  - Usually expressed in bits
  - Example: ADC that converts analog value to 256 discrete quanta has a resolution of 8 bits ($2^8 = 256$)
- Electrical resolution
  - Expressed in volts
  - Essentially, this is *Q*

Analog-to-Digital Conversion

What is the electrical resolution of a 12-bit ADC with an input range of -5V to 5V?

$$Q = \frac{S_P}{N_S} = \frac{A_H - A_L}{2^{N_B}}$$

$$Q = \frac{5\text{ V} - (-5\text{ V})}{2^{12}} = \frac{10\text{ V}}{4096} = 0.00244\text{ V} = 2.44\text{ mV}$$

The electrical resolution of the ADC is 2.44 mV

Analog-to-Digital Conversion

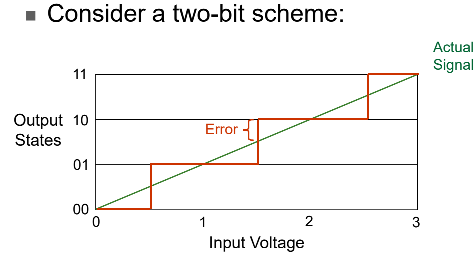
- Define the value of the digital output as:

$$D = \text{integer}\left[\frac{A - A_L}{Q} + 0.5\right]$$

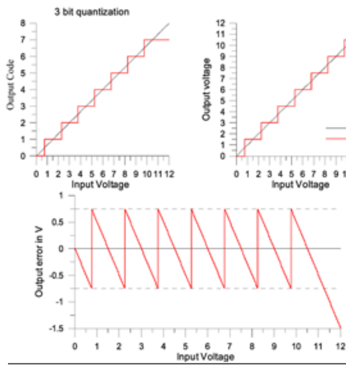
  - A = Analog input
  - A_L = Lower limit of analog input range (e.g., 0 V)
  - D is an integer and is rounded *down* (i.e., chop the decimal)
  - $0 \le D \le N_{S-1}$ (D is <u>never</u> equal to N_S)

Binary Quantization Error

- With any quantization scheme, there is always some error
- Consider a two-bit scheme:



Binary Quantization Error

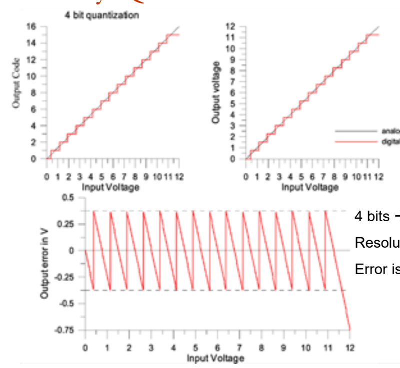


3 bits → 2^3 = 8 states

Resolution: 12V/8 = 1.5 V

Error is mostly within ± 0.75 V

Binary Quantization Error

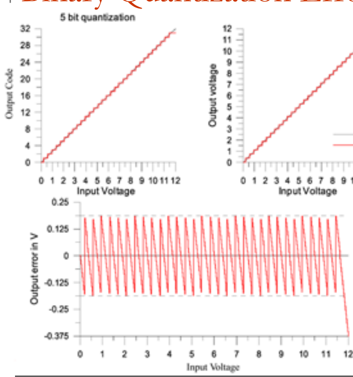


4 bits → 2^4 = 16 states

Resolution: 12V/16 =0.75 V

Error is mostly within ± 0.375 V

Binary Quantization Error



5 bits → 2^5 = 32 states

Resolution: 12V/32 =0.375 V

Error is mostly within ± 0.1875 V

Analog-to-Digital Conversion

- Required bit resolutions to achieve:
  - 0.1 m s^{-1} resolution for wind speed over the range 0–25 m s^{-1}:

    Required number of quantization levels (states) is

    N_s > (25 m s^{-1}) / (0.1 m s^{-1}) > 250

    2^{N_B} > 250 → N_B > ln(250) / ln(2) = 7.966

    $N_B = 8$
  - 0.03 m s^{-1} resolution for wind speed over the range 0–60 m s^{-1}:

    Required number of quantization levels (states) is

    N_s > (60 m s^{-1}) / (0.03 m s^{-1}) > 2000

    2^{N_B} > 2000 → N_B > ln(2000) / ln(2) = 10.966

    $N_B = 11$