# Intelligent Sensors

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With many thanks to *Ricardo Gutierrez-Osuna,* TAMU

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# Agenda

- Definitions
- Overview of Basic Sensors
- Instrumentation
- Intelligent Sensors
- Communications

# Intelligent Sensor Systems (ISS) Definitions

- System
  - A combination of two or more elements, subsystems and parts necessary to carry out one or more functions
  - To interact with the real world, a system requires
    - Sensors: inputs devices
    - Actuators: output devices
    - Processing: signals, information and knowledge
- Sensor
  - A device that receives and responds to a stimulus [Fdn97]
    - Stimulus: mechanical, thermal, magnetic, electric, optical, chemical…
    - Response: an electrical signal (in most cases)
- Intelligence
  - The ability to combine
    - A priori knowledge (available before experience) and
    - Adaptive learning (from experience)

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# Intelligent Sensor Systems Definitions (cont)

- **Additional definitions**
  - A sensor that is capable of modifying its internal behavior to optimize the collection of data from the external world [Whi97]
    - The concepts of adaptation and compensation are central to the Intelligent Sensor philosophy
  - A device that combines a sensing element and a signal processor on a single integrated circuit [PY95a]
    - The minimum requirements of the signal processor are not clear [PY95b]
      - Basic integrated electronics (signal conditioning, ADC)
      - A micro-processor
      - Logic functions and decision making
  - A smart sensor is a sensor that provides functions beyond those necessary for generating a correct representation of a sensed or controlled quantity (IEEE 1451.2) [Fnk00]
    - This function typically simplifies the integration of the transducer into applications in a networked environment

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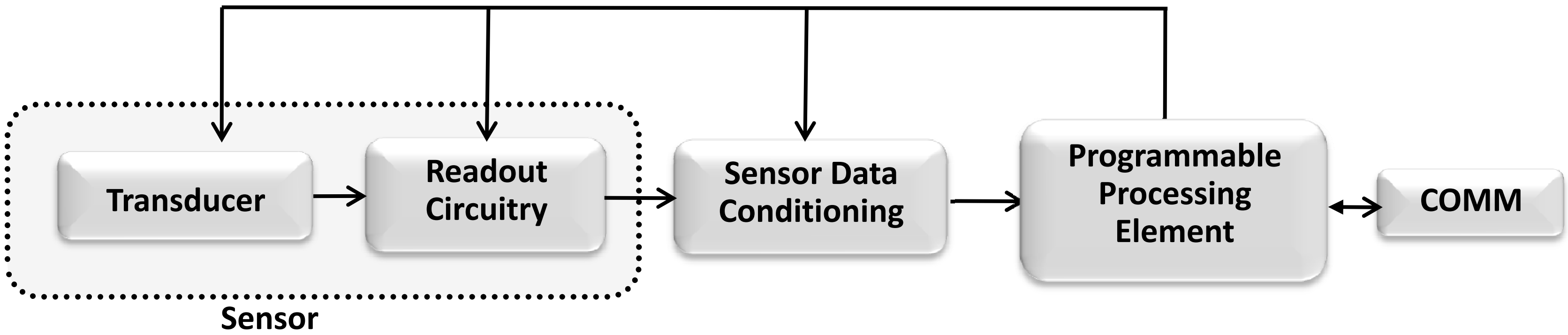
# Building Blocks of an Intelligent Sensor System (ISS)

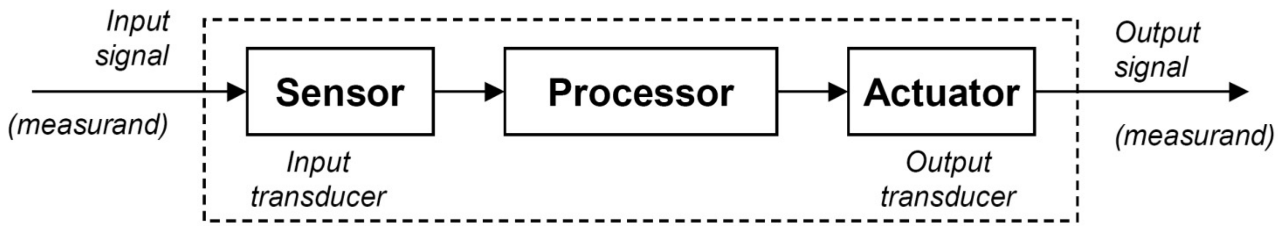
- **The principal sub-systems within an ISS are:**
  - Primary sensing element(s)
  - Excitation control
  - Amplification
  - Analog filtering
  - Data conversion
  - Compensation
  - Digital information processing
  - Digital communications processing



# Overview of Basic Sensors

# Transducers: sensors and actuators

- **Transducer**
  - A device that converts a signal from one physical form to a corresponding signal having a different physical form
    - Physical form: mechanical, thermal, magnetic, electric, optical, chemical…
  - Transducers are ENERGY CONVERTERS or MODIFIERS
- **Sensor**
  - A device that receives and responds to a signal or stimulus
    - This is a broader concept that includes the extension of our perception capabilities to acquire information about physical quantities
- **Transducers: sensors and actuators**
  - Sensor: an input transducer (i.e., a microphone)
  - Actuator: an output transducer (i.e., a loudspeaker)

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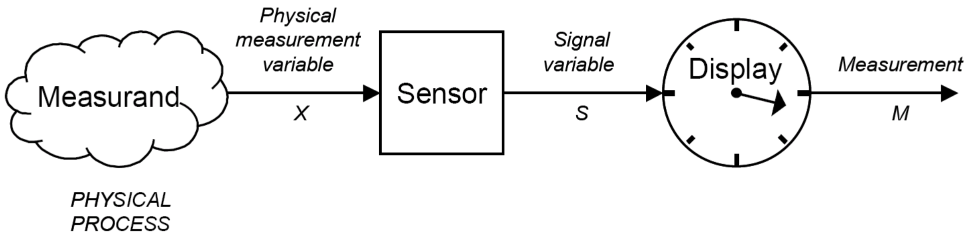
# Measurements

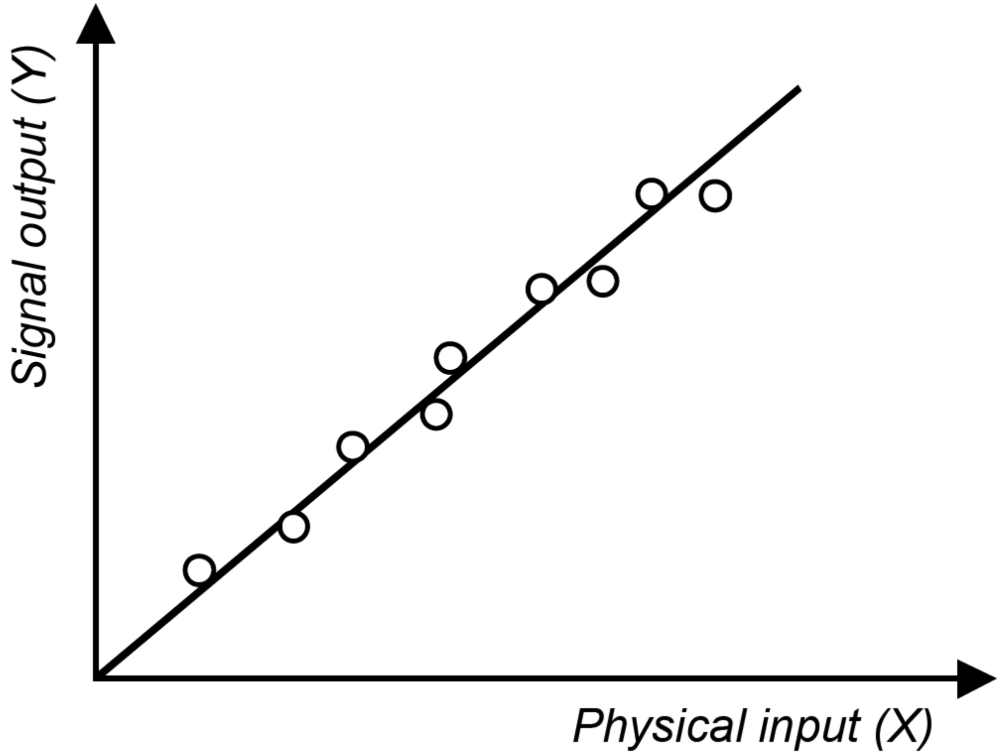
- **A simple instrument model**




  - A observable variable X is obtained from the measurand
    - X is related to the measurand in some KNOWN way (i.e., measuring mass)
  - The sensor generates a signal variable that can be manipulated:
    - Processed, transmitted or displayed
  - In the example above the signal is passed to a display, where a measurement can be taken
- **Measurement**
  - The process of comparing an unknown quantity with a standard of the same quantity (measuring length) or standards of two or more related quantities (measuring velocity)

# Calibration

- **The relationship between the physical measurement variable (X) and the signal variable (S)**
  - A sensor or instrument is calibrated by applying a number of KNOWN physical inputs and recording the response of the system

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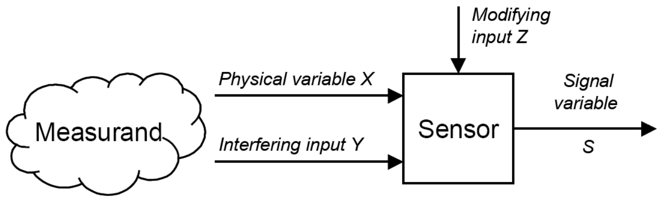
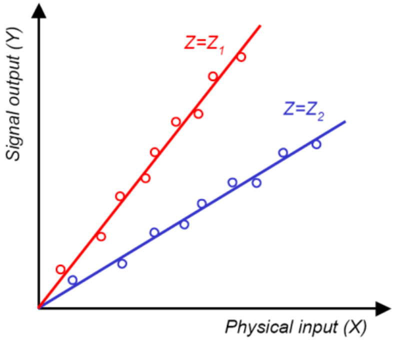
# Additional Inputs

- **Interfering inputs (Y)**
  - Those that the sensor to respond as the linear superposition with the measurand variable X
    - Linear superposition assumption: S(aX+bY)=aS(X)+bS(Y)




- **Modifying inputs (Z)**
  - Those that change the behavior of the sensor and, hence, the calibration curve
  - Temperature is a typical modifying input

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# Sensor characteristics

- **Static characteristics**
  - The properties of the system after all transient effects have settled to their final or steady state
    - Accuracy
    - Discrimination
    - Precision
    - Errors
    - Drift
    - Sensitivity
    - Linearity
    - Hysteresis
- **Dynamic characteristics**
  - The properties of the system transient response to an input
    - Zero order systems
    - First order systems
    - Second order systems

# Accuracy, discrimination and precision

- **Accuracy is the capacity of a measuring instrument to give RESULTS close to the TRUE VALUE of the measured quantity**
  - Accuracy is related to the bias of a set of measurements
  - (IN)Accuracy is measured by the absolute and relative errors

$$\text{ABSOLUTE ERROR} = \text{RESULT} - \text{TRUE VALUE}$$

$$\text{RELATIVE ERROR} = \frac{\text{ABSOLUTE ERROR}}{\text{TRUE VALUE}}$$

- **Discrimination is the minimal change of the input necessary to produce a detectable change at the output**
  - Discrimination is also known as RESOLUTION
  - When the increment is from zero, it is called THRESHOLD

# Precision

- The capacity of a measuring instrument to give the same reading when repetitively measuring the same quantity under the same prescribed conditions
  - Precision implies agreement between successive readings, NOT closeness to the true value
    - Precision is related to the variance of a set of measurements
  - Precision is a necessary but not sufficient condition for accuracy
- Two terms closely related to precision
  - Repeatability
    - The precision of a set of measurements taken over a short time interval
  - Reproducibility
    - The precision of a set of measurements BUT
      - Taken over a long time interval or
      - Performed by different operators or
      - with different instruments or
      - in different laboratories

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# Accuracy and errors

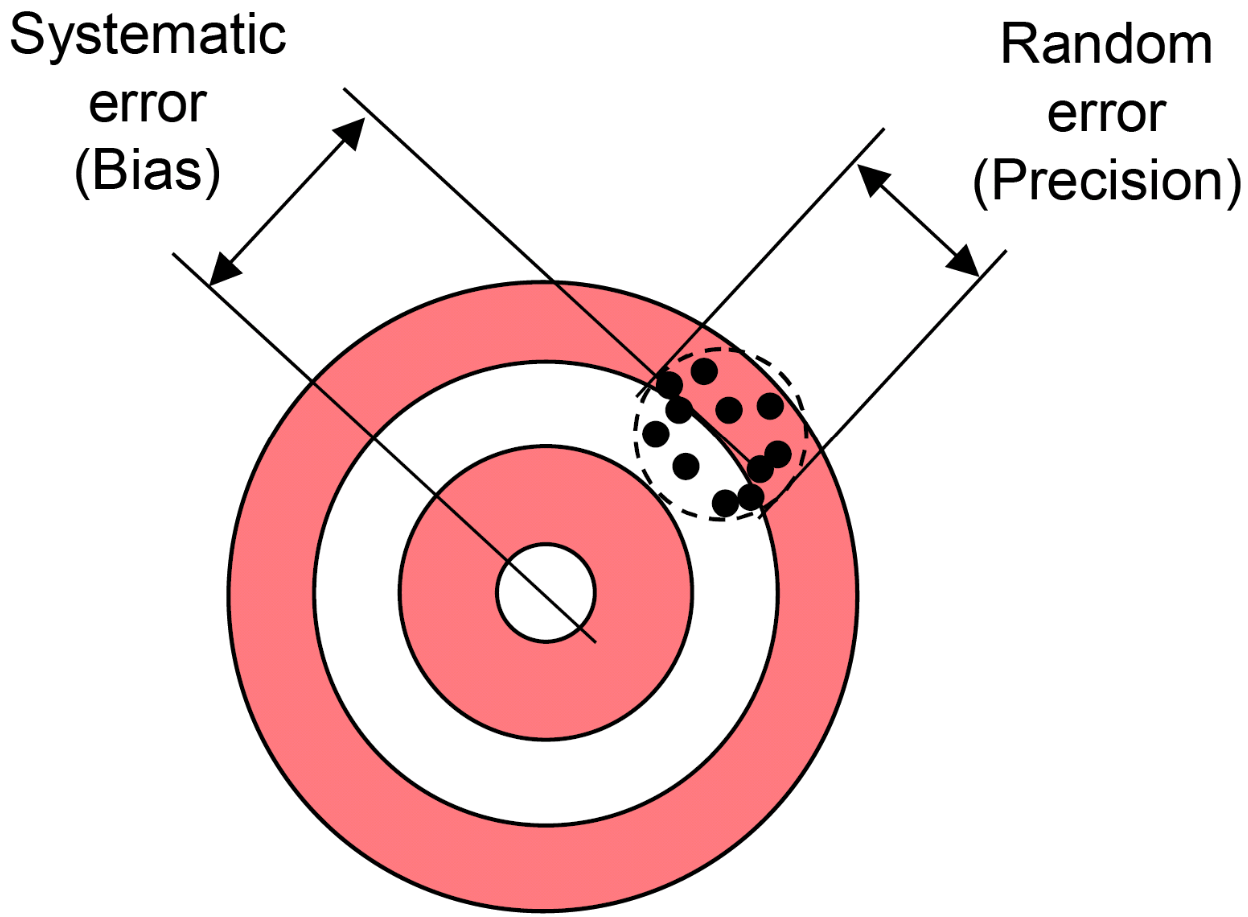
- **Systematic errors**
  - Result from a variety of factors
    - Interfering or modifying variables (i.e., temperature)
    - Drift (i.e., changes in chemical structure or mechanical stresses)
    - The measurement process changes the measurand (i.e., loading errors)
    - The transmission process changes the signal (i.e., attenuation)
    - Human observers (i.e., parallax errors)

Systematic errors can be corrected with COMPENSATION methods (i.e., feedback, filtering)

# Accuracy and errors (cont)

- **Random errors**
  - Also called NOISE: a signal that carries no information
  - True random errors (white noise) follow a Gaussian distribution
  - Sources of randomness:
    - Repeatability of the measurand itself (i.e., height of a rough surface)
    - Environmental noise (i.e., background noise picked by a microphone)
    - Transmission noise (i.e., 60Hz hum)
- **Signal to noise ratio (SNR) should be >>1**
    - With knowledge of the signal characteristics it may be possible to interpret a signal with a low SNR (i.e., understanding speech in a loud environment)

# Example: systematic and random errors

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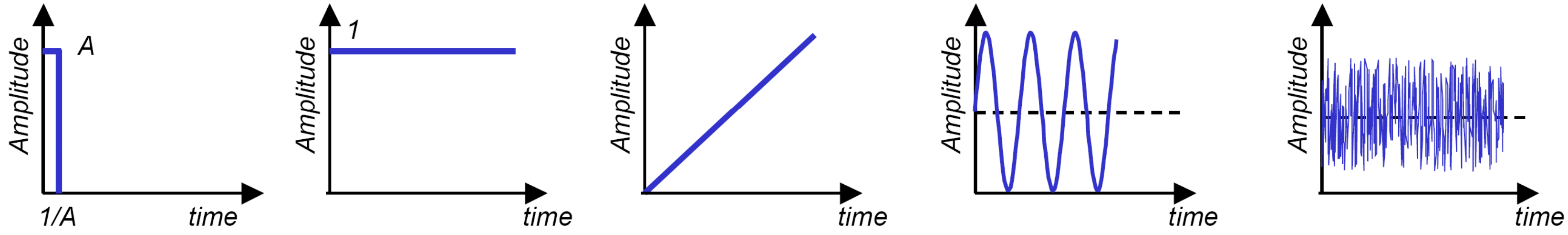
# Static Characteristics

- **Input range**
  - The maximum and minimum value of the physical variable that can be measured (i.e., -40F/100F in a thermometer)
  - Output range can be defined similarly
- **Sensitivity**
  - The slope of the calibration curve y=f(x)
    - An ideal sensor will have a large and constant sensitivity
  - Sensitivity-related errors: saturation and "dead-bands"
- **Linearity**
  - The closeness of the calibration curve to a specified straight line (i.e., theoretical behavior, least-squares fit)
- **Monotonicity**
  - A monotonic curve is one in which the dependent variable always increases or decreases as the independent variable increases
- **Hysteresis**
  - The difference between two output values that correspond to the same input depending on the trajectory followed by the sensor (i.e., magnetization in ferromagnetic materials)

# Dynamic Characteristics

- The sensor response to a variable input is different from that exhibited when the input signals are constant (the latter is described by the static characteristics)
- The reason for dynamic characteristics is the presence of energy-storing elements
  - Inertial: masses, inductances
  - Capacitances: electrical, thermal
- Dynamic characteristics are determined by analyzing the response of the sensor to a family of variable input waveforms:
  - Impulse, step, ramp, sinusoidal, white noise…

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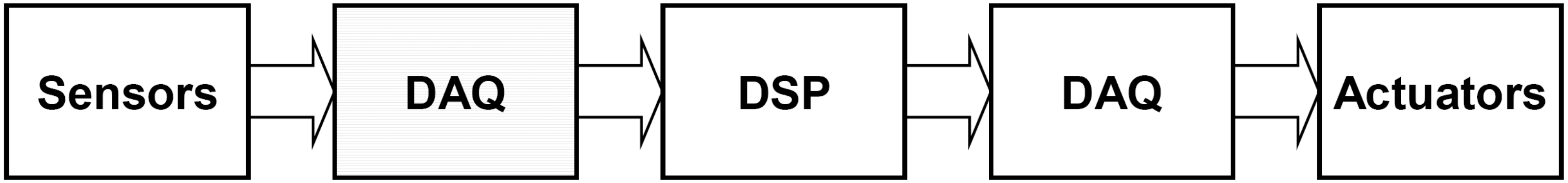
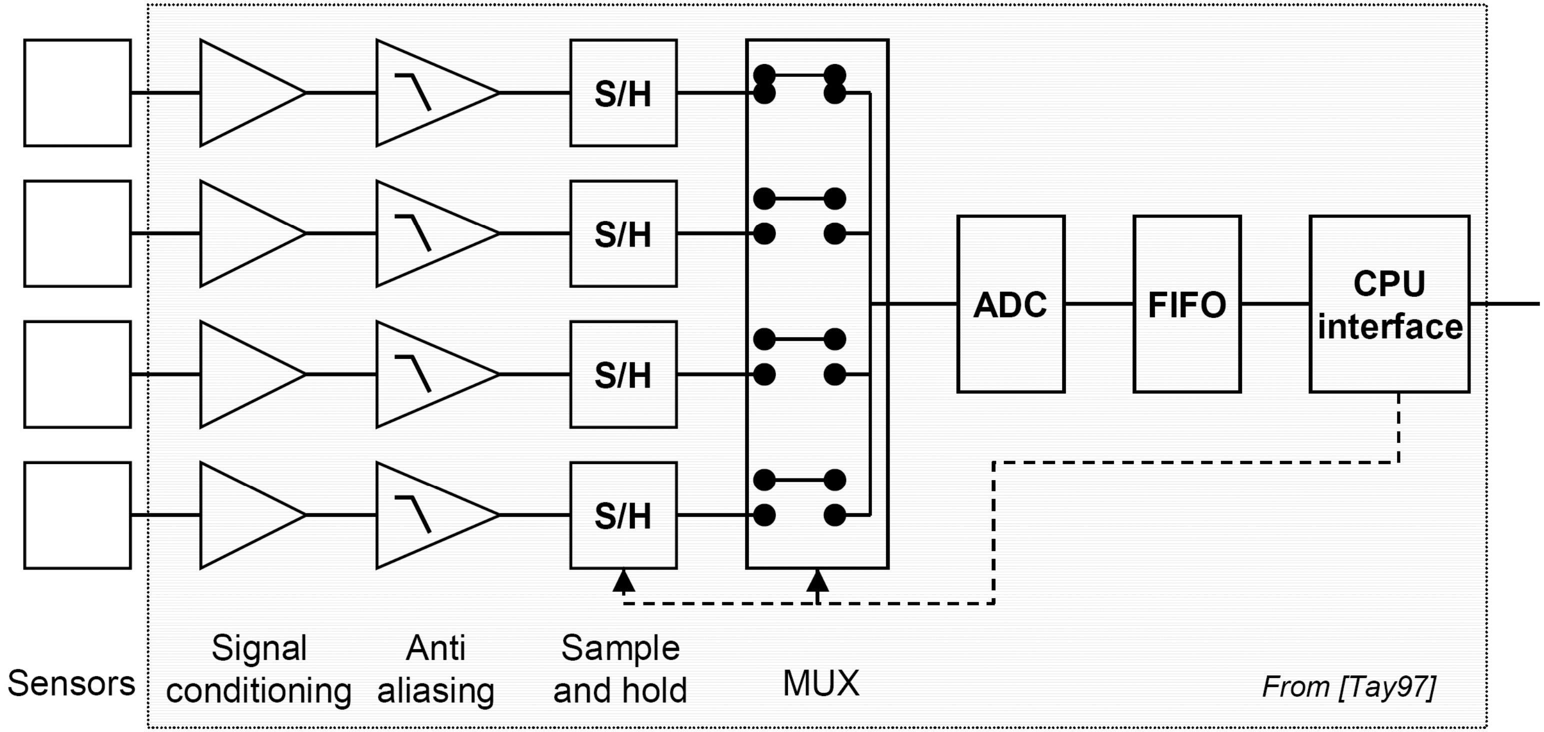
# Instrumentation

# Architecture of a data acquisition system

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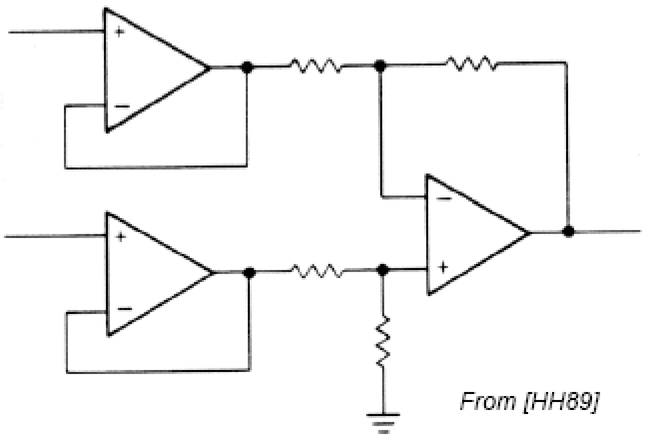
# Instrumentation Amplifier

- **The term INSTRUMENTATION AMPLIFIER is used to denote a difference amplifier with**
  - High gain
  - Single-ended output
  - High input impedance
  - High CMRR
- **High input impedance may be achieved by buffering the differential inputs.**
- **This solution, however, requires high CMRR both in the followers and in the final op-amp**
  - Otherwise, since the input buffers have unity gain, all the CM rejection must come in the output op-amp, requiring precise resistor matching



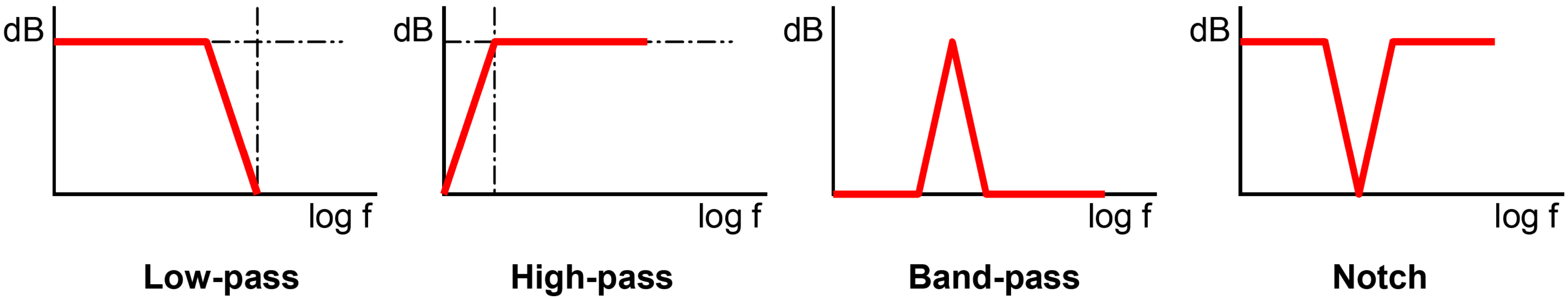
*From [HH89]*

# Filters

- Filters are used to remove *unwanted bandwidths from a signal*
- Filter classification according to implementation
  - Active filters include RC networks and op-amps
    - Suitable for low frequency, small signal
    - Active filters are preferred since avoid the bulk and non-linearity of inductors and can have gains greater than 0dB
    - However, active filters require a power supply
  - Passive filters consist of RLC networks
    - Simple, more suitable for frequencies above audio range, where active filters are limited by the op-map bandwidth

# Filters

- Filter classification according to frequency response
  - Low-pass filter
  - High-pass filter
  - Band-pass filter
  - Band-stop (Notch)

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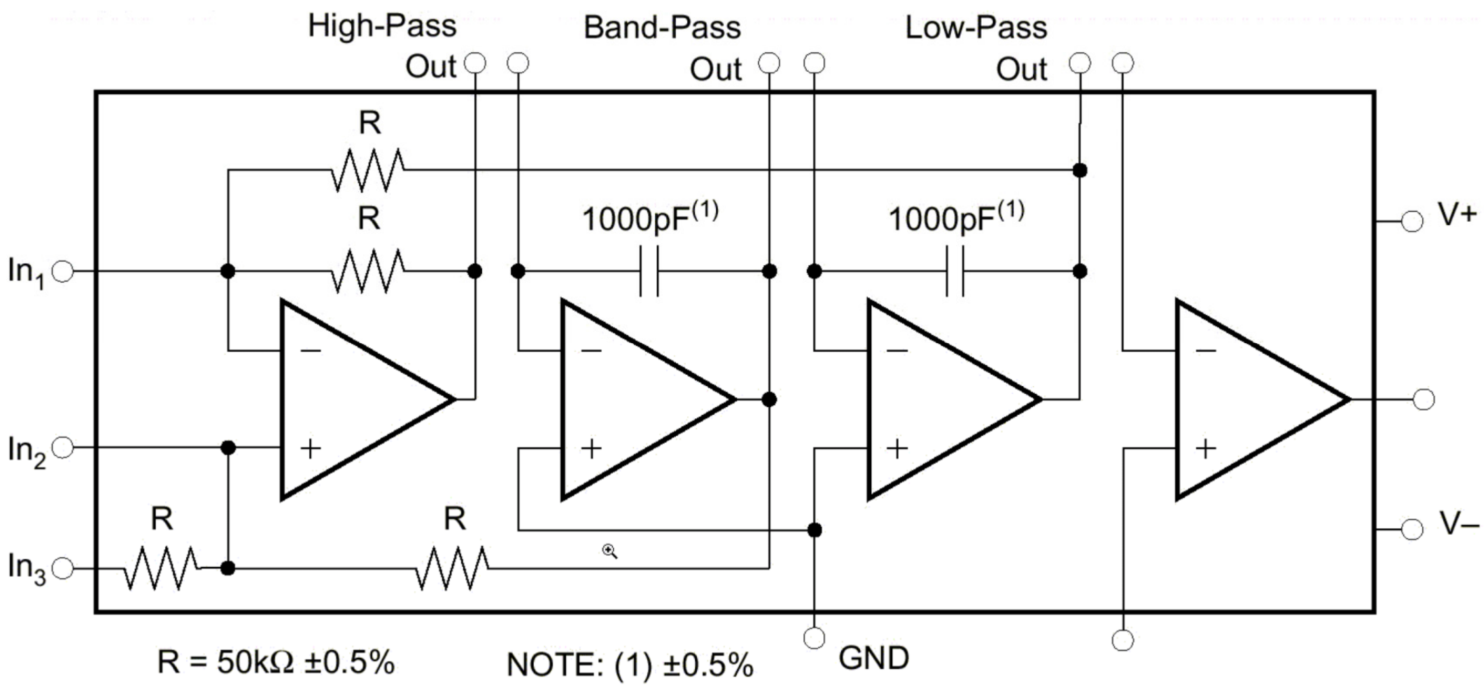
# Active Filters

- Consists of one amplifier and two integrators
- High-pass, low-pass and band-pass in the same IC
- Example below: Burr Brown UAF42

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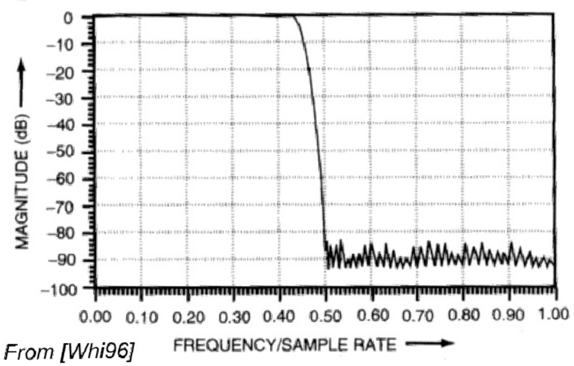
# Anti-aliasing Filters

- **An anti-aliasing filter is a low-pass filter designed to filter out frequencies higher than the sampling frequency**
  - An anti-aliasing filter should have
    - Steep cut-off and
    - Flat response in the frequency band




*From [Whi96]*

- **Typical filters are:**
  - Butterworth: flattest response in the frequency band but phase shifts well below the break frequency
  - Bessel: phase shift proportional to frequency, so the signal is not distorted by the filter
    - Recommended for anti-aliasing if it is important to preserve the waveform
  - Chebyshev: steepest cut-off but it has ripples in the band-pass

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# Intelligent Sensors

# Intelligent Sensor Systems (ISS)

- **Compensation**
  - Self-diagnostics, self-calibration, adaptation
- **Computation**
  - Signal conditioning, data reduction, detection of trigger events
- **Communications**
  - Network protocol standardization
- **Integration**
  - Coupling of sensing and computation at the chip level
  - Micro electro-mechanical systems (MEMS)
- **Others**
  - Multi-modal, multi-dimensional, multi-layer
  - Active, autonomous sensing

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# Compensation

- **Self-diagnostics versus self-calibration**
  - An intelligent sensor should be able to answer the following
    - Is the output a reasonable value?
    - Does it agree with the result of an adjacent sensor?
    - Is the rate of change of the output reasonable?
    - Is the output actually changing?
- **Compensation**
  - Offset compensation
    - To fully utilize the dynamic range of ADCs
  - Gain
    - By means of programmable gain amplifiers
  - Linearity
    - By means of look-up tables
  - Cross-sensitivity
    - Temperature control and/or compensation

# Computation

- Various degrees of computation
  - Signal conditioning (e.g., filtering)
  - Signal conversion (e.g., analog to digital)
  - Logic functions (e.g., triggering events)
  - Data reduction (e.g., feature extraction)
  - Decision making (e.g., classification)
- Advanced sensing systems have a hierarchical structure with different abstraction layers
  - LOWER LAYER performs Signal processing
    - Conditioning, filtering, conversion, contrast enhancement
  - MIDDLE LAYER performs Information processing
    - Feature generation, sensor signal fusion and parameter tuning
  - UPPER LAYER performs Knowledge processing
    - Clustering, prediction, classification, decision making, communications

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# Processing Techniques

- Classical
  - Statistical signal processing
  - Statistical pattern analysis
- Connectionist
  - Multilayer feed-forward neural networks
  - Unsupervised learning
- Fuzzy logic
  - Fuzzy control
  - Fuzzy signal processing
- Evolutionary
  - Genetic algorithms
  - Genetic programming
- Hybrid approaches
  - Neuro-fuzzy
  - Neuro-genetic

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# Communications

- Traditionally, each sensor system is custom-designed for specific applications by experience designers
- This approach has several limitations
  - Complexity: a limited number of sensors may be installed in each system, imposed by the level of complexity that human designers can deal with
  - Cost: system is composed of a small number of highly specialized, relatively expensive sensors
  - Flexibility: the resulting system cannot be easily expanded, modified, maintained or repaired. Highly trained personnel is required for these functions
- Solution
  - Standardization of transducer interfaces
    - Electrical, mechanical(?), communications protocol
  - Addition of communication capabilities
    - The ideal: Plug-and-play sensors
    - Autonomous, distributed, re-configurable sensors

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# Integration

- **DATA ACQUISITION**
  - Instrumentation amplifiers
  - Filters
  - Sample and Hold
  - Analog to Digital Converters
  - Voltage to Frequency Converters
  - Multiplexers
  - Oscillators
  - Voltage references
  - Sensor-specific devices
  - Complete DAQ sub-systems
- **COMMUNICATIONS**
  - Line drivers
  - Line receivers
  - Bus transceivers
  - Bus controllers
- **COMPUTING**
  - Embedded
    - Micro-controllers
    - Digital Signal Processors
    - 4,8,16,32-bits
  - Monitoring devices
  - Volatile memories
    - Static RAM
    - Dynamic RAM
  - Non-volatile memories
    - ROM
    - EEPROM
    - Flash
    - Disk-on-a-chip
- **CONTROL**
  - Digital to Analog Converters
  - Frequency to Voltage Converters
  - Switches
  - Power drivers

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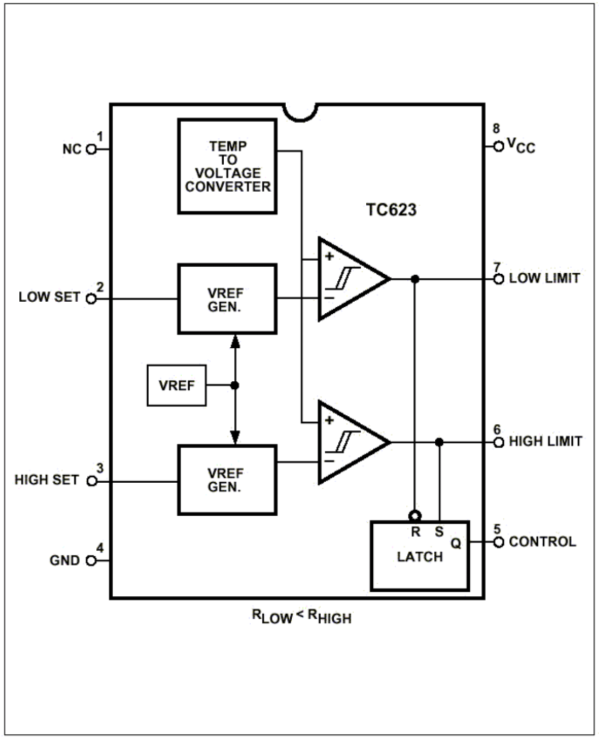
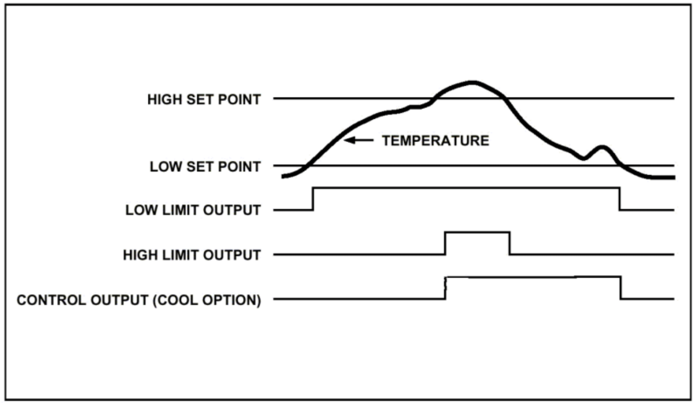
# Integration

- Microchip® dual-trip temperature sensor (TC623)
  - Integrated temperature sensor and logic threshold
  - 8-pin DIP or SOIC for direct PCB mounting
  - 2 user-programmable temperature set-points (w/ external resistor)
  - 2 independent temperature limit outputs
- Application
  - Low temp reduces CPU CLK
  - High temp further reduces CPU CLK
  - Control output starts fan

FUNCTIONAL BLOCK DIAGRAM

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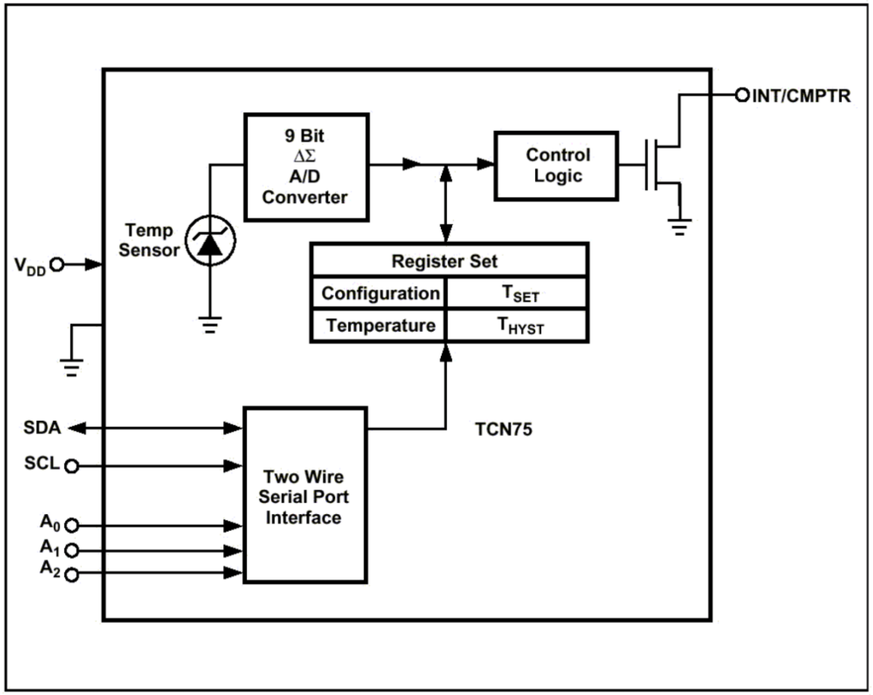
# Integration

- Microchip® 2-wire serial temperature sensor
  - Standard 2-wire serial interface
    - Programmable trip point and hysteresis
    - Digital readout
    - Device configuration
  - Multiple operation modes
    - Comparator
    - Interrupt
    - Standby (power management)
- Address lines
  - Up to 8 devices can share the 2-wire bus lines

FUNCTIONAL BLOCK DIAGRAM

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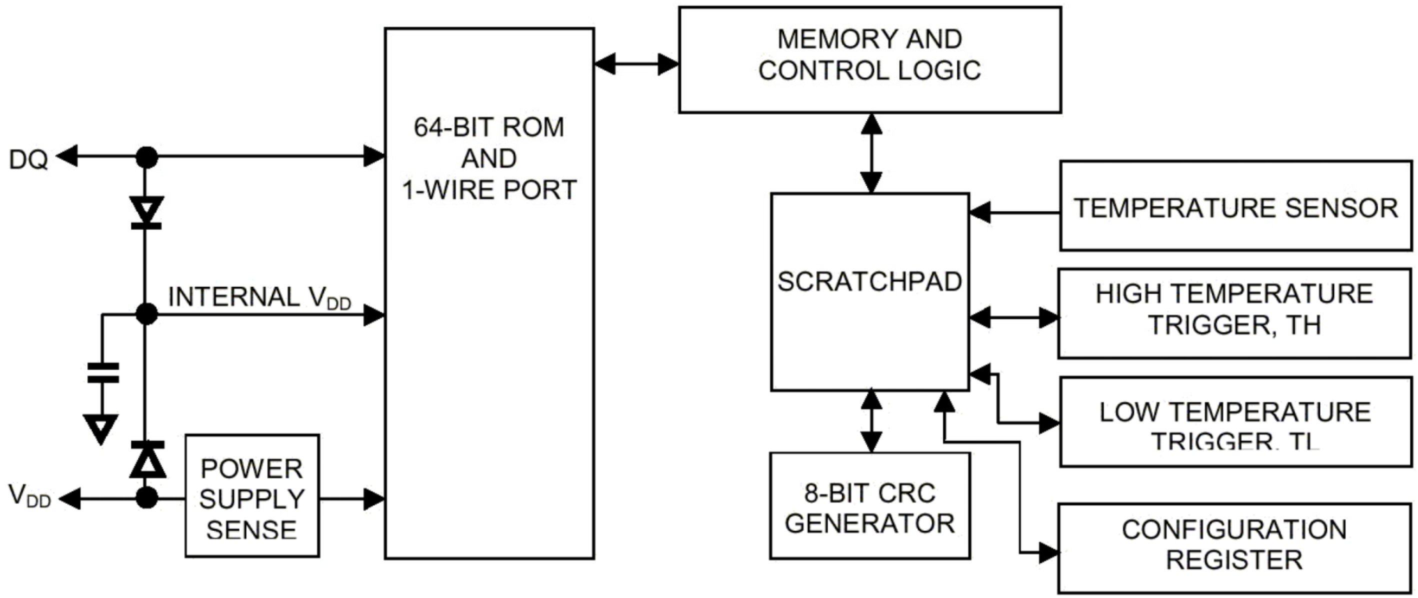
# Integration

- **Dallas Semiconductor 1-Wire® digital thermometer (DS18B20)**
  - One wire interface requires only one communication pin
  - Can be powered from a data line
  - Programmable thermometer resolution from 9 to 12 bits
  - 2 and 3 wire versions are also available

**DS18B20 BLOCK DIAGRAM** Figure 1

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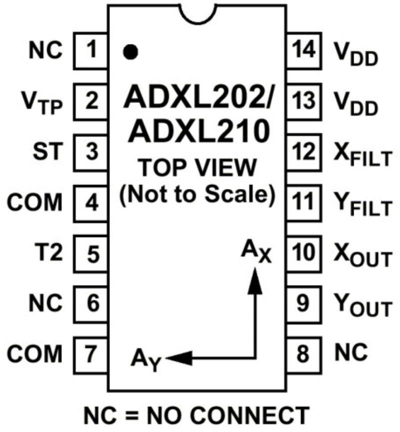
# Integration

- Analog Devices 2-axis accelerometer (ADXL202)
  - Can measure both dynamic acceleration (e.g., vibration) and static acceleration (e.g., gravity)
  - The outputs are Duty Cycle Modulated (DCM) signals
    - Duty cycles (ratio of pulse width to period) proportional to the acceleration in each of the 2 sensitive axe
    - These outputs may be measured directly with a microprocessor counter, requiring no A/D converter or glue logic.
  - If an analog output is desired, an analog output proportional to acceleration is available from the XFILT and YFILT pins
    - or may be reconstructed by filtering the duty cycle outputs
  - Bandwidth may be set from 0.01 Hz to 6 kHz via capacitors CX and CY

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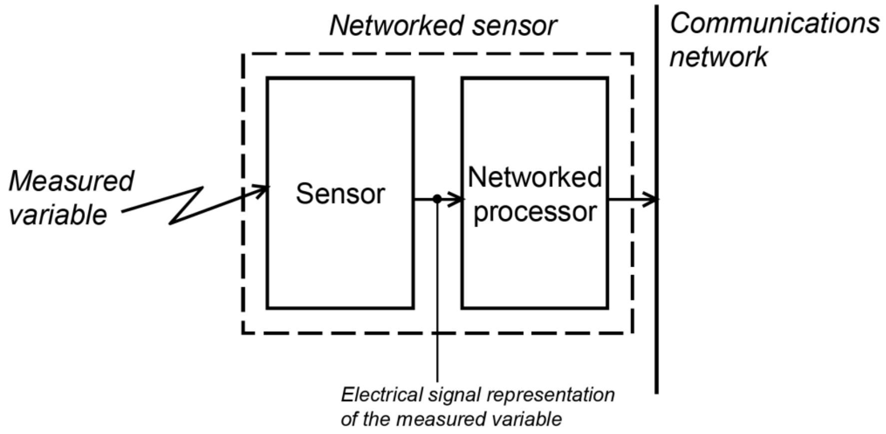
# ISS Communication

# Networked Sensors

- **When?**
  - Used in applications where a number of sensors are needed or where the sensor devices are distributed geographically
- **Why?**
  - Simplification of the wiring required for signal transmission
    - Assuming N nodes, full connectivity would require 2N-1-1 wires
  - Digital nature of networked signals
    - Digital transmission is relatively immune to the effects of distortion and signal degradation associated with carrying an analog signal over long distances
    - This implies that networked sensors have ADC capabilities

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# Networked Sensors (cont)

- **Why? (Cont)**
  - Ability to communicate a much wider range of information in both directions
    - Networked sensors typically contain a local microprocessor that handles sensor signals and their transmission
  - No need to limit the microprocessor to transmission functions only
    - µP may be able to perform calibration or signal corrections
    - Sensors can be designed to have multiple sensing functions. Each signal can be handled and transmitted separately by the µP without extra connections
    - Sensors may be designed to store ID information (manufacturer, calibration parameters…)
    - Sensors may be designed to have intelligent functions, such as self-diagnostics or triggering of events
- **Potential problems**
  - More complex circuitry is required than for non-networked sensors
  - Quantization errors as a result of ADC
  - Network bandwidth, which may cause queuing delays or even lost data

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# Network Technologies

- A number of protocols exist, each one having its own interface requirements:
  - Header formats, data word length and type, bit rate, cyclic redundancy check, etc

| Automotive | Sponsor |
|---|---|
| J-1850 | SAE |
| J-1939 (CAN) | SAE |
| J1567 $C^2D$ | SAE (Chrysler) |
| J2058 CSC SAE | Chrysler |
| J2106 Token Slot | SAE (General Motors) |
| CAN | Robert Bosch GmbH |
| VAN | ISO |
| A-Bus | Volkswagen AG |
| $D^2B$ | Philips |
| MI-Bus | Motorola |
| **Industrial** | **Sponsor** |
| Hart | Rosemount |
| DeviceNet | Allen-Bradley |
| Smart Distributed Systems | Honeywell |
| SP50 Fieldbus | ISP+World FIP=Fieldbus Foundation |
| SP50 | IEC/ISA |
| LonTalk/LonWorks | Echelon Corp |
| Profibus | DIN (Germany) |
| ASI Bus | ASI Association |
| InterBus-S | InterBus-S Club |
| Seriplex | Automated Process Control (API Inc) |
| SERCOS | VDW (German tool manuf. assoc) |
| IPCA | Pitney Bowes Inc |

| Building/office automation | Sponsor |
|---|---|
| BACnet | Building Automation Industry |
| LonTalk/LonWorks | Echelon Corp |
| IBIbus | Intelligent Building Institute |
| Batibus | Merlin Gerin (France) |
| EIbus | Germany |
| **Home automation** | **Sponsor** |
| Smart House | Smart House LP |
| CEBus | EIA |
| LonTalk/LonWorks | Echelon Corp |
| **University protocol** | **Sponsor** |
| Michigan Parallel Standard | University of Michigan |
| Integrated Smart-Sensor Bus | Delft University of Technology |
| Time-Triggered Protocol | University of Wien, Austria |

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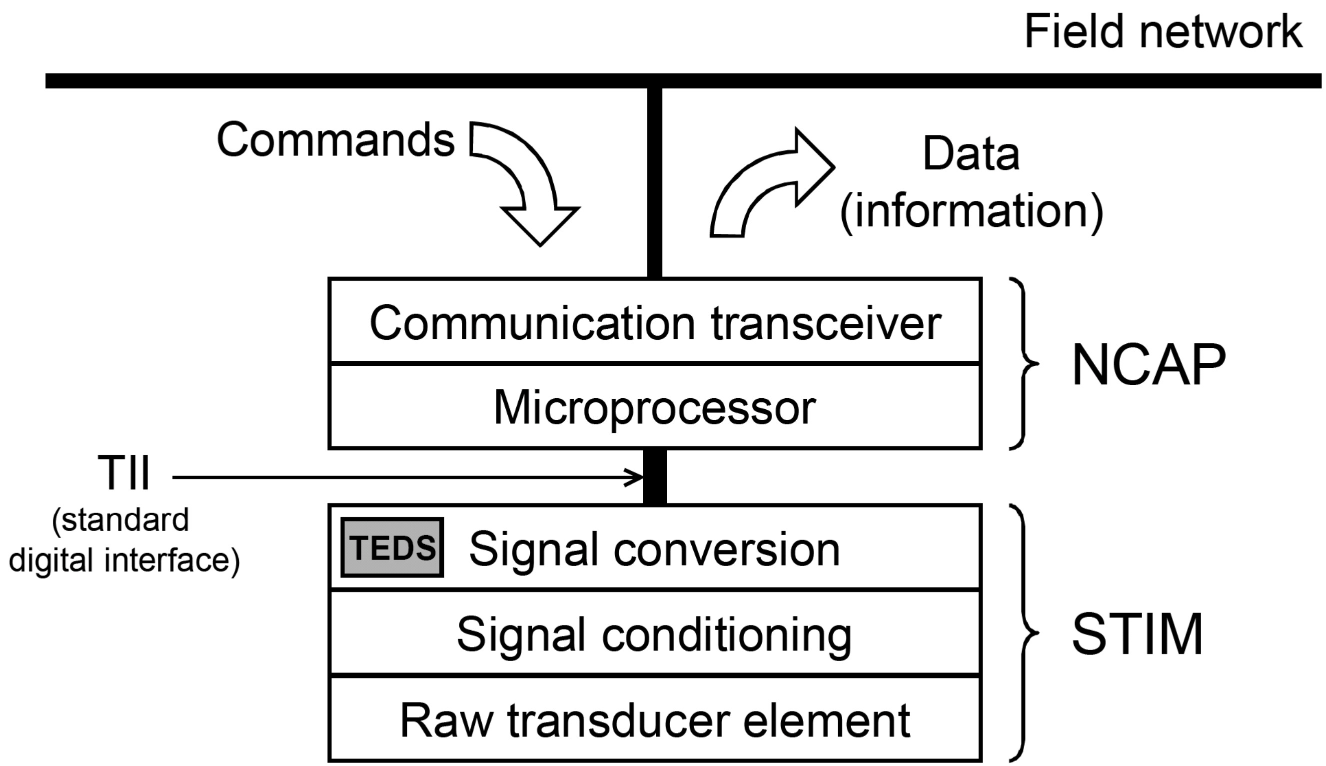
# Network Technologies (cont)

- The lack of a universal interface standard impedes the incorporation of "intelligent" features into the sensors such as
  - On-board electronic data sheets, on-board ADC, signal conditioning, device-type identification and communications handshaking circuitry
- In 1994, the IEEE and NIST decided against adopting any of the existing network protocols as a single standard (IEEE 1451)
  - A new hardware-independent standard is being developed to lower the networking entry barrier for S&A small companies
- The standard encompasses the formation of two separate software models
  - IEEE 1451.1: developing a network-independent common object model for smart transducers
  - IEEE 1451.2: enabling connection of transducers to network processors

# The P1451.2 standard

- **The basic building blocks**
  - NCAP: Network Capable Application Processor
  - STIM: Smart Transducer Interface Module
  - TII: Standard digital interface
  - TEDS: Transducer Electronic Data Sheet

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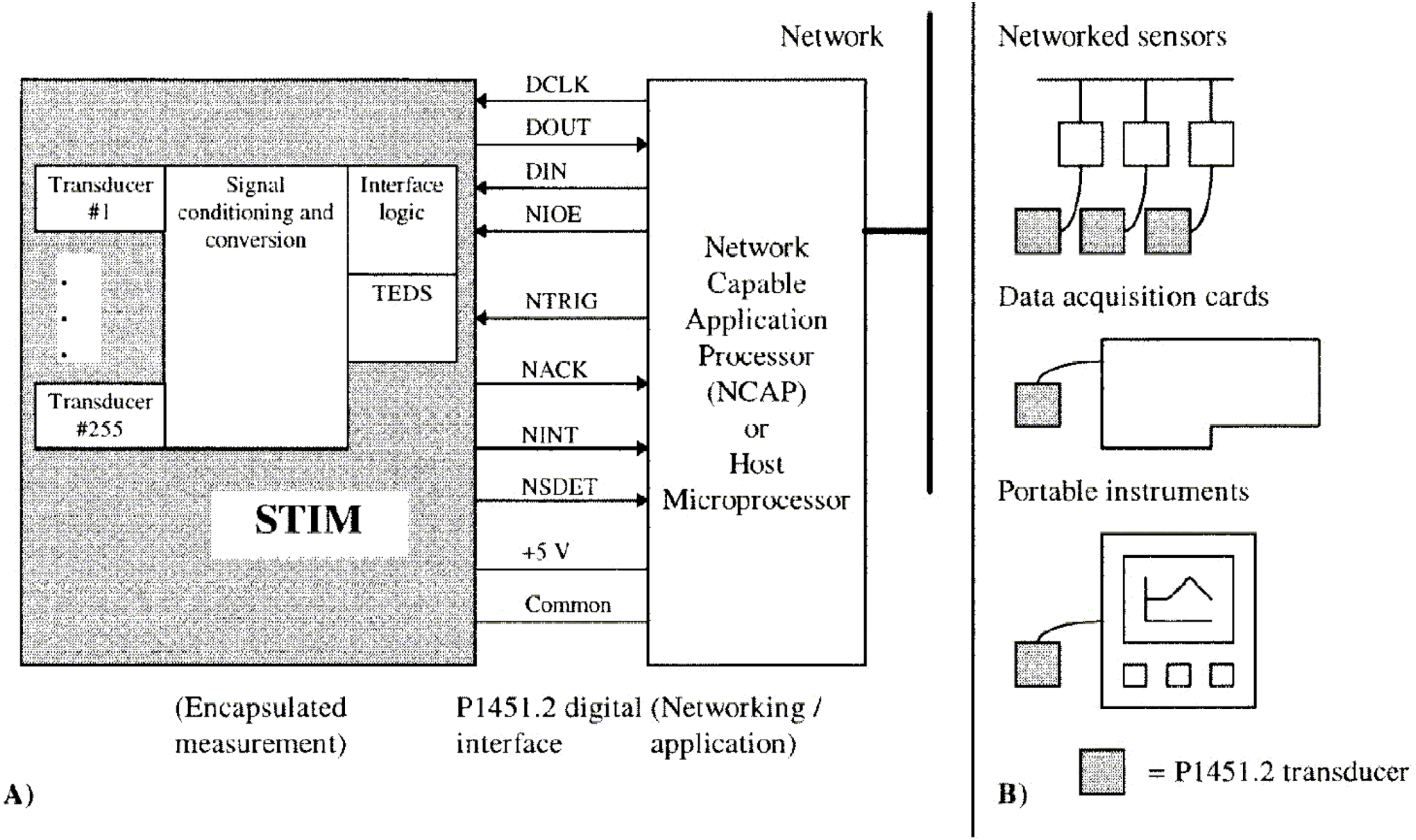
# The P1451.2 standard

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# Features of STIM

- **Single general purpose TEDS**
  - A unique data structure that can support a wide variety of transducers
- **Representation of physical units**
  - A binary sequence encodes physical units as a product of the seven SI basic units and the 2 SI supplementary units, raised to a rational power
- **General calibration model**
  - Transducer calibration may be specified (linear, multi-variable, piecewise polynomial with variable segment widths and offsets)
- **Triggering of sensors and actuators**
  - HW trigger lines allow the NCAP to initiate sensor measurements and actuator actions, and the STIM to report completion of the requested operations
- **Variable transfer rate between host and STIM**
  - A field in the TEDS specifies the maximum data transport rate that the STIM can support
    - This provides flexibility for matching STIMs and NCAPs
    - Alternatively, the STIM may use a hardware line (NACK) to pace the transfer of bytes

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# Features of TEDS

- TEDS contains fields that fully describe the type, operation and attributes of a transducer
- TEDS is attached to and moves with the transducer
  - This way, the information necessary for using the transducer is always present
- TEDS contents
  - Mandatory
    - Meta TEDS
    - Channel TEDS
- Optional
  - Calibration TEDS
  - Application specific TEDS
  - Extension TEDS

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# Features of TEDS

- **Meta TEDS (required, one per STIM)**
  - Contains the overall description of the TEDS data structure, worst case STIM timing parameter and channel grouping information
- **Channel TEDS (required, one per STIM channel)**
  - Contains upper/lower range limits, physical units, warm up time, presence of self-test, uncertainty, data model, calibration model, and triggering parameters
- **Calibration TEDS (optional, one per STIM channel)**
  - Contains the last calibration date, calibration interval and all the calibration parameters supporting the multi-segment model
- **Application specific TEDS (optional, multiple per STIM)**
  - For application specific use
- **Extension TEDS (optional, multiple per STIM)**
  - Used to implement future and industry extensions to P1451.2

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