CLASS NOTES ON PROCESS INSTRUMENTATIO N

BY

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1.1 Elements of Process Parameter Measurement Systems

A measurement system is a chain of components that transforms a physical quantity (like heat or pressure) into a readable or usable signal.

The Functional Stages:

1. **Primary Sensing Element:** The part that first interacts with the process (e.g., a diaphragm for pressure).
2. **Variable Conversion Element:** Converts the physical signal into a more convenient form (e.g., a Bourdon tube converting pressure to mechanical displacement).
3. **Variable Manipulation Element:** Adjusts the signal level (amplification) without changing its nature.
4. **Data Transmission Element:** Sends the signal from the field to a control room (4-20mA, HART, or wireless).
5. **Data Presentation Element:** Displays the value for the operator (Digital screen, gauge, or HMI).

1.2 Characteristics and Classifications

Instruments are categorized based on how they behave and how they are built.

A. Performance Characteristics:

- **Static:** Accuracy, Precision, Sensitivity, Dead zone, Hysteresis, and Linearity.
- **Dynamic:** Response time, Speed of response, and Fidelity.

B. Classifications:

- **Active vs. Passive:** Active instruments require an external power source (like a radar level transmitter); passive ones do not (like a glass thermometer).
- **Analog vs. Digital:** Analog provides a continuous signal; digital provides discrete pulses.
- **Null vs. Deflection:** Null methods (like a balance scale) maintain equilibrium; deflection methods (like a spring scale) move a pointer.

1.3 Application of Various Process Instruments

Modern plants use a variety of "tools" to maintain safety and efficiency:

Instrument	Function	Example Application
Sensors	Detects physical change.	Thermocouple detecting heat.
Transducers	Converts energy from one form to another.	Piezoelectric crystal (Pressure → Voltage).
Converters	Changes a signal type.	I/P Converter (Current signal → Pneumatic signal).
Indicators	Provides a local visual reading.	Pressure gauge on a steam pipe.
Recorders	Keeps a historical log of data.	Chart recorders or digital data loggers.
Process Switches	Triggers an ON/OFF action at a setpoint.	A high-level float switch in a tank.
Alarms	Warns operators of abnormal conditions.	A siren or flashing light for "High Pressure."

1.4 Instrumentation Diagrams

Standardized diagrams allow engineers to communicate the design of a plant accurately.

1. Process and Instrument Diagram (P&ID):

The "blueprint" of the process. It shows the piping, vessels, and all instruments using standardized symbols (circles for instruments, lines for signals).

2. Loop Diagrams:

Focuses on a single control loop (e.g., Loop 101). It shows every terminal connection, wire color, and junction box from the field sensor to the PLC/DCS.

3. Functional Diagrams:

Focuses on the logic of the control system rather than the hardware. It uses blocks to show how signals are processed (e.g., Lead-Lag, Summing, or PID blocks).

2.1 Mathematical Modeling of Processes

To control a process, we must first describe it using equations. This is called **Mathematical Modeling**.

- **Definition:** A set of equations (usually differential equations) that represent the dynamics of a system.
- Transfer Function ($G(s)$): The most common way to represent a process. It is the ratio of the Laplace transform of the output to the Laplace transform of the input, assuming zero initial conditions.

  $$G(s) = \frac{Y(s)}{X(s)}$$

- **Purpose:** Models allow us to simulate how a process will react to changes without risking damage to actual equipment.

2.2 First-Order and Second-Order Systems

Processes are classified by the "order" of the differential equation that describes them.

A. First-Order Systems:

Characterized by a single "energy storage" element (like a single tank of water).

- **Standard Form:** $G(s) = \frac{K}{\tau s + 1}$
- **Parameters:** K (Process Gain) and τ (Time Constant).
- **Response:** When hit with a step change, the output rises exponentially. It reaches **63.2%** of its final value in one time constant (τ).

B. Second-Order Systems:

Characterized by two energy storage elements (like two tanks in series) or an "inertial" component.

- **Standard Form:** $G(s) = \frac{K \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$
- **Parameters:** ζ (Damping Ratio) and ω_n (Natural Frequency).
- **Response types:** Depending on ζ, the system can be **Underdamped** (oscillates), **Overdamped** (slow, no oscillation), or **Critically Damped** (fastest response without oscillation).

2.3 Process Load and Lag

Process Load: The total amount of material or energy that the process must handle (e.g., the volume of fluid a heater must warm up).

Process Lag: The delay in the response of a process.

1. **Dead Time (Transportation Lag):** A "pure" delay where nothing happens for a period. It's the time taken for a change at the inlet to travel to the sensor at the outlet ($e^{-td s}$).
2. **Transfer Time Lag:** The time required for energy to move through resistances (like heat moving through a pipe wall). This causes the "S-shaped" curve in responses.

2.4 Self-Regulation Property

A **Self-Regulating** process is one that naturally finds a new equilibrium after a disturbance without any controller intervention.

- **Example:** If you open the inflow valve of a tank with a hole at the bottom, the level will rise until the pressure at the bottom makes the "outflow" equal the "inflow." It "regulates" its own level.
- **Non-Self-Regulating (Integrating):** A tank with no hole at the bottom. If inflow > outflow, the level will just keep rising until it overflows.

2.5 Batch vs. Continuous Processes

Feature	Batch Process	Continuous Process
Operation	Starts and stops; distinct "lots."	Runs 24/7 without stopping.
Quantity	Small, high-value (Medicine, specialty beer).	Large, commodity (Gasoline, Steel).
Flexibility	High (easy to change recipes).	Low (designed for one product).
Efficiency	Lower (downtime for cleaning).	High (economies of scale).

2.6 Various Process Control Techniques

To keep a process at its "Setpoint," we use different strategies:

1. **Feedback Control:** Reactive. It waits for an error to occur, then fixes it. (Simple, but always "behind").
2. **Feedforward Control:** Proactive. It measures a disturbance *before* it hits the process and adjusts the valve to cancel it out.
3. **Cascade Control:** One controller's output becomes the Setpoint for a second controller. Great for handling "noisy" fast variables like flow.
4. **Ratio Control:** Maintains a fixed proportion between two flows (e.g., mixing acid and water).

3.1 Relevance of Signal Conditioning in Process Instrumentation

In process instrumentation, the raw output from a sensor is rarely suitable for direct processing by a controller or display unit. **Signal conditioning** is the process of manipulating an analog signal in such a way that it meets the requirements of the next stage of the system.

Why it is essential:

- **Signal Strength:** Most sensors (like thermocouples) produce very weak signals (millivolts) that are susceptible to noise.
- **Compatibility:** A sensor might output a change in resistance, but a PLC (Programmable Logic Controller) requires a 4-20mA current loop.
- **Accuracy:** Sensors are often non-linear; conditioning helps "straighten" the data.
- **Safety:** It provides isolation between high-voltage industrial environments and sensitive electronic equipment.

3.2 Principles of Analog Signal Conditioning

Key Functions:

- **Signal Level & Bias Changing:** Adjusting the amplitude of the signal (amplification/attenuation) or adding/subtracting a DC offset to shift the signal range.
- **Linearization:** Since many sensors have a non-linear output (e.g., Thermistors), conditioning circuits are used to make the output proportional to the measured variable.
- **Conversions:** Changing the signal type, such as converting a resistance change to a voltage change.
- **Filtering:** Removing unwanted noise or frequency components. Low-pass filters are most common in process control to remove high-frequency electrical interference.
- **Impedance Matching:** Ensuring the source impedance and load impedance are compatible to prevent signal loss.

Concept of Loading

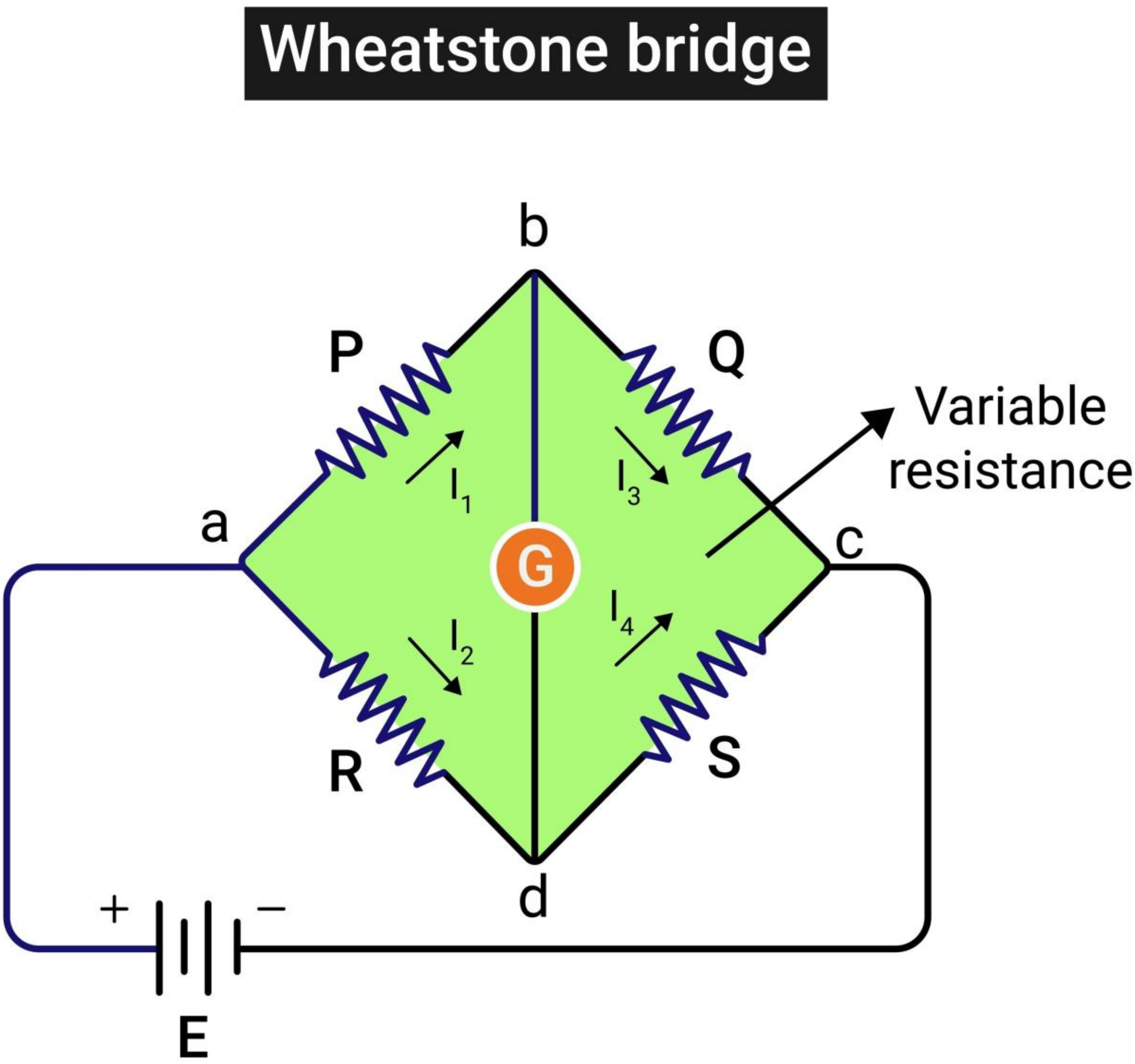
Loading occurs when a measurement device draws power from the signal source, causing the measured voltage to drop. To minimize loading, a signal conditioner should ideally have **high**

input impedance (to draw minimal current) and **low output impedance** (to drive the next stage effectively).

3.3 Passive Signal Conditioners

Passive circuits do not require an external power source to operate and use components like resistors, capacitors, and inductors.

- **Voltage Divider:** Used to scale down a voltage or convert a change in resistance (from a sensor) into a change in voltage.
- **Wheatstone Bridge:** The industry standard for measuring small changes in resistance (used with Strain Gauges and RTDs). It consists of four resistive arms. When the bridge is balanced, the output voltage is zero.



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- **RC Filter:** A simple network of Resistors and Capacitors used to block noise. A **Low Pass RC Filter** allows low-frequency signals (the actual process data) to pass while blocking high-frequency noise.

3.4 Active Signal Conditioners (Op-Amp Based)

Active conditioners use Operational Amplifiers (Op-Amps) to provide gain and isolation.

Converter Type	Full Name	Purpose
I/V	Current-to-Voltage	Converts 4-20mA signals to 0-5V for microcontroller ADC inputs.
V/I	Voltage-to-Current	Converts a voltage signal into a 4-20mA current loop for long-distance transmission.
P/I	Pressure-to-Current	Converts pneumatic pressure (e.g., 3-15 psi) into an electrical current.
I/P	Current-to-Pressure	Converts electrical control signals to pneumatic signals to move a valve.
F/V & V/F	Freq-to-Volt / Volt-to-Freq	Used in digital telemetry or measuring RPM; converts pulses to voltage levels and vice versa.

3.5 Instrumentation & Charge Amplifiers

Instrumentation Amplifier (IA)

An IA is a high-gain differential amplifier with high input impedance and high **Common Mode Rejection Ratio (CMRR)**.

- **Importance:** It is used to extract very small signals (like those from a Wheatstone bridge) in the presence of large common-mode noise. It uses three Op-Amps to ensure that the gain can be adjusted using a single resistor (R_g) without affecting the input impedance.

Charge Amplifier

Sensors like **Piezoelectric crystals** (used in vibration or pressure sensing) produce a charge (Q) rather than a voltage.

- **Importance:** A standard voltage amplifier cannot measure charge because the cable capacitance would affect the reading. A charge amplifier converts the high-impedance charge output into a low-impedance voltage output ($V_{out} = -Q / C_f$), making the measurement independent of cable length and capacitance.

4.1 Necessity of Data Processing in Instrumentation

In industrial instrumentation, "raw" data from sensors is often messy, weak, or non-linear. Data processing is necessary because:

- **Error Correction:** It removes noise and corrects systematic errors (like zero offset).
- **Decision Making:** Raw electrical signals (like 4mA) are meaningless to operators until processed into physical units (like 100°C).
- **Optimization:** It allows for mathematical manipulations (averaging, integration, or differentiation) to determine rates of change or totalized flow.
- **Storage Efficiency:** Processing helps compress data so that only relevant changes are recorded, saving memory.

4.2 Generalized Data Acquisition System (DAS)

A **Data Acquisition System** is a collection of hardware and software used to measure physical phenomena and convert them into a format that a computer can understand.

Block Diagram

Key Components:

1. **Transducer/Sensor:** Converts physical variables (temperature, pressure) into electrical signals.
2. **Signal Conditioner:** Prepares the signal (amplification, filtering, or isolation) for the ADC.
3. **Multiplexer (MUX):** Acts as a high-speed switch to select one signal at a time from multiple sensors, allowing them to share a single ADC.
4. **Analog-to-Digital Converter (ADC):** The "heart" of the system; it converts the continuous analog voltage into discrete digital numbers.
5. **Computer/Processor:** Handles data storage, display, and further analysis via software.

4.3 Objective of DAS

- **Accuracy:** To collect and store data with higher precision than manual logging.
- **Speed:** To capture high-frequency transients that the human eye cannot see.
- **Remote Monitoring:** To gather data from hazardous or inaccessible locations.
- **Automation:** To trigger alarms or control actions automatically based on measured thresholds.

4.4 Signal Conditioning in DAS & Logarithmic Conversion

Signal conditioning in a DAS often includes specialized functions like **Logarithmic Conversion**.

- **Definition:** A logarithmic amplifier (Log Amp) produces an output proportional to the logarithm of the input signal.
- **Why use it?**
  - **Dynamic Range Compression:** Some sensors produce signals spanning several decades (e.g., from $1\mu V$ to $10V$). A standard ADC cannot handle this range without losing resolution. Logarithmic conversion "squeezes" the high values and "expands" the low values so the ADC can read both accurately.
  - **Percentage Changes:** It makes the system sensitive to fractional changes rather than just absolute changes.

4.5 Single Channel vs. Multichannel DAS

Feature	**Single Channel DAS**	**Multichannel DAS**
Complexity	Simple; one sensor to one ADC.	Complex; multiple sensors share one ADC.
Multiplexer	Not required.	**Essential** to switch between inputs.
Speed	Very fast for that specific channel.	Slower per channel (as time is shared).
Cost	Low for a single point.	High initial cost, but cheaper "per channel."

4.6 Data Logger: Block Diagram & Characteristics

A **Data Logger** is a self-contained, battery-powered version of a DAS, usually designed for long-term, unattended operation.

Block Diagram

Characteristics:

- **Stand-alone:** Does not need a permanent connection to a PC.
- **On-board Storage:** Uses non-volatile memory (SD cards or Flash) to store data for weeks or months.
- **Low Power:** Designed to "sleep" between readings to save battery life.
- **Slow Sampling:** Typically records data at intervals (e.g., once every 10 minutes) rather than kHz speeds.

4.7 Comparison: DAS vs. Data Logger

Feature	**Data Acquisition System (DAS)**	**Data Logger**
Sampling Rate	High speed (kHz to MHz).	Low speed (Samples per second/minute).
Operation	PC-dependent (usually).	Stand-alone (Battery powered).
Usage	Laboratory/Real-time testing.	Field work/Environmental monitoring.
Data Storage	Streams directly to a PC hard drive.	Stores to internal memory/SD card.