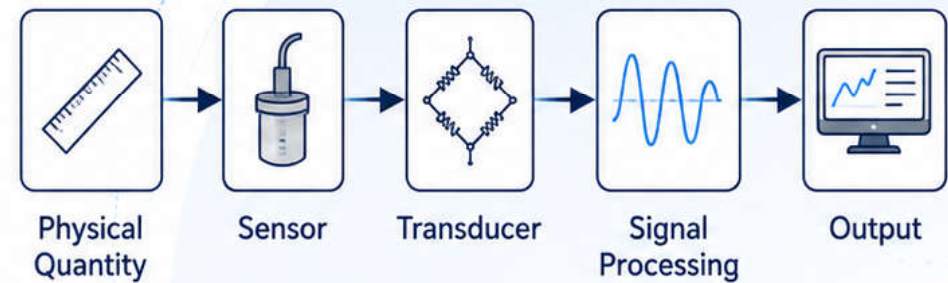


MEASURING INSTRUMENTS

Structure, Characteristics and Dynamic Response



From physical phenomena to reliable numerical results.

Why Do We Need Measuring Instruments?

Our senses can perceive many aspects of the physical world, but they are limited in range, resolution and objectivity.

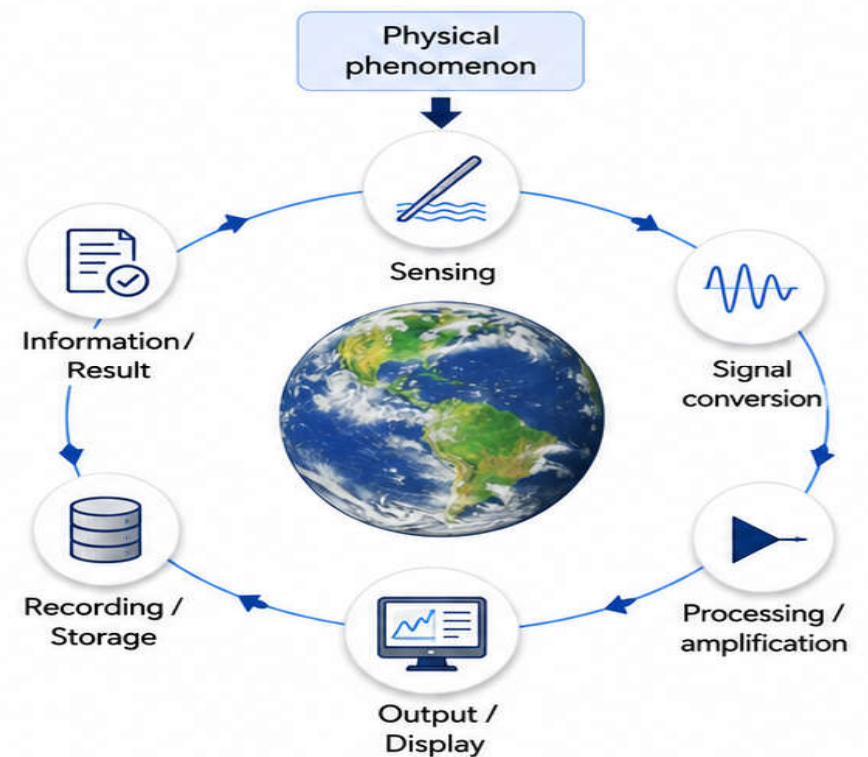
→ Measurements require tools that:

- Extend our senses to a wider range of phenomena
- Provide quantifiable and reproducible results
- Allow comparison with standard units
- Reduce subjective judgement
- Enable continuous, fast or remote observations
- Support data recording and analysis



Examples: thermometers, balances, voltmeters, oscilloscopes, spectrometers, counters, etc.

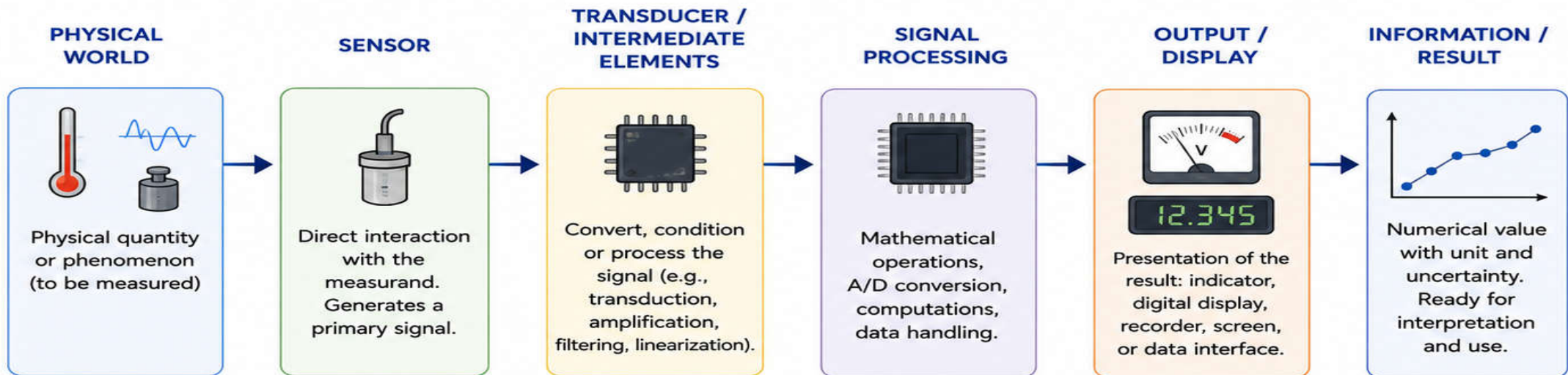
From physical phenomenon to information



Key Idea: A measuring instrument transforms a physical quantity into a reliable numerical result through a **chain of physical and electronic processes**.

The Measurement Process

A measuring instrument transforms a physical phenomenon into a numerical result that can be interpreted and used.



Key Points:

- The measured quantity is the input of the measurement chain.
- Each stage has a specific function and may introduce errors.
- Calibration establishes the quantitative relationship between input and output.
- The quality of the final result depends on the whole chain.
- Understanding instruments is essential for evaluating uncertainty and achieving reliable measurements.



A measurement is more than a number – it is the result of a well-understood process.

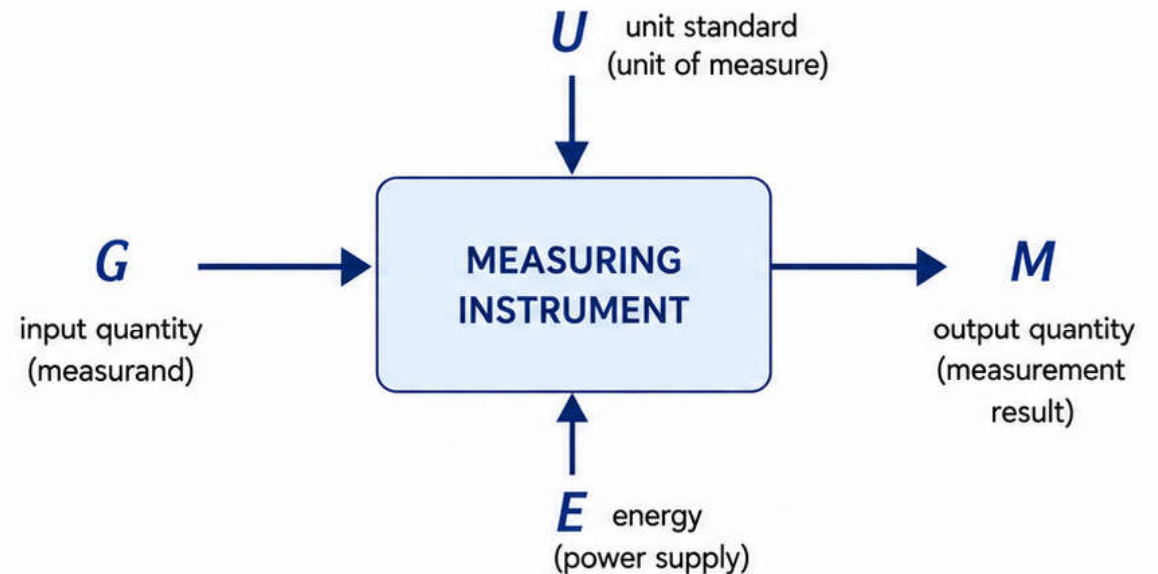
Basic Representation of a Measuring Instrument

The operation of any measuring instrument can be represented in a simple functional diagram.

- **G**: input (measurand, physical quantity to be measured)
- **U**: unit standard used for comparison
- **M**: output (measurement result)
- **E**: energy required for operation



Key idea: A measuring instrument compares the measurand with a unit standard (directly or through a calibration process) and provides an output proportional to it.



Goal of measurement: to determine the value of **G** by producing an output **M** that is related to **G** through **known** and **reliable** relationships.



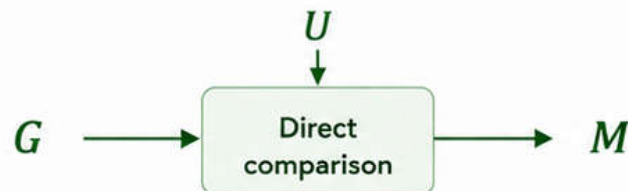
This functional view will be refined in the following slides.

Direct Comparison vs. Calibration

Ideally, the measurand G is compared with a unit standard U .

In practice, this can be done directly or through a calibration process.

1. Direct comparison (no calibration needed)



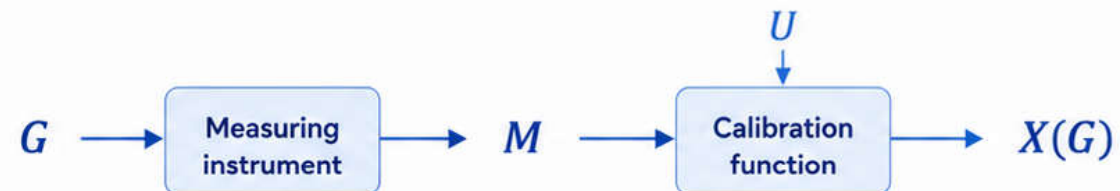
The measurand is compared directly with the unit standard (or with its integer multiple).

Examples:

- Ruler, measuring tape, balance with standard weights
- Graduated cylinder, stop watch



2. Calibrated measurement (most practical cases)



The instrument produces an output M related to G .

Calibration establishes the quantitative relationship between M and G , using the unit standard U .

Examples:

- Thermometer (temperature → expansion → pointer position)
- Voltmeter (voltage → electrical signal → pointer or digital value)
- Spectrometer (wavelength → intensity → digital counts)
- Pressure gauge (pressure → deformation → electrical signal)



Most real instruments cannot compare G directly with U .

Calibration creates the link between the instrument output and the unit standard.

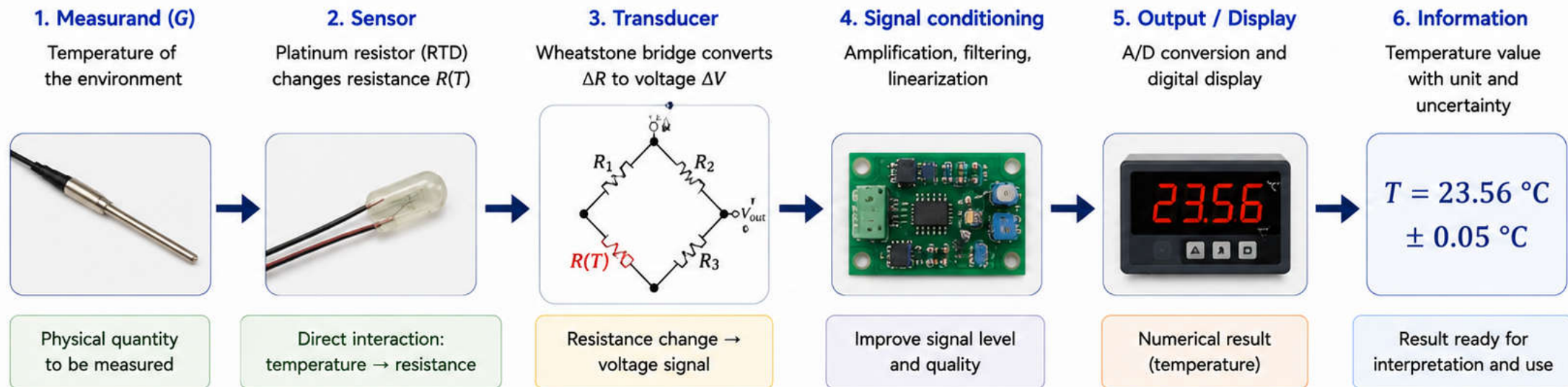


Calibration converts an instrument into a quantitative measuring tool.

The Measurement Chain: A Real Example

A physical quantity often undergoes several transformations before it becomes a numerical result.

Example: Measuring temperature with a resistance thermometer



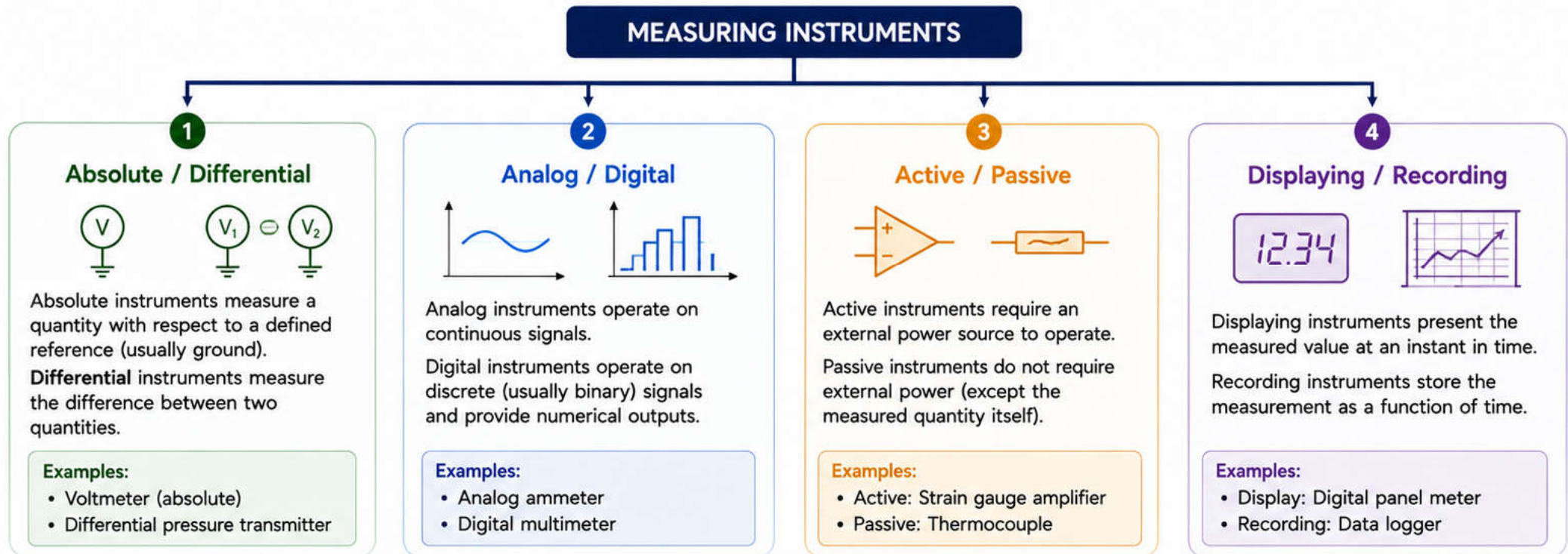
Key idea: A measuring instrument is a **chain of functional elements** that transforms the measurand into a reliable numerical result.



Each element has a specific role and can introduce errors.
The quality of the final result depends on the whole chain.

How Can Instruments Be Classified?

Measuring instruments can be classified in several ways depending on their function and characteristics.



Key idea: Classification helps in understanding the operating principle, connection, and appropriate use of measuring instruments.



Proper classification helps in selecting the right instrument for the right application.

Absolute vs. Differential Instruments

Instruments can measure a physical quantity in two different ways: with respect to an absolute reference or as the difference between two quantities.

1. ABSOLUTE INSTRUMENTS

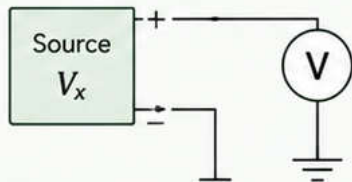
Measure a physical quantity with respect to an absolute reference, usually ground (zero).



Characteristics:

- One input is connected to the measurand.
- The other input is connected to the reference (usually ground).
- Provides the value of the quantity with respect to the reference.

Example: Voltmeter

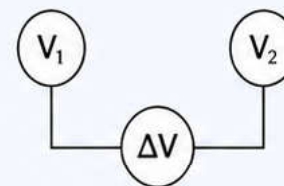


The voltmeter measures the voltage V_x of the source with respect to ground.

Reading: V_x (with respect to ground)

2. DIFFERENTIAL INSTRUMENTS

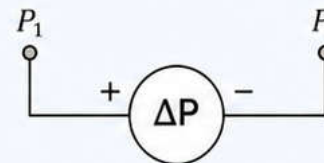
Measure the difference between two points or two physical quantities.



Characteristics:

- Both inputs are connected to the measurand (no reference to ground required).
- Measures the difference between two points.
- Less affected by common-mode effects (e.g., ground shifts, noise).

Example: Differential Pressure Transmitter



The transmitter measures the pressure difference $\Delta P = P_1 - P_2$.

Reading: ΔP (difference between P_1 and P_2)



Key idea: Absolute instruments give a value with respect to a fixed reference (usually ground).
Differential instruments give the difference between two values, independent of any reference.



Where used?

- **Absolute:** Electrical measurements, temperature (e.g., vs. 0°C), level, etc.
- **Differential:** Pressure, flow, strain, bridge measurements, etc.



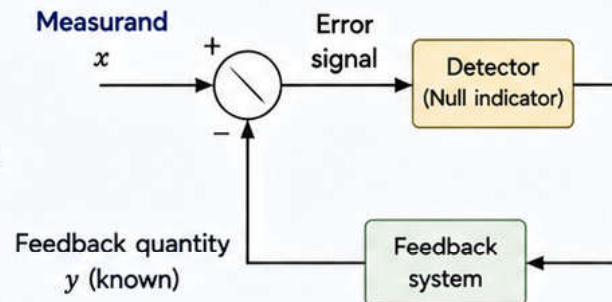
Choosing the right type of instrument improves accuracy, reliability, and noise immunity.

Null Measurement and Feedback

Null (zero-deflection) methods use feedback to balance the measurand with a known reference until the detector output is zero.

PRINCIPLE

A feedback system adjusts a known quantity to oppose the measurand. When the detector output is zero, the two are equal (or in a known ratio), so the measurand is determined from the feedback quantity.



At null (zero output):

$x = y$ (or $x = K \cdot y$)
where K is a known constant of the system.

Null condition:



Detector output = 0

Meaning:

Measurand is balanced by the feedback quantity.
No current (or signal) in the detector.

ADVANTAGES

- ✓ High accuracy and sensitivity
- ✓ Independent of detector sensitivity
- ✓ Reduces effects of drift and nonlinearity
- ✓ Good for precision measurements

EXAMPLES



Wheatstone bridge

Unknown resistance is balanced by an adjustable resistor until the galvanometer reads zero.



Null-type potentiometer

Unknown voltage is balanced by a known voltage from a potentiometer until detector reads zero.



Electrometer (null method)

Unknown charge is balanced by a feedback voltage until the detector shows zero deflection.



Key idea: Null measurement uses negative feedback to force the detector output to zero. The measurand is then found from the known feedback quantity that creates the balance.



Feedback brings the system to balance; balance reveals the measurand.

Active vs. Passive Instruments

Instruments can be classified according to whether they require an external power source (active) or not (passive).

1. ACTIVE INSTRUMENTS

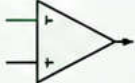
Require an external power source to operate.



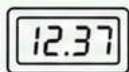
Characteristics:

- Need external energy (battery, mains, or other source).
- Can amplify or process signals.
- Generally provide higher sensitivity and accuracy.
- More complex and usually more expensive.

Examples:



Operational amplifier



Digital multimeter



Strain gauge amplifier



Data acquisition system

2. PASSIVE INSTRUMENTS

Do **not** require an external power source to operate.



Characteristics:

- Do not need external power.
- Operate solely on the energy of the measurand.
- Simpler, more robust, and usually less expensive.
- Generally lower sensitivity and cannot amplify signals.

Examples:



Moving-coil ammeter



Bimetal thermometer



Manometer



Spring balance



Key idea: Active instruments require an external power source and can provide signal conditioning. Passive instruments derive their operating energy from the measurand itself.



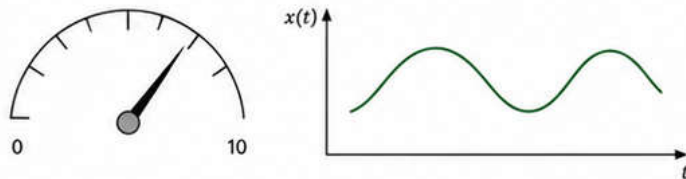
Choosing between active and passive instruments depends on the required performance, simplicity, and available energy.

Analog vs. Digital Instruments

Instruments can provide outputs in **continuous** (analog) form or **discrete** (digital) form.

1. ANALOG INSTRUMENTS

Operate on continuous signals that can take any value within a range.



Characteristics:

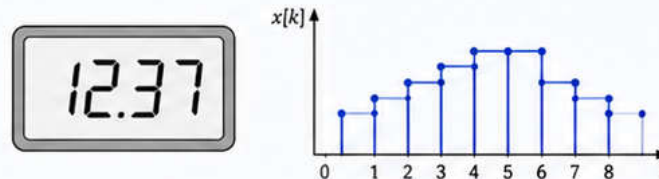
- Output is a continuous function of the input.
- High resolution (limited by noise, friction, etc.).
- Direct indication; easy to observe trends.
- More sensitive to noise and drift.

Examples:

- Analog voltmeter (pointer)
- Analog ammeter
- Bimetal thermometer

2. DIGITAL INSTRUMENTS

Operate on discrete signals that take specific, separate values.



Characteristics:

- Output is discrete in amplitude (and often in time).
- Quantized values; finite resolution determined by bit depth.
- High noise immunity; stable and repeatable.
- Requires A/D conversion for real-world signals.

Examples:

- Digital voltmeter
- Digital multimeter
- Digital thermometer

COMPARISON

Aspect	Analog	Digital
Signal	Continuous	Discrete
Output	Pointer, scale	Numeric display
Resolution	Very high (theoretical)	Finite (depends on bits)
Noise immunity	Lower	Higher
Data handling	Difficult	Easy (stored, processed)
Cost (typical)	Lower	Higher
Trend observation	Excellent	Good (with sampling)



Key idea: Analog instruments provide a continuous representation of the measurand, while digital instruments provide discrete numerical values that are easier to process, store, and transmit.



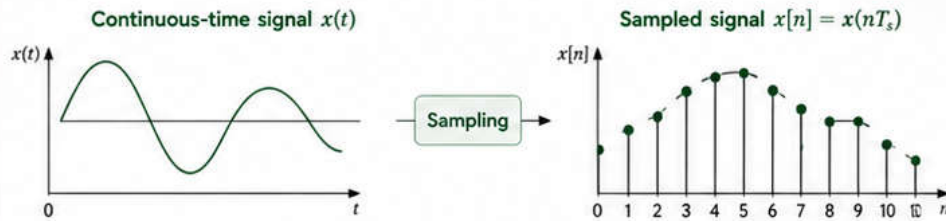
Analog shows the signal as it is; digital handles and communicates it.

Sampling and Digitization

Digital instruments convert a **continuous-time, continuous-amplitude** (analog) signal into a **discrete-time, discrete-amplitude** (digital) signal.

1. SAMPLING (IN TIME)

The continuous signal is measured at uniform time intervals T_s .

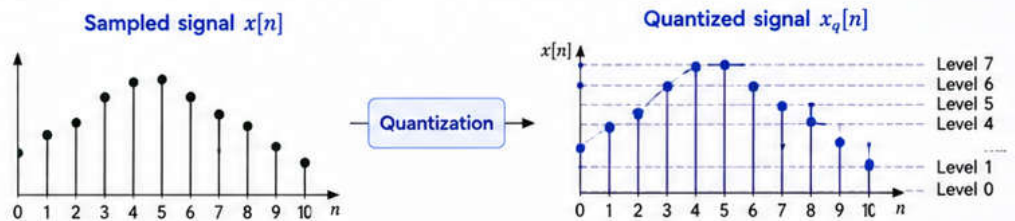


Key points:

- T_s = sampling period (s)
- $f_s = \frac{1}{T_s}$ = sampling frequency (Hz)
- To avoid aliasing: $f_s \geq 2f_{\max}$ (Nyquist criterion)

2. QUANTIZATION (IN AMPLITUDE)

Each sample is rounded to the nearest value from a finite set of levels.

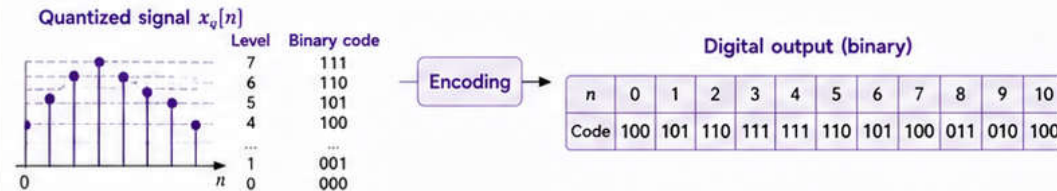


Key points:

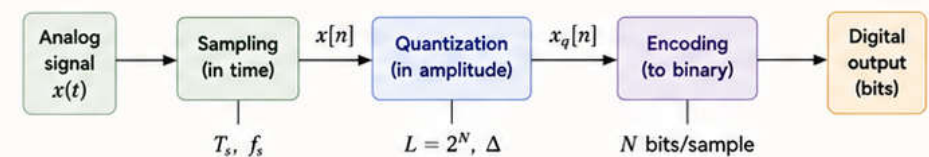
- Signal amplitude is mapped to one of $L = 2^N$ levels (N = number of bits).
- Quantization error $e_q[n] = x[n] - x_q[n]$ with $|e_q[n]| \leq \frac{\Delta}{2}$
- Δ = quantization step size (LSB)

3. ENCODING (TO BINARY)

Each quantized level is represented by an N -bit binary word.



OVERALL PROCESS



Key idea: Sampling captures the signal in time, quantization approximates its amplitude, and encoding represents it in binary. Together, these steps convert an analog signal into a digital sequence.



Aliasing occurs if $f_s < 2f_{\max}$



Sampling converts time-continuous signals to time-discrete; quantization converts amplitude-continuous to amplitude-discrete.

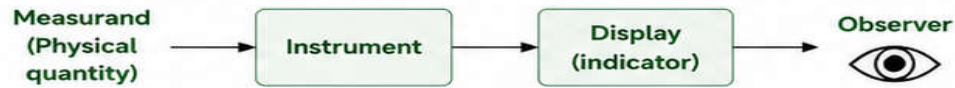
Displaying vs. Recording Instruments

Instruments can be classified according to whether they present the measured value directly (displaying), or store it for future use (recording).

1. DISPLAYING INSTRUMENTS

Present the measured value **directly** to the observer.

- Present the measured value to the observer immediately.
- Output is available only at the time of measurement.
- Typically analog (pointer) or digital (numerical) display.
- Simple to use; do not store data automatically.



Examples:



Analog voltmeter



Digital multimeter



Thermometer (mercury or digital)

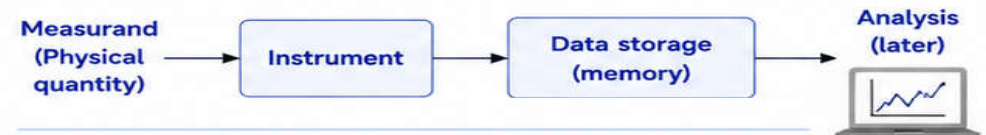


Pressure gauge

2. RECORDING INSTRUMENTS

Automatically **record** the measured quantity.

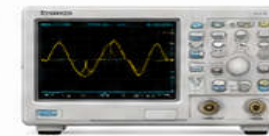
- Automatically record measurements over time.
- Preserve measurement information for later analysis.
- Allow identification of temporal changes and trends.
- Often digital and connected to memory or a computer.



Examples:



Data logger



Digital oscilloscope



Computer-based DAQ system



Chart recorder



Key idea: Displaying instruments provide an immediate measurement result, whereas recording instruments preserve measurement information for later analysis.



Takeaway: Modern measurement systems often combine both functions: **real-time display** and **continuous data recording**.



The choice between displaying and recording instruments depends on the measurement goal: instant information or long-term data analysis.

Static Characteristics of Instruments – Overview

Static characteristics describe how an instrument relates its output to a **constant** or **slowly varying** input.

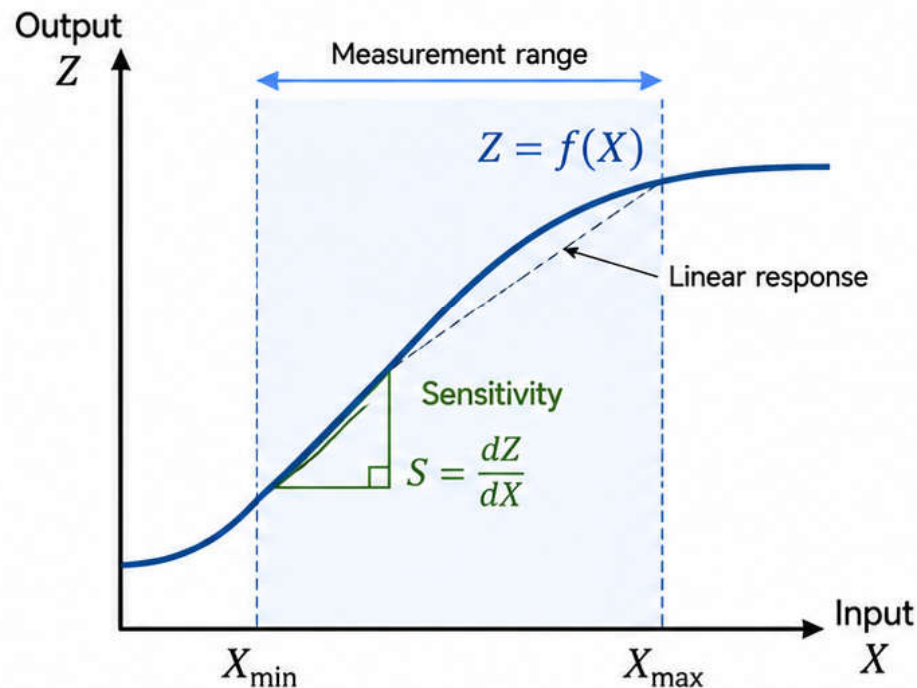
Static behavior

Measured quantity:
 $X = \text{constant}$
or slowly changing.



The instrument output
settles to a **steady value**:

$$Z = f(X)$$



Main static characteristics

- 1 **Measurement range**
Interval of input values giving a reliable response.
- 2 **Sensitivity**
Variation of the output with respect to the input.
- 3 **Linearity**
Proportionality between input and output.
- 4 **Resolution**
Smallest detectable change of the input.
- 5 **Transparency**
Minimal influence on the measurand.
- 6 **Operating conditions**
Range where the specifications are valid.



Key idea: These characteristics determine the accuracy, reliability and useful range of a measuring instrument.

Understanding the static characteristics is essential for correct measurement and uncertainty evaluation.

Measurement Range

The **measurement range** defines the interval of input values within which the instrument provides valid and specified performance.

Measurement range:

$$X_{min} \leq X \leq X_{max}$$

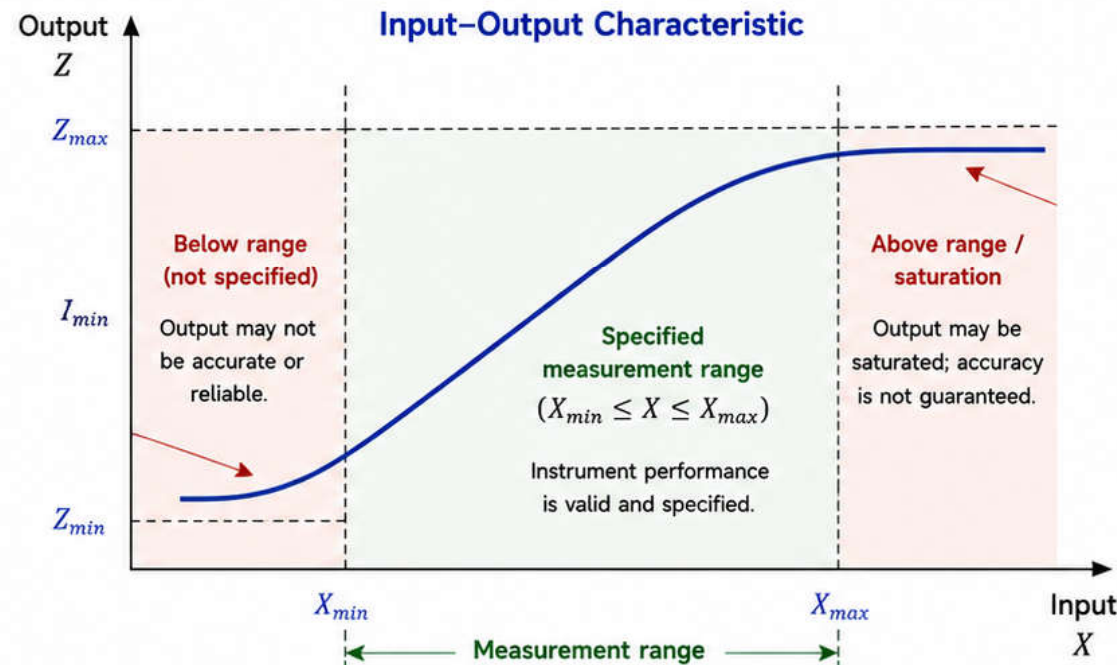
X_{min} : lower range limit

X_{max} : upper range limit

X : measurand (input)

Key points

- Within the measurement range ($X_{min} \leq X \leq X_{max}$), the instrument meets its specified performance (e.g., accuracy, linearity, resolution).
- Outside this range, the instrument may still produce an output signal, but the performance is **not guaranteed**.
- Operating outside the range can lead to **saturation, increased error**, or even **damage**.



Legend

- Actual instrument characteristic
- Output limits within specified performance
- Valid and specified performance
- Outside range: performance not specified



Key idea: Use the instrument within its measurement range to ensure valid and reliable measurement results.



Always check the specified measurement range before using an instrument.

Calibration Curve

The **calibration curve** describes the functional relationship between the known input values and the corresponding instrument output.



Definition

The calibration curve is the experimentally determined input-output characteristic of an instrument.

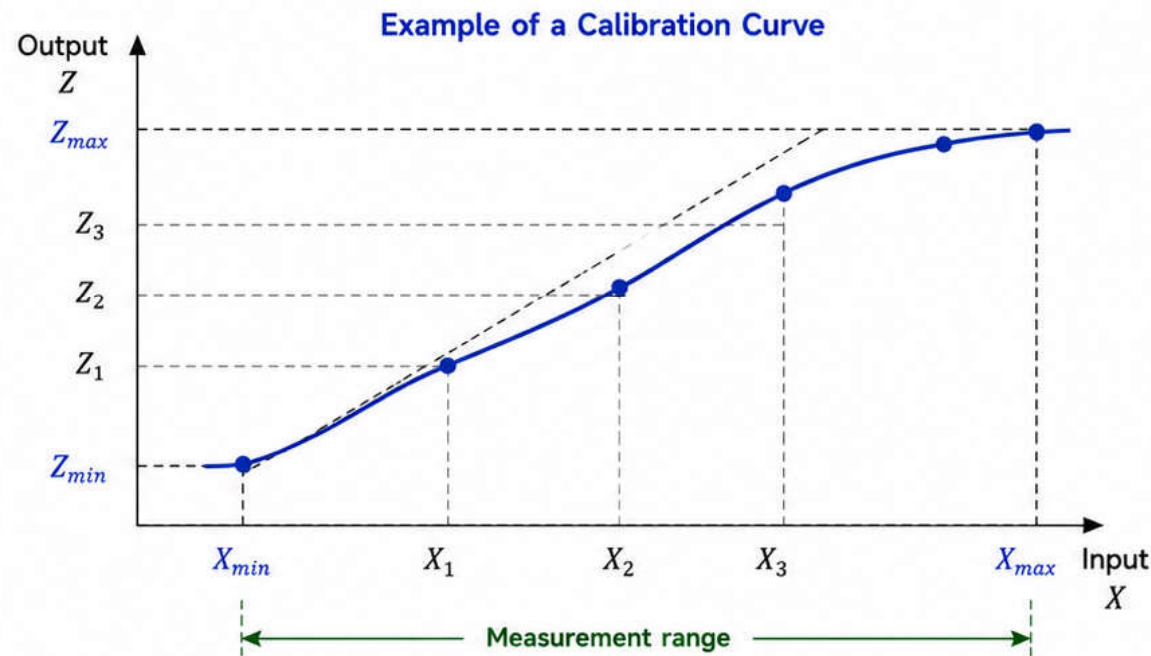
How it is obtained

- Apply known (reference) input values covering the measurement range.
- Measure and record the corresponding output values.
- Plot output versus input.
- The resulting curve is the calibration curve.



Purpose

It allows us to determine the output for any input within the range and to assess **Linearity**, **sensitivity**, and other static characteristics.



Legend

- Calibration curve (measured)
- - - Ideal linear response



Key idea: The calibration curve provides the basis for converting instrument output to the corresponding input value and for evaluating the instrument's static performance.



A reliable calibration requires accurate reference standards and controlled conditions.

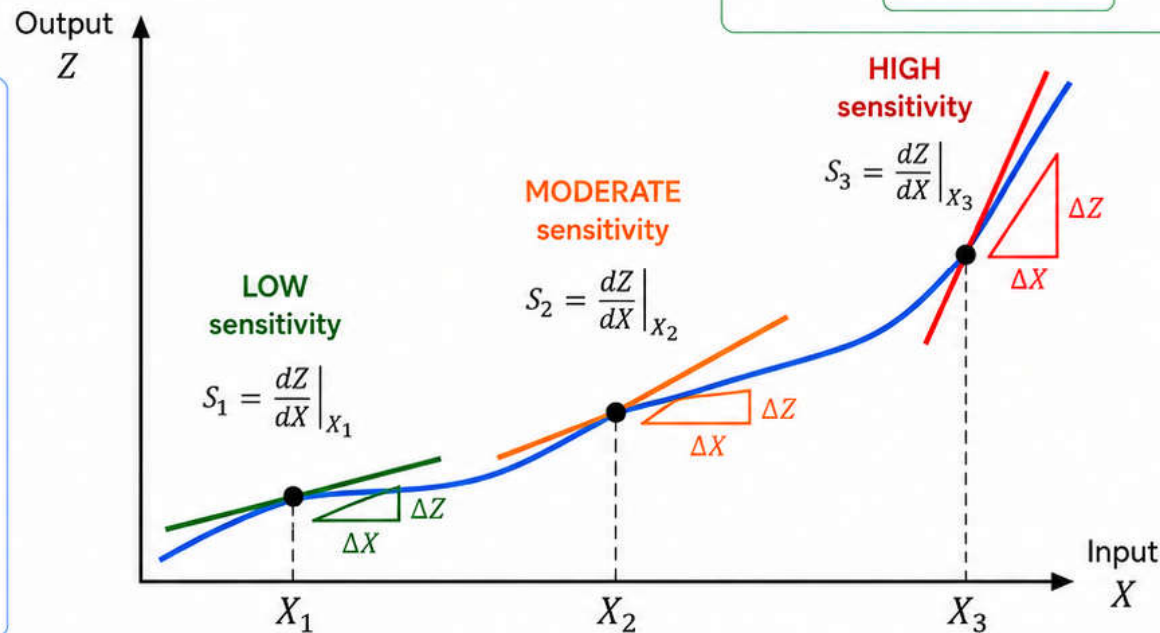
Sensitivity

Sensitivity quantifies how strongly the instrument output changes in response to a change in the input.

Key points

- High sensitivity means a large change in output for a small change in input.
- Sensitivity may vary with the operating point (nonlinear characteristic).
- Units of sensitivity:

$$\frac{\text{Output unit}}{\text{Input unit}}$$



Definition

Sensitivity is the slope of the input-output (transfer) characteristic at a given operating point.

$$S = \frac{dZ}{dX}$$

S : sensitivity

dZ : change in output

dX : change in input

Interpretation

- At X_1 the slope is small → **low** sensitivity.
- At X_2 the slope is moderate → **moderate** sensitivity.
- At X_3 the slope is steep → **high** sensitivity.



Key idea: Sensitivity determines how well an instrument can detect small changes in the measurand. Higher sensitivity enables resolution of smaller input variations.



Sensitivity is not constant in general; it depends on the operating point and the instrument design.

Linearity

Linearity describes how closely the actual input–output characteristic follows an ideal linear relationship.



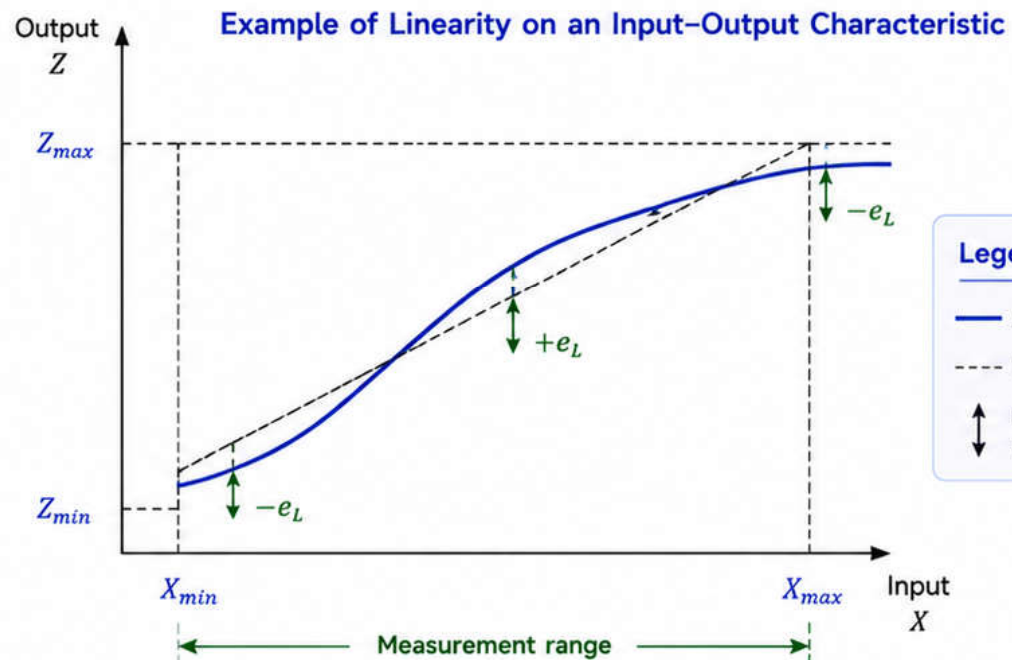
Definition

Linearity is the closeness of the actual response to an ideal linear response over the measurement range. Deviation from linearity causes measurement error.

Key points

- The ideal linear response is a straight line.
- The actual characteristic deviates from this line.
- Linearity error is the maximum deviation between the actual characteristic and the ideal linear line.
- Linearity is usually specified as a percentage of full scale (FS).

$$e_L = \frac{\text{Linearity error } (\pm) \text{ maximum deviation}}{\text{full scale (FS)}} \times 100\%$$



Legend

- Actual characteristic
- - - Ideal linear response
- ↕ Deviation (error) from ideal

Interpretation

- **Positive deviation:** actual output is higher than ideal.
- **Negative deviation:** actual output is lower than ideal.
- The specified linearity error limits the maximum deviation allowed.



Key idea: Good linearity means the instrument response is proportional to the input. Poor linearity increases measurement error, especially near the ends of the range.

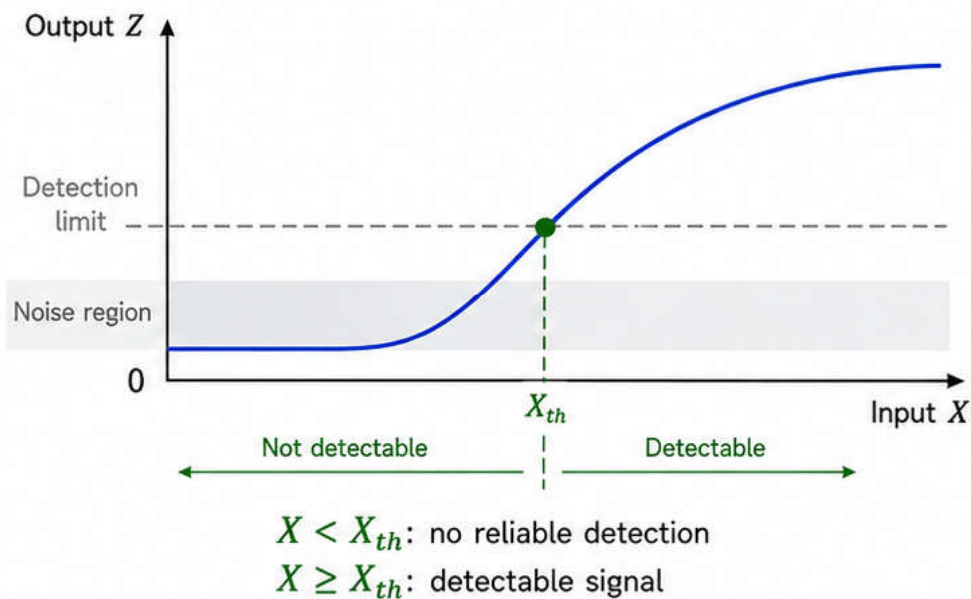


Linearity is essential for accurate conversion of the measured quantity into a meaningful result.

Sensitivity Threshold and Resolution

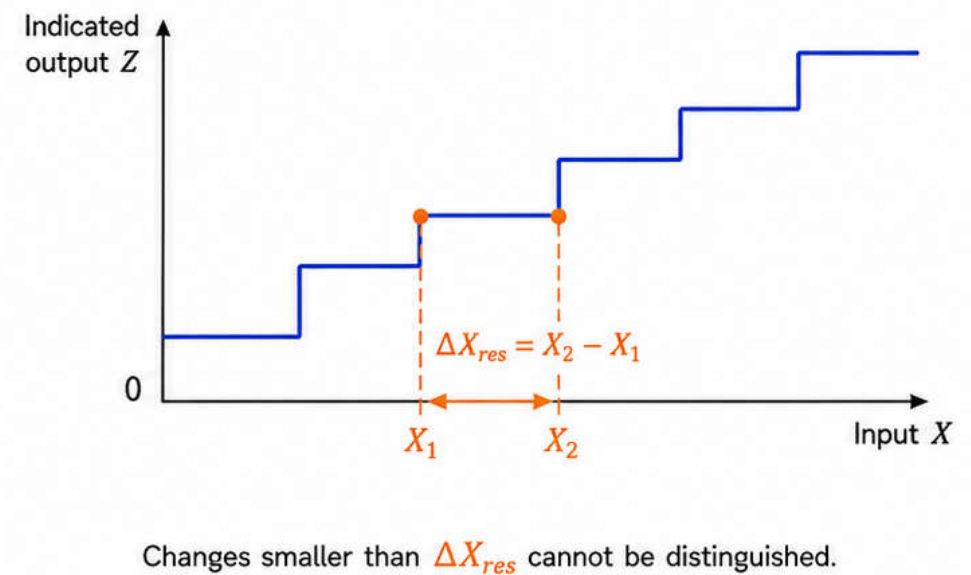
1. Sensitivity threshold

The smallest input value that produces a detectable output.



2. Resolution

The smallest change in input that can be distinguished.



Sensitivity threshold:

Can the instrument detect the signal?



Resolution:

Can the instrument distinguish two nearby values?



Key idea:

Threshold concerns detection; resolution concerns discrimination.



Clear detection requires sufficient signal; accurate measurement requires sufficient resolution.

Operating Conditions

Operating conditions are the environmental and supply conditions within which an instrument is designed to meet its specified performance.



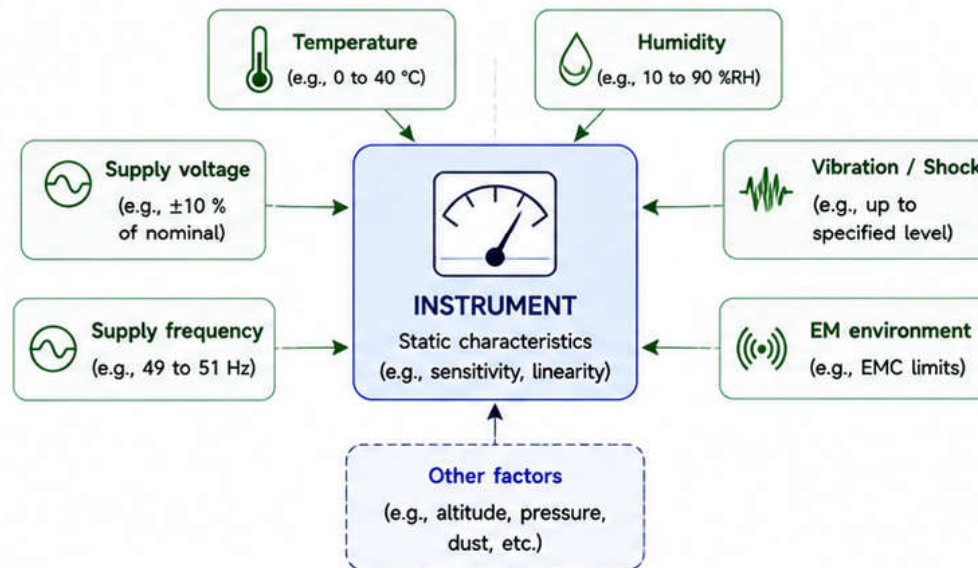
Definition

Operating conditions specify the ranges of environmental and supply variables within which an instrument's static characteristics remain within the specified limits.

Key points

- Instrument performance can change with variations in environment or supply.
- Typical influences: temperature, humidity, supply voltage, frequency, vibration, and electromagnetic environment.
- Specifications define the allowed ranges and the resulting effects.
- Operating outside specified conditions may cause errors or damage.
- Proper use within operating conditions ensures reliability, stability, and accuracy.

Influence of Operating Conditions on Instrument Performance



Performance is guaranteed only within the specified operating conditions.

Typical Specification Format

- Temperature: 0 to 40 °C
- Relative humidity: 10 to 90 %RH (non-condensing)
- Supply voltage: 90 to 110 % of nominal
- Supply frequency: 49 to 51 Hz
- Warm-up time: 15 min
- Altitude: up to 2000 m
- EMC: according to standard (e.g., IEC 61326)
- Performance effect: within specified limits (e.g., linearity error $\leq \pm 0.5\%$ FS)

Interpretation



Staying within operating conditions ensures that the instrument's static characteristics remain within specified limits. Deviations outside these ranges may lead to increased errors or unreliable results.



Key idea: Understand and respect the specified operating conditions to obtain reliable and accurate measurements and to protect the instrument from damage.



Operating within specified conditions is essential for maintaining instrument performance and measurement integrity.

Accuracy, Resolution and Precision Are Not the Same

Accuracy, **resolution**, and **precision** are different concepts.

An instrument can have one without the others.



Accuracy: Closeness of a result (or mean) to the true value.

Precision: Closeness of repeated results to each other.

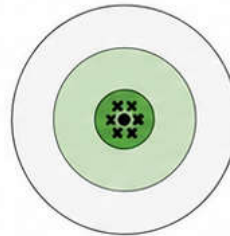
Resolution: Smallest change in input that produces a detectable change in output.

Key points

- **Accuracy** relates to trueness.
- **Precision** relates to repeatability.
- **Resolution** relates to the smallest change that can be detected.
- High resolution does not guarantee high accuracy.
- High precision does not guarantee high accuracy.
- The ideal instrument has high accuracy, high precision, and high resolution.

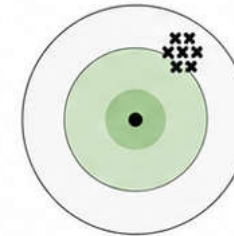
Examples of Repeated Measurements (• = true value)

1 **High accuracy**
High precision
High resolution



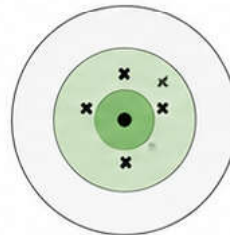
- Results are close to the true value.
- Results are close to each other.
- Small changes can be detected.

2 **Low accuracy**
High precision
High resolution



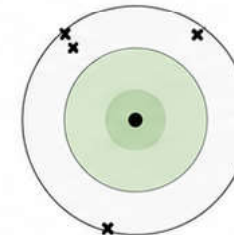
- Results are far from the true value.
- Results are close to each other.
- Small changes can be detected.

3 **High accuracy**
Low precision
High resolution



- Results are close to the true value on average.
- Results are not close to each other.
- Small changes can be detected.

4 **Low accuracy**
Low precision
Low resolution



- Results are far from the true value.
- Results are not close to each other.
- Small changes cannot be detected.



Accuracy (trueness)

How close the average (or a single result) is to the true value.



Precision (repeatability)

How close repeated results are to each other.



Resolution (sensitivity)

The smallest change in input that causes a detectable change in output.



Key idea: A good measurement system should be accurate, precise, and have high resolution. These three characteristics are independent but equally important.



Understand the differences: accuracy is about being right, precision is about being consistent, and resolution is about being sensitive.

Sources of Inaccuracy

Inaccuracy in measurements can arise from **systematic errors** (bias) and **random errors**.



Systematic error (bias): A consistent, repeatable error that causes results to be offset from the true value in one direction.

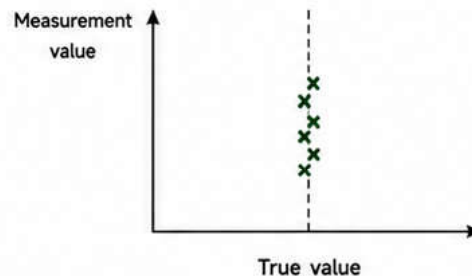
Random error: Unpredictable variations that cause results to scatter around the true value.

Key points

- **Systematic errors** shift all results in the same direction.
- **Random errors** cause scatter in results.
- Average of repeated results reduces random error.
- Calibration and correction can reduce systematic error.
- Understanding the source of inaccuracy is essential for improving measurements.

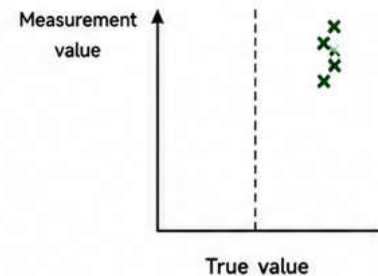
Effects of Systematic and Random Errors

1. No error (ideal)



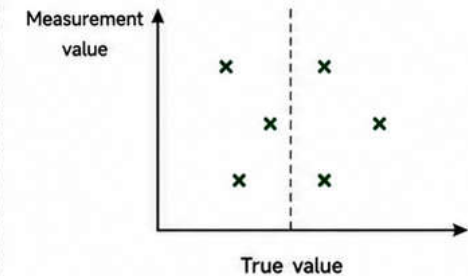
- Results are close to the true value.
- Results are close to each other.
- High accuracy, high precision.
- **Ideal situation.**

2. Systematic error (bias)



- Results are consistently offset from the true value.
- Results are close to each other.
- Low accuracy, high precision.
- Caused by **systematic error (bias)**.

3. Random error



- Results are scattered around the true value.
- Average may be close to true value.
- High accuracy (on average), low precision.
- Caused by **random error**.



Key idea: Inaccuracy comes from bias (systematic error) and scatter (random error). Good measurements minimize both.



Identify the sources of inaccuracy and apply appropriate methods to reduce their effects.

Reducing Inaccuracy: Strategies and Good Practices

Good measurements require more than just a good instrument.

Use appropriate methods to reduce both **systematic errors** and **random errors**.



Goal: Maximize accuracy and precision by minimizing systematic and random errors.

Key points

- Identify the sources of inaccuracy (bias and scatter).
- Use good practice to minimize **systematic** and **random** errors.
- Proper design, calibration, technique, and environment control are essential.
- No measurement is perfect, but inaccuracy can be reduced.
- Always evaluate results and look for possible errors.



Strategies to Reduce Systematic Errors (Bias)

Address causes of consistent, repeatable errors that shift results away from the true value.



Calibrate instruments: Regular calibration ensures measurements are referenced to known standards.



Use proper reference standards: Traceable and appropriate standards reduce bias.



Control environment: Maintain stable temperature, humidity, vibration, and other conditions.



Use correct methods and procedures: Follow standardized procedures and best practices.



Maintain instruments: Keep instruments clean, well-maintained, and functioning properly.



Identify and correct bias: Analyze results, compare with known values, and apply corrections.



Strategies to Reduce Random Errors

Address unpredictable variations that cause results to scatter around the true value.



Take repeated measurements: More data points reduce the effect of random variation.



Average results: The mean of repeated results reduces random error.



Increase sample size: More observations improve reliability and reduce scatter.



Reduce noise: Use shielding, filtering, proper instrumentation, and stable setups.



Allow time for stabilization: Let instruments and systems reach steady state.



Improve technique: Ensure consistent training, careful handling, and repeatable actions.



Key idea: Inaccuracy can be reduced by understanding its sources and applying good measurement practices. Reduce bias with calibration and control; reduce scatter with repetition and averaging.



Good measurement is the result of good instruments, good methods, and good judgment.

Dynamic Behaviour of Instruments

Static characteristics describe an instrument under **steady-state (constant)** conditions.

Dynamic characteristics describe how an instrument responds to **changing (time-varying)** inputs.

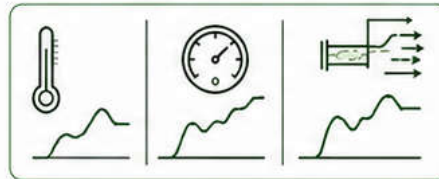


Dynamic behaviour is the performance of an instrument when the measurand varies with time.

Key points

- Most real-world measurands change with time.
- An instrument has finite speed and cannot respond instantaneously.
- Dynamic characteristics determine how well the instrument follows time-varying inputs.
- Important aspects include speed, fidelity, and stability of response.
- Understanding dynamic behaviour is essential for correct selection, use, and interpretation.

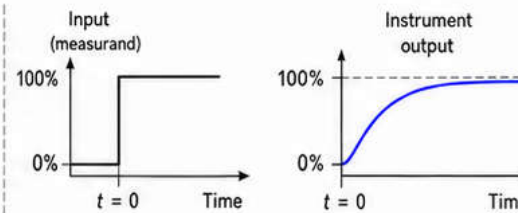
Changing inputs are common



Temperature, pressure, flow, level, voltage, and many other measurands vary with time in practice.

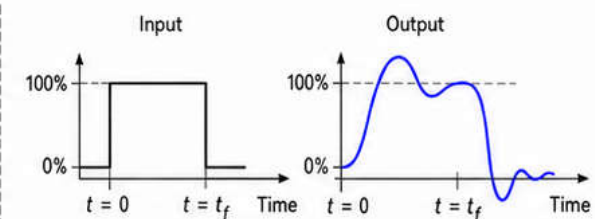
Why Dynamic Behaviour Matters

Instruments are not instantaneous



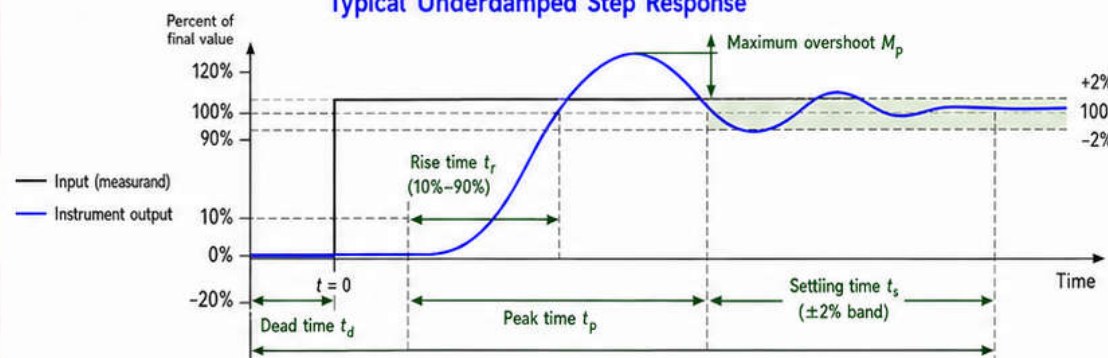
The output takes time to follow changes in the input.

Dynamic errors can occur



Lag, overshoot, and oscillation cause differences between input and output.

Typical Underdamped Step Response



Key idea

Dynamic characteristics tell us how fast and how accurately an instrument can follow changes in the measurand.

Faster and well-damped responses give more accurate dynamic measurements.



In dynamic situations, it is not enough to know the final value—we must also know how the output reaches it.

Key Dynamic Characteristics

Dynamic characteristics describe how an instrument responds to time-varying inputs. The most important characteristics are **speed**, **fidelity**, and **stability**.



Speed: How fast an instrument responds to changes in input.

Fidelity: How closely the output follows the input over time.

Stability: The ability to maintain consistent performance over time.

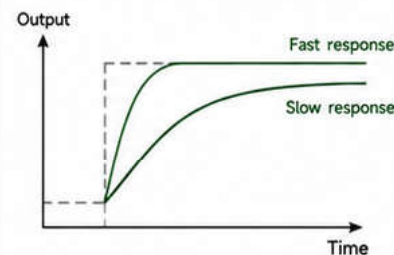
Key points

- Dynamic characteristics determine how well an instrument performs when inputs change.
- Speed** describes how quickly the output responds.
- Fidelity** describes how closely the output follows the input.
- Stability** describes how repeatable the response is over time.
- Good instruments are fast, faithful, and stable.
- There are always trade-offs; improving one may affect another.

Three Key Dynamic Characteristics

1. Speed (Responsiveness)

The ability to respond quickly to changes in the input.

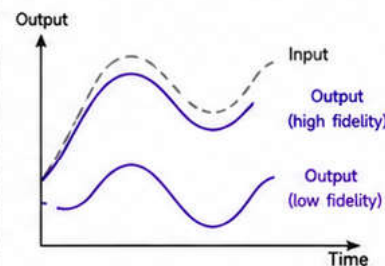


Measured by:

Rise time, delay time, settling time, time constant, bandwidth.

2. Fidelity (Accuracy of Following)

The ability of the output to follow the input waveform over time.

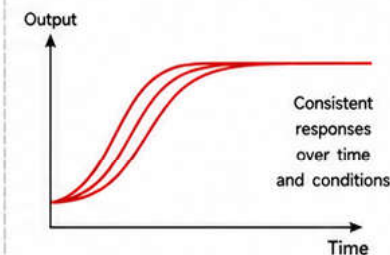


Measured by:

Amplitude error, phase error, distortion, linearity over time.

3. Stability (Repeatability Over Time)

The ability to maintain consistent dynamic performance over time and conditions.



Measured by:

Repeatability, drift, variation with temperature, aging.

Typical Trade-offs



Speed vs. Fidelity

Faster response may increase overshoot or reduce fidelity.



Speed vs. Stability

Very fast systems may be more sensitive to drift and noise.



Fidelity vs. Stability

Highly accurate following may be harder to keep stable over time and conditions.



Good instrument design balances all three.



Factors Affecting Dynamic Characteristics

- Sensor and transducer design
- Mechanical and electrical time constants
- Signal conditioning and filters
- Sampling rate (in digital systems)
- Control algorithms and compensation
- Environmental conditions and load



Key idea: Speed tells us how fast, fidelity tells us how well, and stability tells us how consistently an instrument responds to changing inputs. Understanding these helps us select the right instrument for dynamic measurements.



In dynamic measurements, good performance depends on speed, fidelity, and stability—together.

Mathematical Models of Instruments

Models relate the input $x(t)$ to the output $y(t)$ and predict the response to change.

Common Linear Time-Invariant (LTI) Models

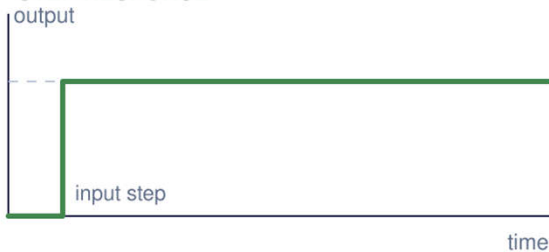
1 ZERO-ORDER MODEL

$$H(s) = K$$

MODEL EQUATION

$$y(t) = Kx(t)$$

STEP RESPONSE



Instantaneous scaling; no delay.

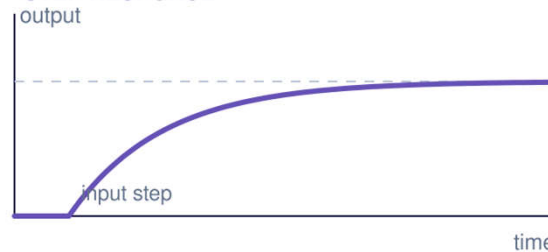
2 FIRST-ORDER MODEL

$$H(s) = \frac{K}{\tau s + 1}$$

MODEL EQUATION

$$\tau \frac{dy}{dt} + y = Kx(t)$$

STEP RESPONSE



Gradual response set by τ .

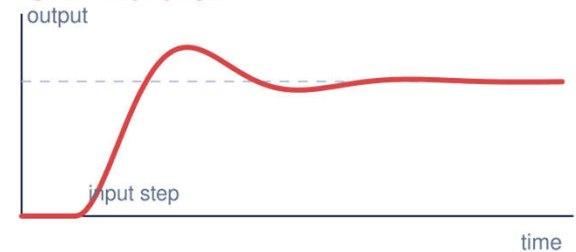
3 SECOND-ORDER MODEL

$$H(s) = \frac{K\omega_o^2}{s^2 + 2\zeta\omega_o s + \omega_o^2}$$

MODEL EQUATION

$$\ddot{y} + 2\zeta\omega_o\dot{y} + \omega_o^2 y = K\omega_o^2 x$$

STEP RESPONSE



Low damping can cause overshoot.

KEY IDEA

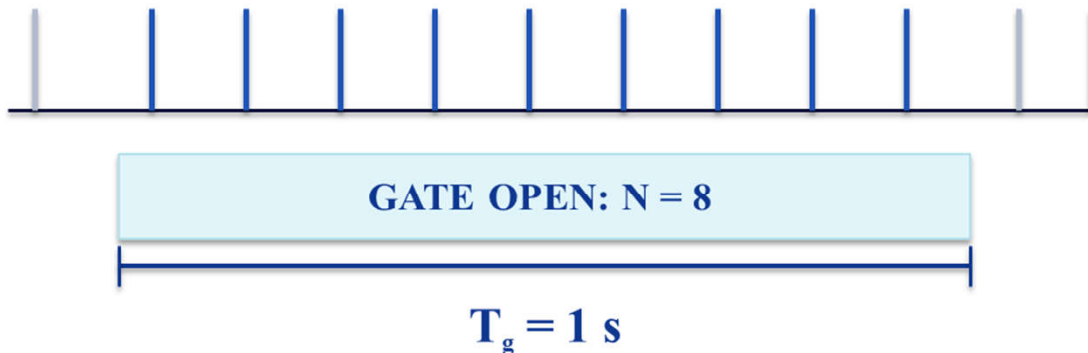
Use the simplest model that reproduces the observed step response.

How a counter measures frequency

A clock opens a gate for a known time. The counter counts input edges during that interval.

FROM THE INPUT SIGNAL TO A COUNT

One rising edge marks each input cycle.



The eight blue edges lie inside the gate; gray edges lie outside it.

$$f = N/T_g = 8/1 \text{ s} = 8 \text{ Hz}$$

Count divided by elapsed time gives the mean event rate.

WHAT THE INSTRUMENT DOES

1 Define the interval

The instrument clock sets the gate duration T_g . Here it observes the input for one second.

2 Count complete events

The register increments for each rising edge that arrives while the gate is open. It stores an integer N .

3 Report the frequency

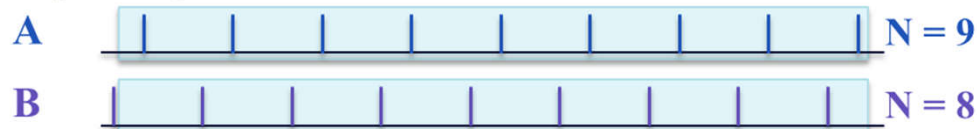
After gate closure, the display shows N/T_g . This averages the full interval, so a changing input is not shown instantaneously.

Gate time sets the count step

The counter can register only whole pulses: a longer gate gives a finer step but a later result.

WHY A ONE-COUNT DIFFERENCE OCCURS

At 8.4 Hz, a one-second gate may enclose 8 or 9 edges depending on where it starts.



COUNT STEP

$$\Delta f = 1/T_g$$

If one extra edge enters the gate, the displayed result rises by $1/T_g$. This is a resolution step, not the complete uncertainty.

EXAMPLE: STEADY INPUT AT 1003 Hz

	0.1 s gate	1 s gate
Count N	100 or 101	1003
Display f	1000 or 1010 Hz	1003 Hz
Step Δf	10 Hz	1 Hz
Update	≥ 0.1 s	≥ 1 s

PRACTICAL LIMITS

Clock: an imperfect time base biases the actual gate duration.

Trigger: noise or missed edges can change the registered count.

Signal drift: the result averages any change during the gate.

Overall Summary – Measuring Instruments



Measuring instruments convert a physical quantity (measurand) into a usable form, conditioned, processed, and presented to provide accurate, reliable information with known uncertainty for decision making and control.

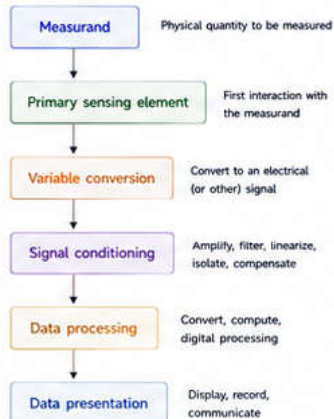


BIG PICTURE

Good measurements require proper **design**, understanding of **static** and **dynamic** behavior, awareness of **errors**, and matching the instrument to **the application**.

1. Functional Elements

A measuring instrument consists of the following functional elements:



Key requirements

- ✓ Accuracy
- ✓ Sensitivity
- ✓ Linearity
- ✓ Stability
- ✓ Repeatability
- ✓ Resolution
- ✓ Bandwidth

2. Classification of Instruments

By output

- Indicating
- Recording
- Controlling

By energy source

- Active (self-generating)
- Passive (modulating)

By nature of output

- Analog
- Digital

By contact with measurand

- Contacting
- Non-contacting

By application

- General-purpose
- Special-purpose

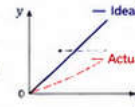
Selection depends on

- ✓ Measurand and range
- ✓ Required accuracy
- ✓ Dynamic characteristics
- ✓ Environment
- ✓ Cost and reliability

3. Static Characteristics

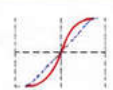
Input-output relationship

Static function: $y = f(x)$
Ideal: linear $y = kx + b$



Linearity

Deviation from best straight line (max. % of full scale)

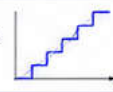


Sensitivity

$$S = \frac{dy}{dx} \text{ (slope)}$$

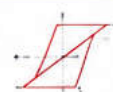
Resolution

Smallest input change that causes a detectable output change



Hysteresis

Different outputs for increasing and decreasing input



Other key static properties

- Accuracy (closeness to true value)
- Repeatability and reproducibility
- Threshold and dead zone
- Drift and stability

4. Accuracy and Errors

Types of errors

- **Gross errors** – human or system mistakes
- **Systematic errors** – bias, calibration, nonlinearity, influence quantities
- **Random errors** – noise, variations

Error representation

Measurement = True value + Error
Error = Systematic + Random

Accuracy metrics

- Absolute error: $e = y_{meas} - y_{true}$
- Relative error: $\epsilon_r = e / y_{true}$
- Percent error: $\%e = 100 \cdot \frac{e}{y_{true}}$

Uncertainty

- Type A – statistical (from data)
- Type B – other sources (specifications, calibration, etc.)

Combined uncertainty:

$$u_c = \sqrt{u_A^2 + u_B^2}$$

Expanded uncertainty: $U = k \cdot u_c$
($k \approx 2$ for ~95% confidence)

5. Dynamic Behaviour

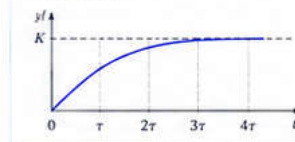
Key concepts

- Time-varying measurands require dynamic analysis.
- Important parameters: Speed of response, delay, bandwidth, time constant, overshoot, settling time.

First-order system

$$G(s) = \frac{K}{\tau s + 1}$$

Step response:



Frequency response

$$|G(j\omega)| = \frac{K}{\sqrt{1 + (\omega\tau)^2}}$$

Phase: $\phi(\omega) = -\arctan(\omega\tau)$

Performance trade-offs

Faster response $\leftrightarrow$ lower accuracy
Higher resolution $\leftrightarrow$ slower update rate (longer delay)

6. Counters (Digital Instruments)

Function

Convert event frequency into digital count during gate time T_g .
Discrete-time, zero-order hold.

Key characteristics

- Update period: T_g
- Resolution (quantization): ± 1 count
- Relative quantization error: $\pm \frac{1}{f_{in} T_g}$
- Gate time accuracy affects frequency measurement
- Trade-off: longer $T_g \rightarrow$ better resolution but slower update (higher delay)

Sources of error

- Quantization (± 1 count)
- Gate time error
- Input event uncertainty
Clock jitter and noise
- Resolution vs. update rate trade-off

Good design

- Appropriate T_g for required accuracy
- Clean input and proper conditioning
- Stable time base and synchronization
- Consider bandwidth and latency needs



Key Takeaway

A high-quality measurement depends on the whole chain: sensing $\rightarrow$ conversion $\rightarrow$ conditioning $\rightarrow$ processing $\rightarrow$ presentation, and on understanding instrument behavior and errors.



For successful measurements:

- ✓ Choose the right instrument for the task.
- ✓ Understand its static and dynamic characteristics.
- ✓ Minimize and quantify errors and uncertainty.
- ✓ Match performance to application requirements.



Good measurements = proper instrument + correct use + awareness of limitations.