Software Metrics & Software Metrology

Alain Abran

Chapter 3
Metrology & Quality Criteria in Measurement

Agenda

This chapter covers:

- Introduction to metrology
- A model of a measuring device
- Quality criteria for the design of a measurement method
- Quality criteria for the application of a measurement method
- Quality criteria for the measurement results

Agenda

This chapter covers:

- Introduction to **<u>metrology</u>**
- A model of a measuring device
- Quality criteria for the design of a measurement method
- Quality criteria for the application of a measurement method
- Quality criteria for the measurement results

Introduction to metrology

- Measurement is one of a number of analytical tools used in the scientific fields, including engineering, as well as in other fields such as business administration and a significant number of the social sciences.

- The basis of measurement in these fields is a large body of knowledge, built up over centuries and millennia, which is the domain commonly referred to as "**metrology**".
  - This domain is supported by government metrology agencies, which are found in most industrially advanced countries.
  - The ISO 'International Vocabulary of Basic and General Concepts and Associated Terms', often referred to as the **VIM**, represents the international consensus on a common and coherent terminology for the set of concepts of metrology.

Introduction to metrology

- The term “metrology” is defined in the VIM as ‘**the science of measurement and its application**’.

- Metrology underlies all measurement-related concepts in the natural sciences and engineering, and to each of the different interpretations of a *software metrics* is associated a related distinct metrology term with related metrology criteria and relationships with other measurement concepts.

History of the VIM

- In 1984, the ISO published the 1st edition of the international consensus on the basic and general terms in metrology (VIM).
- In 1993, the VIM was reviewed, and then the ISO published the 2nd edition.
- In 2007, the ISO published its 3rd edition to integrate, in particular, concepts related to measurement uncertainty and metrological traceability, and nominal properties (Approved by the 8 organizations represented in the Joint Committee for Guides in Metrology).

Introduction to metrology

- The VIM 2007 edition on metrology presents 144 terms in 5 categories and in increasing order of complexity:

  (in parentheses, the number of terms in each category)

  - Quantities and Units (30 terms),
  - Measurements (53 terms),
  - Devices for measurement (12 terms),
  - Properties of measuring devices (31 terms), and
  - Measurement Standards – Etalons (18 terms).

Agenda

This chapter covers:

- Introduction to metrology
- A model of **a measuring device**
- Quality criteria for the design of a measurement method
- Quality criteria for the application of a measurement method
- Quality criteria for the measurement results

A model for measuring devices

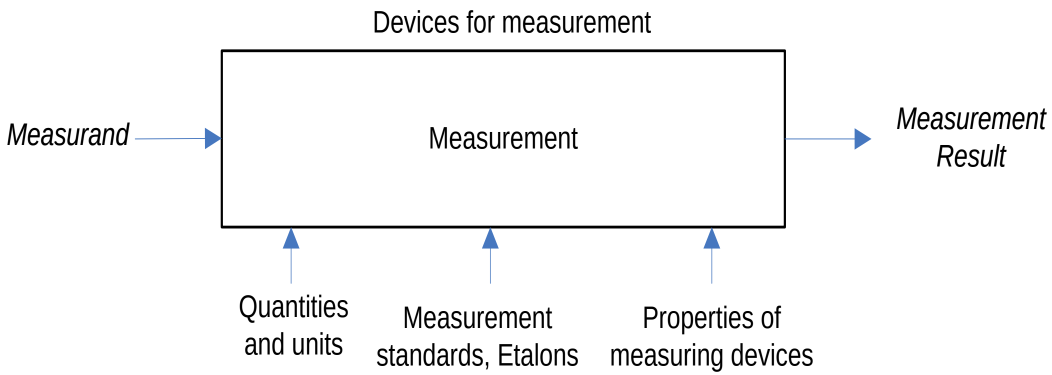
- A measurement process can be entirely automated, partially automated, or entirely manual.

Examples of Types of Measurement Processes

- **Entirely automated**: a measurement process, and the corresponding measuring device, to measure radioactivity in a nuclear power plant
- **Partially automated**: a surveyor who uses a laser-guided device to measure the distance across a river
  - This includes a number of procedures to position his laser-guided device correctly, to carry out various verification tasks and controls, to record readings, etc.
- **Entirely manual**: the counting of apples in a shopping bag.

A model for measuring devices

- How do you describe a measurement process, and what constitutes a measuring device?
- The classical representation of a production process is used here (see below) to identify the necessary elements of a device for measuring and the relevant relationships across these elements, where:
  - The input is labled 'Measurand',
  - the output is labeled "Measurement results",
  - the process itself is labeled "Measurements", in the sense of measurement procedure, and
  - the control variables are "Etalons" and "Quantities and units".



A model for measuring devices

- The set of concepts is represented as the “Devices for measurement”, and the measurement operations are themselves influenced by the “Properties of the measuring devices”.

- Note: in the VIM, the term “measurements”, when used as a single term, corresponds to <u>the process for measuring</u>:

  - That is: having the object of experimentally obtaining one or more quantity values, representing a measurement result that can reasonably be attributed to a quantity intended to be measured – a measurand.

Agenda

This chapter covers:

- Introduction to metrology
- A model of a measuring device
- Quality criteria **<u>for the design</u>** of a measurement method
- Quality criteria for the application of a measurement method
- Quality criteria for the measurement results

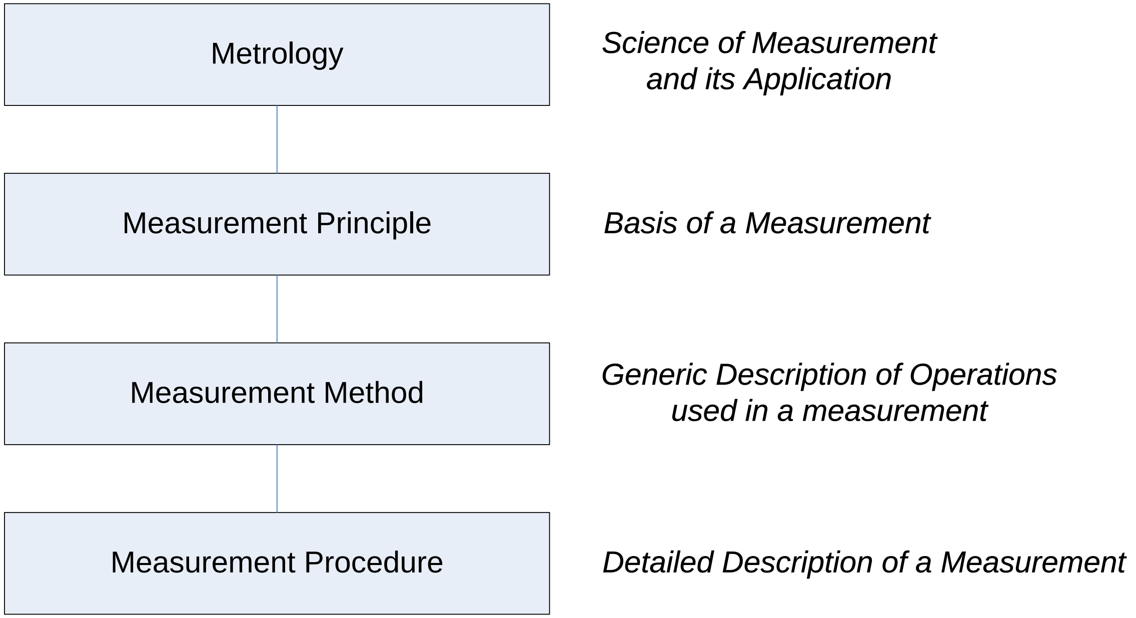
Quality criteria for the design of a measurement method

- The criteria for a ‘good’ design of a software measurement method refer to 3 sets of metrology concepts:
  - Measurement foundation
  - Quantities and units
  - Measurement standards – Etalons

Quality criteria for the design of a measurement method

Measurement Foundation

- A measurement method within a hierarchy of concepts constitutes the measurement foundation.
  - In this figure, the hierarchy is defined top-down, from the most general to the specific



  - The hierarchy of measurement-related concepts in Figure is referred to as the ***measurement foundation***.

Quality criteria for the design of a measurement method

- Level 1: Metrology - includes all the theoretical and practical aspects of measurement & refers to the science of measurement in the VIM, whatever the measurement uncertainty and field of application (science or technology).

- Level 2: Measurement principle - is specific to the measurement of a particular concept to be measured and represents the phenomenom serving as a basis of a measurement.

- Level 3: Measurement method - is defined in the general sense as a logical organization of operations used in a measurement.

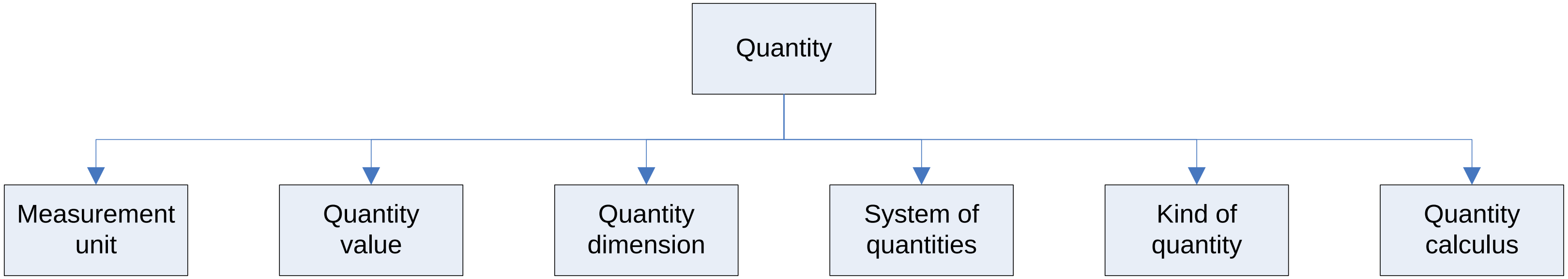
- Level 4: Instantiation of the measurement method in a measurement procedure as a detailed description of a measurement, and based on a measurement model, and including any calculation to obtain a measurement results.

Quality criteria for the design of a measurement method

- **Quantities**
  - Metrology specifies that quantities (typically expressed as numbers) are not sufficient as measures per se.
    - Additional concepts must also come into play in order for a quantity (or a number) to be recognized as a measure in metrology.
  - In particular, metrology requires the following properties (or criteria when analyzing the quality of the design of a measurement method) – see Figure next slide:
    - a measurement unit,
    - the quantity value,
    - the quantity dimension,
    - a system of quantities,
    - kind of quantity,
    - the quantity calculus

Quality criteria for the design of a measurement method

The elements of a quantity in metrology



Quality criteria for the design of a measurement method

Table: Characteristics of the 6 elements of a quantity in metrology

Quantity					
Measurement unit	Quantity value	Quantity dimension	System of quantities	Kind of quantity	Quantity calculus
Base unit Derived unit Coherent derived unit System of units Coherent system of units Off-system measurement unit International system of units (SI) Multiple of a unit Submultiple of a unit	Numerical quantity value Quantity-value scale Ordinal quantity-value scale Conventional reference scale	Quantity of dimension one	Base quantity Derived quantity International system of quantities (ISQ)	Ordinal quantity Nominal property	Quantity equation Unit equation Conversion factor between units Numerical value equation

Quality criteria for the design of a measurement method

A) Measurement unit

Within a measurement unit, there is:

- a base unit (e.g. a meter with the symbol 'm')
- a derived unit (e.g. the meter per second, symbol m/s, of speed)
- a multiple and a sub-multiple of a unit, etc.

The Measurement Unit – Indispensable in Measurement & Metrology

In metrology, a quantity (i.e. a number) requires a reference, such as a unit, in order to be meaningful:
– the quantity 4 is meaningless in measurement (unless its unit is specified as one)
– 4 cm and 4 kg are well recognized, and meaningful, as measurement results.

Summary

A number can only be recognized as a measure if it is accompanied by a unit specified by convention.

Challenge

List software metrics for which:
– units are not specified
– units are specified

Quality criteria for the design of a measurement method

B) Quantity value

- In metrology, a number of concepts are associated with the quantity value, in addition to the purely numerical value obtained from a device, such as a measuring instrument.
  - For example, a numerical value on a thermometer is obtained by reading that value off a conventional reference scale on the thermometer.
    - This reading might be subject to a measurement error of 0.5 degree relative to the measured quantity value of the temperature at that time, had the thermometer been calibrated perfectly and no errors made in reading the quantity-value scale on the thermometer.

Quality criteria for the design of a measurement method

C) <u>Dimension of a quantity</u>

- The VIM 2007 defines the dimension of a quantity as an expression of the dependence of a quantity on the base quantities of a system of quantities as the product of the powers of the factors corresponding to the base quantities, omitting any numerical factors.

- The VIM indicates that a quantity of dimension one (e.g. a dimensionless quantity) might also exist.
  - For example:
    - Some quantities of dimension one are defined as the ratios of two quantities of the same **kind**.
    - Numbers of entities are quantities of dimension one

Quality criteria for the design of a measurement method

D) System of quantities

- A system of quantities may include both base quantities and derived quantities (and the international system of quantities – ISQ) where:
  - A **base quantity** is defined as a conventionally chosen subset of a given system of quantities, where no subset quantity can be expressed in terms of the others.
    - Example: The set of base quantities in the **International System of** Quantities such as: time in seconds, length in meters, etc.
  - A **derived quantity** is defined as a quantity, in a system of quantities, defined in terms of the base quantities of that system
    - Example: mass density is a derived quantity defined as the quotient of mass and volume (where volume is itself = length to the third power).

Quality criteria for the design of a measurement method

E) <u>Kind of quantity</u>

- The kind of quantity is defined as the aspect common to mutually comparable quantities.

F) <u>Quantity calculus</u>

- The quantity calculus is a set of mathematical rules and operations applied to quantities other than ordinal quantities.

Quality criteria for the design of a measurement method

- **Measurement Standards – Etalons**
  - Required in the design of a measurement method in the sciences, and in engineering in particular: a measurement standard, or etalon (from the French, “étalon”):
  - **Measurement Standard – Etalon:** realization of the definition of a given **quantity**, with stated **quantity value** and associated **measurement uncertainty**, used as a reference.
    1. A “realization of the definition of a given quantity” can be provided by a **measuring system**, a **material measure**, or a reference material.
    2. A measurement standard is frequently used as a reference in establishing **measured quantity values** and associated measurement uncertainties for other quantities of the same **kind:**
       - **to** establish **metrological traceability** through **calibration** of other measurement standards, **measuring devices**, or measuring systems.

Quality criteria for the design of a measurement method

The term "realization" is used in the VIM in the most general meaning. It denotes 3 procedures of "realization".

1. The physical realization of the **measurement unit** from its definition and is realization *sensu stricto*.
2. "Reproduction": consists not in realizing the measurement unit from its definition but in setting up a highly reproducible measurement standard based on a physical phenomenon, e.g. in case of use of frequency-stabilized lasers to establish a measurement standard for the metre, of the Josephson effect for the volt or of the quantum Hall effect for the ohm.
3. Consists in adopting a material measure as a measurement standard. It occurs in the case of the measurement of the measurement standard of 1 kg.

Examples of Measurement Etalons

a) 1 kg mass standard
b) 100 Ω standard resistor
c) cesium frequency standard
d) reference solution of cortisol in human serum having a certified concentration

Quality criteria for the design of a measurement method

- Many additional concepts are directly related to the measurement etalon, and presented in Table below in 2 groups:

(Measurement) Standard / Etalon	**Conservation of a (Measurement) Standard**
International (Measurement) Standard National (Measurement) Standard Primary Measurement Standard Secondary Measurement Standard Reference Measurement Standard Working Measurement Standard Transfer Measurement Standard Traveling Measurement Standard Intrinsic Measurement Standard	Calibrator Reference Material (RM) Certified Reference Material (CRM) Commutability of a Reference Material Reference Data Standard Reference Data Reference Quantity Value

Quality characteristics of a Measurement Standard / Etalon

Quality criteria for the design of a measurement method

Examples:

- A “transfer measurement standard” is used as an intermediary to compare standards. Examples:
  - To compare a British national measurement standard kept in London with the corresponding US national standard.
  - Gasoline pumps must be calibrated to a national measurement standard to ensure that the customer receives the volume of gasoline for which he has paid.
    - This is achieved through a “working measurement standard” used by a federal agency to monitor and certify all gas pumps at every gasoline station in the country.

Agenda

This chapter covers:

- Introduction to metrology
- A model of a measuring device
- Quality criteria for the design of a measurement method
- Quality criteria **for the application** of a measurement method
- Quality criteria for the measurement results

Quality criteria for the application of a Measurement Method

The application of a measurement method requires:

1. a measurement procedure
2. devices for measurement
3. operations with devices such as a measuring system
4. properties of such measuring devices.

Quality criteria for the application of a Measurement Method

Measurement procedure

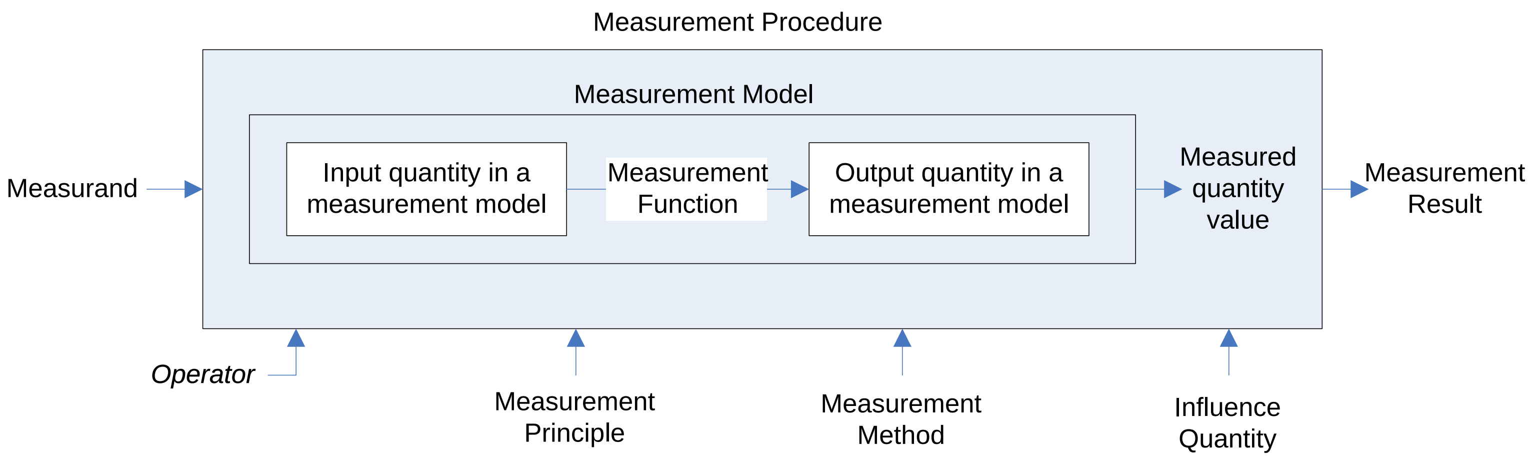
Measurement presupposes the description of a quantity commensurate with the intended use of a measurement result, a measurement procedure and a calibrated measuring system operating according to the specified measurement procedure, including the measurement conditions, in order to experimentally obtain one or more quantity values (See table below)

Measurement				
Measurement result	**Measurement procedure**	**Measuring device**	***Measurement conditions***	**Measurement error**
Measured quantity value True quantity value Conventional quantity value	Reference measurement procedure Primary reference measurement procedure	Measuring system	Repeatability condition of measurement Intermediate precision condition of measurement Reproductibity condition of measurement	Systematic measurement error Measurement bias Random measurement error

Description of the measurement elements

Quality criteria for the application of a Measurement Method

- The application of a measurement procedure requires a number of elements and processes to ensure that the measurement result is of high quality:
  - the necessary elements (i.e. the criteria that must be verified to ensure that a measurement procedure is applied correctly).
- Figure below presents a process representation of a measurement procedure with its corresponding elements described in the VIM
  - again represented as a process model having several inputs, many control variables, and an output representing the measurement results.



The elements of a measurement procedure

Quality criteria for the application of a Measurement Method

- To carry out a measurement exercise, an operator should design and follow a measurement procedure, which consists of a detailed description of a measurement, specifically described, according to 1 or more measurement principles and to a given measurement method, based on a measurement model and including a measurement function to obtain a measured quantity value, representing a measurement result.

- The instantiation of a measurement procedure handles a measurement model representing the mathematical relation among all quantities involved in a measurement.
  - This measurement model can involve 1 or more equations.

Quality criteria for the application of a Measurement Method

- In turn, the instantiation of a measurement model handles a measurement function, which can be symbolized as an algorithm, and produces the value of which, when calculated using known quantity values for the input quantities in a measurement model, is a measured quantity value of the output quantity in the measurement model.
  - This is the value which represents the measurand given in input.
- Finally, the measurement result can be expressed either:
  - by a measured quantity value and a measured uncertainty or
  - by a single measured quantity value if the measurement uncertainty is considered to be negligible for some purpose.

Quality criteria for the application of a Measurement Method

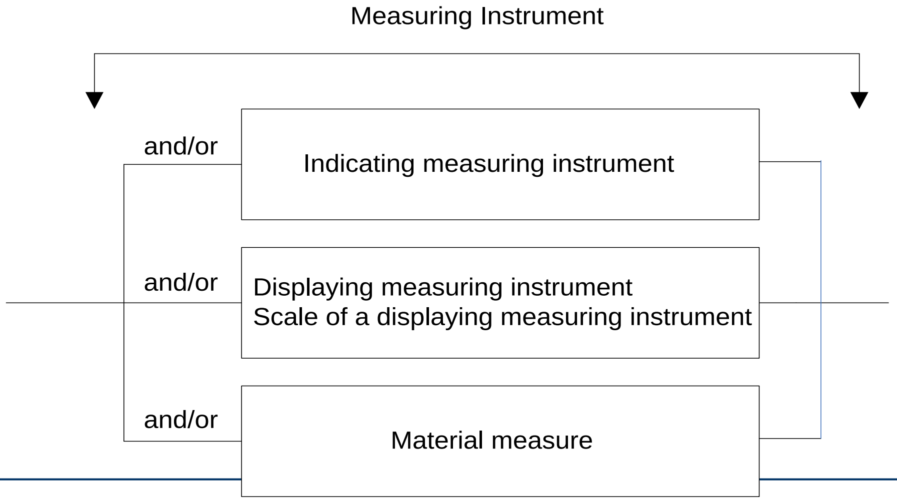
The measurement result can have been influenced by:

- The operator
  - For example: when an operator is an inexperienced surveyor and has never executed a measurement procedure with a laser-guided distance measuring device, he may make many more mistakes than an experienced surveyor.
- The measurement principle
  - For example: thermoelectric effect applied to the measurement of a temperature.
- The measurement method selected
  - For example: there are now 5 ISO-recognized methods for measuring the functional size of software.
- A quantity which influences the measurement process
  - For example: the temperature may need to be taken into consideration during the measurement of the length of an object.

Quality criteria for the application of a Measurement Method

Devices for measurement

- A measuring system may consist of only measuring instrument (see Figure below), which can include:
  - an indicating measuring instrument
  - a displaying measuring instrument (a measuring device may or may not store the measurement results):
    - A household thermometer typically does not record the temperature.
    - An industrial thermometer must often record the temperature (at specified time intervals).
  - a scale of a displaying measuring instrument, and
  - a material measure.

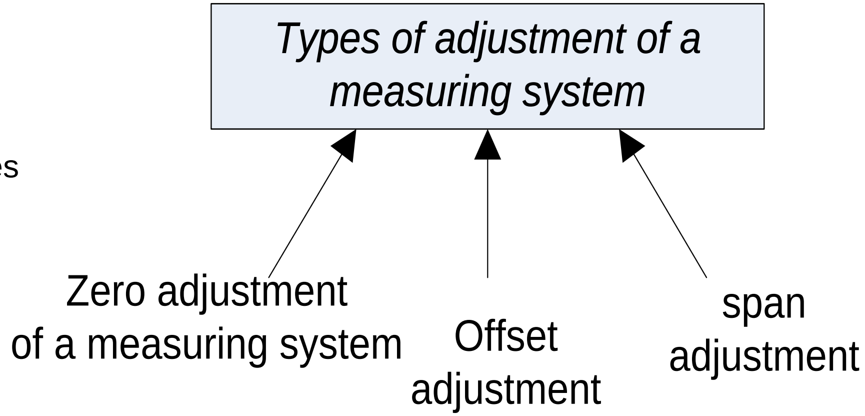


A typical measuring device

Quality criteria for the application of a Measurement Method

- While reading a household lead thermometer typically only involves checking the mark on the thermometer's scale, the use of a more complex measuring system might require a number of other operations, such as an adjustment of a measuring system – see Figure below.
- Many types of adjustment of a measuring system include:
  - zero adjustment of a measuring system,
  - offset adjustment, and
  - span adjustment (called gain adjustment).

Operations on measuring devices



Quality criteria for the application of a Measurement Method

- **Properties of such measuring devices**
  - A measuring device (such as a measuring instrument or a measuring system) has an indication that can be presented in visual or acoustic form or can be transferred to another device, a blank indication and a measuring interval, which represents a set of values of the same kind within which the instrumental uncertainty can be expected
    - i.e. within defined conditions, such as indication interval, nominal indication interval, range of a nominal indication interval, and nominal quantity value.
  - The quality of the measurement results will also depend on a number of properties related to the measuring devices, each of which corresponds to a quality criterion. Table below lists a number of the characteristics described in the VIM.

Characteristics of measuring devices	
	Selectivity of a measuring system **Stability of a measuring instrument** **Step response time** **Accuracy class**

Agenda

This chapter covers:

- Introduction to metrology
- A model of a measuring device
- Quality criteria for the design of a measurement method
- Quality criteria for the application of a measurement method
- Quality criteria **<u>for the measurement results</u>**

Quality criteria for Measurement Results

In metrology, the quality criteria for measurement results can be classified into the following 4 categories (See Table next slide):

- Measurement precision
- Measurement uncertainty
- Calibration
- Metrological traceability

Quality criteria for Measurement Results

Measurement Precision	Measurement Uncertainty	Calibration	Metrological traceability
Measurement accuracy Measurement trueness Measurement repeatability Intermediate measurement precision Measurement Reproducibility	Definitional uncertainty Type A evaluation of measurement uncertainty Type B evaluation of measurement uncertainty Standard measurement uncertainty Combined standard measurement uncertainty Relative standard measurement uncertainty Uncertainty budget Target measurement uncertainty Expanded measurement uncertainty Coverage interval Coverage probability Coverage factor	Calibration hierarchy Verification Validation Correction	Metrological traceability chain Metrological traceability to a measurement unit Metrological comparability of measurement results Metrological compatibility of measurement results

Detailed quality criteria for a measurement result

Summary

This chapter has covered:

- Introduction to metrology
- A metrology model of a measuring device
- Quality criteria for the design of a measurement method
- Quality criteria for the application of a measurement method
- Quality criteria for the measurement results

- Additional material

Introduction to metrology

While metrology has a long tradition of use in physics and chemistry, it is rarely referred to in the software engineering literature. Notable exceptions are:

- Carnahan *et al.* [1997] are among the first authors to identify what they referred to as "IT metrology".
  - They highlight the challenges & opportunities arising from the application of the metrology concepts to information technology.
  - They proposed logical relationships between metrology concepts, specifically 4 steps to be followed to obtain measured values:
    - defining quantities/attributes,
    - identifying units and scales,
    - determining the primary references, and
    - settling the secondary references.

Introduction to metrology

- Gray [1999] discusses the applicability of metrology to information technology from the software measurement point of view.

- The VIM is widely known in the sciences & engineering, however it is almost unknown in the software engineering community.
  - Consequently, most of its concepts are not being used, either by those proposing new software measures to the software engineering community, or by the users of these proposed measures.