# Measurement Uncertainty – Knowing the Unknown


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# This presentation covers

- Fundamental uncertainty principles
- Measurement uncertainty estimation process
- Intermediate level interpretation and application of
  - Measurement uncertainty
  - Treatment of measurement bias
  - Decision Rules

# This presentation does not cover

- Gage R&R methods
- Process capability interpretations
- Monte Carlo simulations
- Economic impact when using uncertainty in product conformance

# Terminology

- Accuracy – Qualitative only
- Uncertainty – Quantitative only
- Traceability – Qualitative and Quantitative

**Inch/Metric**

| Range | Order No. | Accuracy | Resolution | Remarks |
|---|---|---|---|---|
| 0 - 4" / 0 - 100mm | **500-170-20** | ±.001" | .0005" / 0.01mm | .075" rod depth bar |
| 0 - 4" / 0 - 100mm | **500-195-20*** | ±.001" | .0005" / 0.01mm | .075" rod depth bar |
| 0 - 6" / 0 - 150mm | **500-171-20** | ±.001" | .0005" / 0.01mm | — |
| 0 - 6" / 0 - 150mm | **500-174-20** | ±.001" | .0005" / 0.01mm | Carbide-tipped jaws for OD measurement |
| 0 - 6" / 0 - 150mm | **500-175-20** | ±.001" | .0005" / 0.01mm | Carbide-tipped jaws for OD & ID measurement |

**Specifications**

| Order No. | 102-701 | 102-707 | 102-711 | 102-717 | 101-711 | 101-717 | 102-702 | 102-708 | 102-712 | 102-718 |
|---|---|---|---|---|---|---|---|---|---|---|
| Measuring range | 0-25mm | | 0-1" | | | | 25-50mm | | 1-2" | |
| Graduation | 0.01mm | 0.001mm | .001" | .0001" | .001" | .0001" | 0.01mm | 0.001mm | .001" | .0001" |
| Instrument error 68°F (20°C) | ±2μm | | ±.0001" | | | | ±2μm | | ±.0001" | |
| Flatness of measuring faces | 0.6μm | | | | | | | | | |
| Parallelism of measuring faces | 2μm | | | | | | | | | |
| Mass | .40 lbs. (180g) | | | | | | .60 lbs. (270g) | | | |
| Measuring force | 5N-10N | | | | | | | | | |

# Traceability

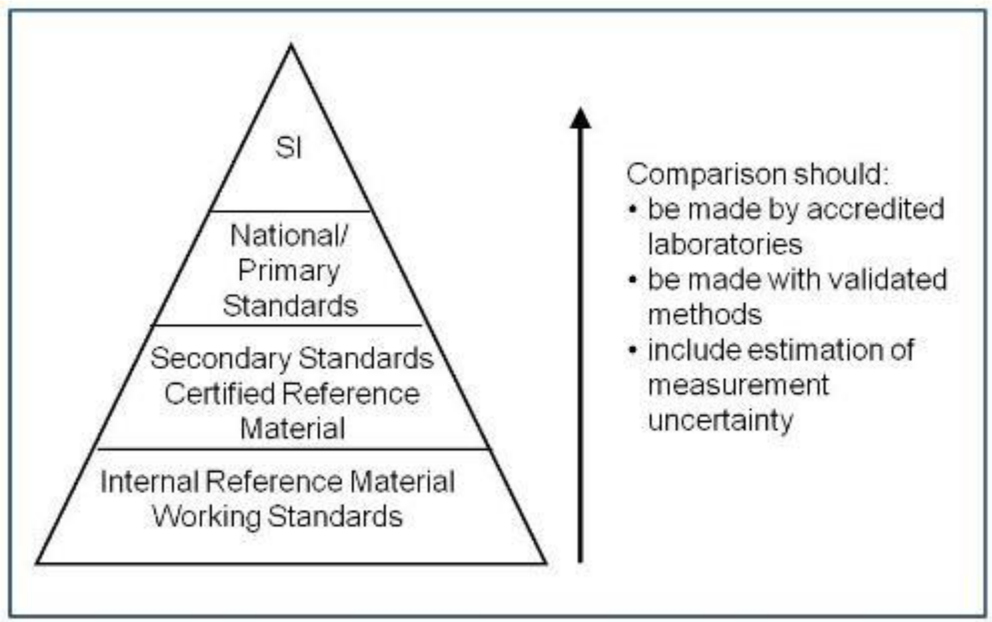
**2.41** (6.10)
**metrological traceability**

property of a **measurement result** whereby the result can be related to a reference through a documented unbroken chain of **calibrations**, each contributing to the **measurement uncertainty**

Le Système international d'unités
The International System of Units
SI

National Institute of Standards and Technology
U.S. Department of Commerce

**MahrFederal, Mitutoyo, others**



# True Value Vs Reference Value

- True Value is the actual value of an artifact
  - unknown and unknowable (with certainty)
- True Value ≠ Reference Value
- Reference Value
  - Accepted value of an artifact or Accepted Reference Value (ARV)
  - Used as the surrogate for the true value
- Uncertainty can be minimized by using a well defined, traceable reference value

# Terminology: The Measurand

- **A clearly stated specification requirement per Y14.5**
- **A set of specifications defining what is intended to be measured**
- **Specifies the "conditions" of all potential influence quantities so ONE "true value" can be realized.**

*Unless otherwise specified "all points on the surface" (infinite set of points) are used for analysis for all geometric controls under the following conditions:*

•Temperature = 20°C
•Sampling = 100%
•Clamp force = none (free-state)
•Tip radius = zero
•Tip force = zero
•Filter = none

**Validity Conditions**

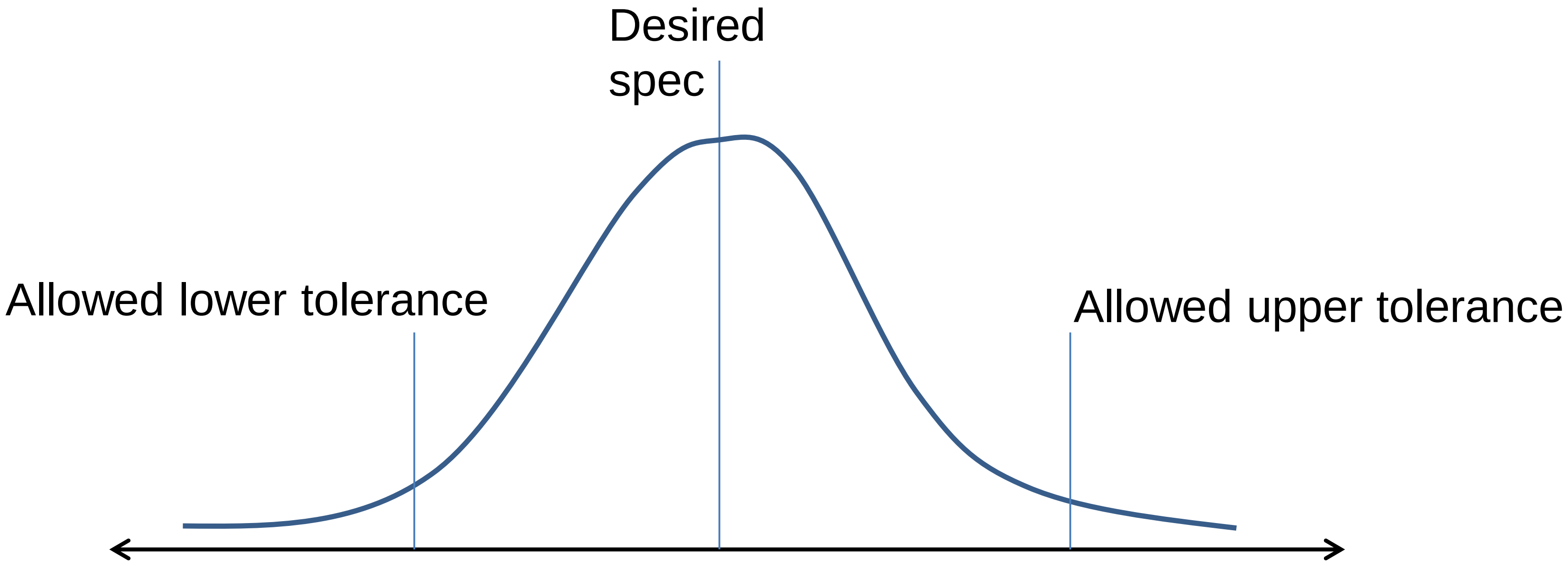
# Measurements help make decisions

- To continue or stop a process
- To accept or reject a product
- To optimize the tolerancing strategy for a design
- To take corrective action or withhold it
- To establish scientific or legal fact

**Importance of a DECISION dictates the criticality of the MEASUREMENT and not the other way around!**

# Typical Manufacturing Process

- Generally assumed to have Gaussian characteristics




- What are the consequences of shipping product which are outside tolerance?
- If no consequence, why not just ship everything?

# Qualifying a Valid Result


- Resolution
- Bias
- Linearity
- Repeatability
- Reproducibility
- Consistency, Uniformity, Sensitivity
- Gage R&R
- Measurement System Capability or Performance
- **Uncertainty**

# Uncertainty

Quantification of the doubt about the measurement result

Allows measurement to be treated as a SCIENCE rather than a mere qualification tool

Smaller (evaluated) is better !!!

# What is not UNCERTAINTY?

- Mistakes made by operators
- Tolerances
- Specifications
- Accuracy (or rather inaccuracy)
- Known Errors (since they would be corrected)
- Statistical analysis

# The Questioning Process

- **Who** is part of Uncertainty evaluation ?
- **When** should Uncertainty be estimated ?
- **Why** is Uncertainty critical to your business ?
- **Where** to implement Uncertainty ?
- **What** is Uncertainty ? - A closer look..

# Measurements Uncertainty Estimation Methods

- Sensitivity Analysis-aka “Uncertainty Budgeting” estimating various contributions
- Expert Judgment-“best-guess” estimate
- Substitution-repeated measurement of calibrated master part
- Simulation-modeling and simulating the measurement process, including the errors

# Measurement Uncertainty Analysis Framework

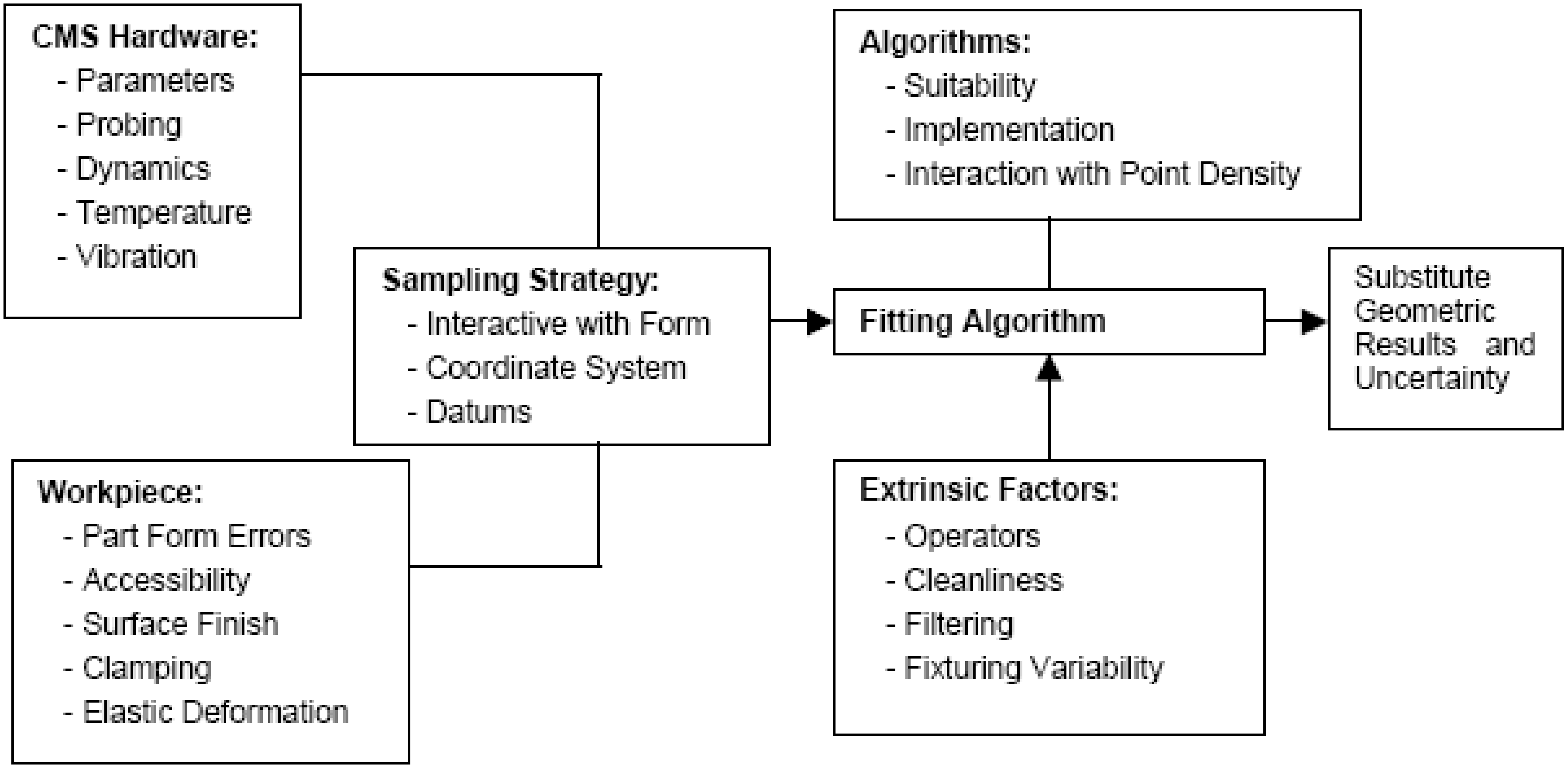
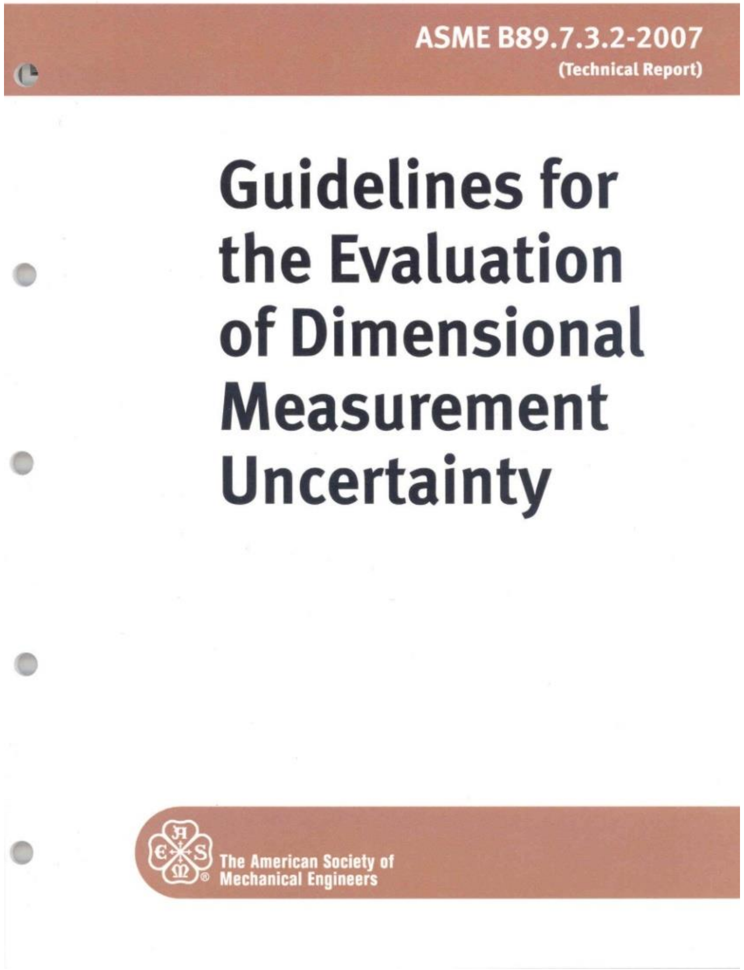



Figure 1: Error components that lead to uncertainties.

**Source :Task Specific Uncertainty in Coordinate Measurement**

# B89.7.3.2 – 2007 Dimensional Measurement Uncertainty

- Simplified approach to GUM
- No effective degrees of freedom
- No correlations
- No partial derivatives
- Uncertainty components modeled as additive corrections
- Uses simple, intuitive assigned probability densities


ASME B89.7.3.2-2007
(Technical Report)

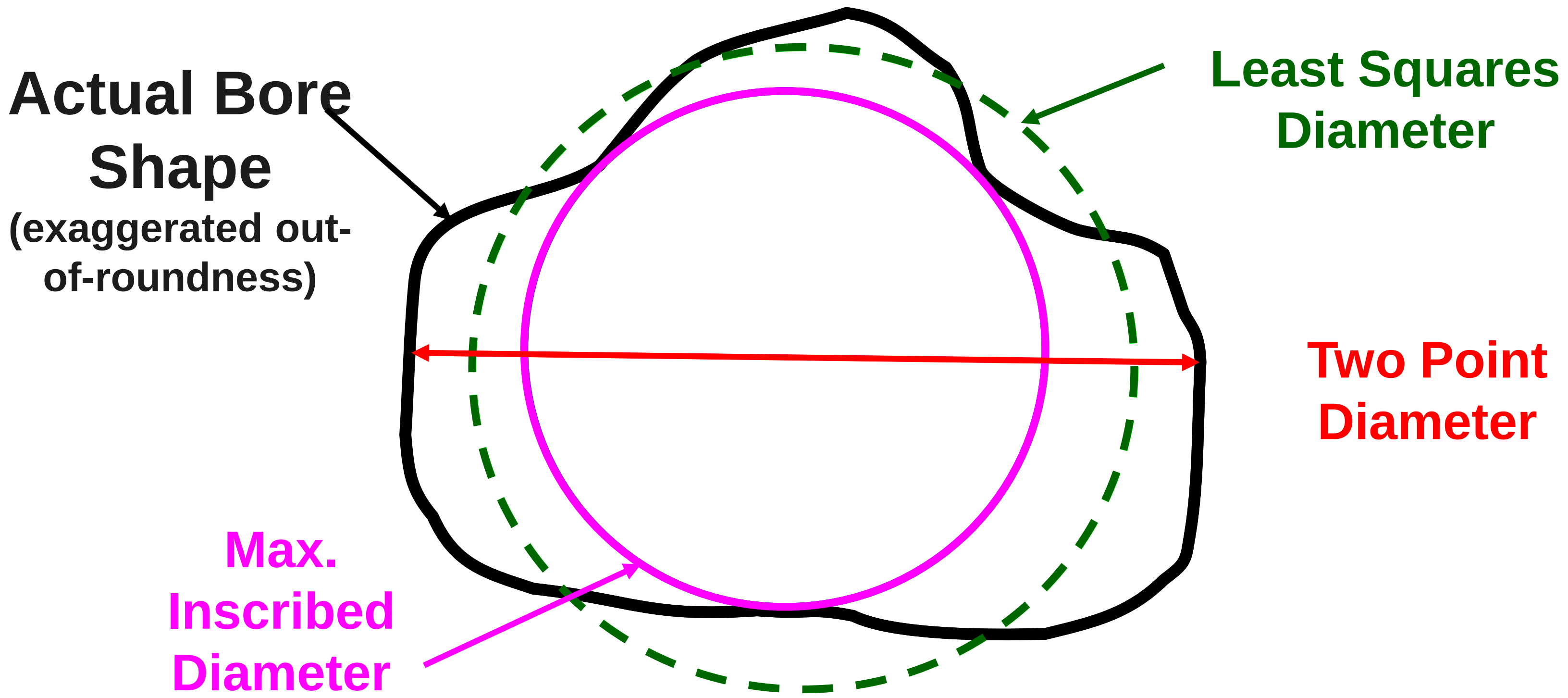
Guidelines for the Evaluation of Dimensional Measurement Uncertainty

The American Society of Mechanical Engineers

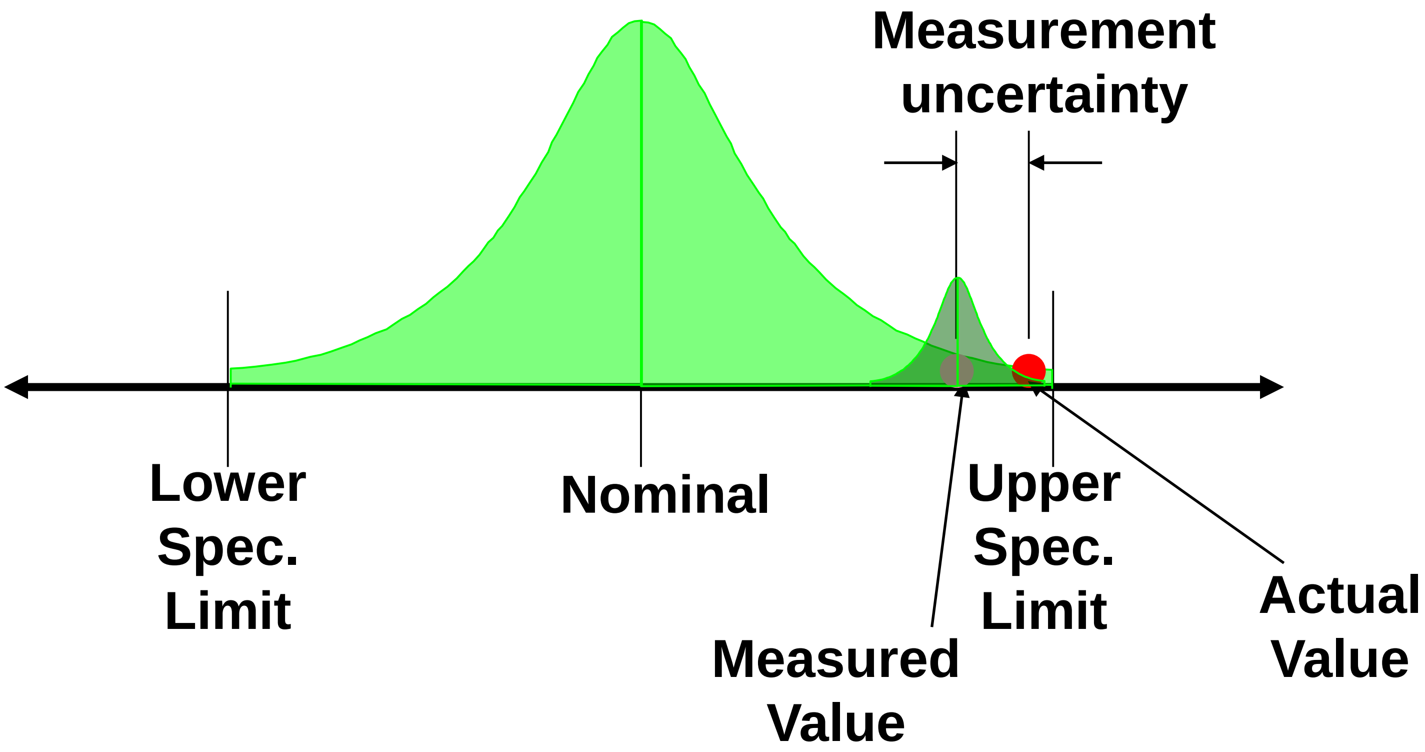
# Terminology: The Measurand

"Diameter of the Bore"

Poorly defined measurand by incomplete or ambiguous instructions: which diameter is desired?



# Understanding measurement uncertainty

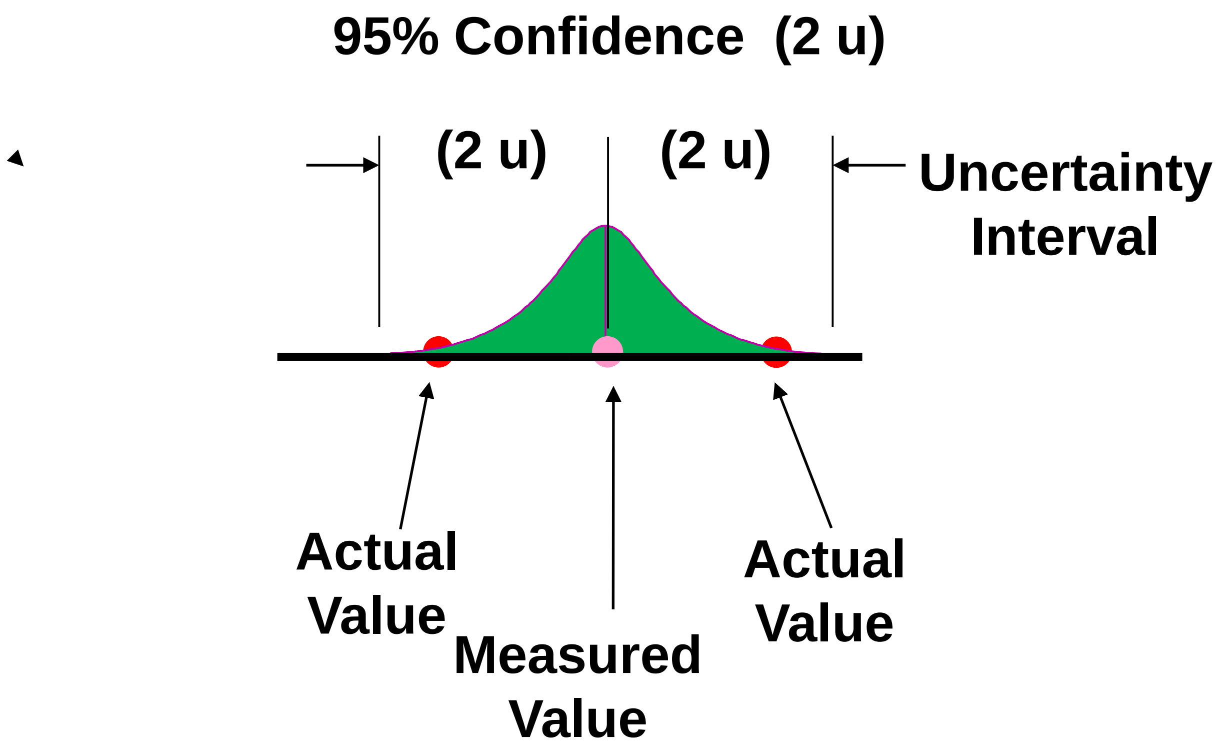



**Estimating measurement uncertainty means:**

1. **Sources of the measurement uncertainty gap**
2. **Magnitude of each source**

# Expanding Measurement Uncertainty

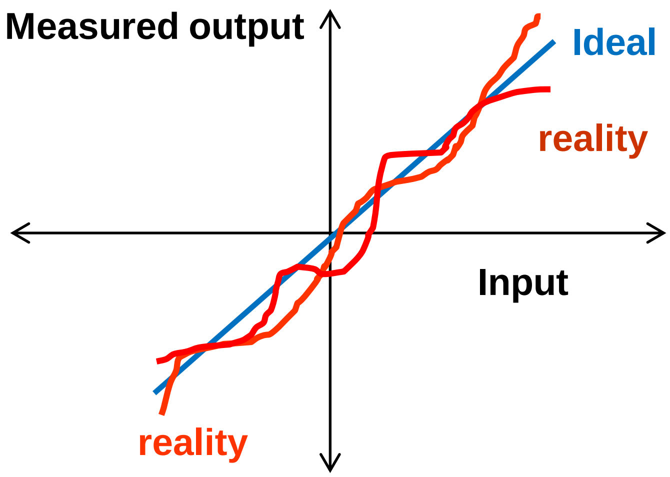
How far do we expand our estimation?



# Type A & B errors

## Type A errors

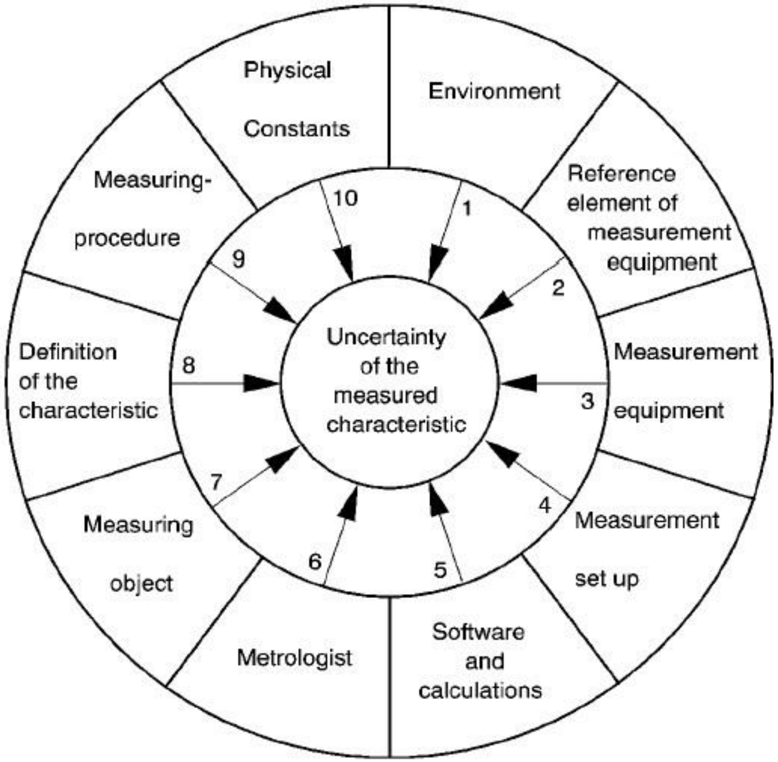
- Result from a test or series of tests
- Statistically estimated
  - Standard Deviation
  - Pooled Standard Deviation
  - Standard Deviation of the Mean




## Type B errors

- Used when Type A cannot be estimated
- Usually
  - Expert opinion
  - Published value
    - Manufacturer's specification
    - Calibration certificate
    - Handbook value
  - Prior history of similar measurement systems

# Uncertainty contributors




(ISO/TS 14253-2)

**100s – 1000s Of possible contributors**

**Reduced to**

**20 or less potential influence quantities**

**Reduced to**

**10 or less input quantities**

# Why is Temperature Important?

- **Materials change size with temperature**
  - thus, temperature affects workpiece dimensions (size and shape)
  - temperature also affects gage (CMM) dimensions (size and shape)

- **Size change can be quite large over a normal range of workshop temperatures**
  - i.e., 'large' relative to size tolerances and measuring uncertainty
  - the part alone can grow bigger or smaller
  - but the CMM (gage) can also change size, and may not be properly compensated

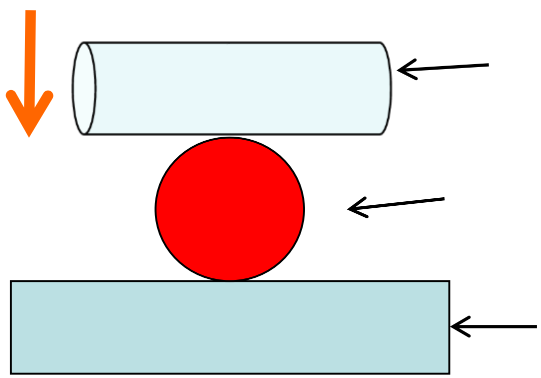
# Two Examples of how Force is employed in a Measurand

- The definition of the size of a cylinder per ASME Y14.5 is specified at **zero** applied force. (Do you measure at zero force?)

- The definition of the size of a thread wire is at **a specified force** and contact geometry (flat and cylinder); see ASME B89.1.17. This definition includes the deformation due to the applied force

- These are fundamentally different size definitions

Force: 40 Oz



Cylindrical contact (steel, 0.75" diameter)

Thread wire for 20 TPI

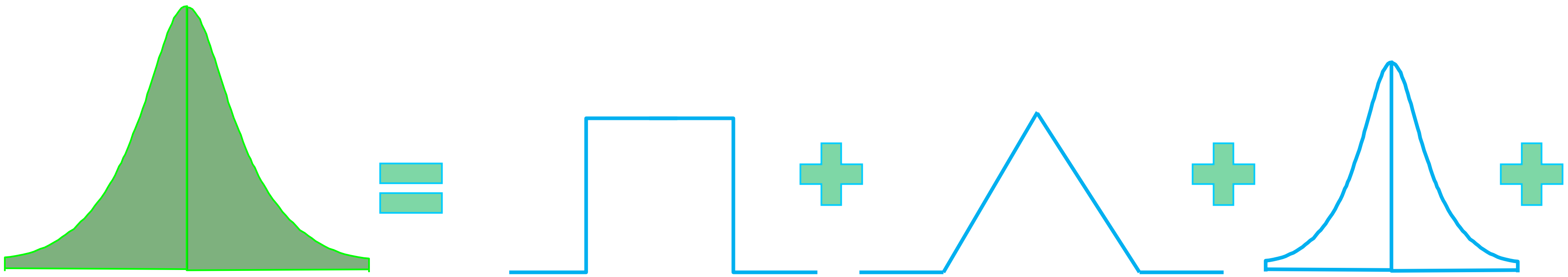
Flat contact (carbide, 0.375 diameter)

# Distributions to analyze data

- Normal
- Uniform (Rectangular)
- Log-normal
- Bi-modal
- Triangular
- U-shaped

# Uncertainty Estimation

## Combining the distributions



**combined standard uncertainty**

**influence quantity distributions**

**Using the ROOT SUM of SQUARES method**

**Table 3. Uncertainty Budget for 10-inch Plain Ring Gage.**

| Uncertainty Source | Estimate (μin) | Type | Distribution | Divisor | Standard Uncertainty (μin) | Variance ($\mu in^2$) |
|---|---|---|---|---|---|---|
| Gage Blocks | 10 | B | Normal | 2 | 5 | 25 |
| Repeatability | 3.2 | A | Normal | 1 | 3.2 | 10.24 |
| Uncertainty of CTE | 20.0 | B | Rectangular | $\sqrt{3}$ | 11.5 | 132.2 |
| Master/part temperature difference | 3.25 | B | Rectangular | $\sqrt{3}$ | 1.88 | 3.52 |
| Probe misalignment | 0.5 | B | Rect | $\sqrt{3}$ | 0.29 | 0.08 |
| Comparator calibration | 3 | B | Rect | $\sqrt{3}$ | 1.73 | 3 |
| | | | | | | |
| Sum of the variances | 174.04 | | | | | |
| Combined standard uncertainty | 13.19 | | | | | |
| Expanded Uncertainty $U$ ($k$=2) | 26.39 ≈ 27 | | | | | |

The uncertainty for the measurement of the 10 in ring gage is 27 μin, which represents an expanded uncertainty expressed at approximately the 95% level of confidence using a coverage factor of k=2.

**Table 3.** Uncertainty budget for NIST master gage blocks

| Source of uncertainty | Standard uncertainty ($k = 1$) |
|---|---|
| 1. Master gage calibration | N/A |
| 2. Long term reproducibility | $0.009\ \mu m + 0.08 \times 10^{-6} L$ |
| 3. Thermometer calibration | N/A |
| 4. CTE | $0.005 \times 10^{-6} L$ |
| 5. Thermal gradients | $0.030 \times 10^{-6} L$ up to $L$=0.1 m |
| 6. Elastic deformation | Negligible |
| 7. Scale calibration | $0.003 \times 10^{-6} L$ |
| 8. Instrument geometry | Negligible |
| 9. Artifact geometry—phase correction | $0.006\ \mu m$ |

**Table 4.** Uncertainty budget for NIST customer gage blocks measured by interferometry

| Source of uncertainty | Standard uncertainty ($k = 1$) |
|---|---|
| 1. Master gage calibration | N/A |
| 2. Long term reproducibility | $0.022\ \mu m + 0.2 \times 10^{-6} L$ |
| 3. Thermometer calibration | N/A |
| 4. CTE | $0.060 \times 10^{-6} L$ |
| 5. Thermal gradients | $0.030 \times 10^{-6} L$ up to $L$=0.1 m |
| 6. Elastic deformation | Negligible |
| 7. Scale calibration | $0.003 \times 10^{-6} L$ |
| 8. Instrument geometry | Negligible |
| 9. Artifact geometry—phase correction | $0.006\ \mu m$ |
| 10. Artifact geometry—gage point position | $0.003\ \mu m$ |

# Measurement Uncertainty: Summary

- Recall that measurement uncertainty is a <u>number</u> associated with a measurement result of a <u>specific</u> measurand
- Hence, metrologists speak of "Task Specific" measurement uncertainty
  - Change either the measurement task or how you measured the feature and you change the measurement uncertainty.
  - Two different metrologist measuring the same measurand with the same equipment will often state different uncertainties because of differences in how they performed the measurement– this might be OK.
  - The same metrologist measuring two different measurands on the same work piece will have two different uncertainties.
  - There is no "one size fits all" uncertainty evaluation where a single uncertainty value applies to all measurement tasks – its all task specific.

# Definitions revisited

- ***Measurand:*** the particular quantity subject to measurement. It is defined by a set of specifications (i.e., instructions) that specifies what we intend to measure; it is not a numerical value. It represents the quantity intended to be measured.
- ***Measurement uncertainty:*** describes an interval centered about the measurement result where we have reasonable confidence that it includes the "true value" of the quantity we are measuring.
- ***Expanded uncertainty (with a coverage factor of 2),*** *U:* a number that defines an interval around the measurement result, *y*, given by $y \pm U$, that has an approximate 95% level of confidence (i.e., probability) of including the true value.
- ***Influence quantity:*** any quantity, other than the quantity being measured, that affects the measurement result.
  - Constructing the list of influence quantities is one of the first steps of an uncertainty evaluation.

# And a few more:

- ***Input quantity:*** a specific "line item" in the uncertainty budget that represents one or more influence quantities combined together into one quantity.

- ***Validity Conditions:*** Included in the definition of the measurand is a description of the set of conditions that specify the values of particular influence quantities relevant to the measurand.

- ***Standard uncertainty:*** a quantitative value describing the magnitude of an uncertainty source.

- ***Combined standard uncertainty, uc:*** the result of combining all of the standard uncertainties of the various uncertainty sources.

# Uncertainty Reporting

1. Define the quantity to be measured (the measurand)
2. Define the measurement method, equipment, and environment
3. State the desired validity conditions of the uncertainty statement
4. List the influence quantities
5. Determine the input quantities and rank the input quantities
6. Estimate and combine the input quantities (combined standard uncertainty)
7. State the expanded uncertainty and the coverage factor used

# Addressing Bias

- When computing an uncertainty statement for cases where there are several sources of uncorrected bias, biases are algebraically added together (explicitly accounting for the sign of the bias).
  - The resulting net bias is stated together with the combined standard uncertainty.

- Occasionally, the case may arise where multiple sources of uncertainty have bias and these biases are not independent.
  - To avoid "double counting" the bias sources, the degree of overlap of the biases is estimated and this amount is subtracted from the bias summation.

- The uncertainty in the overlap correction is added in a RSS manner to the combined standard uncertainty.

- Finally, we point out that the expanded uncertainty must be re-computed if the coverage factor is changed, and in particular,

  that $U_{\pm}$ ($k$ = 2) not equal to 2 X $U_{\pm}$ ($k$ = 1).

# Addressing Bias

- Type A
  - The mean result of several measurement is smaller than the calibrated value of the reference standard, i.e., the bias is negative
- Type B
  - For some measurements, the bias might be estimated rather than directly measured.
- Equations are still the same

  $U+ = 2u_c - \text{(Bias)}$

  $U- = 2u_c + \text{(Bias)}$

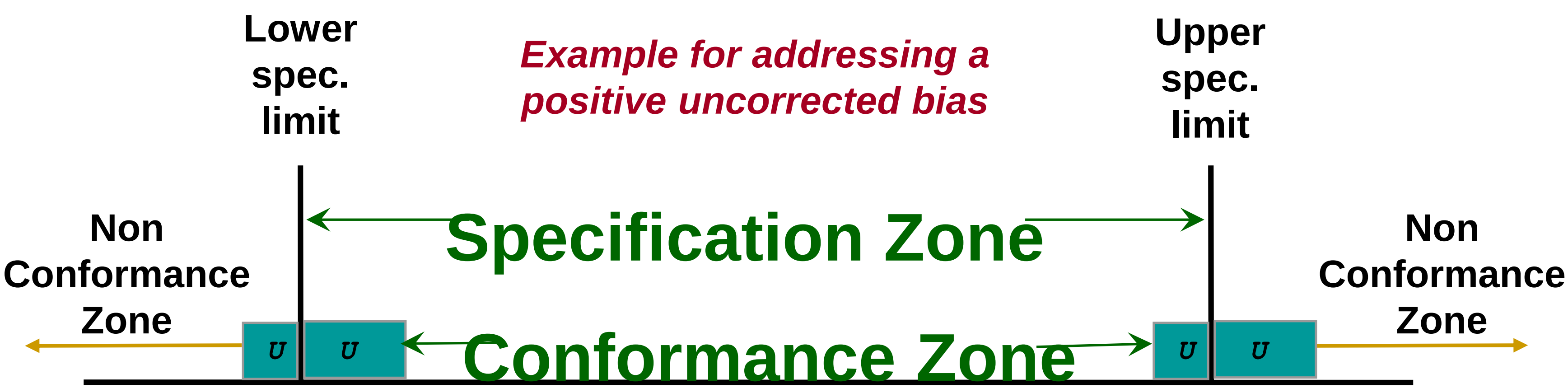
  Note: just watch the sign for the Bias

# Addressing Bias

Volume 102, Number 5, September–October 1997
Journal of Research of the National Institute of Standards and Technology

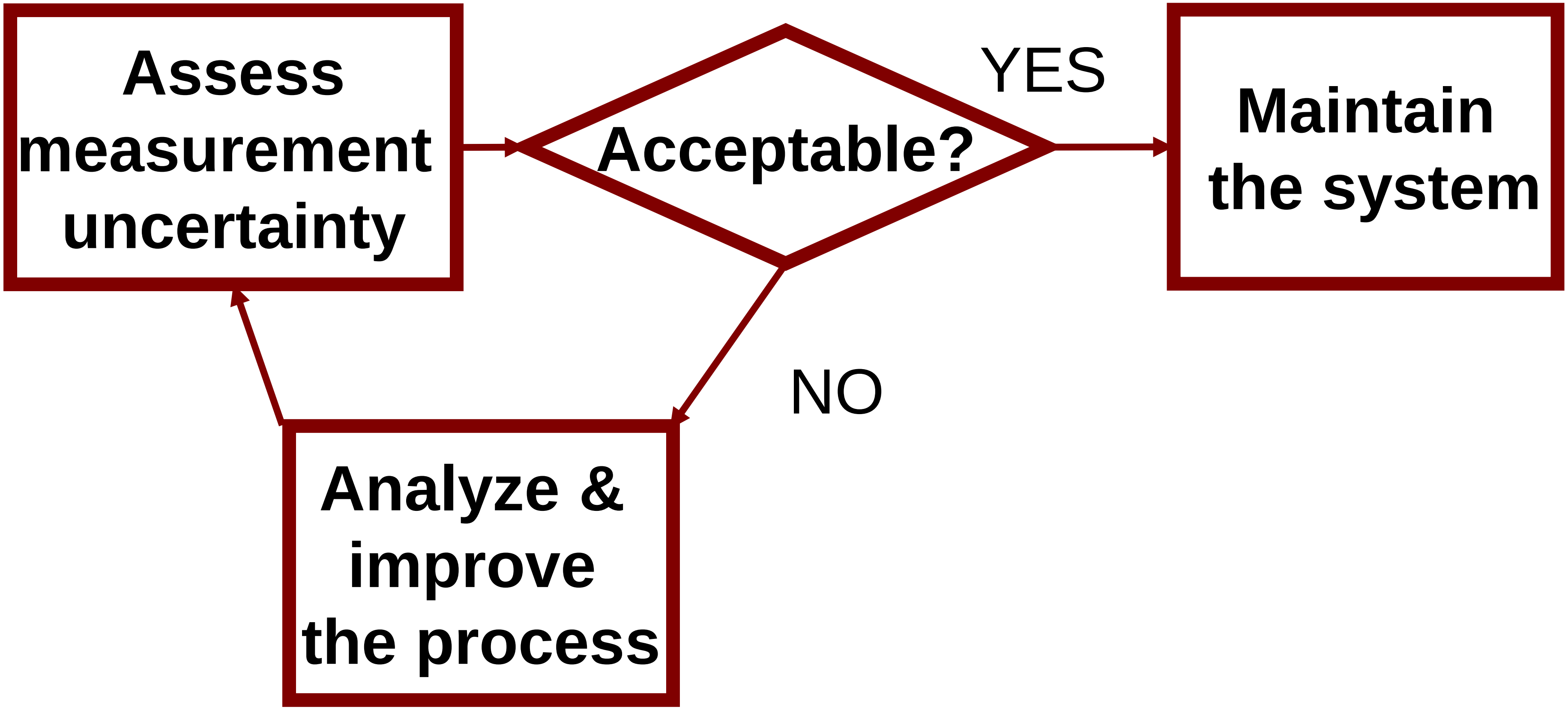
[J. Res. Natl. Inst. Stand. Technol. **102**, 577 (1997)]

*Guidelines for Expressing the Uncertainty of Measurement Results Containing Uncorrected Bias*




**http://www.nist.gov/manuscript-publication-search.cfm?pub_id=820858**

# Managing measurement uncertainty (aka: RISK)



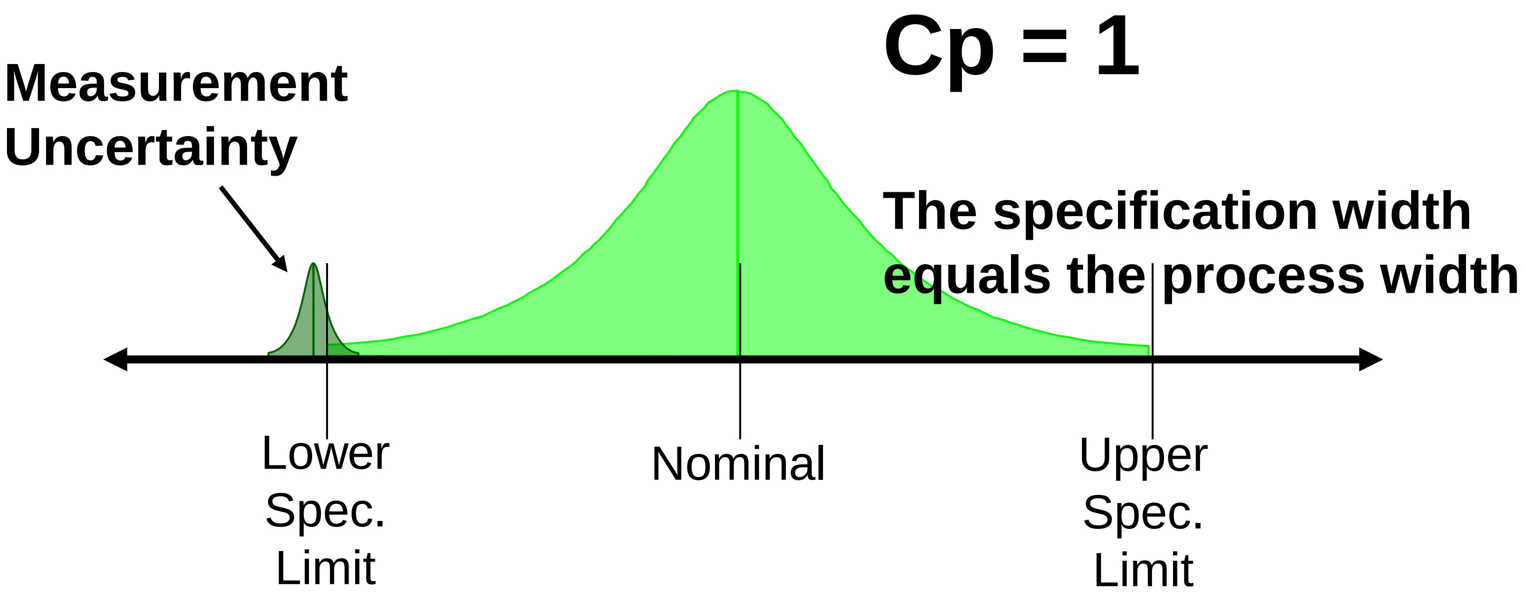
# Who's at RISK?

- "The benefits of risk analysis can far out weigh the costs and are limited only by the imagination of the user willing to apply the science."
  - ASME B89.7.4.1-2005 "Risk Analysis"

- Customer/Buyer Risk = False Accept Risk

- Producer/Supplier Risk = False Reject Risk

# B89-7-4-1 2005 Measurement Uncertainty and Conformance Testing : Risk Analysis




**Non-conforming : Pass = Customer Risk**

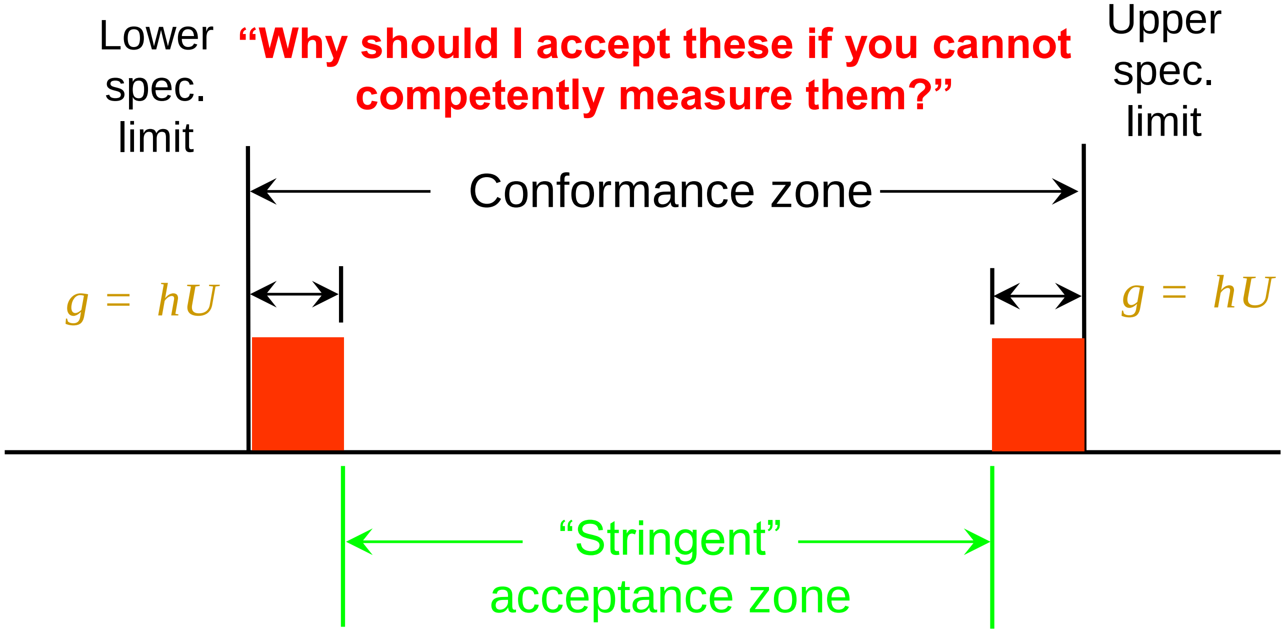
# B89.7.3.1 – Decision rules

Example: Stringent acceptance zone

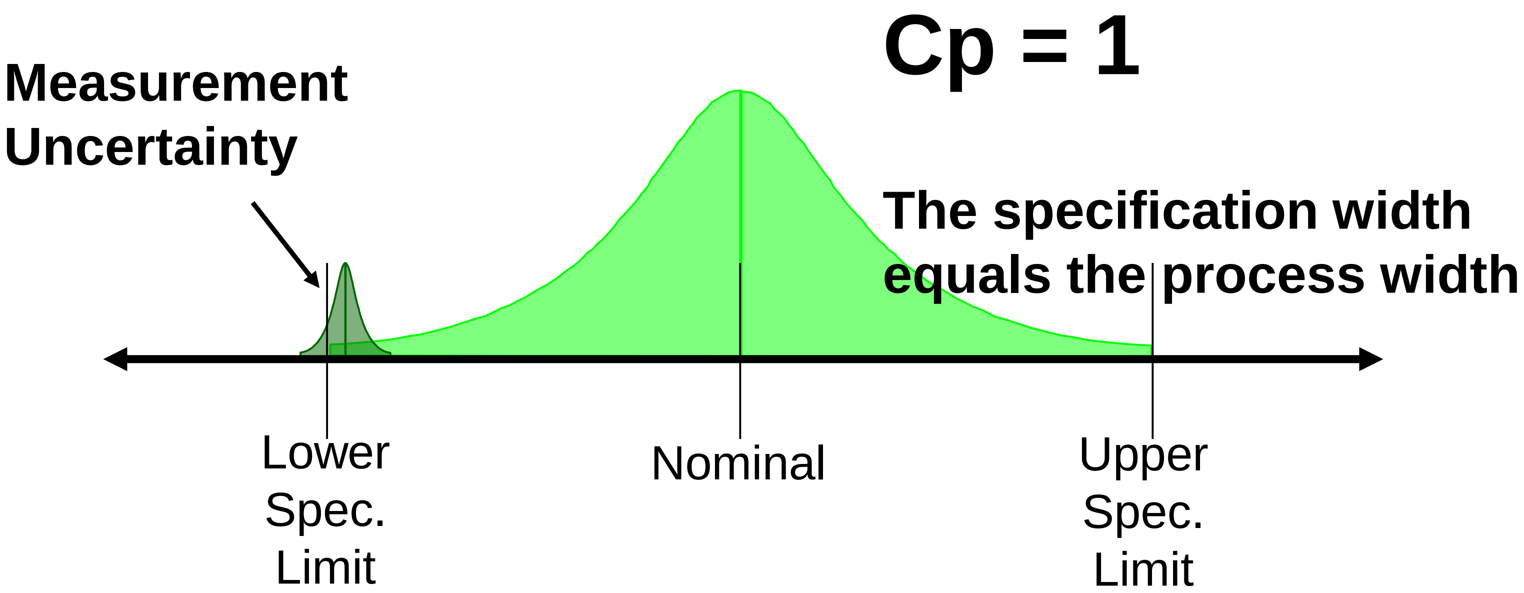
Reducing the risk of accepting a non-conforming quantity

**Buyers' prerogative:**

**"Why should I accept these if you cannot competently measure them?"**



# B89-7-4-1 2005 Measurement Uncertainty and Conformance Testing : Risk Analysis



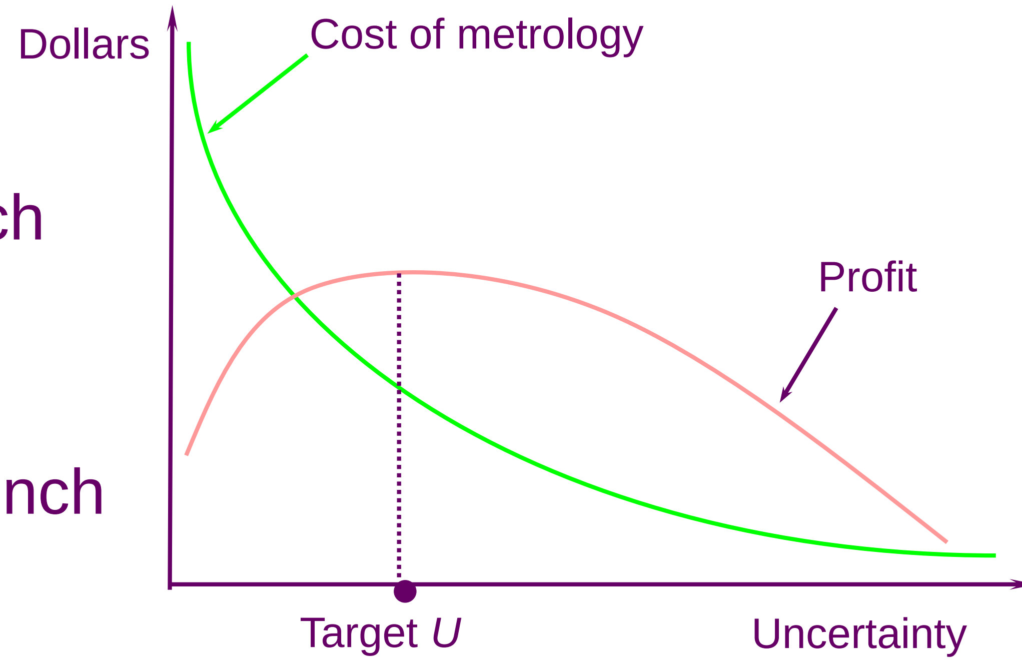

**Conforming : fail = Producer Risk**

# B89.7.3.1 – Decision rules

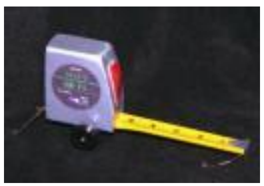
Example: Relaxed acceptance zone

Reducing the risk of rejecting a conforming quantity

# Costs of measurement uncertainty




Eyeball: $L = L_{est} \pm 1$ inch



Tape: $L = L_{est} \pm 1/16$ inch

Micrometer: $L = L_{est} \pm 0.001$inch

Gage block comparator: $L = L_{est} \pm 1$ microinch

# Terminology - revisited

- Accuracy – Qualitative only
- Uncertainty – Quantitative only
- Traceability – Qualitative and Quantitative
- Certainty – Estimated confidence for qualitative and quantitative reasoning

# Measurement Uncertainty: In a Nutshell

- Effective and Timely Measurement Planning
  - Take the time up-front
- Measurement Uncertainty Assessments
  - Account for the deterministic factors
- Decision Making
  - Come to mutual agreements based on known or estimated risks
- A successful relationship requires that mechanisms be in place to monitor and measure the agreements ( i.e., OQs and PQs)

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  - @ the QC Group on Mar10-11
  - @ Hennepin Tech College Mar3-May14

# References


- NIST Technical Note 1297
- Guidelines for Expressing the Uncertainty of Measurement Results Containing Uncorrected Bias – Vol2, Oct 1997
- Uncertainty and Dimensional Calibrations – Vol2, Dec 1997
- G103 – A2LA Guide for Estimation of Uncertainty of Dimensional Calibration and Testing Results, Dec 2008
- ACLASS Measurement Uncertainty Guidance for Hand Tools, Hand Gages, & Scales/Balances Utilizing a Modified NRC Uncertainty Calculator
- International Vocabulary of Metrology – JCGM 200:2008

# © Law of Uncertainty:

**Every physical quantity that can be measured is obligated by an uncertainty value that has to be estimated, except in case of (unlike with) discrete monetary (financial) transactions.**