Optical Metrology

Lecture 1: Introduction

Contact details

Instructor: Andrés G. Marrugo, Ph.D.

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Course web site:

opilab.utb.edu.co/optical-metrology-2021

Mission of the course

- Enables the students to learn the techniques and standard practices in metrology.

- At the end of the lectures, one would be able to:

  - Have clear idea of challenges in metrology due to increasing trend towards miniaturization.

  - Understand many different metrological devices and principles and applicability of those devices.

  - Understand the process and provide metrological solution for the improvement of a process.

Disclosure

Parts of this course have been prepared based on the publicly available information from the courses:

- Experimental design from Oulu University.
- Engineering Metrology and Measurement Systems from Concordia University.
- Metrología Óptica from Universidad Politécnica de Cataluña.

Outline of the Course

Date	Week	Lecture Topics
Aug 6	1	Introduction: Need for Metrology
	2	Random Data and Characterization of Measurement Systems
	3	Light Sources and Imaging Systems I
	4	Light Sources and Imaging Systems II
	5	Methods in Surface Measurement
	6	Lab: Surface Measurements
	7	Optical interferometry
	8	Moiré and phase-shifting interferometry
	9	Optical 3D Reconstruction
	10	Laser Triangulation
	11	Fringe Projection
	12	Strain Analysis by Digital Image Correlation (DIC)
	13	Lab: 3D Reconstruction
	14	Lab: DIC
	15	Final exam
	16	Project Presentations

About the course

- Metrology is the science of measurement that deals with resolution, accuracy and repeatability.

  - Lectures - 2.5 hours each
  - 11 Lectures in all.
  - 3 Laboratory practices.
  - 1 Project - due last week of classes.
  - Mid term and Final exam.

Text book and other references

Textbook

There is no prescribed textbook for this course. Lecture notes available at the course webpage.

References (not exhaustive)

Harding, K. (Ed.). (2013). Handbook of optical dimensional metrology. CRC Press.

K. J. Gasvik, Optical Metrology, Wiley, 2002.

Manuel Servin, J. Antonio Quiroga, Moises Padilla, Fringe Pattern Analysis for Optical.Metrology: Theory, Algorithms, and Applications, Wiley, 2014.

J. Bendat, A Piersol, Random Data: Analisys and Measurement Procedures, Wiley, 2000.

The Project

- A project related to Optical Metrology.
- Literature review and theoretical work will be needed to complete the work.
- There will be a presentation for the project.
- Project report with calculations.

Grading Scheme

- Grade composition:
  - Project: 30%
  - Midterm: 20%
  - Final exam: 30%
  - Lab reports: 20%

Content of the Lecture

- History and Philosophy of measurement.
- Economic benefits.
- International trade.
- Calibration and Traceability.
- Current manufacturing trend.
- Need for precision measurement.

What is Metrology?

Metrology is the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology.

Bureau international des poids et mesures

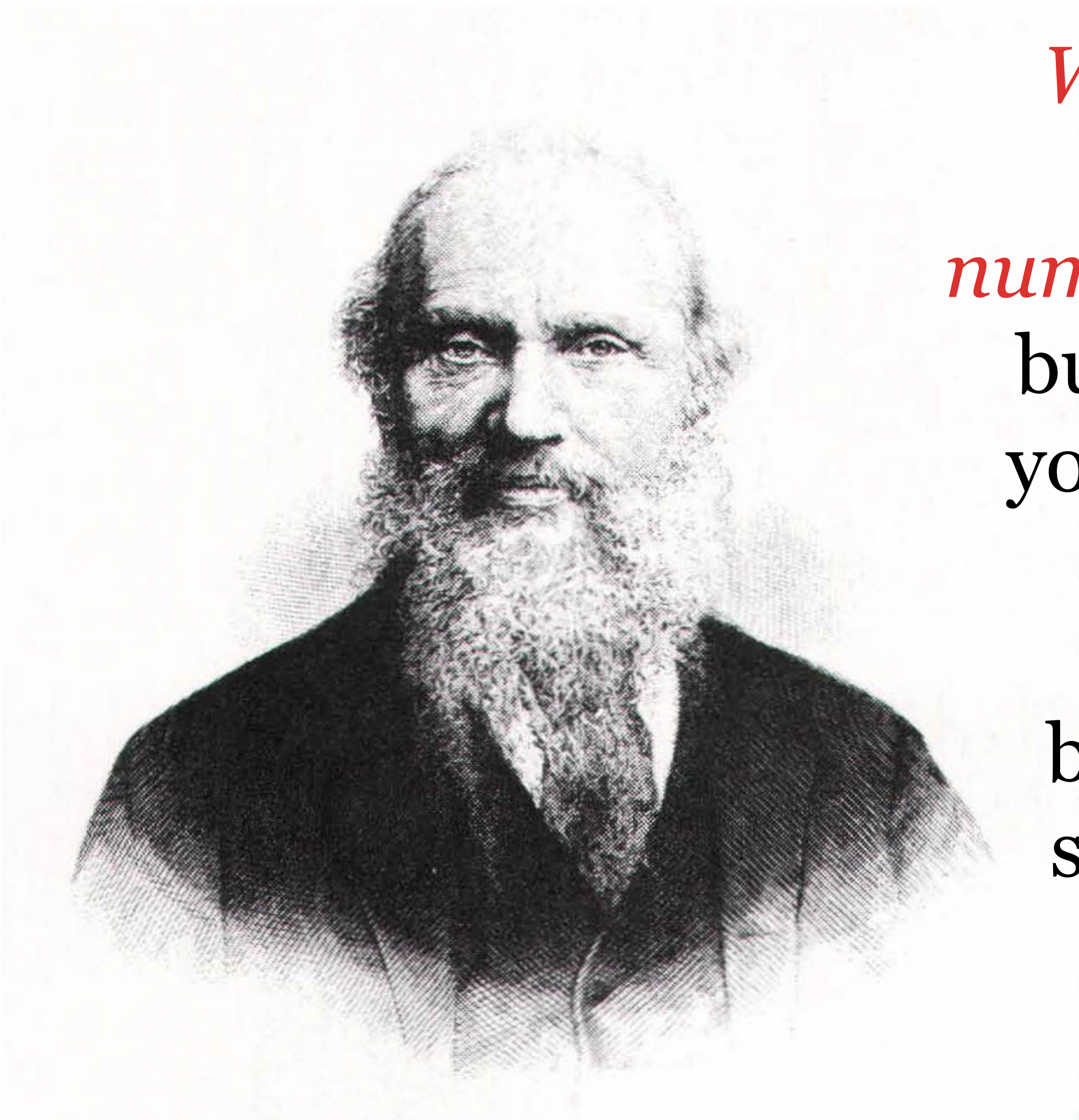
What is Optical Metrology?

Optical Metrology

is the science and technology concerning measurements with light. Such measurements can either target properties of light itself or other properties such as some distance.

RP Photonics Encyclopedia

Why is it important?

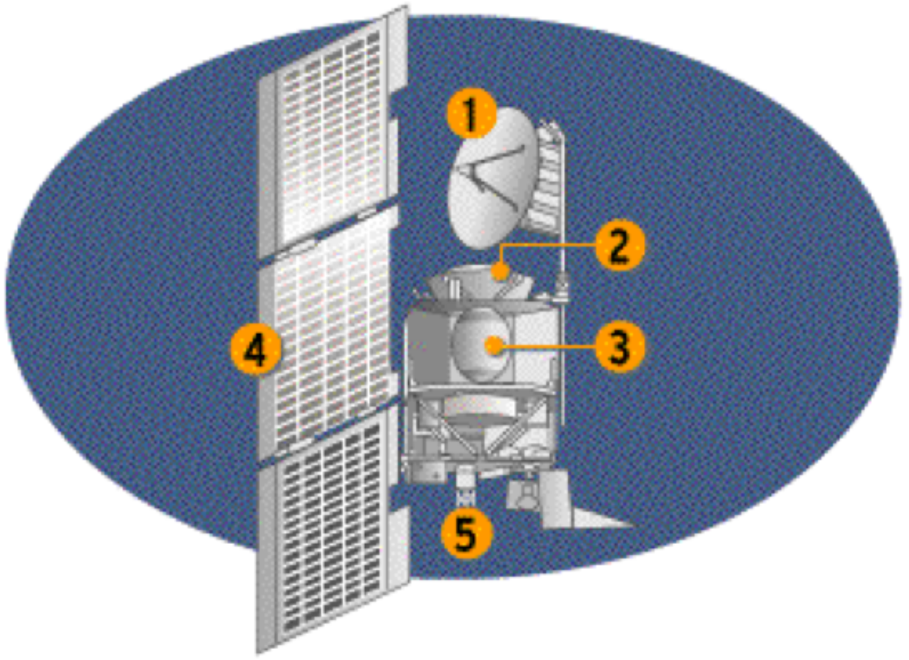


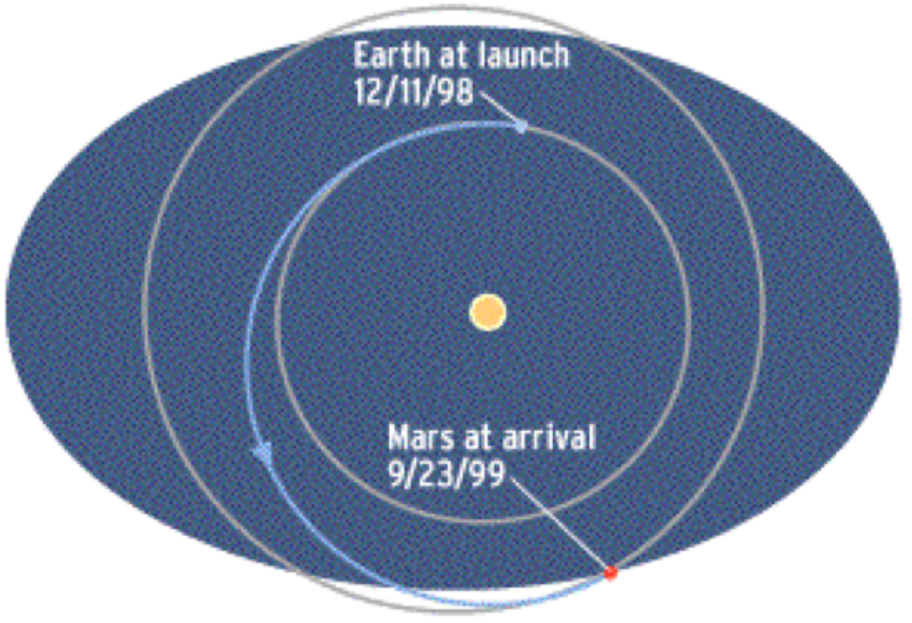
When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of *Science*.

William Thomson, Lord Kelvin

Why is it important?

- Wrong or inaccurate measurements can lead to wrong decisions, that have serious consequences, costing money and even lives. eg.. Metric mishap caused loss of NASA orbiter.
- Failure convert English/US system made the probe travel 60 miles farther and it was lost. (125m USD in 1999 september).
- It is important to have reliable and accurate measurements which are agreed and accepted by the relevant authorities worldwide.

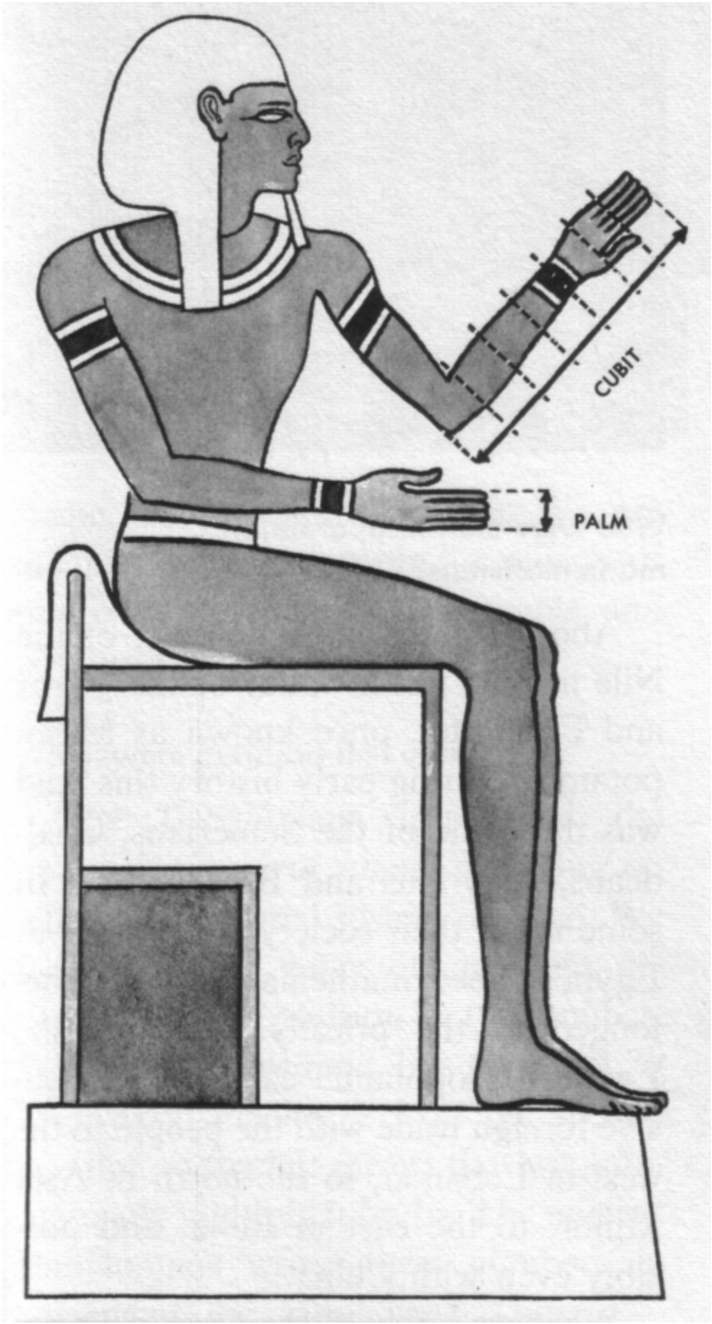




A bit of history

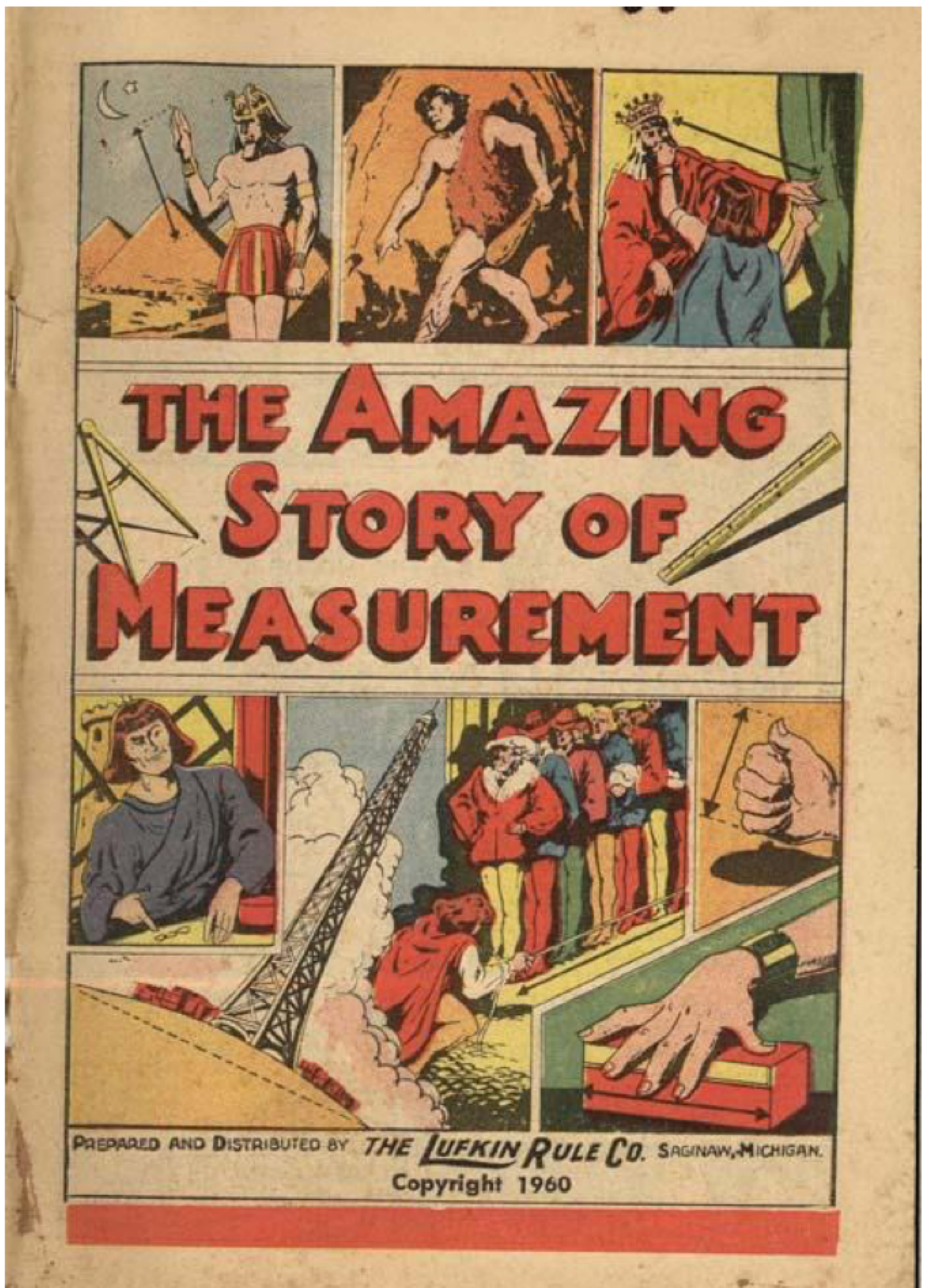
One of the earliest records of precise measurement is from Egypt. The Egyptians studied the science of geometry to assist them in the construction of the Pyramids. It is believed that about 3000 years BC, the Egyptian unit of length came into being.

The "Royal Egyptian Cubit" was decreed to be equal to the length of the forearm from the bent elbow to the tip of the extended middle finger of the hand of the Pharaoh or King ruling at that time



Mark H. Stone, "The Cubit: A History and Measurement Commentary," J. of Anthropology,. 2014

History in Images



History in Images

History of Metrology

- Standardization a goal of social and economic advancement, but only in 18th century a unified measurement system.
- Earliest systems of weights and measures based on human morphology. Thus, units of measurement were not fixed. Varied from town to town, etc.
- Lack of a standardized system was a source of error and fraud in commercial transactions. Delayed international commerce and science.

Economic benefits of Metrology

Metrology is added value.

Today it is a key enabler in many areas.

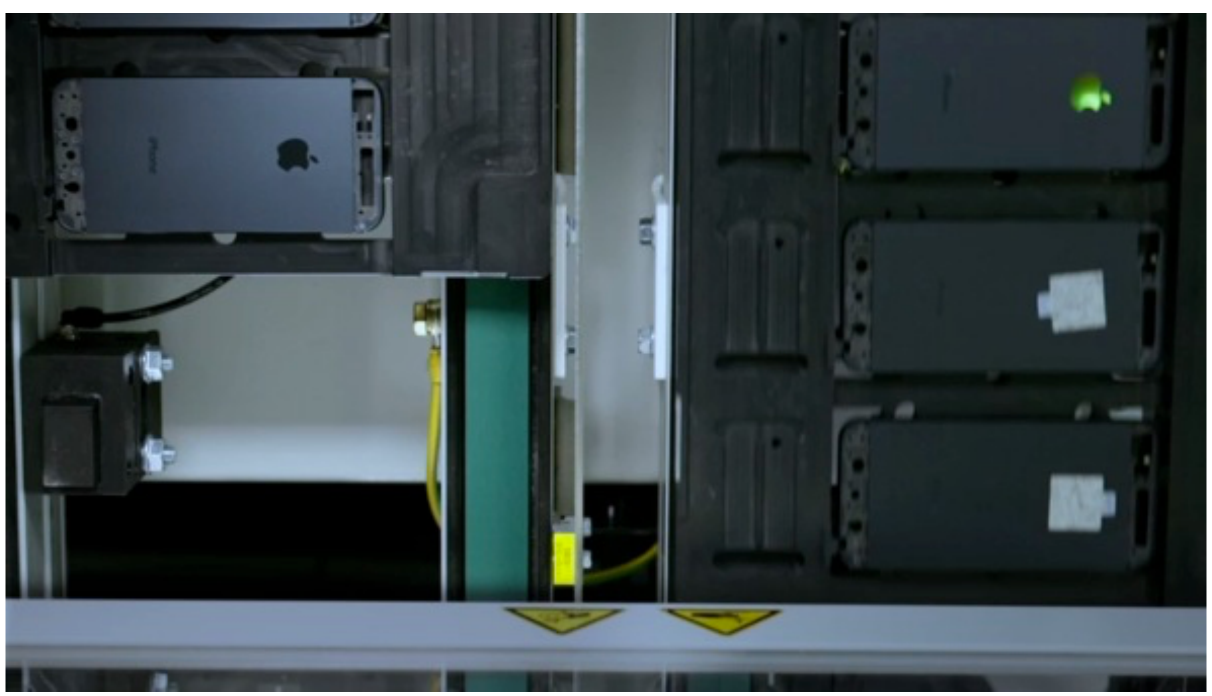
Metrology is a check and balance in manufacturing.

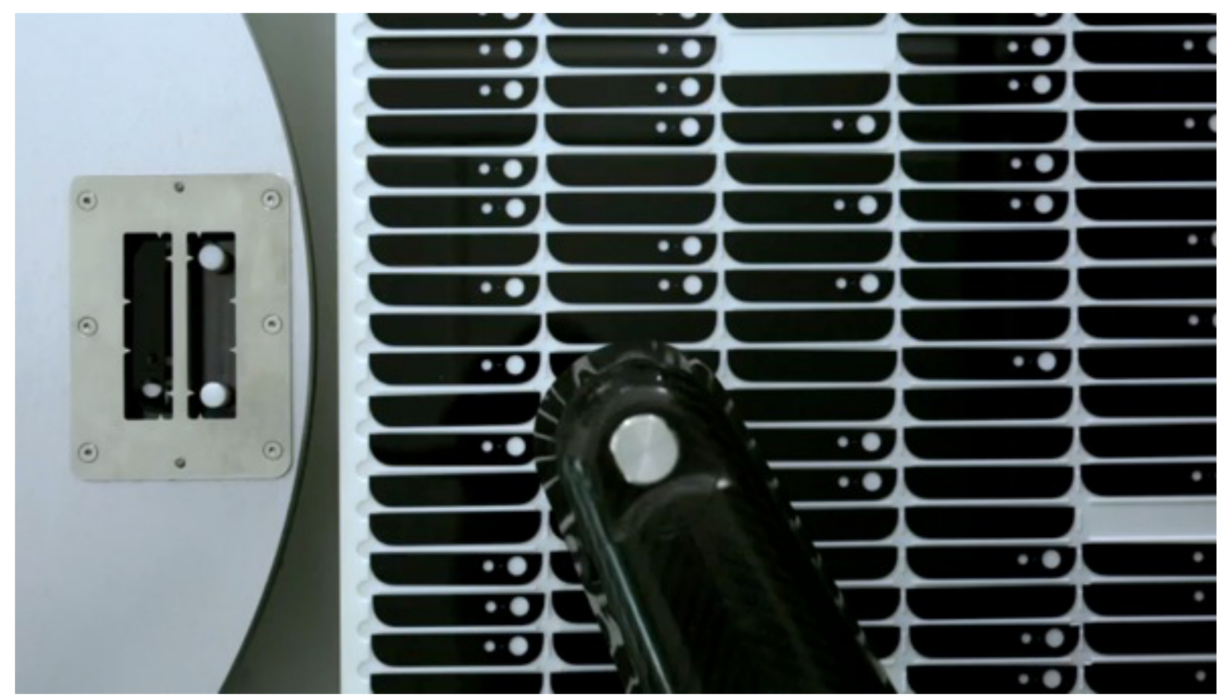
Economic benefit is often difficult to assess.

Metrology is added value.

Example: Production of the iPhone 5.

Problem: The inlays have to match "perfectly" with the enclosure.





The $B Wafer Industry

Process-control is based on measurements

Faulty measurements

↓

Loss of control

Form & function failure

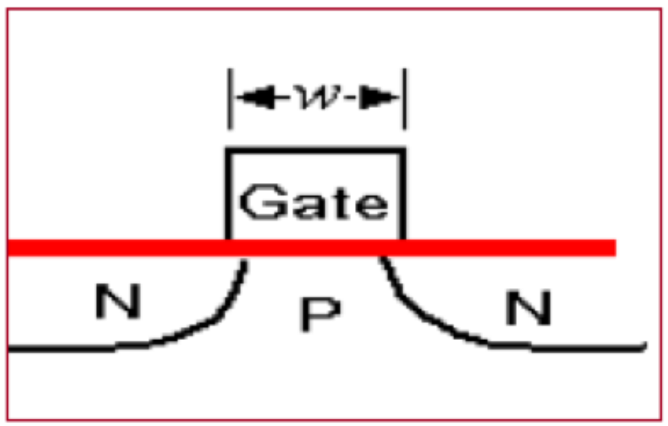
Loss of profits, wealth

Economic Impact

Measurement related operations are estimated to account for 3% to 6% of GDP in industrialised countries.

Economic benefits of Metrology

Example: Semiconductor Manufacturing



What's a Nanometer worth?

•Faster microprocessors fetch higher prices

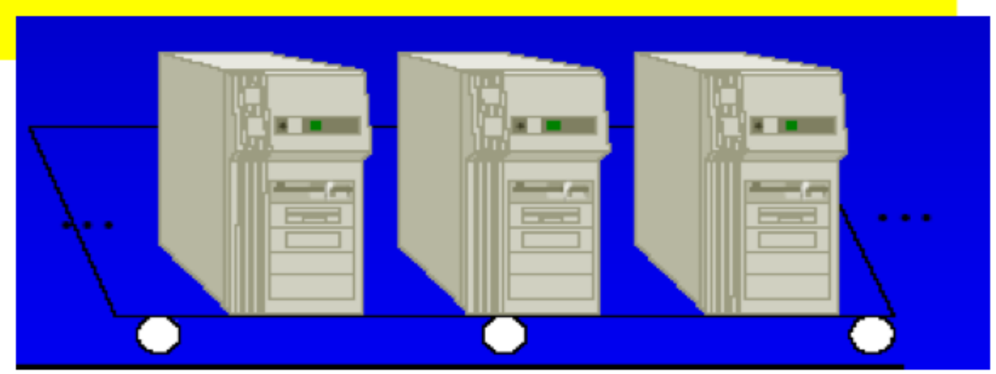
•Narrower gate =>less capacitance => more speed

For 180nm gates, a 10nm improvement in CD control was estimated to an increase of $100 market value per microprocessor

"Under these assumptions, the value of CD control for the 180 nm generation of microprocessors exceeds $10 per nanometer."

C.P. Ausschnitt and M. E. Lagus, IBM Advanced Semiconductor Technology Center, Proc. SPIE Vol. 3332, p. 212 (1998).

1999 Worldwide PC sales exceed 113 million units
(Source: International Data Corp.)



$>10^8$units $\times$\$10/unit $\geq$\$1 billion/nm

It's a big industry, and small improvements yield big economic benefits….

Credit: John Villarrubia, NIST

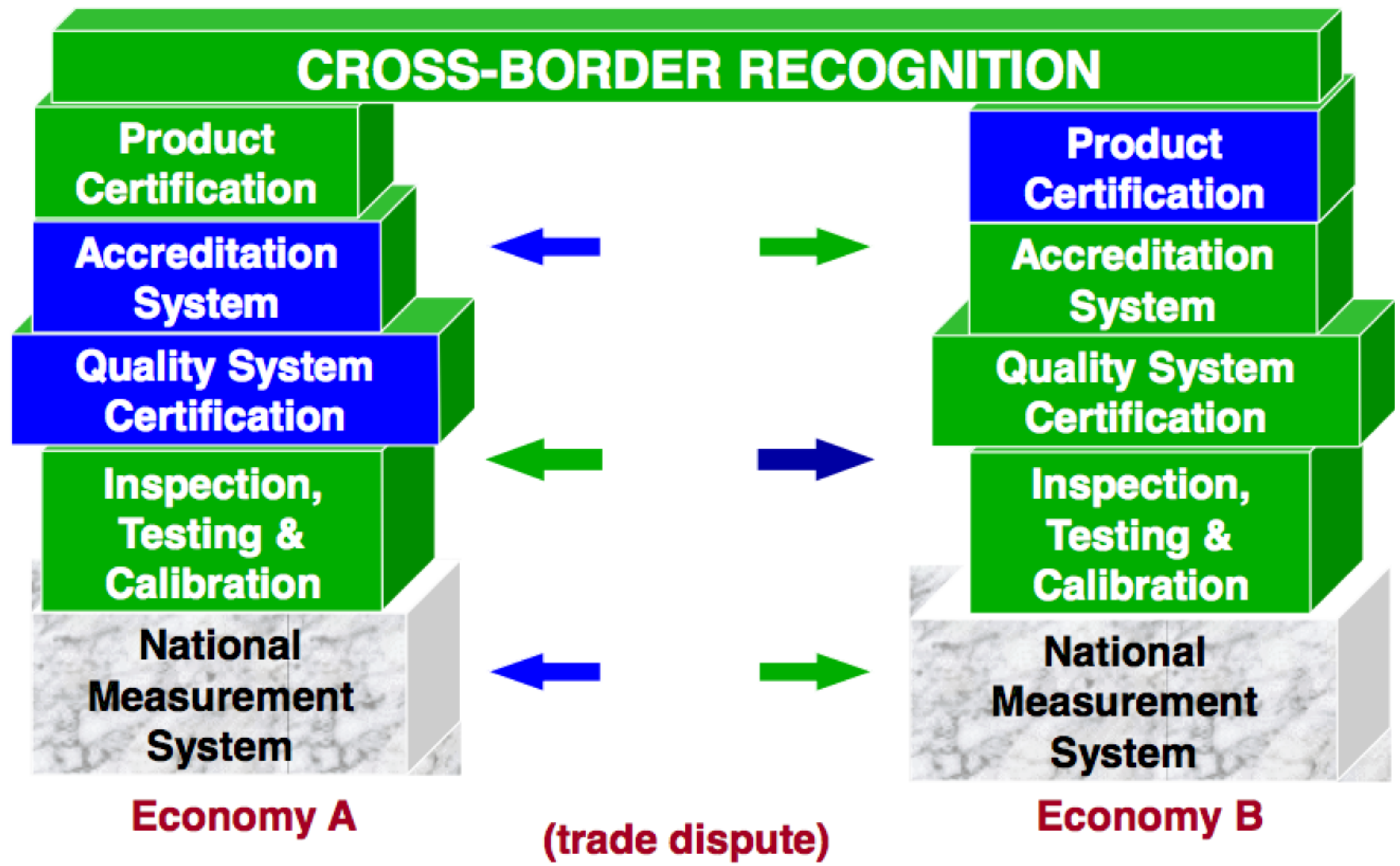
International Trade

- Manufactured products
- Parts
- Services
- Have to fulfill
  - Specifications
  - Regulations
- Delivered worldwide
- Measurements have to be comparable (traceable)

International Trade

Essential and often hidden part of technical infrastructure.

Confidence in results of measurements prerequisite to international trade.



Accuracy and Precision

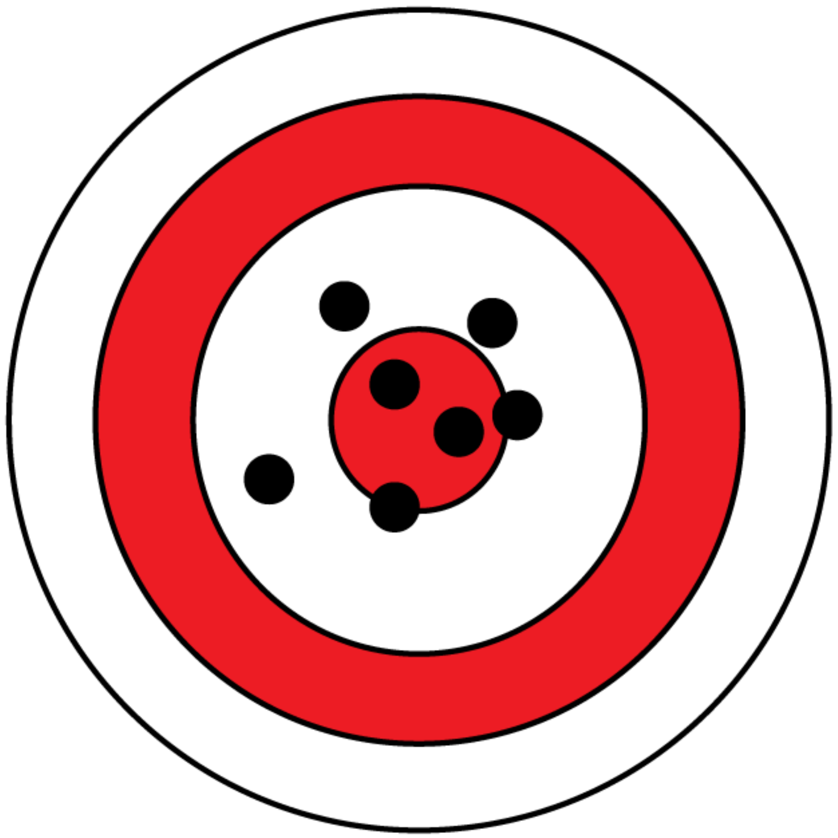
When referring to traceability of measurement and comparison with other measurement methods, we need to differentiate two basic aspects in measurement:

Accuracy

Precision

Perhaps the easiest way to illustrate the difference between accuracy and precision is to use the analogy of a marksman, to whom the "truth" represents the bulls eye.

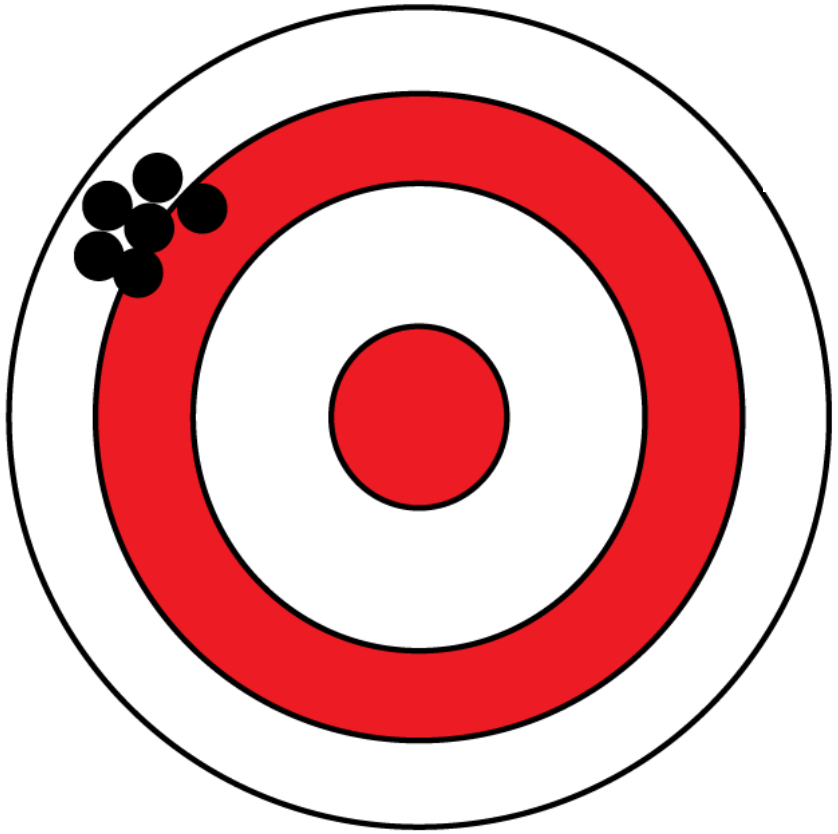
Accuracy the degree of conformity with a standard (the "truth"). Accuracy relates to the quality of a result, and is distinguished from precision, which relates to the quality of the operation by which the result is obtained. In Figure, the marksman has approached the "truth", although without great precision. It may be that the marksman will need to change the equipment or methodology used to obtain the result if a greater degree of precision is required, as he has reached the limitations associated with his equipment and methodology.



Accuracy

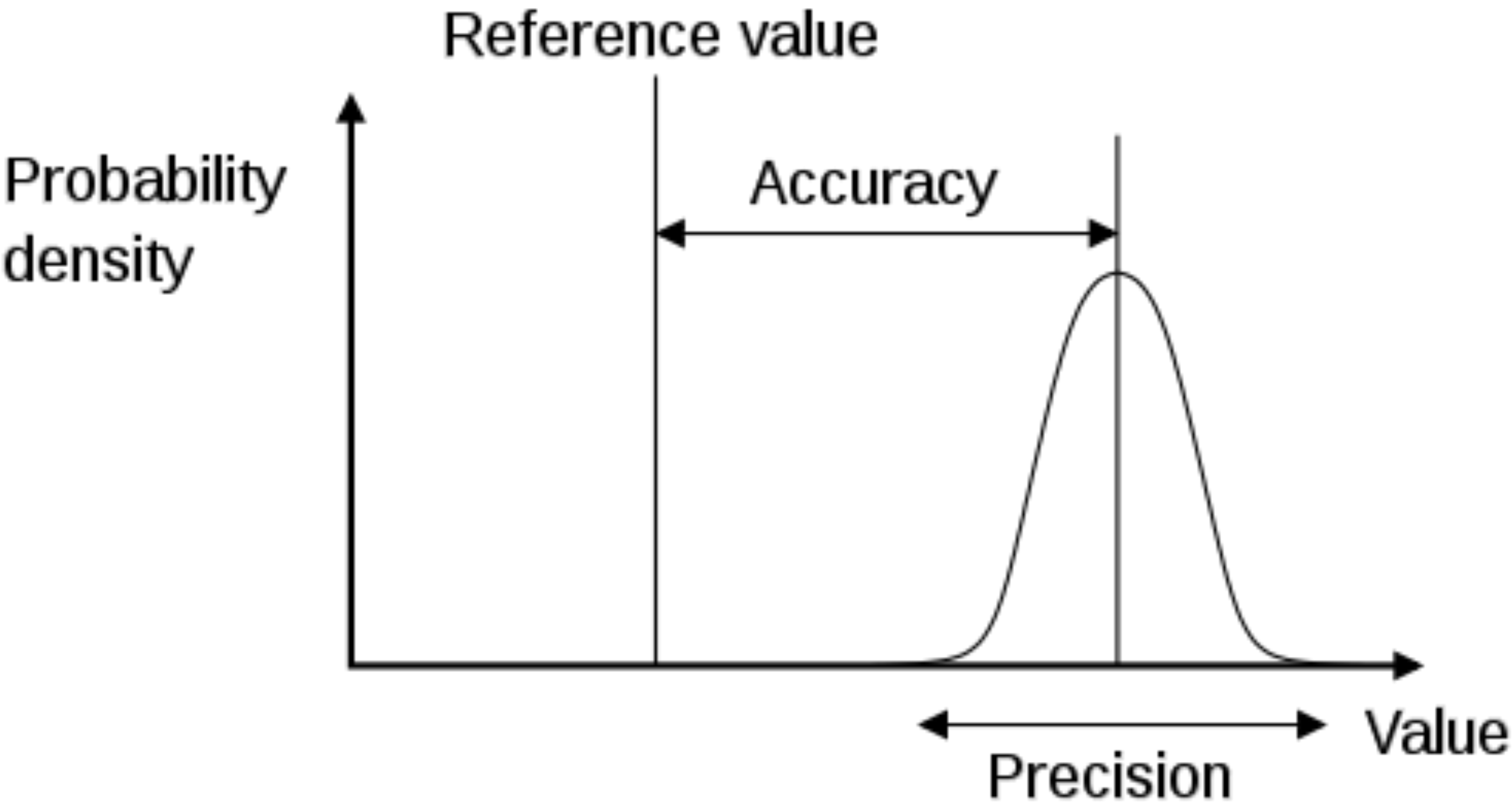
Precision the degree of refinement in the performance of an operation, or the degree of perfection in the instruments and methods used to obtain a result. An indication of the uniformity or reproducibility of a result. Precision relates to the quality of an operation by which a result is obtained, and is distinguished from accuracy, which relates to the quality of the result. In Figure, the marksman has achieved a uniformity, although it is inaccurate. This uniformity may have been achieved by using a sighting scope, or some sort of stabilizing device.

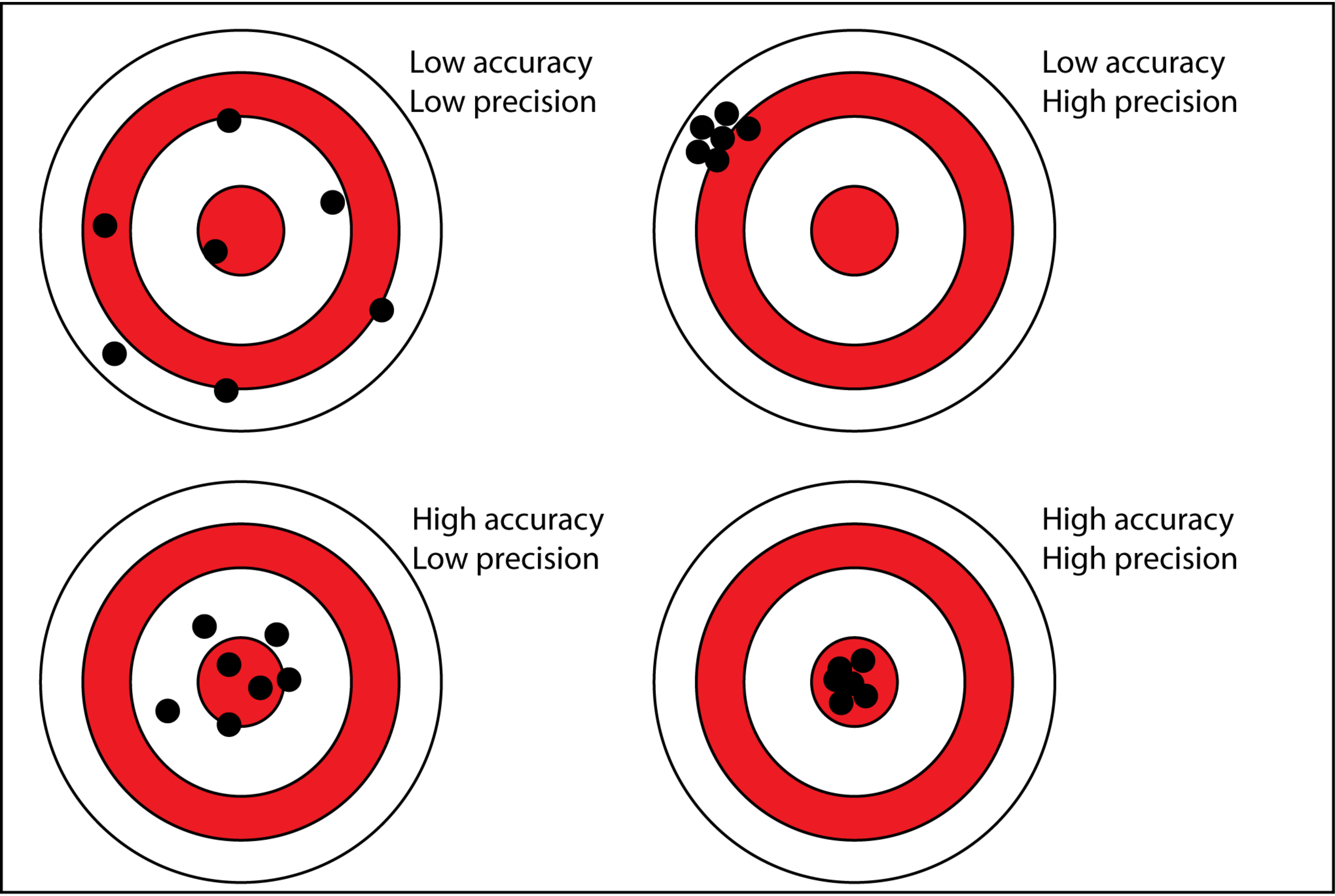
With the knowledge gained by observation of the results, the marksman can apply a systematic adjustment (aim lower and to the left of his intended target, or have his equipment adjusted) to achieve more accurate results in addition to the precision that his methodology and equipment have already attained.



Precision

Accuracy and Precision




Low accuracy
Low precision
Low accuracy
High precision
High accuracy
Low precision
High accuracy
High precision

Accuracy and Precision - Example

A metal rod about 4 inches long has been passed around to several groups of students. Each group is asked to measure the length of the rod. Each group has five students and each student independently measures the rod and records his or her result

Group	Student 1	Student 2	Student 3	Student 4	Student 5	Average
Group A	10.1	10.4	9.6	9.9	10.8	**10.16**
Group B	10.135	10.227	10.201	10.011	10.155	**10.146**
Group C	12.14	12.17	12.15	12.14	12.18	**12.16**
Group D	10.05	10.82	8.01	11.5	10.77	**10.23**
Group E	10	11	10	10	10	**10.2**

Which group is most accurate? Unknown because true value is not known

Which group has greatest error? Unknown because true value is not known

Which group is most precise? C because measurements are repeatable

Which group has most uncertainty? D because maximum variation in results

Accuracy and Precision - Example

We now receive a report from the machine shop where the rod was manufactured. This very reputable firm certifies the rod to be 4 inches long to the nearest thousandths of an inch. Answer the questions below given this new information

Group	Student 1	Student 2	Student 3	Student 4	Student 5	Average
Group A	10.1	10.4	9.6	9.9	10.8	**10.16**
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Group D	10.05	10.82	8.01	11.5	10.77	**10.23**
Group E	10	11	10	10	10	**10.2**

Which group is least accurate? C because most away from true value

Which group has smallest error? A because average is close to true value

Which group is least precise? D because maximum variation in results

Which group has least uncertainty? C because measurements are repeatable

Calibration and Traceability

The International Vocabulary of Basic and General Terms in Metrology (VIM)1 defines traceability as:

"property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties."

Only the result of a measurement or the value of a standard can be traceable!

Measuring equipment cannot be traceable in and of itself.

What is traceable about the equipment is the determination of its imperfections during calibration.

Calibration and Traceability

- A standard cannot be traceable, but the value assigned to it can. ISO/QS 9000 requires calibration (of inspection, measuring and test equipment) against certified equipment having a known valid relationship to internationally or nationally recognized standards.

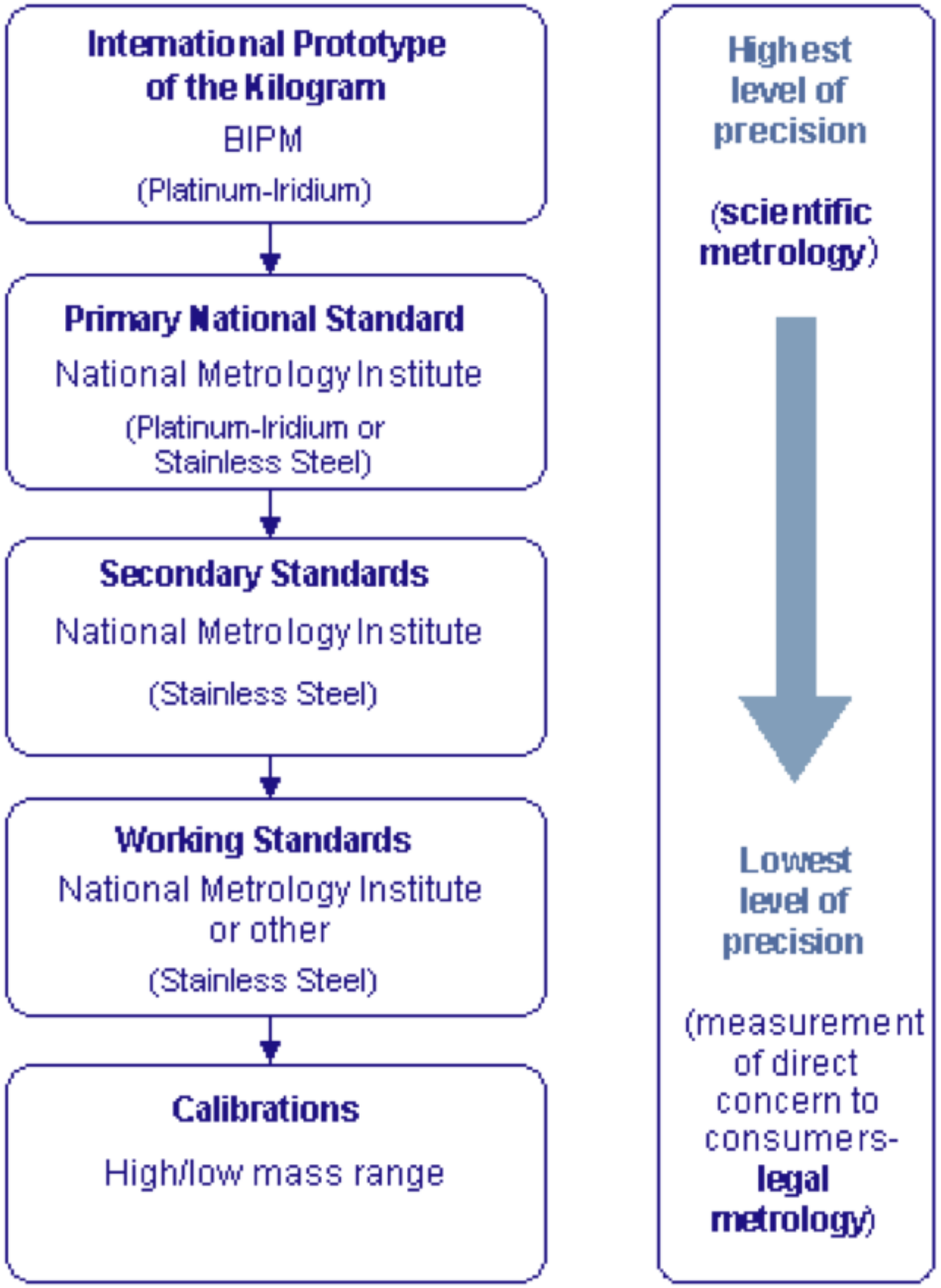
- The customer requiring traceability wants some assurance that the measurements are “right".

- The only way to prove that measurements are right, is to prove that their uncertainty is low enough to allow the desired conclusions to be drawn from the results, such as whether or not a workpiece meets its specification.

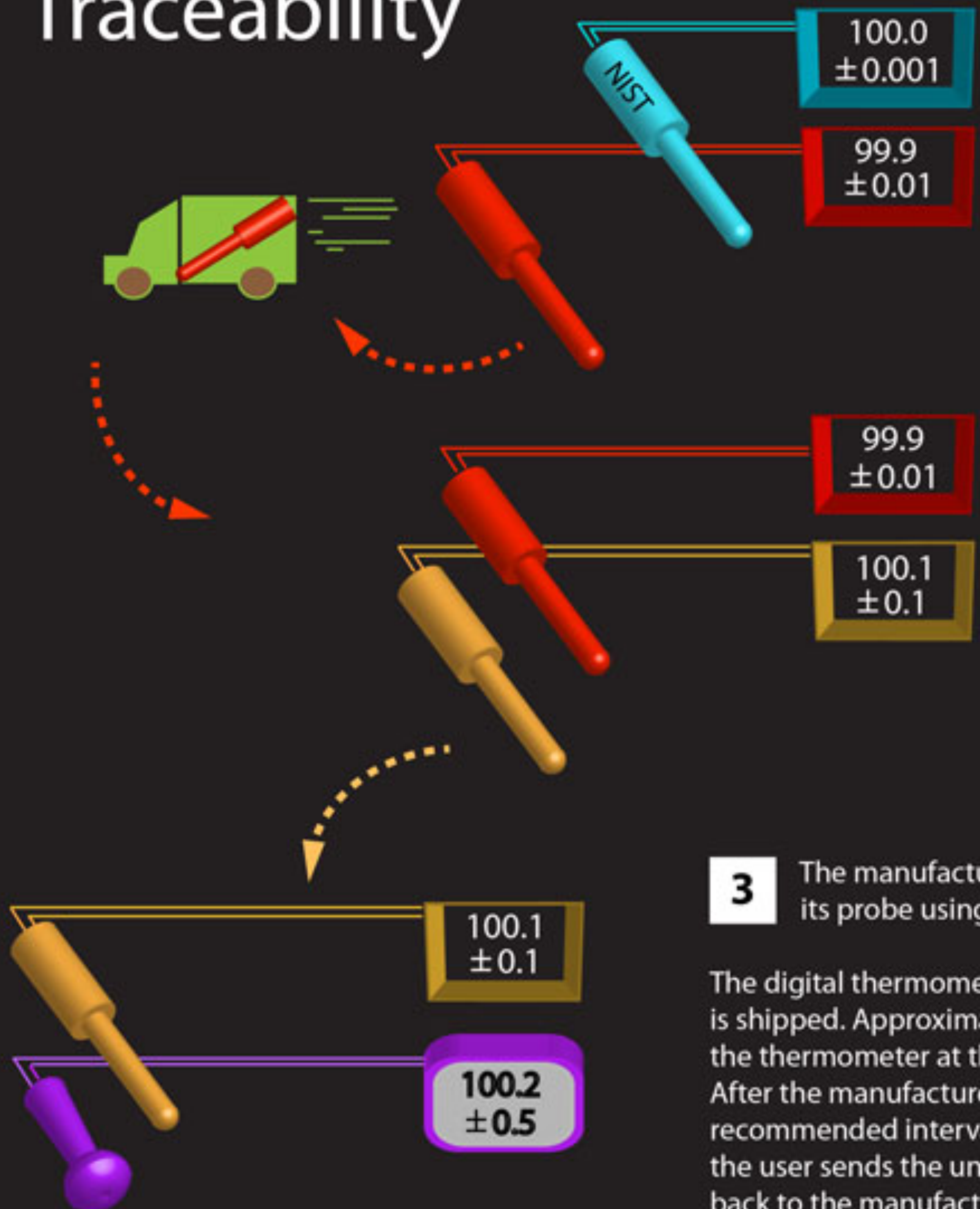
Calibration and Traceability

Traceability Chain

Schematic representation of the various types of standard that exist in a particular area of metrology, and how the level of precision will decrease along the chain of responsibility



Traceability



1 A manufacturer sends a platinum resistance thermometer (PRT -- red) to NIST for calibration against a NIST Standard PRT (blue). The calibrated unit is then returned.

2 The manufacturer calibrates another PRT (gold) against the NIST-calibrated PRT (red). Careful records are kept of the measurements.

3 The manufacturer calibrates a digital thermometer and its probe using the second PRT as a reference.

The digital thermometer, now traceable to NIST calibration, is shipped. Approximately every year, the user measures the thermometer at the ice point. After the manufacturer's recommended interval, the user sends the unit back to the manufacturer for re-calibration.

http://www.nist.gov/pml/mercury_traceability.cfm

When you have an 'I hate my job' day ...

Try this out:

Stop at your pharmacy, go to the thermometer section and purchase a rectal thermometer made by Johnson & Johnson.

Be very sure you get this brand.

When you get home, lock your doors, draw the curtains and disconnect the phone so you will not be disturbed.

Change into comfortable clothing and sit in your favorite chair. Open the package and remove the thermometer. Then, carefully place it on a table or a surface so that it will not become chipped or broken.

Now the fun part begins.

Take out the literature from the box and read it carefully. You will notice that in small print there is a statement:

"Every rectal thermometer made by Johnson & Johnson is personally tested and then sanitized."

Now, close your eyes and repeat out loud five times, "I am so glad I do not work in the thermometer quality control department at Johnson & Johnson."

"Every rectal thermometer made by Johnson and Johnson is personally tested"

http://www.snopes.com/humor/jokes/thermometer.asp

Calibration and Traceability

Uncertainties of physical realizations of the base SI units (pre 2019)

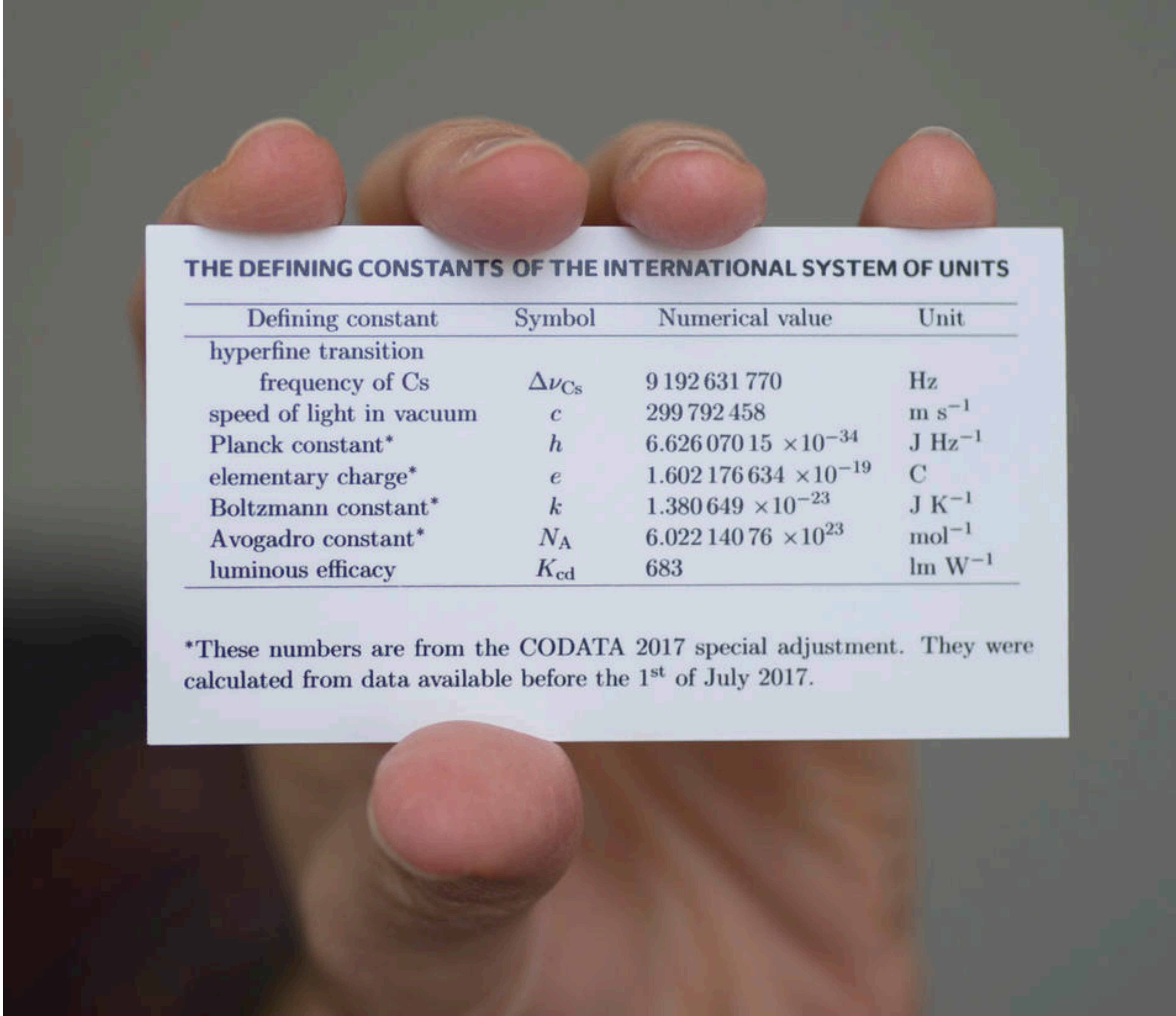
SI Base Unit	Physical Quantity	Uncertainty
Candela	Luminous intensity	1×10^{-4}
Kelvin	Temperature	3×10^{-7}
Mole	Amount of substance	8×10^{-8}
Ampere	Electric current	4×10^{-8}
Kilogram	Mass	1×10^{-8}
Meter	Length	1×10^{-12}
Second	Time interval	1×10^{-15}

Need for redefining SI base units

Drawbacks of the previous SI are:

- Kilogram is defined with an artefact
- The definition of kelvin is based on material properties
- The definition of ampere limits the achievable accuracy and is not currently use (quantum standards of ohm and voltage are used instead through the Ohm's law)

Because of these, drift, non-uniqueness and limitations in accuracy cannot completely be prevented



THE DEFINING CONSTANTS OF THE INTERNATIONAL SYSTEM OF UNITS

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	$m\ s^{-1}$
Planck constant*	h	$6.626\,070\,15 \times 10^{-34}$	$J\ Hz^{-1}$
elementary charge*	e	$1.602\,176\,634 \times 10^{-19}$	C
Boltzmann constant*	k	$1.380\,649 \times 10^{-23}$	$J\ K^{-1}$
Avogadro constant*	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	$lm\ W^{-1}$

*These numbers are from the CODATA 2017 special adjustment. They were calculated from data available before the 1st of July 2017.

2019 redefinition of SI base units

Kilogram

Previous definition: The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

2019 definition: The kilogram, symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be 6.62607015×10–34 when expressed in the unit J·s, which is equal to kg·m2·s–1, where the metre and the second are defined in terms of c and ΔvCs (Caesium 133 freq).

$$1\ \text{kg} = \frac{(299\,792\,458)^2}{(6.626\,070\,15 \times 10^{-34})(9\,192\,631\,770)} \frac{h\, \Delta\nu_{\text{Cs}}}{c^2}.$$

2019 redefinition of SI base units

Ampere

Previous definition: The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 m apart in vacuum, would produce between these conductors a force equal to 2×10–7 newton per metre of length.

2019 definition: The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be 1.602176634×10–19 when expressed in the unit C, which is equal to A·s, where the second is defined in terms of ΔvCs.

$$1\ \mathrm{A} = \frac{e\,\Delta\nu_{\mathrm{Cs}}}{(1.602\,176\,634 \times 10^{-19})(9\,192\,631\,770)}.$$

2019 redefinition of SI base units

Kelvin

Previous definition: The kelvin, unit of thermodynamic temperature, is 1/273.16 of the thermodynamic temperature of the triple point of water.

2019 definition: The kelvin, symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be 1.380649×10–23 when expressed in the unit J·K–1, which is equal to kg·m2·s–2·K–1, where the kilogram, metre and second are defined in terms of h, c and ΔvCs.

$$1\ \mathrm{K} = \frac{1.380\,649 \times 10^{-23}}{(6.626\,070\,15 \times 10^{-34})(9\,192\,631\,770)} \frac{h\,\Delta\nu_{\mathrm{Cs}}}{k}.$$

Calibration and Traceability

- Traceability may therefore require calibration of several attributes of the measuring equipment and not all of them may be in the unit of what we are measuring. For example the uncertainty of a length measurement may be highly dependent on temperature and therefore the ability to measure temperature. Thus the traceability of the calibration of the temperature sensor becomes a significant part of the uncertainty for the length measurement.

- Using this logic, the information needed to prove that a measurement is traceable in the technical sense is:

A list of the significant uncertainty contributors for the measurement.

A list of the significant uncertainty contributors for the measurement.

- ✓ A list of the equipment (serial no. etc.) used in the measurement that adds significantly to the uncertainty.
- ✓ For each piece of equipment a reference to its traceability (Calibration scope, calibration source, calibration date and calibration id, e.g. certificate number).
- ✓ For each calibration source, evidence of its credibility, e.g. accreditation.

- The requirement of credibility of the calibration source is what recursively ensures that this information is available at each link in all the chains back to the national laboratory level.
- Accreditation is intended to provide this credibility. Accreditation is essentially a third party putting a seal of approval on the comparisons and the accompanying uncertainties that a calibration laboratory performs.

Manufacturing Trend

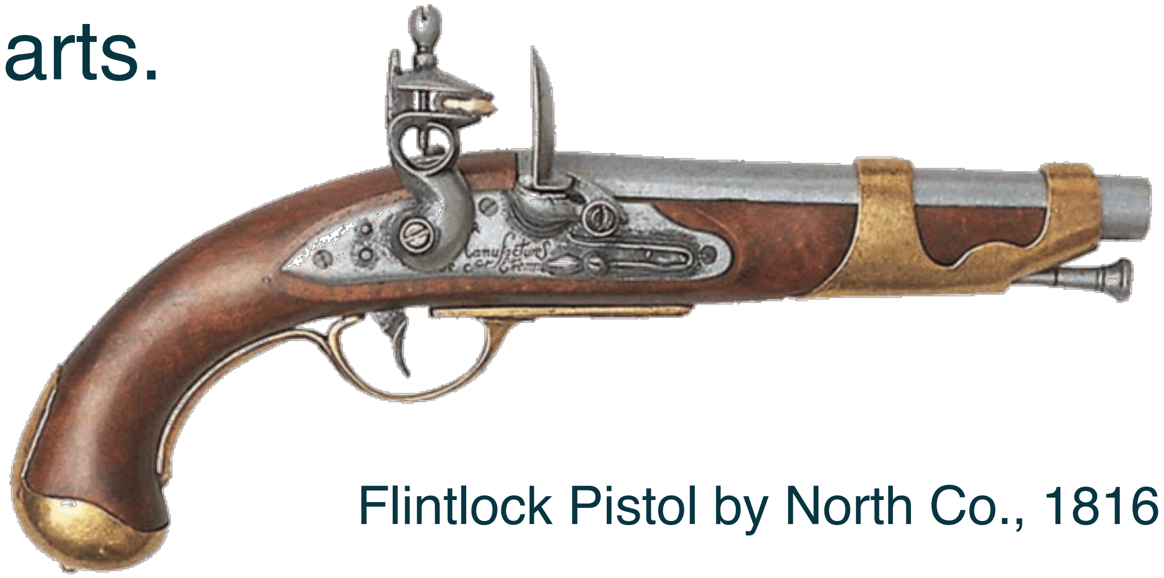
The Machine Revolution 1800-1920 – the milli-inch (1 mil = 25 µm)

- Mass production of firearms, sewing machines, automobiles, etc.
- Process: machining, stamping, casting, forging, etc.
- Essential requirement: accurately dimensioned, interchangeable machine parts.
- Enabled by widespread dissemination of accurate length scale (~1 mil) embodied as gauge blocks.
- Accuracy transferred to work piece by vernier calipers.

Manufacturing Trend

The Machine Revolution 1800-1920 – the milli-inch (1 mil = 25 µm)

- Before the Wat of 1812, interchangeable parts were unknown.
- Dimensional metrology infrastructure was non existant.
- In 1813, the U.S. War Department let the first contract for guns with interchangeable parts.



Flintlock Pistol by North Co., 1816

Manufacturing Trend

The Semiconductor Revolution 1950-2010 – the micro-meter (1 µm = 1000 nm)

- Mass production of semiconductor circuits.
- Process: planar multi-level lithographic processing.
- Essential requirement: accurately dimensioned and placed patterns.
- Enabled by widespread dissemination of accurate length scale (~0.1µm) embodied as laser interferometers.
- Accuracy transferred to work piece by optical or electron imaging.

Current Manufacturing Trend

The Nanotechnology Revolution 2000-2050 – the nano-meter

- Mass production of nanosystems (electronic, mechanical, biological, etc.).
- Process: planar multi-level lithography; self assembly of nano- objects (e.g., nanowires, nanocrystals).
- Essential requirement: accurately dimensioned and placed patterns and nano-objects.
- Enabled by widespread dissemination of accurate length scale (~1 nm) embodied as optical encoders.
- Accuracy transferred to work piece by optical or electron imaging.

Incremental optical linear and rotary encoders now offer 1 nm resolution and ultra-low positional noise

Renishaw, a world leader in measurement and encoder technology, is introducing new 1 nm and 2 nm resolution versions of its successful TONiC™ incremental encoder range. Available in linear encoder and rotary encoder formats, the new higher resolution options comprise a standard TONiC readhead and new Ti20KD (1 nm) or Ti10KD (2 nm) interfaces that apply high interpolation rates to achieve very fine resolution. Furthermore, TONiC's low-noise optical scheme with superior photometry has been combined with advanced filtering inside the Ti20KD / Ti10KD interfaces to

An example to ponder on

- Five pieces of 100-meter length of optical fiber were tested.
- A laser-light signal was sent from one end through each piece of optical fiber, and the output power was measured at the other end.
- The power of the laser source was 80 mW.
- The Power Loss in the last column was calculated in decibels (dB) according to the following formula

$$\text{Power Loss (dB)} = 10 \log_{10} \frac{\text{Output Power}}{\text{Input Power}}.$$

An example to ponder on

Two ways to calculate average output power loss:

1. Calculate the average Output Power, $\bar{P}_{out}$ = 71.44 mW, and then the formula, the resulting power loss is $10\log\left(\frac{\bar{P}_{out}}{80}\right) = -0.4915\,\text{dB}$

2. Calculate the average Power Loss, $\bar{L}_{power} = -0.4928\,dB$

Which is the correct way?

Table 2.1 Experimental Results on Five Pieces of Optical Fiber

Optical Fiber Number	Input Power (mW)	Output Power (mW)	Power Loss (dB)
1	80	72.8	−0.4096
2	80	70.0	−0.5799
3	80	72.0	−0.4576
4	80	68.8	−0.6550
5	80	73.6	−0.3621

Negative dB means that there is loss of power.

An example to ponder on

The answer depends on how such a number would be used.

- **Scenario 1:** If the five measurements were peformed on the same piece of optical fiber, then the sample mean $\bar{P}_{out}$ would estimate the "true" output power of the fiber. The true power loss for that fiber should then be calculated using Method 1 (that is, $10\log\left(\frac{\bar{P}_{out}}{80}\right) = -0.4915\ \mathrm{dB}$).

- **Scenario 2:** The five different pieces tested in the experiment represent an optical fiber used in an existing commucation network, and we are trying to characterize a typical network power loss (over a 100 meters). Here we should use Method 2 (that is, $\bar{L}_{power} = -0.4928\ dB$).

Why? Imagine the five pieces being connected into one 500-meter optical fiber. Its power loss would then be calculated as the sum of the five power-loss values, resulting in the total power loss of $-2.4642\ dB$. The same value (up to round off error) can be obtained by multiplying $\bar{L}_{power} = -0.4928\ dB$ by 5.