

Optical Metrology

Lecture 1: Introduction

Contact details

Instructor: Andrés G. Marrugo, Ph.D.

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Course web site:

agmarrugo.github.io/optical-metrology

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 miniaturisation.
 - 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

Part of this course has 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 Industrial de Santander.
- Metrología Óptica from Universidad Politécnica de Cataluña.

Outline of the Course

Date	Week	Lecture Topics
Feb 5	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 of 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)

Gary Cloud: Optical Methods of Engineering Analysis, Prentice Hall; 1998.

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: Analysis 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?

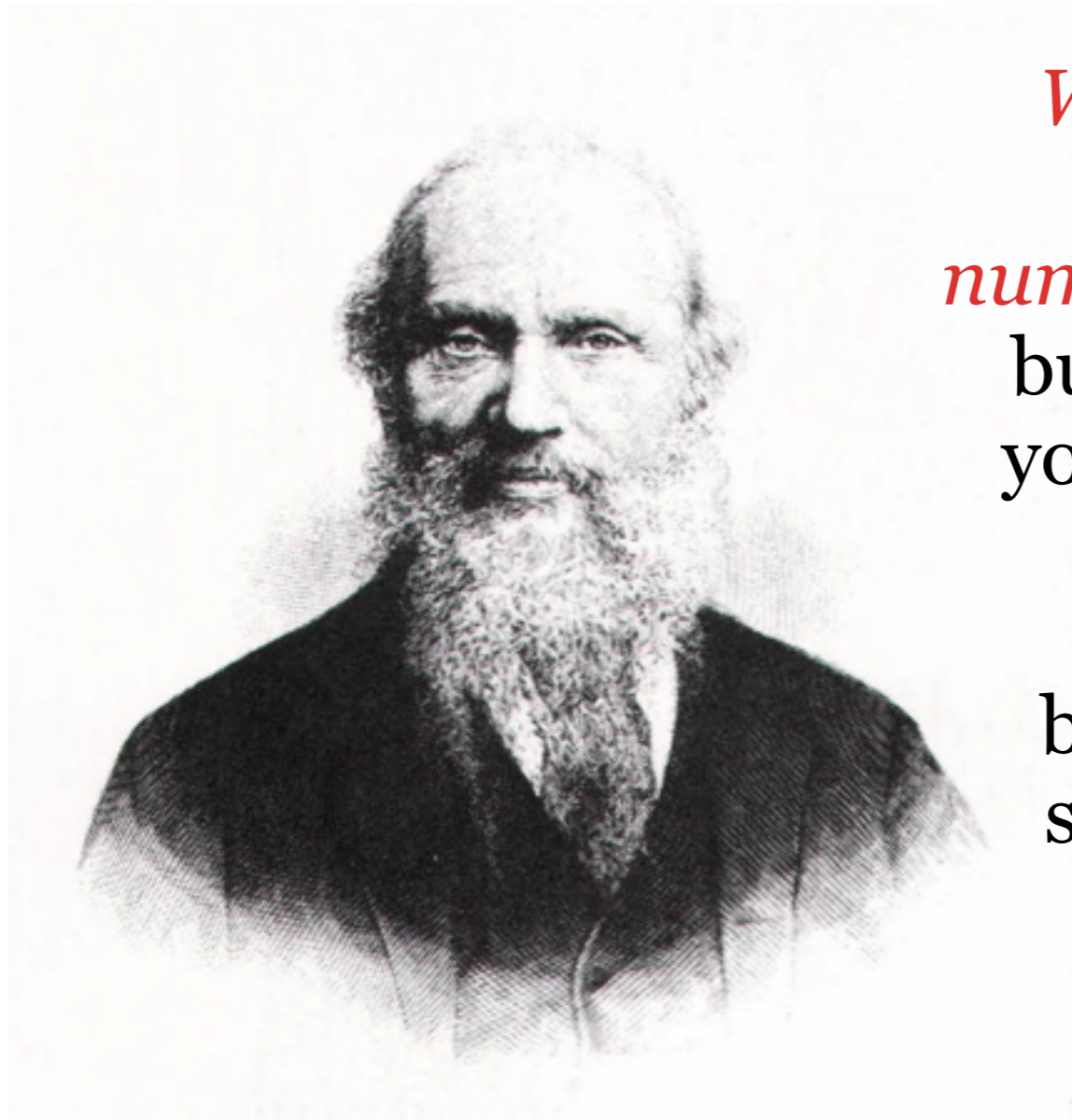
Metrology is the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology.

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.

Why is it important?

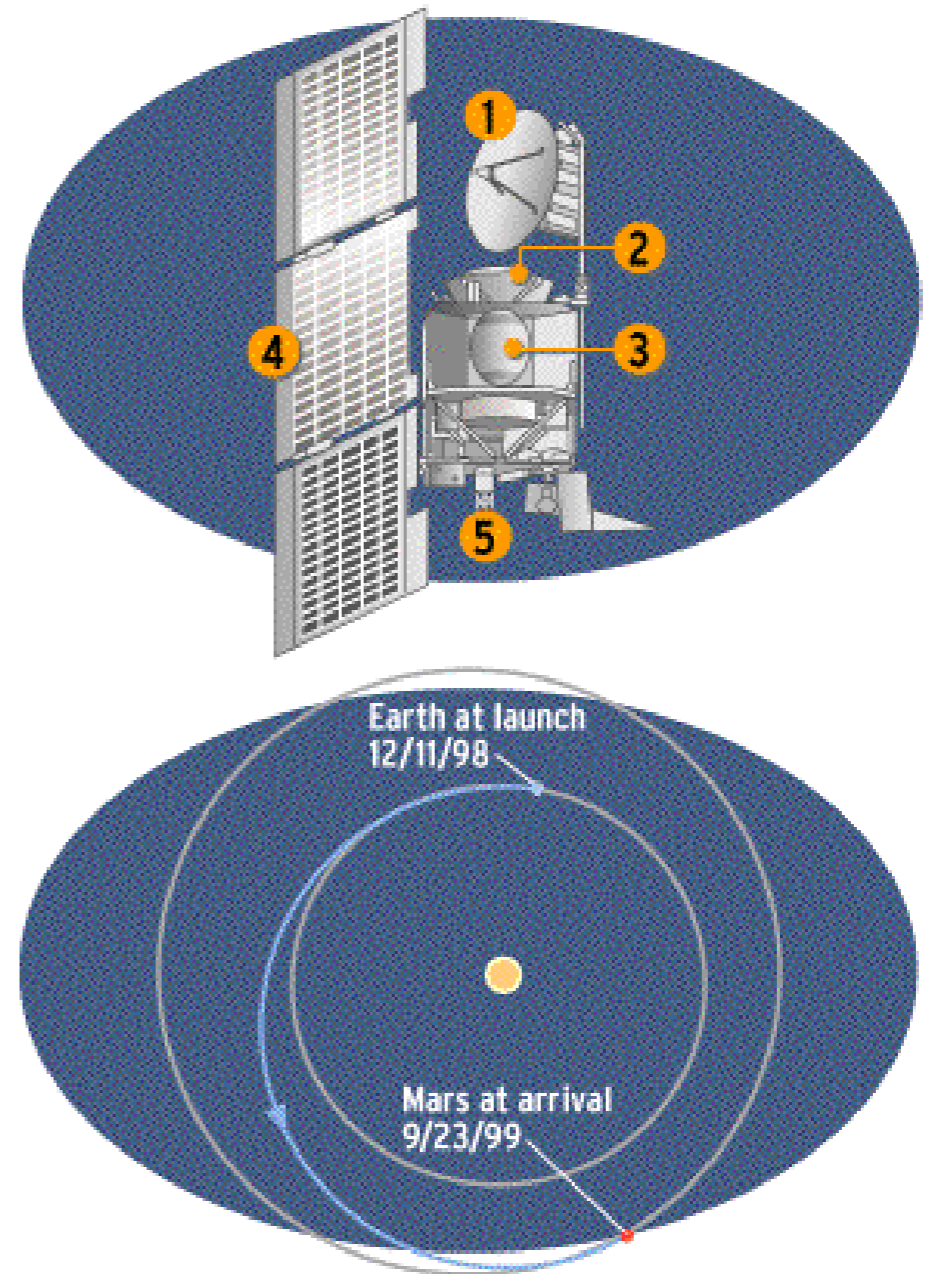


*When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your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

William Thomson, Lord Kelvin

Why is it important?

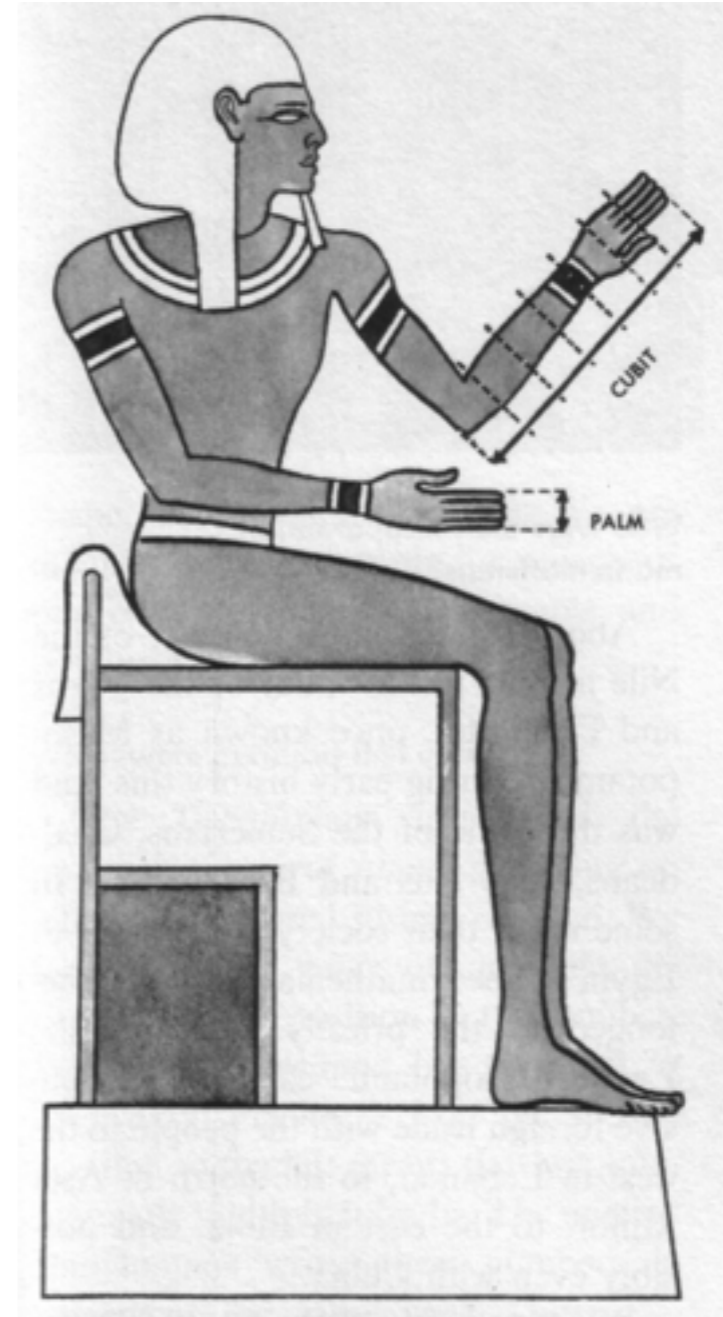
- Wrong or inaccurate measurements can lead to wrong decisions, that have serious consequences, costing money and even lives. eg.. **Metric mishap caused loss of NASA orbiter.**
- **Failure convert English/US system made the probe travel 60 miles farther and it was lost. (125m USD in 1999 september).**
- 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



History in Images

THE AMAZING STORY OF MEASUREMENT

PREPARED AND DISTRIBUTED BY **THE LUFKIN RULE CO.** SAGINAW, MICHIGAN.
Copyright 1960

The illustration is divided into several panels. The top row shows three scenes: an Egyptian pharaoh with a measuring staff, a cavewoman measuring a distance, and a king with a measuring staff. The middle section features the title in large, bold, red letters. Below the title, there are several smaller panels: a man in a blue robe measuring a large structure, a man in a red robe measuring a long object, and a hand holding a measuring tool. The bottom of the page contains the publisher's information and copyright notice.

SINCE TIME BEGAN...

MAN HAS ALWAYS MEASURED THE WORLD AROUND HIM. THE CAVE-MAN JUDGED DISTANCES BY EYE OR TIME, COMPARED SIZES BY PACES OR BY MATCHING OBJECTS WITH TREES, STONES OR MOUNTAINS THAT HE KNEW FROM MEMORY. HIS WORLD DEMANDED NO ACCURACY ---- ANY SIZE CAVE WOULD DO IF HIS FAMILY WOULD FIT INTO IT.

HIS BODY BECAME HIS YARDSTICK--

AS HIS NEEDS REQUIRED GREATER ACCURACY, HIS HEIGHT, HIS ARMS OUT-STRETCHED, HIS FEET AND HIS HANDS BECAME ROUGH METHODS OF MEASURING CLOTHING, WEAPONS ETC.

NO STANDARDS WERE EVER RECORDED ---- EACH PERSON HAD HIS OWN METHODS OF MEASURING FOR HIS OWN NEEDS --- EACH PERSON WORKED ALONE WHEN MEASUREMENTS WERE INVOLVED.

2

The illustration is a single-page comic strip. It features a cavewoman in a brown dress measuring a distance with her body. The text is arranged in a vertical column on the left side of the page, with illustrations interspersed. The top panel shows the cavewoman measuring a distance. The middle panel shows her measuring a distance with her body. The bottom panel shows her measuring a distance with her body. The page number '2' is located at the bottom left corner.

History in Images

In 6,000 B.C.--
THE FIRST KNOWN STANDARDS OF MEASUREMENT WERE ESTABLISHED IN THE ADVANCED CIVILIZATIONS ALONG THE **NILE** AND ON THE PLAINS OF **CHALDEA!**

THE CUBIT
BECAME THE PRIME MEASUREMENT. IT WAS THE BENT FOREARM FROM THE POINT OF THE ELBOW TO THE TIP OF THE MIDDLE FINGER OF THE OUTSTRETCHED HAND--ROUGHLY 18 TO 19 INCHES. IN 4000 B.C., THE CUBIT WAS STANDARDIZED AT WHAT IS NOW 18.24 INCHES.

THE CUBIT WAS USED IN BUILDING ALL THE **PYRAMIDS!** --- EACH SIDE MEASURES 500 CUBITS, AND ALL MEASUREMENTS ARE IN MULTIPLES --- OR FRACTIONS OF CUBITS. THE **PERIMETER** OF THE PYRAMIDS MEASURES 2000 CUBITS--- OR $\frac{1}{2}$ A MERIDIAN MILE.
(SEE PAGE 6)



3

EARLY EGYPTIANS ALSO USED:

THE SPAN-- THE LENGTH BETWEEN THE TIPS OF THUMB AND LITTLE FINGER OF THE OUTSTRETCHED HAND --- $\frac{1}{2}$ A CUBIT OR 9 INCHES.

THE PALM -- THE BREADTH OF 4 FINGERS --- $\frac{1}{6}$ OF A CUBIT -- OR ABOUT 3 INCHES. WIDELY USED BY MERCHANTS FOR MEASURING CLOTH.

THE UNIVERSAL SIZE OF A BRICK IS A SPAN BY $\frac{1}{2}$ SPAN BY A NAIL --- (THE LAST 2 JOINTS OF THE MIDDLE FINGER.)

THE DIGIT -- $\frac{1}{24}$ CUBIT --- THE BREADTH AT MIDDLE OF MIDDLE FINGER --- $\frac{3}{4}$ INCH.

FROM THIS DIVISION OF THE CUBIT INTO 24 DIGITS, AND THE DIVISION OF A SPAN INTO 12 DIGITS, CAME THE NUMBER OF HOURS IN A DAY AND MONTHS IN A YEAR!

THE FOOT -- WAS ADOPTED QUITE LATE IN HISTORY. (JUST AS THE **PYRAMIDS** WERE BEING BUILT.) IT EQUALLED $\frac{2}{3}$ OF A CUBIT, 4 PALMS, OR 16 DIGITS. MEASURED ABOUT 12.16 INCHES.



4

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.

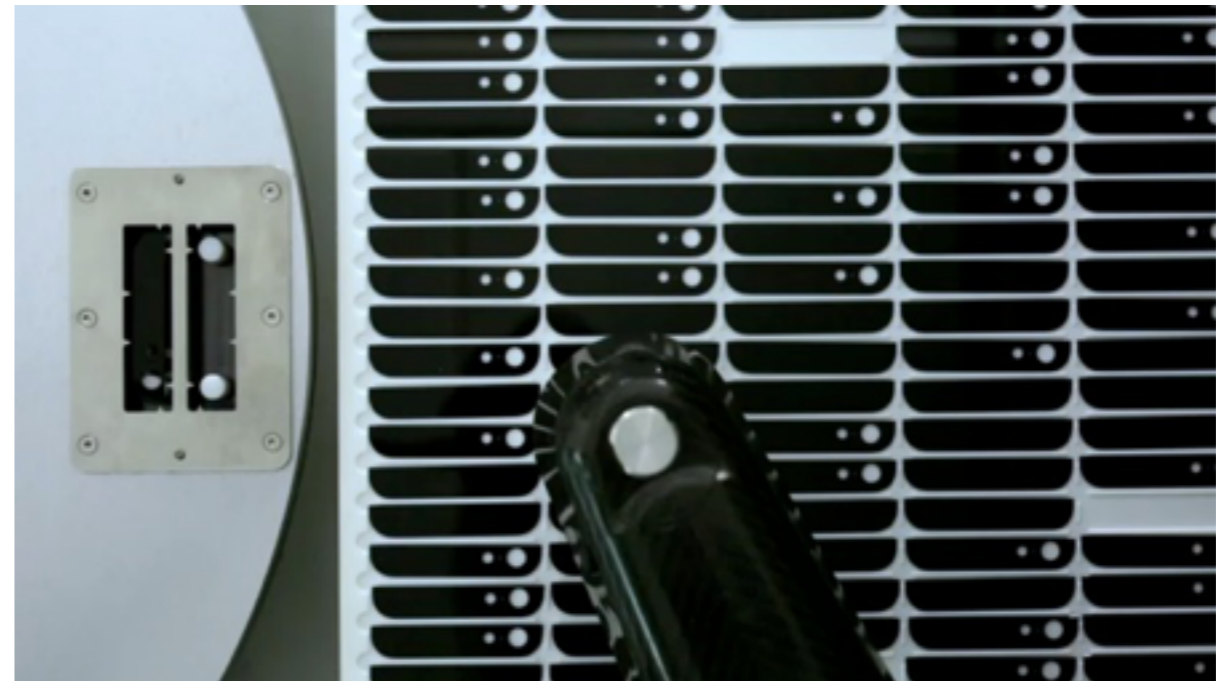
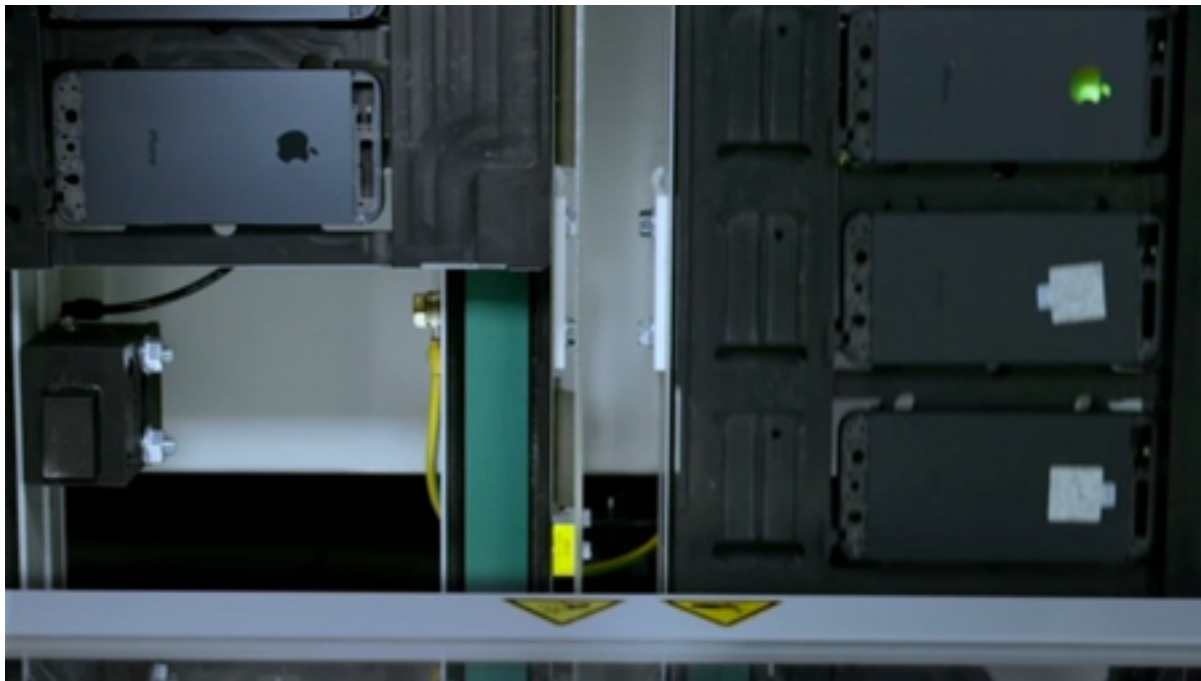
Metrology is a **check and balance** in manufacturing.

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

"If it can't be repeatedly measured, then it is just an opinion." - DeVere Bobier



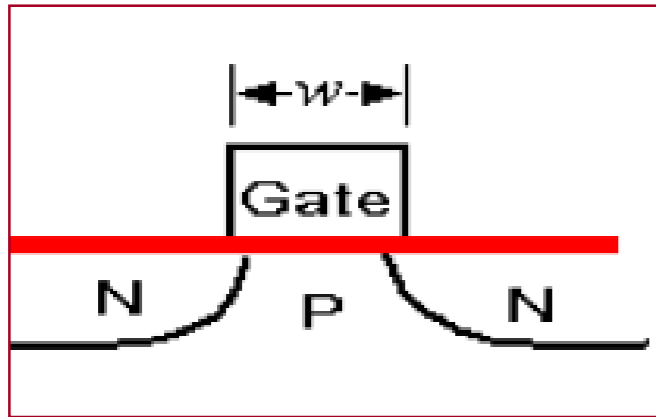
Economic Impact

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?

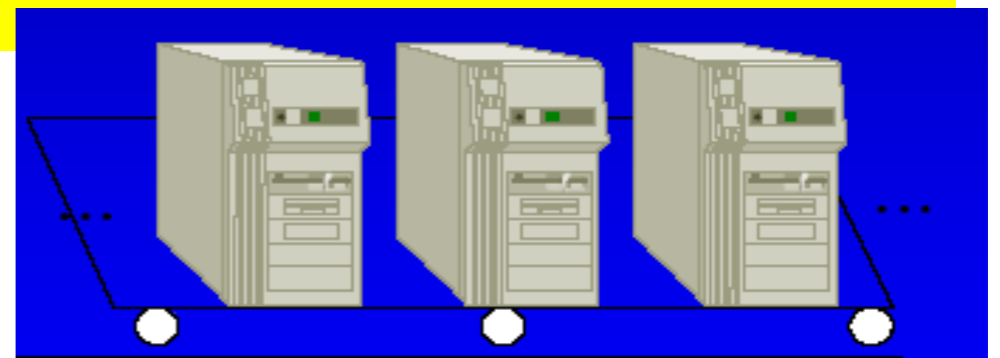
- Faster microprocessors fetch higher prices
- Narrower gate =>less capacitance => more speed

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.)**



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

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

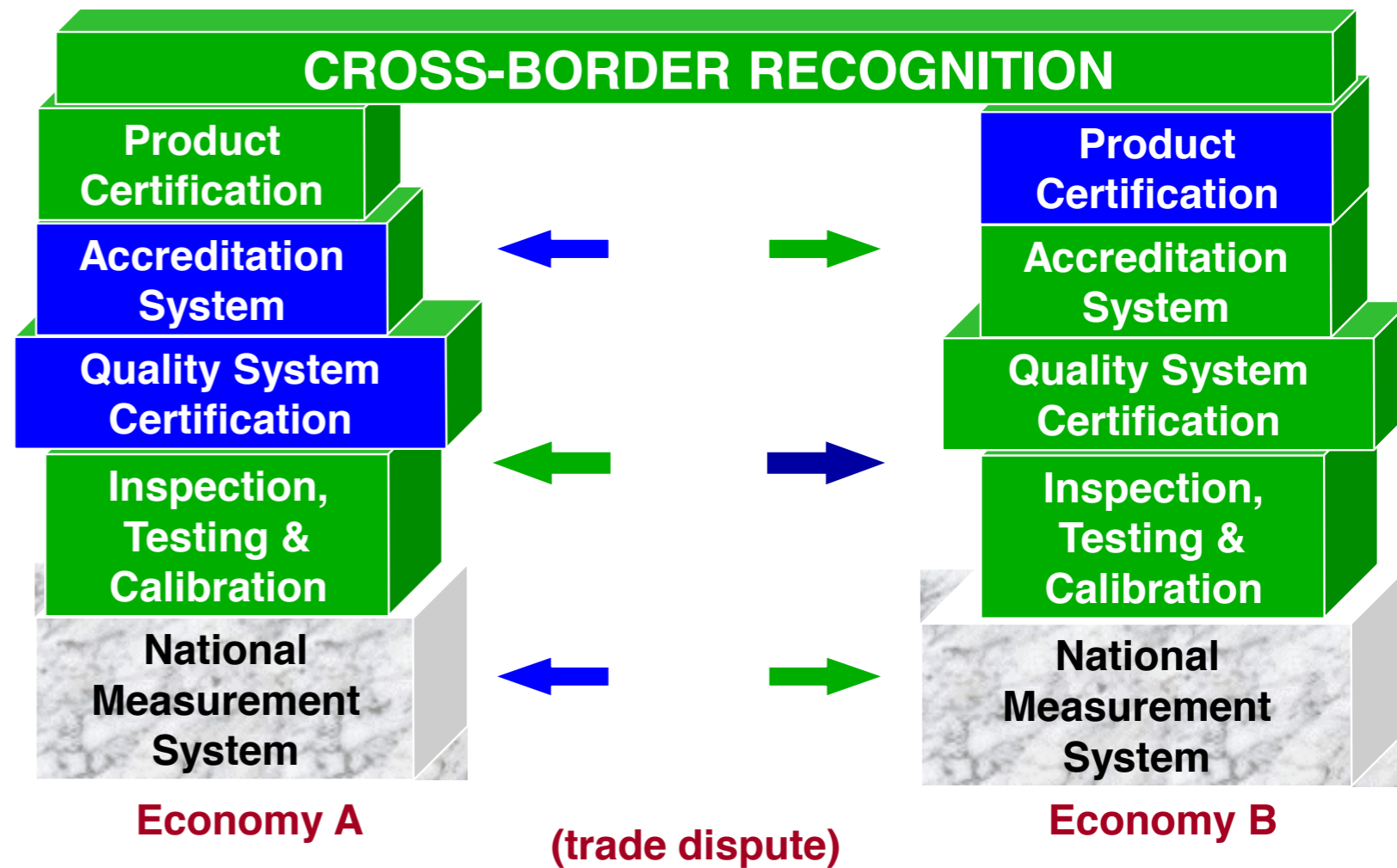
International Trade

- Manufactured products
- Parts
- Services
- Have to fulfil
 - 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**.

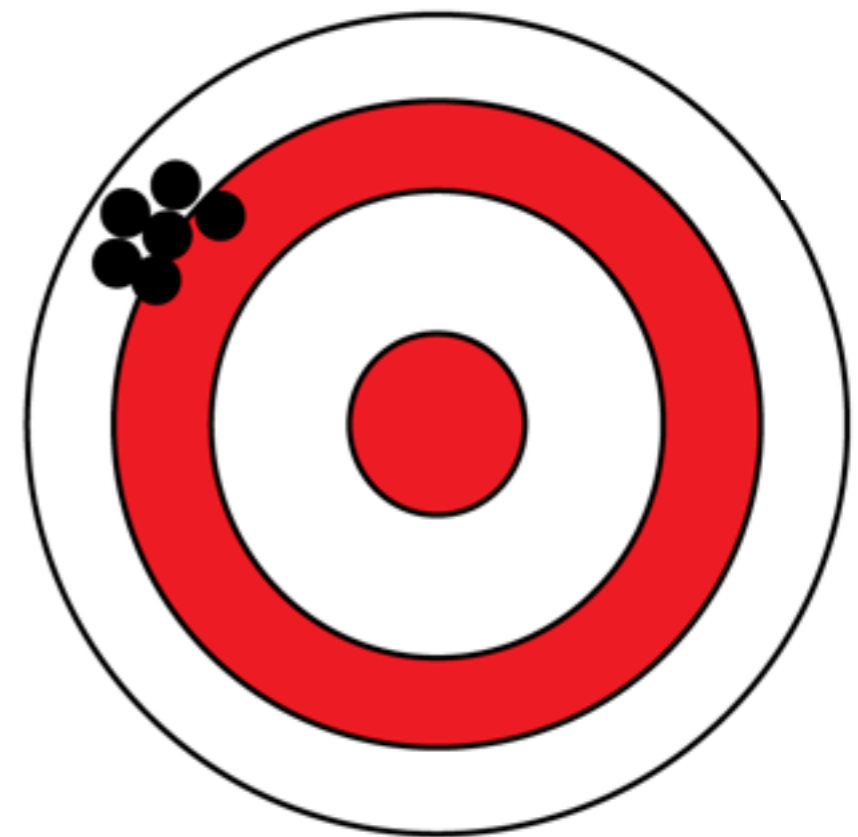
Accuracy the degree of conformity with a standard (the "truth"). Accuracy relates to the **quality of a result**, and is distinguished from precision, which relates to the quality of the operation by which the result is obtained. In Figure, the marksman has approached the "truth", although without great 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

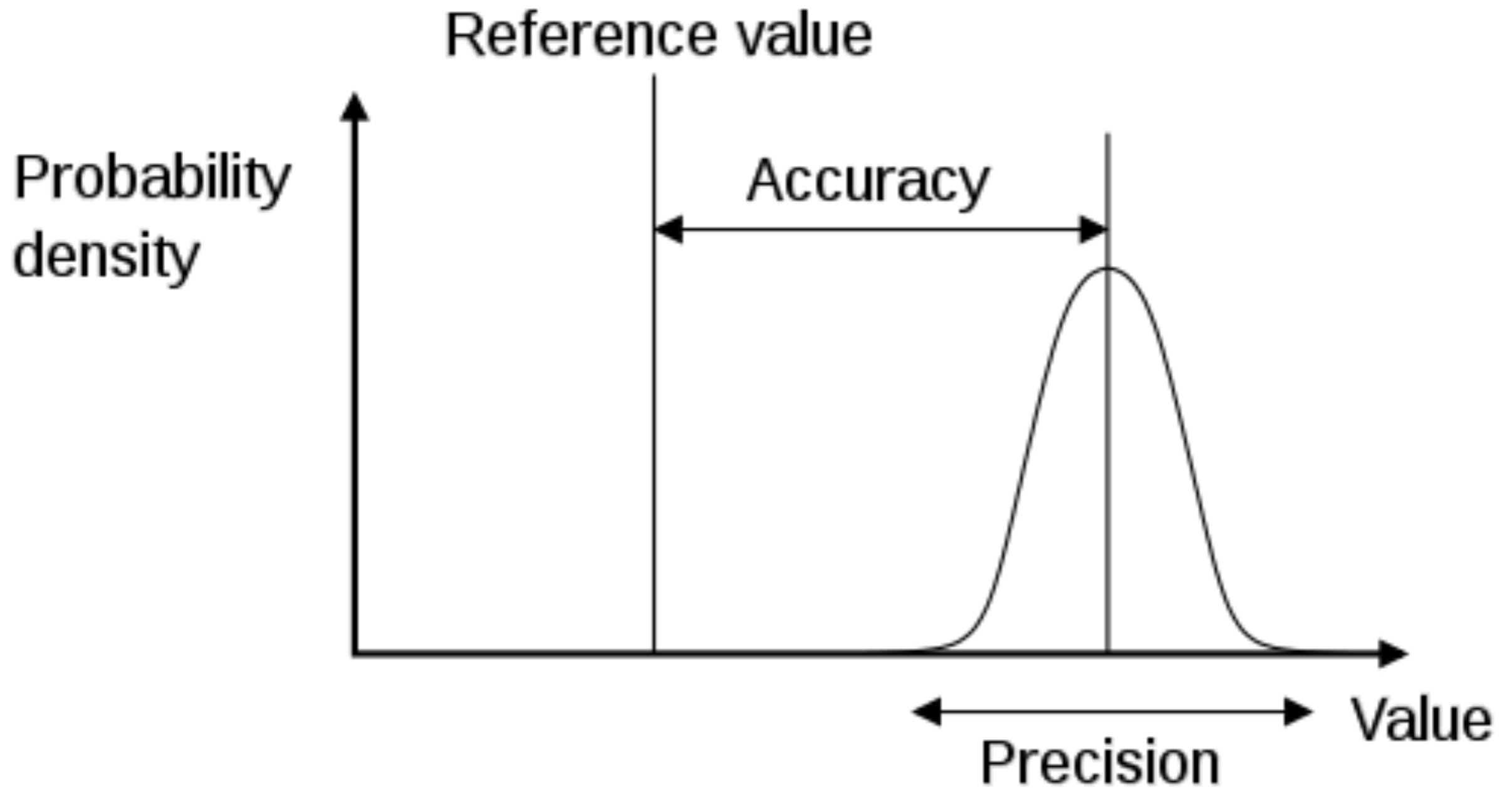
Precision the degree of refinement in the performance of an operation, or the degree of perfection in the instruments and methods used to obtain a result. An indication of the **uniformity or reproducibility of a result**. Precision relates to the quality of an operation by which a result is obtained, 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.

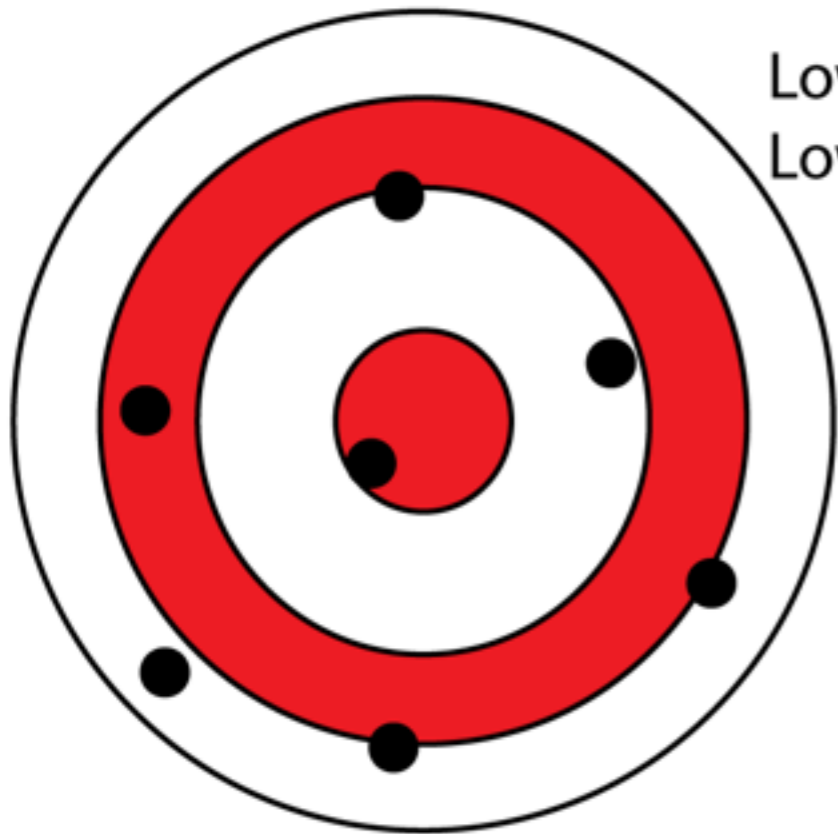
With the knowledge gained by observation of the results, the marksman can apply a systematic adjustment (aim lower and to the left of his intended target, or have his equipment adjusted) to achieve more accurate results in addition to the precision that his methodology and equipment have already attained.



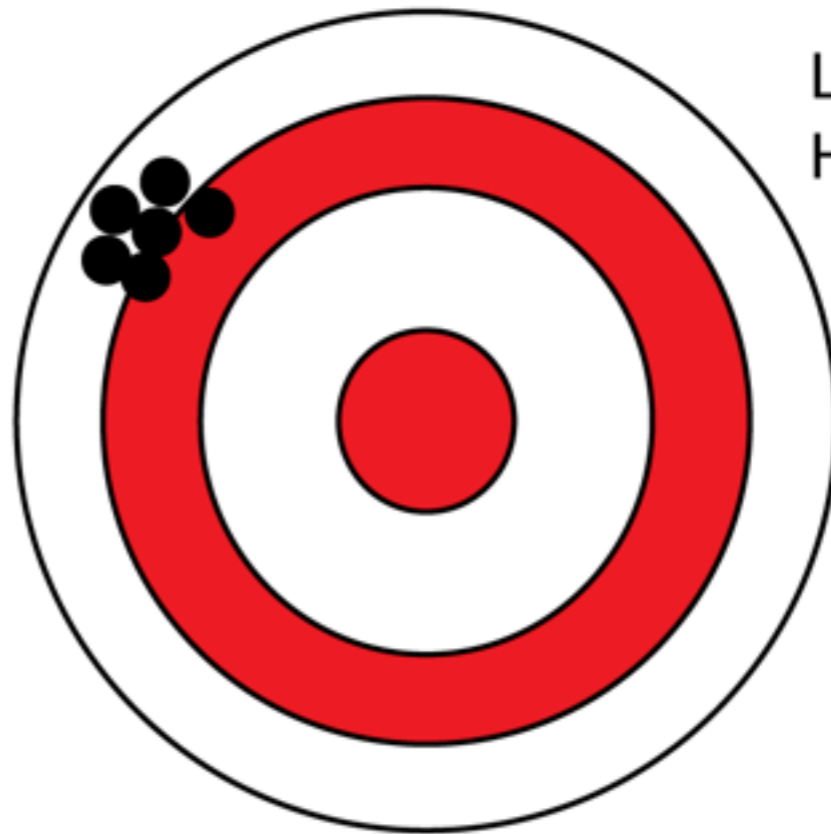
Precision

Accuracy and Precision

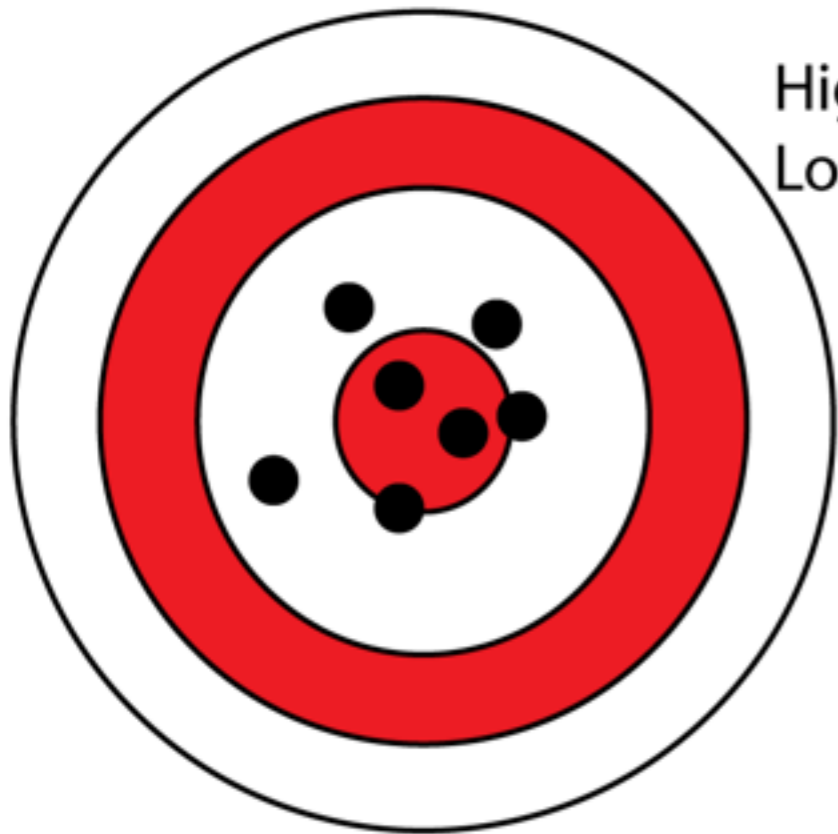




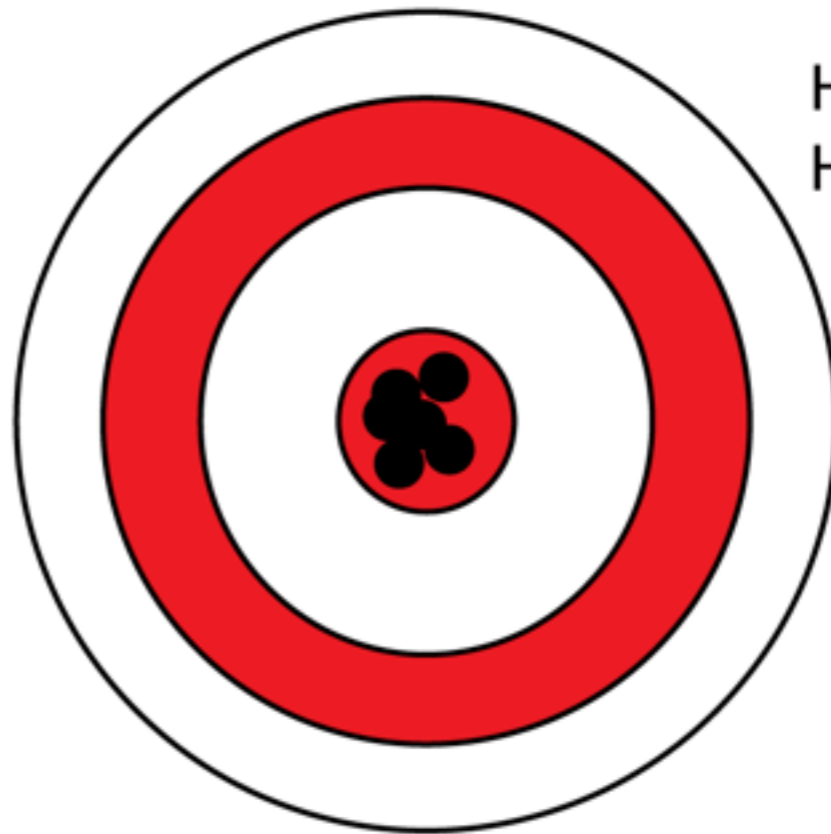
Low accuracy
Low precision



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.

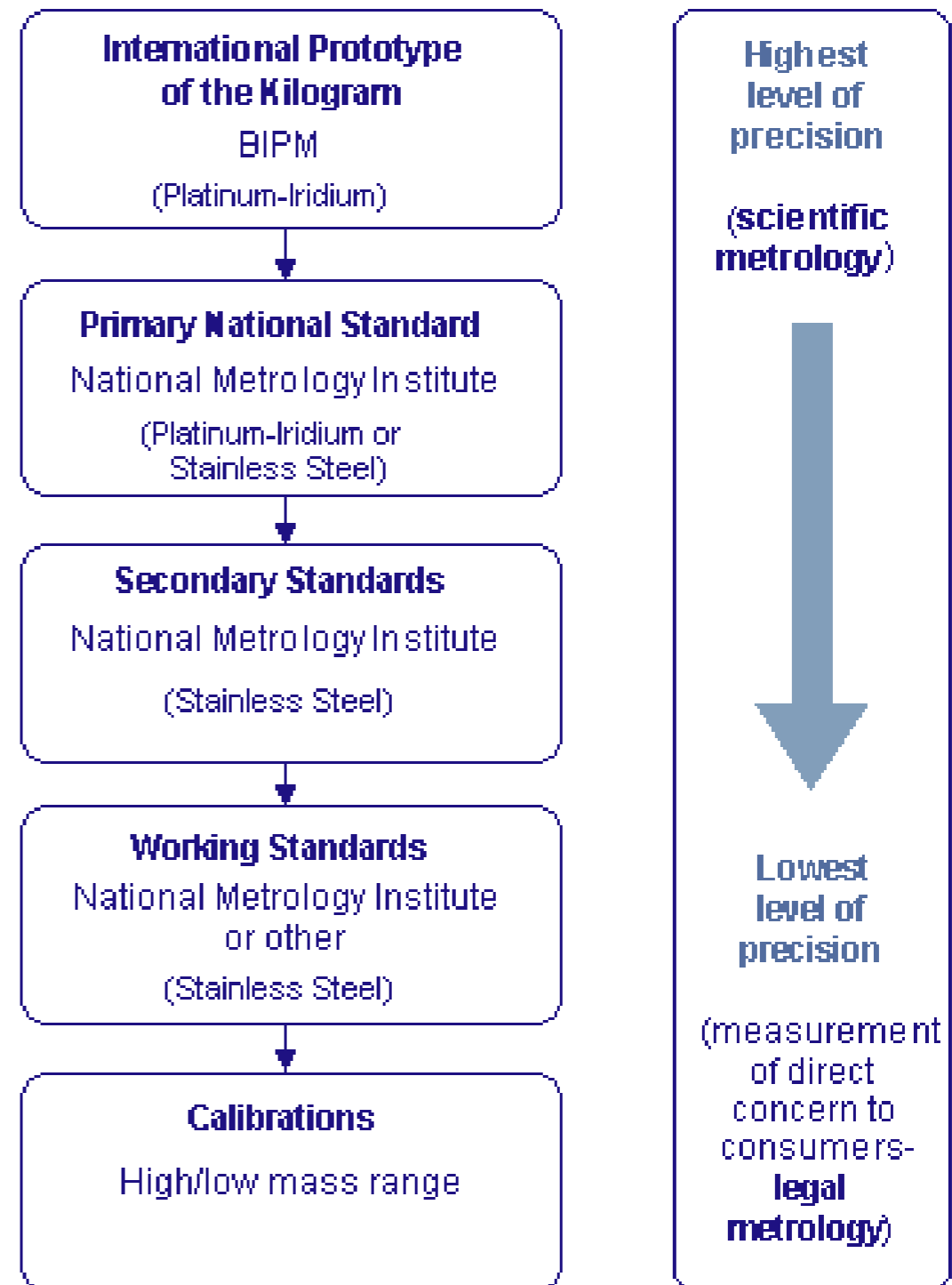
Calibration and Traceability

- 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.

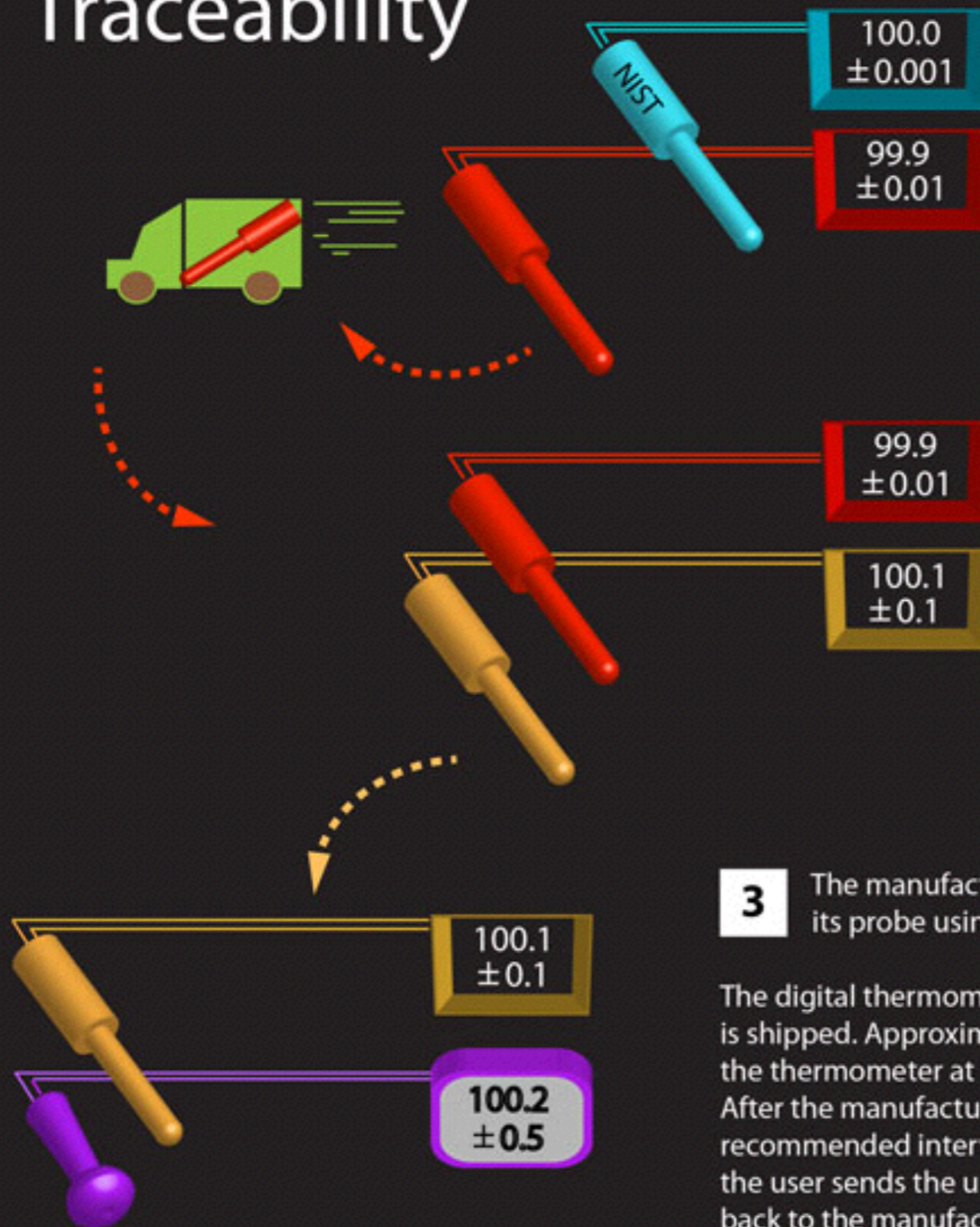
Calibration and Traceability

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.



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"

Calibration and Traceability

Uncertainties of physical realizations of the base SI units

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 current 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

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

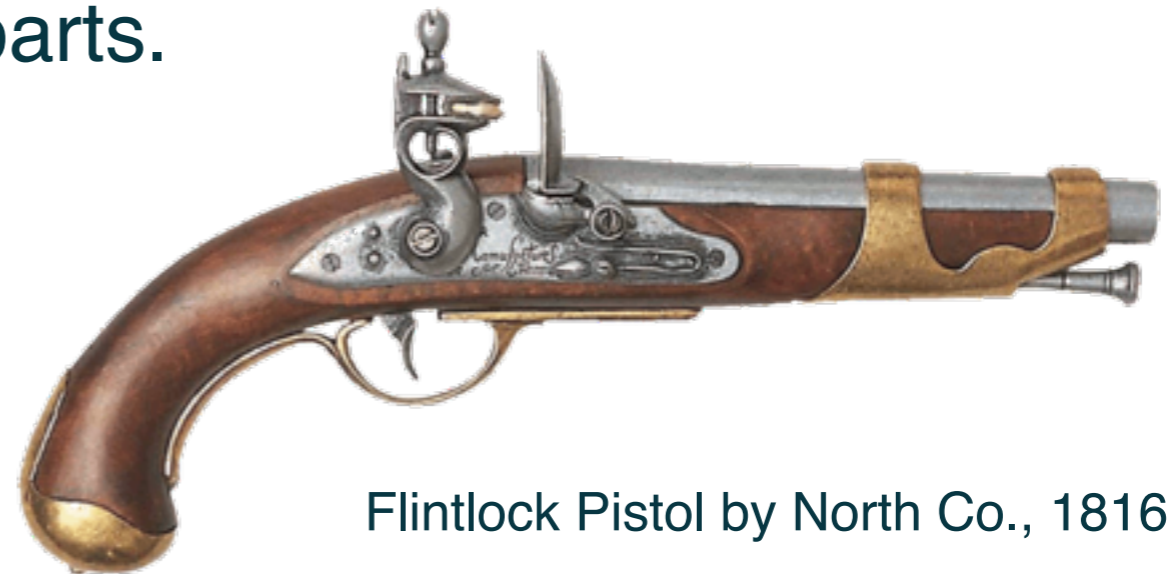
The Machine Revolution 1800-1920 – the milli-inch
(1 mil = 25 μm)

- 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 ($1\ \mu\text{m} = 1000\ \text{nm}$)

- 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 ($\sim 0.1\ \mu\text{m}$) 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

