MECH 6491 Engineering Metrology and Measurement Systems

Credits: 4

Introduction

Lecture 1

Contact details

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Course Web site: http://users.encs.concordia.ca/~nrskumar/

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 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 betterment of part or process

* The amount of acquired skills will be proportional to the capabilities, will and effort of the individuals

Outline of the Course

Date	Week	Lecture Topics
May 3rd	1	Need for Metrology – an overview
May 5th	2	Linear and Geometric Tolerances
May 10th	3	Methods in Surface Measurement
May 12th	4	Fundamentals of Optical Metrology
May 17th	5	Optical interferometry – theory and overview
May 19th	6	Moiré and phase shifting interferometry
May 24th	7	Speckle Interferometry and Holography
May 26th	8	Light sources, detectors and imaging systems
May 31st	9	Application to precision measurement and MEMS devices
June 2nd	10	Special Topics – Nanometrology, Bio Metrology and
June 7th	11	Special Topics – Interference spectroscopy and Review
June 9th	12	Student Presentations
June 14th	13	Student 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 - one is an introductory lecture
  - 1 Project - due during the last week of classes
  - Final exam

Class logistics

- 3 Continuous teaching hours
- Twice a week _ T _ J _ 18:30 – 21:00
- 11 lectures + 2 Project Presentations
- Final exam - scheduled by exam office

Text book and other reference

TEXTBOOK

- **There is no prescribed textbook for this course. Lecture notes available at the course webpage will be enough provided effort is done to research information from the references**

REFERENCES (not exhaustive)

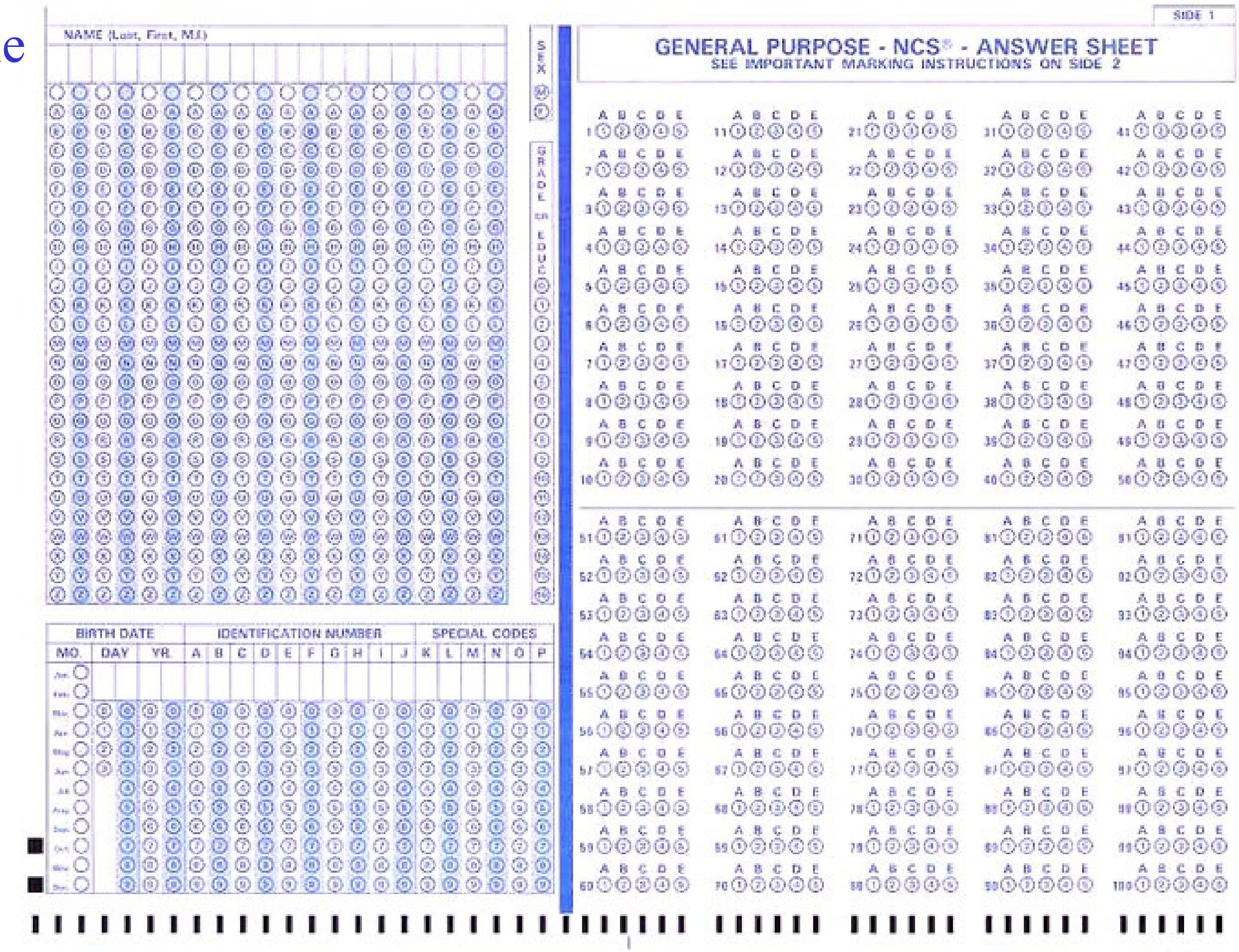
1. Gary Cloud: Optical Methods of Engineering Analysis, Prentice Hall; 1998
2. Eugne Hecht: Optics, Addison-Wesley Pub
3. Scarr: Metrology and Precision Engineering, Mc.Graw Hill, 1995.
4. Hariharan: Basics of Interferometry, Prentice-Hall, Ninth Edition, 1981.

The Assignment

- There will be two assignments. The first one will have some problems to solve and some theory questions to answer and is due on the 24th of May.
- The second assignment is slightly different involving review of a journal paper (provided by the instructor).
- Review should be critical, detailed, and thorough - extended abstract of strictly less than 500 words. Due on 9th of June.
- Proper Concordia guidelines of referencing to be followed. **Plagiarism in any form is strictly prohibited - penalized with 0 marks.**
- *Note: The marker is Vinodh Krishna. For questions regarding assignment/term test marks, contact -* ***c.vinodh1992@gmail.com***

The Term Test

- Term test will be held during lecture hours on the 24th of May.
- You need to bring pencil and calculator on that day
- Exam will be multiple choice.
- 30 or so questions to be filled in 30 minutes.
- The exam will be done on Scantron sheets



The Project

- A team-work based project in the topics related to Metrology.
- Maximum 4 students per group. 20 groups in total. 10 minute presentation per group
- Literature review and theoretical work will be needed to complete the work.
- I need the list of group members by the end of next week.
- There will be a presentation for this project on the last 2 lecture days, 9^{th} and 14^{th} of June. Details will be available in the course website
- Note: All team members will receive same grade - according to the results of the team work.

Final Test

- The final test will be scheduled by the exam office. A number of multiple choice, short answer and comprehensive questions will require answer.
- Duration of the test: 3 hours.
- Write the final exam with confidence that you will do very well

Grading Scheme

- Grade composition:
  - Assignment 20%
  - Term Test 10%
  - Project 20%
  - Final 50%
- To pass the course you have to
  - *Pass the final*
  - *Submit your project and assignment Promptly*

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

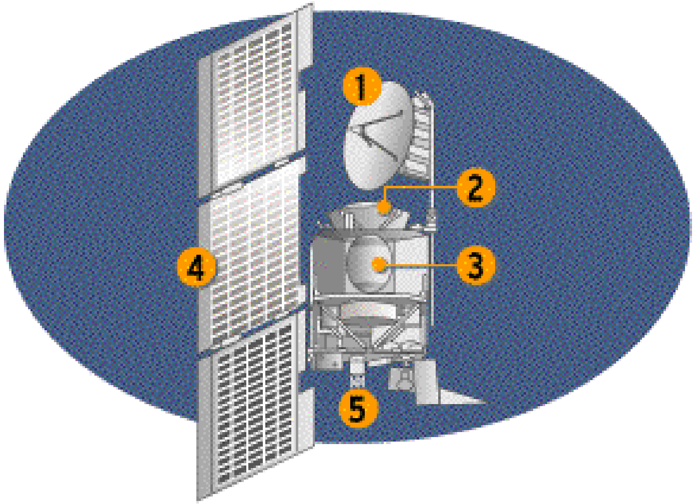
Why is it important?

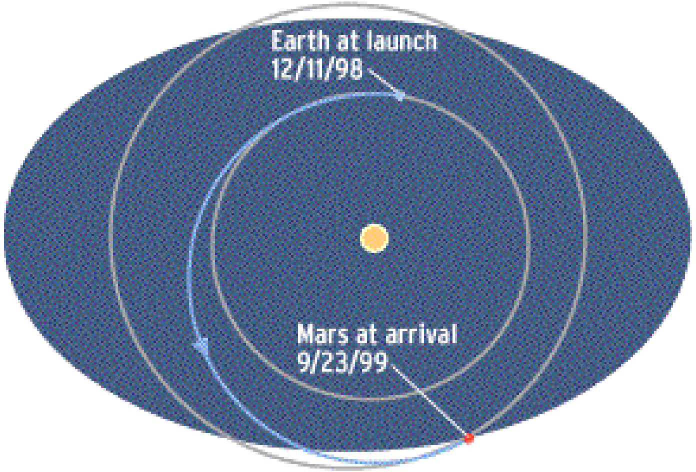
- *When you can measure what you are speaking about, and express it in numbers, you know something about it;*
- *but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.*
- *It may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced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

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.
- Metrologists are therefore continuously involved in the development of new measurement techniques, instrumentation and procedures, to satisfy the ever-increasing demand for greater accuracy, and increased reliability.





A bit of history

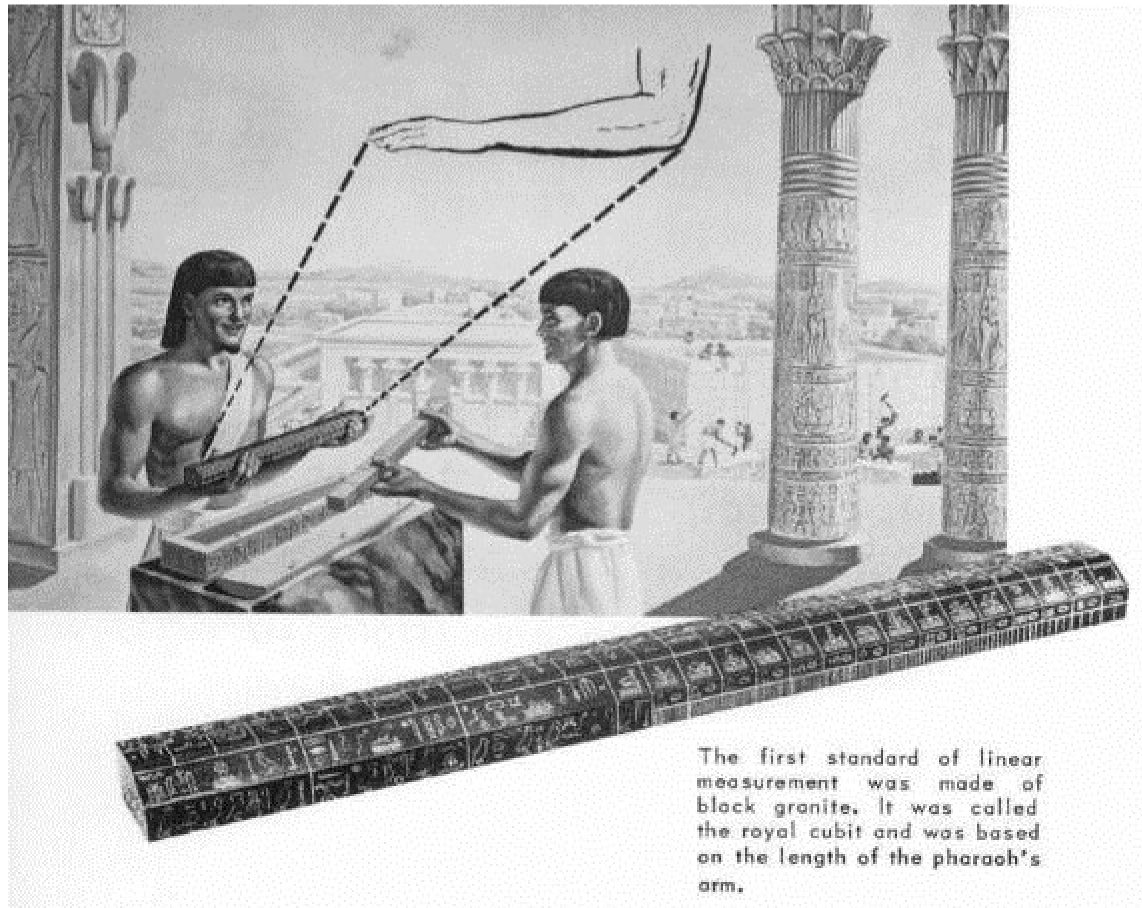
- One of the earliest records of precise measurement is from Egypt. The Egyptians studied the science of geometry to assist them in the construction of the Pyramids. It is believed that about 3000 years BC, the Egyptian unit of length came into being.

www.fairchild-controls.com/ methistory.html

depts.washington.edu/ ctltstaf/cc/gallery.shtml

A bit of history

- 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



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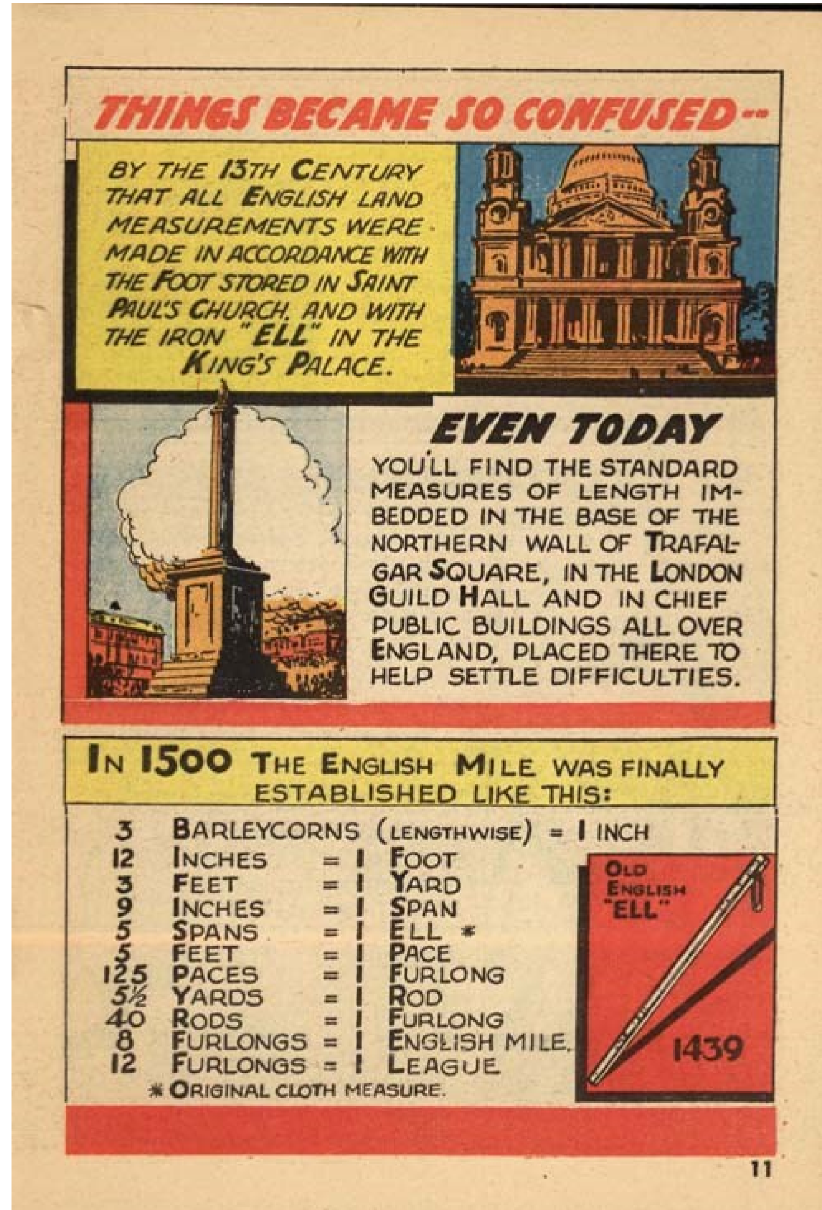
History in Images

History in Images

History in Images



History in Images

History of Metrology

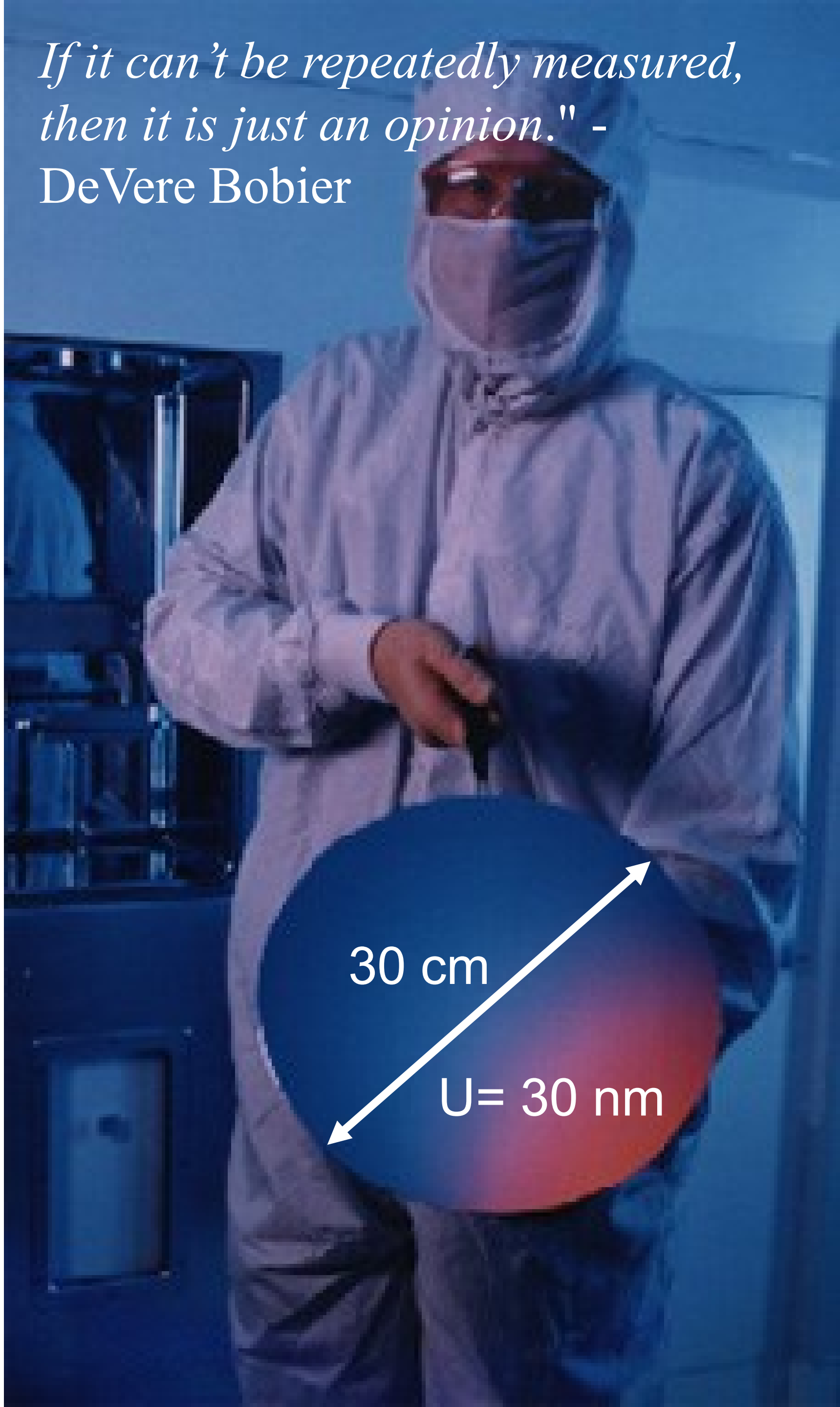
- Although standardization has been a goal of social and economic advancement since very early times, only in 18th century that there was a unified measurement system
- The earliest systems of weights and measures were based on human morphology. Consequently, these units of measurement were not fixed; they varied from one town to another, from one occupation to another, and on the type of object to be measured
- This lack of a standardized system of measurements was a source of error and fraud in commercial and social transactions, putting a brake on international commerce and prevented the development of science as an international endeavor

Economic benefits of Metrology

- Metrology is Value Added
- It is often erroneously stated that “metrology is not value added to the product” but, today it is becoming a key enabler in a number of areas
- Metrology is a check and a balance in the manufacturing process
- Metrology does provide an economic benefit
- It is often difficult to assess this economic benefit as it is often hidden and often forgotten

The $B Wafer Industry

- **process-control is based on measurements**
- **faulty measurements...**
  - loss of control
  - form & function failure
  - loss of profits, wealth



Metrology adds $$$

Economic Impact

- Measurement and measurement related operations are estimated to account for between 3% and 6% of the GDP of industrialized countries
- Other studies for developed countries find 15% of GDP is measurement-related
- Government investments in national metrology of developed countries vary between 20 and 70 ppm of GDP

Economic Impact

- UK study (on behalf of NPL and DTI) find:
- Measurement in the UK delivers a significant impact on the economy of 0.8% of GDP, which equates to 5 000 million GBP
- Government budget of NPL is about 38 million GBP per annum

Economic Impact

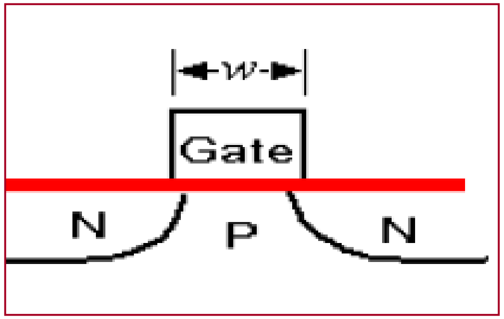
- NIST studies find that NIST investments lead to industry savings including:
- Lower transaction costs
- Lower regulatory compliance costs
- Energy conservation
- Increased product quality
- Enabling new markets
- NIST leverage factors, like benefit-cost-ratio varies from 3 to 110

Economic Impact

- EU study demonstrates:
- IVD (in-vitro diagnostic) industry expects a larger market
- Automotive industry is extremely globalized and cannot do without international metrology infra-structure
- European Union relies largely on gas consumption, which is internationally traded (sold at volume compensated at 15°C)

Economic benefits of Metrology

Example: Semiconductor Manufacturing



What's a Nanometer worth?

•Faster microprocessors fetch higher prices

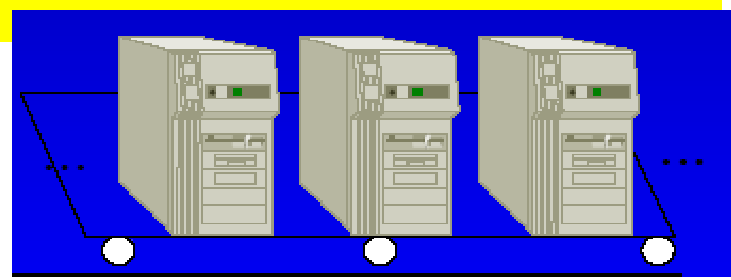
•Narrower gate =>less capacitance => more speed

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.)



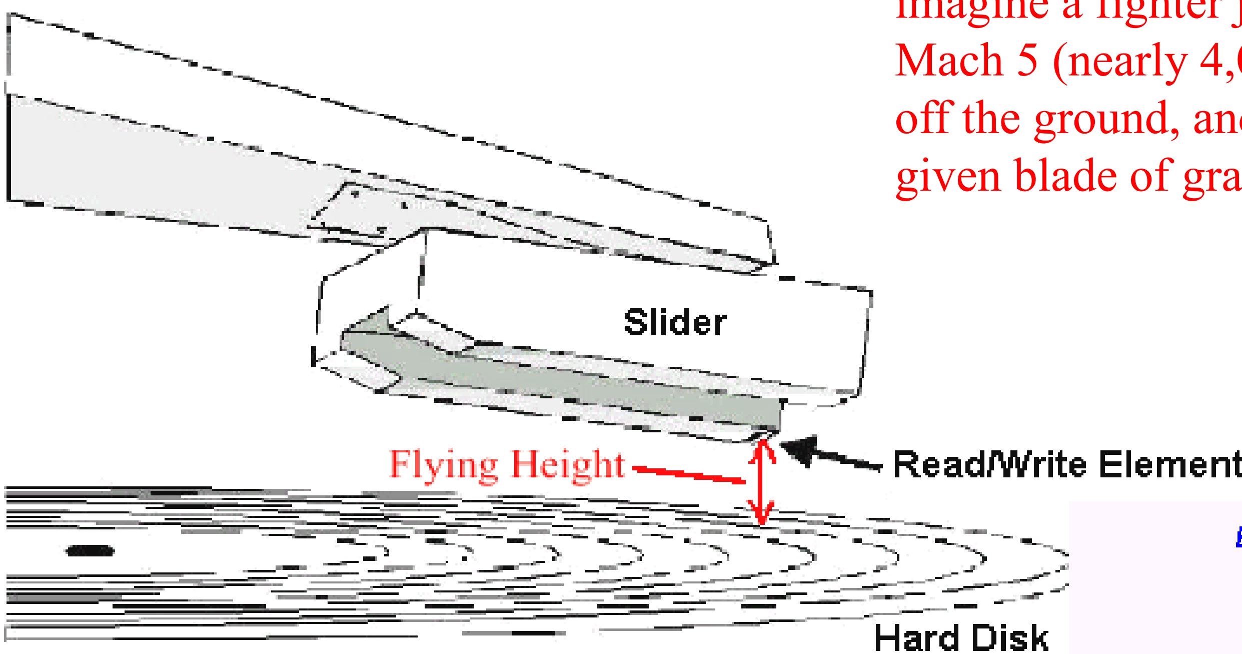
$>10^8$units $\times$\$10/unit $\geq$\$1 billion/nm

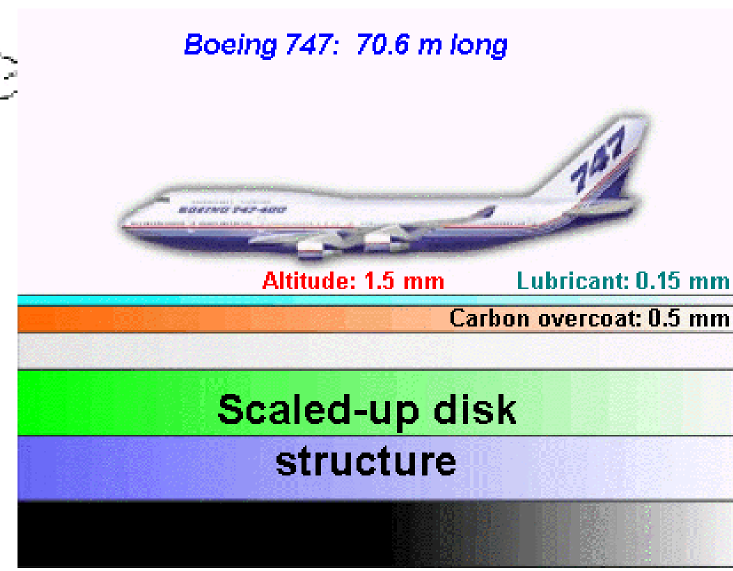
It's a big industry, and small improvements yield big economic benefits….

Credit: John Villarrubia, NIST

Economic benefits of Metrology

imagine a fighter jet traveling in excess of Mach 5 (nearly 4,000MPH) at less than 1-inch off the ground, and being able to stop on any given blade of grass.





Flying height in Hard Disk Drive *

2002	2004	Current
20nm	< 7nm	≅ 4nm

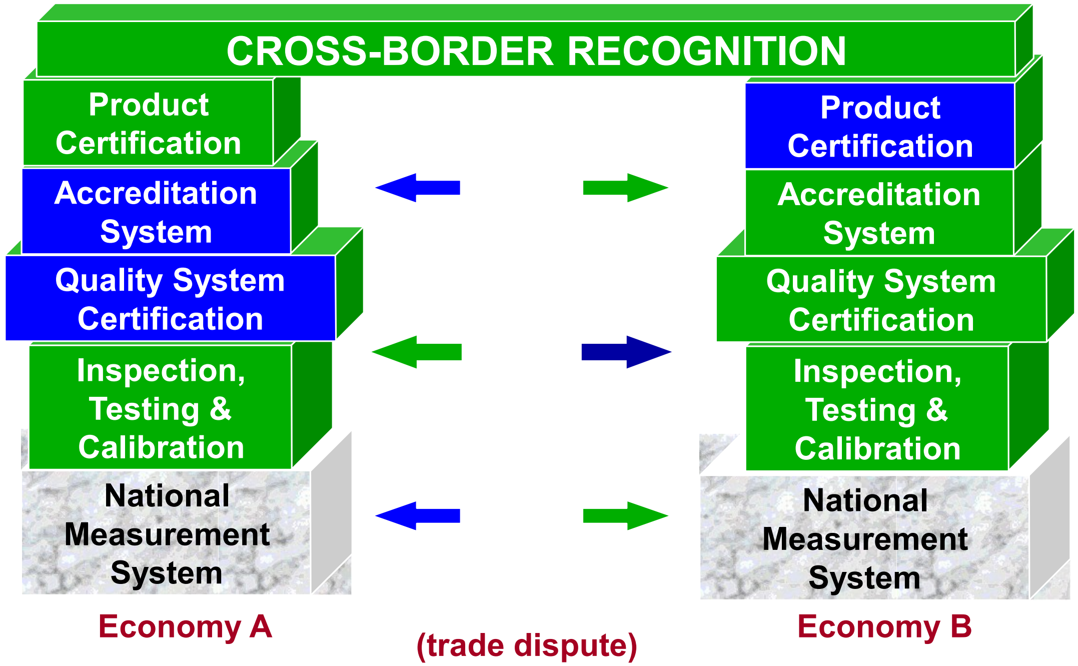
* Centre for Magnetic Recording Research, University of California, San Diego

International Trade

- **Manufactured products**
- **Parts**
- **Services**
- **Have to fulfil**
  - **specifications**
  - **regulations**
- **Are delivered worldwide**
- **Therefore measurements have to be comparable (traceable)**

International Trade

- Is an essential and often hidden part of the technical infrastructure
- Underpins any large scale industrial revolution in history
- Underpins the conformance structure of any modern economy
- Confidence in results of measurements is a prerequisite to international trade*



* **Intercomparison of scanning probe microscopes – Precision Engineering (26)**

International Trade

The importance of metrology to trade

Drivers

- Reliable, traceable, comparable measurements
- Taking away Technical Barriers to Trade
- Trade agreements, accreditation agreements and metrology agreements
- Once tested/measured, everywhere accepted

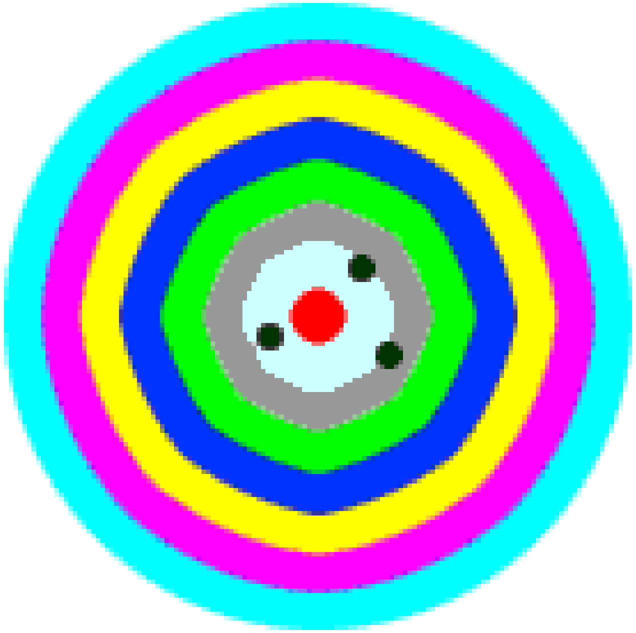
Accuracy and Precision

- When we talk about traceability of measurement and comparison with other measurement methods, one need to know the difference between two basic aspects in measurement
  - ACCURACY
  - PRECISION

Accuracy and 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 resul 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 th "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.

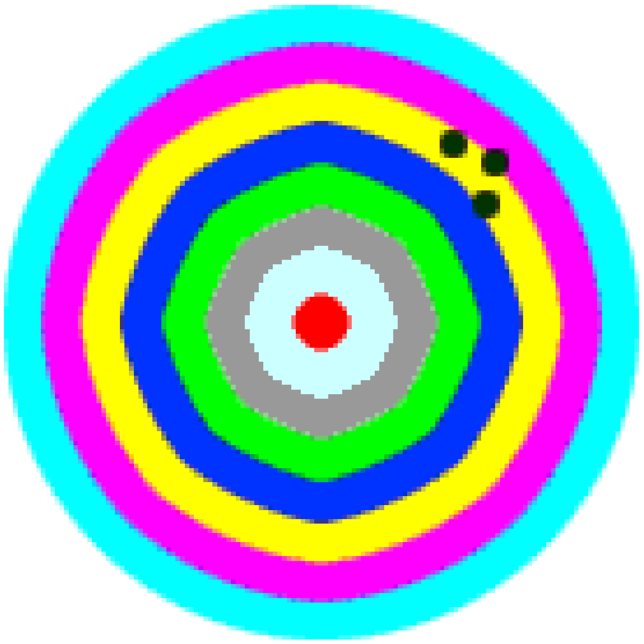


Accuracy

Accuracy and Precision

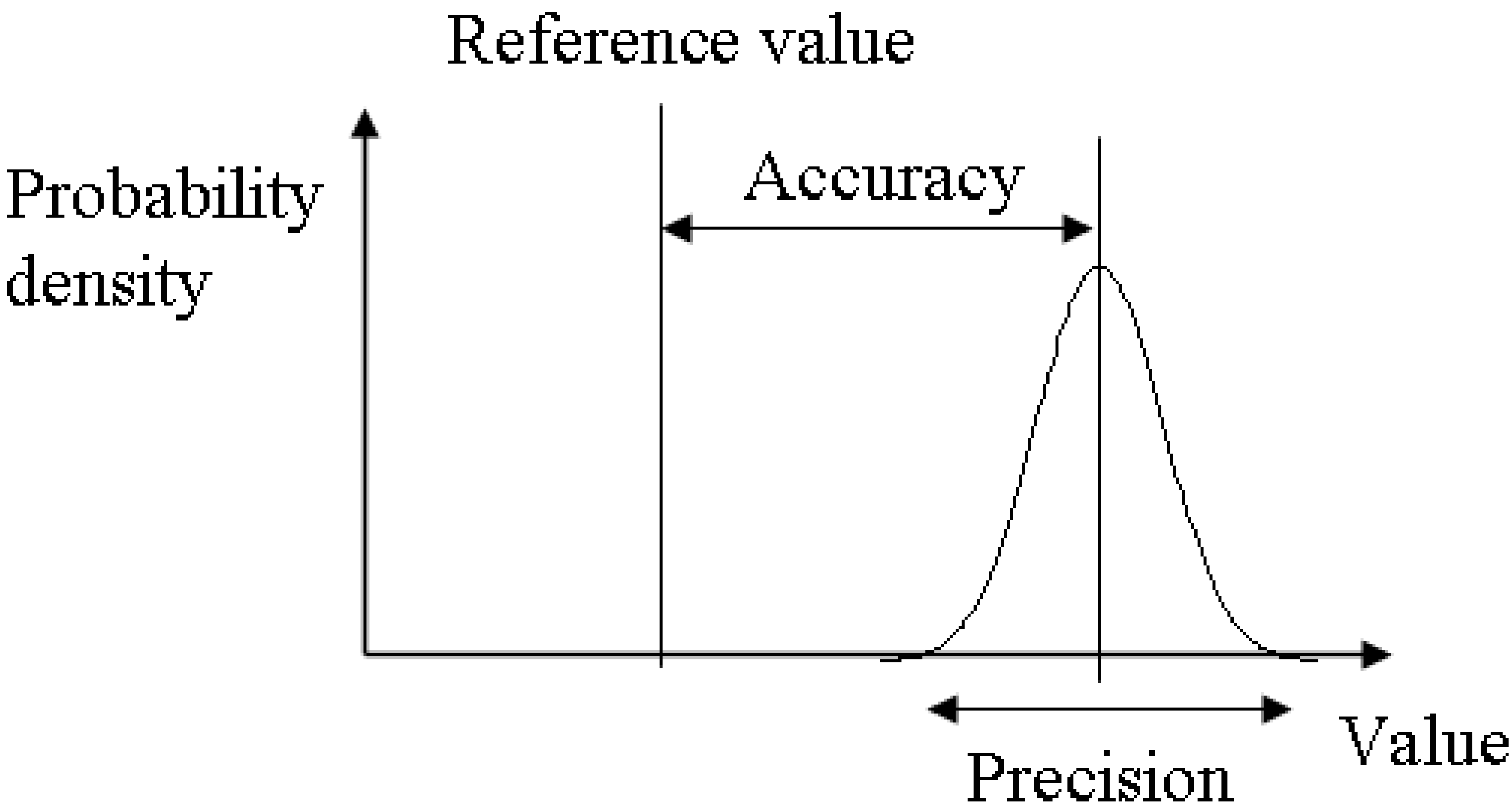
Precision : the degree of refinement in the performance of an operation, or the degree of perfection in the instruments and methods used to obtain a result. An indication of the uniformity or reproducibility of a result. Precision relates to the quality of an operation by which a result is obtained,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

Precision



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.

Accuracy and 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**
Group B	10.135	10.227	10.201	10.011	10.155	**10.146**
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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.“

- The first thing to notice is that 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. What we mean when we talk about traceable equipment is that it is potentially able to produce traceable measuring results.

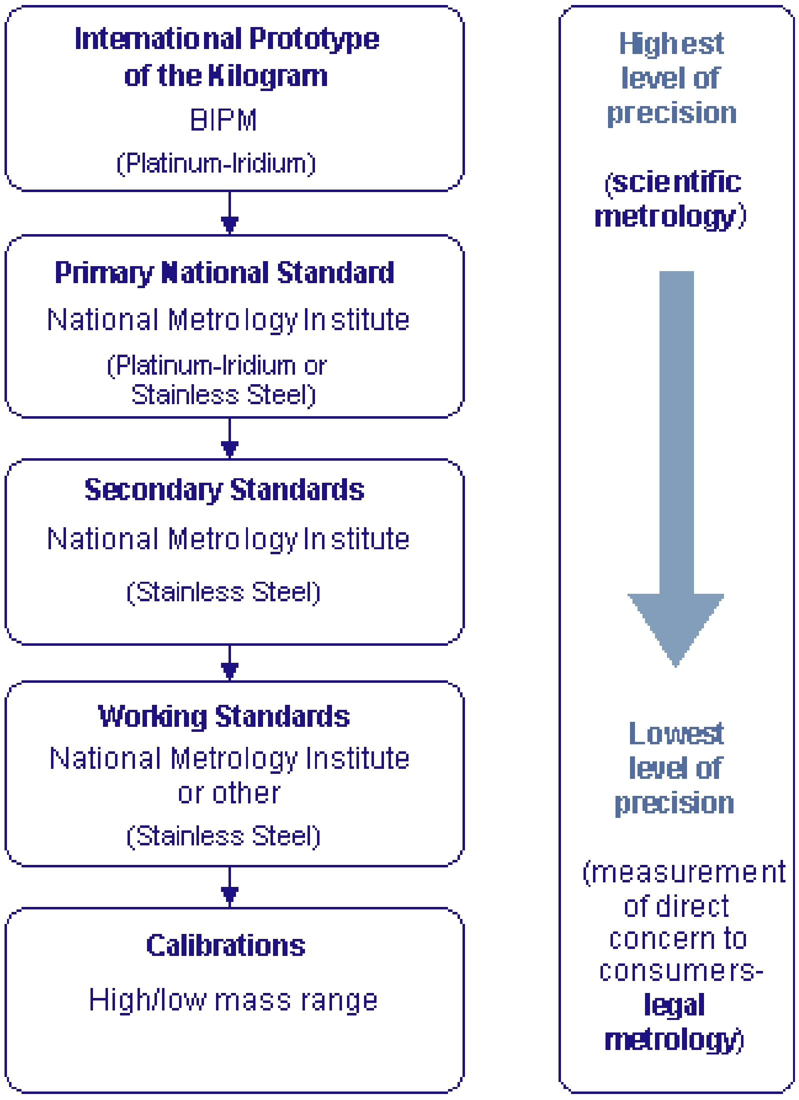
Calibration and Traceability

- 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.
- To understand this question, we need to look at the purpose of the traceability requirement.
- 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

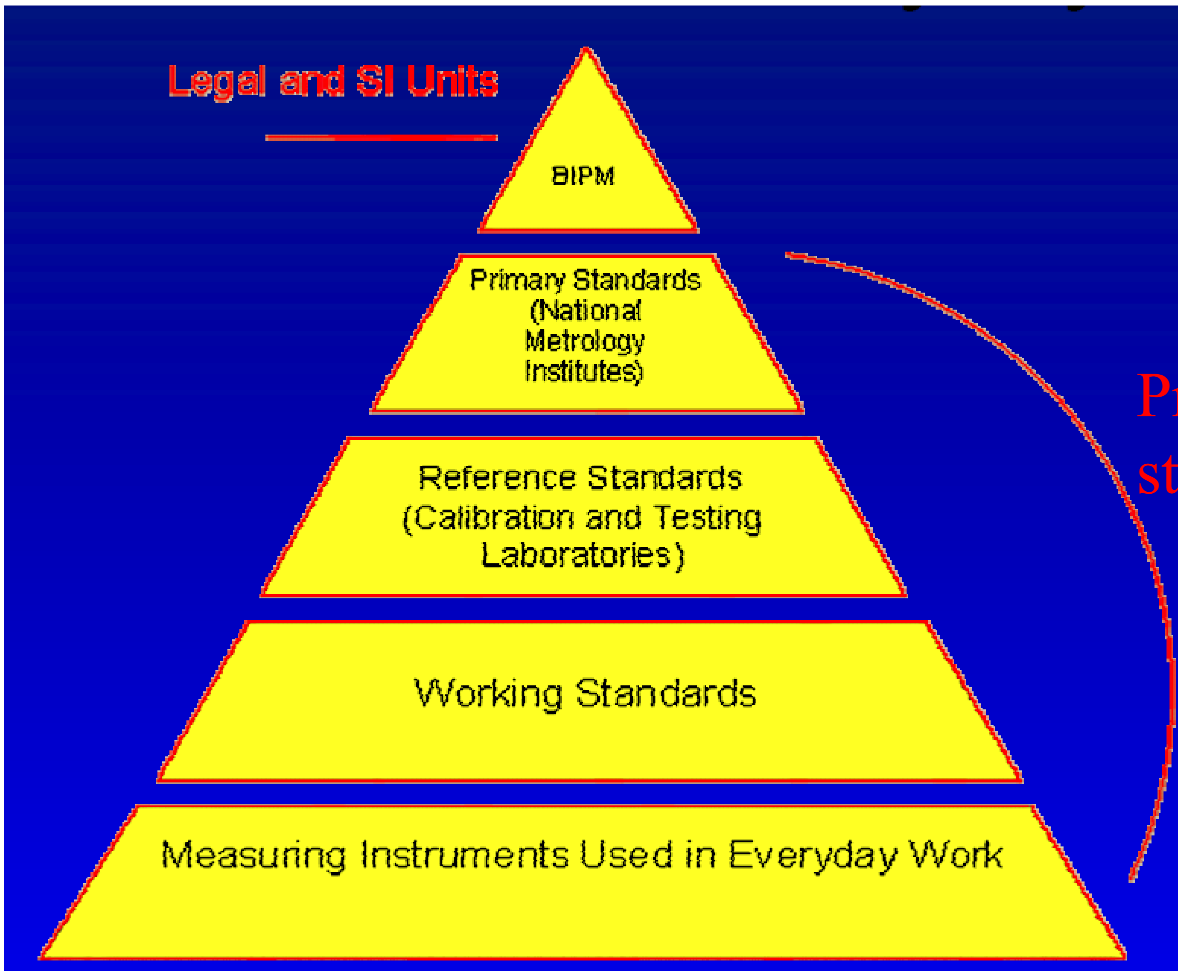
Traceability Chain

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



Calibration and Traceability

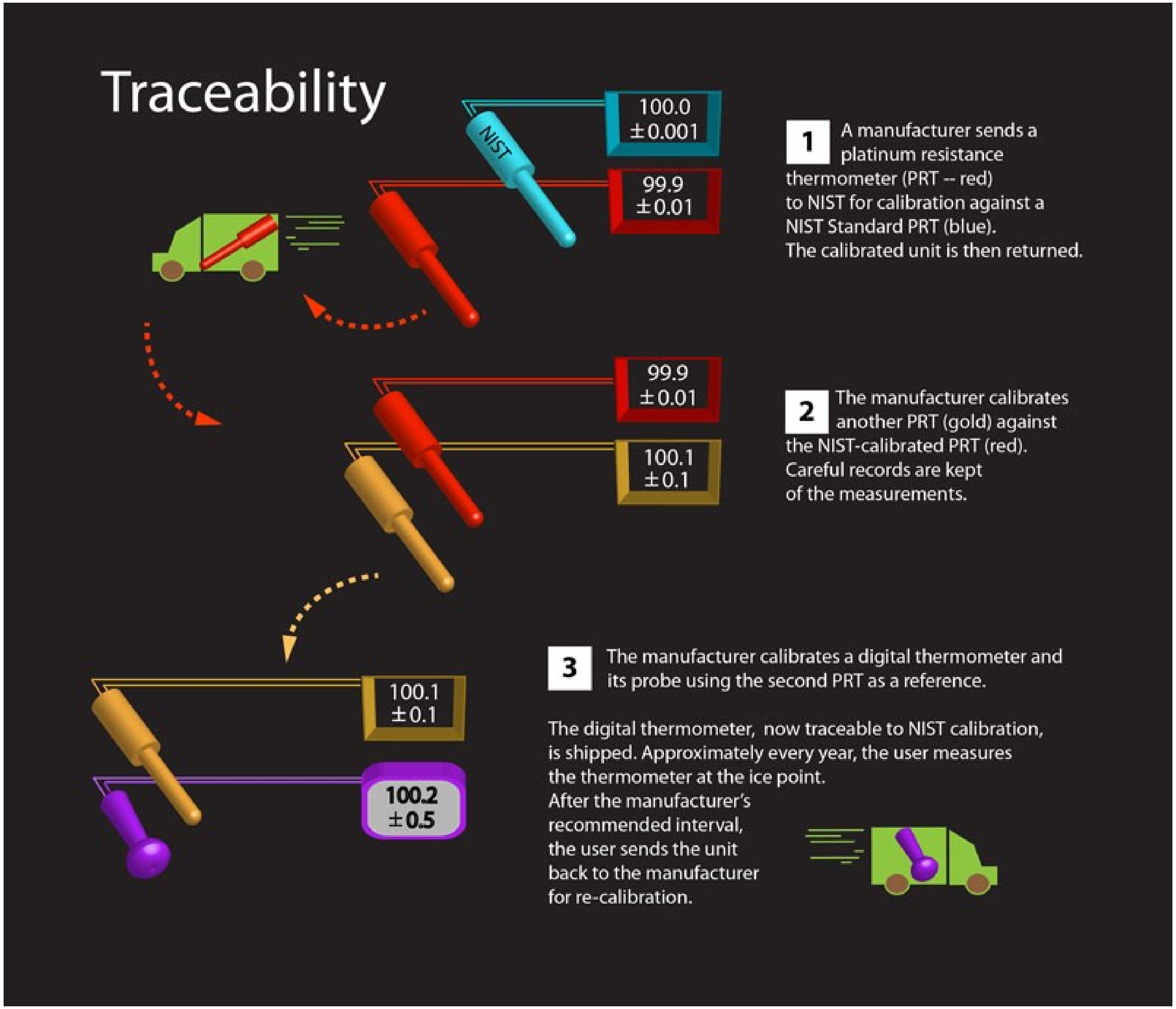
Traceability Chain



Primary standards

Calibration and Traceability

Traceability Chain Example



Calibration and Traceability

Uncertainties of physical realizations of the base SI units

SI Base Unit	Physical Quantity	Uncertainty
candela	luminous intensity	1×10^{-4}
mole	amount of substance	8×10^{-8}
kelvin	thermodynamic temperature	3×10^{-7}
ampere	electric current	4×10^{-8}
kilogram	mass	1×10^{-8}
meter	length	1×10^{-12}
second	time interval	1.3×10^{-15}

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.

Calibration and Traceability

- 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

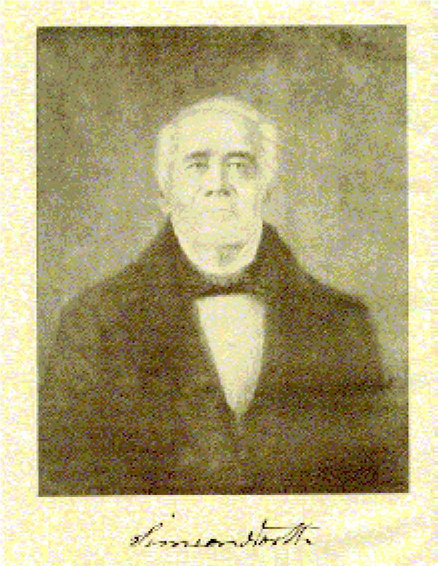
The Machine Revolution 1800-1920 – the milli-inch (1 mil = 25 μm)

- 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 War 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 to Connecticut manufacturer Simeon North.



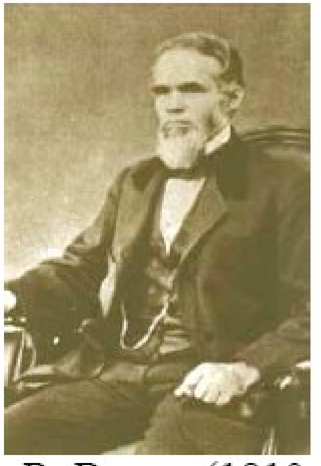
Simeon North (1765-1852).

Flintlock Pistol by North Co., 1816

Manufacturing Trend

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

- In 1851 the Vernier Caliper was developed by Joseph R. Brown of Providence R.I.



Joseph R. Brown (1810-1876)

- 1855 Precision Gear Cutting & Dividing Engine
- 1861 The Universal Milling Machine
- 1861 The Formed Tooth Gear Cutter
- 1868 Micrometer Caliper
- 1876 The Universal Grinding Machine
- 1880 The Automatic Screw Machine

Manufacturing Trend

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

- In 1908, Henry Ford introduces Model T automobile.

Henry Ford, 1863-1947

- ~100 year lag between the development of inter-changeable parts and mass production.
- Lag due to development of metrology infrastructure.

Manufacturing Trend

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

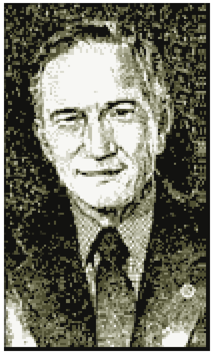
- Mass production of semiconductor circuits.
- Process: planar multi-level lithographic processing.
- Essential requirement: accurately dimensioned and placed patterns.
- Enabled by widespread dissemination of accurate length scale (~0.1 μm) embodied as laser interferometers.
- Accuracy transferred to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

Manufacturing Trend

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

- 1920 Measuring Microscope (Leitz)
- 1944 The Electronic Gage

Jack Kilby (1923-)



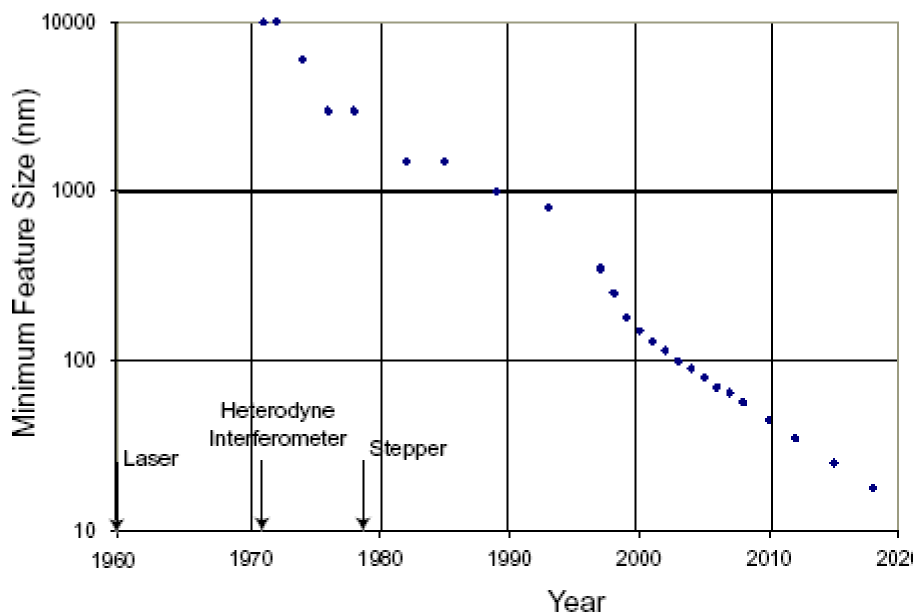
Robert Noyce (1927-1990)

- 1958 Integrated circuit invented by Jack Kilby and Robert Noyce
- 1960 Laser invented by T.H. Maiman at Hughes Laboratories.
- 1971 Intel introduces 4004 IC.
- 1971 Hewlett-Packard introduce heterodyne laser interferometer.
- 1978 First lithography stepper introduced by GCA.

Manufacturing Trend

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

Moore's Law 1970-2020



- Mechanical metrology carried IC industry until ~1980.
- Sub-micron features required metrology revolution (stepper stages).
- Time lag between invention of laser and use in IC metrology was 20 years.

Current Manufacturing Trend

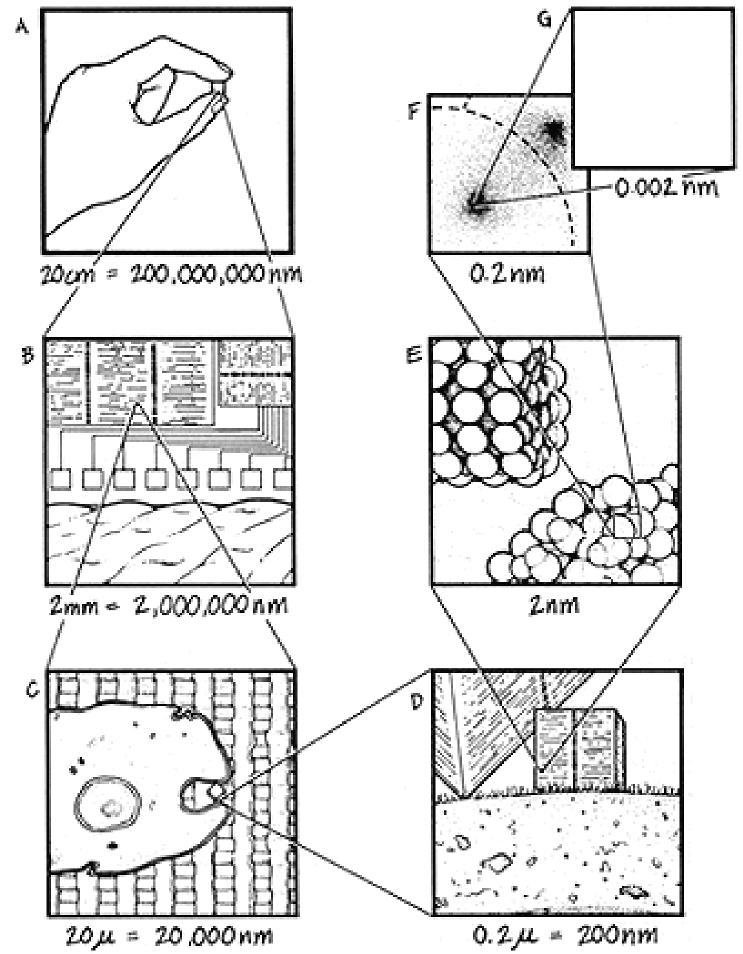
The Nanotechnology Revolution 2000-2050 – the nano-meter (nm)

- 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, electron or atom imaging, nano-tip microscopes.

Current Manufacturing Trend

The Nanotechnology Revolution 2000-2050 – the nano-meter (nm)

- (A) shows a hand holding a computer chip. This is shown magnified 100 times in (B). Another factor of 100 magnification (C) shows a living cell placed on the chip to show scale.
- Yet another factor of 100 magnification (D) shows two nanocomputers beside the cell. The smaller (shown as block) has roughly the same power as the chip seen in the first view; the larger (with only the corner visible) is as powerful as mid-1980s mainframe computer.
- Another factor of 100 magnification (E) shows an irregular protein from the cell on the lower right, and a cylindrical gear made by molecular manufacturing at top left.
- Taking a smaller factor of 10 jump, (F) shows two atoms in the protein, with electron clouds represented by stippling. A final factor of 100 magnification (G) reveals the nucleus of the atom as a tiny speck.



Current Manufacturing Trend

The Nanotechnology Revolution 2000-2050 – the nm

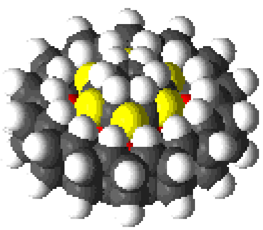
What started this revolution?

This possibility was first advanced by Richard Feynman in 1959 when he said: "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom." His talk entitled "**There Is Plenty Room At the Bottom**" has become a classic milestone.

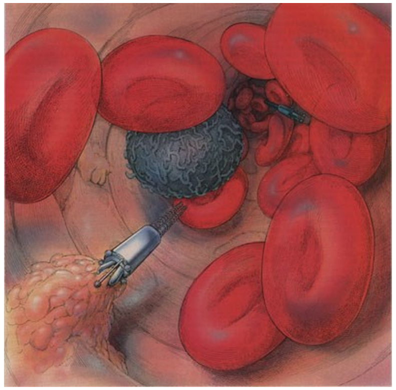
- proposed that tiny robots might be able to build chemical substances. He noted that they could be used to create nanomachines.
- pointed out that a new class of miniaturized instruments would be needed to manipulate and measure the properties of the small "nano" structures. In the 1980's these instruments were invented.
- The scanning tunneling microscope, atomic force microscope and the near-field microscopes provided the eyes and fingers required for nanostructure measurement and manipulation.

Current Manufacturing Trend

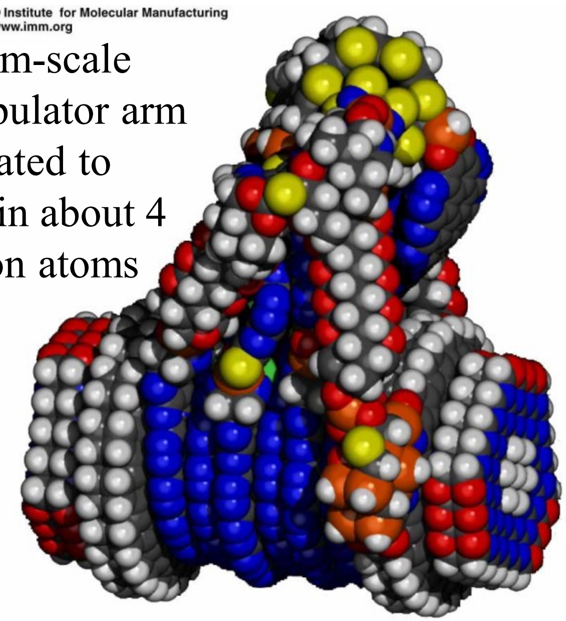
A visual imagery*



Bearing

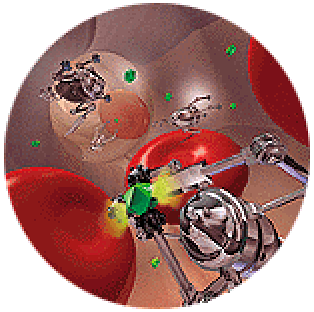


A nanomachine swimming through a capillary attacks a fat deposit

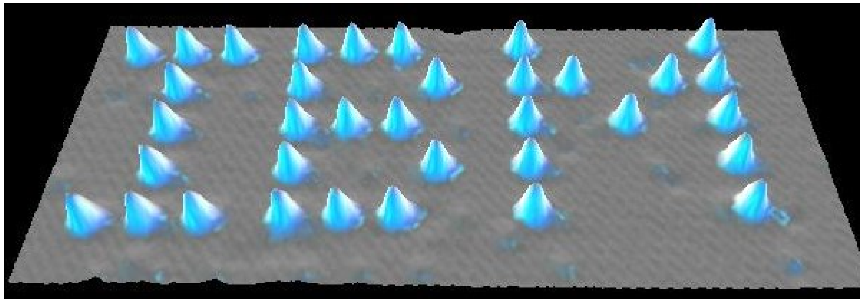


100 nm-scale manipulator arm estimated to contain about 4 million atoms

These miniature devices would roam between the red cells of the bloodstream, seeking out and destroying harmful viruses



Medical nanodevices could augment the immune system by finding and disabling unwanted bacteria and viruses.



Success in moving atomsXenon on Nickel (110)+

***www.zyvex.com/ nanotech/visuals.html**

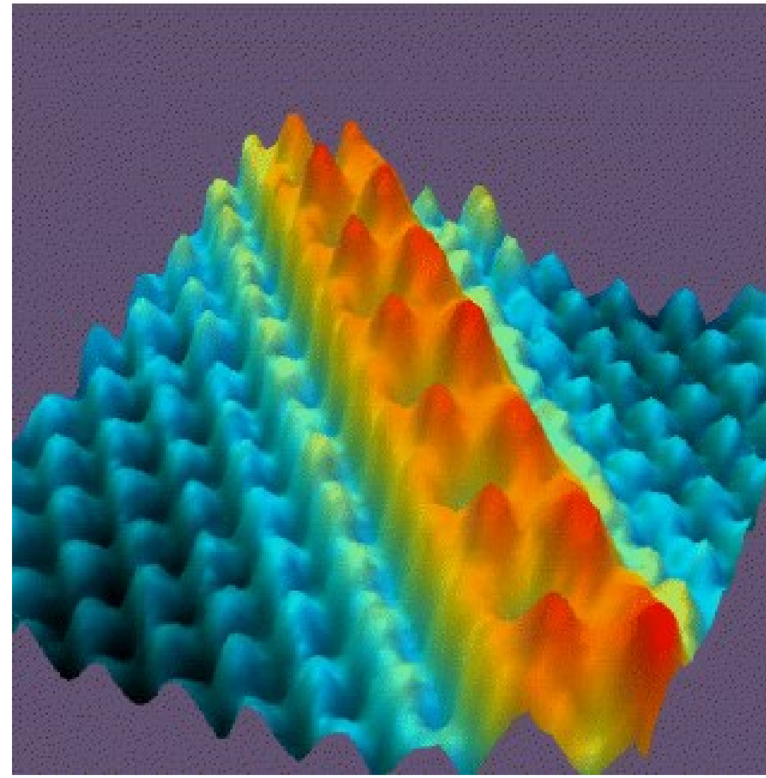
+IBM image gallery

To put things in perspective

- Good metrology practice is more than just reading numbers from a data sheet.

- In order to measure a quantity accurately, it is necessary to fully study and understand the entire measurement process itself

- This may require multiple disciplines working closely together to achieve the final goal



What are the Challenges?

- History teaches that metrology infrastructure essential for manufacturing.
- Metrology technology must be developed well before manufacturing can proceed.
- Current lithography and metrology infrastructure inadequate for non-IC nanotechnology.

- Funding for metrology technology (i.e., high resolution, low cost tools)
- Improved microscopes (higher resolution, lower noise & drift).
- Atoms beams? Electron holography? SW nanotubes? X-rays?
- Resolution standards in the nano-range.
- Improved substrate stages with accuracy in the sub-nanometer range