NIST -- PROMOTING INNOVATION, COMPETITIVENESS AND FACILITATING TRADE

Hratch G. Semerjian
National Institute of Standards and Technology
Gaithersburg, MD, USA 20899-1000
(301) 975-5555, *hratch@nist.gov*

Abstract: Measurement and standards infrastructure of a nation is critical for domestic and international trade; but it is also important for fostering innovation and facilitating the transition of scientific discoveries into the market place. The role of measurements and standards provided by NIST is becoming ever more important as economic development and job creation increasingly rely on advances in high technology manufacturing processes and products. Historical role of metrology in facilitating trade is reviewed, and examples on the increasing role of metrology in promoting innovation and competitiveness are presented.

1. INTRODUCTION

The physical infrastructure of a country, e.g., the highways and bridges, the air traffic management system, the electrical grid and water supply systems, is usually taken for granted; citizens notice the infrastructure only when there is a problem, because it affects our daily lives. The measurement and standards infrastructure is equally important and also taken for granted; we assume that we are getting what we paid for in the marketplace, when we buy food at the grocery store, fill up our car at the gas station, or pay our electric or water bills. And we assume that we can sell our products anywhere in the world; it is extremely distressing for a manufacturer to find out that its product is not accepted in another country, because of non-compliance with certain standards. There is even a lesser appreciation of the importance of the measurement and standards infrastructure for a nation's innovation capacity and competitiveness in the global marketplace. It is important to articulate the critical role of measurements and standards in promoting innovation, industrial competitiveness, and contributing to the economic growth of a nation.

2. HISTORIC ROLE OF METROLOGY

Before discussing the role of metrology into the future, we should take a look at where all this began. The earliest known uniform systems of weights and measures date back 5,000 years to the Bronze Age and the ancient peoples of Mesopotamia, Egypt, and the Indus Valley.

The critical importance to society in adopting a uniform set of weights and measures can be demonstrated in that it appears to be a common discovery in virtually all cultures. Most early measurement systems used parts of the body and the natural surroundings. Length was first measured with the forearm, hand, or finger and time was measured by the periods of the sun, moon, and other heavenly bodies.

The cubit is perhaps the oldest and longest-lived example of a standard measurement unit. The oldest documented cubit is the Egyptian royal cubit—traced back to 2750 B.C. and used for about 3,000 years. And the Egyptians took their cubit seriously. In fact, it has been reported that: *" The death penalty faced those who forgot or neglected their duty to calibrate the standard unit of length at each full moon..."* [1]

To measure volume, people would fill containers with plant seeds which were then counted. When means for weighing were invented, seeds served as standards. For instance, the carat, still used as a unit for gems, was derived from the carob seed.

In China, some 3,500 years ago, a system of standard instruments for measuring length, mass, and volume was created. A special organization was established with the responsibility for checking the accuracy of these instruments twice a year. The Chinese may also have been the first to use an unvarying physical constant as a standard of measure. Similar to the way we now use the distance light travels in a second as a length standard, 2,700 years ago the Chinese used the resonance tone of bamboo whistles to ascertain a length standard.[2]

The good news is that every country, region, and city-state recognized the need for a uniform set of weights and measures. The bad news is that virtually every commercial center developed its own *unique* measurement system making commerce between trading centers cumbersome.

The problems and confusion caused by this measurement menagerie did not go unnoticed. In 1196, King Richard I of England proclaimed in the Assize of Measures that *"…throughout the realm there shall be the same yard of the same size and it should be or iron"*, and had yard standards, in the form of iron rods, distributed throughout the country. The expression "by the King's iron rod," referring to the yard, appears frequently in historic records. Shortly after in 1215, The Magna Carta called for "*one measure for ale, one measure for wine, one measure for corn*", declaring the need for uniform standards for length, mass, and volume standards..

But the problem continued to grow. In 1788, France had about 800 different names for measures and, taking into account their different values in different towns, resulted in around a quarter of a million different units. The Metre Convention, signed in 1875, represents the starting point towards harmonization of measurement standards.

In the U.S., the responsibility for uniform weights and measures was assigned to the federal government. In the U.S. Constitution, Article I, Section 8 states that *"The Congress shall have the power to…coin money, regulate the value thereof, and of foreign coin, and fix the standard of weights and measures".*

During the Industrial Revolution, with the development of the steam engine, the locomotive, the steamboat, electricity, the telegraph, and the telephone, the need for accurate measurement increased. In 1900, the American electrical industry represented an investment of $200 million, but growth was inhibited by a lack of recognized standards, which contributed to frequent and costly litigation. The magazine Scientific American warned that a national laboratory had become "a national need". The National Bureau of Standards (now NIST) was finally established in 1901.

3. METROLOGY LEADING TO INNOVATIONS

Since then, NIST's mission has been, and continues to be, *"to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life"*.

The pivotal role NIST plays in the U.S. economy is illustrated in Fig 1. In its more traditional role, NIST has provided the measurement science and standards that have ensured equity in trade and transaction efficiency; more recently, these tools have become critical to ensure access to the global markets. However, NIST role in developing new measurement capabilities and technology have become even more important for the competitiveness of U.S. industry, by making them more productive and their products accepted in the global markets. The improved measurement science capabilities also make the U.S. R&D enterprise more efficient and more innovative, leading to improved quality of life for U.S. citizens.

From its inception, NIST has addressed measurement and standards issues of national importance. Shortly after the National Bureau of Standards was established, it was asked to provide "Standard Samples" for the American Foundrymen's Association, including various types of iron samples which were certified for chemical composition, in order to ensure the uniformity of cast iron that was used for railroad cars and tracks. Chemical measurements have changed a great deal since then. Instead of wet chemistry, sophisticated new methods such as Isotope Dilution Mass Spectrometry (IDMS) are being used for detailed characterization of super alloys, which are used in gas turbine engines, as well as for measurement of sulfur content in fossil fuels[3,4] . New chemical measurements are also playing a crucial role in improving health care, by enhancing the accuracy of clinical measurements, for example, for cholesterol and more recently for troponin[5,6]. These measurements and standards are also critical to meet regulatory requirements promulgated by the European Union for in vitro diagnostic devices.[7]

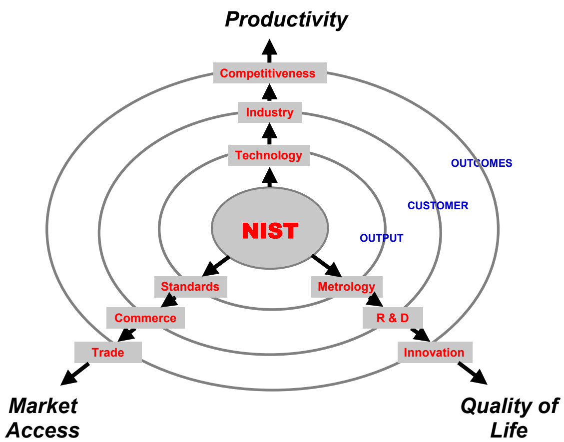

Fig. 1 *– NIST's pivotal role in the U.S. economy*

Another example of how measurements foster innovation -- and one that is used by many in the scientific community -- is the Mass Spectral Library. This is a database NIST has developed that contains information about more than 160,000 chemical compounds. While originally expected to be used primarily for environmental and health applications -- industry has found novel ways of applying that data to forensics, homeland security, food and flavors research, and industrial quality control. This technology has now been extended to include peptides and proteins[8], with potential applications in clinical measurements and health care. This is a great example of how a basic infrastructural component - in this case spectral data - can be leveraged and used in many applications.

For many years, electrical measurements have been of critical importance for a broad range of industries, including power generation, electronics, instrumentation and communications industries. In 1910, the BIPM International Technical Committee established new values for the international ampere, ohm, and volt, based on measurements using a silver voltmeter. Today, an intrinsic standard using a Josephson Junction voltage standard chip (a chip that is 1 cm x 2 cm and contains 20,208 Nb-AlOx -Nb junctions that are serially connected) is the basis for most of the voltage measurements (see Fig. 2a). More recently, NIST has succeeded in making the first 5-junction stacks of Josephson Junctions to further improve this technology[9,10].

To meet future measurement needs, NIST has developed the world's most accurate electron counter as a new standard for capacitance. This counter can place 70 million electrons on a capacitor with an uncertainty of just one electron (see Fig. 2b). The heart of the counter is a special microcircuit that "pumps" electrons one at a time to a capacitor. In the figure, the bullet-shaped regions in the center are micrometer-sized islands of aluminum, separated by tiny "tunnel junctions of aluminum oxide. The capacitance of the islands is so small that at temperatures near absolute zero (less than 0.1 K) only one excess electron can occupy a given island at a time[11].

Another example of how measurement science enables innovation is the work of NIST's most recent Nobel Laureate, Dr. Jan Hall. Dr. Hall transformed the laser from a laboratory curiosity to one of the fundamental tools of modern science. His research improved the accuracy and stability with which lasers generate a specific frequency of light. Through his research, the laser frequency itself became a research tool with an accuracy of 1 part in 10^{15}!

The development of the laser as a measurement tool enabled a series of innovations and resulted in the creation of whole new industries. These innovations include fiber-optic communications; vastly improved clocks which enable accurate navigation; precision spectroscopy for detecting minute quantities of a substance; and measurements of fundamental physical constants.

And better measurements continue to open up new windows on the world. Consider the developments in the measurement of time. In 1904, the NBS pendulum clock had an accuracy of 1 second in 3 years (10^{-9}). In 1949, NIST introduced the world's first "atomic clock," accurate to one second in 300 years. Today, its accuracy is about one second in 60 million years (10^{-15}). And, we are looking ahead to an optical clock accurate to about one second in 30 billion years! Clearly, back in 1949, we could not have predicted that NIST's atomic clocks would be used for setting time on personal computers and guiding deep space probes. Or that the National Association of Securities Dealers would require that all electronic transactions be stamped with a time traceable to NIST. Telecommunications, electric power transmission, transportation, and navigation (including support of the Global Positioning System) all rely on NIST time. This is just another example of innovations enabled by measurement science.

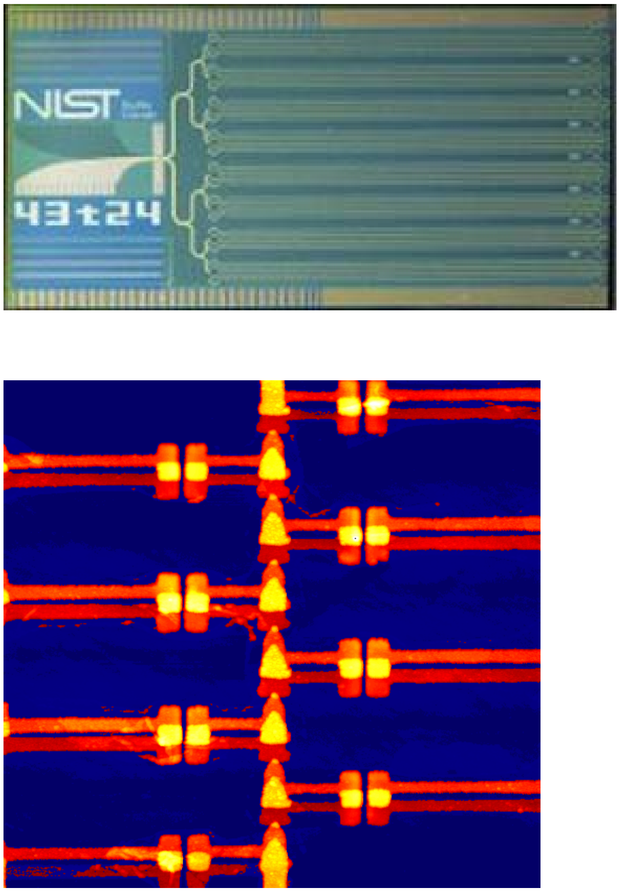

***Fig. 2** – New standards for electrical measurements - a) NIST 10 V Josephson Junction Standard; b) New standard for capacitance measurements.*

But, how do we know that measurements and standards play such an important role in terms of our economic competitiveness? Well, like everything else at NIST - we measure it.

NIST has conducted 19 economic studies to assess our impact on industry. These studies document an average direct return to the economy of $44 for every $1 spent by NIST[12].

Our work to develop standard reference materials for measuring the sulfur content of fuels, for example, led to improved efficiency and lower transaction costs in the fuel industry. This research led to a benefit-to-cost ratio of about 113 to one[13].

One of the lower economic impacts we found was developing the chemical and thermodynamic datasets for alternative refrigerants. The impetus for this research was the need to quickly replace ozone-destroying CFCs. Even with the objective being to develop "ozone friendly" refrigerants - we still achieved an economic benefit-to-cost ratio of about four to one on top of the environmental benefits[14].

NIST is able to demonstrate such large benefits to the Nation because it contributes to the innovation infrastructure of the economy. Advances NIST makes support whole industries or sectors -- as opposed to supporting an individual company. Thus, our advances are leveraged by large segments of the economy creating a favorable multiplier.

4. METROLOGY AND INNOVATION IN THE 21st CENTURY

There is general agreement that if you can't measure something -- you can't control it. And if you can't control it - you can't *reliably* manufacture it. NIST's unique role is to advance measurements and standards so that the next innovation can be realized and commercialized. Innovations in emerging technology areas such as nanoelectronics, nanomanufacturing, fuel cells, biotechnology, renewable energy sources, and quantum information will be highly dependent on advances in related measurement science. NIST has expanded its efforts to develop the measurement science and standards that support innovation and economic competitiveness in such emerging technology areas.

Experts predict that, within the next ten years, at least half of the newly designed advanced materials and manufacturing processes will be products of nanotechnology. The global industry of nanotechnology is predicted to exceed $1 trillion by 2015. Today, "low tech" nanoparticles are already prevalent - from titanium dioxide particles in sunscreen to block out UV while transmitting the visible (and hence appear transparent) to hydrophobic nanoparticles embedded in fabrics to make them stain resistant. These "low tech" nanoparticles are the first to make it into the marketplace because their manufacturing tolerances are relatively large. The size and purity of the particles do not have to be tightly controlled to effectively block UV or resist stains.

The next generation of nanoproducts, however, is likely to require tighter control on size and other properties. For example, if you want to produce a carbon nanotube of a specific length, width, and chirality - we currently have to produce a batch of nanotubes and sort through them to find the closest match. This is not a process that scales well to industry. Thus, we need to develop the measurement tools and the standards to facilitate the development of the next generation of nanoproducts.

NIST is already working on measurements to characterize devices with nanoscale features. Device features on computer chips as small as 40 nanometers (nm) wide - less than one-thousandth the width of a human hair – can now be measured reliably using new test structures developed by NIST, SEMATECH, and other collaborators. The test structures are replicated on reference materials that will allow better calibration of tools that monitor the manufacturing of microprocessors and similar integrated circuits. The new test structures are the culmination of NIST's more than five-year effort to provide standard "rulers" for measuring the narrowest linear features that can be controllably etched into a chip. The NIST rulers are precisely etched lines of crystalline silicon ranging in width from 40 nm to 275 nm. The spacing of atoms within the box-shaped silicon crystals is used like hash marks on a ruler to measure the dimensions of these test structures. Industry can use these reference materials to calibrate tools to reliably measure microprocessor-device gates, for example, which control the flow of electrical charges in chips[15].

Steps of silicon also serve as a natural ruler for measuring vertical dimensions. This silicon "target" has step heights ranging from tens to hundreds of nanometers leading down to a flat, single atomic layer measuring only 0.3 nanometer. The microscope used to make this image sits on an isolated concrete slab equipped with air springs to cancel out even minute vibrations that could ruin the nanoscale measurements[16] (see Fig. 4a).

Using the interferometer-guided probe of the Molecular Measuring Machine, accurate calibration patterns can be produced. To create this artifact, a writing method based on scanned probe oxidation of hydrogen terminated silicon was used[17] (see Fig. 4b).

Tools for manipulating nanocomponents will also help accelerate research on the performance of new nanotechnologies. NIST researchers have developed new methods to manipulate nanowires with "optical tweezers." A highly focused laser beam attracts microscopic objects and can be used to pick up and precisely position nanocomponents for building semiconductor circuits or biosensors smaller than a red blood cell

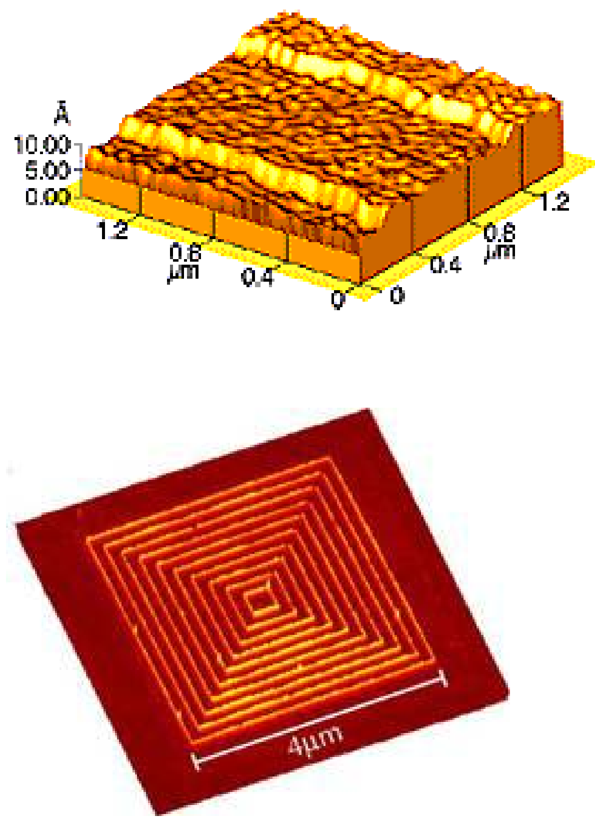

Fig. 4 - *Nanorulers based on silicon technology*

Researchers at NIST currently have requirements to measure force from picoNewtons to MegaNewtons (18 orders of magnitude). For example, NIST has a 4.4 MegaNewton deadweight machine that is used for testing the strength of bridge abutments. This is the largest such device in the world. But, how do you weigh a dust mite? Or determine the force required to pull a molecule apart? Such tasks require a device that measures nanoNewtons -- forces 1 billion times smaller than the force required to hold an apple against Earth's gravity. NanoNewton forces are estimated with atomic force microscopes and instruments that measure the properties of ultrathin coatings like those used on computer hard drives or turbine blades. But the accuracy of such estimates is unknown because they haven't been calibrated with force standards based on the kilogram, the internationally accepted unit of mass.

But, help is on the way. NIST has developed a prototype instrument that reliably measures forces as small as tens of nanoNewtons and simultaneously ties those measurements to forces a thousand times larger based on the kilogram[18]. The device works by connecting a well-calibrated spring-loaded scale with a set of electrodes that generates an electrostatic force. The instrument balances the downward force produced by a one-milligram mass artifact, by keeping the distance between the electrodes constant but varying the amount of voltage between them. The result is a force determination accurate to a few parts in 10,000 that is measured with voltage, electrical capacitance and distance (the location of the electrodes as measured in wavelengths of laser light). The NIST researchers hope to extend the instrument's resolution to tens of picoNewtons.

And as nanotechnology quickly evolves into a potentially trillion dollar industry over the next decade, the requirements for measuring mass and size at the smallest scales will become critical. We are not yet ready for the amazing potential that nanotechnology offers—so NIST, is again also accelerating its efforts in the development of nanometrology. NIST has also established a new Center for Nanoscale Science and Technology to make its measurement capabilities available for U.S. industry.

While the breakthroughs occurring in nanotechnology are amazing, equally breath-taking developments may arise by exploiting purely quantum phenomena. Quantum mechanics plays at a scale where the normal laws of everyday experience break down and new phenomena arise. Through developments made in the last two decades, we are beginning to generate quantum phenomena at classical scales through creation of new forms of matter, like Bose-Einstein condensates which consist of a collection of atoms that behave as if described by a single wavefunction.

Researchers already are using quantum information science to generate "unbreakable" codes for ultra-secure encryption. They may someday build quantum computers that can solve problems in seconds that today's best supercomputers could not solve in years. And, the potential of exploiting the quantum phenomena for developing new detectors, tools, and other devices is just starting to be tapped[19].

With several world-renowned scientists, including three Nobel laureates, NIST is well-positioned to develop the tools for measuring and controlling these quantum phenomena and harnessing their properties to benefit the nation. Our work is widely recognized as one of the most advanced quantum research programs in the world.

Renewable fuels, fuel cells Ref. 20….

Biotechnology is another area of explosive growth. Sequencing of DNA has opened up an entirely new horizon for gene therapy. This will require accurate measurements of gene expression. NIST is working with industry….Ref. 21.

These examples illustrate that innovation -- enabled by U.S. investment in basic science -- will continue to drive our economic security and enhance our quality of life.

5. LOOKING TO THE FUTURE

The American Competitiveness Initiative[22] announced in February 2006 recognizes the critical role that NIST plays in the development of the U.S. innovation infrastructure. The ACI will give NIST the resources needed to provide U.S. industry and the scientific community with the measurement and standards tools they need to maintain and enhance our global competitiveness.

Specifically, NIST will be concentrating in four thematic areas:

1. Targeting the most strategic and rapidly developing technologies -- such as nanotechnology, quantum information science, building the hydrogen economy, and cybersecurity.

2. Increasing the capacity and capability of critical national scientific assets -- by expanding its Center for Neutron Research, and upgrading and expanding the NIST presence at the DOE National Synchrotron Light Source at Brookhaven.

3. Meeting the Nation's most immediate measurement needs -- by addressing manufacturing supply chain interoperability, building codes and standards to minimize losses due to natural disasters, and expand our efforts in international standards, biometrics, and medical imaging

4. Improving NIST physical facilities -- by upgrading some of the older buildings -- so that the physical environment (temperature, humidity, vibration, and cleanliness) does not become the ultimate limit to our measurement accuracy.

REFERENCES

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