An Assessment of the United States Measurement System:

Addressing Measurement Barriers to Accelerate Innovation

Appendix E

NIST's Realization and Dissemination of the Units of the SI

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Table of Contents

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Introduction

As the national measurement institute (NMI) of the United States, NIST has three primary responsibilities in the U.S. Measurement System, or USMS. These responsibilities involve:

- Providing measurements and standards that support the current needs of the well-established measurement technologies broadly used in commerce and science.
- Addressing the emerging measurements-related technological needs of the U.S. economy, in particular by addressing measurement barriers to technological innovation.
- Developing the scientific and technological basis for advancing measurements and standards that will address technological needs not yet fully envisioned.

At its core, an effective national measurement system provides and ensures the reliability of measurement results. Users of these results expect that measurements of an object or material obtained at one location and time will be the same when obtained at another location and time. This expectation provides challenges and requires accuracy, reproducibility, and comparability of results at levels sufficient for the intended use of the measurement result. Extensibility—the capability to add new functionality while not unduly disturbing the existing parts of the system—is also essential.

The International System of Units

The International System of Units (SI) is a logical system of measurements founded on seven base units (Table 1) representing the most fundamental quantities, from which many other measurements can be derived. From computer chips to medicines to food in the grocery store, many measurements related to manufacturing, sales, testing, trade, and research rely on these seven base SI units.

Base quantity	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Table 1 SI Base Units

While many measurements can be traced to base SI units, in practice it is convenient to also use derived SI units, such as power, force, and energy. There are many derived SI units; this appendix focuses only on a small sample, underpinning a broad range of manufacturing, trade, testing, and research. These core SI-derived units, critical to the breadth of U.S. industry, are listed in Table 2.

Derived quantity	Name	Symbol	Expression in terms of SI base units
force	newton	N	$m \cdot kg \cdot s^{-2}$
pressure	pascal	Pa	$m^{-1} \cdot kg \cdot s^{-2}$
energy	joule	J	$m^2 \cdot kg \cdot s^{-2}$
power	watt	W	$m^2 \cdot kg \cdot s^{-3}$
capacitance	farad	F	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
volume	cubic meter	none	m^3
acceleration	meter per second squared	none	m/s^2
activity (of a radionuclide)	becquerel	Bq	s^{-1}

Table 2 Examples of SI-Derived Units

The strength of the SI springs from its roots in the scientific principles of the natural world in which we live. As scientific understanding of physical phenomena has advanced, so have the measurement systems of both commercial and scientific usage. The antecedents of the modern SI evolved to reflect this increased understanding and to support technological innovation and the needs of commerce. This evolution has impacted all realizations of base SI units and, as importantly, the evolution of the relationships between them. Just as a building requires a foundation of sufficient strength, the integrity of the SI and its utility in facilitating trade and the advancement of technology and scientific thought requires the strong foundation of the advanced measurement technologies and standards used in realizing the seven base SI units.

A key part of the mission of NIST—and the NMIs of other nations charged with realization and dissemination of a national system of measurements—is to ensure that the base SI units, and measurement units derived from these base units, have accuracy levels that meet the requirements of industry and science; can be efficiently distributed to industry, government agencies, and researchers who continually rely on measurements; and are consistent in their realization and dissemination.

The need for enhancements to SI base-unit realization and the relationships between the base units will continue, often driven by scientific and technological advances. Primary drivers are the present and anticipated needs of technology developers who often require new measurement capabilities to achieve technological innovations. An effective and healthy measurement system has an anticipatory character to it, thereby providing measurement capabilities and standards of the required accuracy at the time they are required.

The Role of NIST in the SI Measurement Infrastructure

While many organizations in the United States are involved in the application of SI units and measurements, the U.S. Congress, in fulfilling its constitutional responsibility to *"…fix the standard of weights and measures"*, has charged one agency, NIST, with the responsibility for the realization and dissemination of measurement standards. Founded as the National Bureau of Standards in 1901 against the backdrop of the accelerating industrial revolution in the United States and Europe, NBS/NIST has developed the skills, expertise, measurement infrastructure, and ongoing commitment to measurement science and technology required to produce the most accurate realizations of the base and derived SI units, and to effectively distribute them to support industry, commerce, and scientific research. Most other industrialized nations similarly commission their NMIs to ensure national support for the SI measurement system and to ensure that its realization is adequately recognized internationally to support that nation's technological needs and its requirements in global trade. Provision of measurement standards at state-of-the-art levels provides the broad spectrum of users of measurement results with a high degree of confidence, and often promotes technological innovation.

Industrial research centers and university laboratories use SI-based measurements provided by NIST and other NMIs, and many industry and university laboratories make important contributions to measurement science. However, most industrial research focuses on the relatively near-term development of products that can be sold for profit, while most university research tends to focus on making new scientific discoveries that expand the general pool of scientific information. Both types of contribution are crucial to the economy and the state of U.S. technology. As a result of this emphasis on the near term and the new, industry and university laboratories do not have the ongoing commitment of people, funds, and infrastructure needed to improve and distribute precise, accurate and reliable measurement standards. The measurement system is an infrastructure that broadly benefits all companies and consumers, so no individual company tends to invest in measurement system development that would aid their competitors in equal measure to their own benefit. And while development and distribution of the most demanding measurement capabilities often requires cutting-edge scientific and technical skills, spending many years or decades to improve a measurement capability is typically not the kind of research that universities and their financial supporters are willing to undertake, even when such improvements promise significant progress in addressing national-scale technological and societal needs.

NIST provides access to measurement tools for establishing measurement traceability to the SI. These tools are provided to U.S. industry, state and local governments, and the scientific community through three main methods:

- **calibration of customers' precision measuring instruments**

  The calibration services of NIST are designed to help the makers and users of precision instruments achieve the highest possible levels of measurement quality and productivity. These services often constitute the highest order of calibration services available in the United States. They directly link a customer's precision equipment or transfer standards to national and international measurement standards.

- **provision of reference materials of the highest quality and metrological value**

  NIST supports accurate and compatible measurements by certifying and providing more than 1,100 Standard Reference Materials with well-characterized composition, or properties, or both. These materials are used by NIST customers to perform instrument calibrations at the point of use as part of overall quality assurance programs. Standard Reference Materials verify the accuracy of specific measurements and support the development of new measurement methods.

- **provision of documented, evaluated reference data**

  NIST provides well-documented numeric data to scientists and engineers for use in technical problem solving, research, and development. These recommended values are based on data that have been extracted from the world's scientific literature, assessed for reliability, and then evaluated for scientific validity and consistency. Reference data is made available on a broad range of topics, from the electron and positron stopping power of materials to crystallographic surface structures to fire test data. Scientists at NIST and in university data centers work collaboratively to assure the scientific validity of the Standard Reference Data disseminated by NIST.

For more information, please see **http://ts.nist.gov/**.)

The SI measurement system is a crucial infrastructure with substantial impacts on the U.S. economy, the state of U.S. technology, and everyday life. Examples of the national impact of NIST's provision of measurements in base and derived SI units include the following:

- **electric power grid**

  NIST calibrations of standard electric power and energy meters, combined with NIST-provided timestamps, support the U.S. electric power grids, including more than 10,000 power-generating stations. These stations must be synchronized to less than one-millionth of a second per day for efficiency and for the identification of the location of problems occurring on lengthy, remote transmission lines. The power output of generating stations across large geographical distances must be precise to ensure that the power grid functions properly and that customers are billed correctly for the power that they use. In order to provide measurement support to this vital energy infrastructure, NIST performs about 25 power and energy meter calibrations per year for meter manufacturers, electric utility companies, and public utility commissions, serving as the "buck stopper" in the traceability chain. The exact number of timestamps used to synchronize components of the U.S. electric power grids is not known—these timestamps are provided freely and anonymously over the internet and via radio stations. The overall number of timestamps provided by NIST is immense—via the internet alone, 600 billion timestamps are transmitted annually.

- **weights and measures**

  NIST calibrations of mass standards are highly and effectively leveraged by the U.S. legal metrology system through nation's the State Weights and Measures Laboratories. These labs perform approximately 400,000 calibrations annually, impacting more than 50 percent of U.S. Gross Domestic Product. This tremendous volume of calibrations relies on an annual average of just 30 high-accuracy, low-uncertainty calibrations performed by NIST on mass standards from various states.

- **mammography**

  NIST calibrations and measurement services help to ensure the accuracy of mammography and many other radio-diagnostic medical testing procedures. More than 33 million mammograms are conducted each year at more than 9,000 U.S. facilities. Medical professionals need to ensure that mammography machines generate x-rays properly; that the patient receives an x-ray dose required for clear imaging without overexposure; and that the x-ray film or detector will respond correctly to the prescribed radiation dose. Serving as the top of the traceability chain for a cascade of private testing companies, NIST performs approximately two dozen proficiency tests and other calibrations for mammography annually in support of accurate, traceable mammography measurements.

- **wireless telecommunications**

  NIST dissemination of the SI unit of time helps Americans to connect their wireless phone calls. Wireless telecommunications networks must be synchronized to within one millionth of a second per day to ensure that calls can be efficiently switched without interruption between the many thousands of base stations that distribute wireless phone calls. The wireless telecommunications industry is one of many utilizing a portion of the more-than-600-billion free timestamps provided by NIST annually.

NIST's Long-Term Commitment to SI Measurement Infrastructure: An Extended Example of Impact

The SI base unit of time—the second—is currently measured with greater absolute accuracy than is any other measurement quantity. It's improvement over the decades exemplifies the value of NIST's long-term commitment to the SI measurement infrastructure.

Realization and dissemination of the unit of time are crucial parts of the SI measurement system and underpin major portions of our technology infrastructure. Synchronization and timekeeping are vital components of telecommunications systems, computer networks, electric power distribution systems, the Global Positioning System (GPS) used for military and civilian navigation, and many other applications that would not function at all without exceptionally accurate and precise time measurement. From a historical perspective, the ever-increasing capability to measure time has paralleled technological advances in science and industry, and continues to do so to this day.

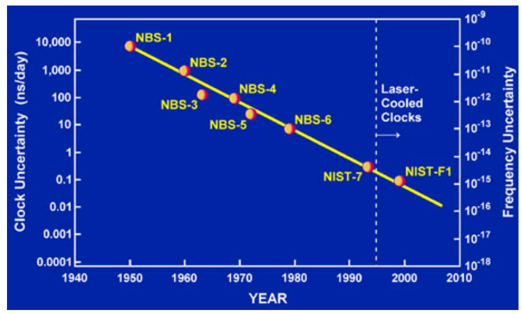
Today's precision measurements of time are the direct result of many decades of measurement science research and commitment by NIST and other NMIs. In the past 50 years, the accuracy of time measurement has improved by a factor of about 500,000.

For most of human history, timing was referenced to the apparent motion of the sun and stars as the earth rotated on its axis and orbited the sun. However, celestially based timekeeping methods continually vary by small amounts due to the natural variation in the period of rotation of the earth. Efforts to remove the effects of such variations from timekeeping were a source of technological development in the 17th and 18th centuries. These efforts served as the initial steps in a series of timekeeping advances that today provide us with accurate measurement of the very fast events of many modern technologies.

As part of a commitment to continually improve the SI measurement system, scientists at the National Bureau of Standards (currently NIST) invented and put into operation the world's first atomic clock over 50 years ago, based on fundamental vibrations in atoms. The atomic clock became the first intrinsic standard for an SI unit, that is, a standard based on *fundamental physical properties*—in this case vibrations of atoms—rather than on a *physical artifact* such as a pendulum-driven clock, meter bar, or standard kilogram mass. So far as is known, the vibrations of atoms do not change over time. In contrast to artifact standards, intrinsic standards are independent of human craftsmanship. In principle, if an atomic clock were to be destroyed, the standard could be reconstructed to the same accuracy, while an artifact standard cannot be exactly duplicated.

The first atomic clock was immediately much better than the best pendulum-driven clocks of the day. Scientists at NIST and other laboratories have continually improved atomic clocks and the technologies used in their realization. As a result, the uncertainty of the world's best atomic clocks has decreased by a factor of about 10 each decade. Now, more than 50 years after the invention of the atomic clock, NIST-F1, a cesium-fountain atomic clock, is about 500,000 times more accurate than the first atomic clock.

The continual improvement of atomic clocks has enabled many of the key technologies and scientific advances of the 20th and 21st centuries. Wireless telecommunications, GPS, space exploration, and many other advances would literally not be possible without atomic clocks and were not even envisioned until the presence and improvement of atomic clocks. In addition, the push to develop better atomic clocks has led to many other key scientific advances, including laser cooling and the production of ultra-cold states of matter. Nine Nobel Prizes related to the development of atomic clocks and "spin-off" technologies have been awarded in the past 50 years, including three Nobel Prizes to NIST scientists in the last ten.



Historical progression of improvement in the accuracy of atomic clocks

Continued development of the science and technology base has been necessary to realize the extraordinary timekeeping capabilities available today. Similarly, continual improvement in the scientific basis of measurements generally results in measurement technologies that support existing technologies, and perhaps more importantly, enable the development of innovative new technologies and products.

NIST's SI Contributions to the U.S. Measurement System

This appendix details NIST's work in supporting the nation's technology base through the accurate measurement and distribution of the seven base SI units. A sampling of NIST's efforts in some of the most important derived SI units is also given.

For each of these SI units, the following sections provide:

- descriptions of the unit and some of the impacts of its realization and dissemination
- the current status of realization and dissemination of the unit
- future opportunities and challenges related to the realization and dissemination of the unit
- a description of paths to improvement in the realization and dissemination of the unit

SI Base Units

The SI Unit of Length: The Meter

The unit of length is a critical element in the manufacturing of products with dimensions ranging in size from nanometer-scale features on an integrated circuit up to the 70-meter length of an airplane. Standardization of dimensional measurements—that is those of length, width, height, distance and the like—was a centerpiece of the industrial revolution, serving as the foundation of the interchangeable-parts economy. It is perhaps even more important in our current era of high-tech manufacturing, where some tolerances may be as small as billionths of a meter. The globalization of manufacturing has resulted in complex products with components produced all over the world that must assemble and function seamlessly in complex machines. Accurate dimensional metrology is essential to meet this goal.

Increased accuracy of dimensional measurements can translate into improved performance of products, ranging from optical fibers, to aircraft, to faster and more reliable computers. Even crime fighting involves dimensional metrology in determining which gun fired a bullet – as the NIST "standard reference bullet" used in ballistic determination can attest to. Furthermore, accurate dimensional measurements are necessary to enable innovation, because they provide the detailed information needed to understand how geometric form and size affect function, or to meaningfully compare the performance of real components to predictions of computer models. Finally, dimensional measurements play an important role in defining several of the derived SI units, such as units of pressure or of spectral irradiance.

The central role of the meter in the SI (metric) system of units is clearly reflected in the title of the 1875 treaty that first established its recognition: "The Convention of the Meter." The meter has evolved considerably since its 1875 definition of the length of a physical bar of metal – the meter bar. Most recently it was re-defined in 1983 in terms of the SI second and a fixed value of the speed of light in vacuum: "The meter is the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second." This 1983 definition may be expected to serve our needs for the indefinite future. However, the technology for dissemination of the unit—for translating the definition into practical length measurements—continues to evolve at a rapid pace.

Current Status: The definition of the meter in terms of the speed of light provides an ultra-precise basis for the SI unit of length, but this basis is of little value unless it can be successfully translated into practical measurement capabilities. If standardization is to be assured, all measurement processes from the shop floor to the defining principle must be accurate. Most of the field of dimensional metrology is directed toward improving and verifying the integrity of this traceability chain, and here reside the primary challenges. If NIST is to fulfill its mission, it is essential that the dissemination of the unit of length, as with all of the SI units, occur in a practical manner. NIST uses a variety of mechanisms to achieve this goal, including calibration services, calibrated reference materials, and informed participation in the development of national and international documentary standards. NIST also strives to understand and improve all the diverse elements of the critical measuring systems in the traceability chain, including optical interferometry, imaging systems, precision mechanical probing systems, and methods for evaluation of the measurement uncertainties associated with each step in the chain.

Future Opportunities and Challenges: As technology and the economy evolve, NIST must continually update its capabilities to meet new challenges. For example, the development of new methods of interferometry is being driven by the increasing use of aspheric optics and by the extreme demands on optical form accuracy needed for advanced applications. Similarly, the technology trend toward miniaturization is taxing the ability of current measurement systems to deliver reliable results. To meet this need, NIST is developing novel measurement systems. For example, the ultra-small holes (smaller than a human hair) used in fuel injectors are critical to improvements in fuel economy; detailed measurements are needed for both process control and to enhance our theoretical understanding of how form affects fuel injector performance. These components will require new probing techniques to provide reliable hole-geometry measurements. In a broader sense, NIST is faced with trends toward further miniaturization in a number of areas, including the growing applications of MEMS (micro electro-mechanical systems), increased use of micro-optical components, ultra-small parts manufactured via micromolding, and the classic example of integrated circuit manufacture where the size of critical features continues to decrease at an exponential rate—now below 50 nanometers. At the opposite end of the size scale, large structures including ships and airplanes are presented with a continued drive for better dimensional measurement capability for improving performance. These ever-increasing demands on measurement precision are accompanied by a need for ever-increasing densities of measurement data, made possible by new optical measurement techniques or scanning contact probes, structured light systems, and other optical techniques. The increased data density often requires the re-thinking of measurement strategies, new methods for analyzing massive data sets, and new documentary standards to ensure that commercial measurement systems with their associated software are delivering the performance promised.

Path to Improvements: While changes in technology present new measurement challenges, they also provide new solutions to measurement problems. NIST continues to explore emerging technologies that present new opportunities for improving the way we perform measurements and deliver services to our customers. For example, the need for dimensional measurements of very small parts such as MEMs may be enabled by the development of MEMs-based probing systems. Another example involves the problem of measuring the wavelength of laser light, the first step in the definition of the meter. Until recently, to relate the wavelength of light to the 1983 definition of the meter required a Herculean effort involving large teams of researchers, and these efforts only provided precise values of the wavelengths for a small number of lasers. The recent development of optical frequency combs (for which John Hall of NIST shared in the 2005 Nobel Prize in Physics) tremendously simplifies the process, so that with modest effort it is now possible to measure the wavelength of nearly any laser of interest with almost arbitrarily high precision. This development is of significant potential importance, allowing NIST to fully exploit new types of laser sources as length standards. Furthermore, the optical comb could provide a direct path of traceability to the definition of the meter, accessible to anyone in the world who owns an optical comb, by using the GPS system to provide a traceable link to the NIST time standard. The eventual development of all-optical communications networks might one day provide yet another path for widespread dissemination of traceable wavelength standards and users' access to the realization of the unit of length at higher frequencies.

For manufactured parts, NIST must continue to provide measurement services and standard reference materials that reflect the emerging needs of the marketplace. Each passing decade brings new measurement challenges, including a change in the critical length scale of primary interest and a perpetual need for higher accuracy. NIST continues to meet the challenge of providing the dimensional metrology infrastructure that is necessary for commerce and trade and provides the underpinning of innovation and progress in manufacturing.

The SI Unit of Mass: The Kilogram

While the kilogram only dates back to the 1880s, the use of weights and balances as tools to perform mass measurements for trade dates back thousands of years. Since those times, mass standards and the technology of balances and mass measurements have greatly evolved to meet the growing and changing needs of society. The activities of everyday life have always been affected either directly or indirectly by mass measurements. Whenever one buys groceries, takes medication, designs a bridge, space shuttle, or airplane, and trades goods, whether grains, gold, or gemstones, mass plays a crucial and vital role. In addition to the direct impact on trade and commerce, mass measurements impact the scientific community as well as a broad range of manufacturing industries, including aerospace, aircraft, automotive, chemical, semiconductor, materials, nuclear, pharmaceutical, construction, and instrument manufacturing. To ensure equity and equivalence in trade and manufacturing at the national and international levels, uniform standards are needed. While mass standards have been in existence for thousands of years and some countries had controlled policies on weights, uniformity was not guaranteed across boundaries and sometimes not even within the boundaries of a country. In the United States, the unit of mass was the avoirdupoids pound, and many standards were brought over from England to the colonies to serve as standards for trade. However, this did not form a robust system, and non-uniformity remained a major issue. The United States government formally recognized the need for uniformity and empowered Congress to "fix the standards of weights and measures" in the Constitution of the United States. Many attempts at adopting a uniform system of weights were made. Not until 1875 did the United States, along with 16 other nations, sign the Convention of the Meter to establish the foundations of the International System of Units (SI) that would provide long-sought uniformity in the standards of weights and measures.

In 1901, the 3rd Conference Generale des Poids et Mesures (CGPM) in Paris established the definition of the unit of mass: "The Kilogram is the unit of mass; it is equal to the mass of the International Prototype of the Kilogram." The International Prototype Kilogram is often referred to as "IPK". In 1884, 40 replicas of the kilogram were manufactured and compared to the mass of the IPK in 1888. In 1889, 34 of these replicas were distributed to the signatories of the Convention of the Meter who requested them. Calibration certificates accompanied the replicas, with mass values based on comparisons with the IPK. These replicas were in turn used by the different countries as national standards. At that time, the United States was allocated two Pt-Ir prototype kilograms, K20 and K4. K20 arrived to the United States in 1890 and was designated as the primary national standard of mass. K4 arrived later that year and was assigned as a check standard to monitor the constancy of K20. More than a century later, K20 and K4 still hold their respective designations. The six remaining replicas were kept at the Bureau International des Poids et Mesures (BIPM) to serve as check standards for IPK.

The International Prototype Kilogram always remains at the BIPM. Therefore, the prototypes serving as national standards of mass must be returned periodically to the BIPM for calibration either on an individual basis, which could be done anytime, or as part of a simultaneous recalibration of all the prototypes known as "periodic verification". The latest periodic verification took place between 1988 and 1992. The results demonstrated a long-term instability of the unit of mass on the order of approximately 30 µg/kg over the last century; this instability is attributed to surface effects that are not yet fully understood. Mass standards, including IPK and its replicas, are stored in ambient air; therefore, their surfaces are subject to the adsorption or absorption of atmospheric contamination resulting in a gain in mass over time; they also may lose mass from usage. The BIPM has developed a recommended method for cleaning platinum-iridium (Pt-Ir) prototypes to remove surface contaminants and restore the artifact to its original state. In 1989, the Comite International des Poids et Mesures (CIPM) interpreted the 1901 definition of the kilogram. The interpretation, which does not imply a redefinition of the kilogram, refers to the kilogram as being equal to the mass of the IPK just after cleaning and washing using the BIPM method.

Current Status: NIST provides industry, government, and academia with direct access to the top level of the kilogram traceability chain in the United States. While the unit of mass is defined at the one kilogram level, NIST realizes the mass scale over a range broad enough to be of practical use in commerce and manufacturing. The first stage in the realization of the mass scale is to disseminate the unit from the International Prototype Kilogram to the national standard by obtaining periodic calibrations of the U.S. standards K20 and K4 from the BIPM. This is then followed by a transfer of the unit of mass to a set of working stainless steel standards at the one kilogram level. This in turn is followed by dissemination to multiples and submultiples of the kilogram covering the range from 1 mg to 27 300 kg. To accomplish this task, NIST developed procedures that combine mass measurements, including buoyancy correction in weighing designs, with statistical analysis that minimizes the uncertainty of the measurements and uses statistical process control to monitor the precision and accuracy process. The relative expanded uncertainty (k=2) is smallest at the 1 kilogram level, with a value of 3×10^{-8}. It increases as the unit is transferred to multiples and submultiples of the kilogram, ranging from 2×10^{-4} to 1×10^{-6} over the mass range of 1 mg to 27 300 kg. All mass labs are kept under tightly controlled environmental conditions.

NIST represents the U.S. in international key comparisons conducted by the Consultative Committee on Mass and related quantities, so that customers receive NIST services that are recognized worldwide by the signatories of the CIPM Mutual Recognition Arrangement. The measurements performed at NIST are highly leveraged—most NIST measurements are used to perform secondary calibrations with larger uncertainty. An example of such leverage is the U.S. legal metrology system, represented by the States Weights and Measures Laboratories, which uses the NIST calibrations to perform approximately 400,000 mass calibrations per year, thereby impacting more than 50 percent of U.S. Gross Domestic Product.

The kilogram remains the only SI base unit defined by an artifact and thus is constantly in danger of being damaged or destroyed. The definition of the kilogram makes no provision for the effects of either the artifact surface parameters or for any environmental storage conditions. Environmental effects, combined with wear and other material and surface properties, constitute the most probable reason for the observed instability in mass over time. The instability of the kilogram propagates to other SI base units that are tied to the kilogram, such as the ampere, mole, and candela, and to derived quantities such as density, force, and pressure, thereby impacting a broad range of applications in the scientific and engineering sectors.

Future Opportunities and Challenges: While comparisons of nearly identical 1 kg mass standards can be performed with a relative precision of 10^{-10} with commercially available balances, the limitation in the field of mass metrology lies within the artifact definition itself. Therefore, the ultimate need for mass metrology is to redefine the unit of mass in terms of a fundamental constant of nature and to develop the necessary mechanisms to transfer this new realization of mass to consumers. At the same time, it is also crucial to pursue more stable artifacts and transfer standards maintained under precisely known environmental conditions—a necessity as this will be the only practical dissemination tool for the foreseeable future. Another way to reduce the uncertainty associated with mass measurements is to minimize or eliminate buoyancy corrections.

Path to Improvements: NIST is beginning a research effort to develop stable artifacts that can be used as primary standards replacing the existing drifting standards. These new higher-stability mass standards will increase the confidence in the dissemination of the unit of mass, reducing the need for frequent calibrations and simplifying the quality control procedures required to maintain control over the mass values of artifact standards. In addition, vacuum mass measurements are being investigated as another means of eliminating sources of uncertainty, such as buoyancy correction in mass calibrations. Full automation of mass calibrations is being implemented to eliminate operator-induced errors and improve the delivery efficiency of measurement services. Further, investigations are underway to develop the mechanisms necessary to make tenable the realization of the unit of mass based on fundamental constants as realized by the Watt balance.

The SI Unit of Time: The Second

The second is the SI unit of time. The second is based on fundamental vibrations in cesium atoms, and can currently be measured more accurately than any other measurement quantity, with an absolute uncertainty of about 5×10^{-16}—the equivalent of about 1 second in 60 million years. Extremely accurate timing and synchronization underpin modern technology, the economy, security, and scientific investigation. Examples include the following:

- wireless telecommunications networks, which must be synchronized to the equivalent of less than one microsecond (millionth of a second) per day to operate
- electric power grids spanning the continent and including more than 10,000 power generating stations, which must be synchronized to less than a microsecond per day for efficiency and for the location of problems on lengthy, remote transmission lines
- the Global Positioning System (GPS), used for numerous military and civilian navigation and location applications, and which require synchronization to less than a nanosecond per day (billionth of a second)

Current Status: At present, the second is most accurately measured by six laser-cooled cesium fountain atomic clocks throughout the world, including the NIST-F1 atomic clock. (Several other atomic clocks around the world are in final stages of development and testing, so this number may soon rise.) All these standards regularly report to the International Bureau of Weights and Measures (BIPM) in France, which coordinates international time—Coordinated Universal Time (UTC). These regular reports demonstrate that NIST-F1 is currently the world's most accurate atomic clock, as it has been since 2003; it is also continually improving. Continual international comparisons through BIPM ensure that no single clock is providing inaccurate information due to unrecognized problems.

The SI second is required for the realization of three other SI base units: the unit of length (meter), the unit of electric current (ampere), and the unit of luminous intensity (candela). Expected redefinitions of the kilogram and mole will also link these base units to the SI second in the future, leaving only temperature (Kelvin) not directly referenced to the second. A large fraction of the derived SI units are also referenced to the second. The most accurate possible realization for the second is thus necessary not only for timing and synchronization applications, but also to ensure the most accurate possible realization of many other SI base and derived units.

The current accuracy of the second is adequate for present-day telecommunications synchronization, barely adequate to support current GPS requirements, and inadequate for many future technical and scientific applications. The most accurate time information is currently distributed via microwave signals through satellite networks. This distribution system is very effective for less-demanding applications such as current telecommunications needs, but barely adequate for the most demanding applications requiring the greatest accuracy, such as GPS and international time synchronization.

Future Opportunities and Challenges: Demands for improved timing and synchronization drive continual reduction in the uncertainty of the SI second. A few well-recognized examples include these:

- improved performance of GPS and other satellite navigation systems planned for future deployment. Better positioning and navigation require an approximate 10-fold reduction in the uncertainty of the SI second over the next 10 years, as well as the development of new types of higher-performance atomic clocks to fly on the satellites themselves
- New applications of remote sensing and secure communications for national and economic security, which will require a 10- to 50-fold reduction in the uncertainty of the SI second in the next 10 to 15 years

- Requirements to synchronize deep-space communications networks for manned space exploration and radio astronomy, which will require a 100-fold reduction in the uncertainty in the SI second in the next 15 to 20 years

Just as the development and improvement of atomic clocks led to entire new technologies not previously envisioned, it is likely that significant future improvements in atomic clock performance will also result in as-yet unrecognized technical and economic opportunities.

In addition, new methods for the most accurate distribution of time and synchronization information are required to support all these applications, since the current microwave-satellite-based system appears to have reached its practical limits. Significant reductions in the uncertainty of the SI second won't leave the measurement laboratory until a substantially new distribution system is developed.

Path to Improvements: Atomic clocks based on laser-cooled cesium atoms can likely be improved by a factor of 2 to 5 in the next few years. But it is unlikely, for fundamental scientific reasons, that cesium-based atomic clocks can be improved much further than that, due largely to the fact that the cesium transition is in the microwave (radiofrequency) range.

The solution, beyond those improvements that can be made to cesium clocks, is likely to be new types of laser-cooled atomic clocks based on optical (visible light) transitions in different types of atoms or ions (electrically-charged atoms), which have the potential to reduce cesium atomic clock uncertainty by factors of 100 to 1,000. Optical clocks rely on atomic transitions that are up to 100,000 times faster than the cesium microwave transition—essentially providing many more "ticks per second" to improve accuracy.

NIST and other NMIs are actively researching several new types of optical atomic clocks with encouraging results. With additional resource investments, it is likely that optical atomic clocks will be able to continue the trend of a factor-of-10 reduction in uncertainty per decade as cesium clocks reach their fundamental limit.

Another advantage of optical clocks is the potential to distribute time and synchronization information through optical signals, over optical fiber or through air and space by lasers. This approach would overcome microwave-satellite limitations. But substantial research is needed to make this vision a reality.

A key breakthrough for optical clocks in the past several years was the perfection of the laser frequency comb—a method previously unavailable for accurately counting the very high frequency of optical transitions ("ticks per second"). This breakthrough was recognized through part of the 2005 Nobel Prize in Physics, shared by a NIST scientist, John Hall.

The SI Electrical Base Unit of Current: The Ampere

The SI base electrical unit, the ampere, relates all equivalent mechanical and electrical quantities, including force, power, and energy. 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 meter apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newtons per meter of length. Historically, the first realization of the ampere was the absolute ampere balance experiment equating mechanical and electrical force. This experiment was was one of the earliest carried out by the National Bureau of Standards (currently NIST) in the early 1900s. Today, electrical units and quantities are traceable through intrinsic quantum voltage and resistance standards and ohms law, V=IR. These practical electrical representations, the Josephson voltage standard (JVS) and the quantized Hall resistance (QHR) are stable below a part in 10^9 at the 1 volt and 1 ohm level, and provide traceability for the most demanding electrical metrology needs:

- **meeting the needs of electrical instrumentation manufacturers**
  A new technology for digital multimeters (DMMs) was developed. However the expected linearity and precision of the device was far more accurate than the available measurement capability could verify. The application of JVS array technology as a means of enhanced-accuracy voltage measurement demonstrated the performance of this technological innovation and generated a multimillion-dollar worldwide business for the manufacturing of the precision DMMs that greatly facilitated improved voltage measurement in a multitude of industries.
- **most accurate temperature measurements**
  The dissemination of the International Temperature Scale (ITS-90) for metrological and industrial needs relies on standard platinum resistance thermometers (SPRT), which are compared to standard resistors traceable to the QHR.
- **most accurate radiant power and energy measurements**
  Measurements in the optoelectronics industry for the characterization of lasers, detectors, displays, and related components, photometric measurements (including the realization of the candela), and radiometric measurements of spatially and spectrally extended sources are all traceable to the SI via voltage and resistance measurements by equating electrical to radiant power.

Current Status: On January 1, 1990, the CIPM introduced new, assigned, conventional values to the Josephson constant, K_J (the quotient of twice the electron charge to the Planck constant), and the von Kiltzing constant, R_K (the quotient of the Planck constant to the electron charge squared), for new practical representations of voltage and resistance. This move established worldwide uniformity in the measurement of voltage and resistance and other electrical quantities. The input data for these “1990” units, $K_{J\text{-}90}$ and $R_{K\text{-}90}$, were gathered from a broad range of research fields and institutions worldwide and related their results through accepted physical laws and their implied values to the fundamental constants of nature. For $K_{J\text{-}90}$, input was provided from the NIST watt balance results, Faraday experiment results, and molar volume of Silicon experiments. The value chosen, however, was mostly influenced by the results of the NPL watt balance due to its relatively small uncertainty. For the $R_{K\text{-}90}$ results, NIST provided results from its calculable capacitor and proton gyromagnetic ratio experiments, with the value chosen determined mostly by the comparison of experimental results of the electron anomalous moment and the prediction of quantum electrodynamic theory.

Today, voltage dissemination at NIST is obtained through three JVS systems developed by NIST: a 10-volt conventional JVS (NIST 10V), a 2-volt programmable JVS (NIST-2V PJVS), and a traveling compact JVS (NIST-10V CJVS). The uncertainty of JVS comparisons using the traveling Zener standards is approximately 20 ppb, while an uncertainty of 2 ppb can be obtained with the CJVS. Recently, the CJVS was used in a JVS inter-laboratory voltage comparison (ILC) that reduced the total uncertainty by a factor of 10 over previous ILCs, providing U.S. military, government, and industrial labs with best-in-the-world voltage dissemination.

NIST provides resistance dissemination from the QHR to key resistance standard values reaching uncertainties of 2 ppb, and then to 20 orders of magnitude of resistance (from 10^{-6} ohms to 10^{14} ohms) using a variety of bridges and current shunts. No other NMI provides these best-in-the-world uncertainties over such a broad range.

Future Opportunities and Challenges: The CIPM adopted Recommendation 1 (CI-2005) calling for, “Preparative steps towards new definitions of the kilogram, the ampere, the kelvin and the mole in terms of fundamental constants” for “possible adoption by the 24th CGPM in 2011,” with the Planck constant, the electron charge, the Boltzmann constant, and Avogadro’s constant being the leading candidates for, respectively, the SI units of mass (the kilogram), current (the ampere), temperature (the kelvin), and amount of substance (the mole). With the values of these (and other) fundamental constants being exactly defined, the uncertainty of most measurements traceable to the SI will decrease by over a factor of 100—especially measurements made in the nanoscale range, the realm of much future technological innovation. Currently the NIST watt balance is leading the way toward the value likely to be chosen for the Planck constant and awaits confirmation from other experiments worldwide. The electron charge will mostly be determined by the value chosen for the Planck and fine structure constants, with input from the closure of the “metrology triangle” utilizing single electron tunneling (SET) devices and a cryogenic capacitance standard. Work at NIST involving Johnson noise thermometry (JNT) utilizing a quantum voltage noise source (QVNS) will also have a major impact on the value chosen for the Boltzmann constant. The dissemination of the electrical units will remain through the existing quantum standards, including SET devices, with the notable exception that the QHR, JVS, and SET will now be SI realizations of the volt, ohm, and ampere.

Path to Improvements: While participation in the SI redefinition by NIST is vital, a more pressing issue is for NIST to have the dissemination mechanisms of the redefined SI units in place when the kilogram is redefined. To this end, NIST is exploring new ways to disseminate the unit of mass. The NIST watt balance will truly earn the name “Electronic Kilogram”, realizing a mass from the value of the Planck constant. A novel vacuum-to-air mass balance is being designed and constructed to connect the results of the electronic kilogram to the existing mass dissemination chain that industry relies on today. AC JVS systems, as well as 10 volt PJVS systems, are being developed to provide all-voltage dissemination through quantum standards. Advances in JNT via QVNS may well lead to the new method of disseminating the kelvin. The ability to manipulate and measure single and fractional charges that have exactly known values within the SI using SET devices will lead to a major reduction in uncertainties for measurements of current, force, and displacement in the nanoscale regime.

The SI Unit of Temperature: The Kelvin

The kelvin is the SI unit of temperature. The kelvin, symbol K, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water—the state where pure water exists simultaneously in its three phases, solid, liquid, and vapor. For historical reasons, temperature is often expressed in terms of degrees Celsius, where the melting point of ice (273.15 K) is defined as 0 °C, and the magnitude of a degree Celsius is the same magnitude as a kelvin. At temperatures other than 0 °C or the triple point of water (0.01 °C), primary thermometry is difficult and expensive. As an alternative, the ITS-90 is readily realized, accepted worldwide, and provides a close approximation to the true thermodynamic temperature that obeys all the laws of thermodynamics. The ITS-90 consists of a defined set of thermometric fixed points (e.g., the freezing point of silver is declared to be 961.78 °C); defined interpolating instruments; and defined interpolation equations. The International Temperature Scale of 1990 (ITS-90) facilitates the comparability and compatibility of temperature measurements internationally over the range 0.65 K to the highest temperature practical using monochromatic measurements of blackbody radiation. The range from 0.65 K to the freezing point of silver is termed the "contact thermometry" range, where the thermometer is in direct contact with the body whose temperature is being measured. Above the freezing point of silver, non-contact radiometric methods are used. Although the qualitative concepts of "hot" and "cold" predate recorded history, by 1607 Galileo had made a thermometer using the expansion and contraction of air in a bulb to move water in an attached tube. The work of Rømer, and Fahrenheit in the late 17th century refined the use of liquid-in-glass thermometers. Such refinement continued through the 19th century, and was combined with the application of physical principles governing the behavior of gases, to develop a scientific basis for the first internationally recognized temperature scale, the so-called "Normal Hydrogen" scale, which came into existence in 1889. It used two thermometric fixed points, the freezing and boiling points of pure water. Subsequent scales extended the defined range of temperature and became more precise through the use of physical state transitions, e.g., freezing or melting points, of highly purified materials.

Current Status: A number of technological advances enabled refinement of temperature scales. Improved purification of materials and methods for fixed-point cell assembly and use have significantly increased the precision and reproducibility of thermometric fixed points, to the extent that the triple point of water can currently be reproduced with a variation of 0.000 050 K or less and reproducibilities of 0.002 K or less for the higher-temperature defining points of the ITS-90. The advent, use, and refinement of electrical thermometers has not only provided the practical means to measure temperature between the defining points of temperature scales, but, more importantly in a technological sense, has been the basis for most practical temperature measurements in industrial processes, i.e., either electrical resistance, thermocouple, or radiometric thermometers.

NIST was the first national metrology institution in the world to realize the ITS-90. NIST uses several methods to disseminate the ITS-90 to the U.S. user community. These measurement services are:

- Thermometer calibration. This is the most often-used method of dissemination. To provide users with traceability to NIST at a high level of accuracy, NIST calibrates defining instruments of the ITS-90, including platinum resistance thermometers (PRTs) and radiation thermometers. NIST also calibrates numerous types of "industrial" thermometers to best serve the needs of particular segments of the user community. For example, thermocouple calibrations are provided to the manufacturers and distributors of thermocouples, who, in turn, provide thermocouple thermometers to a broad range of primarily industrial users. NIST still calibrates liquid-in-glass thermometers, which provide high performance at low cost, but a variety of electrical thermometers have greatly supplanted their use.
- Certification of fixed-point cells. The fixed points of the ITS-90 are commercially available as fabricated cells, in which the fixed-point material is enclosed in a carefully engineered, hermetically sealed cell. NIST validates the performance of fabricated cells for cell manufacturers and users.

- Proficiency testing. The ability of other laboratories to realize and disseminate ITS-90 to the industrial community is rigorously tested by blind comparisons, in which NIST and a secondary laboratory both calibrate the same artifact thermometers and the results compared.
- Standard Reference Materials (SRMs). NIST sells as SRMs certified, high-purity lots of several metals for use in the construction of fixed-point cells and several types of calibrated thermometers.
- Standard Reference Data. For the thermocouple types in common use, NIST has developed reference data, disseminated in the form of reference functions and tabulated data, of the relationship between the electromotive force—or voltage developed by thermocouples—and temperature.

Future Opportunities and Challenges: Temperature measurement will continue to present challenging opportunities for innovation across industrial usage. As new thermometry technologies are developed, evaluation of their performance requires novel methods to demonstrate that performance relative to the ITS-90 or to future temperature scales.

Although existing thermometer types generally meet the accuracy needs of industry, they may not be as user friendly as desired. PRTs are often fragile, and less fragile examples are subject to drift at temperatures in excess of 600 °C. Once used at high temperatures, thermocouples have a unique dependence on the temperature profile of their usage environment, so that thermocouples are often not amenable to recalibration. Although recent developments in solid-state detectors have revolutionized the sensitivity of radiometers, especially at temperatures below 660 °C, radiation thermometers suffer from large systematic errors as compared to contact thermometers, when applied to measurements out of the laboratory. In short, the greatest opportunities for temperature measurement technologies are to make temperature measurement standards more robust and to simplify the measurement process.

Path to Improvements: Although the ITS-90 represents the closest approximation to date of an ideal thermodynamic temperature scale, improvements remain necessary. In the range from approximately 100 ºC to 420 ºC, significant discrepancies in the primary source data existed at the time of construction of the ITS-90. NIST has been working to reduce the magnitude of these discrepancies so that the next international temperature scale will approximate the "real" or thermodynamic temperature more closely. Discrepancies in this region have magnitudes ranging to approximately 0.050 K. Recent experiments at NIST have reduced these discrepancies by a factor of five in this region. Recent collaborations have led to improved primary data in the range -269 °C to 0 °C as well, and work extending to 660 °C is underway. It is anticipated that the developers of the next international temperature scale will use this, and additional, primary data in the next scale definition anticipated to occur in the 2010 to 2015 time frame.

In the area of radiation thermometry, two significant changes are underway. First, advances in absolute radiometry, in which thermodynamic temperatures are determined from radiated power directly without reference to thermometric fixed points, is leading to greatly reduced uncertainty, especially at temperatures above 962 °C. Second, NIST is participating in a large international effort to develop new types of thermometric fixed points, based on carbon- or carbide-metal eutectics, and to assign thermodynamic temperature values to these new points. The adoption of a subset of these eutectic points in the next temperature scale will provide a second path to greatly reduced uncertainty above 962 °C.

The SI Unit of the Amount of Substance: The Mole

The mole (symbol, mol) is the SI unit for the amount of substance. It is the basis for all measurements of concentration or amount content and impacts industries ranging from the manufacture of chemicals to safety and regulatory considerations affecting environmental, medical, food, and other agricultural products. The mole is defined as the amount of substance of a system that contains as many elementary entities, generally atoms or molecules, as there are atoms in exactly 0.012 kg of carbon-12. The mole is applicable to any particular atomic or molecular entity. Carbon-12 was selected as the reference substance because its atomic mass can be measured with particular accuracy.

Avogadro's constant and the molar mass are two related concepts that are closely connected with the mole. Avogadro's constant, sometimes referred to as Avogadro's number, is formally defined as the number of elementary entities that comprise a mole of those entities. Therefore, a mole of a substance comprises Avogadro's number of elementary particles of that substance (atoms, ions, molecules, or formula units). The currently accepted value of Avogadro's constant is $6.022\ 1415 \times 10^{23}\ mol^{-1}$.

The molar mass of an element is the mass of one mole of atoms of the stated element. Many elements exist as mixtures of atoms of two or more coexisting isotopic forms, each of which has a different mass. The molar mass of such an element (or entity containing that element) as it occurs naturally can therefore vary slightly, based on sample-to-sample differences in the relative abundance of the isotopes of the element(s) that form the entity. The uncertainty associated with the differences in the relative abundances of the isotopes for an element is a significant and usually dominant source of uncertainty in the molar mass of that element. Certain elements are however mononuclidic (e.g. Al, P, Mn, Au). Each atom of a mononuclidic element has an identical mass. Thus, the uncertainty in the molar mass, which includes only the uncertainty of the mass of the single isotope, is much smaller for these elements. In both cases, however, the uncertainty associated with natural variations in molar mass is much greater than that of the Avogadro constant.

The internationally accepted values for the molar masses of the elements are based on evaluation of published experimental results for representative natural laboratory samples. These values include the experimental uncertainty in the measurement of the nuclidic molar mass(es) and (if applicable) the natural variability of the associated isotope abundances for representative natural samples. These values, expressed relative to 1 mol/kg, are referred to as relative molar masses or atomic weights and are the values listed, for example, in periodic tables of the elements.

Current Status: As the basis for quantitation of chemical concentration or amount content, the mole is a vital concept. Metrological determinations of the value of the Avogadro constant have involved well-characterized materials, primarily high-purity silicon crystals, and have resulted in a relative experimental measurement uncertainty for this constant of approximately 1.7×10^{-7}, or 0.000 017%. All practical applications of chemical measurements in industry, medicine, or environmental monitoring have measurement uncertainty requirements that are more than adequately supported by the currently available uncertainty of the mole. For example, most natural matrix Standard Reference Materials provided by NIST to support accuracy in chemical measurements have certified total uncertainties in the 0.5% to 5% range. Certified uncertainties for high-purity substances, while smaller, also never approach the uncertainty in the value of Avogadro's constant.

Future Opportunities and Challenges: Future opportunities and challenges in chemical measurements are related to the need for new approaches to address the growing need to know what substances are present in a particular sample or object and at what concentration levels. This need can range from determining elemental impurities in a high-purity material, such as a silicon wafer, to determining complex biomolecules, such as proteins and DNA, in biological tissues. Advancements in chemical measurements are critical to addressing needs in industry, health, nutrition, environment, forensics, and homeland security applications.

Path to Improvements: Currently there is an active discussion within the metrology community about the definition of the seven primary units. Much of this discussion centers on the definition and realization of the mass unit, the kilogram, by assuming an exact value (with zero uncertainty) for either the Avogadro constant or the Planck constant. The kilogram and, by extension, the Avogadro constant, will then no longer be defined by an artifact maintained at the Bureau International des Poids et Mesures but would be defined directly from invariant quantities of nature and the laws of physics. These efforts and goals are described briefly in the sections dealing with the units of mass and electric current within this appendix.

The SI Unit of Luminous Intensity: The Candela

The candela is the SI unit of luminous intensity. Luminous intensity describes the magnitude of light sensation on the human visual system. The candela is the only SI unit that is based on human perception, specifically visual stimulation. Vision is important for interaction, knowledge acquisition, and navigation. The amount of visual information available from the environment depends on the intensity of light present. Light levels affect the ability to perform tasks and make comparisons. Measurement of light intensity is important because minimum levels often are mandated by safety and federal regulations. Light levels also are important to the enjoyment of many leisure activities, such as television viewing, photography, and nighttime events. In addition, virtually every sale of goods depends on the appearance of the goods, which, in turn, depends on the level of light illuminating the goods.

The first realization of the candela occurred around 1860 and used candles made from sperm whale fat, known as spermaceti. In 1898, the candles were replaced by wickless gas lamps that used a mixture of pentane and air. In 1909, the first internationally recognized unit was established collaboratively among the National Bureau of Standards (currently NIST), the National Physical Laboratory in England, and the Laboratoire Central d'Electricité in France. The unit was based on the pentane lamp but was maintained on carbon filament lamps. In 1948, the candle became the candela, and the magnitude of the candela was defined such that the luminance of a full radiator at the temperature of solidification of platinum is 60 candelas per square centimeter.

Current Status: In 1979, the candela was redefined as the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian. The new definition relies on the international standardized human visual response, which is based on research by scientists at the U.S. National Bureau of Standards and other institutions. The Commission Internationale de l'Eclairage (CIE) published this standard function, called the spectral luminous efficiency function (for photopic vision), and it is denoted as $V(\lambda)$. The $V(\lambda)$ function has a shape similar to a bell curve with low sensitivity in the red and blue regions of the light spectrum and high sensitivity in the green region.

Using standard photometers, the candela at NIST is traceable to the absolute cryogenic radiometer, which is the device that realizes the transfer of the electrical watt to the optical watt. The detector-based candela brought significant improvement in the uncertainty of the unit over the previous blackbody-based method. The uncertainties of the photometric base unit maintained at NIST is 0.5 percent (k=2). The NIST photometric scales are primarily disseminated via standard lamps and standard photometers.

Future Opportunities and Challenges: Several critical applications with units that trace back to the candela, such as the lumen scale maintained by lamp companies worldwide and the illuminance scale maintained by the photographic industry, require even lower uncertainties than those available at NIST. To accommodate such needs, research has focused on reducing the uncertainty of the NIST photometric base unit to 0.1 percent (k=2). A number of subtle, sophisticated technical difficulties need to be overcome before this goal can be realized. Areas of research include conversion from radiometric quantities (units based on monochromatic light with a narrow beam geometry) to photometric quantities (units based on broadband sources in a uniform illumination field), determination of the interaction of light with parts of the photometers, and the stability of reference transfer standard lamps.

The $V(\lambda)$ function has been used as the basis of photometry for 80 years. While $V(\lambda)$will continue to serve its purpose as far the legal metrology of light, many cases exist in which a person's visual response does not match photometric measurements. One such example concerns the overall level of illumination. The current photometric system established by $V(\lambda)$ applies only to the high light levels common in the outdoors and commercial offices (photopic conditions). A similar function, $V'(\lambda)$, has been defined for very low light levels, such as nighttime conditions (scotopic conditions). However, much of the human perceptual experience occurs at lighting levels intermediate to these two extremes (mesopic conditions).

Another related issue concerns generalizing measurements of visual sensitivity, which are used as the basis of photometry. Much of the visual data underlying photometric functions were determined by visual threshold measurements (e.g., the dimmest light that is visible to the observer), and sensitivity was assumed to be the inverse of threshold. While such a relationship is appropriate at the dim lighting and stimulus levels used in the experiments, nonlinearities of the visual system (such as gain control mechanisms) likely change those sensitivity relationships under suprathreshold conditions. Systematic investigation into the relationship between measurements of visual sensitivity at threshold levels and suprathreshold levels is an important step toward understanding how applicable photometric measurements are to realistic lighting situations. Another application is flashing lights. Flashing lights are widely used in safety and signaling applications because they attract attention more effectively than steady lights. Existing methods to assess the effective intensity of flashing lights often fail with novel temporal waveforms (flash patterns).

Path to Improvements: To answer these challenges, NIST is creating a new, state-of-the-art vision science program, which will be unique among national metrology institutes. This program will provide the capabilities to perform the critical vision-science experiments necessary to develop colorimetric and photometric metrics optimized for technologies of the twenty-first century. A vision scientist will work in the visual-testing facility to perform the fundamental vision-science experiments required to support the development and commercialization of new lighting technologies. The crux of the new facility will be an illumination source capable of producing nearly any spectral-power distribution within the visible range for testing colorimetric and photometric metrics. The history of artificial lighting shows a strong relationship between the development of new metrics and the introduction of new technologies. NIST has always been a world leader in the development of these new metrics.

SI Units Derived from Base SI Units

The Derived SI Unit of Force: The Newton

The newton (N) is the SI-derived unit of force. A force of one newton applied to an object of one kilogram mass will give that object an acceleration of one meter per second per second. The equation form of the definition is commonly written $1\ \mathrm{N} = 1\ \mathrm{kg{\cdot}m/s^2}$. The pound-force unit (lbf) came into use well before the N and is used throughout much of U.S. industry. Despite widespread encouragement to adopt the use of the N exclusively, a significant portion of the U.S. market continues to work in the conventional nominal lbf system. Use of the conventional system in lieu of the international unit is still practical because conversion between the two units is easily accomplished. One N is approximately 0.225 lbf; or a four-to-one ratio. The need to know and understand forces is integral to modern society in many ways, some of which are listed here:

- The ability of materials to resist expected operating forces when fabricated into the myriad of machines, bridges, structures, vehicles, and nearly all physical hardware found in everyday life is determined only by physical test of that material. Subjecting materials to known forces validates all physical designs and assemblies.
- Determination of jet and other engine thrust is made by measuring the force generated upon test firing.
- Determination of masses acting upon a balance, or weighing, is really the determination of the forces generated by the mass object in the earth's gravity field.
- The SI base unit, the ampere, is defined as that current which, if maintained in each of two infinitely long parallel wires separated by one meter in free space, would produce a force between the two wires of 2×10^{-7} newtons for each meter of length.

Current Status: Force is realized at NIST in multiples of newtons by suspending well-characterized stainless steel deadweights in the ambient gravity field and accounting for the buoyant effect of the surrounding air upon the suspended weights. The weights and lifting components together comprise a mechanism termed a deadweight machine (DWM) that is considered to be a primary force standard and the current best method of accurately realizing standard forces over a wide range. NIST maintains six DWMs that cover an overall force range of 44 N to 4.448 MN; the 4.448 MN (1,000,000 lbf) DWM is the largest such machine in the world. The different machines allow compression or tension secondary-standard-force transducers to be calibrated in the equipment that best matches their force range or capacity.

Standard uncertainty in the vertical force vector generated by a NIST deadweight machine is estimated to be less than 0.0005 percent for all applied forces. Error sources contributing to the NIST force standard uncertainty of 0.0005 percent include uncertainty in the determination of the mass of the deadweights; variation in the buoyant force upon the weights; and variation in the effects of gravitational acceleration upon the weights at the NIST site. All values considered in the determination of uncertainty are fully SI traceable. For example, all weights in the DWMs were calibrated by NBS/NIST mass laboratory personnel by comparison to mass standards that themselves are directly traceable to SI unit of mass through the U.S. national standard kilogram.

Access to the standardized forces produced by the DWMs is made available to customers of the NIST Force Metrology Laboratory through the business office of the NIST Calibration Program. Secondary standard force transducers are sent by industry to the NIST laboratory for calibration versus the appropriate NIST DWM. The user of the secondary device receives a thoroughly documented Report of Force Calibration which provides details of transducer response to various applied forces. The report empowers the user to measure forces with the calibrated transducer that are traceable to the SI through U.S. national standards. NIST-calibrated force transducers underpin industries such as aerospace, automotive, manufacturing, and construction by providing the basis for all subsequent force measurements that are performed through the secondary, tertiary, and other force-dissemination systems. In addition, NIST represents the United States in international key comparisons conducted by the Consultative Committee for Mass and Related Quantities (CCM), so that customers receive NIST services ,which are recognized worldwide by the signatories of the Mutual Recognition Arrangement.

Future Opportunities and Challenges: Demand for improved uncertainties in the dissemination of the unit of force continues to be addressed through incremental advances at the secondary-transducer level. Transducer manufacturers seek lower transfer uncertainties by use of more exacting assembly techniques or by optimizing the current physical designs. NIST is exploring an optical force measurement technique that may greatly reduce parasitic effects found in conventional transducers. Application of accurate force measurements in several further derived units present great opportunities for future growth. Torque measurement realization and uncertainty in the United States does not currently enjoy the refinement found in the force measurement arena. Dynamic force and dynamic torque measurements are areas that may prove to require SI traceability from the NMI level.

Path to Improvements: NIST Force Laboratory is actively involved with potential solutions to several future challenges. Further optimization of the force transfer device can occur through an alternate measurement technique, such as the optical-force research project mentioned above. The exploration of torque measurement is being addressed with the setup of a basic torque laboratory that will be a part of assessing the requirements of the U.S. torque measurement community. NIST's constant interaction with the force industrial community through participation on standards committees and at conferences serves to promote information exchange and is a good method for informally determining areas where research could be beneficial.

The Derived SI Unit of Pressure: The Pascal

The pascal (Pa) is the SI unit of pressure. One pascal is defined as one newton applied uniformly over an area of one square meter. The pascal is derived from the SI units of mass, length, and time. Pressure measurements and controls are important in many manufacturing processes, such as chemical and petrochemical manufacturing, semiconductor processing, automobile and jet engine performance, electric power generation, weather monitoring and prediction, and altimetry in aviation. Accurate pressure measurements traceable to NIST's primary standards are frequently required for custody transfer of gases including natural gas in pipelines, process gases in cylinders, and hydrocarbons (for example,. ethylene in pipelines for polyethylene manufacture). The integrity of containment vessels is often tested and certified using pressure measurements. Such measurement protocols are important to health and safety codes used widely by industry and are used in certain types of consumer goods. Hydraulic and pneumatic systems are ubiquitous in industrialized society and rely upon generation, measurement, and control of pressures for their operation. The measurement of low pressures is required to control vacuum processing, including coating, cleaning, and manufacturing useful devices on semi-conducting wafers.

Currently, there are no intrinsic methods for determining pressure, that is, no fixed points for establishing pressure standards that can be calculated from theoretical considerations with sufficiently small uncertainties. Thus, the practical realization of pressure standards depends upon combining well-understood physical principles with measurements of other quantities that can be related to primary standards. For example, realizing pressures using liquid column manometers combines high-accuracy measurements of the density of a liquid, lengths of liquid columns, and the acceleration of gravity. The density of manometer liquids is determined by measurements of mass and volume (lengths). Over certain ranges of pressure, dual realization techniques can be crosschecked against each other to assess the uncertainty of realizations of the pascal.

Current Status: The range of pressure of practical importance spans at least 16 decades (10^{-7} Pa to 10^{+9} Pa). The lowest pressures (also referred to as high vacuum) are important for semiconductor manufacturing and fundamental physics research, whereas the highest pressures are important for the energy industry and studies of material properties. Employing pressures intermediate to these extremes are numerous applications in industry and the consumer economy. Support of the variety of applications of pressure measurement over the wide range of pressures requires multiple standards, each spanning only a limited range in pressure. NIST uses three fundamentally different techniques for realizing the pascal: piston gauges for pressures of 10^4 Pa and above; liquid-column manometry from 10^{-3} Pa to $3x10^5$ Pa; and orifice flow standards over the range 10^{-7} Pa to 10 Pa. Piston gauges realize pressure using a technique similar to the realization of force: Well-characterized masses in a well-known gravitational field are loaded on round pistons that are inserted in round cylinders. In some cases, the "effective area" of the pistons can be determined at atmospheric pressure from dimensional measurements. In other cases, the effective area is determined by comparing a piston gauge directly with a standard manometer or indirectly by using another piston gauge. Multiple piston-gauge standards, with progressively smaller diameter pistons and overlapping pressure ranges, allow realizing about 5 decades in pressure. A fundamental problem for pressures above 10^6 Pa is that the shape of the piston and cylinder change significantly due their elastic distortion under pressure, limiting the accuracy of pressure measurement. There is no independent method that can verify the pressure determined by the piston gauge at high pressure. Uncertainties range from less than one part in 10^5 at low pressure to tens of parts in 10^5 at the highest pressure.

Currently the most accurate pressure standard in the world is the liquid-column manometer. The technique relies on the accurate measurement of the liquid-column length and knowledge of the density of the manometric fluid, which in turn is a function of temperature. NIST maintains four manometer standards, three of which use mercury and one that uses a commonly-used oil (Octoil-S). Mercury is chosen because its density has been determined with an accuracy of 7×10^{-7}. NIST measures the column height by sending an ultrasonic wave packet up the column and measuring the phase of the returned signal. The NIST standards, referred to as Ultrasonic Interferometer Manometers (UIMs), have an order-of-magnitude better resolution than manometers based on other length-measuring methods, such as the laser interferometer measurement. The uncertainty is 5×10^{-6} at one atmosphere and above.

For pressures of 10 Pa and lower, that is, vacuum conditions, NIST realizes the pascal by producing a known flow of gas through an orifice of known conductance, producing a known pressure drop. The "high" pressure is directly and quantitatively related, that is, traceable, to the UIM standards through a stable, calibrated-pressure transducer. The desired "low" pressure is determined from the flow-rate parameter, the conductance of the orifice, and the measured gas flow. The gas flow is produced by constant-pressure flowmeters based on the measurement of the displacement of a piston in a gas-filled, sealed vessel directly connected to the orifice. State-of-the-art vacuum technology is critical to achieving low-pressure standards. NIST has developed sophisticated vacuum chambers, pumping systems, valves, and sealing methods to support these standards.

The pascal is transferred to U.S. industry and government primarily through pressure gauges and transducers that are calibrated against NIST primary standards, as few users maintain their own primary standards, and transporting them would be difficult. The exception is piston gauges, as they are easily shipped and the user base is large. Overlap of the pressure ranges over which piston gauges and manometers, and manometers and orifice standards operate allows redundancy of the techniques over at least a portion of the pressure range. NIST uses comparison among the three types of devices in their overlapping ranges as a means of checking and assuring the correct operation of these standards.

Future Opportunities and Challenges: In the pressure range of 3×10^5 Pa to 5×10^6 Pa, NIST has made significant progress in the last few years in developing a new approach to pressure standards that may ultimately supersede manometry and piston gauges as primary pressure standards. This approach is based upon improved capability to calculate, from fundamental physical principles, dielectric properties of helium gas using several differing models the results of which agree with a variation of less than 1×10^{-6}. This capability presents the possibility of basing pressure measurement directly upon on a calculable physical property—the dielectric constant—of a pure substance, helium. It is hoped that this standard will have a smaller uncertainty than that of piston gauges and will be easier to use than standard manometers. As pressure value increases, distortion of the piston/cylinder combination becomes a significant source of error in piston gauges that cannot be overcome with current materials. The new approach offers the potential of reduced uncertainties coupled with the possibility of operation at pressures currently unattainable with piston gauges in any practical sense. Current NIST primary standards often have long time constants or require highly skilled operators. This new approach has the possibility of reduced complexity of operation.

Path to Improvements: NIST will examine and improve pressure standards to allow more efficient realization of the pascal at the level of uncertainty necessary for dissemination to users requiring the highest accuracy. For the very low-pressure regime, new approaches to secondary standard-gas-flow meters based on capillary leak conductances could significantly improve efficiency for the widely used ionization pressure gauge. A new vacuum standard based on the expansion of gases into known volumes is under investigation to supplement the orifice-flow standards. In the medium-pressure region, a secondary standard using MEMS-based stable-pressure transducers is being developed. Automation techniques can be more readily applied to these various methods.

The Derived SI Unit of Sound Pressure: The Pascal

Instantaneous sound pressure, expressed in the unit pascals (Pa), is a time-varying quantity, equal to the instantaneous pressure minus the static pressure. Sound pressure is usually expressed as sound-pressure level or sound level in decibels (dB) and is a critical measure of acoustical signals. These signals may be valuable sounds, such as speech, warning signals, or music, or unwanted noise that causes hearing loss, interference with speech reception and sleep, annoyance, and degradation of productivity. A large and increasing number of U.S. national and international legal, regulatory, quality-control, and medical (audiometric) measurements needed for health care, safety, and U.S. domestic and international commerce depend on measurements of sound pressure. These measurements protect the hearing of more than 100 million U.S. workers and military personnel, including commercial and military aircraft pilots who are not permitted to fly unless they pass the hearing tests in required, periodically performed physical examinations. These measurements also enable the diagnosis and appropriate treatment of about 30 million hearing-impaired Americans. They also are used in the design and manufacture of commercial products that must meet regulatory requirements (such as FAA and other noise requirements for aircraft), or for which low noise levels are a measure of perceived quality, often with product standards that must be met to achieve U.S. success in international trade.

Historically, the determination of sound pressure in given kinds of sound fields has been a problem of considerable practical complexity. By the late nineteenth century, Rayleigh determined the threshold of human hearing with his improved method, using a microscope with an eyepiece micrometer to measure the displacement amplitude of the vibrating prongs of a tuning fork, which excited an acoustical resonator as a calculable sound source. Another technique used the Rayleigh disk method to measure the sound pressure in a plane-progressive wave. Subsequent researchers sought better and more convenient sound sources of known strength, or better instruments for measuring sound fields. These included calculable sources of sound pressure or electrostatic equivalent sound pressure: the thermophone, the piston phone, and the electrostatic actuator. By 1920, the invention of the wide-frequency-range capacitor (condenser) microphone by Wente provided an instrument for which the sensitivity (now usually expressed as the ratio of SI-derived units V/Pa or as sensitivity level in decibels with reference 1 V/Pa) could be calibrated by calculable sources. This instrument and a voltmeter could then be used to measure sound pressure.

In 1940, Cook's observations at NBS of systematic differences between various sound sources led to his introduction of what became known as the reciprocity method for the pressure calibration of microphones (determination of sensitivity in a spatially uniform sound-pressure field). His work and the more general independent theoretical work of MacLean, which included calibration in the free field (determination of sensitivity to sound pressure in a plane-progressive-wave incident on the microphone from a specified direction), established the reciprocity method for calibrating microphones. The development of the Western Electric 640AA microphone provided stable laboratory standard condenser microphones that were used in inter-laboratory comparisons of calibration results among the laboratories of NBS, Harvard, and AT&T Bell. By 1945, these comparisons proved that measurements of sound pressure over a wide frequency range, using stable microphones calibrated by the reciprocity method, were superior to the use of the best available calculable sources, such as the thermophone.

Current Status: NIST uses reciprocity methods for the pressure calibration and the free-field calibration of a variety of standard microphones, with frequency-dependent best accuracies (uncertainties) that can be achieved within the United States only at NIST. For example, uncertainties in pressure calibration by reciprocity at NIST are 0.04 dB (expanded uncertainty with $k = 2$) at frequencies from 500 Hz to 4000 Hz. Reciprocity-based comparison calibrations also are offered to customers. NIST represents the United States in international key comparisons conducted by the Consultative Committee for Acoustics, Ultrasound, and Vibration (CCAUV), so that customers receive NIST services, which are recognized worldwide by the signatories of the Mutual Recognition Arrangement.

NIST disseminates the unit and supports the current U.S. Measurement System infrastructure via numerous explicit or implicit chains of traceability. These chains relate a small number of measurements of very high accuracy. For example, calibrations of laboratory standard microphones performed by NIST for major commercial, civilian governmental, and military calibration laboratories and instrument manufacturers, to secondary calibrations of other microphone systems and acoustical calibrators, to much larger numbers of measurements that require lesser accuracy, such as practical laboratory and field verifications and checks supporting survey measurements for occupational hearing conservation purposes, and the testing, quality control, and conformity assessment of manufactured products to required standards and regulations. As a specific example, in the last 30 years, only a few dozen microphone calibrations performed by NIST for just one of our customers—the Mine Safety and Health Administration (MSHA) of the U.S. Dept. of Labor—have provided traceability for over 100,000 calibrations of critical acoustical measuring instruments used in the MSHA noise control program mandated in Federal regulations.

Future Opportunities and Challenges: Newer types of microphones are increasingly being sent to NIST by customers, such as the primary standards laboratories of the U.S. Army and the U.S. Air Force, Lockheed-Martin Corp., NASA, OSHA, and measuring instrument manufacturers, such as Scantek, Inc., and Bruel & Kjaer North America, Inc. New and more demanding customer needs could be met using these microphones because their properties enable them to be calibrated to better accuracies over a wider frequency range than those of current NIST SP250 services. Improved accuracies in next-generation microphone pressure calibration services from NIST will enable customers to realize the potential of new and evolving instruments, such as very stable acoustical calibrators. Because these customers calibrate these devices by comparison with the NIST-calibrated microphones, the accuracy in the reference microphone calibration influences the accuracy in the customer calibration of these calibrators. These calibrators are used to provide traceability to many thousands of other acoustical measuring instruments, including measuring microphone systems, sound level meters, personal sound exposure meters (dosimeters), sound power measurement systems, and audiometric equipment.

NIST provision of next-generation microphone pressure calibration services will enable customers to meet competitive and contractual pressures to provide state-of-the-art measurements, to satisfy legal metrology needs and avoid costly litigation and damages, and to achieve reliable measurements of noise emission close to regulated or mandated limits. For example, a 1 dB difference in noise measurements for an aircraft certification could be worth $100 million, and air conditioning units not meeting new classroom noise standards for school construction could be shut out of that very large market.

Path to Improvements: Reciprocity calibrations involve determination of electric transfer impedances and acoustic transfer impedances of coupled microphones in essentially closed couplers (pressure calibration) or in an anechoic chamber (free-field calibrations). To achieve next-generation capabilities, numerous improvements in many aspects of apparatus and procedure will be made. For pressure calibration, an evolving test bed that was used by NIST in the Key Comparison CCAUV.A-K3 will be modified to enable performing calibrations at controlled ambient static pressure to eliminate the influence of uncontrolled variations that otherwise can limit the accuracy, to provide for varying the ac power line frequency to avoid the influence of the power line frequency and harmonics on measurements near these frequencies, and to provide more accurately known coupler and microphone recess dimensions. For free field calibration, improvements in system configuration and signal processing methods will be used to reduce the influences of noise, electrical crosstalk, and anechoic chamber imperfections. Improved electronic filters, amplifiers, and electrical measurements will be needed in both pressure and free-field calibration systems.

The Derived SI Units of Energy and Power: The Joule and Watt

The joule (J) and the watt (W) are the SI units of energy and power, respectively. The joule is the amount of energy or work that is exerted when a force of one newton (N) is applied to a mass of one kilogram (kg) to move a distance of one meter in the direction of the force.[1] The watt (W) is the amount of power in one second that gives rise to energy of one joule. Power and energy can be generated by thermodynamic, electrical, and optical means. The U.S. consumes more than $280 billion of electrical power annually. The fair, reliable, and efficient generation and delivery of this power is critical to growth of the U.S. economy and to consumers, especially in light of the increasingly deregulated and fragmented areas and aging infrastructure of power generation, transmission, and distribution. Laser power and energy are parameters used to characterize the performance of nearly all optoelectronic devices—from DVD players to complicated medical devices to telecommunications equipment. In 2000, an independent economic impact assessment estimated the net benefits associated with NIST laser-calibration services to be between $17.1 and $30.3 million. For both electrical and optical applications, measurement accuracy is a prerequisite for the design, purchase, and operation of equipment in diverse fields, such as materials processing, medical diagnostics and surgery, computer data storage, barcode scanning, image recording, telecommunications, and entertainment.

Current Status: The joule and watt are realized to an accuracy of 0.05 percent or better through primary electrical and optical standards. Electrical standards are maintained by the NIST Quantum Electrical Metrology Division; optical standards are maintained by the NIST Optoelectronics Division. Both divisions regularly perform international comparisons with other national measurement institutes as part of an ongoing quality-assessment process.

Since the SI watt and joule are derived units, they are realized through standards that are traceable to the realizations of the SI volt, ohm, farad, and time in combination with ac-dc transfer standards that link the dc to ac electrical units through thermal converters. The realizations of the electrical watt and joule are disseminated through calibrations of commercial power and energy meters that compare calibrated impedance, time, voltage and thermal ac/dc standards with the meter measurements. The power covered by the NIST measurement services ranges from less than 5 watts to 60 kilowatts, which is the range of commercial interest for revenue metering of electric power. The watt is realized for phase angle differences between current and voltage that range from $-\pi$ radians to π radians, and for frequencies from 50 hertz to 1 kilohertz. These phase angles and frequencies cover the range of historical commercial interest. The joule is disseminated through the same NIST measurement system but uses the integrated value of the realized watt.

Measurements of laser power and energy at NIST are traceable to an absolute cryogenic radiometer that has been optimized for laser measurements. This device realizes the transfer of the electrical watt to the optical watt through a direct comparison of the heat generated by both electrical and optical methods. With other standards for laser power and energy, NIST supports optical measurements at power levels from nanowatts to hundreds of kilowatts and energy levels from femtojoules to megajoules. Wavelength ranges include the visible through the near infrared and selected wavelengths in the ultraviolet and mid infrared.

Future Opportunities and Challenges: Demands for improved power and energy measurements drive efforts to reduce the uncertainty in the watt and joule. To achieve these goals, NIST has turned to quantum phenomena. They enable relating electrical and optical quantities to unvarying fundamental atomic constants, such as the charge on an electron. Continued success in the implementation of electrical and optical standards based on quantum phenomena could motivate a future redefinition of the SI to provide definitions more readily implemented by a broad range of users.

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[1] CIPM, 1946, Resolution 2 (PV, 20, 129-137).

Concurrent with to efforts to implement quantum-based standards in the realizations of the SI watt and joule, improvements are being made in the conventional devices that scale the outputs of quantum standards to levels compatible with commercial power and energy standards used in the dissemination of the watt. The challenge is to reduce the uncertainties in power scaling in order to fully achieve the potential of reduced uncertainties of quantum devices in the realization of the watt.

In the short term, new applications are being developed which require improved measurement methods and instrumentation for high accuracy laser metrology over a range of powers, energies, and wavelengths wider than currently available. For example, a DARPA program to develop super high efficiency diode sources requires accurate measurements of both electrical and optical power to determine their wall-plug efficiency, that is, the ratio of optical power emitted to electrical power input.

Path to Improvements:

Electrical measurements

Quantum-based ac voltage standards will replace the conventional voltage sources in the realization of the future SI watt as these devices are developed and the scaling improvements are achieved. The frequencies and power levels presently covered by the realization of the SI watt have historically met industrial needs. Due to the modernization of the electric power grid and the proliferation of electronic devices that introduce distortions to purely sinusoidal electric power, the power industry has a strong interest in much higher frequencies and a broader range of power levels in order to maintain better control and response to power grid disturbances than in the past. The development of improved digital sampling techniques and stable distorted power sources will allow NIST to replace the existing systems for realization of the watt and joule with a digital measurement system covering the broader range of power and frequencies.

Optical measurements

The ability to generate and control single photons offers new opportunities to meet customer needs in quantum-based radiometric measurements, where optical power is measured by counting photons. Quantum cryptography is an emerging form of ultrasecure communications that requires an on-demand source of single photons. The single-photon sources and detectors will allow NIST to meet the requirements of this new technology. The single-photon source can be extended to generate pairs of entangled photons. These entangled photon pairs are useful for a wide range of applications, from fundamental tests of quantum mechanics to reduced dimensions with optical lithography.

The Derived SI Unit of Capacitance: The Farad

The farad (F) is the SI unit of capacitance. Capacitance is a measure of the amount of electric charge that a capacitor can hold under a given voltage. In its simplest form, a capacitor consists of two conducting plates separated by an insulating material called the dielectric. Capacitance is directly proportional to the surface areas of the plates and is inversely proportional to the separation between the plates. It also depends on the dielectric constant of the substance separating the plates. The farad is a large unit; in practical circuits, capacitance is often measured in microfarads (μF), nanofarads (nF), or in picofarads (pF, or trillionths of a farad). The unit is named for the British physicist Michael Faraday (1791–1867), who was known for his work in electricity and electrochemistry. The SI farad plays a unique role among all electrical units because its realization from the mechanical units is the most straightforward and the simplest.

Capacitors are ubiquitous in commodity electronic products, such as televisions, computers, and cell phones and in specialized analytical electronic instruments, such as network analyzers and CTs (computed tomography). Precise and traceable measurements of capacitance are essential for reliable operation of electronic circuits and for international trading of electronic products.

Capacitors are also used as transducers to translate changes of other physical quantities, such as distance, temperature, pressure, and dielectric constant, into electrical signals; examples include capacitive motion encoders and fuel gauges for aircraft. Precise calibrations of these transducers are often required for reliability and security.

Current Status: The farad is currently most accurately realized through a calculable capacitor. The calculable capacitor is a unique high-accuracy instrument that directly links the capacitance unit to the mechanical unit of length. It is a physical realization of Thompson-Lampard's Theorem, which shows that in a cylindrical geometry, the mean cross capacitance between opposite segments of any conducting bound path that is divided into four segments is given by a function that is dependent only on the cylindrical length and the permittivity of vacuum. The number of high-accuracy calculable capacitors in the world is small—the most accurate is that of NIST (relative uncertainty about $2x10^{-8}$); the next is NMIA's in Australia. The SI ohm is realized through the SI farad by a measurement chain of capacitance build-up and a capacitance-resistance bridge. The present value assigned to the dc Quantum Hall Resistance (QHR) in 1990 was based effectively on determinations by NIST, NML, and NPL. The NPL capacitor is no longer operational. Because the NIST capacitor is the most accurate, the least-squares weighting of the results from the three institutes strongly favored NIST.

The NIST calculable capacitor is the primary standard in the United States for the SI measurements of impedance and resistance. The calculable capacitor, which measures a change of 0.5 pF, is transferred twice a year, at a frequency of ~1592 Hz, to the as-maintained legal farad which consists of a bank of four 10 pF fused-silica standards (referred to as the Farad Bank) maintained in an oil bath at 25 °C. The Farad Bank, which drifts only 0.02×10^{-6}, per year serves to disseminate from the primary standard to a large number of secondary capacitance standards. Precision ac scaling bridges are used for comparisons between the Farad Bank and any customer-provided capacitance standards from 0.01 pF to 100 uF. Auxiliary impedance standards with characterized frequency dependences are used to provide traceability from power frequencies to radio frequencies.

Future Opportunities and Challenges: The NIST calculable capacitor system is more than 30 years old and is visibly aging. While the calculable capacitor is expected to remain the most direct, readily comprehended means of realizing the electrical unit of capacitance, and hence resistance and inductance, the representation of these units can be improved by using quantum standards. A practical quantum standard offers superior stability and reproducibility. In fact, since the adoption of the QHR for the representation of the ohm by the Convention of the Meter on January 1, 1990, the QHR standard has proved to have better time-invariance and international consistency than the realization of the ohm via the SI farad. All resistance calibrations at NIST are currently referenced to the QHR.

In addition to the path via the calculable capacitor for the QHR to be linked to the mechanical units, the QHR can also be indirectly evaluated through the fine structure constant α. The best value for α arose from experimental atomic physics measurements, together with numerical perturbation method calculations of quantum electrodynamics, with α as the expansion parameter. The relative standard uncertainty is a few parts in a billion for this indirect path of the SI ohm and the QHR realization.

In principle, the farad can be disseminated using the QHR as the ultimate reference. This requires an improved resistance-capacitance (RC) link between the Farad Bank and the QHR standard. This link involves multiple steps and was last made in a series of experiments between 1991 and 1995. For routine dissemination, the major challenge is to simplify and automate the ac bridges needed for the RC link.

Industrial needs for impedance calibrations are changing. With applications of microcontrollers and digital signal processors, commercial electrical instrumentation continues to improve in precision and tends to cover broader parameter space. The farad dissemination has to improve to effectively serve the industry.

Path to Improvements: The ultimate goal is to represent the farad by a quantum standard. NIST and other NMIs are actively researching three different methods. The conceptually simplest method is based on single-electron tunneling. By depositing a counted number of electrons onto the plate of a capacitor and measuring the resulting voltage, one can calibrate the capacitance. The second method is to operate a QHR standard at ac frequencies so that it can directly calibrate a capacitance standard. The third method is to reverse the RC link between the Farad Bank and the dc QHR standard so that the QHR can be used as the ultimate for routine capacitance calibrations. With additional resource investments, it is likely that the as-maintained farad can be represented by a quantum standard, thus ensuring time-invariance and international consistency of the unit.

Digital signal processing (DSP) techniques will be employed to automate and simplify operations of precision ac bridges and thus allow a broader coverage of parameter space of capacitance calibration services from 0.01 pF to 1 μF in the frequency range from a few Hz to a few MHz. Measurement capabilities of dissipation factor, which is a measure of loss of a capacitor, will also be developed to enable improved traceability of energy and power measurements and better characterization of dielectric materials.

The Derived SI Unit of Volume: The Cubic Meter

The SI unit of volume is the cubic meter (m^3) derived from the unit of length. Volumetric measurements in commerce and trade, in the United States and other nations, have a long history and only recently have used the cubic meter, often preferring to use a variety of customary units. Volumetric measurements have a strong lineage in the determination of the quantities of both liquid and solid materials in commerce. Types of materials measured volumetrically include corn or grain, coal, wine, ale, beer, and petroleum. Although the cubic meter is the currently defined SI unit, such was not always the case.

In 1901, the Third CGPM by resolution defined the litre, for high-accuracy determinations, as the volume occupied by a mass of 1 kilogram of pure water at its maximum density and at standard atmospheric pressure.

This definition closely followed experimental practice of the day for the determination of liquid volume using gravimetric methods, that is, using high-accuracy mass measurements to determine the mass of water either contained in a vessel or dispensed from it. Pure, or distilled, water was used because its density had been determined with relative accuracy of approximately 1×10^{-6} several years prior to the Third CGPM. Water-density values combined with accurate mass determination yields the volume of water contained in the vessel of interest. The usage of the litre as the SI unit of volume continued until 1964 when the Twelfth CGPM changed the definition. It abrogated the Third CGPM's definition of the litre, declaring that the word litre may be employed as a special name for the cubic decimeter (0.001 m^3 or 1,000 cm^3), and recommended that the name should not be employed to give the results of high-accuracy volume measurements. This resolution was further refined in 1979 by the Sixteenth CGPM which considered that:

- The symbol l for the unit litre was adopted by the CIPM in 1879 and confirmed in the same Resolution of 1948.
- The name litre, although not included in the Système International d'Unités, must be admitted for general use with the system.

The Sixteenth CGPM also decided, as an exception, to adopt the two symbols l and L as symbols to be used for the unit litre, but provided that in the future only one of these two symbols should be retained and left that decision to the Eighteenth CGPM to be held in 1987. The Eighteenth CGPM made no resolution concerning the litre, and the action of the Sixteenth CGPM is still in effect regarding usage of the term. It should be noted that gravimetric methods predominate for high-accuracy determination of both contained liquid volumes and dispensed liquid volumes, generally involving specially shaped containers often called volumetric test measures.

Current Status: NIST realizes and disseminates liquid volumetric standards using gravimetric methods, recognizing that in commercial practice and usage, customary units remain the most commonly used volumetric unit. The U.S. gallon, defined as 231 in^3, or 0.003785412 m^3, or 3.785412 L, is the common unit of liquid volume used in commerce in the United States. Volumetric test measures are the most often used type of volume standard used in the United States for significantly sized volumes, most commonly denominated in U.S. gallons and most commonly used in the commercial exchange of petroleum. NIST provides calibration services for liquid volume and expresses these customary units in terms of the SI unit of volume. Conversely, normal usage in relatively small volumes involves volumetric glassware as the containment vessels, in which the common unit used is the cubic centimeter and which range in size from ~25 cm^3 to several litres.

The largest number of containers that NIST calibrates for customers are volumetric test measures generally ranging in volume from 1 to 100 U.S. gallons. The primary usage of volumetric test measures, sometimes termed volumetric provers, is for the calibration of apparatus used in the calibration of large flowmeters that must be calibrated in place. They often use specialized devices known as positivedisplacement provers, which are generally realized with a movable piston or displacer along a straight section of circular pipe with appropriate valving and position-detection apparatus to measure the volume of liquid passing through them over a measured time. The determination of such a swept volume is based upon procedures involving the use of volumetric test measures to quantify the volume swept by the displacer or piston. Typical measurement uncertainties in assigning either contained or dispensed volume for these test measures range between 0.1 percent and 0.01 percent. The actual uncertainty varies between containers. This variation is associated with the test measures themselves, particularly the two mechanisms defining the end points of the device, the drain valve and the graduated neck/sight gauge combination.

Future Opportunities and Challenges: As flowmetering devices have attained higher reproducibilities, the demand for smaller measurement uncertainties in the standards used to calibrate them has escalated. This is a trend that will continue and will require more sophisticated methods of volumetric determination.

Path to Improvements: The primary path to improvement is in the design of the test measures themselves. Specialized test measures have been constructed by various national metrology institutions (NMIs), such as NIST, which is the NMI of the United States, for the purposes of comparing volumetric measurement capabilities. The uncertainty in the assigned-volume values of such tests among several NMIs is significantly smaller than those found with commercial test measures. Accuracy among NMIs is often demonstrated below the 1 x 10-5 level. Use of such technology in commerce will be driven by the commercial sector and will require usage protocols that are considerably more stringent than current practices.

The Derived SI Unit of Acceleration: Meter per Second Squared

The SI unit of acceleration is expressed in terms of the SI base units of length and time. Vibration measurements, including acceleration, velocity and dynamic displacement, are used for environmental testing, diagnostics, product development, condition monitoring, process control, servo sensors, and global positioning. Some of the economic outcomes involve products produced at very high volumes. In the auto industry, which is but one example of an industrial segment relying heavily on acceleration measurements involving hundreds of transducers per test, many tens of staff years are spent measuring accelerations on vehicles for airbag deployment systems and for ride control of specific vehicle classes. Delivery of such systems in vehicles is measured in millions of units. Other applications include the development and qualification of products of very high cost, such as aircraft and their components. Calibrations and tests of accelerometers (transducers used to measure acceleration) are performed for customers in the industrial, governmental, and educational sectors, including the aerospace industry, automotive industry, construction industry, nuclear power industry, instrument manufacturers, Department of Defense, Department of Energy, Department of Labor, and university research laboratories. This effort directly supports the needs and demands of U.S. customers for traceability directly to the top of the U.S. measurement hierarchy, including requirements in U.S. law or regulation, maintenance of NIST's position as a global leader in measurement in the CIPM, the CIPM Mutual Recognition Arrangement (MRA), the International Organization for Standardization (ISO), and the requisite recognition of U.S. metrology by the international community.

Measurement of acceleration related to vibration dates back to the late 1920s and early 1930s when measurements of structural dynamics were needed in aeronautics and naval architecture. The calibration of these early transducers was based on subjecting them to a calculable mechanical motion over a relatively limited frequency range. In the 1940s, the piezoelectric accelerometer became commercially available and could be calibrated by the absolute method of reciprocity. Although the technique was used as early as the 1920s, the implementation of interferometry to determine acceleration from dynamic displacement became more practical in the 1950s and 1960s. Currently, the piezoelectric accelerometer is the transducer that is most widely used as a transfer standard to determine vibratory acceleration. The challenge has been and continues to be to furnish traceability over the widest possible range of frequencies and amplitudes with the smallest possible uncertainties.

Current Status: There are four independent calibration systems currently in use to perform vibratory calibrations of accelerometers, with three of these systems used to perform calibrations for customers of the NIST Technical Services Vibration Measurements. These systems have evolved over time beginning in the 1960s. The calibration systems cover different ranges in frequency and peak amplitude of acceleration and use different methods to determine the acceleration associated with the source of vibration. A low-frequency calibration system covers the range of 2 Hz to 160 Hz, with absolute acceleration determined by fringe-counting interferometry. Calibration of accelerometers can be performed using this system with an uncertainty of 1 % to 2 %. A second system, covering the frequency range from 10 Hz to 10 kHz, is made up of two vibration generators, each with internal primary standards that are calibrated periodically by absolute methods. The transducer under test is then calibrated by comparison to the primary standards with an uncertainty of 1 % to 2 %. A third system is used to cover the frequency range from 3 kHz to 20 kHz at a constant displacement of 121 nm, which is determined by the absolute method of fringe-disappearance interferometry. Calibration of accelerometers can be performed using this system with an uncertainty of 2 % to 4 %. The fourth system, which has been under development for a number of years, is capable of the calibration of accelerometers by the absolute methods of either reciprocity or interferometry. The uncertainties associated with these systems have been validated by international and regional comparisons, by application of experimental statistics, and by comparisons of the results of independent measurements of NIST internal check standards.

Future Opportunities and Challenges: Traceability in the absolute calibration of accelerometers using mechanical shock excitation covering peak amplitudes of five orders in magnitude and six orders in frequency is needed by the automotive industry in vehicle testing, by the aerospace industry in airframe testing, by the U.S. Department of Defense in testing the survivability of naval-, air-, and land-based vehicles, and by the U.S. Department of Energy in weapons testing. The U.S. manufacturers of earth-moving machinery and power tools are required to test products to ensure that they meet regulatory requirements imposed by European Directives with respect to whole-body and hand-arm vibration limits. These measurements involve determining vibrations at frequencies much smaller than 1 Hz. There are needs by the automotive, aerospace, and defense industries to provide traceability for laser-based vibration-measuring instruments with frequency ranges extending to 1 MHz and peak amplitude ranges extending to 10 m/s. There is an increasing need by the automotive industry for traceability of angular acceleration measurements as vehicular ride control becomes ever more sophisticated. The private and public sector calibration laboratories that furnish the calibration and provide a fundamental link in the U.S. chain of traceability of hundreds of thousands of accelerometers are continually challenged and therefore request NIST to provide calibrations with reduced uncertainty.

Path to Improvements: The most critical element in reducing the uncertainty in determining acceleration and extending the range of frequencies and amplitudes of vibration is the development and implementation of new, high-quality generators of vibration and shock. This will necessarily involve the replacement of antiquated systems of equipment currently in use. To that end, a new low-frequency calibration system is under development in order to meet repeated requests for calibrations at frequencies below 1 Hz with improved uncertainties. These requests are emanating primarily from manufacturers of transducers, from which hundreds of thousands of transducers in the private and public sectors derive their traceability, and from the nuclear power industry in the calibration of transducers used to monitor vibration levels of nuclear reactors.

The Derived SI Unit of Radioactivity: The Becquerel

The becquerel (Bq) is the SI derived unit for the physical quantity of radioactivity, and is equivalent to the reciprocal second (s^{-1}). The becquerel represents one nuclear transformation (change) of one atomic nucleus to another. This transformation is often accompanied by the emission of alpha (consisting of two protons and two neutrons—the nucleus of a helium atom) or beta (energetic electron or positron) particles, highly energetic photons (X- or gamma rays), or other particles from the atomic nucleus. The number of becquerels changes with time (as activity decreases over time) in a fixed mass of radioactive material. An older and often-used (especially in medicine) unit of radioactivity, the curie (Ci), is defined as 3.7×10^{10} becquerels (37 GBq).

Originally studying phosphorescence and the absorption of light by crystals, Antoine-Henri Becquerel came upon the discovery of natural radioactivity serendipitously. In February 1896, while investigating the absorption of sunlight by crystals of potassium uranyl sulfate (and the supposed resultant X-ray emission by the uranium crystals), weather conditions compelled Becquerel to put his uranium-covered photographic plates (the X-ray detector of the time) in a drawer until the weather cleared. After three days (on the first of March), upon observing the photographic plates, Becquerel was surprised to find that, rather than the faint images he was expecting, the images of the uranium crystals were strong and clear, indicating that the uranium itself was emitting radiation. Becquerel was awarded half of the Nobel Prize for Physics in 1903 (the other half being awarded to Pierre and Marie Curie) for his discovery of natural radioactivity. The CGPM of 1975 accepted a Consultative Committee for Units-recommended proposal of the International Commission for Radiation Units and Measurements (ICRU) to adopt the special name of *becquerel* for the SI derived unit of radioactivity (the non-SI *Ci* had been in use since 1896).

Current Status: The becquerel is realized and maintained at NIST through the development and improvement of radioactive standards and the measurement techniques used for the calibration of radionuclides used in a variety of applications. These standards and calibrations are disseminated both directly to the customer and through various networks of secondary calibration laboratories by means of calibrations and proficiency testing services provided to maintain measurement quality assurance and traceability, which pass on NIST calibration factors to more than 700 tertiary laboratories. NIST radioactivity standard reference materials represent the basis for all accurate radioactivity measurements throughout the United States and are classified into three general categories: (1) environmental and nuclear power, (2) medicine, and (3) basic and applied research (for example, nuclear data and the examination of basic nuclear processes).

Realization of the becquerel requires that the number of radioactive decays that occur during a defined time interval be counted. However, every radioactivity counter, or detector, has inherent inefficiencies, limited size, detection threshold, and background count rates (counts in the absence of radioactive decay). The efficiency of a detector is calculated on the basis of one or more theoretical measurement models, each of which has some degree of uncertainty. For radioactive decay, the theoretical measurement models with the lowest uncertainties are those that use multiple detectors, time correlation measurements, and efficiency extrapolations. These measurement models (and the related measurement methods of coincidence and anticoincidence counting with efficiency extrapolation techniques) cannot be used with all radionuclides, but activity measurements using these models and techniques have become the cornerstone of the international measurement systems for radioactivity, and the calibration of virtually all radioactivity measurement instruments is based upon them.

For most radioactivity measurements, the largest contribution to a lack of confidence in a measurement result arises from the uncertainty in the efficiency of detecting and registering the disintegrations, which vary with the type of radioactive decay, the measurement method, and the type of detector. To validate results, measurements are compared with primary standards (radioactive sources measured by primary methods that do not depend on comparisons with other instruments) held by national measurement institutes worldwide through the BIPM. As the national measurement institute of the United States, NIST holds the primary standards for radioactivity and is uniquely positioned to participate in measurement comparisons with other members of the Convention of the Meter.

Future Opportunities and Challenges: Challenges facing the realization of the becquerel are associated with radioactivity levels and the half-life (the time after which half of the nuclides have transformed), which are key determining factors for many applications in health care (nuclear medicine, imaging), the environment (clean-up, monitoring, archeological and geological studies, etc.), energy (nuclear power), industry (food processing, sterilization, pest control, etc.), and safety (including homeland security). The half-life can range from minutes (for positron emission tomography, PET, imaging) to millennia (for carbon-14 dating). The efficient and accurate measurement of the Bq is a crucial step in validating the utility, efficacy, and quality assurance of radiation applications and monitoring.

As medical imaging applications (such as PET/CT) expand, the difficulties of validating measurements of radionuclides with half-lives of less than an hour, which preclude their direct calibration at NIST or any other single site, will potentially impede the regulatory acceptance of results (both for clinical trials and for patient care). However, this burgeoning industry presents the opportunity to provide measurement traceability and assurance for an industry expected to affect more than two million patients a year within the next five years.

Measuring very low (picobecquerel) levels of radioactivity in complex samples (natural matrices or in cargo containers) presents additional challenges. Whether for environmental monitoring or for homeland security applications, the realization of the becquerel in the presence of relatively higher background or the tracking of radioactivity through chemical processing, generally presents measurements with higher uncertainties. Minimizing the uncertainty on the primary measurement is necessary to minimize this higher uncertainty.

Measurement uncertainties associated with the determination of time, mass, length/volume, temperature, pressure, and relative humidity are small and fairly well known. Improvements in detection instrumentation, advances in software development, and technological evolution in detector technologies can reduce the uncertainties in detection efficiencies.

Path to Improvements: To meet these challenges and to exploit current and future opportunities, NIST is expanding its efforts in developing and improving primary measurement methods (for example, microcalorimetry and triple-to-double coincidence counting). These efforts will minimize measurement uncertainties and provide fundamental tools crucial to the measurement infrastructure of current and emerging technologies in radioactivity measurements and applications. In addition, expanding efforts in proficiency testing, radiochemistry methods, and instrumentation evaluation protocols will address the special needs for extremely low-level measurements in a variety of samples and environments and will facilitate the validation of new technologies for radiation detection for homeland security and for monitoring for nuclear power plants and environmental clean-up. Also, to meet the growing need for measurement quality assurance and traceability to the becquerel for short half-life radionuclides needed in medical imaging, satellite NIST measurement and calibration facilities are being established at key sites throughout the United States. These satellite sites will be within a short drive to producers and clinical users of these types of radionuclides, yet will maintain a tight link to NIST primary standards through training, instrument calibrations, and periodic in-house activities by NIST staff. In this way, measurement results from clinical applications can have a degree of confidence beyond any yet achievable, which will facilitate the development and use of emerging technologies in medical imaging.