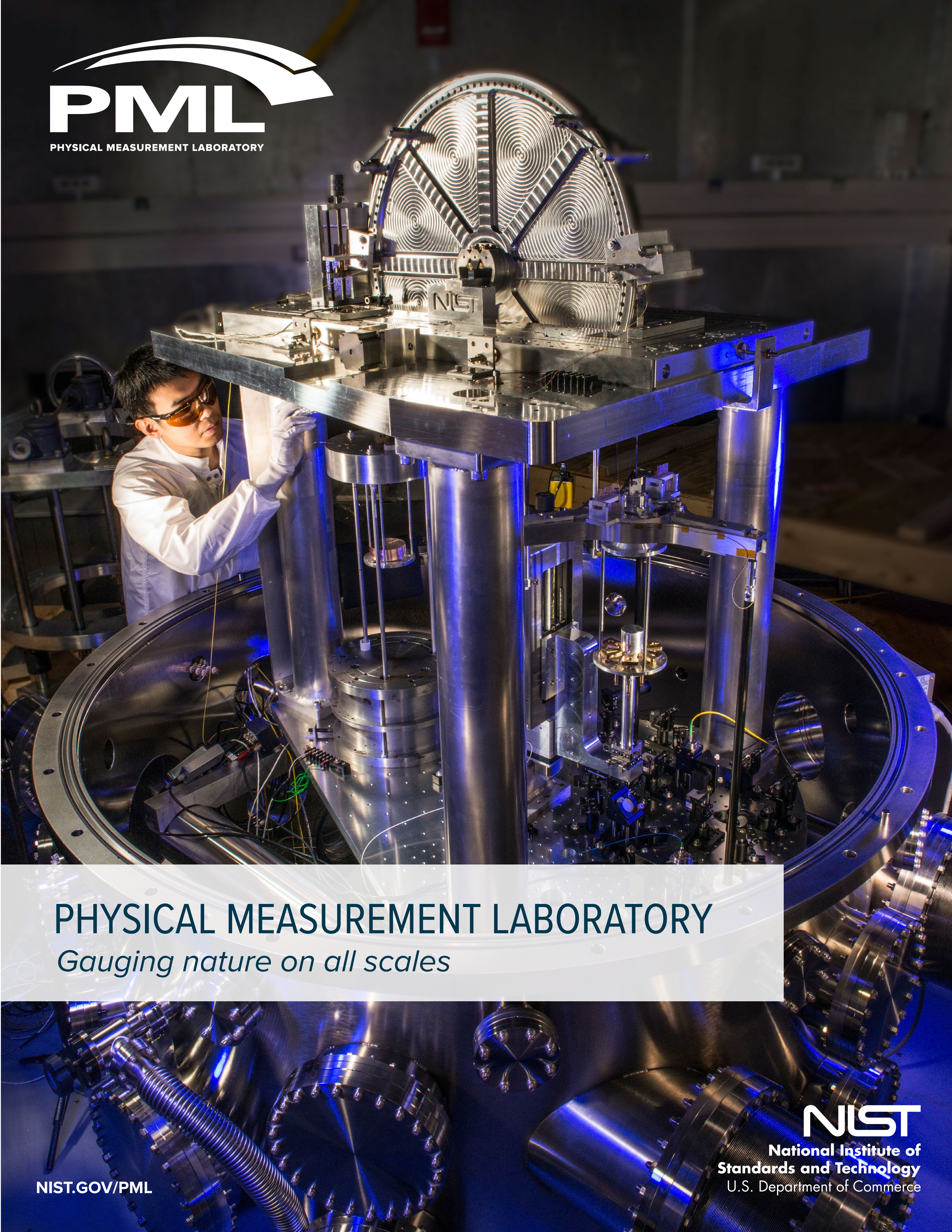

PML
PHYSICAL MEASUREMENT LABORATORY

PHYSICAL MEASUREMENT LABORATORY

Gauging nature on all scales

NIST.GOV/PML

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

PHYSICAL MEASUREMENT LABORATORY (PML)

The Physical Measurement Laboratory (PML), a major operating unit of the National Institute of Standards and Technology (NIST), sets the definitive U.S. standards for nearly every kind of measurement in modern life, sometimes across more than 20 orders of magnitude. PML is a world leader in the science of physical measurement, devising procedures and tools that make continual progress possible. Exact measurements are absolutely essential to industry, medicine, the research community, and government. All of them depend on PML to develop, maintain, and disseminate the official standards for a wide range of quantities, including length, mass, force and shock, acceleration, time and frequency, electricity, temperature, humidity, pressure and vacuum, liquid and gas flow, and electromagnetic, optical, acoustic, and ionizing radiation. PML collaborates directly with industry, universities, professional and standards-setting organizations, and other agencies of government to ensure accuracy and to solve problems. It also supports research in many fields of urgent national importance, such as manufacturing, energy, health, law enforcement and homeland security, communications, military defense, electronics, the environment, lighting and display, radiation, remote sensing, space exploration, and transportation.

IMPACTS

- Provides 700 kinds of calibration services
- Numerous special testing services
- U.S. standard time dissemination
- Over 100 standard reference materials
- Atomic Data Center
- Fundamental Constants Data Center
- NanoFab User Facility

OUR PEOPLE INCLUDE:

- 4 NOBEL LAUREATES
- 7 MEMBERS OF THE NATIONAL ACADEMIES
- MORE THAN 100 FELLOWS OF APS, OSA, IEEE, SPIE, AND AAAS
- MORE THAN 250 MEMBERS OF INTERNATIONAL STANDARDS ORGANIZATIONS
- 470 FEDERAL AND 670 ASSOCIATE SCIENTISTS; 110 NON-SCIENTIST STAFF
- TRAINERS OF OVER 1,000 STATE WEIGHTS AND MEASURES OFFICIALS EACH YEAR

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MESSAGE FROM THE DIRECTOR

The central mission of NIST's Physical Measurement Laboratory (PML) is to develop and continuously improve the best and most trustworthy measurement science possible to support American commerce and ensure the nation's preeminence in the world economy.

It is justly said that you cannot make what you cannot measure, and modern technology demands increasingly accurate and precise measurements of myriad properties and quantities at the lowest possible uncertainties and in ever smaller dimensions.

Progress in manufacturing, medicine, communications, defense, and many other key endeavors depends critically on those capabilities. PML meets those needs through world-leading metrology research and authoritative calibration, testing, and measurement services.

Our scientists and technicians work at the outermost frontiers of physical science to identify and investigate the kinds of measurements that the future will require, from nanoscale imaging, ultra-high-precision timekeeping, and sub-picosecond signal processing to detection of subtle quantum effects, advanced photonics, spin electronics, artificial intelligence, precision medicine, and novel ways to realize the newly redefined SI units.

At the same time, PML provides industry, government, and academia with state-of-the-art standards, calibrations, and methods for making their essential measurements—both at NIST and at customer facilities—and helps solve problems they encounter. In addition, we provide many of the nation's authoritative science databases, and operate numerous active teaching and training programs.

Finally, we are leading a sweeping new program called NIST on a Chip that aims to bring super-miniaturized, quantum-accurate measurement devices directly to the customer's site

That work is conducted by PML's 500 federal and 670 associate scientists; 80 administrative staff working at NIST's Gaithersburg, MD, and Boulder, CO, campuses, and at two joint institutes: JILA with the University of Colorado Boulder, and the Joint Quantum Institute (JQI) with the University of Maryland at College Park.

Each of our many projects and programs, highlighted on the following pages, has a unique focus. But all reflect our devotion to provide unequaled metrology research and measurement services to America both today and tomorrow.

James Kushmerick, Director
Physical Measurement Laboratory

MEASUREMENT SERVICES

NIST calibration services help the makers and users of precision instruments achieve the highest possible levels of measurement quality and productivity. These services provide customers with assurance in their results by communicating the NIST measurement results for carefully selected instruments and artifacts. Nearly all are conducted within or through PML. NIST performs, on average, more then 13,000 tests per year in nine metrology areas covering about 500 calibration services, including:

DIMENSIONAL: Length; Diameter and Roundness; Complex/3D Dimensional Standards; Optical Reference Plane Standards; Angular Measures; Laser Measurements; Surface Texture; Nanoscale Structures

ENVIRONMENTAL: Ozone; Mercury

IONIZING RADIATION: Radioactivity; Neutron Sources and Dosimetry; X-ray, Gamma-Ray, and Electron Dosimetry; Dosimetry for High-Dose Applications

TIME AND FREQUENCY: Broadcast and Measurement Services; Characterization of Oscillators; Phase Modulation and Amplitude Modulation Noise Measurement Systems

METROLOGY AND WEIGHTS AND MEASURES TRAINING: Metrology training at unique NIST training facility; numerous in-person and virtual classes around the country; training at NCSLI and MSC meetings

IMPACTS

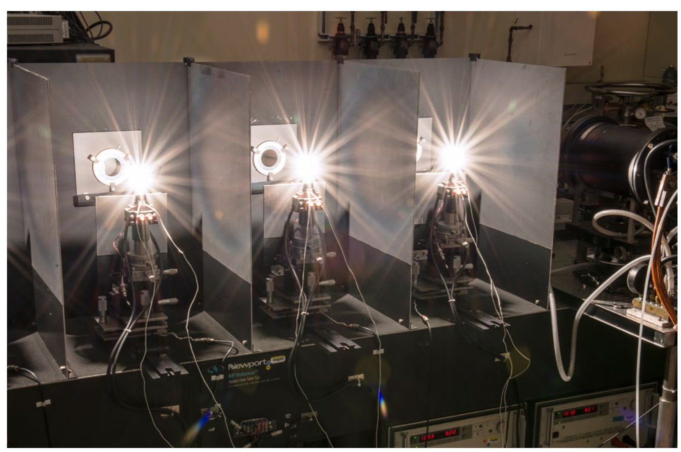
- **Provides NIST-traceable calibrations & reports**
- **Advises on best-practice test procedures & protocols**
- **Responds to unique and/or unusual customer requests**
- **Contributes to quality assurance metrics**

MECHANICAL: Hydrometers; Volume and Density; Flow; Air Speed Instruments; Mass Standards; Force; Vibration; Acoustics

ELECTROMAGNETIC: Resistance; Impedance; Voltage; Precision Ratio; Phase Meters and Standards and VOR; Power and Energy at Low Frequency; RF, Microwave, and Millimeter Wave; EM Field Strength and Antennas; Field Strength Parameters; High-Speed Repetitive Wave Forms; Pulse Waveforms

OPTICAL RADIATION: Photometric; Optical Properties of Materials; Surface Color and Appearance; Spectroradiometric; Detector Calibrations in EUV; High-Frequency Optical Detectors; Lasers and Optoelectronic Components

THERMODYNAMIC: Pressure; Vacuum; Temperature; Humidity; Thermal Resistance



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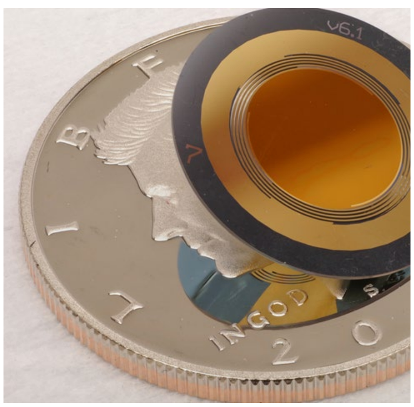
NIST ON A CHIP

The NIST on a Chip program (NOAC) will develop practical quantum-based standards and sensors—often miniaturized to chip scale or smaller—that are traceable to the newly redefined International System of Units (SI). They will be:

- **DEPLOYABLE,** where customers need them, on the factory floor, embedded into products, in laboratories, in space ,or at home;
- **FLEXIBLE,** providing a broad range of "zero chain" SI-traceable measurements and standards that are configurable into a single small-form package and adaptable to customers' requirements;

Many users in industry, government, medicine, defense, and standards labs now ship their often delicate and expensive instruments to NIST for calibration and testing against U.S. national standards. That establishes a chain of traceability, promoting user confidence. NOAC aims to bring that kind of confidence directly to the user's own site.

Eventually, a single chip-scale package will be able to measure multiple quantities: A time and frequency tool might also serve as a length scale, mounted next to a magnetic-field sensor that sits atop a quantum-based thermometer.

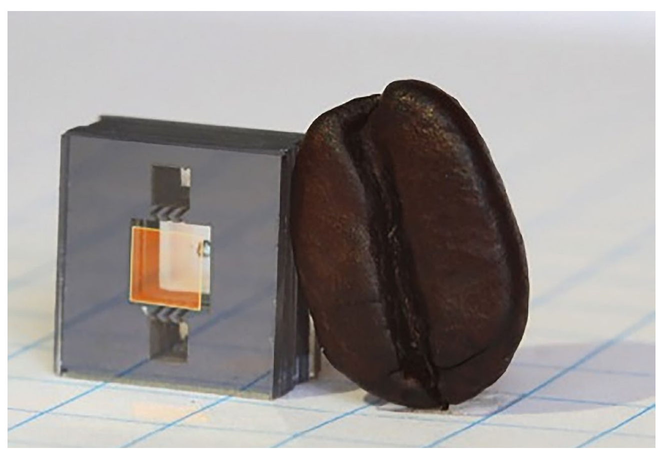


IMPACTS

- Provides chip-scale, often quantum-based technology for precision measurement traceable to the SI
- Enables users to calibrate sensors on the factory floor without having to send devices to a laboratory
- Results in more flexible and efficient manufacturing

- **MANUFACTURABLE,** with production costs that scale appropriately for applications;
- **RELIABLE,** providing either the exact value of a measurement or no value at all; and
- **FIT-TO-FUNCTION,** miniaturized with low power consumption, rugged, easily integrated and utilized, with an operating range and uncertainty required by the application.

Most NOAC designs can be produced with the same silicon platforms and fabrication processes already used to make integrated circuits and microelectromechanical systems (MEMS), potentially resulting in devices that are inexpensive, robust, and small enough to be readily incorporated into new or existing equipment.



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MICROSYSTEMS AND NANOTECHNOLOGY DIVISION

Historical advances in precision control of materials, devices, and information have led to multiple revolutions in science, technology, and industry. New measurement science has preceded each step: *If we can measure it, we can make it*. Nanoscale measurements enable fabrication of diverse nanotechnologies, creation of devices to manipulate photons, phonons, and plasmons at the quantum limit, and probing of the structures and functions of atoms, (bio)molecules, and particles. All of these require new approaches. The Division develops measurement science and technology to advance the state-of-the-art nanofabrication and nanomanufacturing by top-down, bottom-up, and hybrid approaches, and applies these novel capabilities to make innovative, integrated microsystems for critical applications.

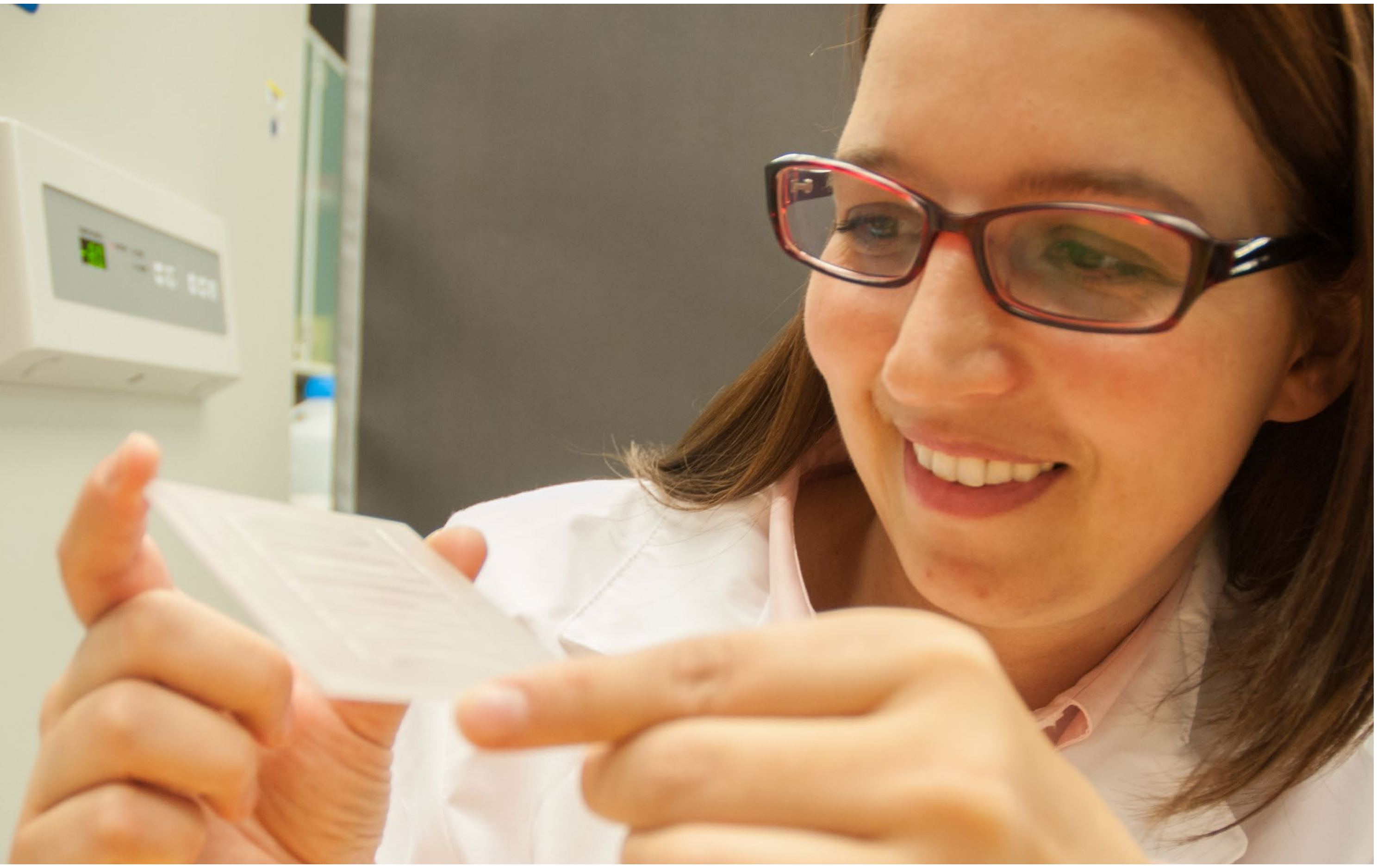
IMPACTS

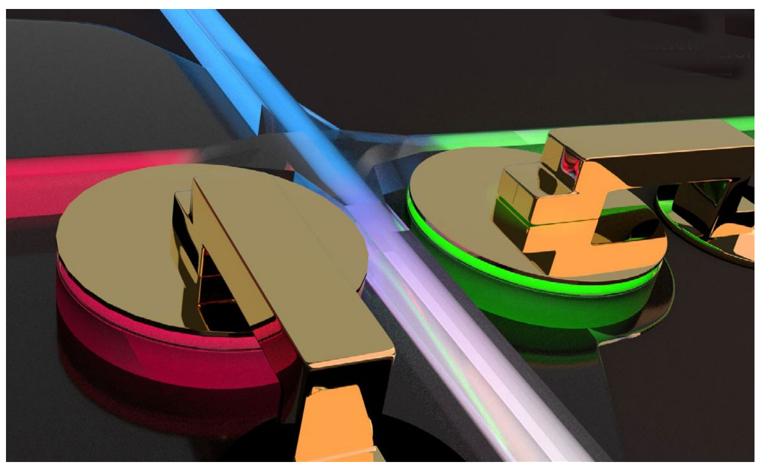
- Advanced fabrication for and by nanoscale measurement
- World-leading, field-deployable sensitivity via micro-fabricated optomechanical sensors
- Photonic devices to control quantum emitters for quantum information science
- Metamaterials for next-gen microprocessors, data centers, telecom, AI and IoT
- Manufacturable microsystems for precision medicine, biotechnology, and biological research

FABRICATION AND MEASUREMENT exist in a synergistic relationship in which more precisely fabricated devices enable improvements in measurement science, which in turn enable ever more precise fabrication. Particle beams, scanning probes, microscopy methods, and manufacturing processes are essential to developing microsystems and nanotechnologies in diverse physical domains including photonic, mechanical, biomolecular, and fluidic. Programs include approaches toward atomic-scale precision and accuracy in lithography and microscopy; fabrication and measurement of nanostructures in three dimensions; modeling to understand and predict fabrication and measurement processes; and realization of practical systems with high efficiency and performance.

PHOTONICS AND OPTOMECHANICS combine to provide arbitrary control over classical, quantum optical, and acoustic fields down to the level of single photons and phonons. Nanofabricated structures create photonic/phononic interfaces between systems from trapped atoms to micro- and nanoelectromechanical systems. Programs include development of metasurfaces/materials that shape light uniquely in temporal and spatial domains for new modulation technologies; chip-scale optical frequency combs as references for precision measurements, optical clocks, and quantum sensors; cavity optomechanical sensors to extend field-deployable measurements to the thermodynamic limit of sensitivity for inertial measurement; plasmonic switching for reconfigurable or adaptive photonic networks; and single photon/phonon transduction for quantum information storage, manipulation, and transmission—an enabling technology for future quantum networks.

QUANTITATIVE MEDICINE & BIOLOGY require new measurement tools, analyses, and diagnostics to combat existing and emerging threats to the nation's health. Micro- and nano-scale devices and methods enable physical measurements—of systems ranging from single molecules and particles to cells in complex biological environments—with new levels of accuracy, precision, and efficiency. Programs include the creation of micro-physiological (body-on-a-chip) systems and kinetic cytometry for high-throughput interrogation of single cells to generate representative and statistically meaningful data on disease states and therapeutic efficacy for drug discovery; development of biotic/abiotic interfaces that permit direct electronic measurement of biomolecular and cellular function with high sensitivity and selectivity; and the creation of measurement systems and biological structures for biomarker detection and biomolecular analysis.





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RADIATION PHYSICS DIVISION

Accurate and authoritative measurements of ionizing radiation and radioactivity are vital for a host of critical applications, including life-saving medical procedures, homeland security and public safety, advanced manufacturing and industrial processes, and basic and applied research including quantum information science.

The Radiation Physics Division develops, maintains, and disseminates U.S. primary standards for ionizing radiation metrology, and investigates and applies the fundamental physical interactions of ionizing radiation with a vast array of materials and systems, including advanced technological materials, biological systems, microelectronic components, environmental contaminants, and radiological and nuclear materials.

The Division comprises three technical groups.

THE DOSIMETRY GROUP DEVELOPS standards by realizing the gray and advancing measurement of quantities important to dosimetry of X-rays, gamma rays, electrons, and other charged particles. Applications include diagnostic and therapeutic uses of radiation in medicine, industrial processing of materials, homeland security imaging quality and radiation protection, and public safety.

THE RADIOACTIVITY GROUP ESTABLISHES the necessary standards and metrology infrastructure to enable the realization and dissemination of the becquerel.

IMPACTS

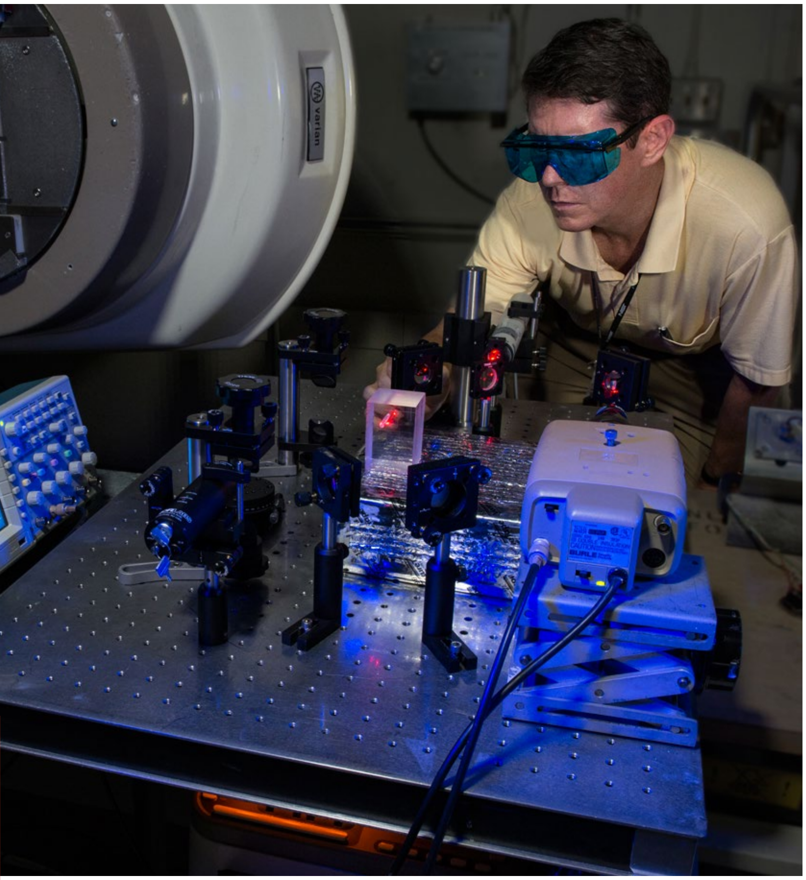
- **Radiation and nuclear applications in health care**
- **Worker protection and assurance for the nuclear energy and radiation industries**
- **The interaction of nuclear radiation with matter**
- **Environmental protection and monitoring**
- **Homeland security and defense applications: detection and countermeasures**
- **Fundamental physics of the neutron and neutron imaging**

In addition to realizing the SI units for absorbed radiation dose (the gray) and radioactivity (the becquerel), the Division conducts research in fundamental neutron physics and interferometry, radiation dosimetry, radionuclide metrology, and radiation imaging technologies.

This work has a dramatic impact on many critically important industrial sectors of the U.S. economy. In medical research and clinical practice, for example, each year the accuracy of nearly 40 million mammograms and 40,000 radiation treatment plans for prostate cancer depend on measurements made by the Radiation Physics Division.

This mission is accomplished through the preparation and distribution of reference materials, the organization of proficiency testing programs, radioactivity calibrations, and basic research. Application areas include diagnostic and therapeutic nuclear medicine, nuclear security, fundamental nuclear science, and environmental monitoring.

THE NEUTRON PHYSICS GROUP PROVIDES measurement services, standards, and fundamental research to support NIST's mission in neutron metrology and physics. The Group maintains and disseminates neutron measurement standards through calibration, technical evaluation, and experimental work. Moreover, the Group maintains and supports NIST's neutron user facility for imaging, interferometry, and fundamental neutron physics.



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NANOSCALE DEVICE CHARACTERIZATION DIVISION

The Division develops and advances measurement science and fundamental knowledge to characterize nano- and atom-scale engineered materials and solid-state devices, enabling innovation in information processing, sensing, and future quantum technologies.

Those activities provide fundamental support for breakthroughs in a wide range of areas, including nanoscale optical spectroscopy and imaging, nanoscale electron physics, future semiconductor devices and their integration in more complex systems, alternative computing, and fabrication and characterization of solid-state atom-scale devices. Research in the Division has a number of focus areas, including those listed below.

MEASUREMENT PROBLEMS IN ALTERNATIVE COMPUTING, especially neuromorphic computing and AI, are being addressed, especially neuromorphic computing and AI, by investigating new devices for analog and stochastic computing and exploring new architectures and algorithms, both theoretically and in medium-scale integrated prototypes.

This effort focuses on designing, fabricating, and characterizing hybrid circuit test platforms and disseminating them to researchers in industry and academia to enable more efficient validation of device and circuit properties at increasingly greater complexity and scale.

IMPACTS

- **World class microscopy: micro-eV tunneling resolution in an in-operando STM, AFM, and Magneto-transport System for Quantum Materials Research**
- **U.S. leadership in atom-scale device fabrication: single-atom transistor arrays with atom-scale control over the devices' geometry**
- **Graphene-based quantum engineered systems: first creation and imaging of coupled quantum dots (islands of confined electric charge that act like interacting artificial atoms) in graphene**

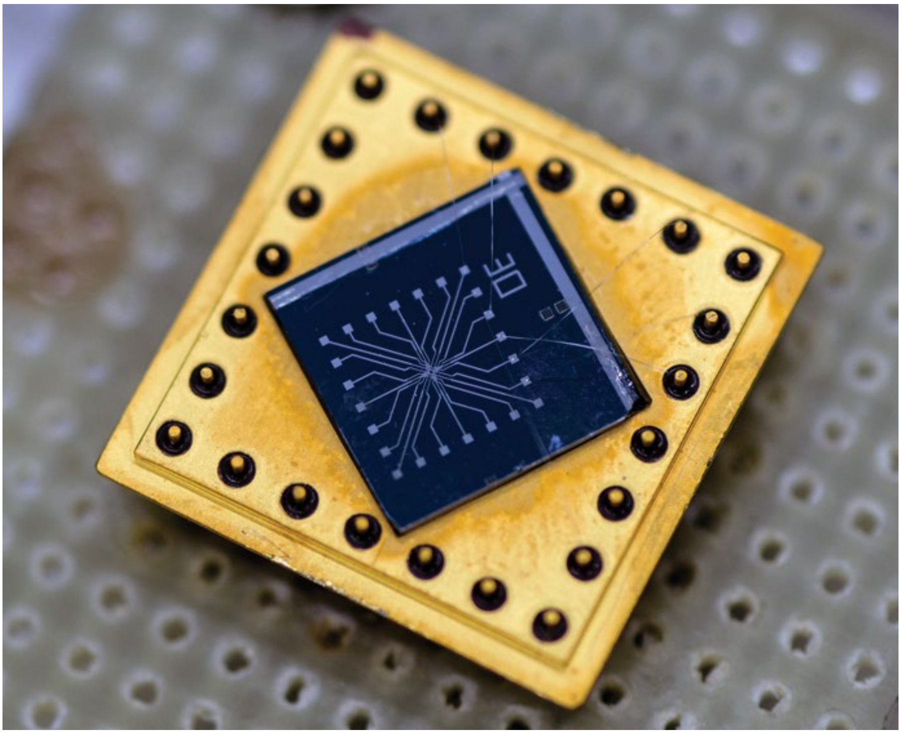
WORLD CLASS ELECTRICAL AND OPTICAL MICROSCOPY PROVIDES provide "local" measurements that characterize nanoengineered solid-state materials and devices as a function of temperature, electrical bias, optical stimulus, or applied magnetic field to reveal the fundamental physical properties and processes that underpin emergent quantum behavior. Advances in nanoscale microscopy instrumentation complement innovative precision electrical and optical spectroscopic measurements, methodology, and test structure design and fabrication.

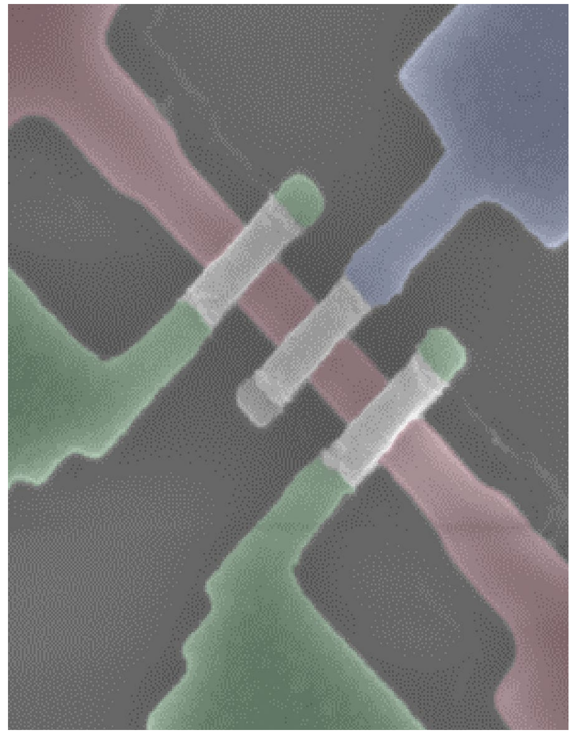
ADVANCED MICROELECTRONICS can minimize the measurement gaps hindering heterogeneous integration of emerging electronic and photonic materials and devices with aggressively scaled silicon CMOS. Innovations in measurements to assure authenticity and reliability of materials, devices, and systems are essential to ensure continued gains in performance and the creation of more complex and specialized functions in the face of revolutionary challenges to CMOS scaling.

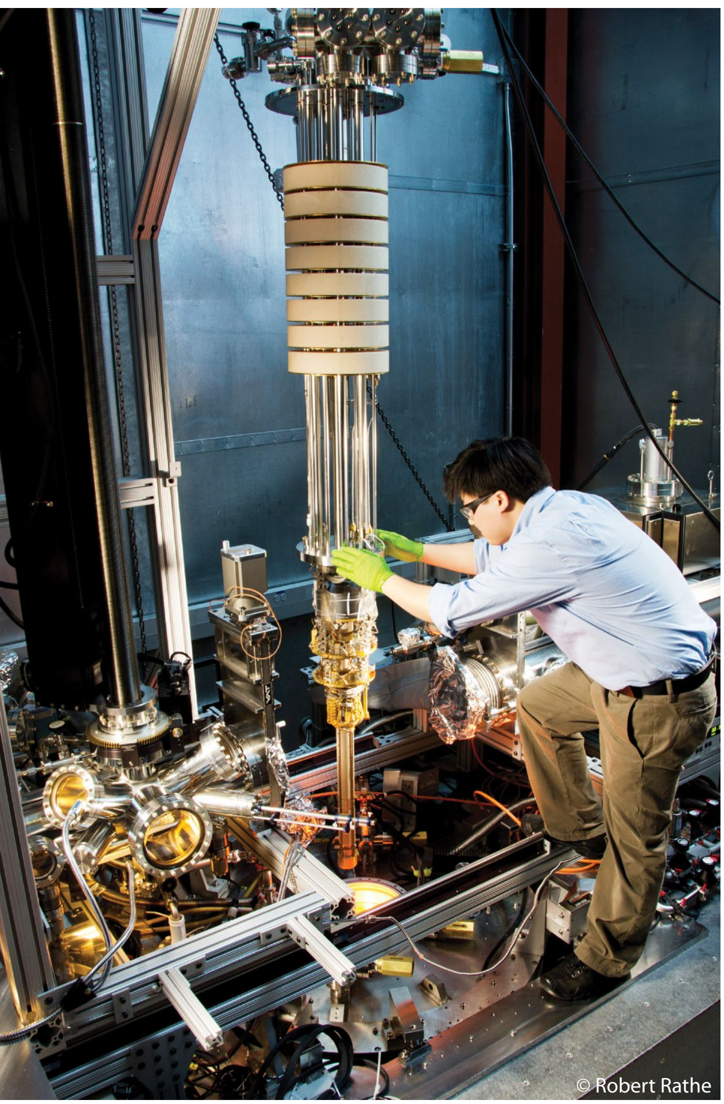
ATOM-SCALE DEVICES develop the foundational knowledge, measurements, and fabrication methods needed to enable nanoengineering of solid-state devices and systems that will lead to new, unexplored emergent quantum behavior.

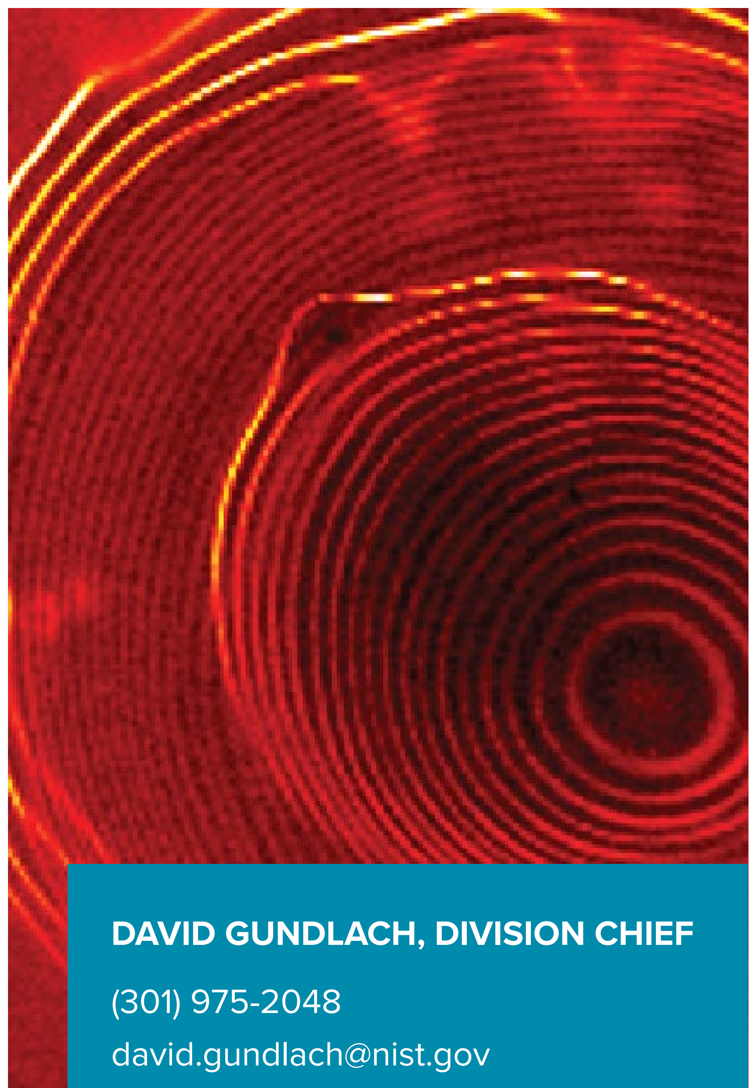
This effort is pushing electronic and quantum devices and sensors to their fundamental operation limits with single electrons and spins on deterministically placed atoms. These devices will be critical for realizing chip-scale quantum information processing, quantum simulators, and field-deployable quantum electrical standards.

STANDARDS DEVELOPMENT involves engaging in international standards development where rigor in measurement methodology, data analysis, and data reporting facilitate a robust consensus-based standards-creation process.









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nist.gov/pml/nanoscale-device
characterization-division

QUANTUM MEASUREMENT DIVISION

In the 21st Century, world-class metrology demands highly accurate measurements of properties on scales ranging from millions of kilograms to single photons and electron spins.

This Division performs basic electrical, mass, and force calibrations, and applies quantum physics research methods to achieve fundamental advances in metrology. The Division has been heavily engaged with the international community in both proposing and contributing to the 2019 redefinition of the International System of Units. In particular, the Division's design and fabrication of a state-of-the-art Kibble balance was essential to the redefining the kilogram.

NEW FRONTIERS. Division researchers are developing new quantum-based electrical standards. Novel graphene-based quantum Hall resistance standards are being transferred to industry, primary calibration laboratories, and national metrology institutes. An electric power standard known as the "quantum watt" is being developed to provide NIST measurement services for power and energy meters.

At the same time, the Division is at work integrating the Kibble balance with measurement services to disseminate mass values based on the new Quantum SI (QSI) to U.S. calibration laboratories. Techniques and technologies that facilitate this transformation include a Magnetic Suspension Mass Comparator and a tabletop version of the Kibble balance.

IMPACTS

- **Plasma modeling, atomic spectroscopy and data to support U.S. industry andresearch, including the search for extraterrestrial planets**
- **Quantum processes and metrology that includes quantum optics, laser cooling and trapping, ultra-cold atoms and molecules, quantum simulations, modeling of quantum systems, single-photon sources and non-classical light, and precision measurements**
- **Quantum-based mass and electrical standards to support the new QSI**

Some focus areas of the Division are:

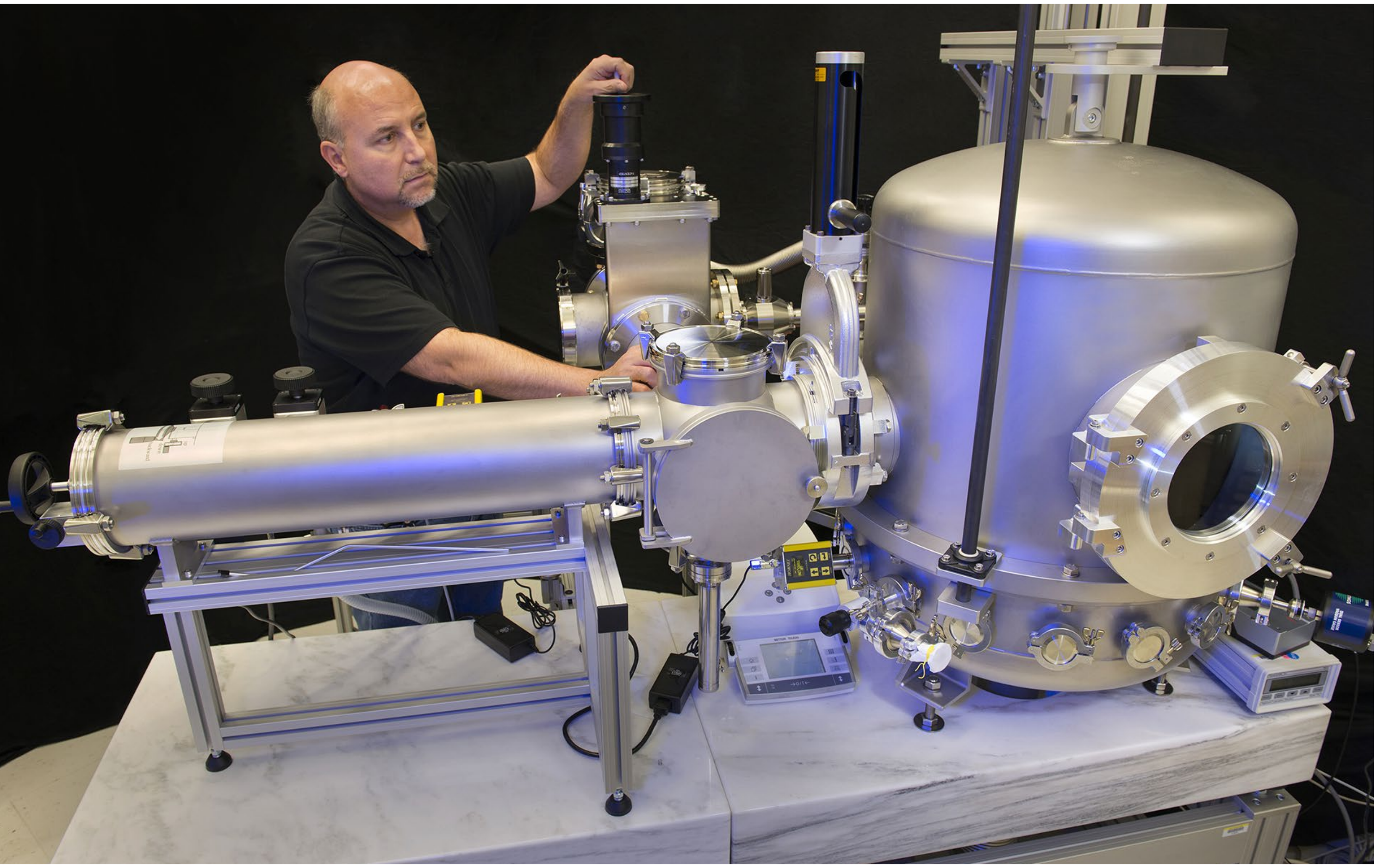
QUANTUM CONTROL. The ability to understand and manipulate objects at the quantum level is among the most urgent goals of modern science. The Division develops quantum measurement techniques and investigates quantum phenomena to better understand the many-body physics that governs behavior of semiconductors and superconductors, and quantum information.

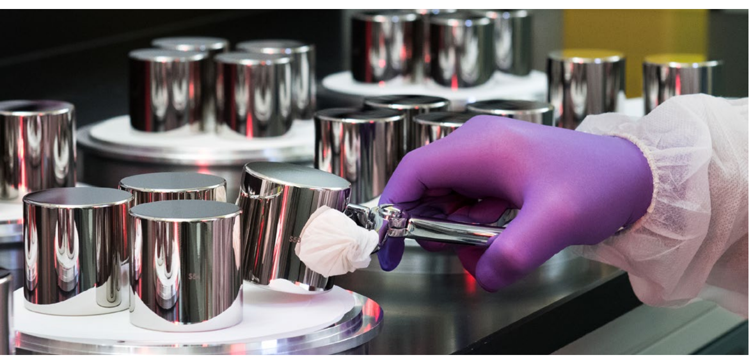
Ultracold atoms are used to perform quantum simulations to study the physics of solid materials where control and measurement of individual atoms and molecules are far more difficult, if not impossible, to do. Groundbreaking experiments have achieved quantum interference of photons from different sources. This basic knowledge and the techniques developed to quantify it are crucial for the development of improved time standards, quantum computers of unprecedented power, and quantum communication technologies.

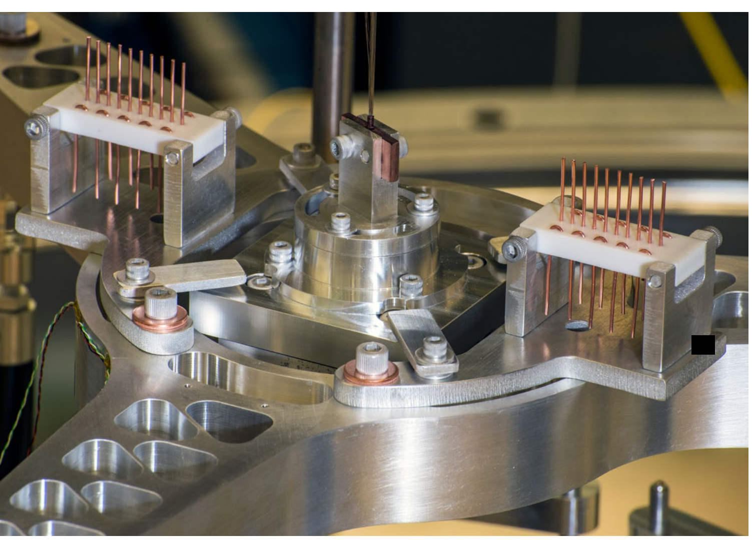
DATA RESOURCES. Exploration of fundamental aspects of the quantum nature of light and matter – and development of quantum metrology to support the QSI—result in both advanced measurement services and authoritative, critically-evaluated reference data on atomic properties and fundamental constants disseminated through a searchable database.

Part of that work is associated with the Division's Fundamental Constants Data Center which determines the best values of the fundamental constants based on the latest measurements and contributes directly to improving international standards through the Committee on Data for Science and Technology (CODATA) and other organizations.

The Division also provides metrology for the "Smart Grid" program to improve America's electric power distribution system.







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SENSOR SCIENCE DIVISION

The explosion of highly sophisticated sensor and imaging technology in recent years has enabled dramatic advancements in personal safety, medical diagnosis and treatment, lighting efficiency, temperature measurement, precision manufacturing, environmental monitoring, and space sciences, to cite a few examples.

The Division supports U.S. industry and technology research dependent on accurate and comparable measurements of length, optical radiation, surface properties, temperature, humidity, pressure, vacuum, flow, and related phenomena. Success is highly dependent on close collaboration with industry, universities, other Federal agencies, and standards development organizations. Our goals are to:

IMPROVE AND ADVANCE THE STATE OF THE ART IN MEASUREMENT SCIENCE through leading research in many fields including photometry and vision science, fluid flow, optical scattering from surfaces, infrared technology, process measurement, optical properties of materials and surfaces, medical imaging, and ultraviolet and extreme ultraviolet radiation measurement. For example, recent Division research in picometer optical interferometry to accurately determine the refractive index of gases will fundamentally change the methods for realizing and disseminating the SI units of pressure, temperature, and length, while research on applications of cold-atom traps is allowing the realization of the first absolute standard for the measurement of extreme levels of vacuum.

IMPACTS

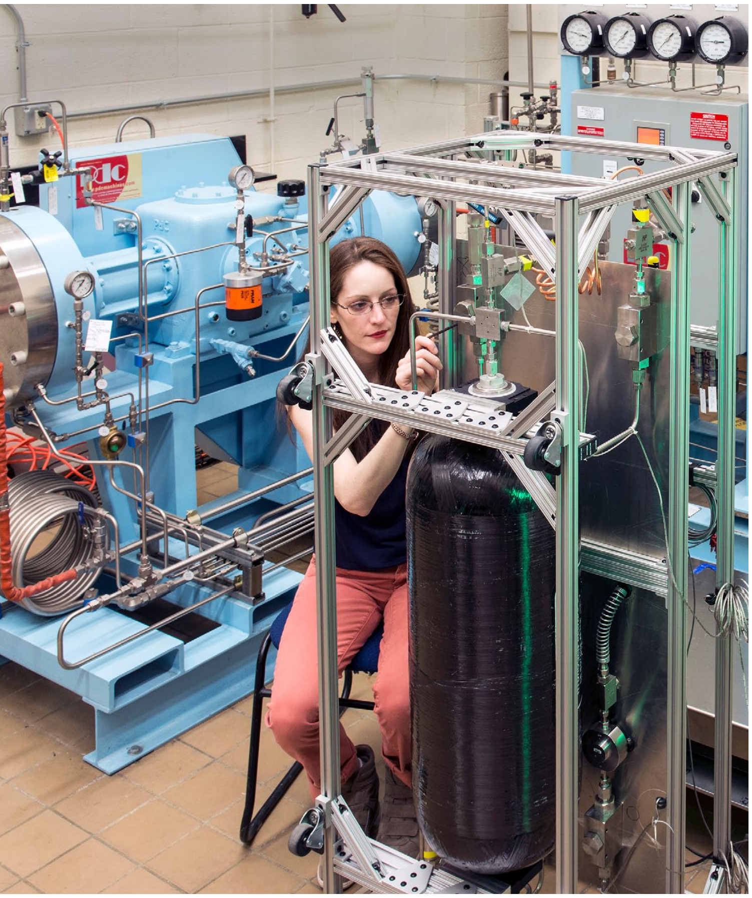
- **Metrology and measurement services for the transition from incandescent and fluorescent to solid-state lighting**
- **Infrastructure for process plant operations and energy commerce**
- **Standards and measurement methods for establishing the accuracy and international comparability of U.S. ground and space-based environmental measurements**

DEVELOP AND MAINTAIN STANDARDS and the necessary physical and knowledge infrastructure for three of the seven SI units: the kelvin (temperature), the meter (length), and the candela (luminous intensity). The Division participates in national and international committees, standards development organizations, and measurement intercomparisons to ensure acceptance of U.S. measurements world-wide. The Division also enters into formal research and development agreements with government and industry partners to collaborate on the development of measurement standards.

DISSEMINATE SI UNITS AND NATIONAL SCALES by way of dimensional, mechanical, optical radiation, and thermodynamic measurement services and through the provision of reference standards and reference data. Services are continually evolving in order to provide the measurements and uncertainties needed to support U.S. innovation and industrial competitiveness.

Advanced measurement protocols, models and novel measurement techniques are shared through participation in international metrology and standards-related activities, training, education, and outreach.

DEVELOP AND MAINTAIN UNIQUE FACILITIES for testing extreme ultraviolet optics, detectors, and photoresists; calibrating optical and infrared sensors; providing precision dimensional measurements; advancing chip-scale sensors for the measurement of thermodynamic variables; testing sensors for measuring smokestack flows; advancing firearm forensics measurement science; and characterizing optical materials and light sources. Key facilities maintained by the Division include the Synchrotron Ultraviolet Radiation Facility (SURF III), the Low Background Infrared Facility (LBIR), and the Horizontal Smoke Stack Simulator.



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APPLIED PHYSICS DIVISION

The Applied Physics Division uses its expertise in radiometry, advanced communications, sensing, spectroscopy, quantitative imaging, and quantum measurements to work with academia, industry, and other government agencies to maximize the impact of its research in the United States and abroad.

OPTICAL POWER MEASUREMENTS—This work provides the optoelectronics industry with traceability to national standards. It involves measuring laser, detector, and component properties such as laser power, laser beam profile, detector spectral responsivity, detector linearity, and the attenuation of transmission components. That enhances the ability of industry to reliably utilize lasers in photovoltaic manufacturing, laser welding, and more.

TERAHERTZ IMAGING RESEARCH—Imaging in the terahertz frequency range enables detection of concealed contraband, such as explosives under clothing, without the use of ionizing radiation. The Division's unique capabilities in this frequency range also result in contributions to industrial processing and remote identification of chemicals.

OPTICAL FREQUENCY COMBS RESEARCH—Groundbreaking research has led to high-precision spectral, temporal, and spatial measurement tools for gas monitoring, three-dimensional length metrology, and more. Highly accurate measurements of frequencies are also essential for many other advanced applications, such as detection of toxic biochemical agents, studies of ultrafast dynamics, and quantum computing.

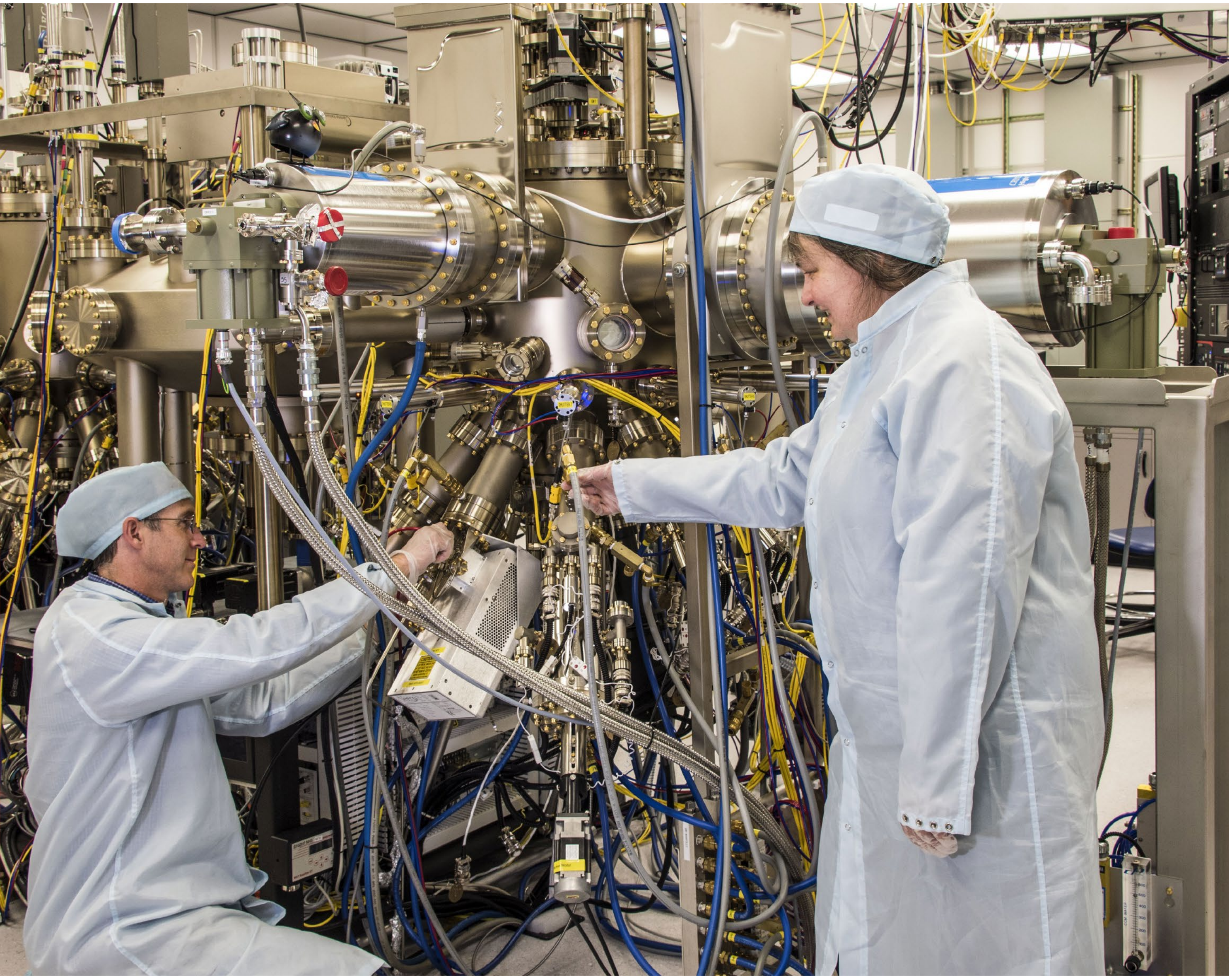
IMPACTS

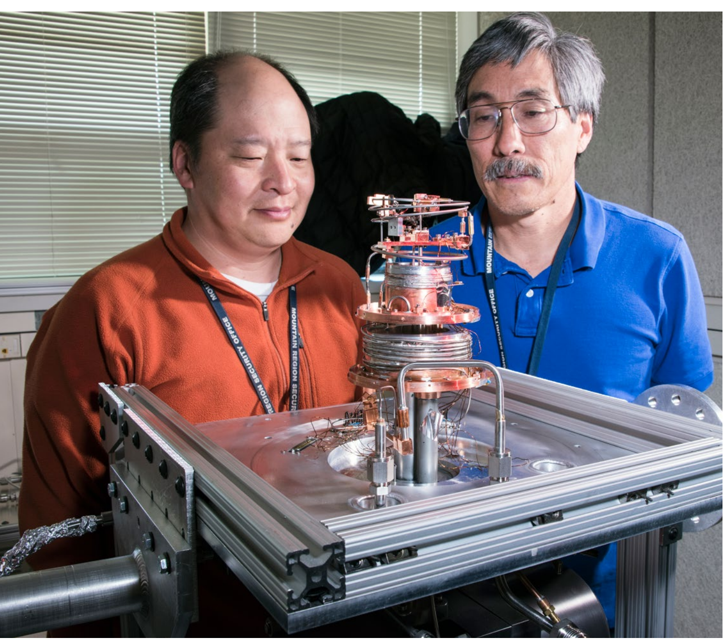
- **Time transfer with optical frequency combs enables precise clock comparison, toward better space clocks**
- **Laser power measurements revolutionized by connecting to photon momentum**
- **Highest-performance camera ever composed of sensors that count single photons**
- **Brightest GaN nanowire LED may enable better display technologies and atom-scale sensing**

QUANTUM INFORMATION—From complex superconducting circuits to state-of-the-art single-photon detectors and sources, this work is foundational to quantum information and quantum networking. Entangled photon sources lead to the generation of novel states of light with which to perform key tests of quantum mechanics and create truly random numbers in support of industry and cryptography.

MAGNETIC IMAGING—NIST develops calibration methods, standards, and contrast agents for magnetic imaging technologies to enable highly accurate images for diagnosis and treatment decisions. The U.S. healthcare industry benefits from advancing and validating quantitative bio-magnetic imaging methods, including shape-shifting biomedical probes, smart contrast agents, ultra low field MRI, and SI-traceable calibrations of MRI- based bio-markers.

QUANTITATIVE NANOSTRUCTURE CHARACTERIZATION—Nanostructures are a critical component of innovations in high-performance computing, electronics, energy conservation, renewable energy, biomedical research, and health care. We develop and demonstrate metrology techniques to address nanoscale measurement challenges. These techniques include scanning microwave microscopy, atom probe tomography, transmission electron microscopy, Raman spectroscopy, and time-resolved photoluminescence. Our goal is to push these methods beyond comparative measurements by evaluating absolute uncertainties and systematic errors.





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nist.gov/pml/applied-physics-division

QUANTUM ELECTROMAGNETICS DIVISION

Harnessing the electromagnetic spectrum—from direct current and voltage through fields in the gigahertz, microwave, and terahertz ranges to X-rays and gamma rays—enables a wide range of present and future applications that are critical to economic and scientific advancement.

The Division utilizes quantum-mechanical, electronic, magnetic, and photonic properties of materials and their interaction with electromagnetic waves to develop high-precision measurement tools, methods, and devices for quantum-based electrical standards, energy-efficient spintronic devices, and high-resolution photon sensors for imaging and spectroscopy. Major focus areas are hardware for artificial intelligence, superconducting quantum information, and hyper-dimensional imaging.

DEVELOPS AND COLLABORATIVELY DISSEMINATES THE DC AND AC QUANTUM VOLTAGE STANDARDS that underpin measurements worldwide. Creates high-bandwidth signal generation techniques and instrumentation to characterize future communications systems and reduce spectrum crunch.

CONDUCTS APPLIED RESEARCH, FABRICATION, AND BENCHMARK TESTING of scalable, coupled quantum bits (qubits), resonators, ultra-low-noise amplifiers, and hybridized qubit and control circuitry for future large-scale, high-coherence, high-fidelity superconducting quantum computing. Develops quantum-based waveform synthesizers for self-calibrated control and readout.

IMPACTS

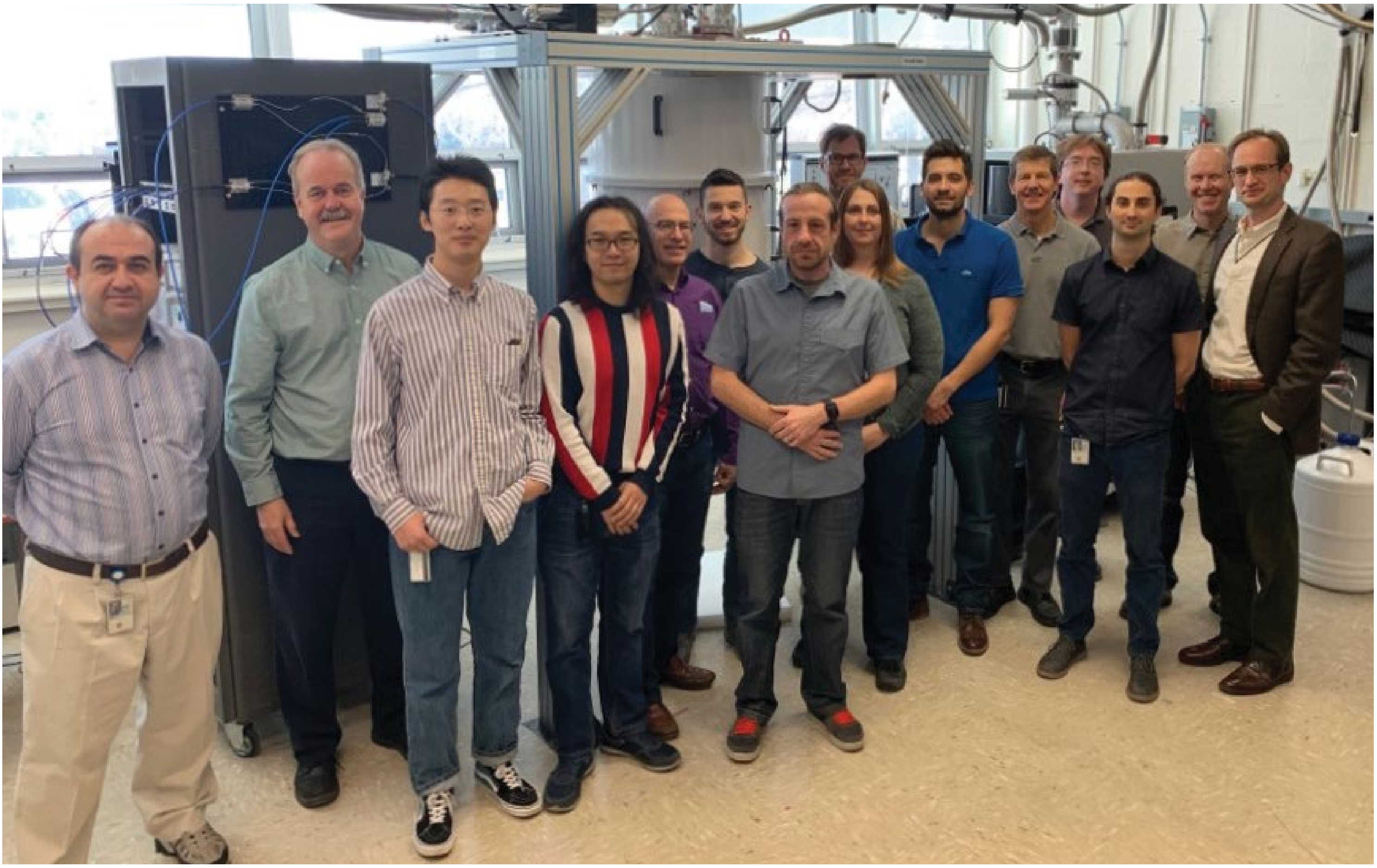
- **Transfer of quantum-based voltage standards advances military and industry metrology**
- **X-ray sensors aid high-resolution material spectrometry and tomography for circuit security**
- **Electric-field noise reduction in ion traps greatly improves quantum computing capability**
- **Magnetic/superconductive neuromorphic hardware supports artificial intelligence**
- **Measurement of ultrafast dynamics in magnetic materials enhances computer memory**

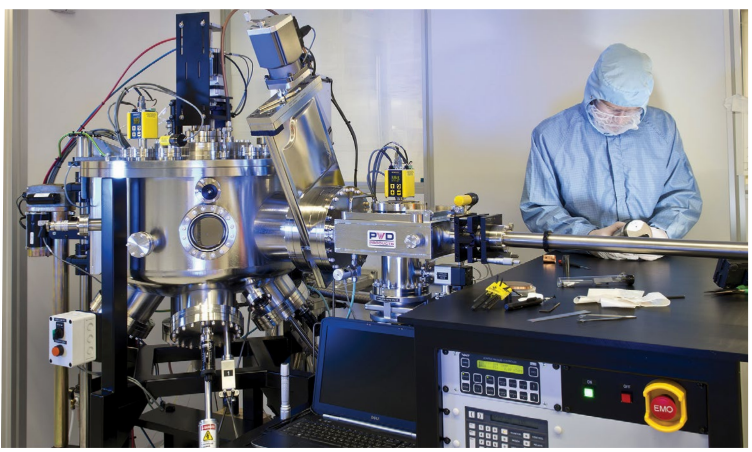
Innovations in metrology and micro- and nano-fabrication (and the rapid feedback between them provided by the fab-to-lab-to-fab cycle) propel critical advances in high-performance superconducting electronics, digital logic, data storage, materials development, quantum processing and engineering, nuclear forensics, and astronomical observations, as well as a deeper understanding of fundamental physics. Among a range of activities, the Division:

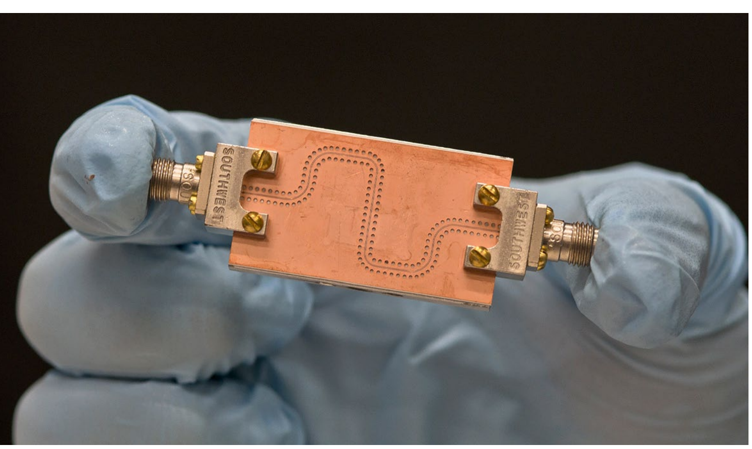
OPERATES THE STATE-OF-THE-ART BOULDER MICROFABRICATION FACILITY for chip-based quantum standards, sensors, integrated photonic circuits, and nanomagnetic devices. The 1,700 m^2 ISO 5 (class-100) cleanroom provides state-of-the-art micro- and nano-fabrication capabilities particularly for NIST-Boulder researchers. Capabilities include: a full lithography suite, providing electron-beam lithography; deposition tools (evaporation, sputtering, chemical-vapor deposition, and molecular-beam epitaxy); reactive-ion etch tools, and chemical-mechanical polishing.

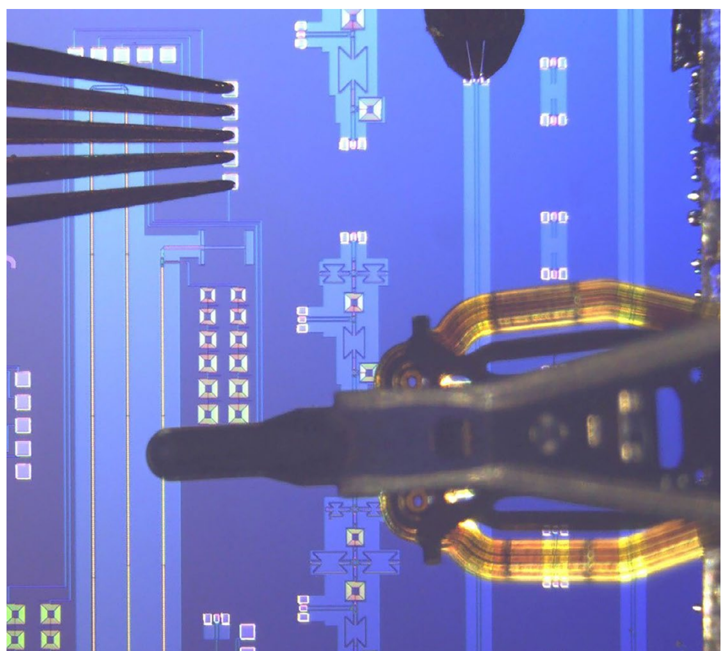
INNOVATES IN SPIN ELECTRONICS AND NANOSCALE SPIN DYNAMICS RESEARCH, developing and measuring materials, devices, and scalable systems to accelerate progress toward dramatically higher-speed and lower-power electronics, information storage, and brain-inspired computing required by future industries and consumers.

FABRICATES BEST-IN-CLASS, ULTRA-SENSITIVE, SUPERCONDUCTING DETECTOR ARRAYS used in ultra-high-resolution spectrometers for advanced materials analysis, microelectronics security, defect identification in integrated circuits, X-ray fundamental line metrology, nuclear nonproliferation applications, and cosmology. The Division develops amplifiers with near-quantum-limited low noise and microwave multiplexers for high-rate readout of superconducting sensors and quantum information processing. It advances the science of cryogenics to enable refrigeration systems for quantum electronics with reduced size, weight, power, and/or cost for sensing, communications, and computing.









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TIME AND FREQUENCY DIVISION

Much of the world's modern technology infrastructure relies on exquisitely precise timing and synchronization, from the Global Positioning System to telecommunications and data networks to electric power generation and distribution. The Division provides official U.S. standards for time and frequency measurements and related quantities. These measurements trace back to the laser-cooled NIST cesium fountain atomic clock, one of the world's most accurate measuring devices of any kind.

The Division provides official time to the United States and is the source of the nation's contribution to Coordinated Universal Time. In addition, the Division distributes numerous time and related measurements customized for different customer needs.

NIST'S YTTERBIUM OPTICAL LATTICE CLOCK achieves a nearly 100-fold improvement in validated accuracy over the cesium clocks currently used to define the second, making it one of the leading candidates for a future redefinition of the second.

NIST'S ALUMINUM ION QUANTUM LOGIC CLOCK demonstrates exceptional accuracy and is a pioneer in the use of quantum information techniques to enable and enhance metrology. It is another leading candidate for the coming redefinition of the SI second and a powerful tool for exploring open questions in fundamental physics and cosmology.

IMPACTS

- **The free Internet Time Service automatically synchronizes clocks in computers and network devices tens of billions of times every day and is built into most computer operating systems.**
- **Special time code radio stations, including radio station WWVB, synchronize many millions of radio-controlled clocks and watches to official NIST time.**
- **Researchers perform cutting-edge research in the measurement of time and frequency, expanding basic knowledge and measurement capabilities for stakeholders around the world.**

QUANTUM INFORMATION PROCESSING WITH TRAPPED IONS continuously demonstrates pioneering achievements in quantum information processing with trapped ions for over 25 years, amassing a long list of "firsts" and "bests."

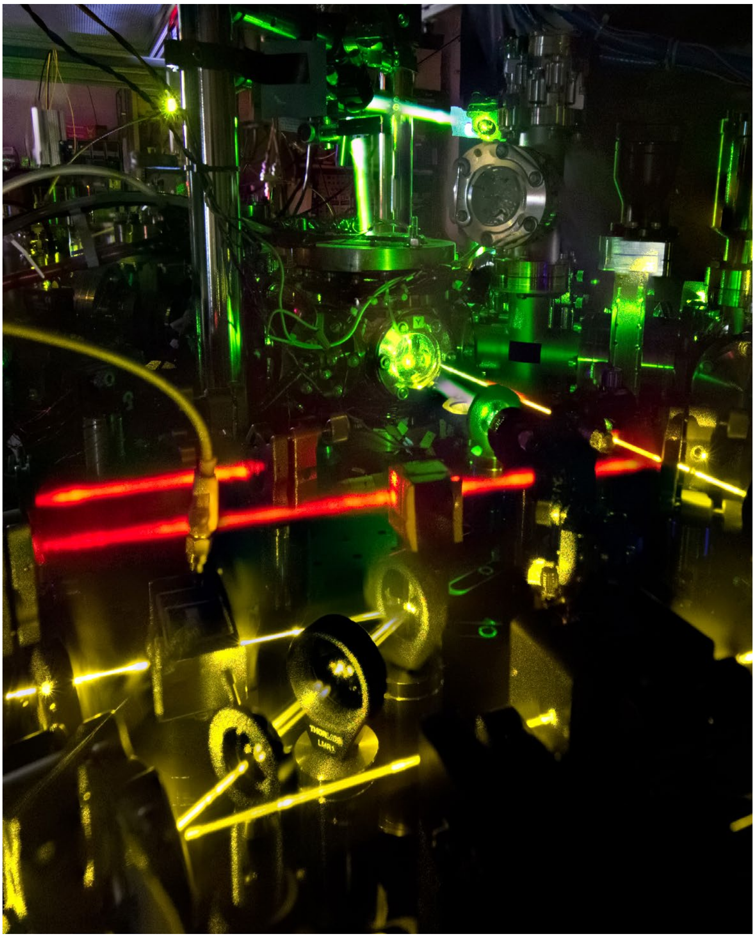
QUANTUM CONTROL OF SINGLE MOLECULAR IONS applies and adapts the quantum information toolbox developed for atomic ions to single molecular ions. With more complicated internal structure compared to atoms, molecules present both experimental challenges and great opportunities for exploring new physics.

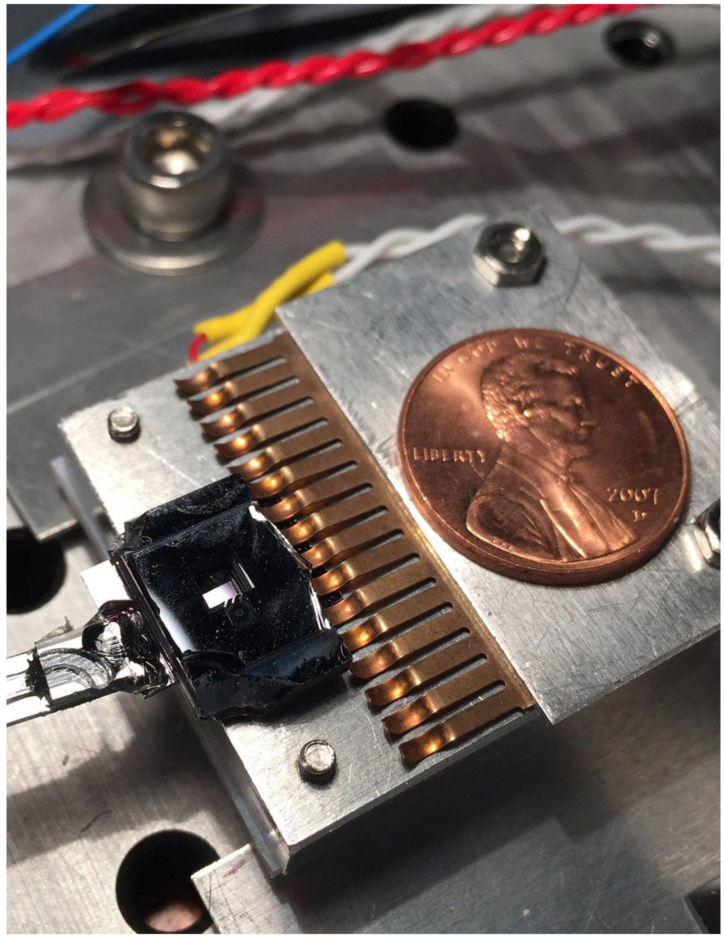
QUANTUM SIMULATION AND SENSING WITH LARGE TRAPPED-ION CRYSTALS pursue Feynman's vision of using a well-controlled and measurable quantum system to emulate and study quantum many body systems that are not understood and cannot be straightforwardly simulated on a conventional computer.

CHIP-SCALE WAVELENGTH REFERENCES AND CLOCKS explore new methods for integrating chip-scale photonics with atomic systems for creating compact, low-power devices for precision metrology, atomic devices for precision measurement of time, magnetic field, acceleration, and a broad range of other applications.

OPTICAL FREQUENCY COMBS support the world's most precise atomic clocks and enable the accurate transfer of phase and frequency information from the microwave to the optical domain to enable the characterization of developing optical atomic clocks against the current definition of the SI second.

MICRORESONATOR DEVICE RESEARCH develops microcombs, integrated reference cavities, and low-noise laser sources. The goal is to understand the fundamental and technical aspects for implementing precision time and frequency metrology in chip-scale devices.





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nist.gov/pml/time-and-frequency-division

QUANTUM PHYSICS DIVISION

This Division is the NIST part of JILA, the joint research institute of NIST and the University of Colorado, Boulder. JILA develops fundamental measurement-science tools and technologies, and trains future generations of scientists and innovators. Division researchers explore some of today's most challenging and fundamental scientific questions about the ultimate limits of quantum measurements and technologies. Understanding the quantum physics underlying the interactions of light and matter is central to the Division's work, and this is then utilized for research applications in physics, chemistry, and biology. Being based on a university campus enables a research environment well-suited to quantum workforce development.

PRECISION MEASUREMENT is central to all the Division's research, from fundamental explorations that seek to reveal new physics not predicted in established physical models of the universe, to investigations that bridge gaps between physics, chemistry, and biology by providing descriptions of important chemical and biological processes at their most basic physical levels.

Flagship research efforts include the development of record-breaking optical clocks based on ultra-cold atoms in optical lattices, and a program to search for symmetry violations centered on precision measurements of the electric dipole moment (EDM) of the electron using exotic trapped molecular ions species.

IMPACTS

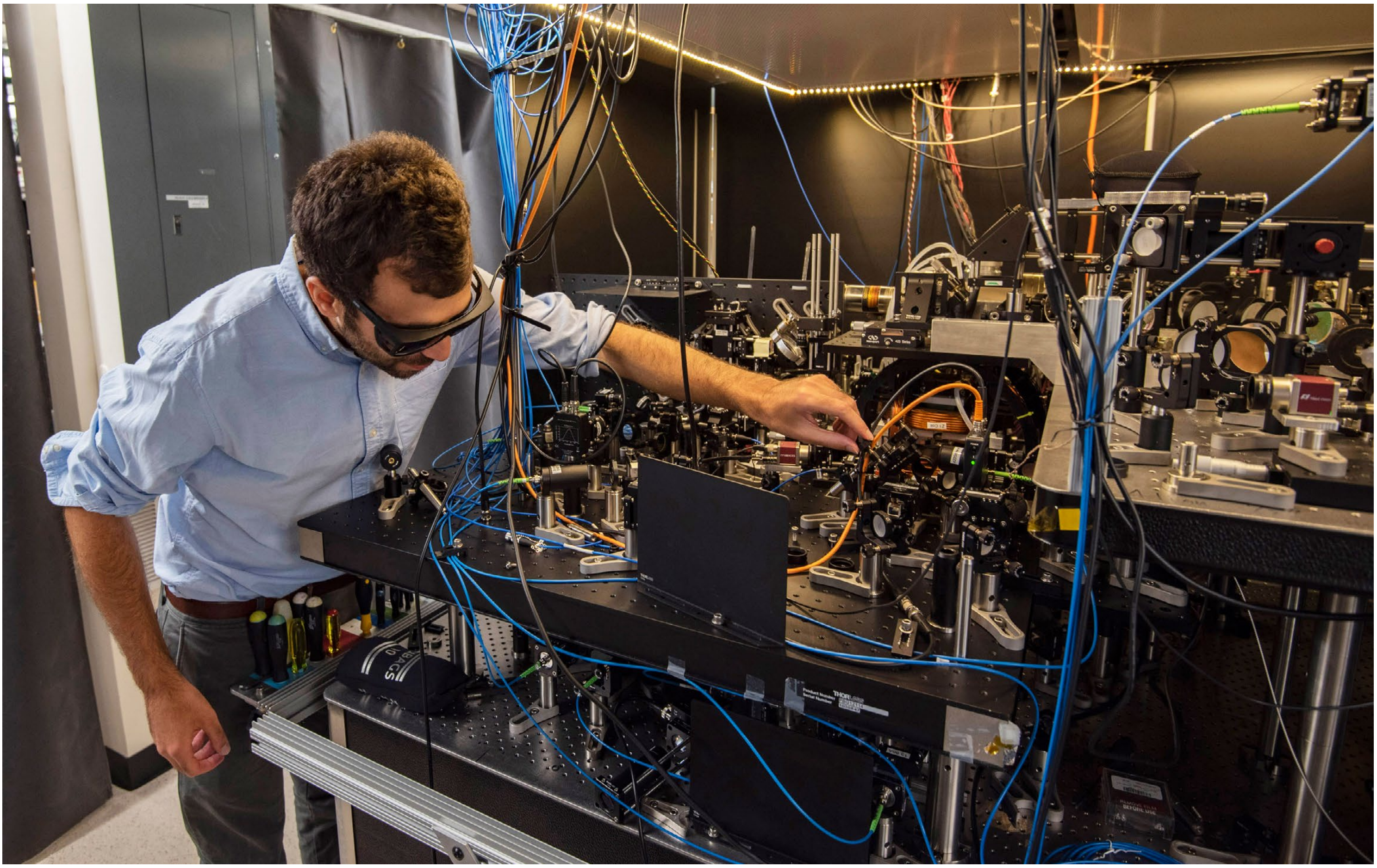
- Record-setting accuracy for atomic clocks
- World's first Bose-Einstein condensate & quantum-degenerate Fermi gas
- Understanding and controlling complex quantum systems
- Extending quantum measurement techniques to nanoscience, chemistry & biology
- Developing a highly skilled workforce for the growing quantum economy

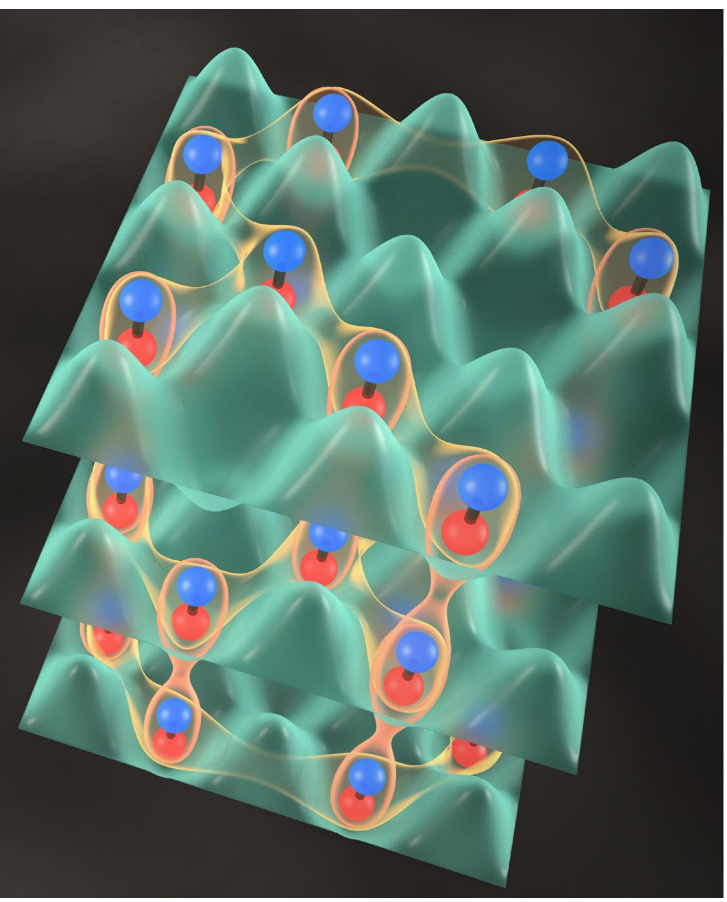
Quantum Physics Division Research spans multiple focus areas.

QUANTUM INFORMATION SCIENCE (QIS) seeks to utilize the quantum properties of light and matter, such as squeezed and entangled states, for applications ranging from quantum-enhanced sensing to quantum information processing and simulation. Leveraging the Division's strong background in laser cooling, atom trapping, and ultra-stable lasers, to understand and control complex quantum systems, drives advances in quantum metrology and the development of new tools for quantum networking and computing. Complementary to the Division's atomic physics efforts in QIS is a major research effort on micro-fabricated electrical and electromechanical devices that are engineered to operate in regimes where quantum-mechanical properties dominate.

ATOMIC & MOLECULAR research focuses on the study of the properties, behavior, and interactions of cold and ultra-cold atoms and molecules. Manipulating single atoms and controlling the interactions between them enables studies of quantum many-body physics and quantum control of molecule formation and chemical reactions.

CHEMICAL & BIOPHYSICS research adapts and applies measurement tools and concepts from physics to understanding the properties of elementary chemical, nanostructured, and biological systems. Research includes single biological molecules and applications of ultrastable atomic force microscopes, ultrafast and quantum-optical spectroscopy of complex molecules, and fundamental studies of the kinetics and dynamics of chemical and biophysical properties.





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THE OFFICE OF WEIGHTS AND MEASURES

This office ensures traceability of state weights and measures standards to the International System of Units (SI), develops procedures for legal metrology tests and inspections, provides technical guidance and online tools to facilitate the implementation and use of the SI, and conducts training for laboratory metrologists and weights and measures officials.

The Office of Weights and Measures (OWM) provides guidance on laws and regulations adopted by the National Conference on Weights and Measures (which promulgates uniform standards across states and other jurisdictions), and coordinates the development and publication of key NIST handbooks used by the states for enforcement purposes.

IMPACTS

- Publication of NIST Handbooks 44, 130, and 133
- Yearly training of 1,000 students in 50 classes for inspectors and metrologists
- Traceability recognition of U.S. state metrology laboratories to SI
- U.S. representative to International Organization of Legal Metrology

The work has substantial impact: Sales of products or services affected by weights and measures laws represent about 50 percent of the U.S. Gross Domestic Product.

In addition, this office serves as the U.S. Representative to the International Organization of Legal Metrology, which brings efficiency and cost savings to U.S. manufacturers and other stakeholders doing business overseas through the promotion of harmonized international standards and regulatory practices. The OWM training program is accredited by the International Association of Continuing Education and Training (IACET).

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CNST NANOFAB

The Center for Nanoscale Science and Technology (CNST) NanoFab provides researchers with rapid access to state-of-the-art, commercial nanoscale measurement and fabrication tools and methods, along with technical expertise, at economical hourly rates. It is well-equipped to process and characterize a wide range of nanoscale materials, structures, and devices. Over 100 commercial tools are available within the NanoFab's 5,600 m^2 (60,000 ft^2) of advanced laboratory space, which includes 1,900 m^2 (20,000 ft^2) of cleanroom. Most tools are located in the 780 m^2 (8,400 ft^2) ISO 5 (class-100) cleanroom.

REMOTE JOBS: Researchers can specify the work they need done and have it performed by the NanoFab staff.

INTELLECTUAL PROPERTY RIGHTS: NIST does not claim any rights to intellectual property used or developed in the NanoFab unless a NIST federal employee is a co-inventor.

IMPACTS

- State-of-the-art fabrication and measurement equipment
- Expert staff for consultation and innovative solutions
- Support for diverse research programs from many sources
- Nanoscale technology to go from discovery to production

RAPID ACCESS: Applications are accepted continuously, with a streamlined application process designed to get projects started promptly.

SHARED-USE OPERATION: Economical hourly rates, based on operating costs, with tools reserved through an online system accessible from mobile devices.

RESEARCHERS MAY APPLY FOR REDUCED RATES: If a non-proprietary project advances the NIST mission, reduced rates may be available.

FLEXIBLE HOURS: The NanoFab is open and staffed weekdays from 7 a.m. to midnight, with access possible 24 hours a day, 7 days a week.

TRAINING: The NanoFab can train researchers in how to use tools.

EXPERT STAFF: The NanoFab is operated by a dedicated support staff of process engineers and technicians who train and assist users, operate and maintain the tools, develop and control the processes, and provide consultation.

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JILA

JILA was founded in 1962 as a joint institute of the University of Colorado Boulder (CU) and the National Institute of Standards and Technology.

JILA is one of the nation's leading research institutes in the physical sciences. Researchers there are exploring some of today's most challenging and fundamental scientific questions about the limits of quantum measurements and technologies, the design of precision optical and X-ray lasers, the fundamental principles underlying the interaction of light and matter, the role of quantum physics in chemistry and biology, and much more.

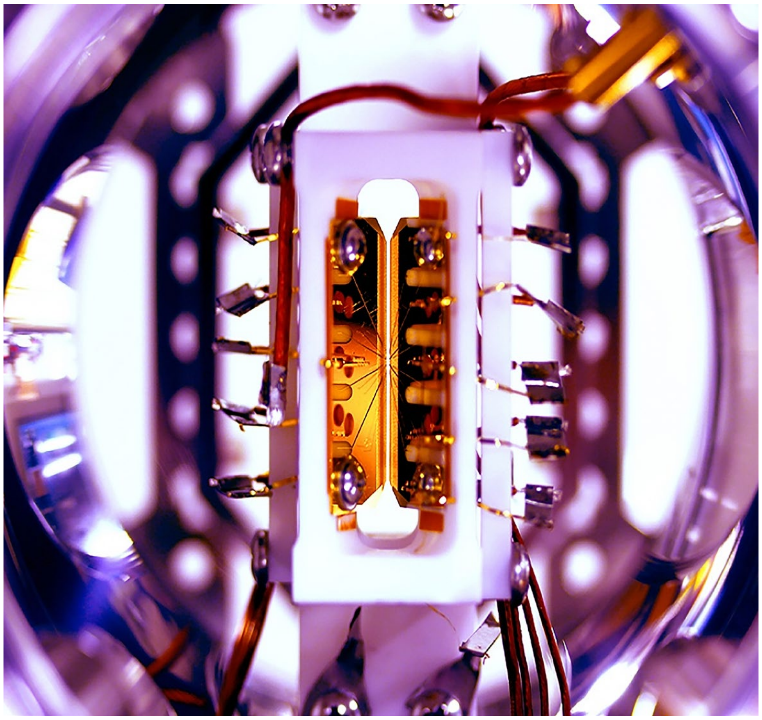
JILA's current faculty includes two Nobel laureates, Eric Cornell and John Hall, as well as two John D. and Catherine T. MacArthur Fellows, Margaret Murnane and Ana Maria Rey.

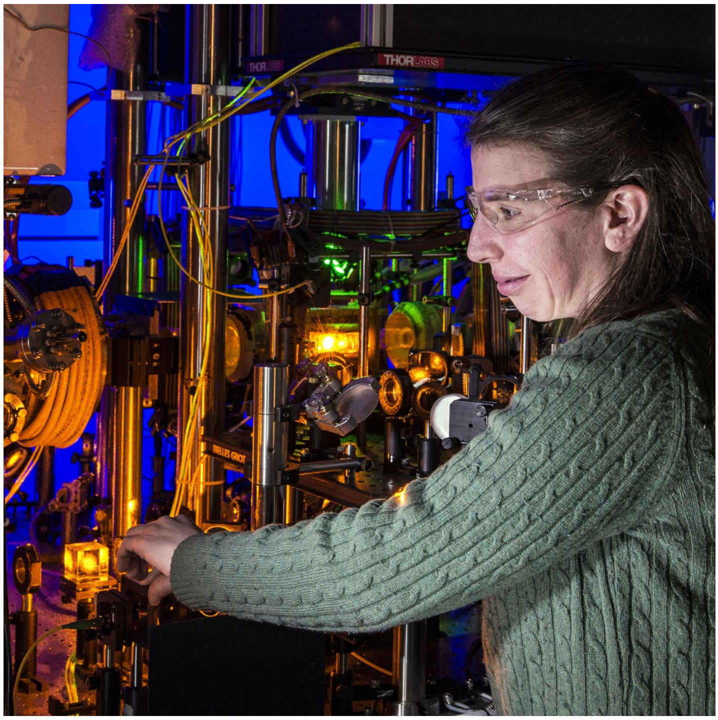
Creative collaborations among JILA Fellows, JILA research associates and students, CU professors, NIST staff members, and other world-leading scientists from around the globe play a key role in generating JILA's renowned pioneering research.

In addition to research breakthroughs, JILA furthers science by training future generations of researchers and innovators. Its education and training initiatives positively impact both the students and our nation's scientific workforce.

IMPACTS

- **Record-setting accuracy for atomic clocks**
- **First table-top X-ray lasers**
- **World's first Bose-Einstein condensate**
- **Creating tools for the quantum Internet**





JOINT QUANTUM INSTITUTE

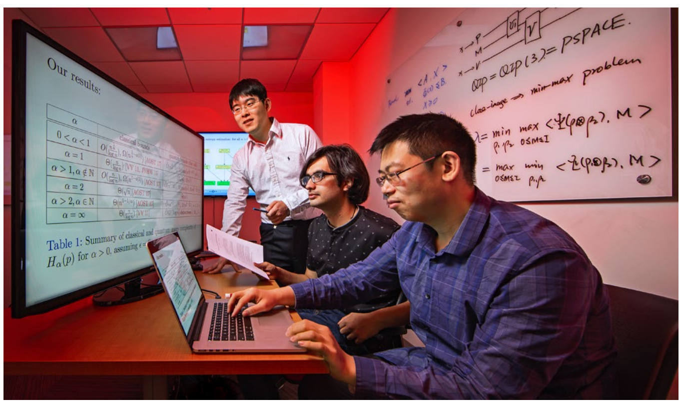
Founded in 2006 as a partnership between NIST, the University of Maryland, College Park (UMD), and the Laboratory for Physical Sciences, and housed on the UMD campus, the Joint Quantum Institute (JQI) conducts major experimental and theoretical research focused on controlling and exploiting quantum systems.

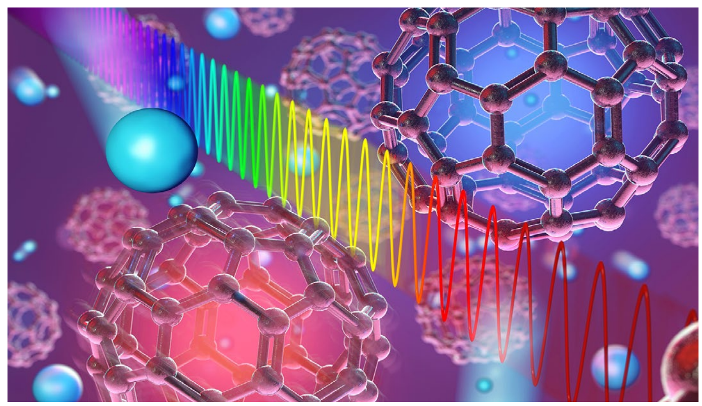
JQI IS A WORLD-CLASS RESEARCH INSTITUTE, home to dozens of leading quantum scientists from all three partner institutions working with more than 100 postdocs and students. JQI's mission includes:

CONDUCTING FUNDAMENTAL INVESTIGATIONS of quantum phenomena to lay the foundation for engineering and controlling complex quantum systems capable of using the coherence and entanglement of quantum mechanics;

MAINTAINING AND ENHANCING THE NATION'S LEADING ROLE IN HIGH TECHNOLOGY through a powerful collaboration in a unique, interdisciplinary center that supports the exchange of ideas among atomic physicists, condensed matter physicists, and quantum information scientists; and

TRAINING a workforce of scientists and engineers for future industrial opportunities.





JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

The Joint Center for Quantum Information and Computer Science (QuICS) is a partnership between the University of Maryland, College Park (UMD) and NIST. Located on the UMD campus, the center advances research and education in quantum computer science and quantum information theory.

Experts in areas including computer science, cybersecurity, mathematics, and physics collaborate with postdoctoral scholars, graduate students, and visitors to form a robust research community that is advancing the state of the art in the field of quantum information processing.

QuICS PURSUES THEORETICAL AND EXPERIMENTAL RESEARCH AT THE FRONTIERS OF QUANTUM INFORMATION SCIENCE:

- Quantum algorithms
- Quantum complexity theory
- Quantum communication
- Quantum error correction and fault tolerance
- Quantum-enhanced metrology
- Quantum cryptography and quantum-secure cryptography
- Implementations of quantum information processing
- Foundations of quantum mechanics
- Applications of quantum information to physics

jila.colorado.edu

jqi.umd.edu

quics.umd.edu

SI REDEFINITION

On May 20, 2019, the world metrology community dramatically redefined four of the seven base units of the International System of Units (SI), with the result that for the first time each unit is based on a fixed value of a fundamental constant of nature. Years of PML advances at the frontier of measurement science were critical to that outcome.

PML had a particularly significant role in the redefinition of the kilogram—the last SI unit still embodied in a physical artifact. In the mid-1970s, a scientist named Bryan Kibble working at the British National Physical Laboratory developed an instrument that compared force exerted on a coil by an electromagnet to the mechanical force exerted by a hanging mass.

PML scientists remain actively engaged in projects related to the new SI. One team is working to develop an electrical current meter compatible with the new definition of the ampere based on the movement of ndividual elementary electric charges. Another group is exploring entirely quantum-based methods to measure temperature in terms of the kelvin, the SI base unit of temperature, now defined by the Boltzmann constant.

And, of course, PML scientists developed and are continuously improving the quantum-based global standard for ac and dc voltage measurements to meet the increasingly demanding needs of high-speed telecommunications and other applications.

IMPACTS

- **World-class Kibble balance results essential to the redefined kilogram**
- **Cutting-edge research on quantum-based temperature measurement**
- **Development of microtechnology for measuring the redefined ampere**
- **Pioneering the quantum-based world standard for voltage**
- **Global leadership in metrology of all seven SI base units**

By the early 1980s, PML built the first of successive generations of the Kibble balance, as the instrument came to be known. At that time, it was used to measure the value of the Planck constant (*h*) using a standard kilogram. Then two PML scientists realized that a Kibble balance employing a calibrated kilogram to measure the value of *h* could be used in reverse: By setting an exact fixed value of *h*, the same system could be used to realize the kilogram. They proposed the new method in 1999.

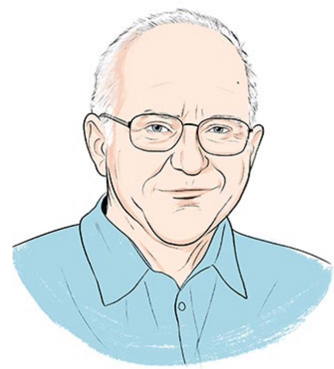
A few years later, PML began constructing its fourth-generation balance (shown on the front cover of this brochure). Its high accuracy, combined with that of a similar instrument elsewhere, met the exacting criteria for redefinition of the kilogram—just as PML's scientists had proposed 20 years earlier.

nist.gov/si-redefinition

NOBEL PRIZE WINNERS

The Nobel Prize in Physics is awarded to scientists who revolutionize the way we understand and apply the fundamental laws of nature. Four PML scientists have received this award for advances that have enabled new types of measurements with direct impact on the progress of science, our national technology base, global competitiveness, economy, and quality of life.

BILL PHILLIPS (1997) for pioneering the use of lasers and magnetic fields to trap and cool a gas of atoms to within millionths of a degree above absolute zero. This breakthrough made possible much more accurate quantum measurements and provided a new kind of technology now used worldwide in many types of quantum research and in applications including ultra-precise timing.

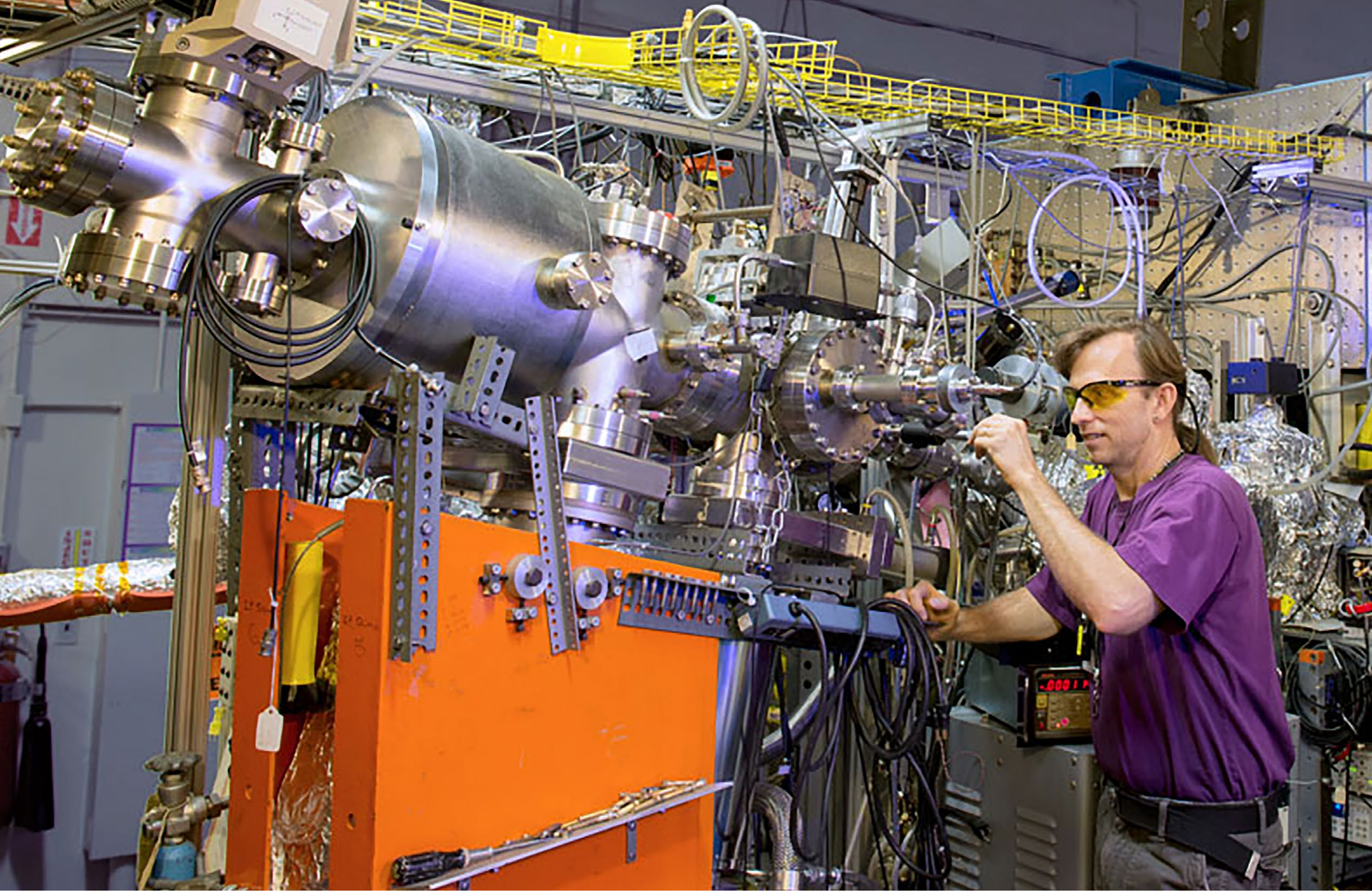


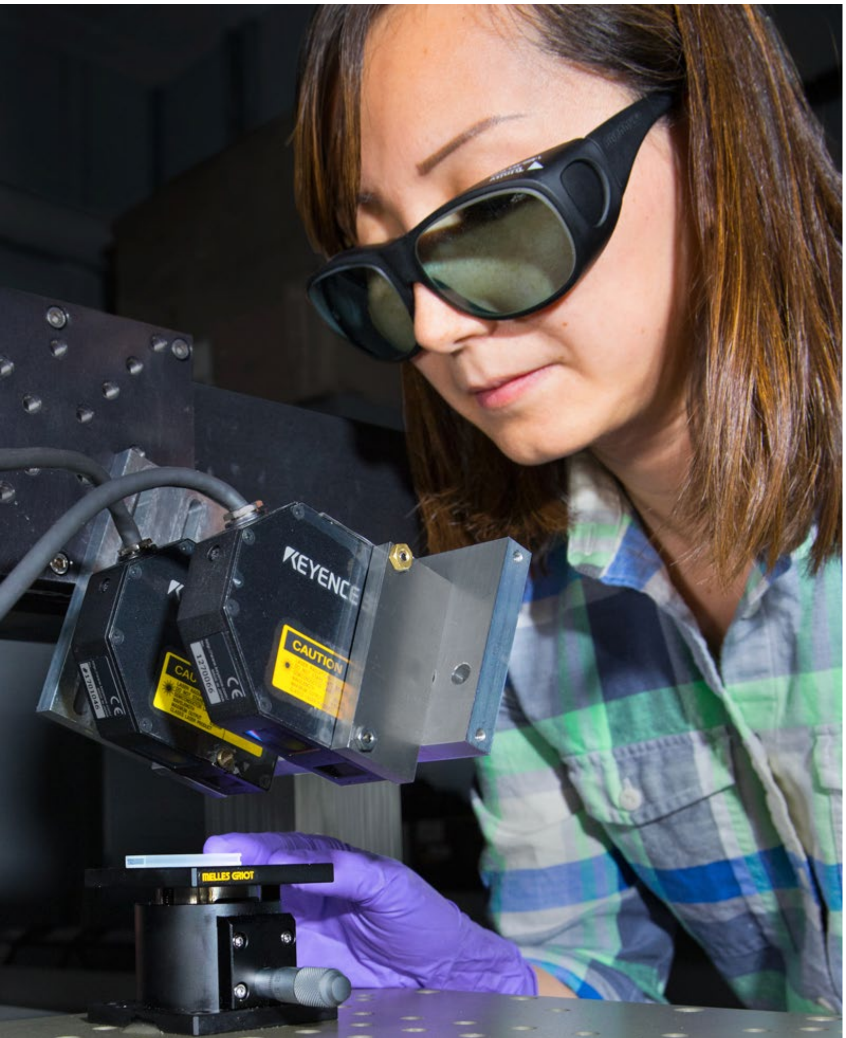
JAN HALL (2005) for inventing an entirely new kind of measurement technique—the laser frequency comb—that marked the most important revolution in precision measurement since the 1960 invention of the laser. The technology is now employed around the globe in many commercial devices and in ultra-precise optical atomic clocks 1,000 times more accurate than the current U.S. time standard.

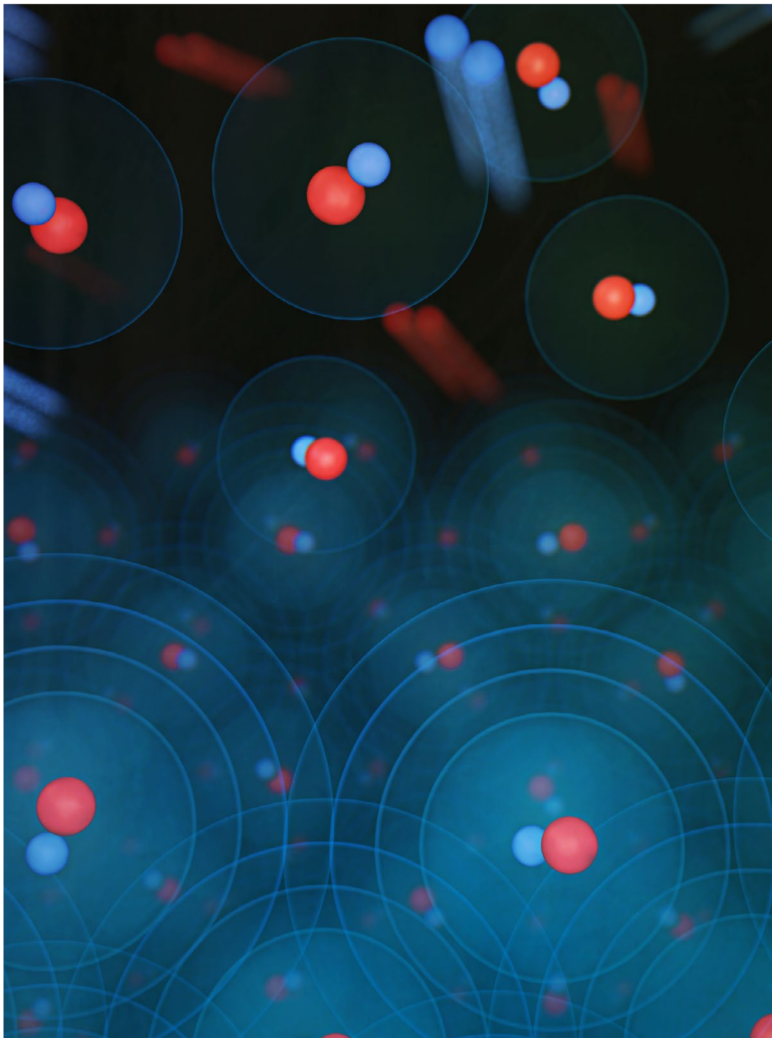
ERIC CORNELL (2001) for extending Dr. Phillips' laser cooling techniques to create an utterly new state of ultracold matter: a Bose Einstein condensate. At billionths of a degree above absolute zero, the atoms are all in exactly the same quantum state, constituting a "super atom" with exotic properties that make it an invaluable way to explore superconductivity, quantum magnetism, and more.

DAVE WINELAND (2012) for perfecting measurement and control of quantum states in individual ions, and generating unique quantum interactions among collections of ions. His pioneering research has made possible dramatic advances in new technologies including quantum computing and simulation through mastery of key quantum phenomena: entanglement and superposition.

Credit: Alex Fine/NIST




KEYENCE
CAUTION
MELLES GRIOT

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MAINTENANCE ONLY
BROOKS