CINT Mission

The Center for Integrated Nanotechnologies (CINT) is a Department of Energy, Office of Science Nanoscale Science Research Center. CINT operates as a national user facility devoted to establishing the scientific principles that govern the design, performance, and integration of nanoscale materials and structures. Through our Core Facility in Albuquerque and Gateway Facility in Los Alamos, CINT provides access to scientific expertise and advanced capabilities for researchers to synthesize, fabricate, characterize, understand, and scale nanostructured materials into the microscopic and macroscopic worlds. This comprehensive approach provides the greatest potential for nanostructured materials to inspire technological innovation with enduring beneficial impact in energy, environment, human health, and security.
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1 Executive Summary

The Center for Integrated Nanotechnologies (CINT) plays a leadership role in the area of nanoscience through its function as a Department of Energy (DOE), Office of Science Nanoscale Science Research Center national user facility. By creating a collaborative community of diverse users and expert scientific staff, CINT fosters high-impact nanoscience discoveries, leads next-generation technique development, and advances the frontiers of knowledge beyond that which is achievable by individual researchers or any single institution.

Each year we revisit our strategic plan to ensure it is focused on meeting the needs of the user community today and into the future. This plan is based upon the extraordinary scientific opportunities involving nanomaterials and quantum phenomena in three challenges inspired by CINT users and staff. These challenges, described in Section 3, include understanding and designing nanomaterials to create new functionalities based on quantum effects; creating hybrid material interactions for generation and manipulation of light; and a new emphasis for 2019 on assembly of soft and hybrid materials. Solving these challenges will have significant impact in important areas such as energy, environment, health, and security.

CINT’s role is to enable world-leading science towards realizing these benefits, and our strategic objectives describe what is needed to deliver on this promise. As a vibrant partnership between Los Alamos National Laboratory and Sandia National Laboratories, CINT leverages the unmatched scientific and engineering expertise, as well as special capabilities, of our host DOE laboratories in an Office of Science open-access user facility, benefitting hundreds of researchers annually. We have world-leading scientific expertise in four thrust areas, as described in Section 2, and specialized capabilities to synthesize, fabricate, characterize and understand nanomaterials in increasingly complex integrated environments, as described in Section 4.

Building upon these current strengths, we continue to identify capabilities and expertise that the nanoscience community will need in the future and that CINT is well positioned to develop and offer as a user facility. These include an expanding portfolio of our signature Discovery Platforms™ to include the new quantum NMR platform to study nuclear spin at the smallest length scales; novel synthetic approaches for exquisitely heterostructured nanowires, nanoparticles and quasi-two-dimensional materials; metamaterials for photonics and optoelectronics; nanomechanics for fundamental understanding of the effects of defects/crystal distortions on the mechanical properties; ultra-fast and ultra-high resolution spectroscopic techniques of nanomaterial dynamics; in situ microscopies that provide real-time, spatially-resolved structure/property information, advanced simulation techniques, and multi-scale theory for interfaces and dynamics. CINT has significant expertise in quantum information science, offering capabilities in measuring single spin electron spin resonance and nuclear magnetic resonance in Si28 quantum dots, defect centers in quantum materials, and electronic and photonic capabilities for creation of novel qubits.

CINT’s transformational and supporting foundational capabilities are made available to the widest possible number of qualified users via a comprehensive communications and outreach effort combined with an efficient user proposal, peer-review, and project management system. We will target research leaders in diverse institutions, early career scientists, and innovators in nanotechnology industries to create an expanded national user community of the future.
2 Introduction

The Center for Integrated Nanotechnologies (CINT) is a Department of Energy (DOE), Office of Science Nanoscale Science Research Center (NSRC) operating as national user facility. As a vibrant partnership between Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL), CINT leverages the unmatched scientific and engineering expertise, as well as special capabilities, of our host DOE laboratories, creating a unique user facility environment among the NSRCs. Our users and staff conduct research projects within and across the Core Facility in Albuquerque, NM, and the Gateway Facility in Los Alamos, NM. By creating a collaborative community of diverse users matched to expert facility scientists with advanced capabilities, CINT fosters high-impact nanoscience discoveries, leads next-generation technique development, and advances the frontiers of knowledge beyond what is achievable by individual researchers or any single institution.

Thus, our overarching goal is to be the national resource for research expertise and advanced capabilities to synthesize, fabricate, characterize, understand, and integrate nanostructured materials in order to achieve unprecedented materials functionality and innovative systems that inspire revolutionary nano-enabled technologies.

In order to achieve this goal, CINT has the following six strategic objectives:

1. CINT will be a nationally recognized leader in nanomaterials.
2. CINT will develop unique experimental and theoretical capabilities to synthesize, fabricate, characterize, and understand nanoscale materials in increasingly complex environments.
3. CINT will continue to develop new generations of Discovery Platforms™ inspired by materials challenges to provide a window into nanoscale and quantum phenomena.
4. CINT will invest to provide foundational capabilities and commercial instrumentation necessary for internationally competitive nanoscience research.
5. CINT will operate safely and effectively by aligning capabilities and capacity with the ever-evolving user demand.
6. CINT will increase the diversity and breadth of our national user community, foster high-impact science, and encourage intellectual risk in basic and use-inspired research.

Together, these CINT strategic objectives support and align with the U.S. DOE’s strategy to deliver the scientific discoveries and major scientific tools that transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation. CINT supports these objectives by: (1) Conducting discovery-focused research, (2) Providing the nation’s researchers with world-class scientific user facilities, and (3) Leveraging the national laboratory system as well as partnerships with universities and industry to conduct mission-focused research.
We have world-leading scientific expertise and specialized capabilities to synthesize, fabricate, characterize, and understand nanomaterials in increasingly complex integrated environments. Our expertise is organized in four scientific thrust areas:

- **Quantum Materials Systems**: Understanding and designing nanomaterials to create new functionalities based on quantum effects that span multiple length scales (from nm to mm).
- **Nanophotonics and Optical Nanomaterials**: Discovery, synthesis, and integration of optical nanomaterials; exploitation and characterization of emergent or collective electromagnetic and quantum optical phenomena, from nanophotonics and metamaterials to quantum coherence.
- **In-situ Characterization and Nanomechanics**: Developing and implementing world-leading capabilities to study the dynamic response of materials and nanosystems to mechanical, electrical, or other stimuli.
- **Soft, Biological, and Composite Nanomaterials**: Solution-based materials synthesis and assembly of soft, composite, and artificial bio-mimetic nanosystems.

In addition, we leverage the strengths of our host DOE laboratories through the alignment of the CINT 2024 strategic plan with the LANL and SNL missions, capabilities, and strategic investments. For example, through the exploration of materials and integration, we support the LANL “Materials for the Future of Los Alamos” scientific pillar which seeks to establish the design principles, synthesis pathways, and manufacturing processes for advanced and new materials to intentionally control functionality and performance prediction relevant to national security missions. Similarly, the SNL Strategic Plan includes explicit objectives in support of the nanoscience capability, Materials Science Research Foundation, Advanced Science and Technology Program, and multiple crosscutting research challenges involving the creation, understanding, and integration of advanced nanomaterials in technologies for national security applications.

The coordination of SNL, LANL, and CINT strategic plans leads to very visible benefits for all three entities. Researchers from LANL and SNL continuously request access to CINT’s capabilities and expertise through User project collaborations. Over the past three years CINT has hosted over 900 host facility researchers, reinforcing the message that the laboratories value our Center, and that CINT closely partners with its host institutions to deliver high impact contributions to the labs’ core missions. These host laboratory projects are funded by a wide variety of sponsors including, but not limited to, the Department of Energy (including Laboratory Research and Development (LDRD)), the National Nuclear Security Administration, the Department of Defense, the National Science Foundation, Homeland Security, and the National Institutes of Health.

The exemplary science and technology that come from the CINT staff and collaborations with host lab and external users has received recognition by renowned sources. Most notably, CINT has won four R&D 100 awards in recent years. The R&D 100 Awards identify and celebrate the top technology products of the year spanning industry, academia, and government-sponsored research. Our R&D 100 winners include:

- LAMMPS Molecular Dynamics Simulator (M. Stevens, et al., 2018)
- Transceiver for Quantum Keys and Encryption (R.M. Camacho, J. Urayama*, P. Davids*, et al., 2016)
• Stress-induced Fabrication of Functionally Designed Nanomaterials (H. Fan*, T.S. Luk, I. Brener, et al., 2016)
• Nano-Enabled, Microfluidic Detection of Bacillus anthracis (J. Harper*, G. Bachand, 2014)

These achievements illustrate the ever-growing potential for CINT to amplify the exceptional nanoscience strengths of our host DOE laboratories. Over 20 CINT scientists have also been named fellows of professional societies, including societies such as the American Physical Society and the American Chemical Society.

Finally, we note the special role that the DOE Office of Science user facilities have in supporting key objectives in 2016 National Nanotechnology Initiative Strategic Plan. Objective 3.3 is to provide, facilitate the sharing of, and sustain the physical and cyber R&D infrastructure, notably user facilities and cooperative research centers. This requires: (3.3.1) Establishing regular mechanisms to determine the current and future infrastructure needs of users and stakeholders of these facilities and centers, and (3.3.2) Developing, operating, and sustaining state-of-the-art tools, infrastructure, and user facilities, including ongoing investment, staffing, and upgrades.

Nanomaterials integration is key to numerous extraordinary scientific and technological challenges. Solving such challenges would unlock great possibilities for innovative technologies and have widely recognized impact in nationally important areas such as energy, environment, human health, and security. We describe three representative challenges in Section 3, followed by the requisite expertise and capability development in Sections 3.4 and 4, respectively. We also see new opportunities to refine the role of a user facility to meet the needs of a highly networked, international community.

Our vision for CINT in the year 2024 and dedication to continued excellence as a DOE Office of Science user facility ensure that CINT will transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation.

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1 CINT users are marked with an asterisk.
3 Science Vision: Challenges in Nanomaterials Integration

Nanoscale materials exhibit extraordinary physical, chemical, and/or biological properties. Isolated, or individual, nanoscale materials are scientifically interesting, but they rarely make significant technological impact. Building blocks comprised of individual nanoscale materials are commonly integrated with other materials into architectures that enhance their properties (up-scaling) or lead to new emergent behaviors. By surveying the integrated environments of greatest potential impact, and by developing a fundamental understanding of the principles that govern the integrated properties and behaviors, we can capitalize on the greatest potential for nanomaterials to have an enduring impact on scientific and technological innovations. Nanoscale integration has the potential to revolutionize the way we live, in the same way that the development of the semiconductor-based integrated circuit (or computer chip) did. The development of the chip required the capability to integrate a large number of resistors, capacitors, diodes, and transistors on a single platform. Once the chip was developed, it enabled countless innovations. CINT envisions similarly transformational technologies will ultimately emerge from nanomaterials integration.

Understanding the principles of nanomaterials integration has been the central theme of CINT since its inception. The CINT2024 Strategic Plan builds upon this foundation by illustrating three representative, forward-looking integration challenges inspired by the nanoscience community. These integration challenges enable us to identify the capabilities that the nanoscience research community will need to realize the smart integration of nanomaterials into innovative and competitive technologies. To accomplish these challenges, CINT will bring together expertise and capabilities across our four Science Thrusts. An underlying theme of all three challenges is a fully integrated feedback loop of synthesis, fabrication, characterization, and modeling, shown in Figure 1 (and also described in more detail on the NSRC Portal) that will allow the nanoscience community to realize and develop the ability to predict and a priori design unprecedented materials functionalities and innovative systems.

3.1 Quantum materials

Scientific opportunity

Quantum materials possess tremendous potential to revolutionize many technologies that could impact our daily life. A few representative examples include: novel sensing platforms capable of detecting very small changes in magnetic fields with resolution beyond the classical limit; quantum photonic integrated circuits enabling eavesdrop-proof communication; ultrafast, energy-efficient magnetoelectric sensors; and, ultimately, a neuromorphic quantum computer capable of mimicking the human brain. CINT has been at the forefront of synthesis, fabrication, and integration of quantum materials as well as in probing and controlling their emergent phenomena for nearly a decade. In the coming years CINT will expand our research efforts into the following areas:

- Deterministic placement and electronic/photonc integration of solitary quantum defects
- Quantum-sensed Nuclear Magnetic Resonance (NMR) Discovery Platform™
- Using light to probe and control novel phenomena in quantum materials
Positional science and capabilities

CINT, working together with other state-of-the-art facilities at LANL and SNL (e.g. LANL’s Laboratory for Ultrafast Materials Science (LUMOS) and the National High Magnetic Field Laboratory (NHMFL) and SNL’s Ion Beam Laboratory (IBL)) has performed numerous trail-blazing works in these areas. In deterministic placement of solitary defects, CINT, in collaboration with IBL, Harvard, and MIT, has successfully demonstrated the placement of silicon defects in a diamond photonic crystal structure. This novel capability has further led to successful demonstration of a quantum-optical switch. CINT scientists have also demonstrated that sp3 defects covalently attached on the side walls of single walled carbon nanotubes (SWCNTs) can serve as single photon emitters at room temperature in the important 1.5 micron telecommunication band. This feat had yet to be achieved, despite over 2 decades of research in this arena by a field of scientists working in a number of material systems. CINT researchers have developed state-of-the-art instrumentation to study single nanostructures and single photons, including optical spectroscopy systems equipped with a 9T magnet and state-of-the-art superconducting nanowire single photon detectors capable of detecting single photons in the near infrared spectral region (e.g. photon detection at 1.55 microns with >85% detection efficiency). This instrumentation has been helping users around the world in investigating exciton/spin fine structure and quantum coherence properties of defects created in SWCNTs, 2D transition metal dichalcogenides (2D TMDCs), and hexagonal boron nitride (hBN).

Nanoscience integration will enable quantum computing techniques to be used for new measurement capabilities of nanoscale systems. At CINT we have expertise in measuring single spin electron spin resonance (ESR) and nuclear magnetic resonance (NMR) in Si28 quantum dots, defect centers in quantum materials, and electronic and photonic capabilities for manipulating the qubit. Furthermore, we can draw upon capabilities in our host laboratories for single ion implantation of color centers in diamond, and quantum information theory.

CINT has a collection of femtosecond laser systems (particularly at LUMOS) with complementary capabilities that are unmatched in the U.S., to the best of our knowledge, and only matched by a few other places in the world. In our laboratories, several amplified femtosecond Ti:sapphire systems generate pulses from terahertz (THz) to soft x-ray frequencies. These can then be used to perform a variety of advanced ultrafast optical experiments, including optical pump-probe spectroscopy, time-resolved second harmonic generation, time-and-angle-resolved photoemission spectroscopy (TR-ARPES), ultrafast optical microscopy, time-resolved x-ray magnetic linear dichroism, THz magneto-optical spectroscopy, and optical pump-THz probe spectroscopy. We have used these capabilities to investigate nearly every class of quantum materials, including 2D-TMDCs, transition metal oxides (TMOs), graphene, and Dirac materials. CINT has also applied and developed advanced theoretical tools, including real-time density functional theory and time-dependent Lanczos, and dynamical mean-field theoretical methods, to tackle both weakly and strongly correlated quantum materials.

Toward the future

*Deterministic placement and electronic/photonic integration of solitary defects:* Due to their ability to mimic trapped ions, solitary defects of semiconductors and insulators have been identified as a key quantum material needing further research. Researchers in this field have a critical need for the following capabilities: (1) deterministic creation of defects with nanometer scale precision, (2) integration of defects into electronic devices for stimulation and control, and (3) integration of defects into plasmonic/photonic integrated circuits.

As discussed above, the collaboration between CINT and IBL has demonstrated the deterministic placement of solitary silicon defects in diamond. We are working toward the development of a generalized implantation process capable of creating defects not only in bulk diamond but also in...
In parallel with this top-down fabrication approach, we will attempt to create covalent defects on TMDC/hBN layers and individual SWCNTs via introduction of sub-micron size droplets of chemical reagents using CINT’s dip-pen nanolithography capability. This capability, together with CINT’s state-of-the-art chemical synthesis and functionalization capability, will open a new bottom-up route for introducing single defects at designed locations in nanomaterials.

We will next integrate these deterministically placed defects into photonic/plasmonic cavities for enhancement of light matter interaction and then into diode or field effect transistor (FET) device structures to achieve electrically driven quantum light generation. Further integration of these quantum light sources into photonic chips comprised of quantum control devices, photonic/plasmonic waveguide circuits, and superconducting nanowire single detectors will ultimately enable CINT to perform experiments demonstrating quantum communication protocols and quantum metrology principles. We will utilize the traditional top-down semiconductor fabrication capabilities of CINT and SNL’s Semiconductor Fab (MESA) to address these integration needs. In addition, we also propose to develop the following three highly complementary bottom-up capabilities: (1) dielectrophoresis platform for fabrication of SWCNTs FET devices, (2) van der Waals epitaxy station for rapid fabrication of multi-layer TMDC/hBN heterostructure devices, and (3) electro-hydrodynamic 3D printing system for bottom construction of plasmonic cavities.

**Quantum Sensed Nuclear Spin Resonance Discovery Platform™**: The extraordinary sensitivity of qubits to their local environment and the established techniques for initialization, control, and measurement will lead to new quantum sensors for nanoscale systems. One example is using the magnetic field sensitivity of spin qubits for local NMR. NMR is an important characterization tool providing chemical information for liquid and solid systems. While a variety of approaches have been used to improve sensitivity, recent demonstrations using nitrogen-vacancy centers to detect NMR in a 5nm³ volume demonstrate the quantum-leap in performance enabled by using quantum information techniques.

Scientific opportunities for a quantum-based NMR characterization will include quantum materials, soft and biological materials, and optical materials. We will characterize the impact of NMR at interfaces, and perform local NMR measurements on nanomaterials such as colloidal quantum dots and biological materials adsorbed to the surface above the sensor. Long-term experiments will incorporate alternate wide-bandgap host materials such as SiC and GaN where nanoelectronic devices can be fabricated, and will explore solitary defects in other quantum materials as a platform substrate. If successful, the NMR sensor can be incorporated into other CINT discovery platforms such as the Microfluidics Discovery Platform™.

Establishing a quantum-sensed NMR discovery platform will require: (1) diamond nanofabrication, (2) implantation of defects in nanostructures, (3) a platform with radio-frequency, magnetic field and temperature control, and (4) optical measurement and control of color-center based qubits.

The quantum-sensed NMR Discovery Platform™ will integrate new technologies from the quantum information community with user-based nanoscience systems. In the future, adapting cutting edge quantum information techniques as a unique sensor will provide new probes for materials systems at the nanoscale.

**Using light to probe and control novel phenomena in quantum materials**: Femtosecond laser pulses are well established as a unique tool for probing the temporal evolution of various quantum states in quantum materials. Recently, scientists have discovered that intense light pulses can also be used to drive these materials into new transient and metastable states, often with unique properties that have no equilibrium counterpart. However, these states have thus far only been
discovered by chance; the development of original methods for predicting and controlling light-driven states would make it possible to reach a desired quantum state “on demand.” CINT is well positioned to take the lead in light-driven quantum phenomena. Our proven ability to generate and use femtosecond laser pulses over a broad range of frequencies gives CINT a substantial advantage over other groups in using light to both probe and control novel phenomena in quantum materials. An additional advantage comes from our strong collaborations with other CINT scientists who are fabricating and theoretically modeling quantum materials. Advanced theoretical tools include the real-time density functional theory and time-dependent Lanczos, and dynamical mean-field theoretical methods for both weakly and strongly correlated quantum materials. Our ultimate goal is to predict new states in quantum materials and use femtosecond laser pulses to both control and probe their temporal evolution. This effort will go beyond previous serendipitous discoveries of transient and metastable states in these systems, which could enable us to leverage the advanced fabrication capabilities at CINT to stabilize these states in equilibrium.

These approaches will be applied to several classes of quantum materials currently being studied at CINT, particularly 2D-TMDCs, TMOs, and Dirac materials. Novel photoinduced transient and metastable phases have been discovered by chance in all of these systems, providing fertile ground for our studies. In 2D-TMDCs and TMOs, we will predict and realize the required parameters for an intense light field to dynamically control the coherence and coupling between the different degrees of freedom (e.g. charge, spin, lattice) that dominate material properties, enabling us to reach a desired quantum state. In parallel, we will develop novel approaches for using light to both drive transitions between known topological states and create new topological states in Dirac materials. This will also build on theoretical predictions, enabling us to generate novel transient and metastable states in topological materials through manipulating both bosonic and electronic modes. This theory-driven discovery will be expanded to heterostructures composed of quantum materials. Interfacing 2D-TMDCs, TMOs, and Dirac materials in an architecture provides additional control of degrees of freedom. The heterostructures will be prepared by a combination of sample transfer systems and the advanced synthesis capabilities in chemical vapor deposition, molecular beam epitaxy, and pulsed laser deposition at CINT.

3.2 Hybrid material interactions for generation and manipulation of light

Scientific opportunity

Structured hybrid materials can be engineered to have novel photonic properties that emerge only as a result of multi-material interactions and can also include pre-designed properties for novel photon generation and manipulation. CINT is advancing the understanding and application of these revolutionary hybrid systems by addressing the most significant open questions surrounding the control, integration, and enhancement of the photonic response of two classes of materials and their associated assemblies: (1) materials and structures that control and modify electromagnetic energy (plasmonics, metamaterials), and (2) materials and assemblies that actively generate and harvest electromagnetic energy.

Positional science and capabilities

CINT’s foundations to lead in this area rest on our multidisciplinary capabilities for generation of unique photonic materials and their characterization with powerful spectroscopic tools, paired with an ability to control compositions and assembly routes to define interaction geometries across multiple length scales and degrees of complexity. We are international leaders in developing exceptional photonic materials with switchable and highly tunable photon emission properties. Examples include proprietary non-blinking quantum dots and novel microfluidic control of
synthesis for axially heterostructured nanowires. Our doped carbon nanotubes provide new multifunctionality and boosted quantum yields and highlight CINT’s ability to isolate specific tube structures and control their surface chemistries. Together, our emitters provide multi-photon to single photon behaviors across classical to quantum regimes (see Figure 2). Pioneering efforts in nanomaterials assembly include soft templating approaches for creation of hybrid functional systems with hierarchical structures that are reconfigurable and responsive. Innovative dip pen nanolithography is providing unprecedented control over placement of emitters on photonic, plasmonic, and metamaterials structures, which provide significant opportunity for manipulation of light.

CINT has been a world leader in the area of metamaterials (THz to near-infrared) for nearly a decade. We now lead the world in all-dielectric metamaterials as well. CINT’s position in this field is enabled by access to nanofabrication and epitaxial growth facilities. Advances in these materials are driven by world-class spectroscopic characterization, including ultrafast tools providing resolution across THz to soft X-ray energies. Paired with the broadest continuous excitation range available for Raman spectroscopy (near-IR to UV) and state-of-the-art tools for microscopic imaging, spectroscopy, and dynamics measurements of single nanoelements, CINT’s abilities for optical characterization of nanomaterials are unmatched. Our first-principles density functional theory (DFT) simulation capability encompasses nearly all flavors of electronic structure codes for understanding electronic, optical, and vibrational properties of complex materials. In particular, LANL-owned nonadiabatic excited-state molecular dynamics capability excels at modeling the largest systems accessible for nonlinear and time-dependent spectroscopy. Theory efforts are further founded in DFT and classical electromagnetic theory simulation for metamaterials modeling and design.

**Toward the future**

Drawing on these strengths, CINT will approach the following opportunities in hybrid photonic materials as we move forward.

*Generation and active manipulation of novel emitting states and photon correlation statistics:* Accessing new emission regimes of expanded wavelengths, enhanced quantum yields, and tunable or selectable photon statistics and dynamics requires defining interactions in terms of the relative placement and orientation of materials within the hybrid structure, while also controlling the hybrid composition over multiple dimensionalities. CINT will expand the hybrid materials community’s ability to generate and actively manipulate novel emitting states and photon correlation statistics by addressing the following challenges:

- Identifying and realizing candidate materials that are likely to generate targeted optical behaviors from hybrid interactions, such as tailoring of plasmonic interactions aimed at enhancing biexciton emission.
- Synthesizing and/or integrating multi-component systems with the appropriate interaction geometries to create a desired functionality, such as harnessing metamaterial interactions with dopant states of emitters for directional emission or enhanced coupling to photonic waveguides.
- Generating desired optical responses in emergent electronic structures by manipulating interactions across multiple length-scales within interfacial environments. Examples
include use of soft responsive systems to modulate coupling between embedded optical emitters for on-demand behaviors.

CINT will employ a variety of materials processing techniques, including direct synthesis, self-assembly, nanofabrication and directed placement, to further our understanding of these issues. CINT will also move beyond traditional synthetic and processing approaches by tapping soft-materials assembly methods with the potential to harness the responsive and highly tunable nature of bio-inspired systems.

Active, multifunctional plasmonic and metamaterial interactions: Hybrid materials interactions have significant potential for establishing new functionality and enhanced manipulation of the medium in which light is generated, harvested, or propagated. Hybrids enable a move from passive to active plasmonic and metamaterials, and form a basis for new concepts including metamolecules (in which the collective interactions of individual metamaterial elements or atoms create new function), “plasmonics on demand” (where localized materials interactions automatically generate desired resonances in optimized locations), and tailored and enhanced optical nonlinearities in metamaterials coupled to different materials. Unprecedented multifunctionality will result, giving simultaneous control of polarization states, beam steering, and focusing; integrating perfect absorption of light directly into optoelectronic architectures; or ultimately integrating hybrid metamaterials directly with emerging concepts in emitting materials. To realize this extraordinary multifunctionality, CINT will utilize our integrated efforts in synthesis, characterization, and modeling to address the following challenges:

- Devising non-traditional plasmonic systems (e.g. graphene hybrids or emerging epitaxial oxides) that cannot be accessed with more traditional noble metal approaches.
- Designing multifunctional metamaterial behaviors through metamolecule concepts (shown in Figure 3).
- Generating hybrid interactions coupled to metamaterial architectures to provide active/dynamic control and tuning of enhanced metamaterial response and their optical nonlinearities.

Meeting the modeling challenge: CINT’s ultimate goal in this area is to create hybrid materials by design. This will entail significant advances in predictive modeling. In particular, the state-of-the-art must be dramatically advanced in such areas as electronic structure, dynamics, environment, and interfacial interactions at length-scales between the molecular and macroscopic. To meet the modeling challenge, CINT will pursue the following opportunities:

- Develop a predictive capability for designing new optical functionality arising from materials interactions such as between plasmons in metallic systems (e.g. metal nanoparticles, Dirac metals) and excitons in semiconductor nanoemitters.
- Understand materials coupling mechanisms and identify the most interesting and promising materials interactions, both in terms of composition and interaction geometries, to pursue as routes to novel optical behaviors.
- Develop new theoretical concepts capable of optimizing electronically active networked structures by accessing the middle-length scales of significance for understanding integrated hybrid behaviors and obtaining targeted optical responses.

CINT’s current expertise and capabilities in hybrid materials provide a strong foundation for pursuing the above questions. However, the full range of effort in this area will require CINT to expand its materials generation capability to include new techniques capable of placement of...
optical nanoparticles with nanometer precision. Additionally, our strengths in single-nanoparticle spectroscopic characterization have been significantly enhanced by adding capabilities for single nano-element Raman and magneto-optical spectroscopy while expanding ultrafast capabilities to include single-photon counting techniques at wavelengths longer than the near-IR. CINT will also bring the full strength of our integrated efforts in synthesis, characterization, and modeling to bear on these issues. Model development will work hand-in-hand with experiment in this rapidly expanding field, to allow us to establish the most relevant test systems for validation of predictive models. There is significant new opportunity for developing robust approaches to model exciton-plasmon coupling and pioneer the area of “phononics” (manipulation of phonons and phonon coupling phenomena).

### 3.3 Soft nanomaterials science

**Scientific opportunity**

Soft and hybrid nanomaterials have had revolutionary impacts in fields ranging from energy storage and conversion to biomedicine. A few specific examples include: magnetic nanoparticles capable of detecting and treating cancer, functionalized, plasmonic nanoparticles for detection of *Bacillus anthracis*, and printable flexible electronics used in solar cells, organic LEDs, and health monitoring devices. CINT has been at the forefront of synthesis, assembly, characterization, and theory of soft nanomaterials and their integration into functional assemblies with desired emergent properties. In the coming years, CINT will expand these efforts with an emphasis on:

- Enhanced molecular and nanoscale building blocks that direct assembly and integration
- Innovative approaches to assemble heterogeneous nanocomponents across multiple length scales and dimensions

**Positional science and capabilities**

CINT’s foundations in this area are based on our multidisciplinary science and capabilities in soft matter nano-building block synthesis, active and directed self-assembly processes, high-resolution characterization tools, and multiscale theory and simulations. At the building block scale, CINT has demonstrated expertise in the custom synthesis of biomolecular nanomachines (e.g., kinesin motor proteins, bacteriorhodopsin) as structural and functional components of hybrid materials and systems. This effort is complemented by capabilities in the synthesis and functionalization of engineered nanoparticles, such as magnetic nanoparticles, fluorescent metal nanoclusters, and plasmonic nanoparticles. CINT’s Microfluidic Discovery Platform™ (Figure 4) also enables the synthesis, functionalization, and real-time characterization of nanoparticles and rods. At the next level, we are pioneering novel approaches to the assembly of nano-building blocks into functional complexes. These include pressure-driven assembly, motor-driven assembly, and stimuli-responsive assembly and self-organization.

![Figure 4. CINT’s Microfluidic Discovery Platform.](image-url)
the near term (FY19) CINT will be standing up a new cyro-EM imaging capability, which will include a Scios 2 dual-beam SEM/FIB with a dedicated cryo-cooled stage and Talos L120C TEM with a camera optimized for low keV imaging. Specialized transfer equipment will allow for cryogenic FIB milling, lift-out and transfer to the TEM, meaning characterization can cover all length scales of soft matter and nanomaterials in their native, hydrated state with the smallest amount of beam damage possible.

CINT’s synthesis and characterization capabilities are underpinned by efforts to develop a fundamental understanding of the interactions among nanoscale components, and how these interactions affect the overall functionality of the hierarchical structures. In response to the user community’s interest in soft, biological and composite nanomaterials, CINT continues to develop methods to model polymer nanocomposites, biomolecules and biomolecular materials and nanoparticle self-assembly using classical density functional theory, self-consistent field theory, Monte Carlo, simulations and molecular dynamics simulations. One of our main tool is the open source, Sandia developed molecular dynamics package, LAMMPS, which is uniquely capable for simulating the dynamics nanoparticles at the single particle level through complex to systems containing a billion atoms.

Toward the future

The promise of nanoscience lies in revolutionary new materials exhibiting emergent properties that are possible solely due to the unique physics at the nanoscale. Here, Nature provides the inspiration and epitome for the structural and functional complexity that is achievable with soft nanomaterials. The immense possibilities that exist in the biological realm provide an underlying confidence and direction for the design and development of more modest but increasingly complex and functional systems through the integration of soft nanomaterial building blocks. CINT has established a strong leadership position in the science and integration of soft nanomaterials that will be expanded over the next few years with a focus on: (1) enhanced molecular and nanoscale building blocks that direct assembly and functional integration; and (2) innovative approaches to assemble heterogeneous nanocomponents across multiple length scales and dimensions.

Enhanced molecular and nanoscale building blocks that direct assembly and integration: While soft nanomaterials have been used in specific applications, the fundamental building blocks are, in general, structurally and chemically simple, at least in contrast to biological analogs, i.e., proteins. Controlling the size, shape, and crystal structure of nanoparticles is readily achievable in many systems. However, imparting precise chemical composition and defining functionality at their surfaces, two aspects critical for controlled assembly, remains an important science challenge. This challenge further extends to the preparation of synthetic (e.g., polymers) and biomolecular nanomaterials (e.g., peptide/proteins) that encode information necessary to instruct assembly and integration into functional architectures. Toward addressing this challenge, CINT will focus on two aspects of developing enhanced building blocks over the next few years.

Biopolymers such as proteins fold and assemble into functional architectures based the high-information content encoded into their compositional sequence. The power of this information enables exquisite control over energy landscapes to precisely control interactions over multiple length scales. Achieving a similar level of control in synthetic systems remains a challenge. We will focus on developing strategies for the synthesis of sequence-controlled nanostructured polymers, polymer nanoparticles, and block co-polymers. In parallel, theory/simulation efforts will address understanding and predicting the structures of these polymers based on their sequences, as well as the energy landscapes that define assembly into functional materials. The incoming cryo-EM capability will be invaluable in this endeavor, enabling investigation of the polymer building blocks in their native, hydrated (or solvated) state. This will include 3D structure via tomography as well as understanding their interactions in solution. Furthermore, isolation of
intermediate growth structures and imaging using low keV, high contrast TEM, will allow for direct correlation to the energy landscapes inferred by theory.

A key opportunity in the synthesis of biopolymers concerns expanding the canonical genetic code beyond the typical twenty amino acids. This may be achieved through post-synthesis chemical modification of biopolymers, and/or direct incorporation of modified building blocks (e.g., unnatural amino acids, UAAs) during synthesis. In the near-term, we will focus on exploring chemical modifications of active proteins/enzymes to enable interfacial coupling with precise orientation and enhanced catalytic activity. Longer-term efforts will incorporate expanded genetic systems capable of expressing biopolymers with multiple, modified building blocks (UAAs). The unique chemical moieties afforded by these modified blocks will be used to tailor protein assembly and integration in hybrid architectures, as well as to provide enhanced stability and function.

*Innovative approaches to assemble heterogenous nanocomponents across multiple length scales and dimensions:* The self-assembly of soft nanomaterials has been intensively studied for close to two decades. In self-assembled systems, weak noncovalent and electromagnetic interactions may be manipulated to achieve desired, thermodynamically stable, ordered states. A critical challenge moving forward involves the development of new strategies to assemble nanoscale building blocks to achieve states that are highly dynamic and far-from-equilibrium. Addressing this challenge will open the door to materials that display responsive behaviors such as self-healing and adaptivity, mimicking many of the desired behaviors found in biological systems. The design and development of information-encoded building blocks that enable their programmable assembly across various dimensions and length scales are a critical component to realizing more advanced soft materials. Achieving dynamic and far-from-equilibrium states, however, necessitates innovative approaches that dissipate energy during assembly.

CINT maintains a demonstrated capability in the active assembly of nanomaterials that span the nano- to meso-scale and display far-from-equilibrium behaviors. Moving forward, we will expand these efforts to include two new approaches. In the first, external pressure will be used to drive the assembly of nanoparticles into far-from-equilibrium structures by altering the free energy in the system. Here, pressure induced mesoscale assembly enables precise and reversible control over the interparticle separation distances, and modulation of nanoparticle coupling and charge/energy transfer. The second approach will involve enzyme-mediated assembly of nanomaterials, where highly selective protein coupling reactions direct the assembly of protein hydrogels and enzyme/nanoparticle composites. The latter is particularly promising as coupling enzymes to nanoparticles has been shown to enhance their stability and rate of catalysis. This effort will leverage outcomes from our work on enhanced building block synthesis, for example functionalizing specific geometric regions of a particle with specific recognition tags.

Assembly of nanoparticles in fluidic environments is also of interest, where assembly can be programmed in advance through molecular or physical structure or be induced in real time by appropriate stimuli. Magnetic nanoparticles are one of the most versatile systems for directed assembly, while surface functionalization of magnetic or non-magnetic nanoparticles by organic molecules can lead to both self- and directed- assembly. We will continue to develop highly reproducible methods for synthesizing and functionalizing nanoparticles with controlled size and shape. Methods include use of the Microfluidic Discovery Platform™ to place reactions under computer control to enhance both reproducibility and the ability to systematically vary properties. Continued development of coarse-grained and mesoscale simulation methods will enable modeling of these more complex assemblies. A new direction includes the use of machine learning to aid in these syntheses.
Characterization of nanostructured materials achieved from these different methods will leverage CINT’s emerging Cryo-EM capability, in which rapid vitrification of the sample medium allows for an accurate snapshot of a species behavior in solution. This approach effectively freezes assembled structures in their various states, which in many cases will be far-from-equilibrium, and allows for complete characterization using EM techniques. The use of SEM and FIB will also allow for direct imaging and elucidation of the internal structure of such assemblies. Moreover, the length scales relevant to cryo-EM are a good match to those achievable in simulation and polymer theory methods, which will allow direct comparisons between cryo-EM characterization and simulation results to enhance our understanding of far from equilibrium assembly.

3.4 Scientific expertise to realize our vision

Nanomaterials integration involves: (1) Synthesizing and fabricating individual nanoscale building blocks, which may be combined to form specific heterostructures, (2) characterizing their functionalities, (3) understanding and predicting their fundamental chemistry and physics, (4) assembling these building blocks, and (5) delivering a functional material system. The fundamental challenges underlying such integration go beyond complex fabrication or the engineering of known solutions; they lead to novel discoveries and new sciences.

Currently, the four thrusts as described in Section 2 (namely, Quantum Materials Systems, Nanophotonics and Optical Nanomaterials: In-situ Characterization and Nanomechanics; and, Soft, Biological, and Composite Nanomaterials) have already demonstrated their specific strengths and scientific expertise at the international level. A wide variety of activities is being initiated within the four thrusts and our user community, including research activities, user projects, new instrumentation, Discovery Platforms™, and cross-thrust activities. These areas are being developed to be mutually supportive and to maximize their value to our user program and the scientific community. Our internationally recognized expertise in different scientific and technological fields has positioned ourselves in a leadership role in the development of novel capability in supporting users and emerging nanoscience research.

However, as both nanoscience programs and nanomaterials integration continue to evolve in response to new scientific challenges in the scientific community, we will need to not only retain our current workforce to remain in the forefront of nanomaterials integration, but also to strategically hire more scientists and technologists with expertise in fields such as system level modeling, architecture designs, and in situ multi-length scale/temporal characterization of materials to address the dynamic integration challenges and other challenges described in Section 3 to realize CINT’s overall vision of nanoscience.

With our current and expanded expertise, we will maintain our leadership role in nanomaterials integration. Our scientists will continue to actively engage our user community through a variety of mechanisms to promote the integration of nanomaterials and to address new scientific challenges, through both world-leading research and the development of unique capabilities important for the future of nanoscience and nano-manufacturing.
4 Foundational and Transformational CINT Capabilities

Through a combination of research expertise, specialized capabilities, and essential foundational techniques, CINT enables our users to perform multidisciplinary research that would otherwise not be possible. Therefore, to address the research challenges of the future, CINT is continuously improving its current capabilities, exploring concepts that can lead to new experimental, theoretical and computational methods, and selectively disinvesting in capabilities that are no longer state-of-the-art.

In this section, we identify a selection of CINT capabilities that will be important in addressing future integration challenges and that will transform the way integration research is conducted (CINT strategic objective 2). Some involve significant upgrades to current capabilities while others will require entirely new efforts that build on our expertise.

In addition to the specialized capabilities highlighted here, CINT has many more which form an essential foundation for the majority of nanoscience research. The complete list can be viewed on our website. As specified in CINT strategic objective 4, CINT must continue to innovate this infrastructure to have the baseline instruments that all researchers need to properly measure and control the relevant conditions in their experiments.

By virtue of having two DOE host laboratories, CINT is uniquely able to leverage a wide range of expertise plus substantial prior investment in research infrastructure. While there are several examples of this synergistic benefit in our capabilities, perhaps the most differentiating among the DOE Office of Science user facilities is our portfolio of Discovery Platforms™.

4.1 Discovery Platforms™: A CINT signature initiative

The need to reproducibly characterize individual nanostructures or synthesize nanomaterials with exquisite chemical control has inspired CINT to develop Discovery Platforms™. These unique research tools consist of micro-fabricated structures or devices for specific nanoscience experiments. Simple platforms are fabricated in CINT whereas the most complicated devices, essentially a lab-on-a-chip, are designed and produced in cooperation with SNL’s Microsystems Engineering Science and Applications (MESA) facility.

Discovery Platforms™ are conceived, designed, and commissioned with user input and active participation. They allow users to conduct experiments that are not possible using traditional laboratory equipment.

The Electrochemical Discovery Platform™ is a microfabricated fluidic platform designed to study electrochemical energy storage processes in real time inside a transmission electron microscope, as shown in Figure 7. CINT’s Electrochemical Discovery Platform™. This platform enables direct observations of solid/liquid interfacial processes, such as electrode/electrolyte interactions, electrode dissolution in electrolyte, and solid-electrolyte interphase layer formation.

Figure 6. Addressing integration through collaborative capabilities and expertise in fabrication, synthesis, characterization, and theory.

Figure 7. CINT’s Electrochemical Discovery Platform.
The Microfluidic Synthesis Discovery Platform™ is an extremely flexible system for nanoparticle synthesis, functionalization, and real-time characterization. The microfluidic system utilizes an array of glass or plastic chips with channels that can hold volumes from 50 microliters to one milliliter. Design features include droplet forming junctions, mixing segments, and serpentine channels all in a single form factor with a standardized chip header for fluidic connections and precision temperature control. Real-time reaction monitoring via visible and fluorescence microscopy, as well as UV-visible and near-IR spectroscopy are currently being used with mid-IR spectroscopy and dynamic light scattering to be added in the future.

The integration science challenges present exciting new opportunities to develop next-generation versions of the Discovery Platforms™ and to invent additional platforms in conjunction with CINT users designed for the synthesis and characterization of integrated nanomaterial systems (CINT strategic objective 3). As with all platform design cycles, the initial step is to specify the desired functions of a new platform, the performance criteria, and the scope of research for which it is expected to be used. These early platform concepts are then vetted with the external scientific community via Discovery Platform™ Workshops and focused sessions at the CINT Annual Meeting.

A central issue in the development of multi-scale materials is large-scale predictive assembly of nanoscale building blocks (e.g. colloidal nanoparticles, polymers, proteins, etc.) into functional mesoscale assemblies. One approach to address this limitation is the development of experimental systems that can achieve reproducible synthesis and most importantly, assembly of the building blocks. Work in this area will build on CINT’s Microfluidic Discovery Platform™ and expand into more complex architectures that enable the rapid prototyping of molecular building blocks, as well as the controlled assembly of soft matter, particularly into 3D mesoscale assemblies. In a new development, there will be a strong emphasis on integrating the Microfluidics Discovery Platform™ with new capabilities and techniques developed as part of the in-situ characterization effort, as described above. The key objective will be developing new Discovery Platforms™ that enable tight coupling of in-situ characterization and microfluidic delivery, enabling real-time control over multi-scale, hierarchical assembly.

4.2 Synthesis and fabrication
Creating novel and integrated nanomaterials requires robust methods to reproducibly synthesize nanoscale constituents with known composition and structure, rigorous control of assembly processes to organize the components (“bottom-up assembly”), and microfabrication tools (“top-down fabrication”) to prepare architectures that connect nano-to-macro length scales. CINT currently offers and continuously develops these state-of-the-art capabilities including the following.

**Semiconductor molecular beam epitaxy (MBE)**
The two CINT systems are in demand worldwide to grow high-purity, ultra-high mobility AlGaAs-based III-V compound semiconductor structures with atomic monolayer precision for fundamental studies of 1D and 2D nanomaterials, as well as nanophotonic materials, including quantum cascade lasers and quantum well infrared photodetectors. Our future plan includes the addition of Indium to both machines to allow the growth of strained In-alloys on GaAs substrates and strained In-alloys on InP substrates.

**Heteroepitaxial growth**
Nanocomposite films with specific electrical, optical, magnetic, thermal, and/or superconducting properties are grown by pulsed laser deposition (PLD), polymer assisted deposition, and laser MBE. Upgrades in progress will enable us to grow epitaxial nanocomposite films incorporating nanoparticles of controlled particle sizes and densities at desired locations.
Quantum materials synthesis
CINT has synthesis capabilities for 2D TMDCs and topological insulator (TI) thin films via solid source chemical vapor deposition (CVD) and pulsed laser deposition (PLD). Future directions are heterostructures composed of quantum materials for novel functionalities and scaling up with precise control of physical characteristics of 2D TMDCs and TIs. Metalorganic CVD and physical vapor deposition with an in-situ monitoring system of quantum materials growth will be developed.

Nanowires
CINT specializes in the synthesis of semiconductor nanowires by solution-phase, CVD, and physical vapor deposition (PVD) approaches to produce single crystal nanowires, radial/axial heterostructured nanowires, and complex architectures consisting of Si/Ge and compound (II-VI and III-V) semiconductor materials. Future directions include advances in atomic-level control to introduce embedded quantum dots and quantum wells, for example.

Atomic-precision fabrication
One of our newest capabilities enables placement of dopant atoms into silicon with atomic-scale precision by using hydrogen resist lithography combined with scanning tunneling microscopy. This technique yields the ultimate in atom-by-atom construction of nano-electronic devices. CINT is one of only a few institutions in the world with this capability and the only user facility to offer the capability (Figure 8).

Integration laboratory
This fabrication laboratory is a class 1000 cleanroom with a comprehensive suite of micro/nanoscale tools including atomic layer deposition (ALD), low pressure CVD, PVD, electron beam and photo lithography, and focused ion beam. Future capability enhancements include: the creation of a soft lithography capability to enable users to fabricate and integrate soft/hard nano/microstructures; expansion of deposition/etching tools to meet user demand; addition of noble metal ALD; and, replacement of legacy tools with the current state-of-the-art in commercial instrumentation.

Solution phase synthesis of optical nanomaterials
CINT is pioneering new optical nanomaterials with advanced functionality and the methods used to create them. We have developed a suite of novel photostable quantum dots that afford non-blinking and non-photobleaching emission from the visible to the infrared. Like other colloidal nanoparticles, these quantum dots are solution processible and can be used as “inks” in the production of thin films, polymer composites, or integrated devices. Their enhanced stability affords chemical robustness and the ability to perform otherwise inaccessible experiments. CINT also possesses a fully automated batch reactor system (FABRS) and a microfluidic setup for substrate-supported synthesis in-flow. These custom synthesis tools enable multistep (>100) reactions to be conducted under software control and solution-phase nanowire growth akin to a CVD process, respectively. Together, the unique methods support new materials discovery and optimization, as well as rapid data acquisition and a pathway toward in situ monitoring and control of reactions ‘on-the-fly.’

Chemical vapor deposition capability for growth of semiconducting nanowires and thin films
Our 3-inch wafer-scale cold wall CVD reactor allows preparation of high-quality and electrically-doped nanowire and thin film heterostructures with well-controlled axial or radial interfaces. We offer a unique capability for flowing metal-organic precursors that provides fine control over elemental composition of catalyst seed particles and abrupt interface generation. This capability
is thus available for generation of a wide range of material types, compositions and architectures (including Si/Ge, III-V, and other compound semiconductor materials), for exploration of light emission, energy harvesting, energy storage, and optoelectronics applications.

**Carbon nanotube processing**

Development of carbon nanotube-based materials is enabled by CINT’s processing capability in both aqueous and organic media. Nanotube samples may be provided as surfactant or polymer suspensions and in sol-gel, aerogel, and polymer matrices. We use state-of-the-art density gradient and aqueous two-phase processing approaches to separations of semiconducting and metallic tubes and by single chirality with expertise for generating filled and empty tubes of variable length. Non-covalent functionalization methods are providing systems for fundamental surface chemistry studies and for the understanding of separations mechanisms. We are pioneering low-level covalent doping strategies via solution and solid-state methods for the introduction of new photoluminescent emitting states of interest for enhancing quantum yields and introducing new functionality.

**Fabrication of metamaterials and plasmonic nanostructures**

World-class tools for lithographic fabrication to sub-10 nm length scales and epitaxial growth form the core of CINT’s world-leading creation of innovative concepts in nanoresonator/nanoantenna, metamaterial and metasurface for manipulation of light. Fabrication with active and passive metallic, semiconductor, dielectric, complex multiferroic, and emerging 2D materials can all be met to generate hyperbolic metamaterials and arrays of meta-atom structures on few-layer heterostructures. Realized functionality includes anomalous refraction, flat optics, customized thermal emission, wavefront engineering, and active control of response such as polarization and phase, and the ability for light concentration and spectral tuning. Light manipulation can be attained from THz to near-IR. Fabrication efforts are strongly supported by off-the-shelf simulation packages running in high-performance workstations and a unique set of CINT-developed capabilities in functional nanomaterial integration including integration with semiconductor heterostructures grown by high quality molecular beam epitaxy.

**Dip pen nanolithography (DPN) for nanointegration**

As a scanning probe lithographic technique, the CINT DPN capability is highly complementary to other lithographic approaches for materials integration and heterostructure generation. We have advanced the tool for delivery of liquid inks onto any desired substrate with precise positioning in the nanometer range. Our focus is on extending DPN to “large” (10-50 nm diameter) nanocrystals mixed into simple solvent carriers, with an ability to write controlled numbers of nanocrystals—from single to monolayer spots or lines—onto 1D, 2D, and 3D pre-patterned structures of both soft and hard materials. Integration of optical emitters to dielectric optical antennae, plasmonic structures, and metamaterial assemblies has been demonstrated (Figure 9).

![Figure 9. DPN using a quantum dot ink.](image)

**Flow-reactor synthesis of nanoparticles**

A computer controlled microfluidic synthesis platform that is capable of both systematic variation of synthesis and continuous synthesis without variation. The system features real time
spectroscopic detection of nanomaterial properties to provide feedback and control of materials synthesis.

**Expression and purification of engineered functional biomolecules**
A library of engineered biomolecular machines to enable their integration and control for the fabrication of hybrid nanomaterials and systems. As an example, kinesin motors that contain a unique ion-binding site that may be used as a molecular on/off switch for motor function.

**Amphiphilic monomers/polymers for preparation of durable artificial membranes**
These techniques can be used to prepare polymersomes, supported lipid bilayers, and genetically encoded polymers. Custom synthesis of monomers that can be self-assembled into organized mesophases and captured into durable yet stimuli-responsive polymer networks. These networks are hierarchically ordered and can be used to order nanoparticles across multiple dimensions.

### 4.3 Characterization
CINT’s current characterization capabilities include an extensive array of differentiating techniques to determine structural coordinates with atomic resolution, chemical composition, and temporal behavior for individual nanostructures to complex integrated environments. Our future emphasis will be to develop methods to extract such information from increasingly complex hierarchical materials with nanoscale to mesoscale complexity. The development of advanced probes plays a critical role in high-impact nanoscience discoveries and innovation of next generation technologies.

**Transmission electron microscopy (TEM)**
The capabilities at CINT offer an array of in-situ techniques for correlating dynamic structural information with associated electrical, mechanical or compositional changes. CINT Discovery Platforms™ are routinely employed as in-situ TEM sample holders to provide unprecedented fundamental information on liquid/solid interfacial reactions, individual nanowires, and related structures. CINT has recently expanded its TEM capabilities with the addition of a corrected environmental TEM with a Gatan K2 single electron camera. This camera greatly increases the potential systems that can be investigated using CINT’s Discovery Platforms™ by minimizing beam damage by up to two orders of magnitude. CINT future plans for TEM include: significantly expanding our capacity to meet the consistent demand for instrument time by highly-ranked user proposals, and developing the expertise/techniques for soft/composite nanomaterials microscopy needed by the integration challenges in Section 3.

**Liquid cell Discovery Platform™**
The CINT Liquid Cell Discovery Platform™ is an in-situ TEM sample holder that allows for quantitative measurements of nanoscale electrochemistry and nanoscale chemical reactions with an integrated lithographically defined heater. Future plans for this platform include adding a mechanical actuation stage.

**Nanomechanics**
CINT is currently the only NSRC with a dedicated nanomechanics capability, including high-throughput statistical measurements at the nanoscale under ambient or multiple extreme environments (e.g. temperature, radiation, fatigue, shock) in combination with dynamic observation of mechanisms using a variety of in-situ TEM and SEM test platforms. Beyond modulus and strength, the CINT tools can be used to explore a broad range of relevant physical processes from tribological degradation to interfacial delamination. Nanoscale measurements are complemented with micro- to macro-scale capabilities for an integrated multi-scale experimental suite.
Quantum transport
The quantum transport capability includes multiple instruments configured for measuring low temperature electrical transport in semiconductor devices. We have demonstrated single shot electron spin measurements and rapid pulsing of the semiconductor nanostructure energy levels using these advanced techniques.

Surface sensitive probe
The low energy electron microscope (LEEM) is a unique and versatile surface microscope that can be used to view dynamic processes on surfaces in real time with a spatial resolution of 7-8 nm and a depth resolution of one atomic layer. We extend this capability to conduct photoemission electron microscopy (PEEM) by the addition of various UV sources to enable probing of the electronic structures of surfaces and nanomaterials. Future developments include the addition of deep-UV CW lasers, which will support high lateral resolution (10-20 nm) electronic structure mapping and magnetic imaging of surfaces and nanomaterials, and an in-operando microscopy capability with electrical biasing.

Ultrafast optical spectroscopy
Ultrafast optical spectroscopy offers an unmatched ability to differentiate the dynamics of spin, charge, and lattice, and the coupling between them in both time and spectral domains with femtosecond temporal resolution. CINT has a full range of time-integrated and time-resolved optical tools, covering terahertz through soft x-ray frequencies, to investigate the fundamental mechanisms of a wide range of nanostructured materials from physical to chemical to biological systems. A multitude of ultrafast experiments can be performed, including: optical pump-probe spectroscopy over the full frequency range, time-resolved photoemission spectroscopy and second harmonic generation, optical Kerr/Faraday spectroscopies, and ultrafast optical microscopy. All measurements may be done from 4K to room temperature and under strong magnetic fields (up to 8 T). Examples of recent applications include studies of multiferroic magnetoelectric coupling dynamics, ultrafast carrier diffusion in individual semiconductor nanowires, ultrafast photocurrents in topological semimetals, and ultrafast switching of metamaterials.

Advanced optical imaging and spectroscopy of single and multiple nanostructures
Optical characterization at the single nanostructure level is essential for revealing behaviors hidden in ensemble-level measurements and for providing spatially-correlated probes. CINT offers multiple scanning confocal laser microscopes for performing photoluminescence (PL) and PL excitation spectroscopies, as well as super-resolution, lifetime, and back-focal plane imaging operations. Direct wide area PL imaging is also available and provides simultaneous correlated imaging at multiple wavelengths. Instrumentation covers the spectral range from 350 nm to 1700 nm, and may be paired with a capability for controlling temperature (4-450K) and gas and humidity of the sample environment. A time-correlated single photon counting capability also provides time-resolved PL and photon correlation/cross-correlation measurements using Si and InGaAs avalanche-photodiodes covering UV to near-IR wavelengths. Of particular note is a new EOS 410 superconducting nanowire single photon detector for ultrafast PL measurements in the near-IR. A cooled-cathode streak camera (temporal resolution ~ 2ps) and a fluorescence up-conversion system (temporal resolution ~ 150fs) are also available for time-resolved PL measurements. This capability also includes instrumentation for performing magneto-PL and magneto-Raman spectroscopies to the single nanostructure level in magnetic fields up to 9 Tesla.

Fully-tunable Raman spectroscopy and microscopy
CINT resonance Raman instrumentation provides a capability for materials characterization via vibrational fingerprinting, probing of electronic structure, electron-phonon coupling, and lattice
response to external perturbation for a wide range of nanomaterials types. Employed as an imaging technique via integration of excitation sources to confocal imaging microscopes, we also provide spatial correlation with other spectroscopic imaging data to provide multi-modal analysis at bulk, thin-film, and single nanostructure levels. Our systems provide unique access to broadly tunable excitation sources, with continuous tunability from 345 nm to 1000nm. Among the many materials studied with Raman at CINT, examples include carbon nanotubes, graphene and other 2D materials, SERS-active structures, bio and soft-material composites, quantum dots, nanowires, and multiferroic complex oxides.

3D tracking microscope
Unique spatial filter geometry and active feedback in XYZ allows sub-diffraction limit measurement of the three-dimensional trajectories of fluorophore-labeled nanoscale objects moving at biologically relevant transport rates (μm/s).

Bessel beam plane illumination microscopy
An alternative to conventional laser scanning confocal microscopy that enables rapid (100 frames per second) imaging in three-dimensions. Bessel beam plane illumination microscopy can be used for rapid 3D imaging of live mammalian cells and to study the 3D dynamics of select soft materials (e.g. diblock copolymer annealing, polymersome fusion).

Super resolution fluorescence microscopy
This instrument provides optical images of fluorescently labeled samples at a spatial resolution of ~10-20 nm, approximately a factor of ten below the diffraction limit (~250 nm) and approaching that of electron microscopy.

Scanning probe spatially correlated atomic force microscopy (AFM) and fluorescence imaging
A combination of optical spectroscopic and topographic information combines single-molecule fluorescence sensitivity with time-correlated single-photon counting (TCSPC) using pulsed laser excitation. Intensity or lifetime images of single emitters can be acquired and spatially registered with AFM images of the same area.

Environmental scanning force microscopy
Scanning force microscope (Asylum) that can measure force between cantilever probe and surface providing information on adhesion and binding. Instrument features humidity control and an extended piezo with a Z-range of 40 mm.

Apertureless scanning near-field optical microscopy
Near-field microscopy overcomes the diffraction limit in optical imaging and spectroscopy, therefore representing an extremely important tool in CINT for the investigation of a host of integrated nanophotonic structures and devices. Combining atomic force microscopy (AFM) with optical imaging and spectroscopy, the apertureless scanning near-field optical microscope (a-SNOM) we acquired recently from neaSpec GmbH allows a spatial resolution of 10-20 nm throughout the electromagnetic spectrum from far infrared (THz) to visible. Local optical properties can be examined via measuring the elastically scattered light resulting from the optical near-field interactions between the metal-coated or dielectric tip and the sample. It allows for subwavelength imaging across a broad portion of the EM spectrum, particularly in the mid-infrared wavelengths ranging from 4.7 to 15.3 μm, and the terahertz frequency range (0.3-3 THz). The a-SNOM also includes a pump-probe capability employing two femtosecond laser sources at 1560 nm and 780
nm. The capability is further enhanced by expertise provided by personnel in the Nanophotonics and Optical Nanomaterials thrust and the LUMOS team. This capability will allow us to investigate complex physical behaviors in systems including, but not limited to, strongly correlated materials, plasmonic response and wave propagation in 2D materials (e.g. graphene and quantum wells), nano-wires and carbon nanotubes, resonances in metamaterials, and other nanostructured functional photonic devices.

**Holographic optical trapping**
Non-contact manipulation of objects suspended in aqueous solutions using holographic optical trapping. The Arryx holographic optical trapping system allows the trapping and manipulation of small objects in 3 dimensions.

**Small- and wide-angle x-ray scattering**
A commercial instrument (Bruker Nanostar) offers the possibility to rapidly evaluate structure of self-assembled soft materials on the Å to 100’s of nm length scale. Sample temperature can be controlled from 5°C – 85°C.

### 4.4 Theory, simulation, and modelling
The unique properties of nanostructured and quantum materials cannot be fully exploited without a predictive understanding of the underlying phenomena. This requires a spectrum of theory/simulation techniques developed and optimized not only for the nanomaterial and quantum material component itself, but also for its interactions with surrounding components and materials. In addition to foundational capabilities like density functional theory (DFT) for electronic, optical, and vibrational properties of solids and nanostructures, some of the specialized techniques being used, under development, and planned include:

**Photoexcited dynamics**
Among these tools, the Nonadiabatic EXcited-state Molecular Dynamics (NEXMD) framework developed by CINT scientists can efficiently and accurately describe photoinduced phenomena in extended molecular systems. It uses the fewest-switches surface hopping algorithm to treat quantum transitions among multiple adiabatic excited state potential energy surfaces. We achieve an accurate description of the multiple excited states by using the configuration interaction single formalism with a semi-empirical model Hamiltonian. The NEXMD methodology offers a computationally tractable route for simulating hundreds of atoms on ~10 ps time scales where multiple coupled excited states are involved. The software is approved at LANL for unlimited release for the broader scientific community.

**Molecular electronic structure database for machine learning (ML) algorithms**
CINT is building a database of high-fidelity quantum-chemical computational results based on the extensive set of over 20 million molecular structures. The calculations were initially performed using a DFT approach and recently calculated in part with a very accurate Coupled Cluster (CCSD(T)) method. The inputs to the calculations are molecular geometries. The outputs contain molecular property information including molecular forces, molecular orbitals, orbital energies, electron densities, multipole moments, localized charges, bonding indices, energy decomposition, steric analysis, and resonance structures. The purpose of this data is to facilitate the construction of machine learning algorithms for energies and properties of molecular and solid state systems.

**Ultrafast quasiparticle dynamics**
CINT is pioneering the theoretical modeling of ultrafast quasiparticle dynamics in strongly correlated electronic materials. In particular, our time-dependent Lanczos approach to electron-phonon and exciton-phonon coupling in solids keeps the full quantum nature of the problem. Our numerically exact approach has been shown to be many orders of magnitude more powerful than
other competing methods. It not only provides microscopic insight into the quasiparticle relaxation process but also guides the further development of phenomenological and effective modeling in complex materials. We will generalize this exact approach to treat the electronic correlation effects. We also plan to develop the time-dependent dynamical mean-field theory and density matrix renormalization group theoretical approaches to tackle correlation effects in high and low dimensional quantum material systems.

Electronic structure with correlations
CINT is also pioneering the theoretical modeling of local electronic structure with strong correlations. This capability has been applied to understand the bulk properties of correlated electronic materials by studying the electronic signatures around local impurities and defects. We have also developed quantum many-body approaches (Quantum Monte Carlo and Gutzwiller Variational Wave Function) into DFT-based first-principles method to tackle the problems of quantum impurities in an otherwise uncorrelated environment. The method will enable us to understand the material-specific localization and delocalization phenomena in quantum materials with strong electronic correlations. We have recently built a first-principles informed tight-binding modeling approach to model quantum materials at a larger scale and added a capability to analyze the topology of quantum materials. CINT has a track of record in applying the GW method (where G = Green's function and W = screened Coulomb interaction) to study the quasiparticle excitation properties in solids, including actinides and the recently discovered perovskite solar-cell materials. We plan to develop a GW-BSE capability within a full-potential based electronic structure method, which enables us to treat more accurately the excitonic properties in semiconductors with strong spin-orbit coupling.

Model for soft materials and interfaces
CINT scientists have developed methods to model soft materials and the interface between soft and hard materials for systems such as polymer nanocomposites, biomolecule/materials and nanoparticle self-assembly using classical density functional theory, self-consistent field theory, molecular dynamics simulations, and Monte Carlo simulations. CINT scientist have contributed to LAMMPS, Sandia’s highly parallel molecular dynamics code, particularly its capability to model nanoscale phenomena over multiple length scales through the introduction of efficient methods for modeling polymer nanoparticle composites, long range dipolar interactions, and atomistically inspired coarse graining of polymer. CINT staff have developed polymer self-consistent field theory codes to calculate self-assembled patterns and phase behavior of tethered polymeric systems. They also continue to develop Sandia’s Tramonto code, a classical density functional theory code that describes equilibrium behavior of complex fluids in inhomogeneous environments, particularly at the nanoscale.

4.5 Leveraging capabilities

Laboratory for Ultrafast Materials and Optical Science (LUMOS)
The LUMOS facility is equipped with ultrafast laser systems covering a broad spectral range that spans the far-infrared to the soft X-ray portion of the electromagnetic spectrum. These systems enable a multitude of ultrafast spectroscopic and imaging experiments, including optical-pump THz-probe spectroscopy, high harmonic generation/extreme ultraviolet spectroscopies, and scanning probe imaging and spectroscopies. These capabilities enable us to understand and control the interaction of photons with the electronic, spin, and structural properties of materials on an ultrafast time scale for scientific and national security missions.

Ion Beam Materials Laboratory (IBML)
The core of the IBML consists of a 3 MV NEC tandem accelerator, a 200 kV Varian ion implanter, and a 200 kV Danfysik ion implanter together with several beam lines. The research capabilities
include routine ion beam analysis techniques such as Rutherford backscattering spectrometry (RBS), nuclear reaction analysis (NRA), elastic recoil detection (ERD), particle-induced alpha- or gamma-ray emissions (PIXE or PIGE), and ion channeling, etc.; ion-enhanced synthesis and modification of materials through ion implantation; and ion irradiation damage effects in materials, including complex oxide ceramics, metals, semiconductors, and polymers.

**Microsystems Engineering and Science Applications Complex (MESA)**

SNL has a significant role in advancing the state-of-the-art in Microsystems research and development, and in introducing Microsystems into the nuclear stockpile. Microsystems incorporate radiation-hardened microelectronics as well as other advanced components such as micromachines, optoelectronics, and photonic systems. The **MESA Complex** is designed to integrate the numerous scientific disciplines necessary to produce functional, robust, integrated Microsystems and represents the center of Sandia’s investment in Microsystems research, development, and prototyping activities. This suite of facilities encompasses approximately 400,000 square feet and includes cleanroom facilities, laboratories and offices. CINT currently leverages this NNSA resource by partnering with MESA staff in the design, development, and production of sophisticated CINT Discovery Platforms™. We are planning to further leverage MESA by bringing selected compound semiconductor synthesis capabilities into the CINT user program.

**In-Situ Ion Irradiation Transmission Electron Microscopy Facility (I3TEM)**

SNL’s I3TEM facility combines a 200 kV JEOL 2100 high-contrast TEM (2.5 Å point resolution) with a 10 kV Colutron and a 6 MV Tandem accelerator. The I3TEM facility can permit a wide breadth of combined experiments in high temperature, flowing liquid, gas exposure, mechanical loading, displacement damage, gas implantation, and numerous sequential or simultaneous combinations thereof to evaluate the structural evolution that occurs during ion beam modification or overlapping combinations of extreme environments.

### 4.6 Future envisioned capabilities

Quantum research is at a critical threshold, with exciting opportunities for fundamental research as well as enormous potential for developing new quantum-based technologies. CINT is developing two new QIS projects, one focusing on the deterministic placement of quantum defects and the other developing quantum sensed nuclear magnetic resonance spectroscopy. Not only will this work bring many transformational advances in QIS research, the new capabilities will also enable the CINT user community to explore new frontiers in QIS, potentially opening the door to quantum information technologies that were previously considered impossible.

Solitary atomic defects capable of mimicking the quantum mechanical behaviors of individual atoms are considered the key materials for many revolutionary quantum information technologies. These defects can serve as fundamental building blocks for technologies ranging from ultrasensitive magnetic field sensors to eavesdropping proof communication schemes and neuromorphic quantum computers. However, the realization of these technologies is hampered by the fact that researchers must primarily rely on serendipitously discovered, naturally formed defects. This means there is no control over the properties of the defects or their placement into devices. CINT aims to change that by developing two complementary strategies for 100% deterministic creation of defects that would also allow seamless integration of defects into nanoelectronic and photonic integrated circuits. The top-down strategy will be based on ion implantation technologies, expanded to demonstrate the deterministic creation of defects not only in bulk crystals (diamond and GaN) but also in low dimensional nanostructures (2D TMD and 1D...
SWCNTs). The bottom-up strategy will involve the development of a new technology for ‘soft’ chemical implantation of quantum defects into 1D SWCNT and 2D VDWs.

CINT’s second QIS project will use a quantum qubit’s extreme sensitivity to magnetic fields to create a unique Quantum Sensed Nuclear Magnetic Resonance (QSNMR) Discovery Platform™ for magnetometry and nuclear magnetic resonance (NMR) spectroscopy at the smallest scale possible—a single spin—requiring orders of magnitude fewer spins than the most advanced techniques available today. The QSNMR Discovery Platform™ will be based on the fabrication of qubits using precise placement of nitrogen-vacancy centers in diamond substrates to serve as a quantum sensor for nanoscale NMR experiments. This will enable us to craft customized nanomagnetometer arrays that will allow CINT’s users, scientists, and research partners the ability to conduct NMR at unprecedented scale and resolution. This capability will enable the measurement of the magnetic properties inaccessible by any other means, in materials such as nanoparticles, topological materials, 2D atomic materials, polymers, single molecules, and biological materials.

In addition to these future QIS capabilities, we also envision developing capabilities in a number of other areas.

CINT will be installing a new cryo-EM suite (Figure 11) including a dedicated cryo-TEM and a dual beam SEM/FIB with cryogenically cooled stage. Hydrated samples will be rapidly vitrified allowing for imaging in their native state present in solution, removing the drying effects inherent in standard EM imaging. The TEM is designed for imaging at low keV with minimal electron dose for the characterization of beam sensitive materials. The FIB capability on the SEM enables serial sectioning and imaging, including lift out and transfer to the TEM, thereby covering all length scales of soft matter and nanomaterials characterization.

CINT is planning a significant expansion of our available excitation ranges for Raman spectroscopy. We envision adding a wavelength-doubled dye laser system to our current doubled-Ti:Sapphire excitation source to push excitations to wavelengths as short as 270 nm. The extended UV excitations will enable us to probe currently inaccessible electronic transitions and energy ranges and expand the set of materials types we can study.

Femtosecond mid-IR microscopy is being planned to provide complementary capability to our other optical microscopies. Of particular interest will be opportunities for new studies in extended wavelength response and dynamics of emerging metamaterials and for probing of phonon coupling and control in opto-mechanical and heterostructured materials.

Expansion of single photon detection capabilities to the mid-IR is under construction using a combination of nonlinear up-conversion techniques. CINT will evaluate the procurement of single-photon superconducting nanowire detectors operating at longer wavelengths if they become available, which will complement our detectors operating in the near-IR.

CINT’s newest theoretical capability under development with users is a computational suite with DFT-informed tight-binding modeling of strongly correlated electron materials. It has the potential to include molecular dynamics with the tight-binding empirical parameters certified by DFT simulations. The method is targeted to address a plethora of emergent phenomena in transition-metal oxide nanocomposites.

In response to the rapid progress of hybrid structures involving nanoscale semiconductors and metals, we will expand our foundational single-band scattering matrix approach to develop a
multiband theory of electronic and optical properties, and the charge and energy transport through the hybrid structures.

To access longer time and length scales, CINT scientists are developing coarse grained models for treating soft materials on multi-length scales. These models along with enhancement to SNL’s parallel molecular dynamics code LAMMPS to run on GPUs and the new high-performance architectures will provide unprecedented capabilities to model soft materials.
5 Engaging the Scientific Community

Realization of our vision of nanoscience integration will continue to require the active engagement of our user community through a variety of mechanisms that both promote the essential practices of integrating nanomaterials and serve to build robust communities around key integrations challenges that by their very breadth and complexity transcend individual project/investigator efforts.

One of CINT’s main goals is to attract research leaders in diverse institutions, early career scientists, and innovators in nanotechnology companies to create an expanded user community. To achieve this, it is necessary to target outreach activities that would increase awareness of our existing portfolio and capabilities within this identified group. We must have continued presence in high-profile journals, organize symposia at national meetings and targeted workshops on nanomaterials integration challenges, host high-profile seminar series, and demonstrate the full suite of CINT capabilities so users will know how to utilize our expertise within all aspects of integration. We plan to take advantage of the NSRC Portal as one way for users to identify CINT capabilities and expertise.

CINT’s unique and distinguished capabilities and expertise are already attracting a collection of experts and young scientists dedicated to solving challenges in nanoscience and nanotechnology. Through these networks we have begun, and will continue to develop, collaborative communities of scientists sharing ideas and working together to speed up development of the technological innovations that will come from solving these challenges.

To best take advantage of the user facility model, we are currently working on the development of partner user agreements. These partner users would receive guaranteed access in return for an investment in CINT. While investment in an instrument is most common, other forms of investment from a partner user could include intellectual investment or expertise shared with CINT staff and other users. Partner user agreements will assist us in remaining in the forefront of nanoscience, through the development of new, targeted capabilities.

The success of nanoscience integration will be in the ability to incorporate the basic science techniques within an engineering application. CINT is in a unique position to bring together the science and engineering expertise of LANL and SNL to expedite the development of nanomaterials integration. Our users and staff have an established working relationship with engineers at SNL to design and develop Discovery Platforms. This is a partnership that will continue and broaden as nanoassemblies become included in chips and other electronic devices.

Figure 12. The NSRC booth at the 2018 Fall MRS Meeting.
6 Operational Excellence

CINT has increasingly developed an identity that transcends Laboratory boundaries, striving for operational “best-in-class” performance at the Center. Efficiency is at the forefront of our business operations focus. We have adopted and embedded standard project management principles and methodologies that continue to be applied throughout the Center to ensure operational efficiencies and impactful cost savings.

The realization and implementation of the online User Program Management System will allow us to improve business intelligence operations throughout the Center. This system allows for creating workplace efficiency by leveraging digital technology to decrease manual hours lost on easily automated tasks and to enable the support of an increased number of users. The tool will increase data accuracy and maintain a shared repository that will provide historical, current and predictive views. This data will allow CINT to track trends in the user program to allow for better decision-making in capability development and stay abreast of increasing science focus areas within our user communities.

With the pool of dedicated scientists available through our Users Executive Committee, Science Advisory Committee, and users in general, CINT is well poised to look for trends in nanomaterials integration across the nation and the world. Between these personal interactions, and the ability to see trends across the user program, CINT will be poised to respond to the needs of the nanoscience community. This information will help to fill gaps in available capabilities, both through the development of specialized instrumentation and in the collective expertise of CINT staff and user community. Strategic hires of scientists, technologists, and postdoctoral researchers will be based around the needs of the community and addressing integration grand challenges.

As with any business operation, CINT is constantly benchmarking best practices for improving on processes and procedures. We have the opportunity to lead the complex in improving cross-laboratory processes, in particular with our activity in creating a safety-training program that is acknowledged at both LANL and SNL.
7 Implementation

CINT2024 presents a vision for potentially revolutionary new technologies that would be enabled by integrating nanostructured materials to exploit their size-dependent properties or emergent collective properties. Realization of this opportunity requires a sustained effort by researchers to tackle more complex nanosystems; however, the optimal methods to do so may not necessarily exist today or may not be available to researchers with extraordinary ideas and insights.

CINT’s differentiating focus on nanomaterials integration and established operation as a DOE Office of Science user facility with a vibrant, growing user community, position us to be a leader at this new frontier in nanoscience. Our six strategic objectives, listed in Section 2, drive us towards the goal of being the national resource for research expertise and unique capabilities to synthesize, fabricate, characterize, and understand nanostructured materials in increasingly complex integrated environments.

This strategy involves harnessing the intellectual leadership and scientific expertise of our staff and users (objectives 1 and 6) by adding CINT scientists and attracting international experts as CINT users. A second strategy complements the people in our community with the capabilities that we invent or optimize for integration research (objectives 2, 3 and 4), thereby ensuring that CINT is unsurpassed as an institution for our chosen areas of nanoscience. In an increasingly competitive world, CINT must also continuously focus its efforts and resources on the potentially most impactful research opportunities (objective 5). This will be done through organized CINT workshops, the CINT Annual Meeting, joint-NSRC workshops, focused symposia at major national scientific conferences, and consultation with the CINT Scientific Advisory Committee and the CINT Users Executive Committee.

When the National Nanotechnology Initiative was launched over a decade ago, the nation was at the dawn of the next technological revolution. Since then, amazing scientific discoveries have validated the promise that nanoscale is different. Just as integration transformed the transistor into the integrated circuit, now the scientific community is prepared to reveal even greater wonders by learning how to build a world of multifunctional materials and systems that can begin to rival the exquisite examples we see every day in nature.