Institute for Soldier Nanotechnologies

Founded in 2002, the Institute for Soldier Nanotechnologies (ISN) is a three-member team designed to leverage the unique capabilities of the US Army, industry, and MIT. The ISN mission is to help the Army greatly improve the survivability of soldiers by working at and extending the frontiers of nanotechnology through basic research, and by transitioning (through technological maturation and scale-up) promising outcomes of that research in collaboration with ISN's Army and industry partners. This mission includes not only decreasing the weight that soldiers carry but also improving blast and ballistic protection, creating new methods of detecting and detoxifying chemical and biological threats, and providing physiological monitoring and medical treatment. The ultimate goal is to help the Army create affordable, integrated systems of nanotechnologies that combine high-tech protection and survivability capabilities with low weight, increased comfort, improved performance, and better compatibility with the end user.

Funding for ISN basic research has been more than $150 million over 15 years, with the majority of these funds having been dispensed through a series of renewable five-year contracts—ISN-1, ISN-2, and ISN-3—that the US Army Research Office administers. The Army has provided nearly $20 million in additional funds to facilitate the transitioning of promising outcomes of ISN research to the next stages of development, with the bulk of these funds distributed to ISN partner companies. There is also substantial co-investment by industry partners and MIT. Following a series of reviews by the Army, ISN was approved for its fourth five-year contract in 2017. That contract, ISN-4, is expected to go into effect on January 1, 2018.

More than 25 faculty members from a dozen MIT academic departments, as well as more than 100 graduate students and postdoctoral associates, participate in ISN research. ISN research typically results in more than 125 refereed publications annually, including papers in such distinguished scientific journals as *Science, Advanced Materials, Nature, Physical Review Letters*, and the *Proceedings of the National Academy of Sciences*. More than 350 people have visited ISN over the past year for briefings on research endeavors and tours of ISN facilities. Of particular note, General Gustave Perna, commanding general of the US Army Materiel Command, visited ISN headquarters in May 2017.

Research

ISN's signature interdisciplinary research agenda evolved over the course of its first 10 years into a focused program reflecting the areas where ISN and the Army see the potential for especially strong effects on soldiers' welfare. For ISN-3, this structure was updated and redefined to align better with, and respond more efficiently to, guidance from the Army while working within the constraints of Army budget reductions. Team-based innovation is a hallmark of ISN's intellectual course, with new ideas and collaborations emerging frequently. The ISN research portfolio is currently divided into three strategic research areas that are, in turn, further divided into research themes and then into specific projects.

Strategic Research Area 1: Lightweight, Multifunctional Nanostructured Materials & Fibers

Theme 1.1 Optoelectronic phenomena in nanoparticles

Theme 1.2 Photonic structure in atomic monolayers

Theme 1.3 Elementary excitations and dynamics in fiber platforms

Theme 1.4 Optical resonance phenomena in nanostructured materials

Theme 1.5 Novel photonic crystal and metamaterial phenomena

Strategic Research Area 2: Soldier Medicine—Prevention, Diagnostics, Far-Forward Care

Theme 2.1 Cellular immune response and nanoengineered drug delivery

Theme 2.3 Synthesis and characterization of therapeutic nanoengineered materials

Strategic Research Area 3: Blast and Ballistic Threats—Materials Damage, Injury Mechanisms, Lightweight Protection

Theme 3.2 Grain and phase boundary manipulation in nanocrystalline metal alloys

Theme 3.3 Physical, biological, and physiological mechanisms of injury

Theme 3.5 Novel carbon-based nanostructured materials

Transitioning

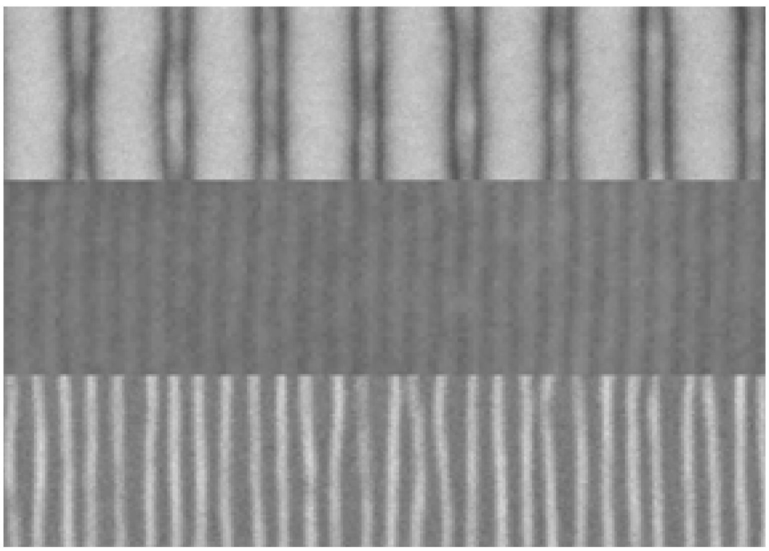
ISN places a strong emphasis on basic research. However, the transitioning of promising outcomes of that research is also a crucial component of the ISN mission. To this end, ISN works with the Army, industry partners, startups and other companies, and with the MIT Technology Licensing Office, to help ensure that promising ISN innovations leave the laboratory and make it into the hands of soldiers and first responders as rapidly and efficiently as possible. ISN is pleased to have an Army Research Laboratory–Army Research Office technology transfer officer on its headquarters team. It is the technology transfer officer's charge to help maximize the effectiveness and efficiency with which ISN technologies progress from the laboratory bench to more advanced stages of development.

ISN has been the source of several important technology transitions. Notably, the recently founded Advanced Functional Fabrics of America Manufacturing Innovation Institute, initiated by the US Department of Defense and led by MIT as part of the National Network for Manufacturing Innovation, is based on foundational ISN research led by MIT faculty member Professor Yoel Fink. In June 2017, Advanced Functional Fabrics of America unveiled its dedicated facilities a short walk from the main MIT campus, along with a sampling of prototypes containing advanced optoelectronic fiber devices.

A Small Sampling of ISN Research Accomplishments

Self-Assembled Microchip Filament Patterns

To improve computer performance by increasing the component density of microchips, substantial efforts are under way to make smaller connective filaments within those chips. Fundamental limitations to the patterning processes currently used have made these success more and more difficult to reach as filament sizes are reduced to a critical scale. A team led by Associate Provost and Professor of Chemical Engineering Karen Gleason has succeeded in using a trio of techniques that, in combination, yield self-assembled wires at sub-10-nanometer scales, several times smaller than those possible using common methods (Figure 1). Although it is not the only new means of creating wires at these tiny sizes, Professor Gleason's method has the additional benefits of scalability, cost effectiveness, and easy integration into existing chip manufacturing processes. Further details of this work have been published in a scholarly article in the journal *Nature Nanotechnology*.



These scanning electron microscope images show the sequence of fabrication of fine lines by the team's new method. First, an array of lines is produced by a conventional electron beam process (top).

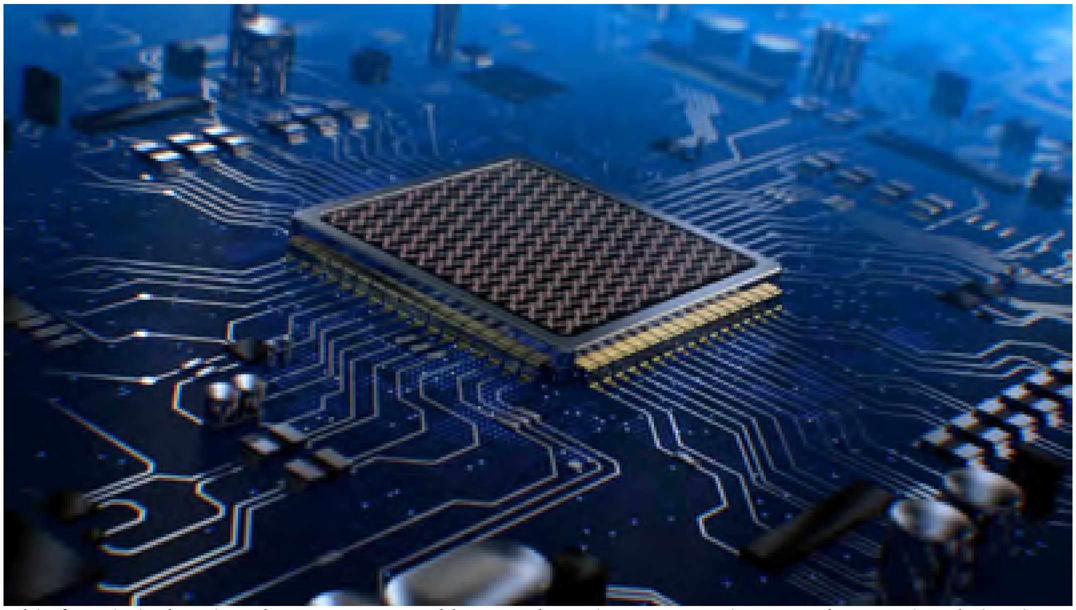
The addition of a block copolymer material and a topcoat result in a quadrupling of the number of lines (center).

Then the topcoat is etched away, leaving the new pattern of fine lines exposed (bottom).

Images courtesy of the researchers.

Optics-Based Neural Networks for Deep Learning

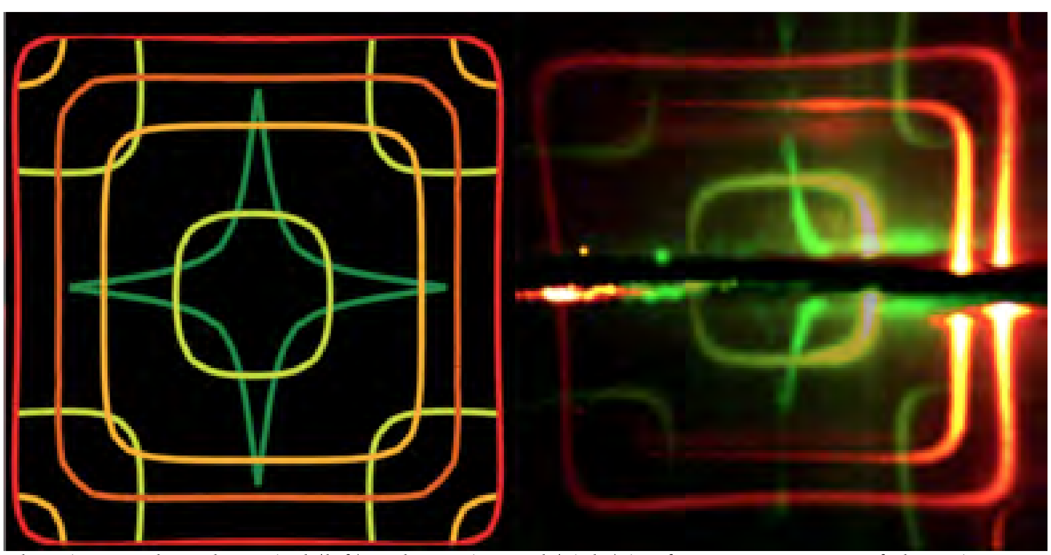
Interest in deep-learning computer systems has grown dramatically recently because of their ability to recognize and analyze patterns in massive amounts of information. Unfortunately, current computer architectures are not well suited to many of the complex calculations necessary to these tasks. Now, a team of researchers that includes Professor of Physics Marin Soljačić, in collaboration with Jamieson Career Development Assistant Professor of Electrical Engineering and Computer Science Dirk Englund, has devised an optical chip, called a programmable nanophotonic processor, that is especially adept at such tasks (Figure 2). In principle, such optical systems could perform the same functions as their electronic counterparts very much faster and with less than 0.1% of the energy required. Further details of this work have been published in a scholarly article in the journal *Nature Photonics*.



This futuristic drawing shows programmable nanophotonic processors integrated on a printed circuit board and carrying out deep-learning computing. Image: RedCube Inc.; courtesy of the researchers.

Experimental Validation of Crystal Structure Theory

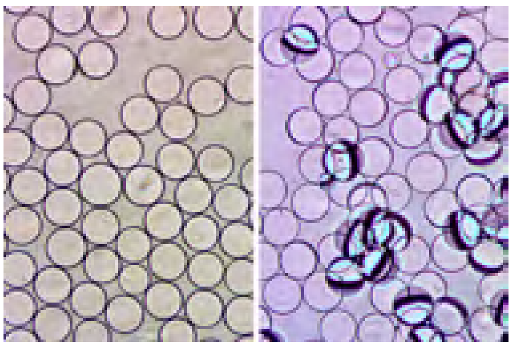
Photonics crystals are an increasingly useful means of shaping light. Historically, however, an important theoretical tool for the prediction of how light will interact with photonic crystals has escaped experimental validation. A team led by ISN Director and Professor John Joannopoulos and Professor of Physics Marin Soljačić has succeeded in directly visualizing iso-frequency contours, lines that display the scattering of light by a crystal's structure (Figure 3). In addition to validating simulations, the method could eventually yield a host of other applications, including an optimized photonic crystal manufacturing process, selectively transparent displays, and computer monitors that are viewable only at specific angles. Further details of this work have been published in a scholarly article in the journal *Science Advances*.



These images show theoretical (left) and experimental (right) iso-frequency contours of photonic crystal slabs superimposed on each other. Images courtesy of the researchers.

Rapid, Low-Cost Food Pathogen Sensing

Timothy Swager, the John D. MacArthur Professor of Chemistry, heads a team of scientists from MIT and the Max Planck Institute in Germany that has devised a new method of testing for dangerous food-borne pathogens that would be faster and less costly than previous methods. The detector relies on recently developed Janus emulsions, liquid droplets consisting of two different materials in precise arrangement. The Janus emulsions can bind to a protein called lectin that is often found in pathogens such as *Escherichia coli*. Binding delivers a signal that is visible to the naked eye, or to simple imaging hardware, such as a cell phone camera (Figure 4). Future plans include optimizing and, ultimately, commercializing the system. Further details of this research have been published in a scholarly article in the journal *ACS Central Science*.

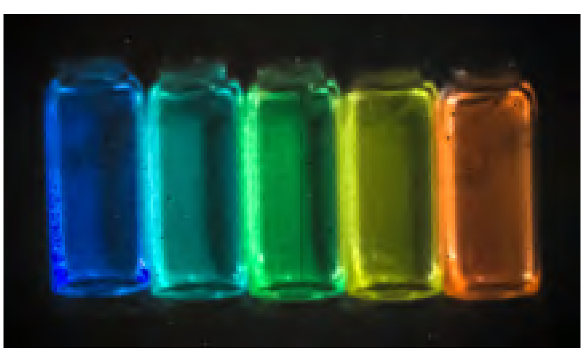


At left, Janus droplets viewed from above. After the droplets encounter their target, a bacterial protein, they clump together (right).

Image: Qifan Zhang.

Quantum Dot Short-Wave Infrared SWIR Emitters for High-Fidelity Biological Imaging

Near-infrared imaging is a frequently used medical technique, but the ability to obtain images in the short-wave infrared (SWIR) frequencies holds substantial advantages because of the transparency of biological tissue to that range of wavelengths. However, the lack of strong SWIR emitters has prevented the widespread utilization of transcutaneous SWIR imaging. Leading an international team of academic and industry scientists, Professor of Chemistry Moungi Bawendi has developed nanoparticles, also known as quantum dots, that provide images that are orders of magnitude better than previously existing materials (Figure 5). In fact, the new particles emit so strongly that they make it possible to use the short camera exposure times required of video recording. Initial use will likely be confined to animal studies because of potential particle toxicity, but work is under way to find appropriate, safer material alternatives. Further details of this work on biomedical imaging were published in a scholarly article in the journal *Nature Biomedical Engineering*; details of the initial particle development work were presented last year in *Nature Communications*.

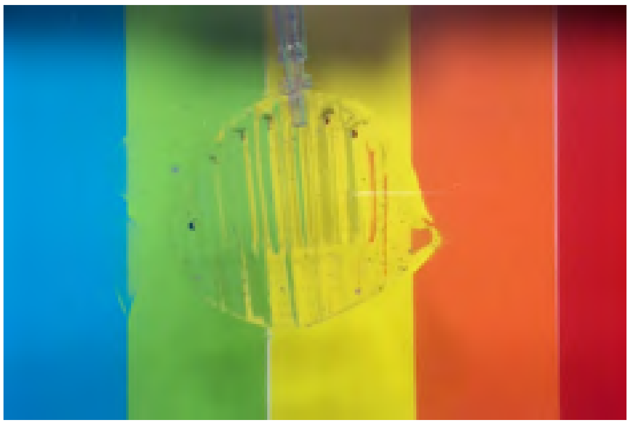


Researchers have found a way to make tiny particles that can be injected into the body, where they emit short-wave infrared light. The advance may open up a new way of making detailed images of internal body structures, such as fine networks of blood vessels.

Image: Bawendi Group at MIT.

Hydrogel Robots for Future Medicine

A team of researchers led by Associate Professor of Mechanical Engineering and Civil and Environmental Engineering Xuanhe Zhao has devised a new type of hydrogel-based robot that is capable of rapid and strong motion, while lacking the brittleness of other versions of such devices. Comprising a series of interconnected, hollow hydrogel segments, these robots have the potential to combine the visual and acoustic properties of water with a level of biocompatibility that would be advantageous for medical applications (Figure 6). For example, further research is currently under way to adapt the robot for use in surgeries, as the hydrogels interact gently with biological tissue. Further details of this work were published in a scholarly article in the journal *Nature Communications.*

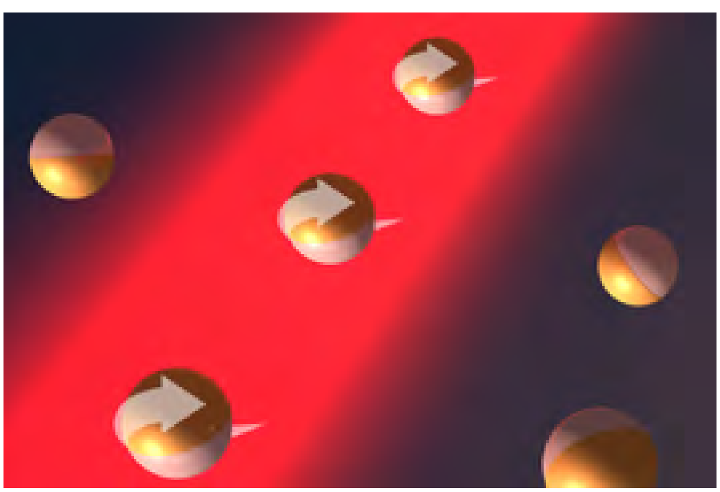


"Hydrogels are soft, wet, biocompatible, and can form more friendly interfaces with human organs," says Xuanhe Zhao, associate professor of mechanical engineering and civil and environmental engineering at MIT.

Image: Hyunwoo Yuk, MIT Soft Active Materials Laboratory.

Particle Manipulation by Normal Light

MIT faculty member Marin Soljačić and his team succeeded in simulating nanoparticles that can be manipulated by a normal beam of laser light, rather than by multiple beams in a specialized configuration. In a significant advancement in the field of topological physics, Soljačić simulated a spherical Janus particle of silica partially coated with gold. When exposed to a light beam, the particle was caused to spin (Figure 7). By designing particles to react with regular light, Soljačić's system opens up the possibility of applications and environments where specialized light would not work. Future plans call for simulations of alternative particle shapes and materials, as well as for the experimental validation of the initial simulations. Further details of this work have been published in a scholarly article in the journal *Science Advances*.



Researchers have created in simulations the first system in which particles can be manipulated by a beam of ordinary light rather than the expensive specialized light sources required by other systems.

Image: Christine Daniloff, MIT.

Historically Black Colleges and Universities and Minority Institutions Program

In 2007, with Professor Paula Hammond as program director, ISN began a program to engage faculty and students from historically black colleges and universities and minority institutions (HBCU-MIs) in research in support of the ISN mission. This program funds peer-reviewed basic research projects at HBCU-MIs and facilitates collaborations between HBCU-MI and ISN scientists. Visiting faculty and students from HBCU-MIs utilize ISN research facilities. Currently, ISN funds two faculty-led projects through its HBCU-MI program; one is at the City College of New York, the other at Howard University.

Army Collaboration

Army research partners are vital to the ISN mission. They collaborate on basic and applied research, provide guidance on the relevance to soldiers of ISN projects, and participate in transitioning. ISN has collaborated with many Army science and technology laboratories and centers. Over the past year, those collaborators included:

- Armament Research, Development, and Engineering Center
- Army Research Laboratory
    - Army Research Office
    - Human Research and Engineering Directorate
    - Sensors and Electron Devices Directorate
    - Weapons and Materials Research Directorate
- Aviation and Missile Research, Development, and Engineering Center
- Communications-Electronics Research, Development, and Engineering Center
- US Army Corps of Engineers
- Edgewood Chemical Biological Center
- Medical Research and Materiel Command
    - Walter Reed Army Institute of Research
    - US Army Medical Research Institute of Infectious Diseases
- Natick Soldier Research, Development, and Engineering Center
- Program Executive Office—Soldier
    - Project Manager—Soldier Protection and Individual Equipment

Other Department of Defense and Government Collaborations

Although ISN's first customer remains the soldier, many ISN research projects are relevant to needs of other government agencies. Collaborations and interactions have occurred with a number of the Army's sister services and other US government entities, including:

- Camp Roberts
- Deployed Warfighter Protection Program

- Naval Postgraduate School
- Naval Sea Systems Command
- US Air Force Medical Service
- US Air Force Special Operations Command
- US Department of Agriculture
- US Food and Drug Administration
- US Special Operations Command
- Walter Reed National Military Medical Center

Industrial Collaboration

Industry partners are critical to the ISN mission, helping turn innovative results of basic research into real products and scale them up for affordable manufacture in quantities needed by various end users. Current ISN industry partners include:

- Center for Integration of Medicine and Innovative Technology
- FLIR Systems
- JEOL USA
- Lockheed Martin
- Nano-C
- Raytheon
- Total American Services
- Triton Systems
- Veloxint
- Xtalic

Outreach Activities

Soldier Design Competition

The ISN Soldier Design Competition (SDC) was established in 2003 to engage MIT undergraduates in the activities of ISN. In 2004, it was expanded to include cadets from the United States Military Academy at West Point. The SDC provides a unique opportunity for students to apply their knowledge and creativity while gaining hands-on experience in designing and prototyping technology solutions to problems faced by today's soldier and first responder. Teams compete for prize money donated by industry companies that have included Boeing, General Dynamics, L-3 Communications, Lockheed Martin, QinetiQ North America, Raytheon, Vecna, and W. L. Gore and Associates. Each year, a panel of leaders from the Army, industry, and MIT determines the winning technology solutions.

SDC participants meet active-duty soldiers and Marines, and develop perspectives on how modern technology can help the US military, as well as firefighters, law enforcement officers, and other emergency response personnel. Army mentors provide SDC team members with advice on the military relevancy and technical viability of proposed technology solutions. Finalists are judged according to the technical design practicality, innovativeness, likely military benefit, and logistical supportability of their prototypes. Competitors are encouraged to further develop and commercialize their inventions.

The final rounds of SDC14, in May 2017, were attended by a number of senior Army officials, including General Gustave Perna, commanding general of the US Army Materiel Command, and Major General Cedric Wins, commanding general of the US Army Research, Development, and Engineering Command. The winning team at the finals was a group of MIT students who developed a means of producing hydrogen for energy generation from water and surface-treated aluminum pellets. The team's ultimate goal is to provide the power for soldiers' equipment more safely, more cheaply, and at a lighter weight than is currently possible. The ABA Power team took home the first prize of $5,000 for their work. An MIT team also took second place, and a $4,000 prize, for their work to make the Joint Service Lightweight Integrated Suit Technology chemical and biological protection suit more comfortable by repurposing a standard respirator system to provide cooling ventilation to the entire suit. Because of the assistance of the Army Research Laboratory–Army Research Office technology transfer officer assigned to ISN, this project generated interest from both the Army's Edgewood Chemical Biological Center and the Department of Defense's Joint Program Executive Office for Chemical and Biological Defense.

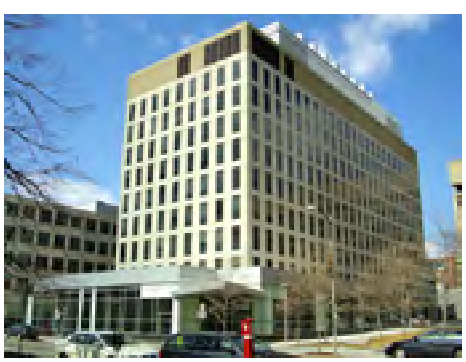
The next cycle of the Soldier Design Competition—SDC15—will kick off in September 2017. The Finals event will be held on April 30, 2018, at the MIT Media Lab in Building E14.

Website

To coincide with the beginning of ISN-4 in January 2018, plans are under way to create an all-new ISN website, maintaining some of the best qualities from the current website while implementing a number of new features and capabilities.

Contributions to the MIT Community

ISN occupies approximately 40,000 square feet of space in a dedicated facility that is located in the northeast sector of the MIT campus, within Cambridge's Technology Square (Figure 8). Since the beginning of the third ISN contract in 2013, more than 1,500 MIT personnel and affiliates have applied for and gained access to the ISN facilities. At any one time, there are approximately 500 active registered users.



ISN headquarters, laboratories, and other facilities occupy approximately 40,000 square feet of space at Technology Square, on the edge of the MIT campus.

Users have access to ISN facilities that include wet and dry laboratories, computer clusters, and mechanical testing and other research instrumentation, including equipment for low- and high-rate mechanical characterization of the dynamic response of materials, electron microscopy, and femtosecond laser spectroscopy. Recently, ISN has acquired a laser scanning confocal microscope, which provides noncontact, nanometer-scale profile, roughness, and film thickness data on any material; an atomic layer deposition system, which is capable of conformal deposition of semiconductors, insulators, and metals on three-dimensional objects; and a Zeiss Xradia 520 Versa x-ray tomography system. The Zeiss Xradia system, which compiles a series of very thin two-dimensional scans of an object into a three-dimensional image, performs similarly to the way in which a computed tomography scan images biological tissue.

Since the beginning of its second contract in 2007, ISN has provided more than $8.5 million in seed and augmentation funding for MIT research projects, supporting research in a variety of different academic departments and research centers. ISN leadership also engages with the broader MIT community through participation in various Institute committees, including the MIT–Department of Defense Engagement Group, the MIT Committee to Evaluate the Innovation Deficit, and the MIT.nano Governance Committee.

Future Plans

The ISN mission remains extremely relevant to the needs of the soldier and the nation. Over the coming years, ISN will seek to build and further strengthen partnerships with the Army, other US military services, and industry while adjusting and enriching its basic research portfolio to respond to new opportunities and evolving customer needs. Working as an Army-industry-university team, ISN will continue to perform basic research and transitioning to improve protection and survivability for soldiers.

More immediately, ISN looks forward to its fourth contract, expected to begin on January 1, 2018. With this new contract will come a roster of new basic research projects that will be led by more than 25 MIT faculty members as principal investigators, including seven who are new to ISN.

John D. Joannopoulos
Director
Francis Wright Davis Professor of Physics