National Nanotechnology Coordinated Infrastructure

NNCI Coordinating Office Annual Report (Year 8)
April 1, 2023 – March 31, 2024
NSF Award 2100059

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NNCI Coordinating Office Annual Report 2024

Table of Contents

1. NNCI Overview

1.1. Introduction

The National Nanotechnology Coordinated Infrastructure (NNCI) is an NSF-funded network of academic nanofabrication and characterization sites and their partners, formed to advance research in nanoscale science, engineering and technology. The NNCI site awards were the culmination of a competition conducted by NSF, under Program Solicitation NSF 15-519, which was generated as a result of input from the science and engineering community following the completion of the National Nanotechnology Infrastructure Network (NNIN, 2004-2015). Over 50 proposals from potential NNCI sites were submitted, and ultimately 16 awards were made. The NNCI network is funded by the NSF through cooperative agreements with the individual sites, with the initial site awards being made around September 15, 2015 with an initial award period of 5 years. The program was renewed for an additional 5 years in 2020. The Coordinating Office (CO) for the network was awarded to the Georgia Institute of Technology on April 1, 2016 and renewed in 2021. Total NSF funding for the 10 years of the NNCI network is approximately $165 million.

The NNCI sites are located in 16 states and involve 29 universities and other partner organizations (see Figure 1) that provide researchers from academia, small and large companies, and government with access to university user facilities with leading-edge fabrication and characterization tools, instrumentation, and expertise within all disciplines of nanoscale science, engineering and technology.

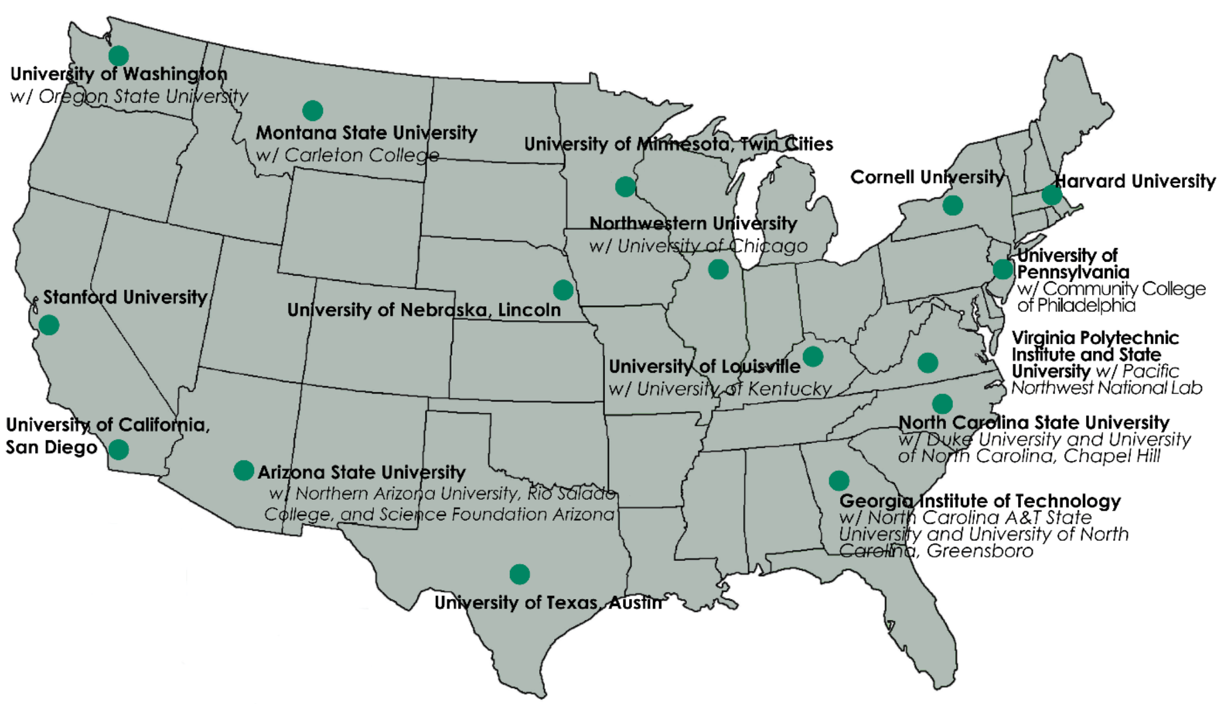


Figure 1: US Map with Locations of the 16 NNCI Sites (Years 6-10)

The goals of the NNCI network are (1) to provide open access to **state-of-the-art nano-fabrication & characterization facilities**, their tools and staff expertise across US, and (2) to use these resources to support **education & outreach (E&O)** as well as **societal & ethical implications (SEI) programs** in/of nanotechnology.

The 16 NNCI sites and their 13 partners (university, college, national lab, and non-profit foundation) provide access to more than 2,200 tools located in 71 distinct facilities. As will be detailed later in this report, these tools have been accessed during Year 8 by more than 13,000 users including nearly 3,600 external users, representing more than 220 US academic institutions, nearly 800 small and large companies, 47 government and non-profit institutions, as well as nearly 40 foreign entities. Overall, these users have amassed more than 1 million tool hours. During Year 8, the network trained more than 5,000 new users. These statistics represent significant improvements compared to Years 5-7 and are comparable to the years before the COVID-19 pandemic, suggesting a return to nearly normal operations.

This report summarizes the activities and progress for Year 8 of the Georgia Tech Coordinating Office of the NNCI, from April 1, 2023 - March 31, 2024. NNCI sites are funded via separate cooperative agreements between NSF and each site, with reporting of site-specific data and activities corresponding to Year 8 (October 1, 2022 – September 30, 2023).

As indicated above, the second 5-year funding period of the NNCI began in 2020. This report reflects changes to the sites, partners, facilities, and network activities proposed and enacted starting in Year 6. In addition, previous reports have described aspects of the NNCI affected by the COVID-19 pandemic, including cancellation of numerous programs throughout the network and the closing of most NNCI facilities from mid-March to mid-June 2020. NNCI and its sites adapted to these conditions, providing a wide variety of online programs to support users and provide education and outreach opportunities, many of which continue during this reporting period. These closures obviously affected the usage of NNCI resources, and a return to pre-pandemic levels of usage in some categories is still ongoing as noted in the network statistics in Section 11.

1.2. NNCI Organization

All of the NNCI facilities, most of which have partners and multiple locations, are available for use by students and professionals from around the country and globally. The sites and facilities within NNCI during Year 8 (Table 1) support research and development for academic education and research purposes, as well as product and process development for commercial purposes. It should be noted that NNCI Year 6 began the renewal period of the network, and some sites either added and/or subtracted facilities which may impact the user statistics reported in Sections 11 and 12. Each site operates under its own procedures for user recruitment, user access, training, rates, billing, and other logistical details. However, each site has agreed to provide open access, with as minimal a burden as possible, to their state-of-the-art nanofabrication and characterization facilities, their tools, and staff expertise. All sites use the resources provided by NSF to support a variety of education and outreach activities (Section 4.1), and many also offer programs or research in societal and ethical implications (SEI) of nanotechnology (Section 4.2) and simulation and modeling (Section 4.3). With the NNCI renewal, the Coordinating Office also began to coordinate network activities that promote and support innovation and entrepreneurship (Section 4.4).

Table 1: NNCI Sites, Locations and Facilities (Years 6-10)

NNCI Sites and Locations	NNCI Facilities
Cornell Nanoscale Science and Technology Facility (CNF) Cornell University	Cornell Nanoscale Science and Technology Facility Cornell High Frequency Test Lab Cornell 3D Visualization and Imaging Facility Cornell Rapid Prototyping Lab
Center for Nanoscale Systems (CNS) Harvard University	Center for Nanoscale Systems
Kentucky Multi-Scale Manufacturing and Nano Integration Node (KY Multiscale) University of Louisville University of Kentucky	Micro/Nano Technology Center Center for Nanoscale Science and Engineering Huson Nanotechnology Core Facility Electron Microscopy Center Conn Center for Renewable Energy Research Center for Applied Energy Research Center for Advanced Materials Additive Manufacturing Institute of Science & Technology
Mid-Atlantic Nanotechnology Hub (MANTH) University of Pennsylvania Community College of Philadelphia	Singh Center for Nanotechnology Quattrone Nanofabrication Facility Singh Center for Nanotechnology Nanoscale Characterization Facility Singh Center for Nanotechnology Scanning Probe Facility
Midwest Nanotechnology Infrastructure Corridor (MiNIC) University of Minnesota	Minnesota Nano Center Characterization Facility
Montana Nanotechnology Facility (MONT) Montana State University Carleton College	Montana Microfabrication Facility Imaging and Chemical Analysis Laboratory Center for Biofilm Engineering Proteomics, Metabolomics and Mass Spectroscopy Facility Center for Bioinspired Nanomaterials
Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth) Virginia Tech Pacific Northwest National Laboratory	Virginia Tech Nanoscale Characterization and Fabrication Laboratory PNNL Environmental Molecular Sciences Laboratory
Nanotechnology Collaborative Infrastructure Southwest (NCI-SW) Arizona State University Northern Arizona University Rio Salado College Science Foundation Arizona	ASU NanoFab Eyring Materials Center Advanced Electronics and Photonics Core Facility Nano in Society User Facility Center for the Life Cycle of Nanomaterials ¡MIRA! Center at NAU

Nebraska Nanoscale Facility (NNF) University of Nebraska-Lincoln	Nebraska Center for Materials and Nanoscience Nano-Engineering Research Core Facility
Northwest Nanotechnology Infrastructure (NNI) University of Washington Oregon State University	Washington Nanofabrication Facility Molecular Analysis Facility Advanced Technology and Manufacturing Institute Materials Synthesis & Characterization Facility Ambient Pressure Surface Characterization Lab Oregon Process Innovation Center
Research Triangle Nanotechnology Network (RTNN) North Carolina State University Duke University University of North Carolina at Chapel Hill	Analytical Instrumentation Facility NCSU Nanofabrication Facility Shared Materials Instrumentation Facility Chapel Hill Analytical and Nanofabrication Laboratory Zeis Textiles Extension for Economic Development Nuclear Reactor Program Public Communication of Science & Technology Project Duke Magnetic Resonance Spectroscopy Center Chemical Analysis and Spectroscopy Laboratory
San Diego Nanotechnology Infrastructure (SDNI) University of California-San Diego	Nano3 Cleanroom Microfluidic Medical Device Facility Chip-Scaled Photonics Testing Facility CMRR Materials Characterization Facility
Southeastern Nanotechnology Infrastructure Corridor (SENIC) Georgia Institute of Technology Joint School of Nanoscience and Nanoengineering (NC A&T State University, University of North Carolina-Greensboro)	Institute for Electronics and Nanotechnology-Micro/Nano Fabrication Facility Materials Characterization Facility JSNN Cleanroom and Labs
Soft and Hybrid Nanotechnology Experimental (SHyNE)Resource Northwestern University University of Chicago	Northwestern University Atomic and Nanoscale Characterization Experimental Center Integrated Molecular Structure Education and Research Center Northwestern University Center for Atom Probe Tomography J.B. Cohen X-ray Diffraction Facility Northwestern University Micro/Nano Fabrication Facility Simpson Querrey Institute Pritzker Nanofabrication Facility Pulsed Laser Deposition Core
NNCI Site @ Stanford (nano@stanford) Stanford University	Stanford Nano Shared Facilities Stanford Nanofabrication Facility Stanford Microchemical Analysis Facility

	Stanford ICPMS/TIMS Facility
Texas Nanofabrication Facility (TNF) University of Texas-Austin	Microelectronics Research Center Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies The Center for Nano and Molecular Sciences Texas Material Institute

Through a 2020 update of the NNCI Staff Directory (following the renewal proposals), sites have identified approximately 250 staff that support the NNCI program (Table 2), although some individuals fulfill multiple roles within a site's operations. Many additional technical staff that assist both internal and external facility users supported by NNCI funds are not included in this count s. In general, Site Leadership includes Site Directors and Deputy, Associate, and Assistant Directors. Some of these individuals also serve as project co-PIs. New User Contacts are those site staff responsible for coordinating access to facilities for external users. Program Managers are identified as those staff who most interact with the Coordinating Office, providing data as requested and communicating information to appropriate site staff. Facility Managers are responsible for the operations of site facilities, often assisted by Technical Staff when identified. Education/Outreach Coordinators handle the K-12 activities and sometimes the university student and professional education as well. SEI and Computation Coordinators are responsible for those aspects of site operations.

Table 2: NNCI Site Staff (2020)

NNCI Site Staff	
Site Directors	16
Other Site Leadership	44
New User Contacts	31
Program Managers	19
Facility Managers	70
Education/Outreach Coordinators	35
SEI Coordinators	7
Computation Coordinators	4
Safety/Facility Director/Technical Staff	22
Facility Administrative Staff	11

An analysis by the Diversity Subcommittee (see Section 5.1) examined the demographics of NNCI site PIs and co-PIs as reported to the NSF. During Year 5 of the initial NNCI awards, 9 of the 61 individuals (15%) listed as PI or co-PI on the sixteen awards were women, which is comparable to the percentage of women tenure-track faculty in departments of electrical and computer engineering in the United States (13%) and engineering departments in general (17%), but significantly under the percentage of PhD degree holders who are women in the US (53%). With the renewal process in 2020, 20 of the 66 individuals (30%) listed as PI or co-PI are now women, indicative of a concerted response to their under-representation within NNCI leadership. In addition, several of these new NNCI leaders are African-American or Latinx, demonstrating broadening participation by race and ethnicity.

2. NNCI Coordinating Office

Since its start in 2016, the NNCI Coordinating Office was led by Prof. Oliver Brand (Executive Director, Georgia Tech Institute for Electronics and Nanotechnology (IEN) and Director, SENIC). Dr. Brand tragically passed away in April 2023. With agreement from NNCI site directors, Georgia Tech research leadership, and the NNCI NSF program officer, Dr. David Gottfried (Senior Assistant Director, Georgia Tech IEN), who previously served as Coordinating Office Deputy Director, assumed the role of **Director**. Dr. Gottfried oversees the Coordinating Office day-to-day operations, assisted by a **Program Manager** Amy Duke (Research Administrative Manager, Georgia Tech IEN and Program Manager, SENIC). Four **Associate Directors** manage the network activities in specific areas. Dr. Mikkel Thomas (Senior Research Engineer, Georgia Tech IEN and Director of E/O, SENIC) coordinates the NNCI education and outreach (E&O) programs. Prof. Jameson Wetmore (School for the Future of Innovation in Society, Arizona State University and Deputy Director, NCI-SW) coordinates the societal and ethical implications (SEI) activities. Prof. Azad Naeemi (School of Electrical and Computer Engineering, Georgia Tech) coordinates the computational activities and facilitates interactions with nanoHUB/NCN at Purdue University. Dr. Matthew Hull (Program Manager, Virginia Tech ICTAS and Associate Director, NanoEarth) coordinates innovation and entrepreneurship (I&E) programs. This Coordinating Office staff meets monthly by conference call.

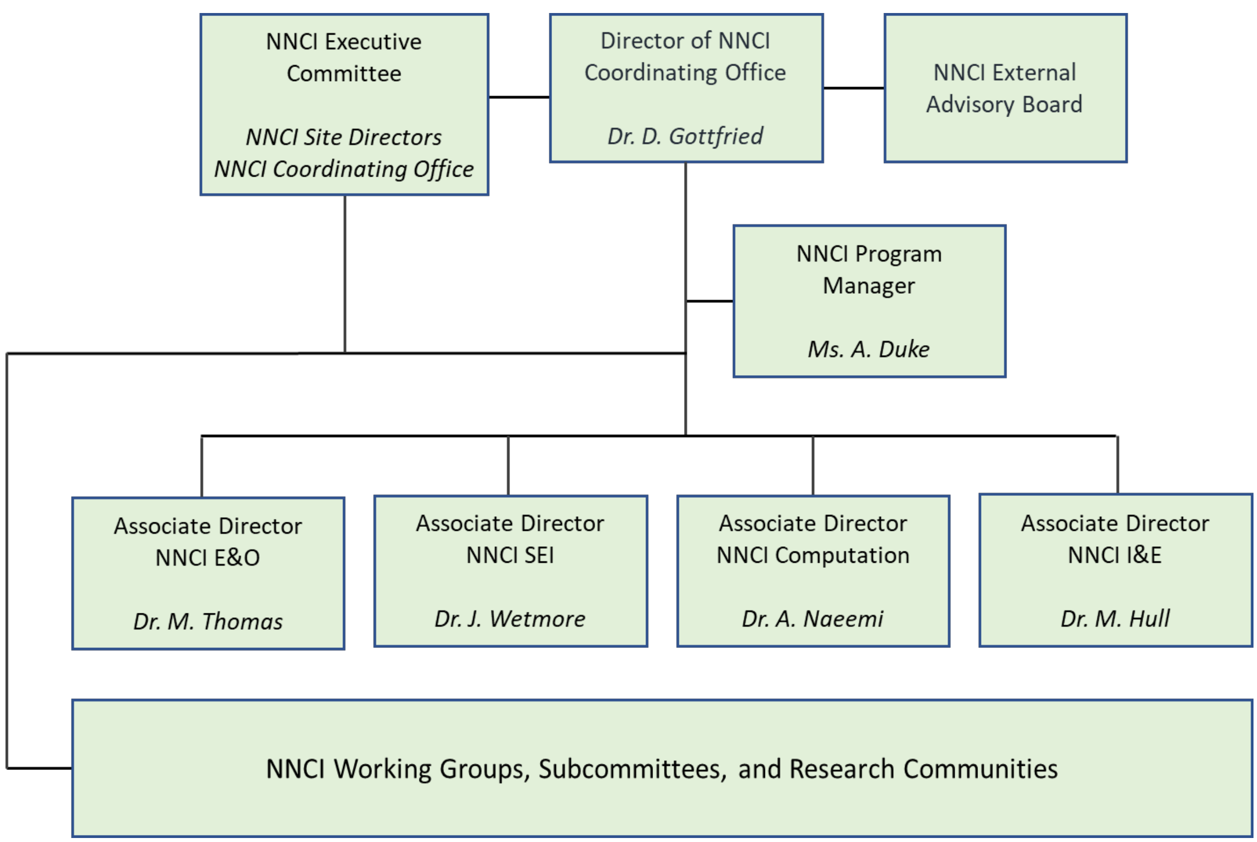


Figure 2: NNCI Coordinating Office Organizational Chart (Years 6-10). Revised May 2023.

The Coordinating Office staff is guided by an **Executive Committee,** which includes the 16 NNCI site directors and other site leadership. The Executive Committee meets monthly via teleconference and annually in person at the NNCI Conference. The Executive Committee and Coordinating Office are advised by an **External Advisory Board** (EAB, see Section 3) comprised of members representing industry, academia, government, education and outreach, SEI, computation and non-traditional disciplines in nanoscience and nanoengineering. The EAB meets in person as part of the NNCI Conference, with additional conference calls as necessary, and provides an annual written report and recommendations.

In addition to the work of the Associate Directors, several **subcommittees** of the Executive Committee have been formed to tackle high-level issues related to the NNCI network as a whole, and these were revised at the start of Year 6 (see Section 5). Leveraging the distributed expertise at the network level, several **working groups**, composed of staff members from the NNCI sites, have been formed to share and develop best practices for site and network operations, technical areas, and education and outreach (see Section 6). Finally, during Year 5 the network created **research communities**, which are organized around key scientific and engineering challenges and represent an opportunity for the NNCI to interact with the broader research ecosystem (see Section 7). Other tasks of the Coordinating Office include:

- creation and maintenance of the NNCI website
- organization of the NNCI Annual Conference
- interfacing with NSF and the External Advisory Board
- coordination of the NNCI webinar series and YouTube channel
- facilitating interactions among the sites via an email listserv
- incentivizing sites to collaborate via support of workshops
- marketing the NNCI at conferences and trade shows and through printed and electronic materials
- organization of an annual REU Convocation
- development of an annual user satisfaction survey
- management of the Outstanding NNCI Staff Member awards
- providing unified outlines and templates for site annual reports and reverse site reviews
- collection of site usage statistics and other impact metrics
- collection of annual user highlights
- preparation of this annual report

More details on these activities are shared in the sections below, and plans for future activities are provided in Section 13.

3. External Advisory Board

During the first year of the NNCI, the Coordinating Office established an NNCI External Advisory Board. To this end, names for potential advisory board members were solicited from the 16 NNCI sites. The Coordinating Office then assembled the Advisory Board from the solicited list, ensuring a diverse board in terms of gender, ethnicity and disciplinary background. Since its inception, there have been periodic changes in the EAB membership and Table 3 shows the Advisory Board members and their affiliations as of January 2023.

Table 3: NNCI External Advisory Board

Name	Affiliation
Dr. Andrew Greenberg	Associate Director, Institute for Chemical Education, University of Wisconsin
Dr. Elaine Cohen Hubal	Acting Director, Computational Exposure Division, US Environmental Protection Agency
Dr. Angelique Johnson	CEO, MEMStim
Mr. Joe Magno	Executive Director, National Institute for Innovation and Technology
Dr. Kurt Petersen	Member, Silicon Valley Band of Angels
Dr. Thomas Theis	Director of Innovation, Utopus Insights, Inc.
Prof. Ken Wise	Department of Electrical Engineering and Computer Science, University of Michigan

The Advisory Board meets in person during the annual NNCI Conference and virtually via teleconference call as needed. Ahead of the first NNCI Conference in January 2017, the Coordinating Office asked the Advisory Board to take a critical look at what NNCI is doing well and areas where it can improve. In particular, the Advisory Board considered the following questions:

1. What activities can/should NNCI support to achieve the goal of the network surpassing the sum of the parts? This should involve not only research facilities aspects, but also consider support of education/outreach, computational tools, and societal and ethical implications activities.
2. The NSF considers increasing usage by external users as well as usage by "non-traditional" users of prime importance. Considering the current activities of the sites and the network, what can be improved to achieve this aim?

3. Since NNCI serves to support cutting-edge research in both academia and industry, what capabilities should sites begin to acquire to anticipate 5-10-year research trends?

From the feedback of the Advisory Board at the January 2017 NNCI Conference it became clear that a more detailed "Charter Letter," with input from the NSF on what would constitute a successful network, was needed. This document was created during 2017 and communicated to the Advisory Board with a copy provided in the 2017 annual report. The report of the Advisory Board following the most recent NNCI Conference (October 2023) is provided in Appendix 14.1.

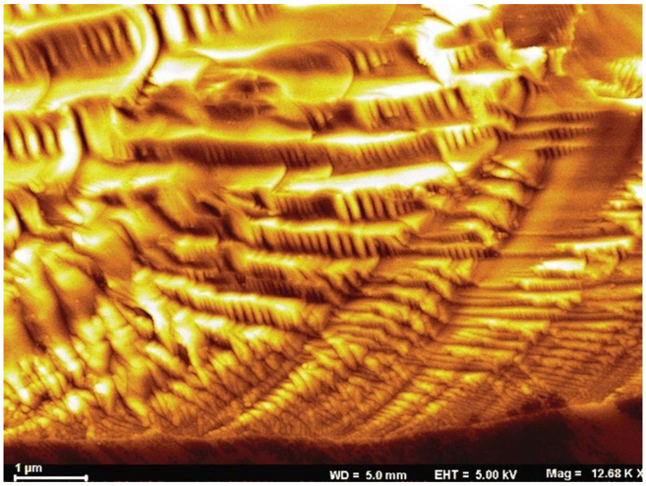
4. Associate Director Reports

4.1. Education and Outreach

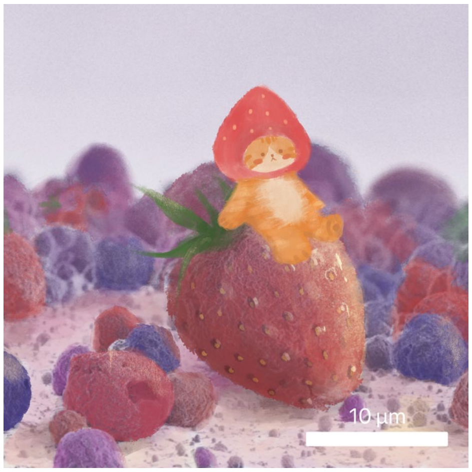
The mission of the NNCI Education and Outreach (E&O) efforts is to offer education and training to address the growing need for a skilled workforce and informed public, provide resources, programs, and materials to enhance knowledge of nanotechnology and its application to real-world issues, and support the US economy by enabling a STEM-literate workforce ready to meet the technological challenges of a nano-enabled economy as well as an informed citizenry that supports continued and safe growth of nanotechnologies.

The 16 sites of the NNCI each have separate E&O programs in order to address these goals. Throughout the NNCI Year 8, E&O coordinators reached more than 40,000 people, achieved in personal/virtual interactions through classroom visits, teacher workshops, remote sessions, short courses, seminars, symposia, community events, conference booths, tours, internships, REUs, and RETs. This reach is a significant increase from the previous year (23,000 people), and surpasses the data from Year 5 (33,000 people), returning to pre-pandemic levels and growth. Most sites have returned to their pre-pandemic formats, while still using the virtual programs developed during the pandemic. Of the people reached this past year, 49% are K-12 students, 6% post-secondary students (undergraduate and graduate students), 5% educators (K-12 teachers and community/technical college faculty), 20% general public, and 18% professionals (short course and workshop participants, seminar attendees, etc.). Outreach to K-12 students continues to improve compared to the previous year. Overall reach has returned to pre-pandemic levels. Participation in programs for educators increased to nearly 2,200 teachers and community or technical college faculty, an increase of 100% over last year. The number of post-secondary students and professionals reached also increased to more than 10,300 (from 9,500 in Year 7) as more sites offered webinars, virtual symposia, and other online options. The 40,000 people reached does not include Nebraska Nanoscale Facility's traveling museum exhibit (102,000), NanoEarth's "Pulse of the Planet" radio programs, or the "Nanooze" magazines distributed by the Cornell Nanoscale Science and Technology Facility. "Nanooze" released its latest issue (#19) this past year with the theme "All About Nano Manufacturing." Also not included are the 9,000+ people enrolled in the online courses offered through RTNN and nano@stanford.

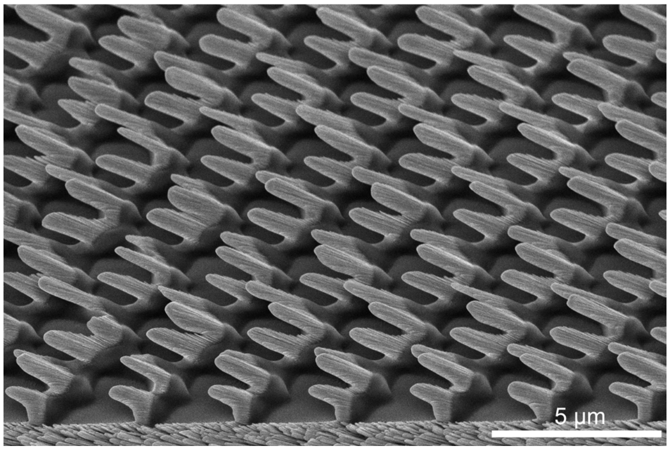
In celebration of National Nanotechnology Day, the NNCI again hosted its image contest, *Plenty of Beauty at the Bottom*. Eleven sites submitted 28 images created at one of their facilities during the past two years to three categories: Most Stunning, Most Unique Capability, and Most Whimsical. Public voting took place during the week of National Nanotechnology Day (Oct. 10-17) with sites promoting the contest through their various channels. More than 2,100 votes were cast to determine the winner in each category. Besides the image contest, individual sites hosted local National Nanotechnology Day events with more information provided later in this report. In addition to the winning entries shown below, honorable mentions were awarded to entries from MiNIC (Most Stunning), MONT (Most Whimsical), and nano@stanford (Most Unique Capability).



2023 Most Stunning (SENIC)



2023 Most Whimsical (nano@stanford)



2023 Most Unique Capability (KY Multiscale)

To facilitate the sharing of information across the network, coordinators participate in monthly calls and post to the education and outreach listserv. The purpose of the calls is to share information about upcoming events, partnerships, conferences of interest, and for working group leads to update the entire group on relevant information. This is also an opportunity for coordinators to connect over common interests and plan follow-up conversations. Additionally, topic specific teleconferences are organized if multiple sites are interested in learning more from each other. Topics have included launching a multi-site virtual Nano Summer Institute for Middle School Teachers, best practices for pivoting to virtual programs, and strategies for approaching the workforce needs of the microelectronics and semiconductor industries. Each year education coordinators are also asked to update a worksheet that lists all the different types of activities offered across the NNCI. Everyone has access to the sheet so if someone wants to learn how to run a specific activity they have never done before, they know which site(s) to contact for information.

Across the network, E&O coordinators make an effort to reach groups historically underrepresented in STEM fields. The addition of virtual and asynchronous instruction has allowed sites to extend their reach beyond their traditional areas, increasing connections to rural communities. For example, the team at MONT have been working diligently to develop a meaningful relationship with a tribal college's high school outreach program, Upward Bound. Developing relationships and trust are essential to making a relationship with these tribal colleges. After working to build this relationship, and then navigating the Covid-19 disruption, a group of about 35 high school students from Salish Kootenai College's (SKC) program visited MONT for three days. Educators from MONT took the group to Yellowstone, made silver nano particles, looked at the particles in the imaging facility and had several other nano-related lessons as well as other campus experiences. In the end, the Upward Bound director of 35 years, said, "I get it! This is really cool! No one has ever put it together for us like this before." What she meant was that no one had even made the connection for them between the convergence of the natural world (what they learned in Yellowstone) with work/discovery in the lab, followed by applications and technology that improves our lives. MONT is now working to engage with SKC Upward Bound kids that are particularly interested in STEM for more experiences at their facility.

Many other sites also leverage their efforts by working with local organizations, such as local Boys and Girls Clubs, 4-H chapters, Society of Women Engineers sections, Girls, Inc., Oakland Promise, Upward Bound, and local school districts, as well as national organizations including national 4-H and Hitachi High-Tech America STEM Education, to provide programming. In addition, most sites work closely with other NSF-supported NSE education efforts like NACK's Remote Access Instruments for Nanotechnology (RAIN) and the Micro Nano Technology Education Center (MNT-EC). The Associate Director for Education and Outreach for the NNCI coordinating office holds monthly meetings with the PI for MNT-EC, Dr. Jared Ashcroft, in order to better align their activities. NCI-SW, SENIC, NNF, nano@Stanford, SDNI, and RTNN all provide remote sessions through RAIN.

Through outreach to K-12 students, the NNCI is inspiring our future skilled workforce and helping to create an informed citizenry. Many sites participate in summer camps, high school student internship programs, after school programs, career fairs, and both off-site and on-site visits. In response to the pandemic, many sites used the switch to virtual activity as an opportunity to expand outreach. During this past year, in order to further increase the effectiveness of activities with students, many sites provided hands-on materials for students to work with during virtual instruction. SENIC's virtual class trips, in which middle and high school teachers invite staff to join their classroom, reached over 1,100 students and helped strengthen connections with school districts across Georgia. CNF launched the ATLAS (Accelerated Training for Labor Advancement in Semiconductors) Program in the fall of 2022. This program brings high school seniors from the Tompkins, Seneca Tioga (TST) BOCES New Visions Engineering program for an in depth look at the world of micro and nanofabrication. During the two-week course, students enter the CNF cleanroom and learn about key areas of cleanroom operation. NNI is also involved in the Summer Experience in Science and Engineering for Youth (SESEY) high school program focused on recruiting high school girls and underserved communities into STEM. This is a well-established program which has served over 1000 students worldwide, with >90% of the students being from underserved populations. SESEY not only addresses the systemic barrier for females and ethnic minorities to experience campus life and participate in STEM activities but is also economically accessible through low program fees and scholarships funded through various PIs' grants. Through this program, high school students get week-long hands-on research experience in nanotechnology. Every summer approximately 45 SESEY students are hosted by NNI research groups to work alongside graduate students, post docs and PIs on a mini research project, which they present in an open poster session at the end of the week. Both CNF and SENIC partnered with Micron Technology on their Micron Chip Camp. The camp is designed for middle school students and exposes them to STEM and semiconductor activities. MiNIC partnered with the Northstar STEM Alliance, an NSF-funded program to increase BS grads in STEM fields. Through Northstar, they've begun to offer programs, tours, and activities to more students of color, particularly indigenous communities in Minnesota.

Micron Chip Camp at SENIC

In order to develop a STEM-literate workforce and informed citizenry, coordinators provide many activities for educators. Often sites provide multi-day workshops, summer long RET programs, or sessions at conferences in which teachers leave with free resources and a personal connection to a nearby site. The Research Experiences for Teachers across the National Nanotechnology Coordinated Infrastructure collaborative proposal, submitted to NSF by SENIC, MiNIC, SHyNE, and NNF, held its third cohort of teachers in summer 2023. All four sites were able to welcome high school teachers and community/technical college faculty to campus, 5 at SENIC, 4 at SHyNE, 6 at MiNIC, and 5 at NNF, for in-person research. In addition to research, teachers participated in career webinars to give them both a local and national understanding of careers in nanotechnology featuring industry users of NNCI facilities. The educators will present their experience and lessons at the 2024 annual National Science Teachers Association Meeting. Their lessons will also be posted on the NNCI's searchable database and nanoHUB, and the teachers are recording short videos intended to help their

20223 RET cohort at SHyNE

peers implement the lessons. SDNI virtually hosted their Annual Education Symposium (Nov. 2023) with the theme "K-12, Community Colleges, and Universities: Building the Next Generation of US Nanotechnology Workforce." The symposium featured presentations from NNCI sites, NNCO, the SEMI Foundation, and middle and high school teachers from across the country. In the 1-day virtual event, people exchanged ideas and collaboration plans to promote nanotechnology in K-gray education efforts and to increase the number of individuals entering into the nano workforce.

More than half of NNCI sites offered some version of the Nano Summer Institute for Middle School Teachers (NanoSIMST) virtually or in-person. Teachers in these programs engage in 4 to 5 days of instruction on nanotechnology and how to implement it in the classroom. Classroom supplies are provided to teachers (mailed in advance or provided at the workshop) to facilitate hands-on activities. Teachers also participated in virtual/in-person cleanroom tours, listened to guest speakers, and alumni of the program shared their implementation strategies. SDNI hosted 48 high school and middle school teachers during their in-person session. Nano@Stanford offered NanoSIMST in 2023 as a virtual workshop to further expand the reach of the program and enrolled 24 teachers in 13 states sponsored by eight NNCI sites including Stanford (CNS, RTNN, MiNIC, SDNI, NCI-SW, KY Multiscale, and NanoEarth). Another resource used during NanoSIMST and available to the community are video recordings of talks on nanotechnology careers posted on the NNCI's YouTube channel: "X/Nano: The enabling Potential of a Career in Nanotechnology" (Matt Hull, NanoEarth) has nearly 700 views and "Careers in Nanotechnology: Opportunities for STEM Students" (Jim Marti, MiNIC) has more than 2,000 views. The nano@Stanford education coordinator maintains a listserv for educators that have participated in an NNCI program, and it is also open to teachers who have not yet participated in an NNCI program. Twice a month the teachers receive an email highlighting 1 or 2 NSE education resources with information on how they connect to the Next Generation Science Standards and tips on implementation.

NanoSIMST Virtual Session led by nano@stanford

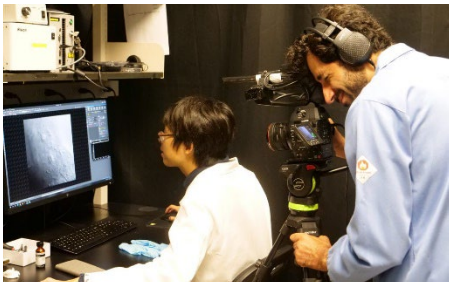
As part of building a skilled workforce, NNCI sites provide technical workshops, short courses, seminars, webinars, and/or symposia for undergraduates, graduate students, post-docs, and other professionals. The network continues to maintain a strong connection to this group by providing virtual and in-person resources. Three NNCI sites (SDNI, NCI-SW, and SENIC) participated in the Microelectronics and Nanomanufacturing Certificate Program. This NSF-funded program targets veterans and their families for training in microelectronics and nanotechnology. The 12-week program is designed to prepare veterans for working in the microelectronics and semiconductor workforce. Students are recruited from partner community/technical colleges, attend virtual lectures from researchers at Penn State University, and then receive hands-on training in the NNCI facilities. SHyNE hosted the 3rd annual *Women in Microscopy Conference* with over 200 global attendees. The event highlighted the work of female researchers, product specialists, and lab managers from universities, national labs, and microscope vendors. The conference was inspired by the desire to enhance female representation in the field, which historically has been limited. KY Multiscale hosted their Nano+Additive Manufacturing Summit in the summer of 2023. The Nano+Additive Manufacturing Summit is an annual event dedicated to bringing together researchers/users in the advanced manufacturing fields of additive manufacturing and micro/nanotechnology to discuss new findings, share results, showcase capabilities, generate ideas, debate the future, and network with one another. MONT partner Carleton College hosts the "Nanotechnology in STEM" website which showed a surge in visitors during the previous year (an increase of more than 40,000 website visitors). The website contains content from the Earth and Environmental Sciences Research Community Workshops and houses equipment databases and tutorials directed at researchers in the Earth and geological sciences. This past year, they added new K-12 resources and saw an 11% growth in page visits to their teaching resources.

Twelve NNCI sites were able to have their regular Research Experience for Undergraduates (REU) programs this past summer and all were hosted on campus and in-person. NanoEarth participated in the network REU program for the first time, sponsoring students from Concord University's Artic REU: Greenland. All of the sites participated in a network wide lecture series organized by Jessica Hauer of the NCI-SW site and Yves Theriault of the SDNI site, in collaboration with the NNCI Assoc. Director for Education and Outreach and local REU coordinators. The NNCI REU Convocation was hosted by Montana State University (MONT) August 6-8, 2023. The convocation was a 3-day event and featured 87 student short talks and posters on their summer research. They also heard keynote talks from academia, industry, and the NSF, discussion of entrepreneurship, a career panel, and they learned about follow-up research opportunities in Japan. As an alternative to a summer program, the TNF site has continued to host a yearlong REU program in collaboration with Austin Community College.

REU Convocation 2023 Attendees at Montana State University

In further support of undergraduates, NNI is focused on the retention and providing bridge programs for underprivileged students entering into college. This college transition program led by Dan Ratner at the University of Washington included 87% first generation college students, 60% low income, 43% underrepresented minorities, and 38% women. This past year 11 students from this underserved population participated in a week-long hands-on workshop in the WNF and 2 were hired as student assistants. To date, retention rates into the second year of college exceed 95%. NCI-SW continues to provide hands-on lab sessions for community college students enrolled in Rio Salado College's Nanotechnology AAS/Certificate programs and MANTH provides the hands-on programming for the "Introduction to Nanotechnology" course offered at the Community College of Philadelphia. Both MANTH and nano@Stanford offer robust internship programs for community college students. Students generally work at the facility for at least a year. Both sites have hired students coming out of this program to work in their facility. MONT has a very successful undergraduate internship program for students at Montana State University. These internship programs allow students to gain experience in all aspects of working and managing a university cleanroom.

Finally, NNCI sites provide outreach to the general public through participation in science festivals, science cafes, science days at their institutions, and National Nanotechnology Day and Nano Days celebrations to help enable an informed citizenry. RTNN organized a Girl Scouts STEM Day and took part in the Greensboro Science Center Extravaganza in partnership with JSNN (SENIC). SHyNE, collaborating with Northwestern's Medill School of Journalism and School of Communications, has established a novel Nano-Journalism focus within the existing Health, Environment and Science Journalism program. The program is designed to bring journalism students into the facilities to learn about nanoscience research and connect scientists and researchers with the Medill experts in science writing to help them effectively communicate their research to a general audience. This has led to the production of multiple articles and videos presenting complex science in a way that is accessible to a general audience. The Kearney Children's Museum hosted NNF's traveling nanoscience exhibit from Dec. 2022 – May 2023. Over 60,000 people were able to interact with this exhibit during that time. SENIC organized the first Georgia Tech Science Day as part of the annual Atlanta Science Festival. More than 1,500 campus visitors interacted with more than 40 interactive demos of work that is being done on Georgia Tech's campus.



Filming a Video for SHyNE's Nanojournalism Program

Education and outreach coordinators have embraced the move to virtual outreach as an opportunity to reach a larger and more diverse audience. While sites are moving back to in-person activities, the online content that has and continues to be developed will be integrated into sites' programming. Moving forward, sites are working together to engage with larger organizations including other NSF-funded NSE education and workforce development efforts, expanding the opportunities they offer to students, implementing teacher workshops developed by other sites, and creating more virtual content for training and outreach. More details on education and outreach efforts across the NNCI can be found in the education working group reports. The report of the *Workforce Development and Community Colleges* working group (Section 6.10), led by Andrew Lingley (MONT), includes information on approaches for addressing workforce readiness. The report of the *Evaluation and Assessment* working group (Section 6.11), led by Jessica Hauer (NCI-SW), shares results from the company survey/economic impact study developed in collaboration with the *Innovation and Entrepreneurship* working group.

4.2. Societal and Ethical Implications

Nanotechnology holds great promise, but the NNCI Coordinating Office recognizes that the introduction of any new technology can have significant societal and ethical consequences. We believe it is important to consider nanotechnologies' impacts as we conceive, develop, design, and implement them. To that end, the Coordinating Office is working to help all NNCI sites develop Societal and Ethical Implication (SEI) research and engagement programs. Associate Director Jameson Wetmore (also Deputy Director of the NCI-SW site) leads these activities. Between summer 2021 and spring 2023 graduate student research assistant Martin Perez Comisso assisted with the SEI program. Martin completed his PhD in the Human and Social Dimensions of Science & Technology (HSD) and is now on the faculty of the University of Chile. Beginning in summer

2023 Toby Shulruff, also a student in the HSD PhD program at Arizona State took over the role of graduate research assistant.

Over the past year, the NNCI Coordinating Office has advanced SEI efforts in three primary ways: 1. Through coordinating with the four main SEI sites in the NNCI; 2. Through small events and meetings within the NNCI and beyond; and 3. Through the coordination of two major events: The Winter School on Emerging Technologies and the Science Outside the Lab Washington, DC programs.

Coordination of NNCI-SEI sites:

SEI work continues to be largely advanced by four NNCI sites with significant SEI expertise and commitment. Dr. Lee Ann Kahlor at TNF continues to develop SEI lab training and is working with a number of other NNCI sites to determine the ways in which SEI makes its way into classrooms and presentations. Over the last year, Dr. David Berube at RTNN has led an assessment of the NNCI user base to determine a broad number of factors including satisfaction levels and new instruments that would be desired. The SENIC site's SEI efforts have been coordinated by Dr. Diana Hicks, Professor in the School of Public Policy at Georgia Tech. Dr. Hicks worked with graduate student Sergio Pelaez to determine the career paths of former research facility users and look to work on a new project on how aware nanotechnology inventors are of the broader societal impacts of their work. All four SEI sites gathered at the annual meeting at Stanford, presented their current and future projects, and discussed possible SEI approaches in a future nano infrastructure.

Events:

In addition to coordinating the other core SEI Sites, Dr. Wetmore has been extending the reach of SEI throughout the NNCI through forums, panels, and online workshops. For instance, in June 2023 he led an REU/RET webinar on "Science Policy: Where Values meet the Laboratory," which brought together participants from a number of NNCI REU and RET programs. In May 2023, the SEI team organized an NNCI webinar entitled "Scientists and Engineers in State Governments," that brought together a panel of Science Outside the Lab (see below) alumni – Moriah Locklear (University of Nebraska PhD, now at ASU), Stephanie Mitchell (University of Minnesota PhD, now California State Assembly), Sawyer Morgan (University of Washington PhD, now New Jersey Board of Public Utilities), and Jacob O'Connor (University of Washington PhD, now California Senate) – to discuss their transition from NNCI labs to science policy practitioners.

Wetmore also served on the organizing committee of the Workshop on Nanotechnology Infrastructure of the Future, held at the National Academy of Sciences on September 12-13, 2023. In addition to general organizing, he helped to coordinate and moderated the panel on "Reimagining the Research Ecosystem & Social Responsibility." He contributed summaries and suggestions on how to advance SEI in a future nano infrastructure in both white papers that resulted from the workshop.

Immersive trainings and sessions:

The flagship exercise of the NNCI Coordinating Office SEI effort is the Winter School on Emerging Technologies. The Winter School is held every January at Saguaro Lake Ranch, just east of Phoenix. While the first four Winter Schools were sponsored by the NSF-funded Center for Nanotechnology in Society, the NNCI has now sponsored six, which made the 2023 school the 10th annual event. After pivoting focus during the pandemic, since 2022 the Winter School has brought social science, natural science, and engineering graduate students together to address a concern that graduate students across the disciplines are increasingly interested in – increasing their impact. The winter school uses a cohort approach to train, mentor, and inspire young scholars.

The 2023 Winter School was led by a team including Ira Bennett (ASU), Nich Weller (ASU), Rider Foley (UVirginia), Lauren Keeler (ASU), Vasiliki Rahimzadeh (Baylor College of Medicine), and Martin Comisso Perez (ASU). Throughout the seven-day program participants met with a series of scholars and professionals who help them develop unique ways to increase the chances that their work will make a difference in the world well beyond their laboratories. It began with a series of eight talks addressing different types of scholarly impact including: community engagement, publication, teaching and mentorship, policy, partnerships, and the media. The organizers then developed a variety of strategies and pedagogical tools that enhanced participants' ability to think about the impact of their own personal career including: partnership strategies, worksheets for relevant funding, and self-assessment exercises such as the "Impact Hexagon" to leverage the critical capacities of the participants with the support of speakers and facilitators. The 2023 program brought together a dozen graduate students including seven from four NNCI universities: Stanford (3), NC A&T (2), ASU, and UNC Greensboro.

The 2023 winter school leadership team subsequently held a panel focused on ten years of the Winter School at the Annual Meeting of the Society for Social Studies of Science in November 2023 in Honolulu. Vaso Rahimzadeh, Martin Perez Comisso, and Jameson Wetmore gave presentations about the history and impact of the program. This was followed by over half a dozen alums who took the stage to describe their personal experiences and how the winter school focused and accelerated their careers.

The 2024 winter school, held January 3-10, was coordinated by Jameson Wetmore, NNCI RA Toby Shulruff, alum and former coordinator Vaso Rahimzadeh, alum Dalton George, and staff members Deron Ash and Bethany Lang.

Our annual summer event, co-sponsored with the NCI-SW, is "Science Outside the Lab" (SOtL), a science policy summer school traditionally held on site in Washington, DC. After two years of hosting the program online because many DC-based policymakers had not yet returned to their offices, we returned in full force in 2023. This year we held two nano SOtL programs: our traditional program for graduate students and, for the first time ever, a special 3-day program specifically tailored to faculty.

After several years of NNCI faculty asking if they might be able to sit in on a day or two of the SOtL program, we decided to see if there was enough interest in a bespoke faculty program. We envisioned it as a reframed version of the traditional graduate student program. To better accommodate faculty schedules, it was condensed to three days and slightly reframed. As we crafted it, we started with the assumption that unlike graduate students, faculty participants have a pretty good idea of how the traditional university/government funding process works and likely have served as reviewer of NSF proposals or other similar funding streams. We, therefore, focused on helping participants better understand how to increase the chances that the work done in their labs can inform the policy process and have a positive impact on the world.

We found out in the spring of 2023 that there was indeed interest. The inaugural program attracted 12 participants; 11 from NNCI sites including: University of Pennsylvania (2), Georgia Tech (3), Virginia Tech, North Carolina A&T, Harvard University, Stanford University, and Oregon State University. Over the course of three days the participants met with 16 speakers including museum coordinators, Senate staffers, NAS program managers, EPA regulators, and a Federal Circuit Judge who specializes in IP cases.

The response of the participants was overwhelmingly positive. One participant asked if their university's VP for Research could attend in the future. Another participant gave the following summary of their experience:

> I've been around the science-policy area for the majority of my professional career. Going in, I was a little nervous that the faculty SOtL experience might be limited in terms of the new insights it could offer someone with my prior experience. I could not have been more wrong! Even meeting with DC-based colleagues and agencies I'd worked with for years offered new insights when experienced through the SOtL lens. The program was so incredibly well-done, insightful, and fun – I wouldn't change a thing. Arguably the best 3 days I've ever spent in DC!

One of the participants – Kristin Field, University of Pennsylvania – is working with our team to develop a one-off bespoke SOtL for students participating in some of her other NSF funded research projects in 2024 or 2025. Based on the positive response from this year's participants we will be offering a faculty version of the program again in 2024.

The 2023 graduate student SOtL was the first program held face to face since the beginning of the pandemic (2019), and it is clear that students were incredibly excited to return. After slightly decreased interest in our 2022 online program, we received over 70 applications for the 14 spaces available in the 2023 program. The candidate pool was so strong, we could have easily filled 3 programs with highly qualified candidates.

This year's program brought together 16 graduate students representing 11 NNCI universities: UNC Greensboro, University of Minnesota, Georgia Tech, Montana State, Oregon State University, Harvard University, Northwestern University, Arizona State University, University of Nebraska, University of Pennsylvania, and North Carolina A&T. During the first week of June the participants met with nearly 30 science policy professionals including NSF program managers, EPA regulators, NAS program managers, DOE policy advisors, and the directors of the NNCO.

As with the faculty version, the feedback from the students was overwhelmingly positive. At the end of the program one participant reflected:

> I cannot express fully how grateful and lucky I am to have been able to join SOtL. I always knew I wanted to do something in relation to policy with my career, but I had no idea what that might mean or where to start. SOtL opened my eyes to a plethora of future career paths that I can follow in science policy. Participating in this program showed me that science policy can mean a number of different things, and that there are a host of different job opportunities out there that I am well positioned to enter into with a background in STEM research.

From the very beginning the SOtL program has sought to train scientists and engineering students in the social and political dimensions of their work not just for their own knowledge, but so that they could spread that understanding throughout their communities and colleagues. Thus in the 2023 program all of the participants were trained in basic techniques to bring what they learned in the program back to their home institutions. Each participant produced a proposal for an independent project to continue the conversations they had in the program with others at their universities.

These "SEI Ambassador" projects have been carried out over the summer and into the fall. Many students worked with the education coordinators at their NNCI site to more fully integrate them, and SEI work, into their local programs. This year most of our alums were especially interested in bringing what they learned back to their fellow graduate students. Some of them hosted graduate student seminars to discuss science policy and share their experiences. A few connected with science policy practitioners already at their university (i.e. faculty who had done stints at places like the DOE and NSF) and hosted panels where science policy and career opportunities were discussed with graduate student groups.

4.3. Computation

Modeling and simulation play a key role in enhancing nanoscale fabrication and characterization as they can guide experimental research, drastically reduce the required number of trial and error iterations, and enable more in depth interpretation of the characterization results. The main objectives of the computation activities within NNCI are 1) to facilitate access to the modeling and simulation capabilities and expertise within the network, 2) to identify strategic areas for growth, and 3) to promote and facilitate the development of the new capabilities.

To facilitate access to the modeling and simulation capabilities and expertise available within various NNCI sites, an inventory of available modeling and simulation resources and expertise has been complied. The directory is hosted by **nanoHub.org** and can be accessed via https://nanohub.org/groups/nnci_computation. So far, 10 sites have reported collectively more than 65 commercial simulation tools and 40 internally developed simulation tools available for internal and/or external users (with and without access fees).

In addition to software resources, 9 supercomputers or major computing clusters are available at various sites. Most of these hardware resources serve internal users, with the exception of the UT-Austin computing cluster which can be accessed by external users with a nominal fee and the CNF Nanolab Computing Cluster that is available to all users. The users of the CNF Computing Cluster have access to a wide range of modeling software packages tailored for nanoscale systems. Several classes of nodes, all linked via Gigabit Ethernet, are available on the cluster. The cluster runs Scientific Linux 7 with OpenHPC and a batch job queuing system. The staff would install new scientific codes on the cluster upon user request. The users can also remotely access software tools via "CNF Thin" Hotdesking service such as Computer Aided Design (BEAMER, L-Edit, Java GDS, AutoDesk); Simulation (Coventor, Cadence, PROLITH, Layout LAB, TRACER) and Image/Data Analysis (ProSEM, NanoScope Analysis, WinFLX). For tasks that are heavily memory or time demanding, Amazon Web Services (AWS) conversion capabilities are also available. More information on CNF computing resources is available at http://computing.cnf.cornell.edu/Cluster.

Regarding education for computational capabilities, Professor Dragica Vasileska from Arizona State University (NCI-SW) and her team have been collaborating with Prof. Gerhard Klimeck at nanoHUB to develop educational materials for Silvaco Victory usage such as PowerPoint slides, videos, sample problems regarding device and simulations ranging from low to room temperatures. A new collaboration between nanoHUB and Silvaco now provides access to Slivaco Victory to nanoHUB users. To publicize the availability of these tools on nanoHUB to the NNCI community, a webinar entitled "Silvaco Technology CAD, Background, Overview, and Future," was organized in August 2023. More than 1000 users have used the tools in less than a year.

Prof. Vasileska has also been working on a self-paced short course on device and process simulation. The five-week course is roughly equivalent to 1 credit hour and is similar in structure to nanoHUB University courses. The course consists of lectures, quizzes and projects and is based on Silvaco TCAD software. Prof. Vasileska is working with nanoHUB leadership to make the course publicly available on nanoHUB. The course content and slides are now ready, and she is in the process of recording the lectures.

On the modeling and simulation side, Prof. Frank Register and his collaborators at UT-Austin (TNF) have developed rigorous models to study transport in strained MoS_2 using density functional theory and semiclassical Monte Carlo simulations. They have used the models to project the potential performance of field-effect transistors of various channel lengths and studied the impact of contact resistance on the on-current of such transistors. They found that tensile strain decreases the bandgap, increases the inter-valley band-edge energy separation between the light-mass K-valleys and heavier-mass Q-valleys, and decreases the K-valley effective mass in a way that depends on the direction and the amount of the applied strain. Biaxial tensile strain and uniaxial tensile strain along the x- or y-directions are found to have the largest effect. The methodology and results have been published in *Journal of Applied Physics*.

Prof. Vasileska and her team have developed a modeling framework for self-heating effects in nanoscale devices using an energy balance approach accounting for hot electron transport generated by high electric field in such devices. The models show good match with experimental data covering a wide range of power densities and operating temperatures (78K-300K).

Prof. Azad Naeemi's team at the Georgia Institute of Technology is working to make their compact models for ferroelectric devices publicly available on nanoHUB.org. They have been collaborating with Intel researchers and have developed a generalized and fast multidomain phase-field based compact model for the metal-ferroelectric-metal (MFM) capacitors. Time-dependent Landau-Ginzburg (TDGL) and Poisson's equations are solved self-consistently to model the polarization dynamics. The developed model is 30,000 times faster than the equivalent multidomain phase-field simulation in which time-dependent tuning of energy coefficients was necessary to produce results of similar accuracy. The model shows a good agreement with the experimental results of both transient characteristics and minor hysteresis loops. This model enables fast and accurate simulation of large-scale circuits containing ferroelectric capacitors. This work has been published in *IEEE Transactions on Electron Devices*.

Another major education activity in the past year has been a webinar series on computation with talks from three modeling and simulation experts. The talks were recorded and are available on the NNCI YouTube channel (See Sections 10.3 and 10.4 for more information).

4.4. Innovation and Entrepreneurship

The 2021 NNI Strategic Plan calls for *"innovative mechanisms to realize the transformational societal benefits that flow from faster commercialization of nanotechnologies."* More recently, in 2022, the NSF launched the Regional Innovation Engines or "NSF Engines" program to help catalyze and foster innovation ecosystems across the US. Additionally, in 2022, the US National Nanotechnology Coordination Office (NNCO), launched the Nano4EARTH program, which aims to mobilize the nanotechnology community to help develop and commercialize nano-enabled solutions to climate change. The NNCI is well-positioned and resourced to contribute to these federal initiatives through its NNCI Innovation and Entrepreneurship (I&E) program, which was established in April 2021. The mission of the NNCI I&E program is to connect and amplify an ***NNCI-wide Innovation Ecosystem*** focused on training a new generation of "nano-savvy" innovators and entrepreneurs, identifying and meeting the unique needs of industry users, particularly start-ups and small to medium-sized enterprises (SMEs), and supporting the translation of nano-enabled innovations to society. Unlike NNCI programs around education and outreach, societal and ethical implications, and computation, I&E activities are undertaken at sites in a more indirect and decentralized manner (i.e., dedicated funding and reporting mechanisms are not specifically defined or required for I&E activities). Consequently, I&E activities pose both unique challenges and opportunities for collaboration across the 16 NNCI sites. The sections below summarize NNCI I&E accomplishments during the past year.

I&E Working Group

In 2023, the NNCI I&E Working Group (Figure 3) met quarterly on the following dates: February 28th (Q1), May 9th (Q2), August 29th (Q3), and October 26th (Q4). Once again, the Q4 meeting coincided with the NNCI Annual Meeting hosted by Stanford. The I&E presence at the NNCI Annual Meeting was significant, as the I&E WG contributed to the meeting in two unique ways: 1) assisting with development of the special topic session on "Translating from R&D to Market" and 2) sharing initial results of the 2023 Economic Impact Survey.

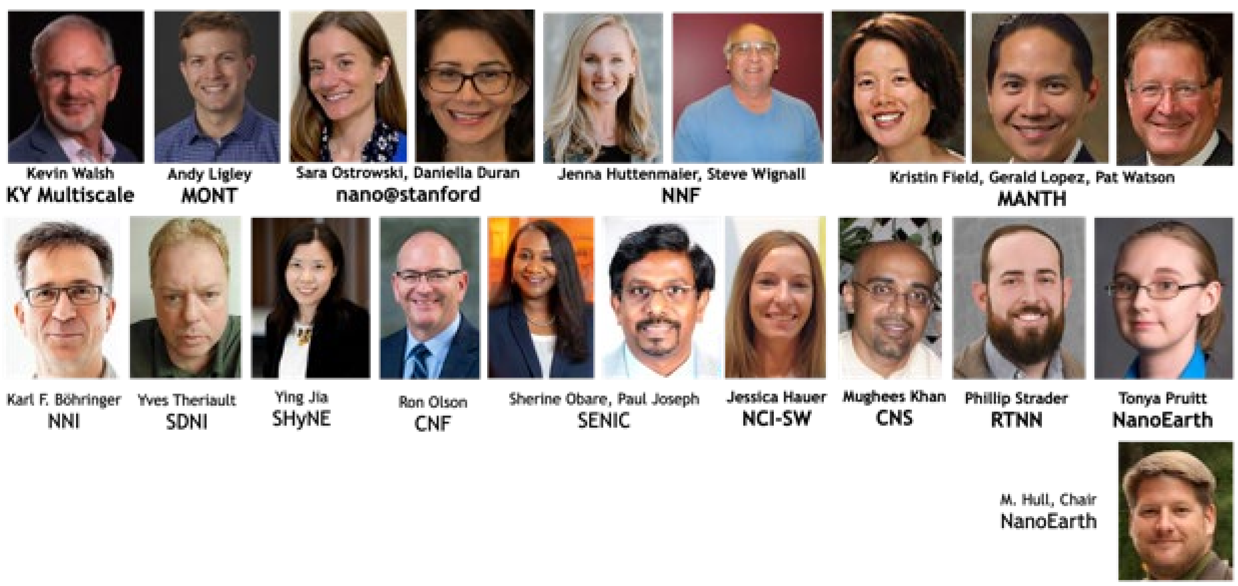


Figure 3: The 2023 NNCI I&E Working Group includes representatives from 14 NNCI sites.

The NNCI Economic Impact Assessment Survey (EIA) was distributed to 1812 unique email addresses representing companies gathered by NNCI-funded user facilities. At the time of this reporting, the usable response rate for the survey is 7%, with a total of 167 partially completed or complete usable responses. Among NNCI sites, CNS, nano@stanford, and SDNI had the greatest response rate at 19%, 13.5%, and 12.3%, respectively. Initial results from the 2023 Economic Impact Survey (See Section 6.11), which were presented by Jessica Hauer (NCI-SW) and Tonya Pruitt (NanoEarth), are summarized below:

- Company Demographics:
  - Most companies (about 60%) were privately owned.

  - Company size was bimodally distributed with most companies (46%) having fewer than 20 employees, but 26% had more than 500.
  - The top 5 fields represented (accounting for about 40% of respondents) were: 1) Technology and Semiconductors, 2) Health and Medical, 3) Manufacturing, 4) Chemicals and Materials, and 5) Photonics and Optics
  - 30% were launched since 2015.
  - 78% began using NNCI facilities since 2015.
  - 75% used NNCI facilities within the last 6 months.
  - Most companies (38%) use NNCI facilities "a few times a year" whereas 11% cited daily use.
- Trends:
  - The top 5 factors driving NNCI usage were: 1) the availability of specific equipment or tools – 79.8%, 2) proximity of the site to the business user – 68.7%, 3) staff support and/or expertise – 66.3%, 4) affordability – 50.3%, and 5) familiarity – 31.9%
  - 16% indicated that NNCI facilities were the only option available to them.
  - The top 3 uses of NNCI facilities were: research and development (83%), prototyping (29%), and quality control (16%)
  - 61% indicated they had filed at least one patent from using NNCI supported facilities in areas such as sensors, medical devices, photovoltaic devices, microtools, optics, quantum devices, microfluidics, packaging, and textiles.
  - Companies cite the following as the top 3 major influences of the NNCI on their business: 1) increased learning and understanding, 2) development of new products and services, and 3) new research and development.
  - NNCI cited as instrumental in starting 35% of businesses.
  - NNCI enabled 75% of businesses to achieve continuous product innovation.
  - About half (49%) indicated that their business had products and services that would not exist without NNCI supported facilities.
  - 92% noted that they would be affected if they were to no longer have access to NNCI-supported facilities.
  - Businesses reported raising $2.3 billion dollars in financing since they began work with NNCI facilities.
  - 39% agree NNCI helped them hire more employees.
  - 64% agree NNCI facilities helped increase their Intellectual Property portfolio.
  - 79% attributed some success with financing to work done at NNCI-supported facilities.
  - 32% of businesses earned more than $1 Million in revenue in 2022.
- Notable Quotes from NNCI Industry Users:
  - "NNCI supports 92% of our users' products and services."
  - "None of the research conducted through my company would have been possible without access to a NNCI facility."
  - "Our work (with NNCI) allowed us to avoid investing in this area too early. We avoided tens of thousands of dollars of wasted work."
  - "Access to this equipment enables us to perform R&D leading to private and public grant funding and ultimately to functional prototypes, manufacturing, and revenue."
  - "NNCI-supported facilities provide access to critical equipment that is too expensive for us to buy at this stage. Access to this equipment enables us to perform R&D leading

to private and public grant funding and ultimately to functional prototypes, manufacturing, and revenue."

- o "In doing research and development, being able to operate the tools ourselves means we have a better chance to understand why the process does and does not work and we have a better chance at setting priorities and schedule."

Looking ahead, the I&E WG survey team hopes to collect additional responses. Upon conclusion, the team will share the full set of raw data with "survey champions" based at each NNCI site. A written report is anticipated by mid-2024.

In addition to the economic impact survey, the I&E WG contributed to the planning and reporting for the 2023 Workshop on Nanotechnology Infrastructure of the Future, which took place in Washington, DC and online September 12-13. Specifically, the I&E WG contributed to the session on September 13th entitled "Translating Nanotechnology from R&D to Market". Finally, the I&E WG contributed to the synthesis of feedback and recommendations received that were relevant to translation, innovation and entrepreneurship, and industry engagement, and these contributions can be found in the final workshop report.

The objective of the I&E Working Group is to ensure site-level representation in NNCI I&E programming development, decision-making, and assessment. The activities of the I&E Working Group will complement and support those of other NNCI working groups.

The primary program areas and topics addressed by the I&E Working Group agenda are described below:

- **NNCI I&E Speaker Series** – recommendations for NNCI-wide speakers who can speak on topics pertinent to I&E and industry engagement as part of the NNCI Webinar series.
- **NNCI-wide Entrepreneurs-in-Residence (EiRs)** – faculty/staff entrepreneurs based at individual sites (including external users from small companies) who may be interested in serving as EiRs in an assortment of capacities
- **NNCI-wide Student-led Nanotechnology Entrepreneurship Challenge (NTEC)** – strategies to develop/sustain student-focused entrepreneurship at the site-level and NNCI-wide
- **"REEU" program** – collaborative effort with the NNCI education program focused on sharing and scaling an "entrepreneurship" module/experience to complement existing REU programs
- **Development of an "NNCI Innovators Academy"** – coupling of virtual learning modules across sites to train and support "nano-savvy" innovators and entrepreneurs
- **Industry user recruitment** – sharing of strategies to recruit/engage industry users, particularly users from start-ups and SMEs
- **Underrepresented and minority entrepreneurs** – focused engagement and support of nanotech entrepreneurs from diverse & underrepresented groups
- **Lessons Learned** – general sharing of I&E lessons learned across sites
- **Goals** – establishing and refining I&E goals

<u>NNCI Site-Specific I&E Activities</u>

In addition to the I&E activities organized through the NNCI I&E WG, individual NNCI sites continue to be a source of impactful I&E programming. Lessons learned from these programs are shared broadly and openly across the NNCI either ad hoc or during quarterly I&E WG meetings. Some notable I&E activities organized by individual sites are summarized below.

- In January 2023, a "Pain to Pitch 180™" experience was developed and initiated in collaboration with the ASU Winter School to immerse attendees in the commercialization process. Participants had 180 minutes to uncover a pain point and pitch a solution.
- January 24-24, 2023, the NNCI was represented at the NNCO's Nano4EARTH Kick-Off Workshop, which initiated a cross-sector focus on rapidly translating nano-enabled technologies to combat climate change. A follow-up Nano4EARTH event led by RTNN and hosted at NC State University was held February 21, 2023.
- On April 25th, 2023, Dr. Ron Olson, Dr. Judy Cha, and the Cornell Nanoscale Science and Technology Facility (CNF) continued their annual New York State Nanotechnology Network (NNN) Symposium, which helps connect students and industry participants from across the state.
- Dr. Kevin Walsh and colleagues from the Kentucky Multi-Scale Manufacturing and Nano Integration Node (KY Multiscale) hosted the 2023 NNCI Nano+Additive Manufacturing Summit July 25-26. The event featured examples of regional start-ups focused on nano/AM.
- On August 8th, 2023, MONT hosted an entrepreneurship and innovation panel at the 2023 NNCI REU Convocation in Bozeman, MT. The panel featured perspectives and lessons learned from a diverse group of innovators and entrepreneurs with experience translating nano-enabled innovations to market.

Research and ENTREPRENEURSHIP Experience for Undergraduates (REEU)

The REEU program sits at the interface of the NNCI Education and Outreach (E&O) and I&E domains and aims to expose NSF REU students to nano-enabled entrepreneurship opportunities linked to research. Since the extent to which entrepreneurship might "fit" within one REU program or another can vary from site to site, flexible REEU options are offered and tailored to meet the needs of individual REU coordinators. Coordination with the NNCI E&O program area facilitates engagement with REU coordinators and helps ensure careful integration of REEU content at an appropriate level. Four general REEU levels are offered and span from only a brief consideration of entrepreneurship to more advanced programming:

- **Level 1:** No/brief discussion of entrepreneurship
- **Level 2:** General/theme-focused (i.e., aligns with REU theme) entrepreneurship lecture and Q&A (~1 hr)
- **Level 3:** Series of I&E lectures/seminars and/or visit/tour at nearby start-up facility
- **Level 4:** Extended duration project ("I-Corps lite")

REU program coordinators can contact NNCI Associate Director Matthew Hull to discuss incorporating an entrepreneurship module within their REU program.

In 2023, the number of NNCI sites participating in the REEU program, increased to eight (Figure 4). REEU modules are offered in collaboration with the NNCI Assoc. Director for E&O (Mikkel Thomas) and local REU coordinators. In 2021-2023, 98 REU students participated in the program. Dr. Yves Theriault (SDNI) continues to leverage the NNCI REEU program to implement a series of I&E seminars within the SDNI REU program at UC San Diego.

Figure 4: 2021-2023 REEU Participation: 8 sites and 98 REU students engaged.

Interest in industry research careers remains high among REU students participating in the NNCI REEU program. More than half of all REEU participants indicated that careers in "industry research" or "entrepreneurship" were of greatest interest to them (Figure 5). The remaining students expressed interest in careers in government labs, academic/faculty positions, non-profit organizations or "other". Across all years, about half of the REEU participants claimed that they did not know much about entrepreneurship (Figure 5). Students claiming to know "a good bit" about entrepreneurship has fluctuated between 10-20%.

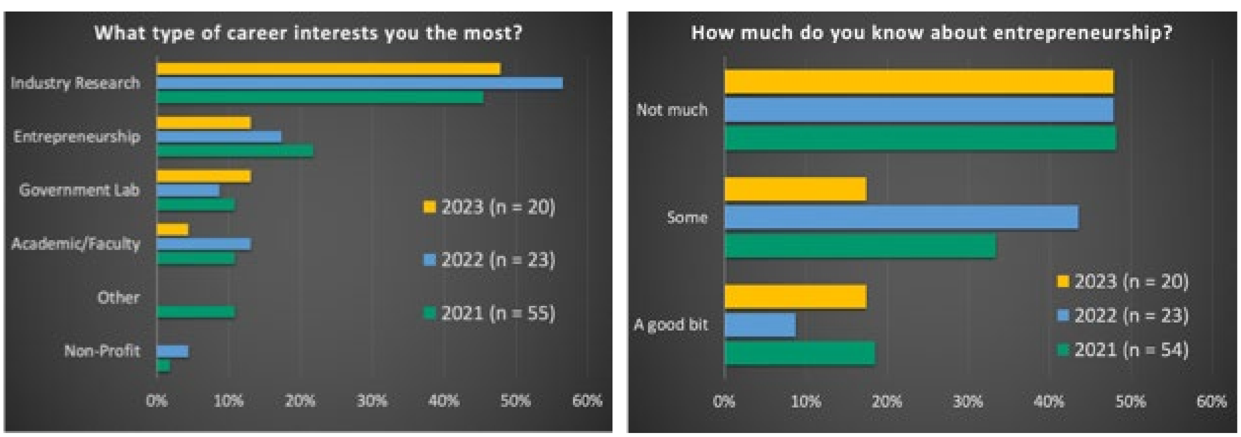


Figure 5: Feedback to date (2021-2023) from REU students participating in the NNCI REEU module when asked (left) about the type of career interests that interests them the most, and (right) how much they know about entrepreneurship.

Overall, the students continue to express a favorable opinion of entrepreneurship, using terms like "creativity", "innovation", and "leader" as entrepreneurship descriptors (Figure 6). Ongoing assessments of REU student perceptions of entrepreneurship can help the I&E and E&O working groups continue to better understand student interest in entrepreneurship and tailor program content for maximum efficacy.

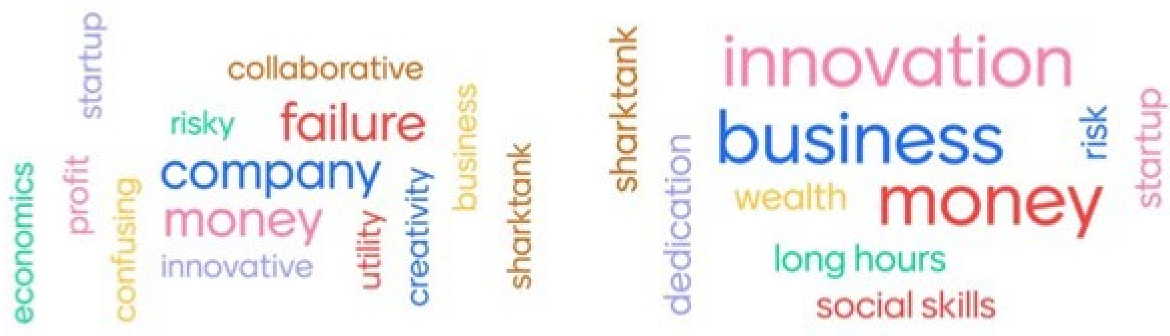


Figure 6: 2023 word clouds based on student responses from multiple REEU sessions when asked "What comes to mind when you think of entrepreneurship?"

<u>NNCI I&E Webinar Series</u>

To date, five I&E seminars (two in 2023) have been hosted as part of the broader NNCI seminar series and shared virtually across the NNCI to help foster awareness of industry-specific challenges and engagement of industrial problem solvers. Industry seminars foster awareness of key I&E topics or issues and enable the deeper relationships required to effectively engage and recruit non-traditional NNCI users, particularly small business users pursuing opportunities such as SBIR/STTR. Compared to site-level seminars, however, NNCI-wide I&E seminars: a) have relevance across multiple or all NNCI sites by elevating the message of an impactful I&E story (e.g., a success story), collaboration, trend, or opportunity, b) are promoted by the NNCI coordinating office, and c) are often co-hosted along with an NNCI site (e.g., the home site of the I&E WG member who proposed the seminar).

In 2023, the I&E WG hosted two industry seminars. The first seminar was held on May 3, 2023 and was delivered by a panel including Karin Lion, Chief Growth Officer of Activate; Hannah Murmen, Managing Director of Activate Anywhere; and Austin Hickman, CEO of Soctera and an Activate Fellow. The seminar/panel discussion was entitled "Activate Fellowships – Empowering Scientists and Engineers to Bring Their Research to Market." The seminar was organized by the NNCI Coordinating Office with strategic input from Dr. Sherine Obare of SENIC (Figure 7). The second seminar was held on December 19, 2023 and was delivered by a panel including Nathan Hancock, Senior Principal, Flagship Pioneering, and Cristina Jauset, Associate, Flagship Pioneering. The seminar/panel discussion was entitled "Venture Creation for Sustainability." The seminar was organized by NanoEarth.

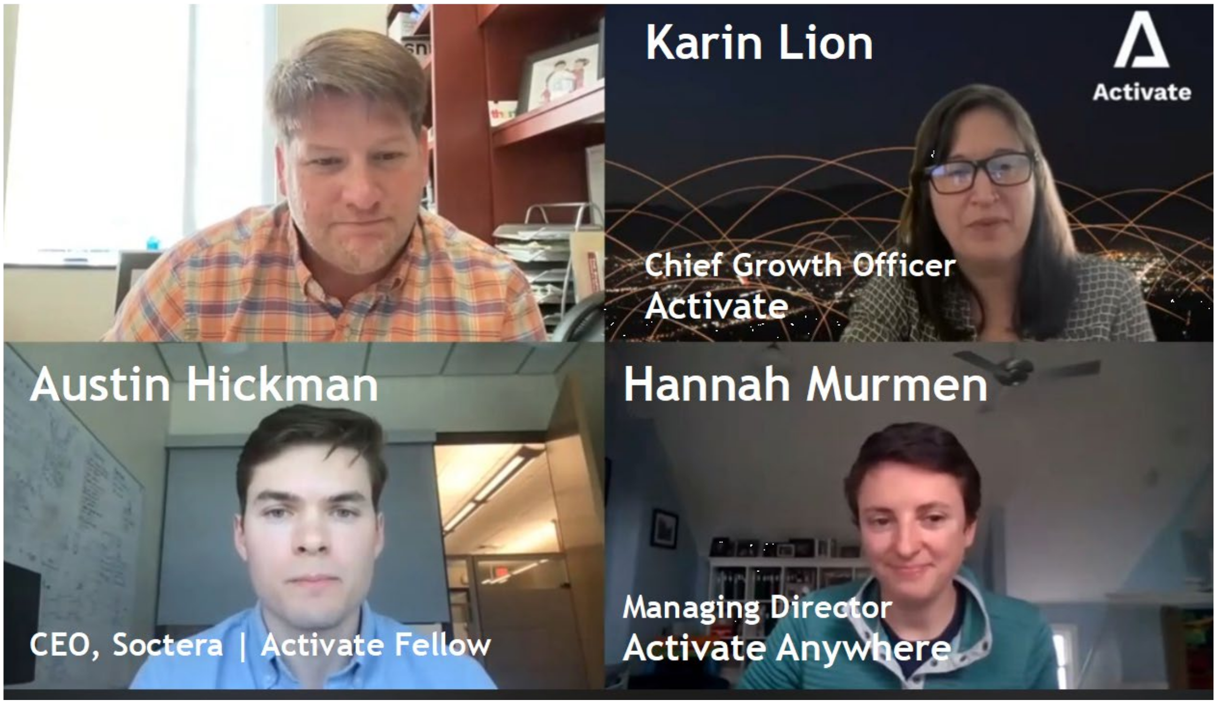


Figure 7: In 2023, the I&E WG hosted an industry seminar/panel focused on Activate Fellowship, which help scientists and engineers bring their research to market.

Planning is currently underway for the 2024 seminar series and should be announced in late January/early February. Live online attendance at the five previous seminars totaled approximately 150 guests but the majority of attendees continue to view the archived seminars on the NNCI YouTube channel, asynchronously, where total views (as of this report writing) exceed 300. Members of the I&E Working Group select seminar topics and host speakers. Emphasis is placed on selecting topics and speakers of broad interest across the NNCI sites.

NNCI Nanotechnology Entrepreneurship Challenge (NTEC)

The NanoTechnology Entrepreneurship Challenge (NTEC) is an NNCI-supported program that aims to train a new generation of "nano-savvy" student innovators and entrepreneurs about the process of commercializing nano-enabled technologies to solve global sustainability challenges. 2023 marked the second year of the NNCI-wide NTEC program. Ten student-led teams participated in the 2023 NNCI NTEC program and teams consisted of 12 students from four different NNCI sites who participated in a seven-week NNCI Virtual Accelerator program. The program began March 13th and concluded May 4th, 2023, with an NNCI Showcase event. Table 4 summarizes the 2023 NNCI NTEC cohort projects.

Table 4: 2023 NNCI NTEC Cohort

Student Lead(s)	NNCI Site	Award	Mentor(s)	Title
Hunter Holden	SENIC (JSNN)	Diversity	Dennis LaJeunesse	Structural bacterial cellulose
Victor Mukora	NanoEarth	Regular	Anne Brown	Applications of real-time machine learning to solar energy
Trayda Murakami	NanoEarth	Regular	Matthew Hull, Tonya Pruitt	Women in NanoEARTH
Naimat K. Bari	NanoEarth	Regular	Bahareh Behkam	Nanofibrous living materials for pathogen detection
Mayuk Sengupta	NanoEarth	Regular	Marc Michel	Non-lethal ceramic/crystal tipped bullets
Micheal Erb, Charles McKee	NanoEarth	Regular	Marc Michel	Chemical upcycling of polystyrene waste in aryl ketones
Charlie Ver Beek, Chloe Nyhart	NanoEarth	Regular	Craig Tollin	The effect of organic dye used in an organic photovoltaic cell on efficiency
Cade Toth	NanoEarth	Regular	Marc Michel	Characterization of natural iridescent iron oxyhydroxide from Graves Mountain, Georgia
Haoxuan (Angelo) Lyu	MANTH	Regular	Marc Allen	Exploration of degradable encapsulants of bilayer wax systems
Ivonne Gonzalez Gamboa	SDNI	Diversity	Yves Theriault	Nanoparticle-embedded pesticides for reduced environmental toxicity

The 2023 top overall NTEC team as well as the top Diversity Award team was led by Ivonne Gonzalez Gamboa, a UC San Diego student affiliated with the San Diego Nanotechnology Infrastructure (SDNI). Hunter Holden (SENIC) and Naimat Bari (NanoEarth) received second and third place honors, respectively (Figure 8).

Figure 8: Top NNCI NTEC Teams of 2023. Left: SENIC's Hunter Holden (lead); Center: Top Overall and Diversity Award Winner UCSD's Ivonne González-Gamboa, Dr. Yves Theriault (advisor), Manuel Martinez (industry advisor); Right: NanoEarth's Amrinder Nain and Bahareh Behkam (faculty advisors), Naimat Bari (lead)

Designed as a pre-NSF I-Corps experience, NTEC provides experiential entrepreneurship education for teams led by undergraduates, graduate students, and post-doctoral scholars. NTEC teams learn about the importance of customer discovery and how to leverage NNCI resources to develop a nanotechnology-enabled minimum viable product (MVP). The seven-week program culminates in a "pitch" event where teams share their progress with business leaders. At one NNCI site, the site-level version of the NTEC program supported more than 30 students from 16 teams; nearly half were led by students from underrepresented groups and minorities; four invention disclosures were filed, and four student-founded companies were supported. By leveraging entrepreneurship resources available at each site, NTEC can be scaled and competed across the NNCI. Importantly, since Spring 2020, the NTEC program has been successfully administered virtually due to the pandemic, which demonstrates the potential for the program's broad reach.

The NTEC program is implemented across NNCI sites on an entirely voluntary basis (there is no requirement for sites to participate). Figure 9 summarizes the schedule for the 2024 NNCI NTEC program. Tentatively, the program will be announced by the NNCI Coordinating Office on January 9, 2024 with applications due February 11, 2024 (National Inventor's Day). The NNCI I&E Working Group will review the applications and recommend top applicants to the NNCI sites from which the applications were submitted. Sites will have the final say in which program they do/do not support based on their available resources (i.e., personnel, instrument time, funds for materials and supplies).

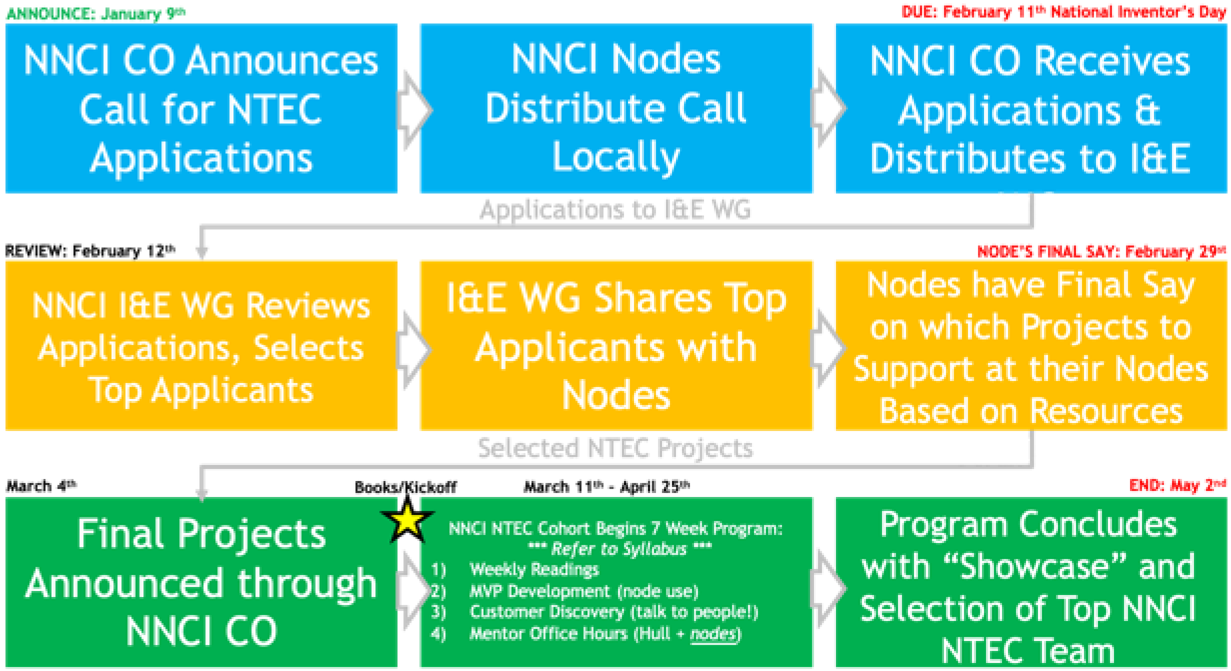


Figure 9: Timeline for the 2024 NNCI NTEC program.

In 2024, an additional $20,000 will be available to support NTEC awards at NNCI sites. This funding will allow the allocation of up to $1,000 per site with $4,000 available as an incentive for top teams. Once again, we anticipate awarding multiple award types – from in-kind instrument time to $500 team awards and $1,000 NTEC Diversity awards (to encourage teams led by underrepresented groups and minorities) – to allow for the broadest participation possible. Winning teams will once again participate in a seven-week, virtual NNCI NTEC Accelerator program aimed at providing teams with a gentle introduction to the concepts of the minimum viable product (MVP), business model generation and business model canvas (BMC), and customer discovery. Teams will work at their own pace but will have weekly readings, work with NNCI staff to use NNCI tools in the creation/evaluation of their MVP, and have the opportunity to engage with NNCI NTEC mentors via weekly virtual office hours.

In 2024, we anticipate that the weekly virtual touch-base meeting will include multiple members of the NNCI I&E WG, including Dr. Matthew Hull (NanoEarth), Dr. Yves Theriault (SDNI) and Dr. Paul Joseph (Georgia Tech – formerly of SENIC). These I&E WG members provide additional mentorship capacity to complement resources offered at local NNCI sites. Participation in the NNCI NTEC Accelerator program can help teams prepare for local/regional start-up pitch competitions or more intensive and highly successful programs like NSF I-Corps. Ultimately, the aim of the NTEC Accelerator program is to help inspire a generation of "nano-savvy" innovators and entrepreneurs across the United States who have both the technical competence and business acumen to translate nano-enabled breakthroughs from the lab bench to society.

The NNCI NTEC program concludes with a one-hour, fast-paced, virtual showcase event where teams share two-minute video clips of their progress during the NTEC Accelerator Program (Figure 10). A distinguished panel of innovators and entrepreneurs scores each team in real-time according to key performance metrics. The 2024 NNCI-wide NTEC showcase is expected to occur on May 2, 2024.

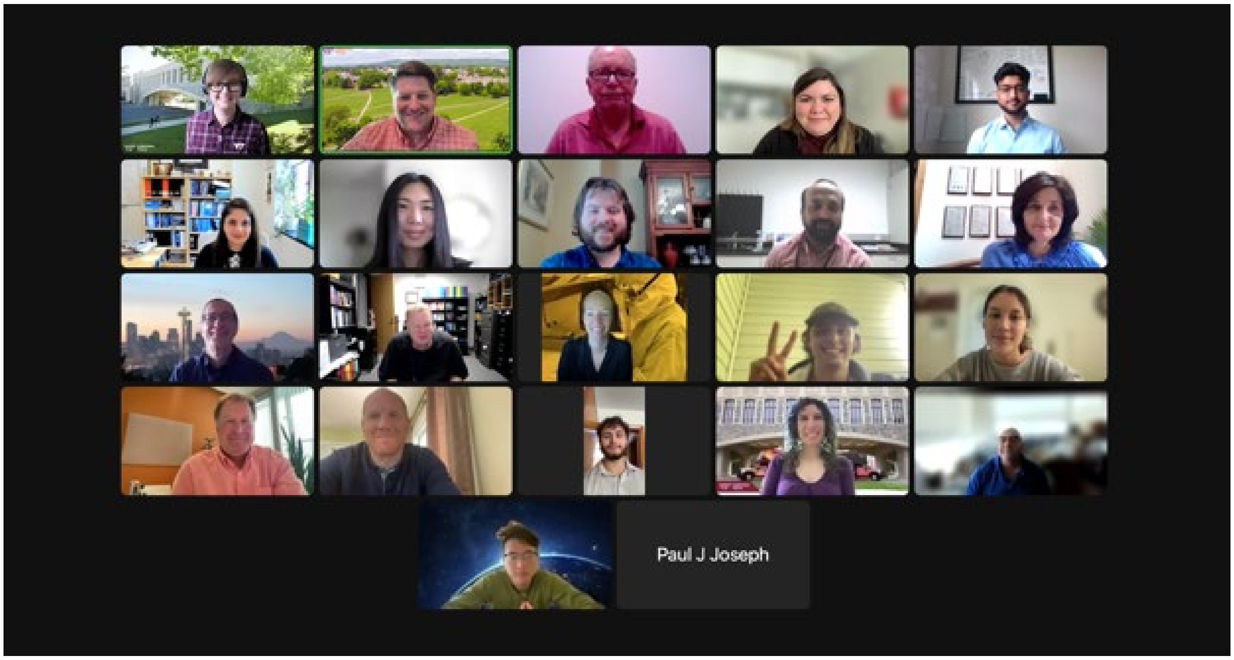


Figure 10: Zoom capture from the 2023 NNCI NTEC Showcase.

Entrepreneurs-in-Residence (EiR)

Currently, there are four identified NNCI EiRs (Table 5). The I&E Assoc. Director serves as the NNCI EiR in situations where a site-specific EiR has not been identified. In 2024, we will work to identify additional EiRs at other sites, establish regular office hours during which EiRs can be consulted by prospective student and faculty entrepreneurs, and meet regularly with EiRs to evaluate activities and ensure successful outcomes. The role of the NNCI EiR is to help mentor (typically on an ad hoc and informal basis) NNCI users, faculty, students, and staff about topics related to entrepreneurship and commercialization, such as starting (or not starting) a new venture, where to find start-up capital, what local I&E resources (e.g., business accelerators) are available, how to navigate the university intellectual property process, and what common pitfalls to avoid. Developing entrepreneurs can benefit greatly from this mentorship and many established entrepreneurs are more than willing to provide it. A good candidate for an NNCI EiR role will have a “mentor mentality” and a strong existing connection with a particular NNCI site or group of sites. In many cases, an ideal NNCI EiR may be a faculty or staff member who already plays a role at an NNCI site but who also has prior or ongoing entrepreneurship experience and is willing to share that experience with others. The EiR may serve voluntarily, as part of assigned duties, or, if resources allow at a particular site, they can be additionally compensated.

Table 5: NNCI Site Entrepreneurs-in-Residence

Site	EiR
MONT	Trevor Huffmaster
SDNI	Yves Theriault
NNI	Mike Robinson
NanoEarth	Matthew Hull
NNCI (when local site EiR is not available)	Matthew Hull

5. NNCI Subcommittees

In addition to the work of the Coordinating Office and specific topical areas of the Associate Directors, several subcommittees of the Executive Committee have been formed to tackle high-level issues related to the NNCI network as a whole (Table 5). Positions on these committees were offered to each member of the Executive Committee (site PIs), along with any site co-PIs who wished to participate. Most Site Directors serve on two of these subcommittees with a subcommittee chair selected by the Coordinating Office. Additional input may be sought from members of the External Advisory Board and other experts as needed. Members of the Coordinating Office serve on some of the subcommittees as ex-officio members. As a starting point, the Coordinating Office created a number of guiding questions for each subcommittee. One of the subcommittees is selected to report to the full group of site directors and coordinating office (Executive Committee) every other session during the regular monthly meetings. Subcommittee topics, chairs, and members were reviewed and updated during 2021. The Entrepreneurship and Commercialization subcommittee was sunsetted, replaced by the new Associate Director and working group. The New Equipment and Research subcommittee was refocused on Research and Funding Opportunities. Finally, a new subcommittee on Nanotechnology Infrastructure of the Future was added. Reports of the subcommittees on current and future activities are presented below as provided by the subcommittee chairs.

Table 5: NNCI Executive Committee Subcommittees (2023)

Subcommittee Topic	Subcommittee Chair(s)
Diversity	Bill Wilson (CNS)
Metrics and Assessment	Christian Binek (NNF)
Global and Regional Interactions	Vinayak Dravid (SHyNE), Yuhwa Lo (SDNI)
Research and Funding Opportunities	Jim Cahoon (RTNN), Chris Ober (CNF) – retired during 2023
Nanotechnology Infrastructure of the Future	Debbie Senesky (nano@stanford)
Building the User Base	Shyam Aravamudhan (SENIC)

5.1. Diversity Subcommittee

The following summarizes Year 8 work in the area of diversity, equity, inclusion, and access (DEIA) at several sites within the NNCI network.

Cornell NanoScale Facility (CNF): Since 1977, the Cornell NanoScale Science & Technology Facility (CNF) has engaged in efforts to broaden participation in nanoscience, taking a broad view of the many research fields reflected within the science and non-science communities. We take pride in providing access to any person interested in any application of nanofabrication.

In 2023, CNF hired seven undergraduate students to take part in the REU program— three women, two Hispanics, and two Blacks. We specifically work with Morgan State University (MSU) where up to 3 students will be supported by our college of engineering to take part in our REU program. We also hired eight 2022 NNCI REU students to participate in our second-year program, sending them to Japan to perform research working with the National Institute for Materials Science (NIMS), five of whom identified as female. Finally, we hosted one female graduate student from the Hokkaido University, Sapporo Japan.

In Year 8 we hosted or participated in at least 116 outreach events with well over 4054 visitors — over 1,000 of whom were K-12! These numbers do not include the fact that we brought a Nano-Exhibit to our local Sciencenter (https://www.sciencenter.org) who reported that their 99,377 visitors enjoyed the nano-activities. We mailed out over 100,000 copies of our youth newsletter, Nanooze (https://www.nanooze.org), to K-12 schools across the country. The focus of all Nanooze issues is to excite and recruit a diverse community of students to the nanoscience field.

Tom Pennell our Education and Outreach Coordinator piloted ATLAS (Accelerated Training for Labor Advancement in Semiconductors), a program in cooperation with TST BOCES New Visions Engineering to further workforce development educational opportunities. This program provided students with a comprehensive in person/hands on training in the key areas of the cleanroom semiconductor environment.

CNF continues its annual outreach events, which include "Expanding Your Horizons"—a weekend of on-campus STEM activities for middle school girls, "4-H Career Explorations"—two days of STEAM activities on campus (Cornell serves as the land grant school for New York State and is therefore the headquarters for NYS 4-H), and three Micron Chip Camps engaging with over 300, 7-8th graders from Syracuse area schools. The Chip Camps featured a virtual tour of the CNF cleanroom, hands-on activities, and the opportunity for participants to put on bunny suits. We eagerly anticipate hosting more Micron Chip Camps in 2024.

This year, Tom took the CNF activities "on the road" and spent a day at the New York State Fair, introducing over 400 kids and their families to our nano-activities and our brand-new CNF virtual cleanroom experience! https://www.cnf.cornell.edu/about/virtual_experience.

The CNF continued hosting the FIRST LEGO Expo, where 200 middle-school students showed off their "Super Powered" LEGO creations. The CNF staff, CNF ambassadors and Cornell's Society of Women Engineers volunteered to judge the LEGO creations and hand out group awards.

CNF partners with Tompkins Cortland Community College (TC3) to provide workforce development opportunities for veterans, Native Americans, un/underemployed and underrepresented workers, and economically and academically disadvantaged students.

Twice a year, we hold our short course — Technology & Characterization at the Nanoscale (TCN). We specifically host the CNF TCN virtually in January, at a reduced cost, so that anyone can attend, regardless of distance, economic ability, and weather. In June, the CNF TCN is in person, so we can work, hands-on, with our TC3 and REU students as well as researchers from academia and industry.

Annually the CNF presents the Whetten Memorial Award in recognition of women scientists whose work and professional lives exemplify a commitment to scientific excellence, interdisciplinary collaboration, professional and personal courtesy, and exuberance for life. The

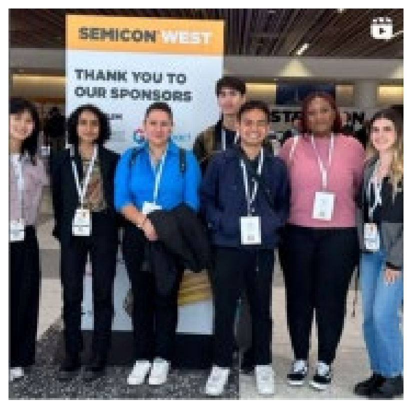
2023 award was presented to Melody Lim of the Laboratory of Atomic and Solid-State Physics, Cornell University.

At the CNF Annual Meeting, Dr. Sophie V. Vandebroek, our 1989 CNF Whetten Memorial Award recipient and founder of Strategic Vision Ventures, shared career insights, and Dr. Robert Simmons, Head of Social Impact and STEM Programs for Micron, discussed workforce development. Our annual meeting was enjoyed by 157 participants.

Over the year, the CNF was an active member of the NNCI Diversity Subcommittee, bringing concerns to the CNF staff for discernment. We are excited to take part in the planned NNCI HBCU Summer Fab Bootcamp using our teaching experience through our established (TCN) short course. In addition, we collaborate with Cornell Diversity Programs in Engineering to recruit students to Cornell and to studies in nanoscience and engineering. We regularly review and affirm the NNCI diversity statement and goals with CNF staff. Finally, CNF takes part in Cornell-required annual training activities that provide staff the opportunity to learn and develop practical skills for cultivating a diverse, equitable, and inclusive workplace that fosters a culture of belonging.

nano@stanford: Stanford's diversity, equity and inclusion efforts in Year 8 have been incorporated into: (i) our community college internship program, (ii) middle school teacher program and (iii) learning content development.

Our year-round, community college internship program provides hands-on, paid experience in nanotechnology for students from local colleges. The program has undergone substantial growth in Year 8, increasing from 9 to 21 interns. We have intentionally targeted minority serving institutions (MSI) when recruiting interns, which has resulted in 88% of our interns coming from underrepresented groups. Additionally, 69% of our interns have been female. This year we started to overlap new interns with senior interns, who assist with training to reduce staff time for onboarding, and this facilitates scaling. Out of the 25 interns that we have hosted since 2018, 10 transferred to 4-year institutions, 1 accepted a full-time job, and 1 participated in a REU at Harvard's NNCI site.



nano@stanford sponsored an intern field trip to SEMICON West.

Nanoscience Summer Institute for Middle School Teachers (NanoSIMST) is a middle school teacher professional development workshop during which participants learn about nanoscience and prepare classroom lessons. Since 2017, NanoSIMST has grown to become a network-wide activity, led by nano@stanford. Last summer, we partnered with 9 other NNCI sites which either adopted the in-person program or provided financial support to sponsor teachers from their areas. The agenda this year included guest speakers from our sister sites at CNS and KY Multiscale, exemplifying the power of a network. To date, NanoSIMST has trained 145 teachers, impacting an estimated 7000 students. We strategically target diverse cohorts of teachers based on subject matter expertise and school location/demographics. The addition of a virtual format increased the participation of Title 1 schoolteachers from an average of 48% in previous years, to 71% in year 8. This year we hosted a field trip for 150 eighth graders from a Title 1 school where a NanoSIMST alumna teaches. During the last two years of the award, we plan to both increase the number of teacher participants and to enhance the program content with industry guest speakers and career resources.

To further augment the internship program and NanoSIMST, we plan to incorporate career oriented content (e.g., industry speakers, career resources, industry opportunities) and have begun building connections with industry towards this goal. For example, we have been working with the SEMI Foundation to share and leverage the resources they have developed for educators and career explorations for both NanoSIMST and the intern program.

Field trip for 150 8th graders to visit nano@stanford, led by a NanoSIMST alumna. This demonstrates the impact of a single teacher.

With the help of a mini grant, Stanford graduate students created DEI-targeted STEM experiential learning content, along with numerous facility tours, demos, workshops, curriculum support etc., reaching a total of 2445 participants this year alone. In Year 8 we have continued to create content for our edX courses, reaching 10,228 learners since 2019. While most learners are based in the US (26%) and India (23%), the course has a truly global reach.

Northwest Nanotechnology Infrastructure (NNI): The NNI continues to focus on promoting equity, inclusivity, and diversity through inclusive hiring processes, holistic graduate student reviewing and recruiting, outreach, and research opportunities for undergraduate students. All staff and faculty searches at Oregon State University (OSU) follow processes designed to minimize the impact of cognitive and structural biases and include a search advocate to help watch for unintended biases and to advance diversity and social justice in the hiring process. All application pools are analyzed for diversity and compared to the diversity in the down-selected interviewing pool. This practice has greatly increased the diversity among the interviewing candidates and has led to the hiring of highly qualified and diverse faculty and staff. These efforts have helped increase diversity among users; for example, almost 40% of the regular users of the Oregon Process Innovation Center (OPIC) at OSU are female.

Both OSU and University of Washington (UW) follow a holistic admission review process for graduate student recruiting, this process accesses and increases the weight of the unique experiences of the applicants in addition to more traditional measures such as grades which has helped increase the diversity of the graduate student class. At OSU all graduate students take a year-long seminar class on DEI in engineering, which has helped increase awareness of different aspects of DEI in the profession. Many graduate students choose to continue their education through elective courses or become involved in teaching the seminar, which is on a volunteer basis.

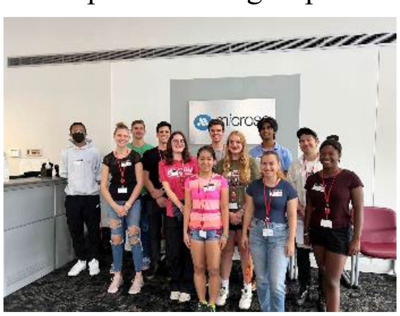
Both OSU and UW have returned to full in-person operation after the pandemic but with more online modules, and flexibility than before. The Washington Nanofabrication Facility (WNF) hosted a week-long Micron-funded nanofabrication workshop for underrepresented undergraduate students. The workshop included, among other things, a "Talk with an Engineer" event with

Micron engineer Brenda Kraus and was a great success. Funding for future courses has been secured from Intel and Mircon. NNCI has increased its interactions with Intel to support undergraduate education and increase diversity in the workforce, a key goal for Intel as well as NNI. In addition to supporting the previously mentioned workshop, Intel will support 3 undergraduate research assistants who will be co-mentored by WNF and Intel engineers, and the undergraduate OSU-Intel research experience continues to be hosted by NNI facilities. Intel is supporting a curriculum development plan to integrate semiconductor learning modules on all levels in undergraduate education at OSU and will help bring diverse speakers from Intel into the classroom to help increase and promote diversity in the semiconductor industry workforce. The School of Chemical, Biological, and Environmental Engineering at OSU hosts the annual Summer Experience in Science and Engineering for Youth (SESEY) program for high school students in the summer. This camp brings about 40 high school students from diverse backgrounds for a week-long on-campus engineering experience every year, and 75% of the participants are female. In addition to providing opportunities for students of different ethnicities and gender identities, the cost is kept at a minimum and scholarships are provided for students to provide opportunities for economically-challenged students which has attracted students from across the country to the camp.

In addition, the WNF director Maria Huffman was recently awarded a five-year workforce development grant through the Microelectronics Commons hub led by Stanford and UC Berkley to develop workforce development opportunities for veterans, community colleges, and underrepresented students.

Research Triangle Nanotechnology Network (RTNN): In Year 8, RTNN continued its commitment to inclusion and promoting diversity in all activities. Many outreach programs engage directly with diverse communities (URM, women, indigenous) and Title-I schools with socioeconomically disadvantaged students, i.e. Girl Scouts STEM Day @ Duke (>600 participants, 95% URG), Community STEM Day with a Waccamaw-Siouan Tribal community (145 participants, 100% URG). RTNN also maintains strong relationships with other internal/external programs in the area to include nanotechnology education activities in their programs. These include internal programs like Duke's BOOST (Building Opportunities and Overtures in Science and Technology) and external programs like "School Days," which both serve Durham Public Schools students from underrepresented groups and/or economically disadvantaged backgrounds. At least 110 outreach events were in-person this year with a total of >12,830 participants reached. This is largely a result of large-format events, including booths at museums, libraries, Science Olympiads, and many more.

Young Waccamaw-Sioux students learning how and why to gown up for a career in nanotechnology.



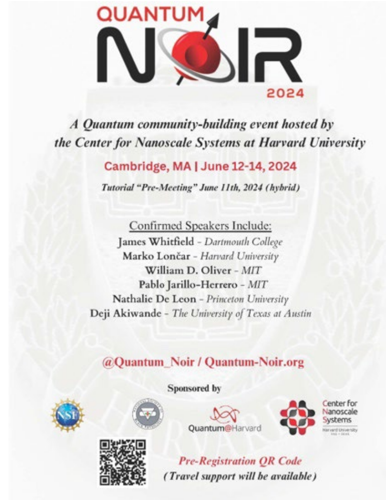
2023 RTNN REU Cohort

Recruitment and success of RTNN programs relies on fostering relationships with diverse communities and talent pools to help improve recruitment and contribute to diversity in RTNN STEM activities. For example, of 12 total 2023 REU program participants, 5 students self-identified as URM/AAPI and 5 self-identified as women.

Diversity of staff and leadership was enhanced further in Year 8 through these additions: Emily Snell (Duke SMIF Program Coordinator), Lydia Skolrood (Duke SMIF Engineer), Sameera Pathirinage (NC State AIF Surface Analysis Postdoc), Folasewa Olatunde (NC State PCOST Graduate Research Assistant), Caitlyn Obrero (NC State AIF X-Ray CT Lab Assistant), Inno Shuro (UNC CHANL Outreach Engineer)

Center for Nanoscale Systems (CNS): The Harvard team is focused on organizing the first *"Quantum Noir,"* a biennial Quantum, Nanoscience and Engineering conference targeted at researchers of Color (+). This is a "community building event" for the Quantum\Nano research community. The primary goals of the meeting are to educate participants of the scope and potential of Quantum Science and Engineering, *illuminate* scientific opportunities nationwide, and to network researchers from under-represented groups, connecting participants *"collaboratively"* with leaders in the Quantum Science and Engineering Community focused on new technologies, national policy, and workforce training. The conference serves as a training and recruiting event for faculty, researchers, and students from under-represented groups into the Quantum Sciences. The ongoing revolution in Quantum Information, Quantum Sensing, and Quantum Networking is a national challenge we must meet with all our resources, human and otherwise. With this support, *Quantum Noir* will help bridge this critical resource gap. The meeting is scheduled for June 12-14, 2024.

We are witnessing the emergence of Quantum Science & Engineering, a technology disruption as significant as the revolution in microelectronics. The ascent of this new discipline demands we rally the nation's scientific community to address this opportunity. Nanotechnology has been an important tool in this, defining technologies and systems where *size* has been used to exploit quantum effects to enable technical function. Now, an array of new technologies that harness the unique quantum properties of *coherence and entanglement* are also emerging from fundamental advances. Much of the foundation of this work is based in condensed matter science and engineering where historically, there has been a barrier of entry for researchers of color, particularly at small and minority serving institutions, due to limited access to the extensive infrastructure and resources required to do *world-class* work. Fortunately, today, because of diligent efforts at NSF and other agencies, creating ample shared facilities and support, that barrier to entry is lower than ever. Unfortunately, too few researchers are availing themselves of these opportunities. Creating connection is the key. If we are to meet the challenges of innovation in Quantum Technologies we need to enable all potential innovators and train a workforce that will ensure that Quantum Supremacy will reside in the US. *Quantum Noir* aspires to fill this gap. The conference will serve as an important workforce training and development event by enabling technology dissemination of the *"state-of-the-art"* from Quantum Engineering leaders, directly to a new generation of diverse researchers. The conference, funded by NSF CMP, will create a collaborative nexus for researchers and students and will allow industry and the venture community access to an untapped source of innovators. The first meeting will be at Harvard University hosted in part by the Harvard Center for Nanoscale Systems (CNS), (*PI Wilson is the center Executive Director)*. The Harvard/MIT research community is home to international leaders in Quantum Materials and Device development. The Quantum Materials Science, Quantum Networking, and Quantum Information Science thrusts supported by CNS has driven technology advances not only leading to cutting edge discoveries, but also several efforts that have moved on to commercialization. This community has contributed transformational work in quantum materials and device research and is poised to help connect and train the next generation of quantum researchers. *Quantum Noir* will leverage this expertise to truly diversify Quantum science, but also *to build community,* ensuring we are optimizing the nation's talent and human resources available by connecting *"all"* researchers with the available infrastructure, resources, and training.



Members: Bill Wilson (CNS, Harvard), Jacob Jones (RTNN, NC State), Maude Cuchiara (RTNN, NC State), Liney Arnadottir (NNI, Oregon State), Yuri Suzuki (nano@Stanford), Kristin Field (MANTH, UPenn), Yu-Hwa Lo (UCSD), Sherine Obare (SENIC, NC A&T and JSNN), Christopher Ober (CNF, Cornell), Melanie-Claire Mallison (CNF, Cornell), Heather Rauser (MONT, Montana State), Charles Lowry (Virginia Tech), Gabriel Alonzo Montano (NCI-SW, Northern Arizona University)

5.2. Metrics and Assessment Subcommittee

This subcommittee report reflects the communication between committee members Christian Binek (chair, Nebraska, NNF), Trevor Thornton (Arizona State University, NCI-SW), David Berube (NC State, RTNN), Sanjay Banerjee (Texas, TNF), Mitsu Murayama (Virginia Tech, NanoEarth), and David Gottfried (Georgia Tech, SENIC) during a subcommittee Zoom meeting on April 12, 2023. It includes suggestions and discussion points which came up during the subsequent presentation of the work of the subcommittee. The presentation was given by the subcommittee chair on behalf of the subcommittee at the NNCI directors meeting in May 2023. In addition, the report contains input from in-person conversations at the NNCI annual conference in October 2023. The report aims to conclude on assessment activities of the maturing NNCI and tries to guide assessment in a potential next iteration of national nanotechnology infrastructure networks supported by the NSF.

Reflections on the evolution of NNCI assessment which led to the wealth of collected data:

The subsequent list contains the basic and advanced metrics the committee identified and implemented over the years. The advanced metrics have been added in recent years, mostly voluntarily, to provide NSF with an even better assessment of the network activities.

Basic Metrics:

- # Users, # Lab Hours, #Monthly Users, # New Users Trained, User Fees Collected
- User Affiliations

- Research Disciplines (based on those previously used in the NNIN)
- External Institutions List and Geographic Distribution
- Patents
- Research Publications, Presentations, Highlights (with NSF/National Priorities)
- Centers Supported
- Company Success Stories
- User Satisfaction Survey
- Non-Traditional Users
    - Research Disciplines
    - Under-Represented Minorities and Women (Institutions)
    - Non-R1 Academic Institutions, including 2-Year/4-Year Colleges and K-12
    - Small Companies and Start-ups
- K-12 Education/Outreach Assessment
    - Participant Diversity (School Demographics/Title I Status)
    - Survey Results
    - Internship Outcomes

Advanced Metrics:
- Research Funding Sources (collected bi-annually: 2019, 2021, 2023)
- Students Graduated (by degree and academic department) (collected annually – new in 2021)
- Courses supported by facilities and number of students enrolled (collected annually – new in 2022)
- Longitudinal Outcomes (REU Students, Users)
- Economic Impact
- Workforce Development Impact

<u>The ever-diminishing role of the subcommittee in a mature NNCI network:</u>

The consensus of the subcommittee is that the metrics requested to assess NNCI have been identified by now. It requires good reasons to add new metrics in the last stages of NNCI, especially against the background that those late data lack comparison to previous years. The subcommittee doesn't want to sunset but sees limitations to request additional data. Exceptions may be data which provide strong hitherto not presented evidence that a national nanotechnology infrastructure should continue after NNCI.

<u>Open tasks for the M&A subcommittee:</u>

It remains an important task for the M&A subcommittee to find ways alternative to additional metrics which allow NNCI to identify and quantify the level of interaction between sites. Those other ways include highlighting that NNCI sites are diverse in size and expertise, with different strengths represented by each site. The significance of NNCI is, among other things, to leverage this diversity and create measurable synergy between sites for the benefit and democratization of nanotechnology throughout the US.

One way to highlight these synergies beyond the collection of metrics is through success stories. A remaining task of the M&A subcommittee is to write and disseminate those success stories with the help of the NNCI Coordinating Office. Arguably, NNCI's biggest synergy creating assets are the research communities. Those include Nanotechnology Convergence, Nanoscience in the Earth and Environmental Sciences, Nano-Enabled Internet-of-Things, TransformQuantum, Understanding the Rules of Life, and Microelectronics/Semiconductors. Research communities organize workshops that are open to the entire community. Those workshops help grow the user base of NNCI sites and help advertise NNCI. If deemed necessary, the number of participants in workshops could serve as a metric quantifying their impact.

Research communities also produce publications. Examples of these are mostly still in preparation but include topics on convergence, food and nutrition security, nanotechnology for addressing climate change, and the future of the nano internet of things.

Similar to research communities, there are success stories to disseminate about NNCI's working groups. In working groups, facility and education/outreach specialists share best practices, experiences and resources. There are network support working groups, technical working groups, and working groups on education and outreach. If deemed necessary, there is a possibility to quantify the achievements of working groups by number of different sites involve, number of participants, effectiveness of dissemination, number of working group gatherings, and more.

Members: Christian Binek (NNF/Nebraska), Trevor Thornton (NCI-SW/Arizona State University), David Berube (RTNN/NC State), Sanjay Banerjee (TNF/UT-Austin), Mitsu Murayama (NanoEarth/Virginia Tech), David Gottfried (SENIC/Georgia Tech)

5.3. Global and Regional Interactions Subcommittee

The main objectives behind the Global & Regional Interactions (GRI) subcommittee are to:

1) Engage and leverage local NNCI node activities with regional programs and local institutions.
2) Explore plans and develop ideas to identify and potentially connect the NNCI network to analogous programs across the world.
3) Encourage individual NNCI sites to identify their local partners and regional collaborators.

Toward these objectives, the GRI subcommittee convened periodic meetings with interested members and site representatives to discuss and share experience in regional and global interactions as well as updates to provide other members with some examples of such interactions. The NNCI network model revolves around regional strengths and impact of individual sites as well as coordination and cooperation across the network. In this spirit, the GRI subcommittee met and shared experiences periodically in the past year.

While not meant to be exhaustive, the examples below are representative of some of the NNCI sites that may also spur interest among other sites and may find inspiration to consider analogous programs and ideas at their respective sites.

Regional Coordination in Metropolitan Area: SHyNE represents an example of a large metropolitan site that has several academic and research institutions surrounding the site. SHyNE actively engages in collaborative endeavors, fostering frequent communication with other networks to exchange good practices, engage in technical and management discussions, and initiate collaborative initiatives. SHyNE plays a pivotal role in the NNCI Collaborative RET Program, where it brings together researchers from diverse disciplines, including medical and engineering schools, to facilitate collaborative efforts in research, education, and workforce training. SHyNE staff attended the NNCI Annual Meeting at Stanford University, which took place October 25-27, 2023. The Global and Regional Interactions (GRI) sub-committee has emphasized and advocated for international and intra-network staff exchange, as well as workforce development initiatives on both a global and local scale. Notably, SHyNE hosted five Research Experiences for Undergraduates (REUs) and five Research Experiences for Teachers (RETs) during the summer, for fostering educational opportunities. In addition to these programs, SHyNE actively engages in community outreach, exposing high school students to nanotechnology. The organization is strategically focused on collaborating with various regional community colleges, participating in RET/REU programs, and contributing to educational experiences in field museums.

Many regional sites have taken efforts to establish collaborative relationships with local colleges and educational institutes in the metropolitan area. By way of example, some of these institutions include Chicago State University (CSU), Oakton Community College, and Northern Illinois University, which also represents outreach and DEI considerations (CSU is considered HBCU, while NIU serves rural communities, and Oakton for workforce development). SHyNE also led a regional i-Nano event in close collaboration among Northwestern, University of Chicago and Argonne National Laboratory; as a regional nano-initiative. The i-Nano event has become staple of SHyNE's regional initiative and represents a generic example of regional cooperation and coordination in education/outreach in nanoscience and nanotechnology.

SDNI (UCSD) Activities: The San Diego Nanotechnology Infrastructure (SDNI) at UCSD is actively engaged in several impactful initiatives aimed at education, workforce development, and economic growth in the region. Examples of some key and representative activities include:

Veteran Training Program: SDNI, in collaboration with Penn State, Georgia Tech, ASU, and Southwestern College, has launched a 12-week training program for veterans preparing them for roles in the semiconductor industry. The inaugural cohort of 11 veterans yielded a commendable success rate, with 7 graduates receiving certificates and securing three job interviews each from semiconductor companies.

CHIPS Act Initiatives: SDNI is actively participating in CHIPS Act related activities, fostering alliances with companies and universities in southern California. Initiatives include pursuing the Manufacturing Ecosystem (ME) Commons and other education and workforce development (EWD) initiatives.

Economic Development & Workforce Training: SDNI has played a pivotal role in developing relationships with the local economic development office and labor department. Special emphasis is placed on training underrepresented minority (URM) groups without a college degree for technical positions, contributing to the creation of high-paid jobs in the region.

Cornell Nanofabrication Facility (CNF) Activities: The Cornell Nanofabrication Facility (CNF) has been a driving force within the NY-State Nanotechnology Network (NNN), fostering collaborations and initiatives that showcase the cutting-edge capabilities in micro and nanotechnology. CNF organized a successful Student Showcase and Career Fair at SUNY Albany, attracting 142 participants with a focus on the latest developments in the semiconductor industry. CNF has extended its influence globally through strategic partnerships, including a Staff Exchange Program with UPenn, surplus equipment exchange with U Minnesota and UPenn, and an International Research Experience in Japan, which received an NSF IRES award. The facility's commitment to education is evident through programs such as the Research Experience for Undergraduates (REU), where seven students, including two from Morgan State, were selected to participate. Additionally, CNF collaborates with local industries and Tompkins Cortland Community College (TC3) to develop Micro/Nano training programs, emphasizing the importance of bridging academia with industry needs.

CNF's impact extends beyond national borders, participating in the Global Quantum Leap/AccelNet network and leading international collaborations with institutions in Europe and Japan. The facility plays a key role in the NNCI's international activities, hosting Micron's "Chip Camps" to introduce microtechnology to middle school students and collaborating with universities like Morgan State and the University of Washington on cleanroom education initiatives. Moreover, CNF has been at the forefront of international student exchange programs, facilitating collaborations with the National Institute of Materials Science in Tsukuba, Japan, since 2008. With a rich history of almost 150 students benefiting from these programs, CNF stands as a beacon of excellence in micro and nanotechnology, contributing significantly to education, research, and global collaborations.

Northwest Nanotechnology Infrastructure (NNI) Activities: The Institute for Nano-engineered Systems (NanoES) announced the award of four seed grants in support of the use of nanotechnology tools to develop new, innovative technologies and devices. Awardees will receive up to $10,000 to carry out work in the UW's Washington Nanofabrication Facility (WNF) and the Molecular Analysis Facility (MAF). On a collaborative front, the second meeting of the Northwest Nanotechnology Laboratory Alliance (NWNLA) took place at the University of Washington in Seattle on August 3-4, 2023. This meeting served as a platform for bringing together staff and management from micro and nanofabrication facilities, as well as imaging and analysis facilities. The participants represented a diverse range of stakeholders, including academia, industry, and government entities in the Northwest. The workshop facilitated discussions and collaborations, contributing to the overall advancement of nanotechnology initiatives in the region.

These examples are meant to provide regional sampling of interactions across the NNCI network. They also represent innovative and comprehensive approaches by sites in expanding the impact beyond the node with regional and global implications. Moving forward, the GRI subcommittee will not only continue to share individual experiences and examples, but also consider specific initiatives and activities that can further improve network camaraderie and impact (e.g., staff exchanges, AI/ML short courses and implementation across regional networks, etc.).

Members: Vinayak Dravid (Northwestern), Yuhwa Lo (SDNI), Debbie Senesky (Stanford), Mariana Bertoni (Arizona State University), Maria Huffman (University of Washington), Kevin Walsh (Louisville), Steven Koester (MiNIC), Stephanie McCalla (Montana State University), Karl Bohringer (University of Washington)

5.4. Research and Funding Opportunities Subcommittee

In 2023, the NNCI Subcommittee on Research and Funding Opportunities met three times (January 26, March 16, and June 15), with select members also meeting at the Fall 2023 NNCI conference hosted by Stanford. The committee delivered a report to the NNCI Directors in August 2023.

Continuing from 2022, the subcommittee focused on the development and discussion of two key opportunities:

1. New federal opportunities: The subcommittee has monitored federal opportunities, primarily connected to the CHIPS and Science Act. Particular attention is given to focus areas that could work synergistically with the NNCI network, including on core facilities and infrastructure and workforce training. Specific programmatic elements that were discussed included:

- Membership of the CHIPS for America Research and Development Office and potential points of contact for the NNCI network
- Elements of the CHIPS for America Workforce Development Planning Guide that could be met by the NNCI network
- Elements of the NIST Metrology program, especially the metrology for next-generation microelectronics, that represent opportunities for the NNCI network
- Technical centers to be developed in the National Semiconductor Technology Center (NSTC): a public-private consortium that will conduct research and prototyping of advanced semiconductor technology, support workforce-training programs, and maintain an investment fund to help startup companies commercialize new technologies.
- Development of new Manufacturing USA Institutes

2. Industry relations via a student conference and career fair: Industry has been identified as a potential partner to the NNCI network to enhance workforce training and ensure access to state-of-the-art instrumentation to maintain U.S. competitiveness. The goal is to facilitate deeper industry engagement with the NNCI network and core facilities to foster a less transactional relationship and better engage industry in the success of NNCI. The subcommittee had discussions with the coordinating office about opportunities to showcase students at NNCI events. For 2023, local events to highlight students were held at individual sites, including the RTNN and CNF.

Members: Jim Cahoon (UNC Chapel Hill), Chris Ober (Cornell University), Shaya Fainman (UC San Diego), Bob Westervelt (Harvard University), Todd Hastings (Univ. Kentucky), Julia Aebersold (Univ. Louisville), Theresa Reineke (Univ. Minnesota), Mo Li (Univ. Washington), Yuri Suzuki (Stanford)

5.5. Nanotechnology Infrastructure of the Future

In response to the approaching end of the 10-year NSF NNCI awards, the Nanotechnology Infrastructure of the Future Subcommittee (“Futures Subcommittee”) hosted an NSF-funded “Workshop on Nanotechnology Infrastructure of the Future” — a workshop to gather feedback and identify opportunities for future national nanotechnology infrastructure resources. The culmination of 8 months of planning was a two-day, interactive workshop held September 12-13, 2023 at the National Academy of Sciences (NAS) in Washington, D.C. and virtually. The workshop organizing committee was comprised of Futures Subcommittee members, as well as other NNCI volunteers including Shyam Aravamudhan (SENIC) and Coordinating Office Associate Directors Matthew Hull (NanoEarth), Mikkel Thomas (SENIC), and Jameson Wetmore (NCI-SW).

Approximately 80 in-person participants and approximately 200 virtual participants attended the workshop, including stakeholders from the NNCI, universities outside of the NNCI network, community colleges, K-12 schools, government agencies, government labs, industry, and other partners. Participants explored the strengths, gaps, and growth areas of the NNCI relative to the future nanotechnology infrastructure needs of academia, industry, and government. The workshop agenda included keynote speakers and distinguished panelists, as well as interactive Q&A sessions and brainstorming activities using a digital collaboration tool (XLeap). Professional facilitators (Nexight Group) and workshop organizers guided both in-person and virtual participants in discussing focus questions related to five nanotechnology infrastructure focus areas:

1. Key research priorities
2. Education and workforce development
3. Technology translation
4. Research ecosystem and social responsibility
5. Organizational structure, governance, and assessment

The full workshop agenda is shown below.

DAY 1 (SEPTEMBER 12, 2023)	
Time (EDT)	**Topic and Speaker**
10:00am	Welcome (Professor Debbie Senesky, Stanford University; Dr. David Gottfried, NNCI Coordinating Office; Dr. Mihail Roco, NSF)
10:15am	**Setting the Stage for the Future of Nanotechnology Infrastructure** ● NSF Nanotechnology Infrastructure: Past & Present (Dr. Mary Tang, Stanford University) ● The Future of the NNI & Critical Role of Infrastructure (Dr. Branden Brough, NNCO) ● Preparing a Diverse STEM Workforce to Advance Emerging Industries (Dr. James Moore, NSF Directorate for EHR)

12:30pm	**Preparing for the Future: Nanotechnology 2035** (Panel Discussion) Lightning talks on technology roadmaps, related infrastructure & workforce needs. *Panelists*: ● Dr. Melissa Cowan (Intel Corporation) ● Dr. Jeffrey Miller (Kavli Foundation) ● Dr. Victor Zhirnov (Semiconductor Research Corporation) ● Professor Cherie Kagan (University of Pennsylvania) ● Dr. Nadia Carlsten (SandboxAQ)
1:00pm	Panel Discussion
1:45pm	Brainstorming Session
3:00pm	**Catalyzing Nanotechnology Education for K-to-Gray** (Panel Discussion) Lightning talks on educational, infrastructure, and workforce development needs for all learners. *Panelists*: ● Dr. Jared Ashcroft (Micro-Nano Technology Education Center) ● Dr. Rae Ostman (National Informal STEM Education Network) ● President Tavarez Holston (Georgia Piedmont Technical College) ● Dr. Holly Leddy (Duke University) ● Mr. Landon Loeber (Micron Technology)
3:30pm	Panel Discussion
4:15pm	Brainstorming Session
5:00pm	Day One Highlights
5:15pm – 5:30pm	Closing Remarks (Professor Debbie Senesky)

DAY 2 (SEPTEMBER 13, 2023)	
Time (EDT)	**Topic and Speaker**
10:00am	Welcome (Professor Debbie Senesky, Stanford University)
10:15am	**Translating Nanotechnology from R&D to Market** ● CHIPS R&D (Dr. Lora Weiss, Director of the CHIPS R&D Program Office) ● Crossing Nanotechnology Startup Valleys of Death: Insights and Lessons from Raxium's Journey (Dr. Rick Schneider, Google) ● NSF's Lab-to-Market Programs (Dr. Barry Johnson, Directorate for Technology, Innovation, and Partnerships (TIP) at NSF)
11:15am	Brainstorming Session
1:15pm	**Reimagining the Research Ecosystem & Social Responsibility** ● Societal and Ethical Implications of Nanotechnology (Dr. Ira Bennett, Arizona State University) ● Digital Interconnection for Sustainable Innovation (Dr. Vijay Narasimhan, EMD Electronics) ● Diversity, Equity, Inclusion, and Belonging (Professor Raymond Samuel, NC A&T State University)
2:15pm	Brainstorming Session
3:15pm	**Engineering Radical Networks** ● Core Facility Scientist: An Emerging Career Path (Professor Philip Hockberger, Northwestern University) ● Networked Nanofab Capabilities Down Under (Dr. Christopher Gourlay, Australian National Fabrication Facility) ● Radical Infrastructure Partnerships (Professor Michael Spencer, Morgan State University)
4:15pm	Brainstorming Session
5:00pm	Closing Remarks (Professor Debbie Senesky)

The workshop organizers and facilitators collaborated to distill the information gathered during the workshop to provide the basis for a white paper that would make recommendations to the NSF for future nanotechnology infrastructure resources. The final white paper was submitted to the NSF on November 30, 2023, and was made publicly available on the NNCI website and by email to workshop participants on December 8, 2023. A high-level, cross-cutting summary of the workshop recommendations is outlined below:

- Advance the frontiers of research for the nation by providing the necessary tools, facilities, expertise, and collaborative spaces.
- Prioritize inspiring and training the next-generation workforce via education, outreach, and training programs that make "K-to-gray" learners aware of the nanotechnology field and pathways into it, and by partnering with industry and community colleges for workforce development.

- Partner radically with industry, government agencies, and related academic disciplines to maximize the impact of our nanotechnology infrastructure on the US technology ecosystem.
- Be intentional about increasing access across geographical regions and social barriers with a focus on rural communities, underrepresented individuals, and women.
- Build and expand upon the NNCI model's successes by protecting individual site autonomy and flexibility, as well as coordinating, incentivizing, and resourcing collaboration across the sites within the nanotechnology infrastructure.

More details about the major takeaways and recommendations from the workshop can be found in the full white paper.

The Futures Subcommittee will remain active through NNCI Year 9 at a minimum. The committee will serve as the central NNCI team to respond to any NSF requests for additional information or recommendations related to the next call for proposals.

Members: Debbie G. Senesky (nano@stanford), David Dickensheets (MONT), David Gottfried (SENIC), Maria Huffman (NNI), Nan Jokerst (RTNN), Steven Koester (MiNIC), Shamus McNamara (KY Multiscale), Christopher Ober (CNF), Sara Ostrowski (nano@stanford), Mary Tang (nano@stanford), Andrea Tao (SDNI), Robert Westervelt (CNS)

5.6. Building the User Base Subcommittee

At the end of 2023, the NNCI Building the User Base (BUB) subcommittee was sunsetted after accomplishing its objectives and deliberations with NNCI Coordinating Office. In the past, the NNCI BUB subcommittee worked on the following:

- NNCI BUB subcommittee revisited the stated goal to "disseminate best practices for sites and NNCI as a whole to increase the user base, with emphasis on non-traditional users." A non-traditional user may be defined based on: 1) Research areas that do not typically use nanotechnology facilities, 2) demographic groups –women and under-represented minorities; 3) users from non-R1 institutions; 4) small companies and 5) students and teachers from K-12 and community colleges.
- In 2022, the BUB subcommittee worked with the NNCI Metrics subcommittee to broaden the definition of user and user success metrics that capture impact. Both the committees jointly worked on a) broadening the definition of "user" with other types of users, other than research users, and b) focusing on impact e.g., success stories (center-level grants/SBIR, venture investments, jobs etc.) and other ways to highlight impact, diversity of users, interaction between sites etc.
- In 2021, the BUB subcommittee conducted a survey among NNCI sites to collect information specifically on the non-traditional user base, interactions with Research Communities and user success stories (for use as a qualitative measure of success in addition to quantitative metrics).

Members: Shyam Aravamudhan (SENIC, North Carolina A&T State University), Trevor Thornton (NCI-SW, Arizona State University), Todd Miller (NNI, Oregon State University), Sanjay Banerjee (TNF, University of Texas, Austin), Mark Allen (MANTH, University of Pennsylvania), Mitsu Murayama (NanoEarth, Virginia Tech), Lara Gamble (NNI, University of Washington), Andrew Cleland (SHyNE, University of Chicago)

6. Working Groups

One of the greatest strengths of the NNCI network is the combined staff expertise of the individual sites. To leverage this expertise at the network level, the Coordinating Office initiated the formation of working groups composed of staff members from the NNCI sites. While these working groups meet primarily via phone and video conferences, they also have the ability to organize workshops and/or dedicated sessions at the annual NNCI Conference. We have created and are encouraging working groups (Table 6) in (1) important "network" responsibilities, such as environmental health & safety, vendor relations, or equipment maintenance, (2) particular process technologies, such as lithography or characterization (although these are only examples of possible topic areas), and (3) education and outreach activity. Most of these working groups began in Year 1, while new ones were added in Years 2 and 3. In addition, some topical areas (EBL, Etch, and ALD) have begun working groups through grass-roots efforts of NNCI staff, with support from the Coordinating Office. The outcomes of these working groups can have many forms, including process recipes, recommendations to vendors for future equipment development, maintenance and training videos/webinars, recommendations on how to evaluate the safety of new processes, or direct recommendations for new users. Each working group has one or more dedicated coordinators selected from one of the NNCI sites, and staff participation in the working groups can be one measure for site performance. Participation in these working groups can also be considered as a mechanism for staff growth and career development or as support for an NNCI Outstanding Staff Award. During 2021, leadership the working groups was examined, and some changes implemented, and all working groups were opened to new members from NNCI staff. During 2023, a new working group on Regional Networks was added.

Table 6: NNCI Working Groups (2023)

Working Group Topic	Working Group Lead(s)
Network Support Working Groups	
Equipment Maintenance	Jeremy Clark (Cornell)
Vendor Relations	Charles Veith (Univ. Pennsylvania)
Environmental Health & Safety	Andrew Lingley (Montana State Univ.)
Regional Networks	Ron Olson (Cornell)
Technical Working Groups	
E-Beam Lithography	Devin Brown (Georgia Tech) Stanley Lin (Stanford)
Etch Processing	Ling Xie (Harvard)
Photolithography	Pat Watson (Univ. Pennsylvania)
Atomic Layer Deposition	Mac Hathaway (Harvard)
Imaging and Analysis	David Bell (Harvard)
Education and Outreach	

K-12 and Community	VACANT
Workforce Development and Community Colleges	Andrew Lingley (Montana State Univ.)
Evaluation and Assessment	Jessica Hauer (Arizona State)
Technical Content Development	Daniella Duran (Stanford) Eric Johnston (Univ. Pennsylvania)
4-H	Lynn Rathbun (Cornell)
Societal and Ethical Implications (SEI)	Jameson Wetmore (Arizona State)
Innovation and Entrepreneurship (I&E)	Matt Hull (Virginia Tech)

During NNCI Year 8, sites or groups of sites hosted seminars and technical workshops related to fabrication, research, or education topics (see Section 10.1). The Coordinating Office encourages working groups to use these programs as opportunities for the working group to meet in a face-to-face setting, as a supplement to virtual discussions. When travel is an option, the Coordinating Office provides financial support (up to $1000 travel funding each for 5 attendees) to encourage staff participation. Recent events included:

- NNCI Advanced Lithography Symposium, October 24, 2023 (Stanford Univ.)
- NNCI Education Symposium, Nov. 11, 2023 (UC San Diego)

Received reports of current working groups, as provided by the leads, are presented below. SEI and I&E activities are described within the Associate Director reports (Section 4).

6.1. Equipment Maintenance

Communication within the Equipment Maintenance working group has continued to occur primarily through email exchanges. The group's efforts remain focused on the collection and sharing of our tacit knowledge regarding the troubleshooting and maintenance of primarily vacuum and RF process equipment. Most of this information continues to not be available directly from vendors and is often difficult to relay in public forums.

Looking forward, we are hoping to create more opportunities to share our tribal knowledge with each other, particularly notes on alternative sourcing of OEM parts, the pros and cons of software upgrades, as well as critical reviews of newer companies. We have also discussed the creation of an online resource to share these details, though this has remained hypothetical thus far.

Members: Jeremy Clark (Cornell), Mary Tang (Stanford), Bob Geil (UNC-Chapel Hill), Jesse James (UT-Austin), Kyle Keenan (UPenn), Tony Whipple (Univ. Minnesota), Patrick Driscoll (UCSD), Jeff Wu (UCSD), Ahdam Ali (UCSD), Sarice Jones (UW), Darick Baker (UW), Mark Brunson (UW), Steven Crawford (JSNN), Thomas Johnson-Averette (Georgia Tech).

6.2. Vendor Relations

The Vendor Relations Working Group has had success this year with supplying data about, and receiving leads on, new vendors to support nanoscale research across the country. Here are few examples:

1. An anhydrous HF supplier for Louisville (Transene, Ascensus, Matheson).
2. Electropolished stainless steel tubing for several sites (Semitorr).
3. New vendor for precursor gasses for Georgia Tech (ErezTech).
4. Precious metal reclamation vendor for Cornell (ACI).
5. Metal racking for internal garment cleaning at Minnesota (Intermetro).

In the future, the working group will work on the availability of safety equipment and materials; in particular, finding and maintaining access to high quality materials at reasonable cost. The area of focus is to find US-based vendors to reduce supply chain issues. Two thrusts include:

1. Contamination by cancer causing agents can be a problem in the garment cleaning industry. This was originally identified in manufacturing in the early 2000s. Finding ways to disseminate safe garment cleaning alternatives will be a priority next year.
2. As working group member Gary Spinner (Georgia Tech) made clear recently, when new semiconductor manufacturing facilities come on line, encouraged by the CHIPS Act, safety equipment and materials will be harder to find for academic labs. To prevent university research from being shut out of the market for these materials, the creation of one very large database of needs by all members was discussed. With such a database, schools would be able to view each other's vendors to compare value and availability. This project is presently led by Georgia Tech, University of Washington, Stanford, and Arizona State University, through the working group.

Members: All 16 NNCI sites are invited to inform, to lead efforts to lower supplies costs, and to build stronger relations with vendors in order to support NNCI Research. Working Group members come from the following sites: Harvard, Cornell, U. Penn, U. Louisville, Georgia Tech, Virginia Tech, UT-Austin, Arizona State U., UC-San Diego, Stanford, U. Washington, Montana State U., and U. Minnesota.

6.3. Environmental Health & Safety

The EH&S working group met in December 2023 to discuss per- and polyfluorinated substances, known as PFAS. These substances are very chemically stable, are used in many industries, and can be found in the air and in water supplies. They are also used extensively in semiconductor manufacturing [Ober, C.K., F. Käfer, and J. Deng, Review of essential use of fluorochemicals in lithographic patterning and semiconductor processing. Journal of Micro/Nanopatterning, Materials, and Metrology, 2022. **21**(01)]. We discussed mitigation efforts, including reducing or eliminating the number of chemicals we use that contain PFAS. We are currently compiling a list of photoresists and electron beam resists that do and do not contain PFAS and will distribute the list to the NNCI sites. Lastly, we distributed a list of web resources on PFAS facts, toxicology, measurement, and testing.

Our second main discussion topic in December was following up on tetramethyl ammonium hydroxide alternatives.

We were thankful to continue our relationship with SESHA (sesha.org). In our December meeting, Troy McCuskey from SESHA and the National Renewable Energy Laboratory (NREL), joined our discussion. SESHA has several relevant free webinars, such as https://sesha.org/webinar/sesha-pfas-an-overview-of-the-six-steps-of-the-end-to-end-treatment-solutions/ and https://sesha.org/abstract/tmah-and-its-alternatives-where-do-we-go-from-here/. SESHA will have an annual meeting in April, and it is likely one or more members of the NNCI EH&S working group will attend the EH&S high tech bootcamp and report back to this group.

Members:

Name	**Affiliation**	**Name**	**Affiliation**
Andrew Lingley	MONT	Mary Tang	nano@stanford
Nasir Basit	SHyNE (NW)	Brian Olmsted	MiNIC
Mahdi Fahim	SENIC (JSNN)	Julia Aebersold	KY Multiscale (Louisville)
Philip Infante	CNF	Hang Chen	SENIC (Georgia Tech)
Shane Patrick	NNI (UW)	Grant Shao	nano@stanford
Mark Walters	RTNN (Duke)	Darick Baker	NNI (UW)
Philip Barletta	RTNN (NCSU)		

6.4. Regional Networks

The inaugural meeting of the NNCI Regional Network Working Group was held on July 18, 2023, via Zoom (12 noon-1:00 pm). Attendees included representatives from all regional networks. Established the past year, this working group set out to share information and best practices. During the initial meeting each regional site presented details on the following topics:

- What is the goal and mission of your network?
- How does it operate?
- How is your regional network structured?
- What are some of the challenges?
- What are some of your best practices?
- How can the regional netoworks be leveraged in developing the next infrastructure of the future?

A summary of group responses was compiled and distributed to the team. The objective of the first meeting was to garner an understanding of how each regional network operates. Future meetings will have clear objectives and agendas to ensure meetings are purposeful and productive. A team consensus supported the idea that regional NNCI network meetings should be held quarterly.

The working group held a second meeting on October 9, 2023. Discussions focused on the direction of future meetings, NNCI expectations of the regional networks, and identification of future deliverables supporting a positive outcome. The group decided the posed question should be revisited after the NNCI Annual Meeting and careful consideration of other CHIPS Act-related activities.

We look forward to the valuable insights and outcomes that will emerge from these quarterly meetings. The group is committed to strengthening our NNCI regional network impact and influencing the future. Below is a summary of the initial meeting.

The goals and missions of the regional networks within the NNCI are varied and designed to meet the specific needs of their respective regions. The Northern Nano Lab Alliance (MiNIC) aims to assist members in enhancing facility operations while supporting academic research in applied nanotechnology. In the Southeastern Nano Facility Network (SENIC), the focus remains on establishing and nurturing connections between nano facilities in the region and providing a pool of resources (infrastructural, technical, and human) the entire network can utilize. The Mid-Atlantic Nanofab Managers Meeting (MANTH) seeks to create a forum for nanofabs within a day's drive, fostering the exchange of facility practices, networking, and socialization. The Northwest Nanotechnology Laboratory Alliance (NNI and MONT) is committed to providing a low-overhead opportunity to engage with regional labs, offering a forum for discussing broadly useful topics, and building camaraderie within the region. The Southwest Nano Lab Alliance (NCI-SW) endeavors to establish a southwest regional association of university nanotechnology lab managers, inspired by the successful program at the MiNIC site. The Ohio Valley Nano+AM Regional Network (KY Multiscale) is a coordination of universities, colleges, and community colleges in the Midwest that exchange information on facility operations and highlight exciting research in micro/nanotechnology and additive manufacturing. The RTNN Affiliates Network focuses on connecting facilities in the Research Triangle, enabling efficient communication, and developing strategic partnerships to support nanotechnology research. Finally, the CNF's NY State Nanotechnology Network mission is to build local relationships, solve common problems, and raise awareness of the state's capabilities in Micro and Nanotechnology. Details of each network's structure and membership, can be found. https://nnci.net/regional-networks

The Northern Nano Lab Alliance (NNLA) operations have changed over the years. Initially, regular in-person meetings and phone calls were the normal mode of operation. However, from 2020 to 2022, the network experienced significant turnover, losing members due to retirements and job changes. During this time, the group was less active. Presently, there is a concerted effort to rebuild the lab alliance, with a focus on recruiting new members. Future operations will involve the sharing of resources, such as tool SOPs, training videos, and chemical safety training. Coordinated purchasing of consumables, tool and service backstopping, shared tool knowledge, strategic tool acquisition planning, and used/surplus equipment exchange are some of the key activities being planned by NNLA. The Southeastern Nano Facility Network (SENFN) typically holds annual meetings. In-person sessions were conducted in 2018 and 2019, and a virtual meeting in 2020. The group planned to have an in-person meetings in 2023 with mid-year exchanges among individual members. The Mid-Atlantic Nanofab Managers Meeting organizes two events per year. One-day workshops are on Fridays followed by networking events sponsored by equipment vendors in the evenings. The Northwest Nanotechnology Laboratory Alliance (NWNLA) is in the early, formative stages of development. The Southwest Nano Lab Alliance (SW-NLA) plans to meet annually for a one-day workshop, rotating between participating sites. The Ohio Valley Nano+AM Regional Network convenes annually at the NNCI Nano+Additive Manufacturing Summit in Louisville, staying connected through email and newsletters. The RTNN Affiliates Network maintains regular contact and held half-day workshops before the pandemic to share best practices. The NY State Nanotechnology Network (NNN) has a steering committee driving initial actions, coordinated by CNF at Cornell, and focusing on workforce development. The NNN Student Showcase and Career Fair connected NYS undergraduate and graduate students with industry partners. Successful events were held at Cornell University in May 2022 and SUNY Albany in April 2023.

The regional networks share common challenges: Staff turnover and the effort to schedule regular gatherings present difficulties. Additional challenges include securing substantial funding for in-person meetings and events, as well as determining the inclusion criteria. Furthermore, other regional networks encounter unique challenges associated with regional participation and the establishment of self-sustaining infrastructure. These issues contribute to the difficulties of managing and sustaining regional networks.

Best Practices: The Northern Nano Lab Alliance emphasizes regular contact, streamlining communication processes, and identifies a limited number of achievable goals, particularly focusing on providing value to smaller partners. The Southeastern Nano Facility Network adopts a rotational approach for their annual meetings to showcase various locations and capabilities. They promote inter-member collaboration, including staff enrichment initiatives and interactions between institutions like the University of Memphis, Georgia Tech, and Oak Ridge National Laboratory. SENFN considers key practices from other regional networks, including forming a meeting committee, organizing biannual gatherings with specific activities, involving vendors and sponsors, and emphasizing a post-meeting follow-up survey and newsletter. The Mid-Atlantic Nanofab Managers Meeting opts for a more informal approach, with events and presentations held at rotating host sites, encouraging participation and simplicity in organizational structure. They focus on topics relevant to facility management and integrate socializing and networking, with vendors contributing to event costs. The Northwest Nanotechnology Laboratory Alliance employs proactive measures such as sending interest surveys before organizing meetings and engaging in extensive phone calls before official communication. Meanwhile, the Ohio Valley Nano+AM Regional Network relies on a newsletter, an annual NNCI Nano+Additive Manufacturing Summit held in Louisville, a Seed Program, and the provision of micro/nano/additive services to sustain its regional network. The RTNN Affiliates Network emphasizes regular contact, hosts open house events, and utilizes Kickstarter initiatives, offering free facility access to encourage participation. Facility cross-training is prioritized where appropriate. Lastly, the CNF NY State Nanotechnology Network adopts a steering committee and a partnership model dedicated to advancing nanotechnology across disciplines. Continuous improvement is pursued through surveys, and feedback implementation is integral to the approach.

Leveraging regional networks for the infrastructure of the future: The Northern Nano Lab Alliance views regional networks as a "force multiplier" for spreading network benefits and fostering collaboration**.** The Southeastern Nano Facility Network identifies a hub-and-spokes model, leveraging relationships with entities like ORNL to position the regional network as a bridge for basic science, workforce development, and technology advancement, overcoming challenges in the R&D "valley of death" to achieve TRL 4/5. The Mid-Atlantic Nanofab Managers Meeting sees that regional networks can facilitate affordable professional development, workforce opportunities, and help break down silos between local sites. In the Northwest Nanotechnology Laboratory Alliance, it was suggested that regional networks can help avoid redundancy, partnering on education and outreach events, and maximizing impact without spreading resources too thin. The Ohio Valley Nano+AM Regional Network imagines a more formal "wheel and spoke model" for the future NNCI, recognizing the challenges of making an impact with limited resources if spread too thin. The RTNN Affiliates Network believes that a regional network can enable more formal funding and support mechanisms, highlighting a broader definition and clearer connection to the field of nanotechnology. Finally, the NY State Nanotechnology Network (NNN) imagines that regional collaboration between universities, industry, and government will significantly impact national technology growth and development.

Members:

Regional Network	NNCI Site	Contacts
Northern Nano Lab Alliance	MiNIC	Jim Marti, Brian Olmstead
Southeastern Nano Facility Network	SENIC	Gary Spinner, Walter Henderson, Steven Crawford, David Gottfried
Mid-Atlantic Nanofab Managers Meeting	MANTH	Eric Johnston, Pat Watson
Northwest Nanotechnology Laboratory Alliance	NNI/MONT	Darrick Baker, Andrew Lingley
Southwest Nano Lab Alliance	NCI-SW	Trevor Thornton
Ohio Valley Nano+AM Regional Network	KY Multiscale	Kevin Walsh, Ana Sanchez-Galiano
RTNN Affiliates Network	RTNN	Philip Strader
NY State Nanotechnology Network	CNF	Ron Olson

6.5. E-Beam Lithography

We are an active working group that aims to host at least 1-2 meetings per year. A survey was sent out to gauge if an in-person meeting was desirable, but this year's busyness at various NNCI Sites led to hosting one online meeting this year. Discussions resumed with the suggestion of potentially making such a morning or afternoon of a MAEBL meeting.

Our meeting was on April 24, 2023, with 11 tool owners in attendance. Each member in attendance covered site highlights of new tools or new research as well as shared questions, troubleshooting problems or tips.

Since last year, EBL usage has been steady in all locations and stronger at a few sites. Several sites have upgraded or are in the process of upgrading tool specifications or installed new tools all-together including nano@stanford (Stanford), MANTH (UPenn), SDNI (UCSD), CNS (Harvard), MiNIC (University of Minnesota). Many of these upgrades are considered necessary as current tools in service are a decade or more old and seeing hardware failures or lacking the latest capabilities for spearheading new research. The CHIPS Act will likely create new opportunities for different sites for new tools.

Several staff retired or resigned, and a few new staff members were introduced: Roberto Panepucci at CNF (Cornell), Doc Daugherty at NNI (University of Washington), David Barth at MANTH (UPenn), and Andrei Sokolov NNF (University of Nebraska, Lincoln). NNCI users and graduates can be a pool for replacing future staffing needs.

With several sites updating staff and equipment, we also updated the membership and the active tools list to be submitted to the NNCI Coordinating office to update the website and the NNCI EBL Brochure as an ongoing project.

Other discussions included: spin-on charge dissipation layer quality, costs, and vendors; UV and Ebeam exposable resist; new BEAMER fracturing software GUI critiques.

The NNCI EBL Working Group continues to maintain a mutually helpful network. A good example of NNCI EBL staff helping each other is David Barth of MANTH (UPenn) shared training documentation with Stanley Lin of nano@stanford on Stanford's newly installed Raith EBPG 5200+ to help jumpstart the initial learning and training curve.

Overall, our EBL working group had a successful year with one meeting and fruitful discussions with a bright outlook on the EBL research and support that each NNCI Site has to offer. We anticipate the network's growing capabilities as newer state-of-the-art equipment become available within our facilities. Our working group is well attended with 11 members, and everyone willingly participated in discussions.

Members:

NNCI Site	Institution	Tool Owner
SENIC	Georgia Tech	Devin Brown
	JSNN (NCAT/UNCG)	Steven Crawford
RTNN	NC State	Greg Allion Backup: Saroj Dangi
	Duke	Talmage Tyler Backup: Jay Dalton
	UNC Chapel Hill	Amar Kumbhar Bob Geil
MANTH	U. Penn	David Barth David Jones
CNS	Harvard	Yuan Lu Backup: Jiangdong Deng
CNF	Cornell	Alan R. Bleier Roberto Panepucci Giovanni Sartorello
KY MMNIN	Univ of Kentucky	Brian Wajdyk
SHYNE	Univ of Chicago	Peter Duda
MiNIC	Univ. of Minnesota	Kevin Roberts
NNF	Univ of Nebraska-Lincoln	Andrei Sokolov Ather Mahmood
TNF	UT Austin	Bill Ostler
NCI-SW	Arizona State Univ	Kevin Nordquist

SDNI	UC San Diego	Maribel Montero Backup: John Tamelier
nano@stanford	Stanford (SNSF Spilker)	Rich Tiberio Stanley Lin Grant Shao
NNI	Univ. of Washington	Doc Daugherty
NanoEarth	Virginia Tech	Eric Carlson
MONT	Montana State Univ.	Andrew Lingley

6.6. Etch Processing

The objective of the Etch Working Group is to provide an interactive forum for etch personnel in all the NNCI participating sites. This interaction includes but is not limited to the sharing of information regarding etch capabilities, established etch processes, processes under development, equipment maintenance issues, preventative maintenance, baselining efforts, equipment modification, and the acquisition of new etch tools/technologies.

In March 2023, the longtime etch working group leader Vincent J. Genova retired from the Cornell NanoScale Facility and passed on the leadership role to Ling Xie of Harvard CNS. In April, a committee for planning and organizing the next NNCI etch symposium was formed. Members of that committee include Durga Gajula (Georgia Tech), Ling Xie (Harvard University), Lavendra Mandyam (Stanford University), and Vince Genova (independent consultant). Since then, the team has been meeting monthly via zoom, working on formulating a symposium theme, contacting speaker candidates, reaching out to industrial partners and sponsors, and looking at logistics. It was decided that the next symposium will be held at the Institute for Electronics and Nanotechnology, Georgia Institute of Technology, April 24-26, 2024, and will be called "Advances in Micro- & Nanoscale Patterning of Strategic and Emerging Materials for Electronic, Photonic, Quantum, & MEMS Devices." The event spans two and a half days, with major activities outlined below:

Day 1 (April 24): NNCI etch personnel and invited non-NNCI technical staff will update etch technologies, equipment, and processes at their sites; open discussions on etch equipment and process issues are held; leading R&D etch equipment vendors will present their latest developments; exhibit booths are available for industrial sponsors.

Day 2 (April 25): An open public symposium features invited and contributed talks by experts from academic and industrial labs, addressing the challenges of etching novel materials in emerging nanoscale devices. A student poster session will be held, and vendor exhibits will be available.

Day 3 (April 26): A half-day program dedicated to a panel discussion focusing on topics like accommodating new materials, the importance of chamber conditioning for optimal and consistent etch results, etc.

This will be the 4th large-scale workshop that the working group has organized since 2018 and there are a few points that stand out this time.

1. We have reached out to many more potential industrial sponsors, and in turn more industrial companies have expressed a willingness to participate and financially support

the event. The table below lists those companies that have responded to our invitations and plan to attend:

	Name	Relevant products or services
1	KLA -STS	RIE, PECVD, metrology tools
2	Sentech	RIE, ALE, PECVD, metrology tools
3	Samco	RIE, PECVD
4	EFC	Gases and advanced materials
5	Plasma-Therm	RIE, PECVD
6	Oxford Instruments	RIE, ALE, PECVD
7	Impedans	Plasma diagnostic tools
8	ULVAC Technologies, Inc.	RIE
9	Avantor	Materials, consumables
10	Thermal Fisher Scientific	Scientific lab supplies
11	Nova Electronic Materials	Wafer retailors
12	Suss	Mask aligner, wafer bonder
13	Elionix	E-beam writer

2. A student poster session has been added to this event, and the best or top few posters will be selected and awarded prizes by a voluntary judging committee.
3. The half-day panel discussion has been added and may serve as a template for future workshops.

Identification and documentation of the broad and complementary etch tools within NNCI allows us to effectively process wafers within the network to meet the diverse specifications of individual projects, and to provide back-up systems within the network to avoid any extensive downtimes in user processing. An updated 2023 NNCI Dry Etch Capabilities listing was uploaded to the NNCI website. This listing identifies each site's dry etch based equipment. This document will assist users who seek etch process capabilities when requirements cannot be satisfied at a specific university fab or which need to be fulfilled on a specific etch platform.

Members:

Cornell University (T. Pennell, J. Clark, G. McMurdy)
Harvard University (L. Xie, K. Huang)
Stanford University (J. Tower, L. Mandyam)
Georgia Institute of Technology (T. Averette, H. Chen, T-V. Nguyen, A. Gallmon, D. Gajula)
University of North Carolina (B. Geil)
UNC Greensboro (Q. Dirar)
University of Louisville (E. Moiseeva, J. Beharic)
University of Minnesota (T. Whipple, P. Kimani)
University of Nebraska (J. John)
University of Pennsylvania (E. Johnston, H. Yamamoto, S. Azadi)
University of Texas-Austin (J. Heath)
University of Washington (M. Morgan, M. Brunson)

Arizona State University (S. Ageno, S. Myhajlenko)
UC San Diego (X. Lu, D. Prescott)
Montana St, (J. Heinemann)
Virginia Tech (D. Leber, M. Hollingsworth)
U. Chicago (P. Duda, S. Kaehler)

6.7. Photolithography

The NNCI Photolithography Working Group is composed of representatives from 12 institutions (from 10 NNCI sites and UC Berkeley). Our mission is to share photolithographic techniques, processes, and experiences with members and with the larger research community.

In 2023, the working group held a hybrid meeting at Stanford University on October 25, sandwiched between the Advanced Lithography Symposium (October 24), featuring talks by vendors about new developments in lithography tools, materials, and techniques, and the NNCI Annual Conference hosted by Stanford. The 11 attendees came from U. Washington, Stanford, Georgia Tech, Cornell, and Penn. One of the attendees was a new member of our community and one joined remotely. Based on earlier email exchanges, the topic selected for discussion at this meeting was the status of extreme ultraviolet (EUV) lithography in integrated circuit manufacturing. Our hosts at Stanford provided a conference room and services for remote access.

Garry Bordonaro from CNF led the discussion, presenting an overview of the state-of-the-art, based on presentation slides and videos provided by equipment manufacturers ASML, Trumpf, and Zeiss. Garry described the economic and logistical challenges faced by the integrated circuit manufacturers as well as the technical challenges of the sole manufacturer of the tools, ASML. The immense cost of each tool (up to $140 million) demands that the throughput operate at 300 wafers per hour (WPH) in order to compete with the more arduous conventional multi-level lithography required to fabricate the most advanced ICs. However, it appears that 100 WPH is the current practical throughput. The electrical power required to operate these machines is staggering. Garry also described new technologies that may go into future tools, including larger numerical aperture optics. This may require that the optical elements (all reflective) may have to be anamorphic, with an 8x demagnification in one direction and 14x in the other to prevent obscuration. The photomask designs and chip dimensions will have to be significantly changed as a result.

Members:

Harvard Univ.	Guixiong Zhong
	Christine Yi-Ju Wang
Stanford Univ.	Grant Shao
	Shivakumar Bhaskaran
	Swaroop Kommera
	Phil Himmer
	Mahnaz Mansourpour
	Mary Tang
	Rich Tiberio
	Stanley Lin
	Cliff Knollenberg

	Sara Gillian Ostrowski
UC San Diego	John Tamelier
	Xuekun Lu
	Shu Xiang
Univ. Louisville	Curtis McKenna
Georgia Tech	Tran-Vinh Nguyen
	Hang Chen
Cornell Univ.	Garry Bordonaro
Univ. of Nebraska	Jiong Hua
Univ. of Minnesota	Paul Kimani
	Kevin Roberts
	Mark Fisher
	Laura Parmeter
	Emma Jory
Univ. of Pennsylvania	Gyuseok (Q) Kim
	Eric Johnston
	David Jones
	Pat Watson
	David Barth
	Anna Cohen
Univ. of Washington	Brant Hempel
	Jean Nielsen
UC-Berkeley	Allison Dove
Univ. of Kentucky	Brian Wajdyk

6.8. Atomic Layer Deposition

The ALD Working group has been staying in contact via email group discussions this past year. The forum has been a valuable place for group members to exchange ideas and solutions for safe operations and training specifically around ALD as well as lab operations in general. One of the current goals of the working group is to organize another conference in the upcoming year. The group will be surveyed as to the timing and the nature (in-person vs. virtual) of the 2024 ALD Working Group conference.

Members:

Anil Dhote	Northwestern
Bangzhi LIiu	Penn State
Bill Mitchell	UC Santa Barbara
Darick Baker	University of Washington
Don Leber	Virginia Tech
Fred Newman	University of Washington

Bob Geil	University of North Carolina
Hang Chen	Georgia Tech
Jeremy Clark	Cornell
Kyle Keenan	University of Pennsylvania
Mac Hathaway	Harvard
Matthew Oonk	University of Michigan
Michael Martin	University of Louisville
Mahendra Sunkara	University of Louisville
Paul Kimani	University of Minnesota
Robert Amundson	University of Minnesota
Gary Spinner	Georgia Tech
Stefan Myhajlenko	Arizona State University
Tony Whipple	University of Minnesota

6.9. Imaging and Analysis

The annual Imaging and Analysis working group meeting was held at the 2023 Microscopy and Microanalysis conference in Minneapolis. The attendance was low, but we did agree to hold a "facility operations and best practices" meeting at Harvard in March 2024 (date to be determined). This leverages the fact that we can hold a two-day meeting and can make it hybrid if attendance (travel) is difficult.

There will be a basic questionnaire that will be emailed to group participants in January 2024 that will discuss possible group questions in general, the best date for the meeting and what if anything extra is needed. Last year we discussed topics for a set of recorded topical lecture series that would work well virtually. This lecture series needs to be discussed more fully in a future meeting. Currently the tentative topical workshop focus will be on ion beam preparation of nanomaterials and in-situ microscopy.

The first meeting of 2024 will be held in February, virtually via Zoom.

Members:

David Bell	Harvard University
Evgenia Moiseeva	University of Louisville
Jasmin Beharic	University of Louisville
Jillian Cramer	University of Louisville
Phillip Strader	NC State University
Sarmita Majumder	UT-Austin
Recep Avci	Montana State University
Tobi Beetz	Stanford

Peter Crozier (TEMP)	Arizona State University
Matthew Brukman	University of Pennsylvania
Lanping Yue	University of Nebraska)
Jeff Wu	UC San Diego
Weinan Leng	Virginia Tech
Mark Brunson	University of Washington
Ellen Lavoie	University of Washington
Kyle Nowlin	JSNN

6.10. Workforce Development and Community Colleges

The Workforce Development and Community Colleges working group met virtually in February, June, and September of 2023. In February, several sites gave community college engagement updates. Allison Weavil at JSNN (SENIC) discussed their collaboration with four local community colleges that require work-based learning or internships. On average, they hire four to five interns a year. They also discussed funding opportunities for interns through companies like Intel and BioMADE. Kristin Field from the Singh Center for Nanotechnology at MANTH worked with the Community College of Philadelphia to hire three summer interns. Daniella Duran gave an update on the intern program at SNF at nano@stanford, which had grown from 5 to 9 participants, with about 60 applicants for those four positions. Their program is continuing to grow, and is a great model for long term success of individuals and a program (https://nanolabs.stanford.edu/education-outreach/community-college-internships). Philip Strader at RTNN discussed restarting their Nanotechnology Workshop for Community College Educators (https://www.rtnn.ncsu.edu/education/community-college-workshop/). This was a free program designed to help educators incorporate nanotechnology and science into their classrooms that stopped during COVID. RTNN is also budgeting money for summer paid internships. Andrew Lingley at MONT has been engaged with their local community college, Gallatin College, to provide a three-night course that covers semiconductor fabrication and inspection basics. MONT is also participating in the Micro Nano Technology Education Center by working to recruit members for the Business Industry Leadership Team (BILT) that creates KSAs for semiconductor process and equipment technicians. Tom Pennell from Cornell discussed a micro credential Micro-Nano Fabrication Safety offered at the Tompkins Cortland Community College in cooperation with the CNF (https://www.tompkinscortland.edu/academics/micro-nano-fabrication-safety-credential) and a 3-day Technology and Characterization at the Nanoscale (https://www.cnf.cornell.edu/education/tcn) course that is available virtually.

We discussed difficulties in having community college interns work at NNCI sites due to the travel difficulties and lack of space. Most attendees considered having a shared space for interns and employees to be valuable in developing a community and ensuring the interns felt supported. Some facilities aided with commuting or parking and by providing access to facilities on campus like the gym. Finally, several sites discussed Research Experience for Undergraduates (REU) and Research Experience for Teachers (RET) programs and the impact these programs have on the workforce pipeline.

In June, select members gave updates on workforce programs of broad interest. First Tom Pennell from Cornell gave a presentation on their ATLAS Program (Accelerated Training for Labor Advancement in Semiconductors: https://www.cnf.cornell.edu/education/atlas). In this course, students from the New York BOCES New Visions Engineering Program team up with CNF staff to learn about cleanrooms, semiconductor equipment, characterization at the nanoscale, and finally get hands-on experience fabricating on silicon wafers in a cleanroom. This two-week course gives advanced high school students a comprehensive overview of nanofabrication basics. We discussed disseminating the content and curriculum from this course to other facilities to broaden its reach.

Andrew Lingley of MONT then described the student employee program at the Montana Microfabrication Facility. At the MMF, students are hired as freshmen or sophomores and are expected to work multiple years and at least one summer full-time. Student employees learn valuable professional, organizational, and operational skills, and learn the importance of careful documentation and procedures for effective succession planning between cohorts of students. At the MMF, first year student employees do the majority of the purchasing, stocking, cleaning, while second-year and third-year students do the majority of the equipment maintenance and user training. The most senior employees work on customer projects to bring in revenue to the facility and help to manage and mentor incoming students.

In September, we started with a brief overview of some of the workforce development grants that institutions were working on, including the NSF Experiential Learning for Emerging and Novel Technologies (EXLENT) Award and the Innovative Technology Experiences for Students and Teachers (ITEST) Program. We had a lengthy discussion about potential funding from the CHIPS Act and related programs for workforce development, including the Microelectronics Commons Hubs, NSF Engines, and the future of the NNCI.

We also discussed the potential for making more use of core facilities at NNCI sites as on-the-job experiential learning for undergraduate students, and about funding mechanisms to hire them. We discussed using normal operational budgets, grant funding, and potentially a joint appointment program with companies. In this model, students would be paid to work in core facilities by companies after committing to internships or full-time employment. In this model, students get more training, companies get better-prepared employees, and core facilities get more labor.

For immediate workforce recruiting, we circled back on 101-level engineering outreach and discussed student nanotechnology groups. At the Montana Microfabrication Facility at MONT, student employees created the Nanocats, an official MSU student group that coordinates speakers and recruiting events for semiconductor companies at MSU career fairs.

Members:

Andrew Lingley (MONT)
Maude Cuchiara, Phillip Strader (RTNN)
Kristin Field (MANTH)
Dave Mogk (MONT)
Tonya Pruitt (NanoEarth)
Allison Weavil (SENIC)
Julia Aebersold (KY Multiscale)
Dan Ratner (NNI)
Tom Pennell (CNF)
Trevor Thornton (NCI-SW)
Daniella Duran (nano@stanford)
Phillip Strader (RTNN)
Steven Wignall (NNF)
Sylvianne Velasquez (NanoEarth)

6.11. Evaluation and Assessment

The significance of the NNCI is that it has created a network of sixteen university user facilities and coordinated nanoscale research and development activities involving over 20 federal agencies. NNCI-funded facilities are situated within research-focused universities and national laboratories and have experience supporting technology innovation and commercialization for start-ups and larger and more established companies. This essential NNCI infrastructure and toolkit address the unique and often costly demands of nanoscale science and engineering equipment and specialized knowledge for smaller academic institutions and the small to medium-sized commercial sector. By bridging resource gaps and providing access to leading-edge nanotechnology fabrication and characterization tools, instrumentation, and expertise, NNCI supports nanotechnology product innovations and process development.

In the middle of year 7, the NNCI Evaluation and Assessment Working Group (E&A WG) discussed collaborating with the NNCI Innovation & Entrepreneurship working group to create and distribute a 2023 NNCI Economic Impact Assessment (2023 EIA). Both working groups are interested in learning how NNCI facilities provide value to businesses, contribute to the national economy, and inform federal policy. Demonstrating that the program has a significant economic impact will be a strong justification for the NSF to continue to fund the next iteration of a nanotechnology infrastructure program, allowing us to continue to open our doors to external researchers.

Survey Background and Rationale

During the spring of 2023, a team including Matt Hull, Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth); Jessica Hauer, Nanotechnology Collaborative Infrastructure Southwest (NCI-SW); Tonya Pruitt, (NanoEarth); Yves Theriault, San Diego Nanotechnology Infrastructure (SDNI); and Phillip Strader, Research Triangle Nanotechnology Network (RTNN) reviewed the 2013 NNIN Economic Impact Survey & Report and began creating a goal, objectives, and a timeline for 2023 survey.

The objectives of the 2023 Economic Impact Assessment are:

- Understand the economic value that the NNCI created for the nation.
- Determine the economic value the NNCI creates for its users.
- Count how many jobs the NNCI has helped to contribute to the economy.
- Determine how much money the NNCI has contributed to the economy (salaries and taxes).
- Understand the kinds of new technologies that have been brought to the market from development activity that took place inside NNCI facilities.
- Outline how NNCI users rely on NNCI facilities for their continued productivity and survival.
- Compare 2013 results with 2023 results.

This project relies on the 2013 survey tool to help address key evaluation questions and objectives. In June of 2023, E&A WG reviewed the 2013 survey and created a 2023 instrument. The team initiated data collection via the Qualtrics assessment tool in collaboration with NNCI sites. Surveys were distributed to external users, including businesses, startups, corporations, non-profits, and others, and collected June - December 2023. The 2023 EIA was distributed to 1812 unique email addresses representing companies identified by NNCI-funded user facilities. Each NNCI site assigned a Survey Champion from their site team to assist the working groups with developing, distributing, and analyzing surveys. Ultimately, one site abstained from distributing the survey for fear the survey was in violation of IRB regulations. Arizona State University Office of Research Integrity & Assurance assured our team that IRB review was not required for this evaluation survey and assessment.

The usable response rate for the survey was 12%, with a total of 220 usable responses. The information below summarizes the significant survey findings.

The table below shows a breakdown of which NNCI site the respondents collaborate with for business purposes.

Table 7: NNCI Economic Impact Assessment Responses

Q7: NNCI Site name	Count	Percent
Center for Nanoscale Systems (...	31	19.0%
nano@stanford at Stanford Uni...	22	13.5%
San Diego Nanotechnology Infr...	20	12.3%
Nanotechnology Collaborative I...	15	9.2%
Mid-Atlantic Nanotechnology H...	13	8.0%
Northwest Nanotechnology Infr...	13	8.0%
Southeastern Nanotechnology I...	13	8.0%
Montana Nanotechnology Facili...	9	5.5%
Cornell Nanoscale Science and ...	8	4.9%
Virginia Tech National Center fo...	6	3.7%
Midwest Nanotechnology Infras...	4	2.5%
I am unsure of which NNCI-sup...	3	1.8%
Nebraska Nanoscale Facility (N...	3	1.8%
Kentucky Multi-Scale Manufact...	1	0.6%
Research Triangle Nanotechnol...	1	0.6%
Texas Nanofabrication Facility (...	1	0.6%
Total	163	100.0%

Figures 11 and 12 describe who participated in the 2023 EIA survey: 30% of companies launched since 2015, 78% of users began using NNCI facilities since 2015, and 75% of respondents have used NNCI in the last 6 months.

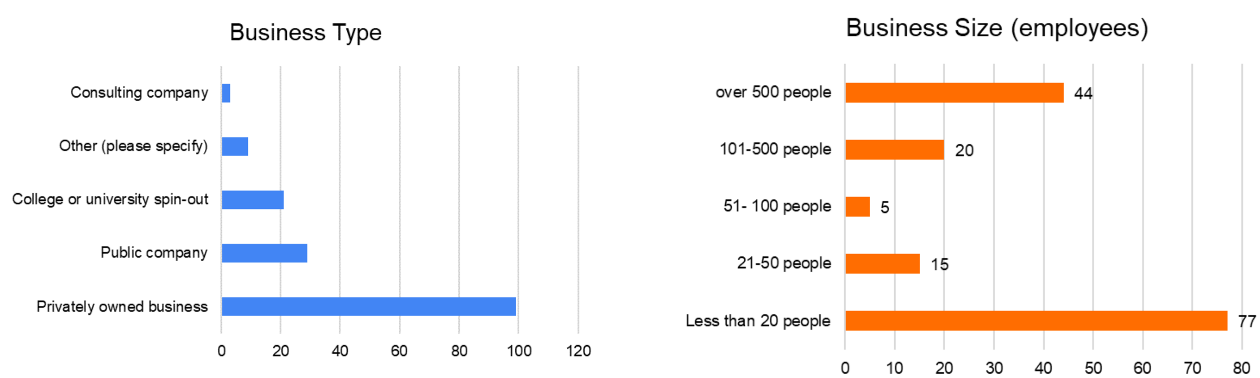


Figure 11: NNCI Economic Impact Assessment Responding Company Type (left) and Size (right)

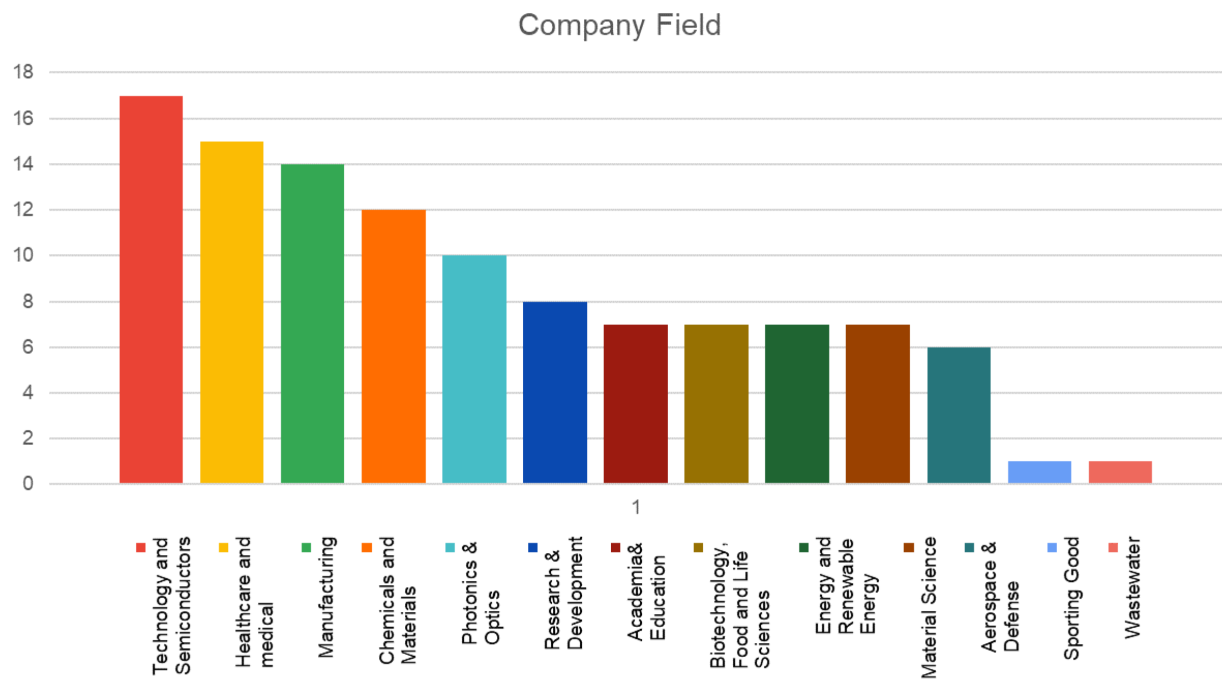


Figure 12: NNCI Economic Impact Assessment Responding Company Technology Fields

Survey data were used to address key evaluation questions and objectives. Our E&A WG evaluated responses and determined the following trends based on preliminary results from the Economic Impact Survey:

- NNCI-supported facilities are central to the continued productivity and survival of the companies that use them.
- NNCI supports 92% of our users' products and services.
- Connecting and accessing the NNCI facility is an excellent "peace of mind" for our external clients and colleagues.
- Connecting to state-of-the-art research labs is important for our users' reputation.

Why Users are Choosing NNCI-Supported Facilities

When asked what made NNCI-supported facilities more useful to their business than alternative facilities, respondents indicated the following (Figure 13):

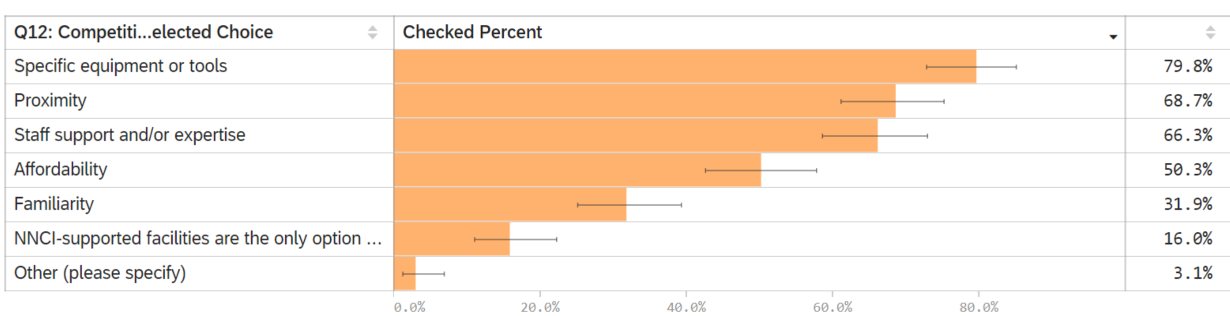
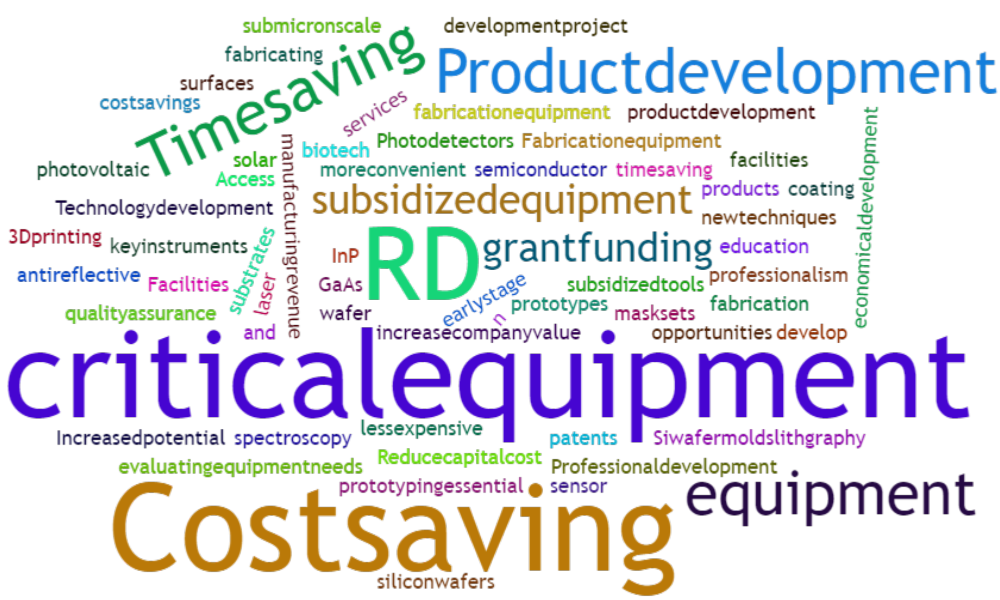


Figure 13: NNCI Economic Impact Assessment – Why Companies Use the NNCI

When asked to describe how NNCI-supported services and equipment are useful to the respondents' business development, several testimonials stood out as significant. These include:

- "In doing research and development, being able to operate the tools ourselves means we have a better chance to understand why the process does and does not work, and we have a better chance at setting priorities and schedule."
- "NNCI-supported facilities provide access to critical equipment that is too expensive for us to buy at this stage. Access to this equipment enables us to perform R&D leading to private and public grant funding and ultimately to functional prototypes, manufacturing, and revenue."
- "We have been able to hire researchers to work at NNCI-supported facilities. We would not have secured the necessary funding or access to the equipment needed for these employees to complete their work without these facilities."
- "NNCI has helped us gain further and deeper knowledge on research and development projects allowing us to make better progress."
- "NNCI facilities allowed training and for us to purchase the 'right' equipment."
- "We avoided tens of thousands of dollars of wasted work."
- "NNCI facilities' Impact was critical in the first several years of our business."

The word cloud below summarizes the key phrases and words that respondents use to describe and explain NNCI-facilities' impact.



Users selected a primary use of an NNCI-supported facility. The results of their selection are shown in Figure 14.

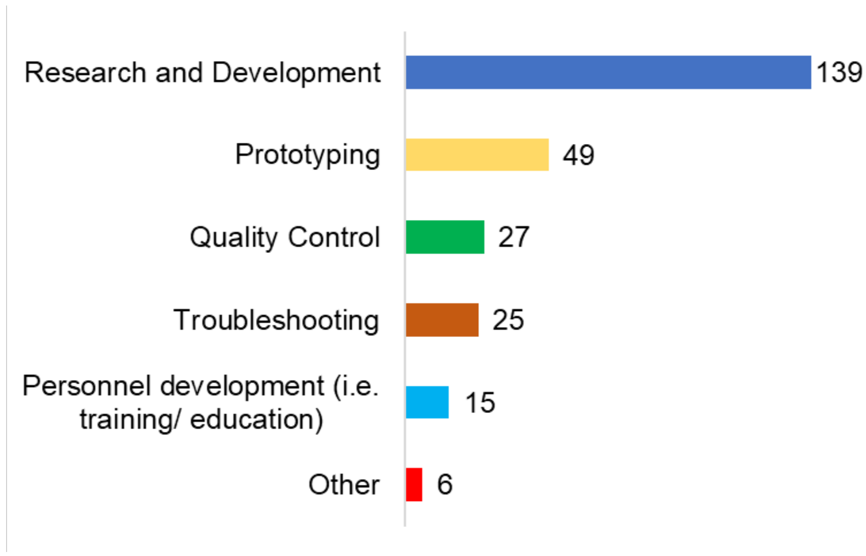


Figure 14: NNCI Economic Impact Assessment - Responding Company NNCI Usage

Effect on Business

In addition, 61% of businesses report that they have filed at least one patent from using NNCI-supported facilities. Some of the patent areas include:

- sensors (nanopore, temperature, MEMS, medical)
- implantable medical devices/sensors
- photovoltaic devices
- microtool design
- optics, optical surfaces, optical detectors
- quantum devices
- microfluidics
- chitosan & chitosan-silver packaging film
- carbon nanotubes and graphene
- hemp-derived cannabis products
- compostable product packaging
- functional textiles
- lead detection in drinking water

92% of users who participated in the survey reported that they would be affected if they were to no longer have access to NNCI-supported facilities. When asked to rate how influential access to NNCI-supported facilities are to their business, users reported the results in Figure 15.

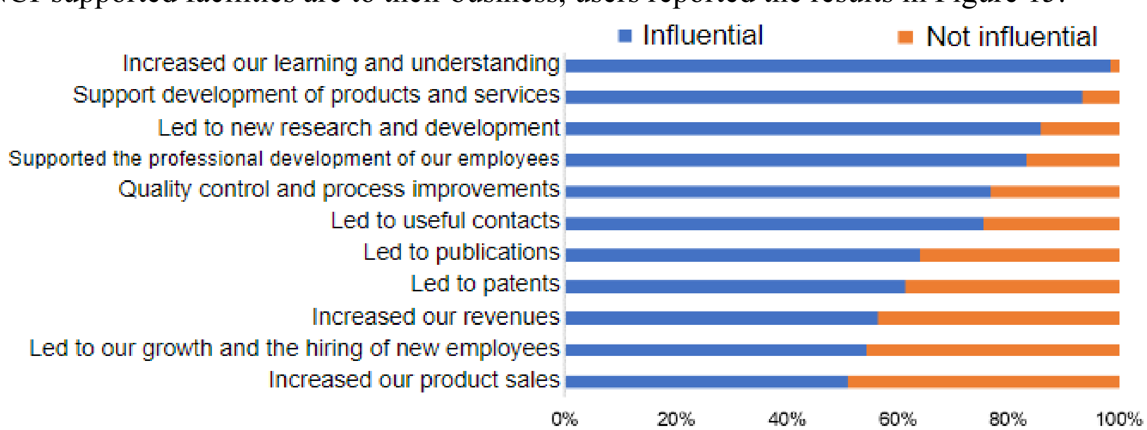


Figure 15: NNCI Economic Impact Assessment – NNCI Influence on Business

35% of businesses report NNCI-supported facilities and staff were instrumental in starting their business. 75% of businesses report NNCI-supported facilities enabled them to achieve continuous product innovation. When asked if NNCI-supported facilities are a major contributor to their success today, 87 respondents agreed.

Economic Impact of Access to NNCI-Supported Facilities

Businesses reported raising $2.3 billion dollars in financing since they began work with NNCI facilities. 32% of businesses earned more than $1 Million in revenue in 2022, 39% agree NNCI helped them hire more employees, 64% agree that NNCI-supported facilities helped increase their Intellectual Property portfolio, 79% attributed some success with financing to work done at NNCI-supported facilities, and 49% agree that some of the business's products and services would not exist without access to NNCI facilities. As one survey respondent explained, "Access to this equipment enables us to perform R&D leading to private and public grant funding and ultimately to functional prototypes, manufacturing, and revenue." Another user shared, "Our work (with NNCI) allowed us to avoid investing in this area too early. We avoided tens of thousands of dollars of wasted work."

In conclusion, NNCI user companies are innovators, job creators, taxpayers, and revenue generators. The evaluation findings indicate that NNCI-supported facilities are central to the continued productivity and survival of the companies that use them. A vast majority (90%) of respondents indicated that they would be affected if they were to no longer have access to NNCI-supported facilities.

For next steps, the E&A working group recommends a complete, external evaluation of the benefit of NNCI-supported facilities to its users and the national economy. We believe a full external review that can be published will provide a deeper understanding of the impact of NNCI and allow the NNCI Network to quantify our progress better.

The E&A WG would like to thank the following individuals for supporting this evaluation process:

NNCI Site	Survey Champions
Nanotechnology Collaborative Infrastructure Southwest (NCI-SW)	Jessica Hauer
Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth)	Tonya Pruitt
San Diego Nanotechnology Infrastructure (SDNI)	Yves Theriault
Research Triangle Nanotechnology Network (RTNN)	Phillip Strader
nano@stanford	Sara Ostrowski
Montana Nanotechnology Facility (MONT)	Andrew Lingley
Kentucky Multi-Scale Manufacturing and Nano Integration Node (KY Multiscale)	Ana Galiano
Mid-Atlantic Nanotechnology Hub (MANTH)	Gerald Lopez

Midwest Nanotechnology Infrastructure Corridor (MiNIC)	Jim Marti
Cornell Nanoscale Science and Technology Facility (CNF)	Melanie Mallison
Center for Nanoscale Systems (CNS)	Jim Reynolds
Nebraska Nanoscale Facility (NNF)	Jenna Huttenmaier
Northwest Nanotechnology Infrastructure (NNI)	Karl F. Bohringer
Soft and Hybrid Nanotechnology Experimental (SHyNE) Resource	Chad P. Goeser
Southeastern Nanotechnology Infrastructure Corridor (SENIC)	Shyam Aravamudhan & Amy Duke
Texas Nanofabrication Facility (TNF)	Christine Wood & Burt Fowler

Members: Jessica Hauer (NCI-SW), Carolyn Plumb (MONT), Sylvianne Velasquez (NanoEarth), Tonya Pruitt (NanoEarth), Ana Sanchez Galiano (KY Multiscale), Dan Ratner (NNI)

7. Research Communities

Research Communities are groups of faculty, students, and staff from NNCI sites organized around a particular research topic, national priority, or grand challenge, many of them based on the NSF's "10 Big Ideas." In contrast to NNCI working groups, which are focused on a particular tool or process with the objectives of sharing best practices, the Research Communities are more outward facing helping to develop products that benefit the larger scientific and engineering communities. The current Research Communities are shown in Table 8 along with the lead and participating sites. In 2022, a new community focused on Microelectronics and Semiconductors was added, as a partial response to increasing national interest in this area. The Research Communities provided an overview of their past and planned activities at the 2023 NNCI Annual Conference, and these can be viewed along with other resources on the Research Community page of the NNCI website.

Table 8: NNCI Research Communities

Research Community	Leader(s)
Nanotechnology Convergence	Jacob Jones (RTNN)
Nanoscience in the Earth and Environmental Sciences	Trevor Thornton (NCI-SW), Mitsu Murayama (NanoEarth), David Mogk (MONT)
Nano-Enabled Internet-of-Things	Mark Allen (MANTH), Christian Binek (NNF)
TransformQuantum	Andrew Cleland (SHyNE), Robert Westervelt (CNS), Steven Koester (MiNIC)
Understanding the Rules of Life	Vinayak Dravid (SHyNE)
Microelectronics and Semiconductors	Sanjay Banerjee (TNF), Philip Wong (nano@stanford), Trevor Thornton (NCI-SW), Shyam Aravamudhan (SENIC)

Activities of the communities may include:

- NNCI-sponsored symposia/workshops/webinars
- Road-mapping exercises
- Identifying future infrastructure needs

These groups will address questions such as (a) What infrastructure capabilities are needed to support the research topic? (b) What are the challenges of current fabrication infrastructure for the specific research area? In addition, they can provide opportunities for networking among faculty and students working on similar themes. They also can be used to convey information about tools, capabilities, and expertise within the wider NNCI network to researchers who may not typically look outside their own local site or who are not part of an NNCI institution.

Each Research Community provided a summary of past activities and future plans for this report.

7.1. Nanotechnology Convergence

The NNCI Research Community for Nanotechnology Convergence is a collaboration between the RTNN, SDNI, and Kentucky Multiscale sites. Major individual contributors in 2023 included: Jacob Jones (RTNN), David Berube (RTNN), Maude Cuchiara (RTNN), Kevin Walsh (KY Multiscale), Ana Sanchez Galiano (KY Multiscale), Phillip Strader (RTNN), Yves Theriault (SDNI), Ross Sozzani (RTNN), Khara Grieger (RTNN), Sarah J. Kariko (Harvard), and Elaine Hubal (NNCI External Advisory Board member).

In 2018, NSF announced their **10 Big Ideas**, one of which is Growing Convergence Research. NSF said this about Growing Convergence Research: "*The grand challenges of today -- protecting human health; understanding the food, energy, water nexus; exploring the universe at all scales -- will not be solved by one discipline alone. They require convergence: the merging of ideas, approaches and technologies from widely diverse fields of knowledge to stimulate innovation and discovery.*" [1]

The NSF-accepted definition of convergence research is that it fulfills two primary criteria [2]:

1. The research is driven by a specific and compelling problem.
2. It involves deep integration across disciplines, often involving the integration of theories, methods, data, and research communities and the creation of new frameworks or paradigms.

Growing Convergence Research is a process-oriented Big Idea. It involves *how* the research is conducted, not necessarily the vehicle of the research. In Convergence Research, researchers who are intellectually diverse come together and develop effective transdisciplinary communication methods and create common frameworks or new scientific languages in the pursuit of highly complex or vexing problems, ideally problems that are of great societal significance. Historical examples of disciplinary convergence can be found, for example, in bioinformatics, bioengineering, and nanotechnology. It is important to note that the concept of Convergence Research extends beyond the converging of disciplines to include the convergence of stakeholders, economic sectors, different categories of educational institutions, the public-private sectors, and other segments.

While many researchers work in convergent fields today, e.g. nanotechnology and bioengineering, the process of converging has not been widely studied. Therefore, there is not much known about best practices for converging disciplines or convergence research. In a recent report [3], for example, this was emphasized by saying "*…given the newness of the Convergence Research literature, most of our references are to the antecedents of Convergence Research*." Nevertheless, the opportunities that Convergence Research presents, particularly in addressing highly complex and societally-relevant problems, outweigh the dearth of insight into how to pursue it.

In the area of nanotechnology, Roco and Bainbridge [4] reinforce the idea of a convergence-divergence cycle. At the beginning of convergence for nanotechnology, the disciplines, materials, sectors, tools, and methods came together to control matter at the nanoscale, a phase that lasted decades. After four nanotechnology generations, they evidence divergence by spin-off disciplines, new business models, new products and applications, and new expertise and decision making.

The premise of the **Research Community for Nanotechnology Convergence** is that nanotechnology facilities of the future will play central roles in tackling wicked [5] and global challenges that require convergence approaches and, in many cases, facilities may require major adaptation to facilitate convergence. This can occur, for example, at the interface of nanotechnology with agriculture, health, or advanced manufacturing.

The Research Community goal is to bring together researchers and staff from diverse disciplines and perspectives, facilitate their collaboration, and work toward a common vision and public report for the future design and role of university open-access facilities in specific research areas. To phrase this more informally, the Research Community seeks to answer the question, "*How do we use our Nanotechnology Infrastructure, currently supported by the NNCI, to converge and advance research on complex and compelling problems?*"

A specific Research Community topic around nanotechnology convergence is selected for each year, enabling the Research Community to be dynamic and respond to emerging opportunities.

The 2021 topic was **Convergence in Nanotechnology for Food and Nutrition Security**. A major activity in 2021 involved an event designed to bring stakeholders together and learn more about research community needs. The event, held March 9 from 10:00 AM until 2:00 PM Eastern time, attracted ~150 registrants and >100 participants who were from academia, industry, government agencies, NGOs, consortia, policy fellows, etc. The team had IRB approval to record transcripts of the break-out rooms for purposes of conducting research. A social science team led by David Berube has completed analysis of all content from the meeting and conducted additional follow-up interviews with experts. The material is being integrated to produce an article on convergent needs in Agriculture-Nanotechnology areas. The manuscript was under review as of the writing of this report.

The 2022 topic was **Convergence in Nanotechnology and Additive Manufacturing**. Convergence in this area was discussed at a National Academies Workshop and perspectives were published in a 2022 NAE Workshop Proceedings report [6]. Some needs identified in the report include integration of nanoscale additive manufacturing into larger-scale additive manufacturing, the development of in situ diagnostics, updates to our paradigm for education to a 'convergent education model,' and offering cross-training opportunities for students e.g. through bootcamps. A major activity in 2022 was the NSF NNCI Nano+Additive Manufacturing Summit held on August 9-10, hosted by KY Multiscale and contributed by many additional sites. This 2-day conference attracted over 260 participants from across the US and brought together a diverse group of micro/nanotechnologists and additive manufacturing researchers from academia, industry, and government. Keynote presentations were given by 5 nationally-renowned speakers, at least three of which pushed the boundaries of convergence, e.g., through topics on neural interfaces, entrepreneurship, and additive manufacturing for the medical field. The Summit was hosted jointly with the annual NNCI REU Convocation, which added 60 top undergraduates from leading universities all over the country, integrating education and workforce development into the meeting, consistent with the recommendations from the NAE report [6]. The Summit also contained 38 Technical Presentations in 2 parallel sessions, 113 Research Posters, 20 Vendors and Sponsors, an engaging Career Panel session, tours of the UofL micro/nano/additive core facilities, and several networking opportunities. In the feedback to survey questions after the meeting, it was noted that 19 self-identified disciplines of respondents included bioengineering, computer science, organic materials, and safety and health, which could be considered non-traditional areas in additive manufacturing. Moreover, many respondents self-reported "Additive Manufacturing" as their discipline, which may be an early indicator of convergence during which Roco and Bainbridge [4] state that the disciplines, materials, sectors, tools, and methods come together, e.g. as we saw many decades ago for nanotechnology.

The 2023 topic of the Research Community was **Convergence in Nanotechnology for Addressing Climate Change**. To accelerate our resilience against climate change, we must leverage the full force of society's knowledge base, science, and technology to advance both sustained mitigation strategies as well as implementing adaptation measures. Nanotechnology, developed as an interdisciplinary research area over the past several decades, is one of those major past investments that can offer opportunities to address key climate change mitigation and adaptation challenges, helping to reduce significant losses and damages in the future. Especially over the past 20 years, the U.S. invested in nanotechnology through a concerted, multi-agency National Nanotechnology Initiative (NNI). In 2000, the genesis of the NNI catalyzed organizations and individuals from academia, industry, and government to develop new foundational knowledge of nanoscale phenomenon and materials and develop novel and economic applications for nanotechnology. Moreover, an important goal from the outset of the NNI was to support the responsible development of nanotechnology, for example, by considering the environmental, health, and societal implications of the technologies themselves and their applications. Since that time, over $40B USD has been invested to advance our fundamental understanding of and ability to control matter at the nanoscale [7] and we now have nationally-supported nanotechnology infrastructure centers sponsored by many federal agencies including the Department of Energy (e.g., Nanoscale Science Research Centers, or NSRCs) and the National Science Foundation (e.g., the National Nanotechnology Coordinated Infrastructure Sites, or NNCI Sites). The time, investment, and successes were so substantial that Roco said nanotechnology is now for "general-purpose and mass use"[8].

More recently, nanotechnology and its associated disciplines have been more strongly connected to climate change at national and global levels. In early 2021, U.S. President Biden elevated climate change in the U.S. national agenda at the beginning of his term [9]. Later, in 2022, the U.S. White House Office of Science and Technology Policy (OSTP) released 37 "Net-Zero Game Changer Opportunities," physical science and engineering challenges that could help transform our energy system and infrastructure, seeking to motivate and direct the full potential of the U.S. public and private innovation ecosystems [10]. Soon thereafter, the Engineering Research Visioning Alliance (ERVA), a project sponsored by the U.S. National Science Foundation (NSF), published a workshop report that identified specific opportunities in science, engineering, and technology that are necessary to advance solutions to addressing climate change [11]. These opportunities became grouped topically into four natural categories: i) energy storage, transmission, and critical materials, ii) greenhouse gas (GHG) capture and elimination, iii) resilient, energy-efficient, and healthful infrastructure, and iv) water, ecosystems, and geoengineering assessment. The ERVA report emphasized the importance of engineering tools that require significant and sustained investment, some of which are the tools and facilities supported under the NNI, e.g. currently available NSRCs and NNCI Sites. Nanotechnology, now poised as a general-purpose and mass use technology within these open-access facilities, presents opportunities to address challenges in all four of these research categories.

The identification of nanotechnology as an opportunity to address climate change mitigation and adaptation challenges was further solidified in 2023, when the National Nanotechnology Coordination Office (NNCO) issued a "Nano4EARTH Challenge." Nano4EARTH was motivated by a need to act quickly, with mature science and technologies, to advance compelling nanotechnology commercialization opportunities for climate change mitigation and adaptation [12]. In an inaugural convening event for Nano4EARTH, the NNCO brought together hundreds of stakeholders in a hybrid event to identify the most impactful research opportunities for nanotechnology to help address climate change and to identify technologies that were ripe for translation into the market. Common themes that emerged involved immediate opportunities in battery technologies, catalysts and advanced materials and sorbents for addressing greenhouse gas emission and capture, and coatings and other material innovations for increased efficiency in industrial processes [13].

While these efforts address certain immediate commercialization opportunities of mature technologies, there remain other relevant questions around how the nation's basic research activities and infrastructure in nanotechnology, which was built up and maintained through decades of national investments, could evolve to help support both commercialization and basic research underpinning nanotechnology for addressing climate change and to do so in a way that is inclusive and provides equitable solutions. To fill this information gap, the Research Community identified and is in the process of reporting key needs in research, the research process, and infrastructure to advance climate change solutions in the longer term.

In 2023, the Research Community convened a range of stakeholders from research, industry, and government and from disciplines across the physical, life, social, and economic sciences throughout the year to discuss key questions about the future needs and opportunities at the intersection of nanotechnology and climate change. An initial event was an open, online workshop in February 2023, which was followed by synthesis meetings of a working group and select participants to further elaborate and prioritize key needs. An emphasis was placed in the project on the underlying infrastructure that supports nanotechnology research such as NNCI Sites, although insights related to infrastructure could be related to other shared user facilities supported by universities, the Department of Energy, federally funded research and development centers (FFRDCs), or government laboratories. In fact, the most inclusive definition of infrastructure used in the context of this project includes nanotechnology and microelectronics cleanrooms, materials characterization facilities, environmental engineering laboratories, field research test sites, greenhouses, pilot plants, shared computational resources, etc. The working group synthesized the input and discussions and is finalizing a manuscript to submit to a peer-reviewed journal. From the activities emerged five high-level characteristics of future research that can most effectively advance nanotechnology solutions to address climate change:

1. Long-term basic research in nanotechnology needs use-inspiration, i.e. connection to specific solution spaces in climate change needs.
2. Systems-level thinking is needed to create new discoveries and effective nanoscale innovations that can ultimately be adopted by society as solutions.
3. Stakeholders must be involved in guiding the prioritization of nanotechnology research effort and the design of research projects.
4. The research process needs to converge diverse disciplines physically and intellectually on specific and compelling topics of appropriate scope.
5. Nanotechnology infrastructure, e.g., equipment, personnel, and facilities, needs to be designed or adapted to a different and evolving user base which is increasingly interdisciplinary and who work on increasingly complex systems.

The five characteristics are themselves distinct yet also highly complementary. For example, higher level constructs such as Convergence Research can capture most, if not all, of these characteristics.

As the fifth characteristic, which is related to infrastructure, may be the most interesting to this NNCI audience, we summarize a few key recommendations from this section of the full report:

5.1 An important observation is that nanotechnology infrastructure facilities and programs may need to reconsider how the value proposition of existing nanotechnology infrastructure is framed to users and stakeholders from disciplines or sectors which do not traditionally use these facilities. Moving forward, one cannot expect that highly application-oriented researchers working on, for example, climate change, are able to navigate and identify the right resources, opportunities, or technical expertise inside specialized nanotechnology facilities.

5.2 There are opportunities to evaluate and possibly realign the breadth of technical expertise throughout nanotechnology user facilities, for example, in its technical staff and leadership. As convergence research brings a broader set of users and knowledge bases that present both more opportunities and demands, facilities can consider recruiting technical experts with expertise in specific application spaces, for example, biological sciences or ecology, or individuals who have experience in conducting convergence research. In some cases, existing staff may desire new professional development opportunities that would be able to address some of this diversification.

5.3 When working with an increasingly diverse user base, there will be increasing requirements to pivot across diverse applications, which may require increased adaptability in available equipment or daily process flows, or even the complete redesign of spaces within infrastructure facilities. Here, we emphasize reward systems for technical staff in nanotechnology facilities; these systems may need to be reevaluated such that staff are encouraged to assume and be rewarded for any additional burden or complexity associated with supporting convergence research.

5.4 Finally, a major challenge in advancing nanotechnology to address climate change is the need to scale technologies from the bench scale to the environmental scale, which is not only much larger in size scale, but often contains much more diversity in conditions. Current capabilities at nanotechnology user facilities typically support small-scale bench/prototyping research with predictable conditions, although deploying nanotechnology-based solutions in the environment will require both significant scale-up (e.g., prototype manufacturing) and testing and performance at scale (e.g., for validation).

References:

[1] https://www.nsf.gov/news/special_reports/big_ideas/convergent.jsp

[2] https://www.nsf.gov/od/oia/convergence/index.jsp

[3] Frechtling, Gajaray, Schnell, Desai, Silverstein, Misra, and Wells, "Exploring Convergence Research: An Initial Examination of What it Means and What it Hopes to Accomplish," Westat - Clarivate, April 30, 2021.

[4] Roco and Bainbridge, J. Nanoparticle Research, 15, 1946 (2013)

[5] Head, B. "Wicked problems in public policy," Public Policy 3, 101–118 (2008)

[6] National Academies of Sciences, Engineering, and Medicine. 2022. Convergent Manufacturing: A Future of Additive, Subtractive, and Transformative Manufacturing:

Proceedings of a Workshop. Washington, DC: The National Academies Press. https://doi.org/10.17226/26524

[7] https://www.nano.gov/sites/default/files/pub_resource/NNI-FY23-Budget-Supplement.pdf

[8] Roco, "Principles of convergence in nature and society and their application: from nanoscale, digits, and logic steps to global progress," J. Nanoparticle Research, 22, 321 (2020). https://doi.org/10.1007/s11051-020-05032-0

[9] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/23/fact-sheet-president-bidens-leaders-summit-on-climate/

[10] https://www.whitehouse.gov/ostp/news-updates/2022/12/07/the-potential-role-of-arpa-i-in-accelerating-the-net-zero-game-changers-initiative/

[11] https://www.ervacommunity.org/visioning-report/visioning-event-report/

[12] https://www.nano.gov/nano4EARTH

[13] https://www.whitehouse.gov/ostp/news-updates/2023/01/26/readout-of-nano4earth-kick-off-workshop/

7.2. Nanoscience in the Earth and Environmental Sciences

The goals of the Nanoscience in the Earth and Environmental Sciences (Nano-EES) research community are:

- Develop research tools and infrastructure to provide us with the capacity to approach more complex questions than ever before.
- Train the next generation of researchers to approach scientific inquiry in a way that crosses scales and scientific disciplines.
- Foster collaboration and convergent research across the network and beyond by helping us to consider multiple levels of organization and complexity in addressing key trans-disciplinary questions.

Nano-EES Workshop

To further the Nano-EES RC goals we run an annual workshop, with the third meeting held April 15 – 16, 2023 (virtual, hosted by NCI-SW). Lead institutions for this event were: NCI-SW (Paul Westerhoff, Trevor Thornton), NanoEarth (Tonya Pruitt, Mitsu Murayama), MONT (David Mogk, David Dickensheets), and Nano@Stanford (Kate Maher). The Science Education Resource Center at Carleton College (Monica Bruckner), part of MONT, provided logistic and data collection support.

The Nano EES-RC workshops target researchers in non-traditional fields in nanoscience and nanotechnology including environmental, agricultural, water, and geosciences. They are designed at a level that would be accessible to both nano-novices and those with significant prior experience. The goal for Day 1 was to introduce the audience to environmental nanoscience research using examples from water and agricultural research, with four invited talks:

- "Nanotechnology Enabled Water Treatment: Impacts from an NSF ERC'
  Pedro Alvarez (Rice University)
- "Nano/Micro-plastic pollution: Weathering and Implications"
  Francois Perreault (ASU)
- "Detection and significance of nanomaterials in plants and agricultural systems"
  Jorge Gardea-Torresdey (UTEP)
- "Measurement of Indoor and outdoor airborne particles"
  Pierre Herckes (ASU)

Following the talks there were Q&A sessions with the invited speakers.

Day 2 started with two keynote presentations. Julie Zimmerman (Yale University) gave a lecture entitled "Sustainable Nanotechnology" while Branden Brough (NNCO) presented a national update about the Nano4EARTH initiative. Following the keynote presentations we held another session of the following "Office Hours with Experts":

- Emmanuel Soignard (ASU) – Raman for nano-geology
- Rick Hervig and Maitrayee Bose (ASU) – SIMS and Nano-SIMS
- David Mogk (Montana State)– TOF-SIMS and Auger Electron Spectroscopy
- Marc Michel (Virginia Tech) – X-ray equipment and Sample prep

The office hours allowed participants to sign up for 15-30 minute sessions with experts in topics of interest. Participants were able to talk directly about their research interests and to solicit advice and feedback.

All workshop presentations and video demonstrations are posted on the program webpage at: https://serc.carleton.edu/msu_nanotech/nnci_spring2023/program.html

There were a total of 88 registrants in advance of the workshop, with 44 participants attending on Day 1 and 27 on Day 2. Results from a post-workshop survey indicated an average participation satisfaction of 9.4/10, where 10 is extremely satisfied and 1 is extremely dissatisfied. Verbatim comments from the survey included:

- *"I am new to the nanoscience field. Although I have been practicing for 35 years this is bring a deeper understanding of emerging ideas and implications."*
- *"The videos from the workshops are very helpful to share with potential facility users and colleagues. This year having the pre-recorded talks makes them even easier to share."*
- *"All topics were interesting and very well presented. The most valuable for my immediate needs were the ones dealing with advanced analytical techniques."*

Convergence of Biology and Earth Sciences Virtual Event

A second webinar was presented on November 1, 2022 as a collaboration between the Rules of Life and Earth and Environmental Science Research Communities: The Convergence of Biology and Earth Sciences. This webinar was sponsored by MONT and supported with logistical and web services by SERC. The webinar had 38 attendees (out of 60 registrants), representing numerous STEM disciplines, mostly from academic institutions (faculty and graduate students). Details of this webinar are posted at https://serc.carleton.edu/msu_nanotech/mont_fall2022/index.html. Four invited speakers presented on a variety of topics at the interface of life and Earth science: Rachel Spietz (Assistant Research Professor, Dept. Microbiology and Cell Biology): Reductive biomining of pyrite by methanogens; Christine Foreman (Professor, Dept. Chemical and Biological Engineering): Exploration of microbes in icy environments; Stephan Warnat (Assistant Professor, Dept. Mechanical and Industrial Engineering): Detection of Microbes in Ice Using Microfabricated Impedance Spectroscopy Sensors; and, Chelsea Heveran (Assistant Professor, Dept. Mechanical and Industrial Engineering): From bones to stones: engineering living building materials. A following breakout session allowed participants to "Chat with the Experts".

Next Steps for the Nano EES-RC

The Nanotechnology Convergence Research Community shares common interests with the Nano-EES RC and we plan to host a joint workshop in the spring of 2024. The workshop will focus on earth and environmental research, climate change, and convergence, with the following goals:

- Engage new audiences in discussions of nanotechnology in diverse environmental and climate science topics.
- Introduce the resources that are available in the NNCI network to help address challenges in these topics and identify areas of new need.
- Find more specific topical issues of interest to subgroups of attendees, enabling follow-on, in-person activities at a site of relevance.

We envisage a three-day virtual workshop with 2-3 hours of activities each day, comprising keynote presentations, discussions, and Q&A sessions. It will be designed to engage both new researchers as well as well-established researchers to converge on topics of mutual interest, create connections, and further advance the ideas post-workshop.

7.3. Nano-Enabled Internet-of-Things

This report is based on virtual and in-person meetings as well as e-mail exchange between the members of the Nano-enabled Internet-of-Things (nan-IoT) Research Community including chair Mark Allen and Pat Watson (Univ. of Pennsylvania SINGH), Christian Binek (Univ. of Nebraska-Lincoln, NNF), Chris Ober (CNF director until July, 2023) and his successor Judy Cha (Cornell Univ., CNF), Kevin Walsh (Univ. of Kentucky, KY Multiscale), Oliver Brand (Georgia Tech, SENIC director until his passing in April 2023) and his successor David Gottfried (SENIC). The report is primarily based on discussion points that came up during the annual presentation of the research community activity, given by Christian Binek at the NNCI Annual Conference in October 2023. This report lays out the general tasks and vision of the research community, reflects on its history with special emphasis on previous symposia, and explains future plans that include crafting a review article and concluding the research community work with a final symposium in 2025.

Vision and evolving tasks of the nano-IoT research community

The research community activity is based on the hypothesis that IoT devices, defined as physical objects with sensors and actuators that communicate with computing systems via wired or wireless networks, are often and increasingly will be enabled by nanotechnology. Specifically, we envision that the ubiquitous sensing potential of the nano-IoT will provide the input necessary for data mining/big data processing to understand complex system behavior, augment the interaction environment in future workplaces, be the transducers that can monitor living things from agriculture to medicine, and catalyze the convergence of researchers from many intellectual backgrounds. In response to this vision, the research community organizes and participates in nano-IoT symposia, members present research from their respective participating sites, disseminate information and lessons learned, and report at the annual NNCI conference. The research community embraces the tradition that the member in charge of organizing the last nano-IoT symposium presents at the NNCI meeting.

A brief history of the nano-IoT research community

The inauguration of the nan-IoT symposium series took place in September 2021. The virtual event was organized by Mark Allen with support by Pat Watson and staff (Univ. of Pennsylvania). It focused on the visionary approach to develop the IoT for agriculture as well as the impact of the IoT on transportation and logistics and the challenge of enabling an IoT infrastructure. The second nano-IoT symposium took place in August 2022 at CNF and was organized as a hybrid event by the former CNF director Chris Ober and company. Invited presentations focused on the role of the nano-IoT in medicine where flexible electronics and hybrid electronics and sensing is needed and continued to explore the subject of precision agriculture and the internet of living things.

Planning stages of the 2023 symposium ultimately postponed to 2025

With previous symposia having foci on IoT for agriculture, transportation, medicine, flexible as well as hybrid electronics, the time was right for a shift towards the role of the IoT in data mining and data processing. This subject is particularly appealing with recent advances in machine learning and data driven artificial intelligence (AI). With that in mind, the plan was to have a nano-IoT symposium in September 2023 at the University of Nebraska-Lincoln organized by NNF director Christian Binek. Preparations for the first in-person symposium bridging AI and IoT, known in the literature as AIoT, were in full swing. This subject was also motivated by the fact that, according to the International Data Corporation, there will be about 41.6 billion IoT devices in 2025. They will be capable of generating 79.4 zettabytes (ZB=10^{21} bytes) of data. To put this number into perspective, the amount of IoT-generated bits corresponds roughly to the number of stars in the visible universe. Against this background it becomes apparent that AI is needed to convert this massive amount of IoT data into useful information. Speakers presenting on neural computers realized by MEMS and software-defined reconfigurable intelligent surfaces (AI-enabled meta-surfaces) were already secured when the organizers realized that the density of events in September 2023 where NNCI participation was critical became too demanding. Those events included the 2023 Workshop on Nanotechnology Infrastructure of the Future, organized by NNCI, and the Nanotechnology Infrastructure Leadership Summit (NILS), organized by the National Nanotechnology Coordination Office (NNCO). Both of these events took place back-to-back in Washington D.C. and required in-person participation of all research community members. As a result of this time conflict, the members decided to postpone the third nano-IoT symposium.

Future plans of the nano-IoT research community

Discussions between research community members at the NILS and the nanotechnology infrastructure workshop in Washington D.C., the annual NNCI meeting at Stanford, and subsequent e-mail exchange helped to develop a strategy for continuing the work and maximizing the output of the community. The members concluded that it is time to think about the legacy that the nano-IoT research community will leave behind after NNCI sunsets. As a result, the organizing members aim at crafting a review article that will disseminate what the research community learned about the path forward of nano-IoT and the role of a nanotechnology infrastructure for advancing the field of the IoT. The goal is to write this article in 2024. Because NNF director

Christian Binek is leading multiple center reviews and the organization of the annual 2024 NNCI REU convocation, the subcommittee concluded that the third symposium of the research community will take place in 2025. It will be organized by NNF and will allow the research community to complete its mission with an event which is envisioned to become as successful and visionary as the preceding symposia.

7.4. TransformQuantum

Overview: The **TransformQuantum Research Community** was established in 2020 to organize and systematize considerations of how the NSF-supported National Nanotechnology Coordinated Infrastructure (NNCI) and its community of users could better prepare for and respond to the needs of the ongoing quantum revolution and its demands for quantum-relevant fabrication capabilities. This report provides an update to the TransformQuantum (TQ) activities over the past twelve months.

TransformQuantum comprises members from each of the 16 NSF NNCI sites as well as members from several other institutions both in the U.S. and internationally. Most of the members represent academic institutions, all with nanofabrication facilities, sharing a common interest in the development of specific quantum-related nanofabrication processes that enable and improve the performance of a range of quantum technologies. There are also some representatives from government-supported research labs and research facilities.

With key players from theoretical, computational, and experimental backgrounds, our focus areas are:

→ Collating and distributing information about quantum-relevant nanofabrication infrastructure and expertise
→ Formulating scalable designs for intermediate-scale and large-scale quantum computation,
→ Developing theory and experimental methods for quantum communication over short- and medium-range networks
→ Investigating and implementing realistic methods for error detection, correction, and mitigation
→ Developing materials science-based approaches for higher fidelity qubits and quantum information storage
→ Developing realistic roadmaps for quantum computation and quantum communication

There are a wide variety of different technologies that are being pursued related to quantum information. These include atomic systems (neutral atoms; Rydberg atoms; ions); atomic-like solid state systems (color center defects in semiconductors; spins in semiconductors; rare earth ions in glasses); photonic systems; and solid-state systems such as qubits based on superconductors, and on quantum dots in semiconductors. There are also more exotic systems, such as developing acoustic phonons as quantum information carriers, or developing qubits based on electrons on liquid helium or solid neon, that are being pursued as well, but are not currently represented in this research community, due to their small size. However, we are open to supporting these activities as well.

Annual Update: Over the past year, most of the activities were conducted through the Global Quantum Leap (GQL) AccelNet program, led by the University of Minnesota (PI: Steven Koester). The Global Quantum Leap (GQL) is funded through the NSF AccelNet program and creates a network-of-networks in the fields of **nano-fabrication** and **quantum computing & information sciences**, aligning well with TransformQuantum. One of the main goals of the GQL is to train nano- and quantum scientists to work in diverse, international environments.

The three main activities, some ongoing and some planned, comprise:

- Student/faculty exchanges coordinated and funded through the GQL;
- Bootcamps and short courses for K-12, undergrads, teachers, and professionals;
- A second Workshop on Quantum Engineering Infrastructure II (WQEI 2; planned).

In Summer 2022, GQL organized and supported an International Research and Training Experience (IRTE) at our partner NIMS, in Tsukuba Japan. This involved 2 students, and 1 postdoc participant, and we had very good feedback, despite concerns about COVID.

Also in 2022, GQL organized four separate exchanges:

- A student exchange from FZ Jülich (Germany) to University of Minnesota,
- A student exchange from UC Berkeley to University of Tokyo,
- A student exchange from Oxford University to the University of Oregon,
- A postdoc exchange from Delft University (Netherlands) to Cornell.

Six US participants in the 2023 IRTE program.

Based upon the success of the 2022 programs, the GQL exchange programs were expanded for Summer 2023. Here, GQL also ran two International Research and Training Experience (IRTE) programs, one at RWTH Aachen in Germany and one with the NIMS in Tsukuba, Japan. These programs offered eight separate projects:

- Project 1 (Japan): Coherent control of electron spin in diamond for quantum device application
- Project 2 (Japan): Fabrication and characterization of moiré superlattice devices
- Project 3 (Japan): Theory and simulation of nano-patterned 2D materials
- Project 4 (Germany): Mapping of local valley splitting in Si/SiGe by forming a quantum dot by magneto-spectroscopy and pulse spectroscopy at 10 mK
- Project 5 (Germany): Pre-characterization of electron shuttle devices at 4 K and 10 mK
- Project 6 (Germany): Topological Quantum Error Correction
- Project 7 (Germany): Quantum Neural Networks and Machine Learning
- Project 8 (Germany): Spin Qubits in Graphene Quantum Dots

We had a tremendous response to this program, with 94 applications requested, 43 applications received, 19 recommendations requested, from which 14 students were short-listed and 6 US students chosen (thus not providing students for every project, erring on the side of ensuring that the students chosen were a good fit for a particular project).

At the end of the IRTE program, we received very positive feedback from the project mentors, including comments such as "I am very satisfied with this first experience…we are planning to write up a research paper on his research results, which is a remarkable outcome for an undergraduate internship," and "I will be happy to participate as a host group again next year, and I will be happy to encourage colleagues of mine, too."

For 2024, we are again offering summer IRTE opportunities with NIMS in Japan and RWTH Aachen, open to students at US universities. We have received a strong response for these two opportunities and are in the process of selecting candidates.

In other activities, the University of Minnesota's MiNIC NNCI node hosted a 10-day program called "Quantum+Chips" designed for undergraduate students to introduce them to key topics in quantum phenomena and their computing devices. The program included tutorials on quantum devices and concepts, a computer lab to learn how to program an actual quantum computer, presentations from industry on recent advances in chips, lab tours, and visits to local high-tech companies. This program was targeted toward early-stage undergraduate students, to get them interested in quantum and nano topics and provide enthusiasm to future REUs and graduate school.

Other opportunities from some of our partner institutions include a program supported by the NSF Quantum Leap Challenge Institute for Hybrid Quantum Architectures & Networks (HQAN), a joint research effort between UIUC, UChicago and UW Madison, which hosts TeachQuantum, a program targeting teachers in K-12, especially high school, that involves a 6-week summer research experience as part of a multi-year immersive program, exposing these teachers to real-world quantum research environments in a way that facilitates teaching quantum-focused STEM concepts and activities.

HQAN, partnering with the Chicago Quantum Exchange (CQE) at UChicago, offers a course in "Quantum Science, Networking, and Communications," comprising an 8-week course in quantum technology that targets early and mid-career engineers with bachelor's degrees in science, covering quantum information processing, quantum networks and quantum communication, with the course including technical demonstrations and simulations. CQE also supports a more intensive program in Quantum Engineering and Technology, comprising a 4-day course in quantum engineering that targets current professionals in transition to quantum careers, where participants are recommended to already have a master's or higher degree.

Finally, TransformQuantum will participate in the planning and organization of an NSF-supported Workshop on Quantum Engineering Infrastructure II (WQEI2), to be held in person on Sunday, March 3, 2024, the day before the start of the APS March Meeting in Minneapolis, on the campus of the University of Minnesota.

The three main goals of this workshop, with invited speakers and panelists, are to:

- Review the outcomes from the first (2021) edition of this workshop (WQEI I) and evaluate progress toward recommendations,
- Understand how new developments have altered the needs and best practices for quantum fabrication,
- Provide a vision for the future of quantum fabrication infrastructure, particularly in light of the CHIPS & Science Act and other infrastructure investments.

7.5. Understanding the Rules of Life

Preamble: "Understanding the Rules of Life" (RoL), a key focus in the National Science Foundation's "big ideas," presents a unique challenge within the National Nanotechnology Coordinated Infrastructure (NNCI) network. RoL spans from molecular intricacies of life to broader ecological impacts, making it diverse and complex. The complexity and diversity of RoL themes are also a major strength that complements the existing foci of NNCI and opens new opportunities with the increasing convergence of disparate disciplines. The RoL-RC within NNCI should continue to emphasize interdisciplinary collaboration, integrate existing resources, remain flexible, prioritize education and training (workforce issues), consider hierarchical connectivity, engage in strategic planning, and uphold ethics and social impact considerations. This is particularly germane to the RoL theme given its profound implications, from disease intervention at the genomic level (e.g., with CRISPR) to potential "enhancement" of human attributes and capabilities.

A deliberate approach that incorporates these considerations ensures that the NNCI network effectively addresses the multifaceted nature of RoL, fostering impactful research in the context of infrastructure development.

Much of the past two years of the RoL-RC was focused first on defining the theme within NNCI context. We believe that continued refinement and targeted focus in the framework of "metrology" and ensuring NNCI strengths are aligned within RoL themes would position the network for improved posture and increased emphasis in the coming years, especially in the next phase of the Network. The RoL-RC initially focused on defining the core themes in RoL, followed by current and proposed activities and plans.

Defining the RoL RC within NNCI: The quarterly meetings and discussions within the RoL-RC revolved around strategically defining opportunities and key initiatives within the realm of "Rules of Life." The RC actively engaged in discussions, contributing to the formulation of the RoL themes with a specific emphasis on "soft" and "soft-hard" (hybrid) interfaces and structures. The overarching purpose of the RoL RC is to facilitate meaningful interactions among member institutions and partners, serving as a platform for collaborations, joint projects, and the exchange of valuable information.

The ongoing discourse within the RoL-RC theme is focused on identifying targeted themes that not only resonate broadly within the research community but also align closely with the mission and overarching goals of NNCI at large. Through these discussions, the RoL RC aims to establish a framework that generates network and infrastructure context for Rules of Life research, contributing to the advancement of scientific understanding and collaboration in this dynamic field. The NNCI RoL-RC has identified three major themes for focus for the wider future activities.

These include:

1. "*Synthetic Biology (SynBio)*"; with a focus on "road-mapping" for infrastructure and facility needs for SynBio. Here the focus is analogous to SRC roadmap activities to identify and target "metrology" needs for SynBio and help define performance needs and attributes.
2. "*Seeing & Sensing the Invisible*"'; i.e., encompassing broad and relevant length-scales for "imaging", spanning sensing, diagnostic and imaging fields. This is an obvious and relevant RoL theme that aligns firmly with NNCI goals and activities.

3. *Outreach and Workforce Development* as they relate to RoL-RC. There is ample diversity and scale/scope of RoL-RC and has potential global societal impact through business and commercial opportunities. Thus, workforce development is a naturally relevant and timely opportunity to target education, professional development and outreach related to RoL.

RoL RC Activities & Plans: In the past year, discussions within the NNCI participating sites have primarily focused on fostering collaboration among participating sites, specifically in the areas of medical diagnostics and workforce training. Quarterly webinars have been a key platform, emphasizing the integration of soft-bio with nanoelectronics. These discussions aim to meet broad criteria while maintaining a focused and targeted approach to align with NNCI's mission, objectives, goals, and activities.

Each Network site contains detailed information about RoL activities and plans within the focus areas of the site. Below are a handful of examples and assorted nuggets from a few sites as representative activities.

As the host site for the RoL RC, SHyNE continues its commitment to interdisciplinary exploration and advancement across fields such as Syn-Bio and its implications for “nano-bio” or “soft nanotechnology.” The RoL RC has fostered connections within individual network sites and cross-orchestrated noteworthy webinars like "Polymer Vehicles for CRISPR Gene Editing and Plasmid DNA Payloads," featuring insights from Prof. Theresa Reineke of the Minnesota Nano Center (MiNIC). We plan to increase awareness of the RoL RC across the network to emphasize the prospects for diversifying the user base and capabilities of the NNCI network.

Several NNCI sites are extending collaborative efforts, particularly in the realms of diagnostics and biomedical devices, developing infrastructure for synthetic biology and biomedical devices.

The Cornell Nanofabrication Facility (CNF) is exploring RoL themes with an emphasis on leveraging local strengths in fabrication and electronics. CNF has such a notable partnership with the Cornell Center for Biotechnology. It highlights the importance of collaboration across disparate fields to foster innovative solutions in the realm of micro and nanotechnology for sensing/diagnostics. By bringing together experts from different disciplines, CNF embodies the RoL principle that emphasizes the power of collaboration in driving technological advancements. CNF's global outreach efforts align seamlessly with the RoL theme of embracing a global perspective and encouraging knowledge exchange on an international scale. Initiatives such as the Staff Exchange Program with UPenn and the International Research Experience in Japan, supported by an NSF IRES award, exemplify a commitment to breaking down geographical barriers and promoting a diverse range of ideas and approaches.

In the arena of education, CNF's dedication to programs like the Research Experience for Undergraduates (REU) reflects a commitment to the RoL principle of continuous learning and nurturing the next generation of researchers. By providing hands-on experiences and training opportunities, CNF contributes to the development of a skilled workforce and reinforces the idea that education is a foundational element for personal and professional growth. Moreover, CNF's focus on microfluidic device production and its in-house capabilities for fabrication and testing align with the RoL theme of practical application and technology transfer. This emphasis on translating knowledge into tangible advancements underscores the facility's commitment to making a real-world impact through the development and application of cutting-edge technologies.

Locally, SHyNE has established collaboration with the Center for AIDS Research to develop rapid diagnostics technology for HIV detection based on microfabricated cantilevers and a microelectronics detection paradigm. It involves extensive use of classical nanofabrication and traditional microelectronics (e.g. MOSFET) integrated for signal transduction and detection. Like several NNCI sites, SHyNE hosted five Research Experiences for Undergraduates (REUs) and five Research Experiences for Teachers (RETs) during the summer, illustrating its dedication to fostering educational opportunities and workforce development.

As a regional activity, the RoL RC participated in the November 2023 M3S meeting in the Chicago region that was held at Baxter Healthcare in Deerfield, IL. In attendance were those from Chicago-based industries (e.g. Baxter), researchers from Midwest universities/national labs, and vendors such as Hitachi, JEOL, Gatan, Leica, ThermoFisher, and others. The RoL initiative was introduced at iNano (UC, ANL, NU Initiative), Chicago Biomedical Consortium (CBC), and also with UC Innovation Exchange (CIE) and Illinois Science + Tech Park. RoL benefits from two new local centers in the Chicago region:

- National Institute for Theory and Mathematics in Biology (NIMTB): Developing new mathematical methodologies inspired by biological problems.
- Chan Zuckerberg Biohub – Chicago: Instrumented tissues toward understanding inflammation underlying many diseases.

By way of another example, the Research Triangle Nanotechnology Network (RTNN) is actively contributing to workforce development and nanotechnology research. Two community college interns at RTNN are engaged in sample preparation for bio and bio-EM, aligning with the National Nanotechnology Coordinated Infrastructure's (NNCI) third pillar focused on technical development. This internship initiative serves as a potential avenue for cultivating skilled individuals in the field. RTNN has recently been awarded the NSF Engineering Research Center (ERC) named PreMiEr. PreMiEr's objective is to develop diagnostic tools and engineering approaches that prevent the colonization of harmful microorganisms in building designs while encouraging beneficial ones. In an effort to make nanotechnology facilities accessible, RTNN has established the Kickstarter Program. This inclusive approach aims to overcome financial barriers and foster a diverse community of users.

In terms of education, RTNN collaborates with educators to develop nano-themed lesson plans for K-12 students, utilizing the facility's tools related to RoL. Additionally, the network has created immersive lab experiences for K-12 students, allowing them to participate in hands-on activities within RTNN facilities in the RoL arena.

Moving forward, we will further strengthen collaboration and organization within the NNCI network addressing key questions in the life sciences and its connections to physical science and engineering. We will develop ideas for research tools and infrastructure to further Rules of Life Research and strategies to leverage RoL such as vendor/webinar events, workforce training, outreach/SEI. The RoL RC quarterly meetings are planned and set in the calendar. We expect that RoL RC will continue to grow and diversify across the NNCI networks in the year ahead.

7.6. Microelectronics and Semiconductors

During NNCI Year 8, the Department of Defense announced that the Microelectronics Commons would be established with funding from the CHIPS and Science Act to "create direct pathways to commercialization for US microelectronics researchers and designers from lab to fab." In anticipation of the ME Commons announcement, the Microelectronics and Semiconductors Research Community held a 2-day workshop in Sept 2022 and the outcomes were published in a white paper in December 2022. The white paper highlighted the importance of upgrading aging academic cleanrooms by using CHIPS funding to expand the capabilities and geographical reach of NNCI. Many NNCI sites that support the research community submitted proposals to the ME Commons and in September 2023 the following eight regional Hubs (with NNCI site participation) were announced:

- The Northeast Microelectronics Coalition Hub (Harvard, CNS)
- The Silicon Crossroads Microelectronics Commons Hub (Northwestern University, SHyNE)
- The California Defense Ready Electronics and Microdevices Superhub Hub (UC San Diego, SDNI)
- The Commercial Leap Ahead for Wide Bandgap Semiconductors Hub (North Carolina State University, RTNN and NC A&T State University, SENIC)
- The Southwest Advanced Prototyping Hub (ASU, NCI-SW)
- The Midwest Microelectronics Consortium Hub in Ohio (University of Louisville, KY Multiscale)
- The Northeast Regional Defense Technology Hub (Cornell, CNF)
- The California-Pacific-Northwest AI Hardware Hub (Stanford University, nano@stanford and the University of Washington, NNI)

The eight Hubs selected for the Microelectronics Commons are tasked with domestic prototype development for DoD systems applications in the areas of 5G/6G Technology, Artificial Intelligence/Hardware, Commercial Leap-Ahead Technologies, Electromagnetic Warfare, Secure Edge/IoT Computing, and Quantum Technology. There is also a significant workforce development program with training programs designed to meet the needs of an expanded semiconductor manufacturing industry within the US. This will be an opportunity for the NNCI to collaborate with the Microelectronics Commons.

<u>Future Plans</u>

The initial round of funding from the ME Commons was to establish capability areas at each of the Hubs. The next phase will focus on developing prototype demonstration within the six technical areas with an annual call for projects. During Year 9, the Microelectronics and Semiconductors Research Community will serve as a conduit between the NNCI user base and the ME Commons Hubs. The ME Commons investments in the Hub capability areas has the potential to upgrade core facilities at a number of NNCI sites, and the annual call for projects is an opportunity to accelerate the 'lab-to-fab' transition that has always been part of the NNCI mission. By enabling the cross-communication between NNCI users and ME Commons Hub partners we hope to significantly expand this Research Community during Year 9.

8. NNCI Network Promotion

8.1. Marketing and User Recruitment

Marketing and user recruitment strategies vary widely across the NNCI network, based on a range of local and regional factors unique to each site. During the January 2017 NNCI Conference, a breakout session on marketing and user recruitment identified a number of strategies to help sites develop their plans to increase facility usage and those were provided in previous reports. A follow-up breakout session on this topic was held at the October 2019 NNCI Conference and the updated discussion is provided below. While much of the focus is on recruiting new external users, many of the approaches and best practices apply to internal users, particularly non-traditional users, as well. Some sites have staff with external user engagement as a primary job responsibility, while other sites do this on a more ad hoc basis. Previous NNIN sites generally seem to have a more mature marketing strategy based on previous trial and error, although most new sites have significant pre-NNCI experience with external users as well. Challenges to any marketing strategy include the often-significant time lag between when a certain marketing tactic is employed and when actual usage may happen. This can make it particularly difficult to gauge the effectiveness of various approaches. Certain NNCI sites also possess geographic advantages and a built-in clientele of tech companies, start-ups, and other academic users, while other sites need to work hard to engage non-traditional users. Finally, IP concerns and overly burdensome access agreements can often discourage new users.

User Marketing and Retention Breakout Session (NNCI Annual Conference, October 25, 2019)

Continuous internal marketing should include:

- Brown bag seminars
- Posters around campus
- Departmental seminars throughout institution
- Take 10 minutes in departmental faculty meetings
- Facility tours
- Send info posters to pertinent student groups

Sites had some of the same challenges that impact usage:

- Needed equipment upgrades
- Down time (opportunity to refer other NNCI sites)
- Space needs
- Staff retention/turnover
- Cap rates on student time in facility. PIs will send only one student to reach the fee cap quickly when more students could be trained in a facility
- Some sites had reviewer comments to target diverse users in specific community groups (Hispanic/Latino, Native American).

Sites also had some unique challenges:

- How to be sensitive to a neighboring facility that is 30+ years outdated and struggling? How can this site be complimentary and not competitive?
- Paperwork process for external users that can take 2-4 months before external users can get in the facility.

Ideas for increasing external users:

- Some sites have a position that at least a fraction of FTE is devoted to external user development.
- Give and attend talks at industry symposia
- Join local industry groups, attend their meetings
- Focus on SBIRs; find recent awardees; incubate current SBIR grantees to apply for addition funding and have them write the facility into proposals.
- Give and attend seminars/brown bags at neighboring institutions, community colleges
- Facility open houses for industry/Industry summits your institution
- Watch key accounts and investigate any major changes in usage. *Ex: Why hasn't company XYZ been for the last several months?*
- Find business incubators and see if your institution has something similar
- Short courses (both for internal and external users)
- Alumni associations donor resources (funding)
- Talk with deans and department heads
- Undergraduate interns from other institutions paired with research at your institution
- Contact economic development offices, manufacturing extension services, chamber of commerce
- Note that building these external relationships takes time and persistence

The consensus of the sites is that the role of the Coordinating Office in marketing and user recruitment efforts should include the following:

1. *Represent the network at national conferences.* While normally the Coordinating Office would have hosted a booth at conferences such as TechConnect or MRS, this activity was suspended in 2020 and 2021 due to pandemic-related travel restrictions. NNCI was represented at TechConnect 2022 through invited oral presentations by Matt Hull and David Gottfried. David Gottfried, Trevor Thornton, and Mary Tang all attended and presented at the 2023 ENRIS Conference (bi-annual meeting of the Euro Nano Lab network).

2. *Provide an NNCI website with tools and expert databases.* At the January 2017 NNCI Conference, there was significant discussion about the website and a desire to present a more applications-focused user experience. During the first year of its existence (2017), the website contact forms generated approximately 25 inquiries related to becoming a new user, education/outreach, or other general information, and this increased to 75 inquires during 2018-19 but decreased in 2020-21. Any potential users are referred to NNCI sites for follow-up, and we have recently begun tracking outcomes in order to assess the efficacy of this user recruitment mechanism. More discussion of the website is provided below.

3. *Create an NNCI email list.* During 2017, a listserv was created for subscription by all interested NNCI site staff to share information on site activities, as well as provide another mechanism for sites to solicit assistance on technical and user support matters. Currently there are more than 140 subscribers to this email list with approximately 50-70 announcements or discussions initiated in this forum yearly. Furthermore, an option to create an email list for individual working groups was offered, and both the Etch and

Lithography groups have used this successfully. Other working groups have their own lists, not created by the Coordinating Office.

4. *Create an NNCI newsletter for periodic distribution by all sites.* While this was discussed within the Coordinating Office, it was felt that sites were better positioned to disseminate news and events information to their local users.

8.2. NNCI Website

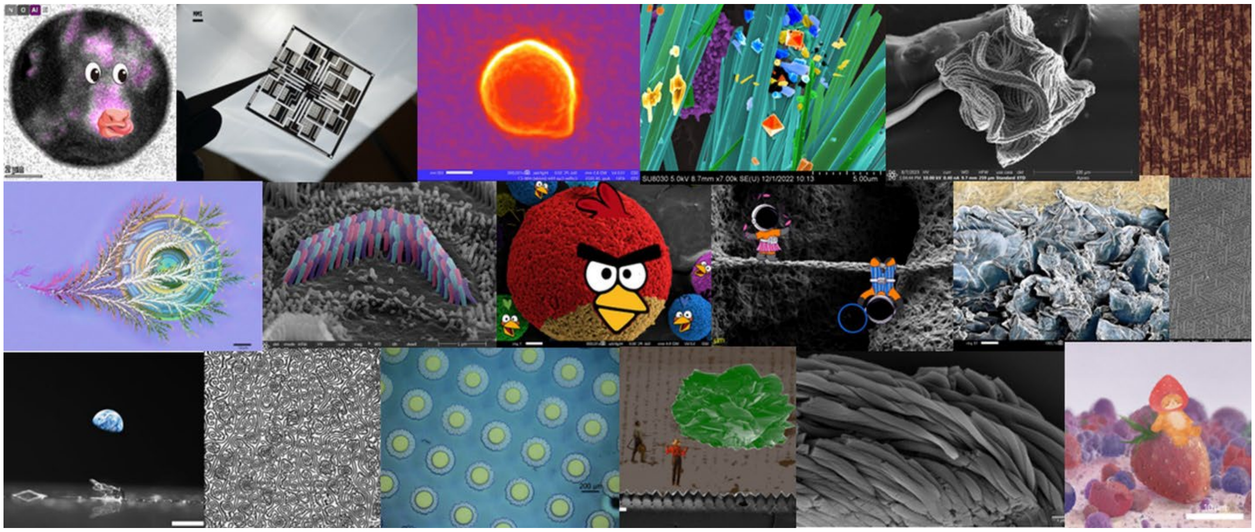
During the first year of the NNCI Coordinating Office, one of the main activities was the creation of a web portal (www.nnci.net) to provide a comprehensive list of tools and experts available within the network for both user recruitment and support. The design of a new, comprehensive website was predicated on the desire to accommodate the different needs of users, potential users, the public, and NNCI staff. The design concepts and structure of the website were reported in detail in the Year 1 report with additional upgrades made during Year 2. Additional features and content were added during Years 3-5.

The NNCI Introduction Video was produced at the end of 2017 and publicly released in February 2018. It was posted to the NNCI home page with the 2019 upgrade. The YouTube URL is https://youtu.be/72ZXh-ESt3U. As of Dec. 31 2022, the video had been viewed more than 2,000 times. During 2021, the NNCI YouTube channel was added to the home page, and more details on this are provided later in this report.

Since the original launch, new content and updates have been uploaded regularly including:

1. News items on the blog (7 news items in 2023)
2. NNCI Annual Reports
3. NNCI Annual Conference agendas and presentation materials
4. NNCI On the Road (list of upcoming NNCI site presence at meetings and conferences)
5. K-16 Educator Resources
6. Technical Resources, including Research Communities and Audio/Video content
7. Home page news spotlights
8. Updates to site pages
9. Backend improvements, changes, and bug fixes

In celebration of National Nanotechnology Day 2019 (October 9), the NNCI website hosted the first “Plenty of Beauty at the Bottom” image contest. Images featured in this contest were produced at one of the 16 NNCI sites during the previous year. This contest has been repeated each year since, with public voting open this past year during Oct. 10-17, 2023 in categories “Most Stunning”, “Most Unique Capability”, and “Most Whimsical”. These images (and winners) are now archived as part of the Education pages on the website and further details are described in the Education and Outreach report in Section 4.1.



Google analytics for www.nnci.net indicate that in calendar year 2023 there were nearly 43,000 visitors to the website, a 21% decrease over the prior year and 28% decrease from the peak in 2021. As in previous years, a large spike in visitors was observed in October, primarily to participate in the image contest voting. For the year, 99% were new visitors with 51% from the United States (up from 46% the previous year). There were more than 84,000 pageviews, which is also an 18% decrease from the prior year. The average session duration was slightly less than 1 minute, with an average of 2 pageviews/session, comparable to previous years. During this time period, the top ten pages visited are shown in Table 9 below. These ten pages account for 53% of all pageviews. Significant differences this year include a large decrease in views of the Home page, and significant decreases in several of the other popular pages compared to 2022. In general, the top pages include the education-related pages ("careers", "what is nano", and "how small is nano" pages), consistent with previous year's observations. Other significant increases in pageviews were seen for the site and tools pages.

Table 9: NNCI Website Page Visits (2023)

Page	# Pageviews in 2023	%Change from 2022	% Pageviews in 2023
/	11,512	-36.3%	13.6%
/careers-nanotechnology	6,876	-12.4%	8.1%
/what-nano	5,763	-17.9%	6.8%
/how-small-nano	3,660	-23.5%	4.3%
/sites/view-all	3,500	+16.5%	4.1%
/research-experience-undergraduates	3,491	+9.9%	4.1%
/nnci-image-contest-2023-stunning	2,951		3.5%
/plenty-beauty-bottom	2,627	-16.9%	3.1%

/search/tools	2,476	+40.1%	2.9%
/about-nnci	2,221	+2.3%	2.6%

Since the NNCI website's debut in late 2016, the growth in annual visitors and pageviews is shown in Figure 16 below and appears to have reached a maximum in annual visitors in 2021 and is now decreasing.

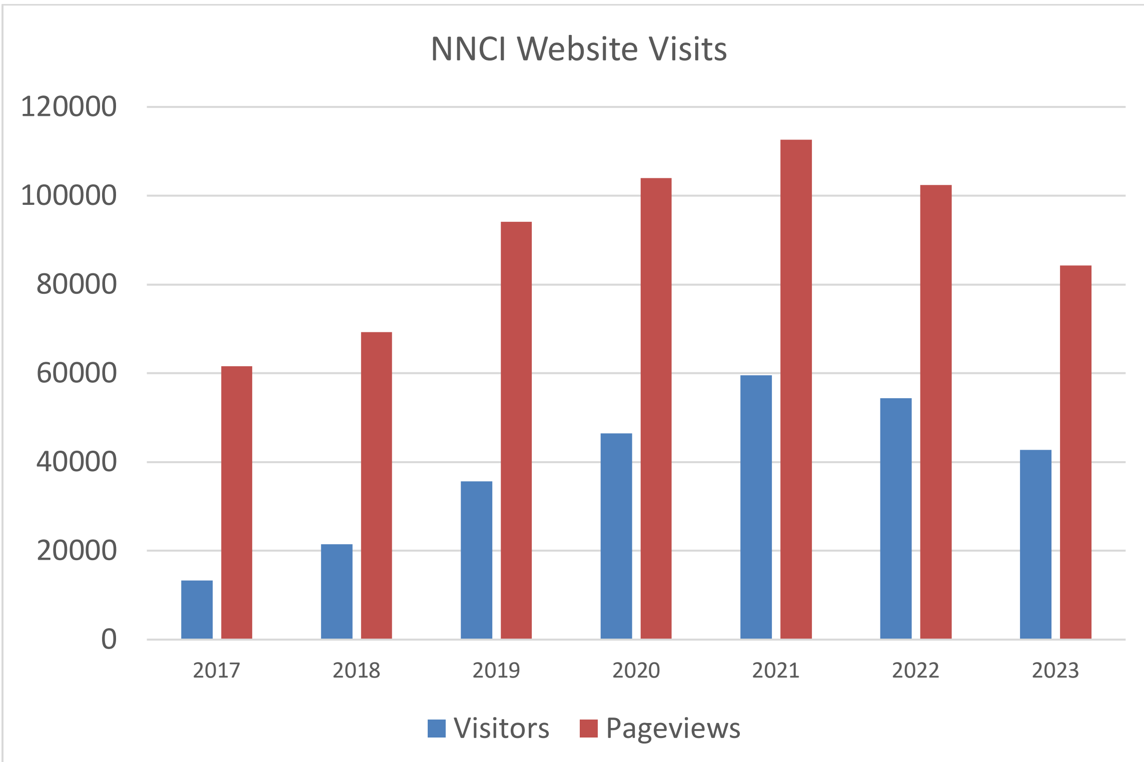


Figure 16: Growth in Annual NNCI Website Usage

Site acquisition (how visitors get to the website) is primarily through four routes: organic search, direct, referral from another website, and social media (see Figure 17). The organic search rate of 61% showed a significant increase this past year from 56% in 2022 after decreasing from a peak of 67% (2020). Direct acquisition decreased to 32% (from 38% in 2022). Both modes showed decreases in overall number of visitors compared to the previous year.

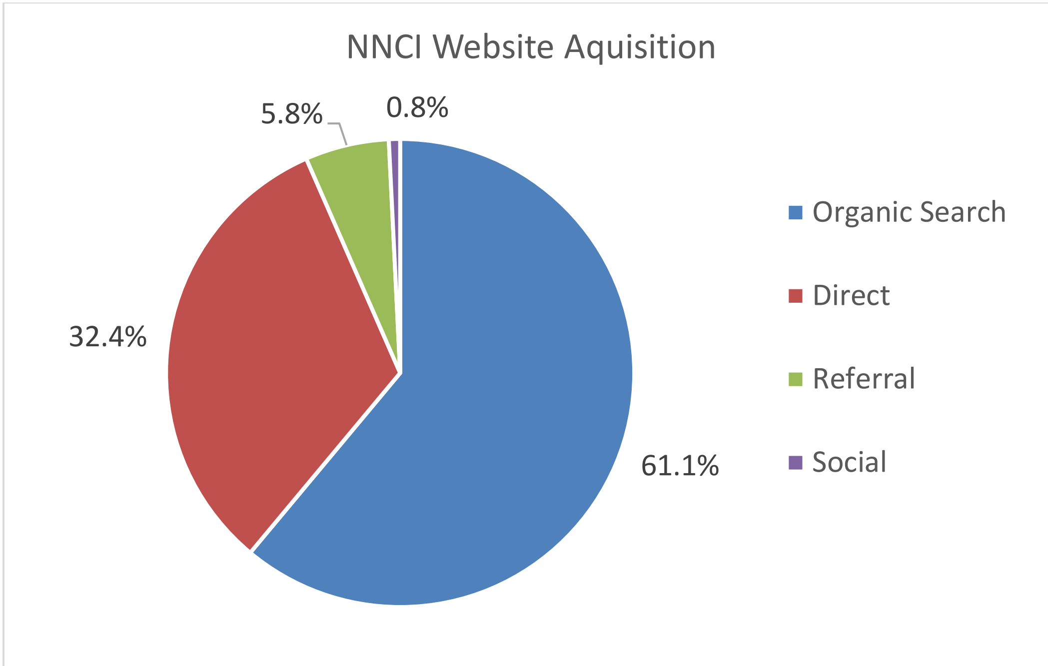


Figure 17: Site Acquisition (how visitors get to the website) for www.nnci.net (2023)

The geographic distribution of visitors to the website is illustrated by the map in Figure 18 below indicating the nearly complete global reach. The top ten locations of visitors are shown in Table 10 and these account for 83% of all visitors to the website.

Figure 18: Geographic Distribution of Visitors to www.nnci.net (2023)

Table 10: NNCI Website Visitors by Location (2023)

Country	# Visitors	% Visitors
United States	21,674	50.7%
India	6,027	14.1%
China	2,738	6.4%
Philippines	1,796	4.2%
Canada	846	2.0%
United Kingdom	667	1.6%
Germany	499	1.2%
Australia	446	1.0%
South Korea	435	1.0%
Japan	417	1.0%

A further examination of the US locations of website visitors not surprisingly reveals that the highest densities are in states with NNCI facilities (California, Virginia, New York, Texas, and Georgia are the top 5, slightly different than in 2022) although all 50 states are represented.

8.3. User Satisfaction Survey

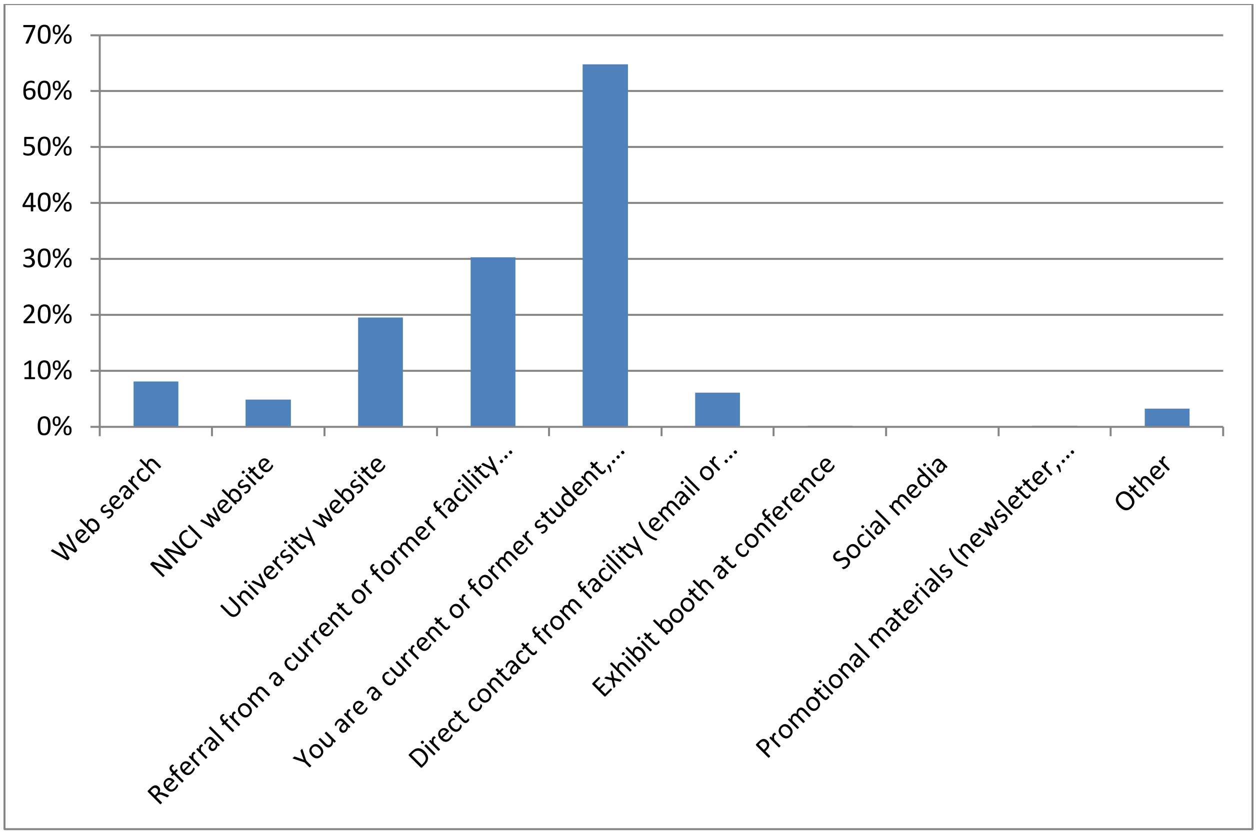
As a result of site director discussions, as well as recommendations from the Advisory Board, the Coordinating Office created a User Satisfaction Survey for implementation throughout the NNCI network. Using a *Survey Monkey* platform, the survey was first made available to sites for forwarding to their user bases during the fall/winter 2017. After receiving nearly 700 responses from 10 sites that participated and combined with the responses from five sites that had already developed their own internal surveys, the results (N>1300) were reported in the NNCI Year 2 Annual Report. Based on the first year of the common survey, the Coordinating Office solicited suggestions for modifications to the survey questions and a number were received and implemented for the 2018 survey which generated 638 responses from 8 sites that participated and an additional 747 responses from the remaining 8 sites which conducted internal surveys over a similar time period. These separate surveys did not all use the same questions as the common version on Survey Monkey, but responses were added to the overall results when possible.

For the 2019 NNCI User Survey, significant changes were implemented based on recommendations from professional evaluators at Arizona State University (Mary White) and Montana State University (Carolyn Plumb). This same survey was used for 2020, with the addition of a new question regarding use of resources specific to the COVID-19 pandemic, and this version was very slightly modified in 2021, and a question about civility was added to the 2022 survey. The 2023 survey, shown below, was not changed from 2022. All sites were encouraged to use the common survey vehicle when possible, and 14 sites had respondents to the common survey while the remaining two sites provided their own data for inclusion on some questions (N=1,090). The site-specific filtered results, with comments, were provided to individual sites for identification of action as needed.

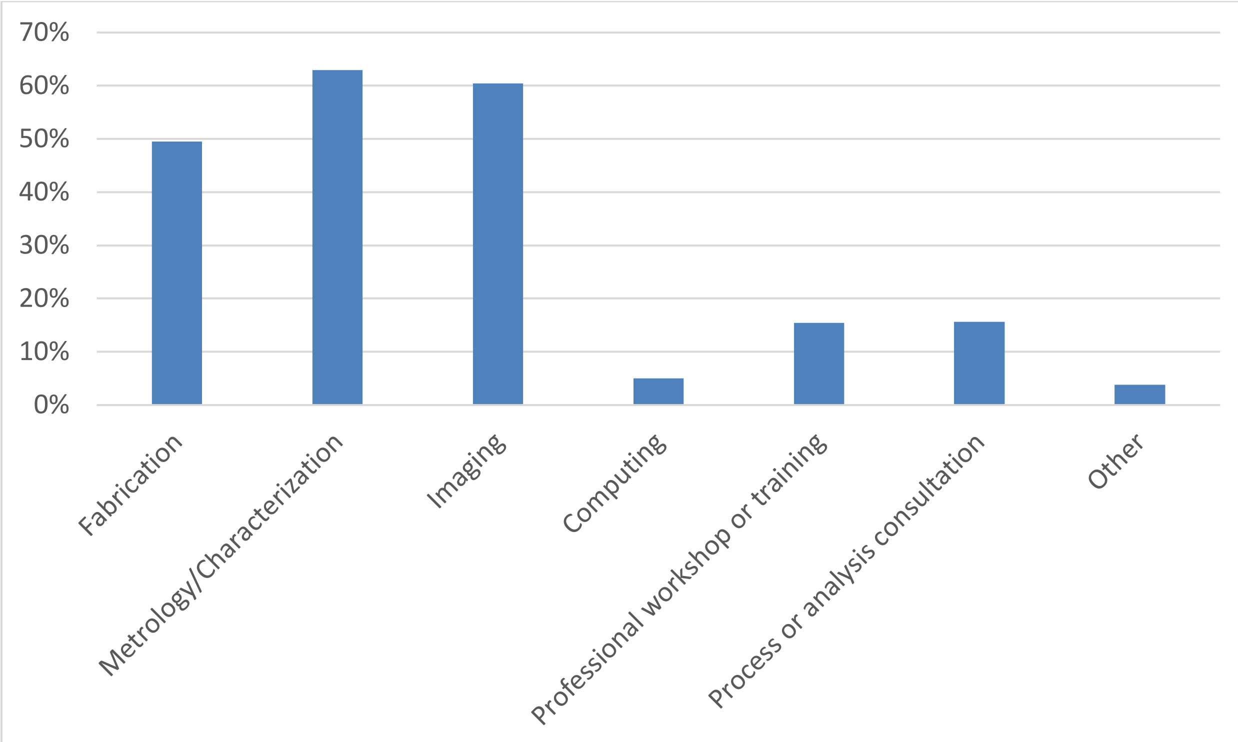
The NNCI facility that was primarily used during the previous 12 months.

The number of responses from each site varies from 17 to 236 (mean=68.1). In this year's survey, users were not asked if they used more than one NNCI facility during the past year although we know anecdotally that this number typically is <5% of users. In addition, users were not asked to identify specific universities or facilities within the NNCI site which were accessed.

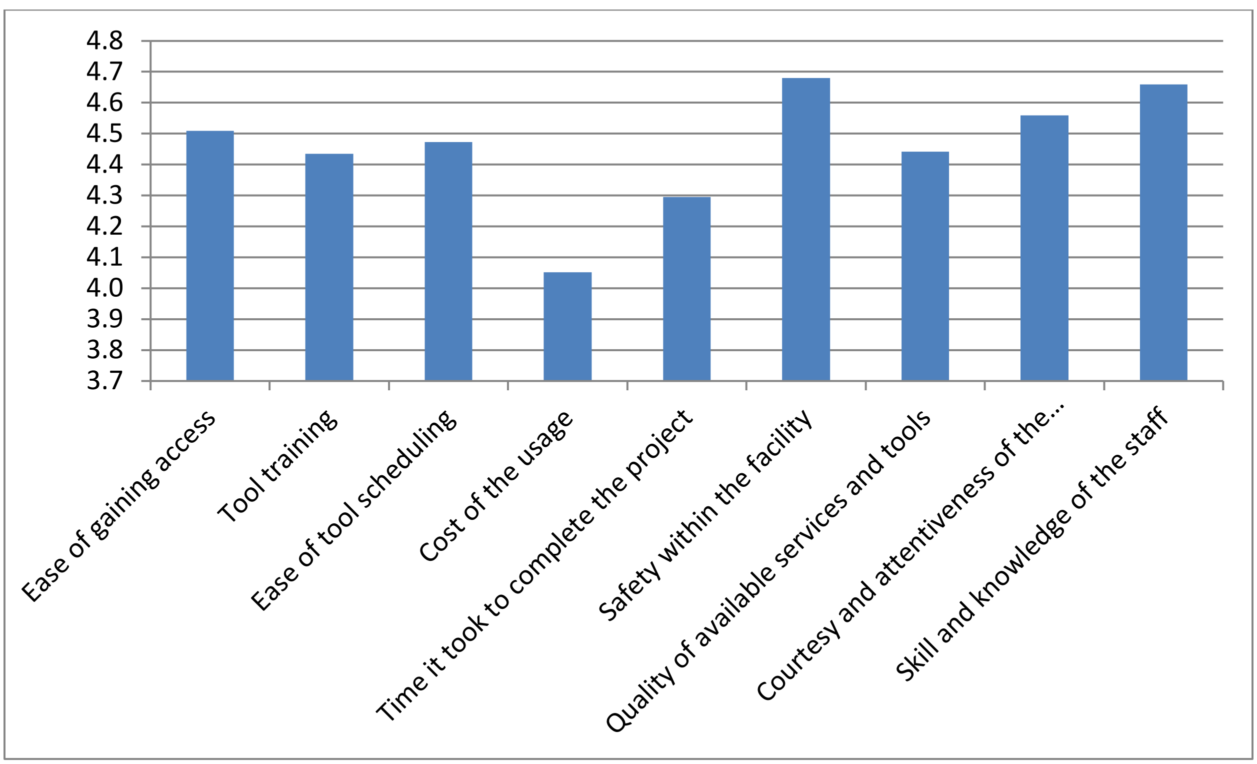
How did the user find out about the NNCI facility? (N=799)



Which services were used at the NNCI facility? (N=990)

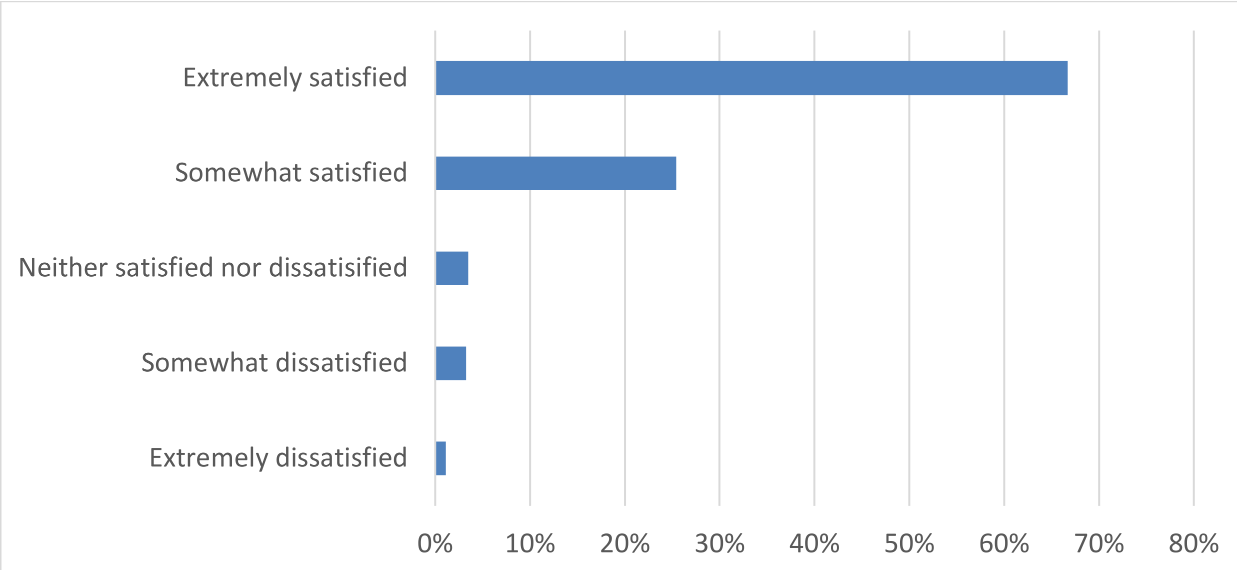


Regarding this NNCI facility, rate your satisfaction with the following (N=851; Scale=1-5, 1=extremely dissatisfied, 5=extremely satisfied)



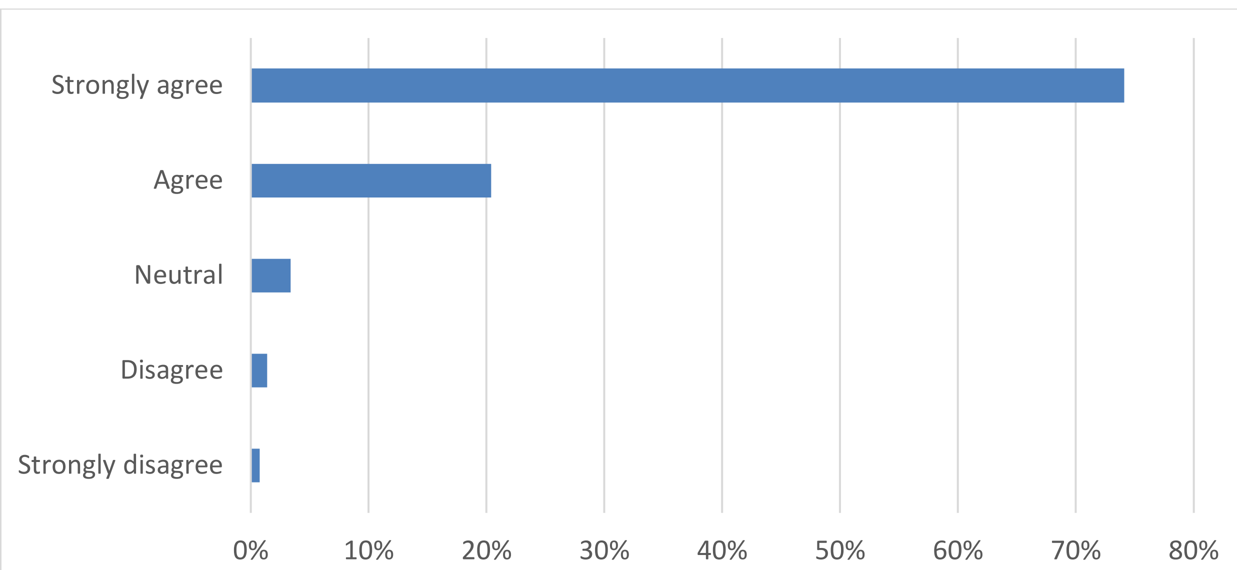
Rate your overall satisfaction with this NNCI facility (N=1035)

For all NNCI sites, the average overall satisfaction rating is 4.53/5. For the common survey (N=799), the detailed ratings are as indicated below, with 92.1% of respondents indicating either somewhat or extremely satisfied.



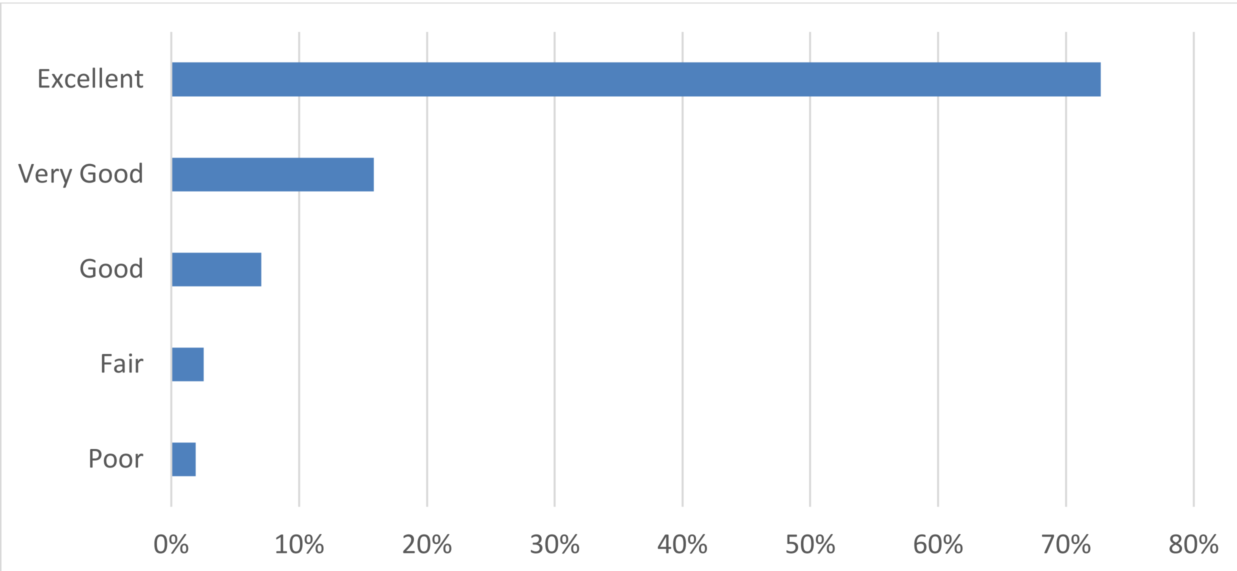
Rate your agreement with this statement: This NNCI facility has had a positive impact on my project goals or research activities (N=799)

This question was first asked in 2021, with 94.5% of respondents agreeing or strongly agreeing with the statement. In 2023, that same percentage agreed or strongly agreed.



How would you describe the level of civility (professional engagement and mutual respect) in your interactions at this NNCI facility? (N=795)

This question was newly added in 2022, at the request of the Diversity subcommittee, as a follow-up to previous specific assessments of environment and culture within NNCI facilities. Less than 5% of respondents rated the level of civility as Fair or Poor (up slightly from 2022), although nearly 180 comments were also provided so sites would be aware of any specific issues that might exist.



Would you recommend this NNCI facility to a colleague? (N=911)

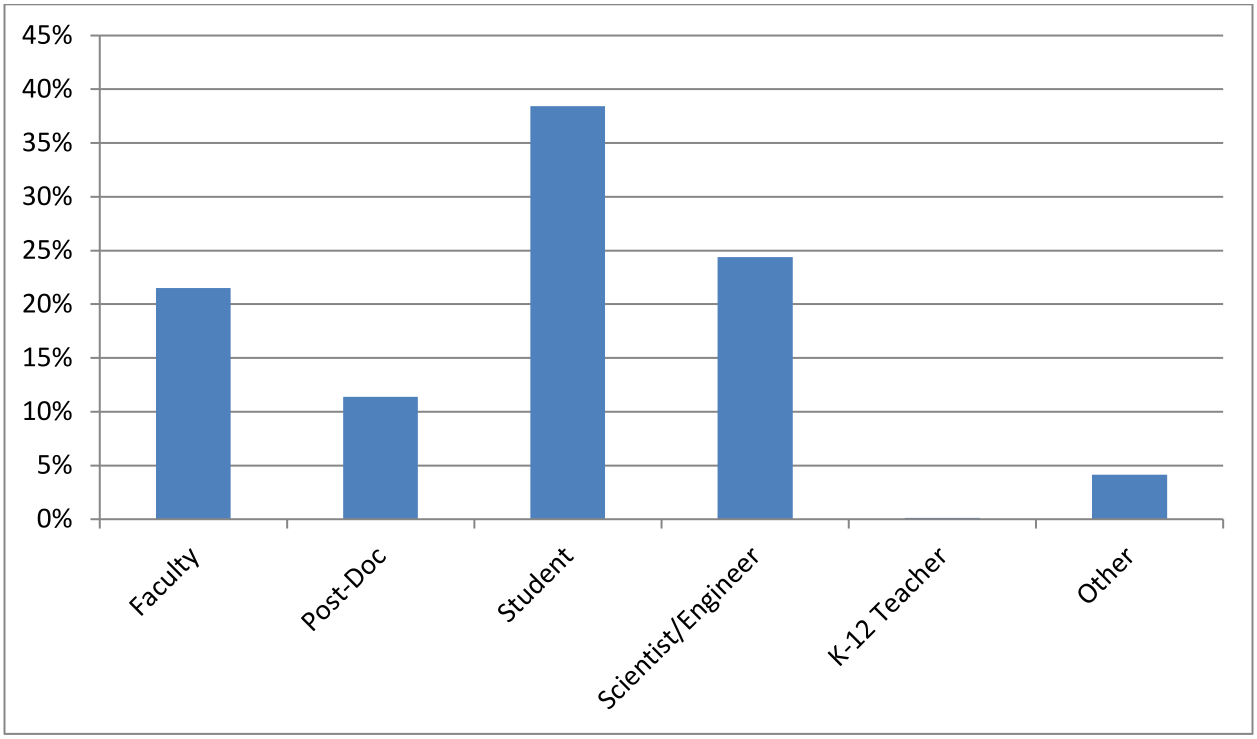
Yes: 96.3% (this is decreased slightly from 97.9% in 2022)

No: 3.7%

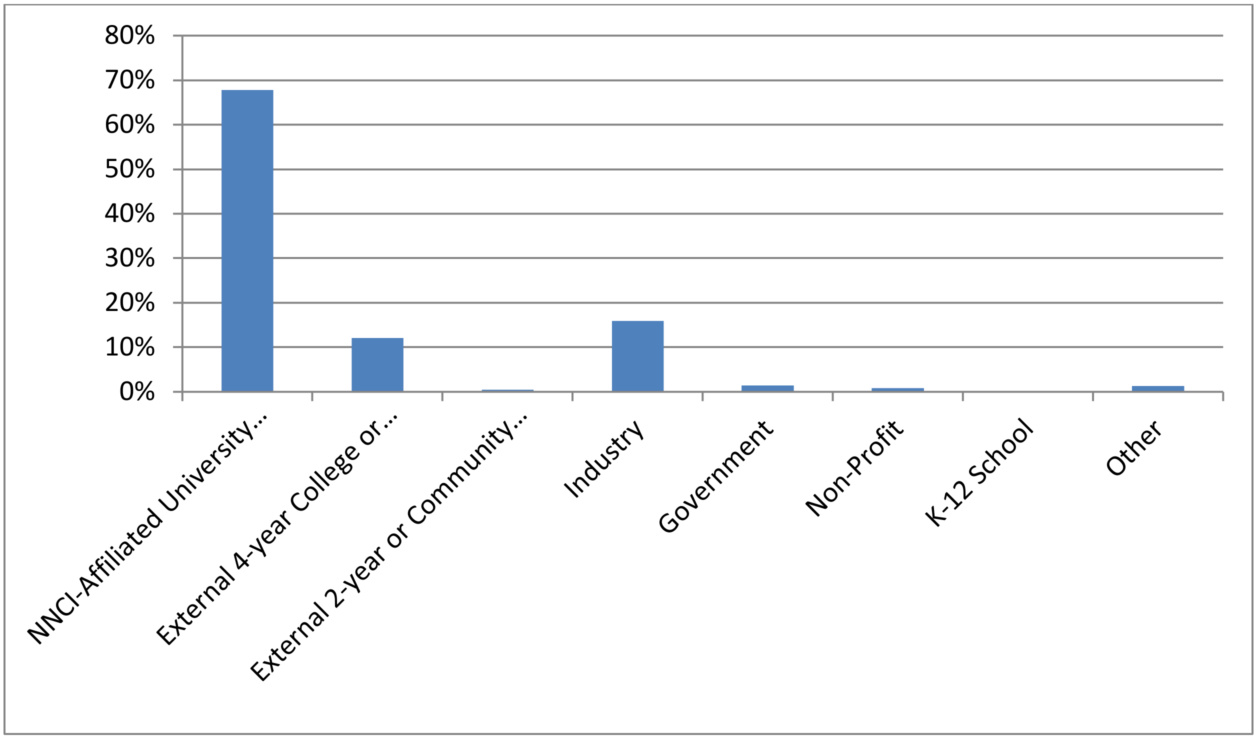
If you have any recommendations for specific new tools or services at this NNCI facility, please indicate them.

More than 200 suggestions were received and provided to the sites. Examples include characterization tools like TEM with in-situ capability, EBSD, FIB-SEM, XPS, SIMS, ICP-MS, and other chemical analysis, as well as fabrication tools and improvements such as maskless lithography, Nanoscribe, improved photoresist process quality, DRIE, newer E-beam lithography, and pulsed laser/flash lamp annealing. In addition, replacing old and outdated tools, as well as additional standard tools (light microscopy, hot plates, oven) were also suggested. Finally, users suggested more remote work options, improved scheduling system, revamped training, and increased staff.

User Position (N=799, this question was only asked on the common survey)



User Affiliation (N=799, this question was only asked on the common survey)



Note that this distribution somewhat mirrors the actual user affiliation distribution for the NNCI network as a whole (see Section 11.1, Figure 30) suggesting that the survey is probing a statistically similar cross-section of NNCI users.

In addition to responses to the survey questions noted above, 75 individual free-text comments were provided, both positive and negative, and a selection of these is provided here (specific facility names removed):

User access to NNCI facilities has a large impact on the educational opportunities for non-NNCI students. It has directly lead to industry hires in US semiconductor companies such as Intel, Applied Materials, ASM, LAM, etc.

There is untapped potential to engage faculty and users to build an interacting scientific community - trading methods, developing new tools, solving problems together, working across and connecting the activities in the different facilities, and laying out and executing a strategic plan for the facilities. The facilities are world class and the staff very dedicated. With more meaningful involvement of stakeholders, the facility can reach its full potential.

There are some instrumental facilities in this NNCI facility which need more helpful instructors, while in some other instrumental facilities of the same NNCI, there were very helpful and awesome instructors who left. It is extremely important to fill those positions with efficient people as it is critical for the continued project success and student training.

Great staff. I would not be able to complete any of the projects I am working on without the facility.

I think that the model adopted at other facilities whereby cleanroom staff hold office hours and directly offer help and advice would be of enormous benefit to the users and ultimately to the quality of the research conducted at the … nanofabrication facilities.

Overall great resource for the … community! Only feedback is to standardize staff training and capture knowledge of former employees as turnover sometimes leads to jumps/gaps in expertise on certain instruments.

… is the best in terms of staff knowledge and support as well as an excellent equipment set with high uptime. I'm a 100% satisfied industrial user who added two full-time staff to my company based on successes in device fabrication at….

Cutting edge science needs cutting edge equipment as well as the people to run, train, and develop these tools. It is easy to focus on the equipment. More of a spotlight should be placed on the people that make this all possible.

… continues to be absolutely critical to maintaining our cutting-edge operations. It is a true strength that helps us maintain millions of dollars in federal and commercial funding- without these readily available capabilities, we could not compete with larger companies and those located in more advantaged metropolitan areas. The … and its staff make bleeding edge science possible for a wider demographic; innovation in our area would suffer greatly without its access and support.

It would be helpful if there were more process engineers that can also do weekly process testing to make sure the tools are running as expected. This often falls on the users after tools come back up, and it can ruin products if the tool is not running normally.

9. NNCI Annual Conference

In the proposal for the Coordinating Office, it was suggested that "A flagship event for the NNCI network will be the annual ***NNCI Conference***, which will be held at different network sites and will not only highlight the research supported by the NNCI facilities, but also provide a venue to share best practices as a result of the work of various working groups and committees." It was further detailed: "The Coordinating Office will work with the site directors to organize the annual ***NNCI Conference***, which will be held each year at a different NNCI site. The conference attendees will include the site directors and other site management personnel, the External Advisory Board, as well as NNCI site staff who are members of the working groups. As mentioned above, individual working groups might organize parallel sessions where findings in the specific topical area can be shared with other interested NNCI staff. We envision a 1.5-2 day meeting, that includes half-a-day of network overview and site presentations, half-a-day of user presentations, possibly in parallel sessions, and at least a half-a-day of time for dedicated panels on E&O, SEI, computation and select working groups (safety, vendor relations, etc.). The goal is to have a working meeting that strengthens the network and its sites, helps with future planning and is not just a review. As an example, each year's conference could have a dedicated panel on "Emerging Research Areas", using invited talks to stimulate discussion among the NNCI sites on promising future research directions and the tools required to support these. We also envision that satellite events, such as an SEI Conference, could be organized in conjunction with the annual NNCI Conference. Poster and presentation awards as well as certificates for certain panel participation may be a way for student and staff development, respectively, as part of the annual event."

After returning to in-person (hybrid) meetings in 2022, this past year's conference was held in-person (with virtual options) at Stanford University on October 25-27, 2023. The 2.5-day event had a registration of 105, including senior representation from every site (14/16 site directors); 6 of 8 advisory board members; NSF officials including new NNCI Program Officer Dr. Richard Nash and ECCS Division Director Dr. Tony Maciejewski; Dr. Branden Brough Director of the NNCO; as well as invited speakers.

This year's program included a ½-day special topic program on "Translating from R&D to Market", with invited guest speakers and a panel discussion on needs for translational activities. Initial results from the 2023 Economic Impact/Company User Survey conducted by the Innovation and Entrepreneurship working group (See Sections 4.4 and 6.11) were presented by Jessica Hauer (NCI-SW) and Tonya Pruitt (NanoEarth).

Invited speakers were:

- Jack Hu (Pumpkinseed)
- Jae-Hyung Lee (Stratio)
- Feinberg (Stanford Ignite)
- Brenna Teigler (Activate Berkeley)
- Paul Pickering (Silicon Catalyst)
- Sesh Ramaswami (Applied Material's EPIC Center)

The agenda also featured:

1. Photolithography Working Group Meeting

2. nano@stanford Open House (with student research posters and vendor booths)

3. Separate meetings for those interested in Education/Outreach and SEI were held during the afternoon before the main conference.

4. Remarks from Dr. Richard Nash (NSF Program Manager for NNCI), Dr. Tony Maciejewski (ECCS Division Director), and Dr. Branden Brough (Director of the National Nanotechnology Coordination Office, NNCO).

5. Presentations by the Director and the four Associate Directors of the Coordinating Office with an NNCI Overview and Reports on Education & Outreach, Societal & Ethical Implications, Computation, and Innovation and Entrepreneurship.

6. Short site reports from each of the 16 NNCI sites. Each site was requested to address the question: “What successful examples of programs, activities, and relationships in the current NNCI could be adapted or expanded for multiple sites in a future network?”

To assist attendees, supplementary information including site user statistics, research, education, SEI, and computation highlights, and impact were provided as PowerPoint files in an online accessible format.

7. Site presentations were grouped into 4 topical areas, with panel discussions featuring the site directors and attendees.
   - “What can a set of future nanotechnology infrastructure sites do to expand their impact regionally?”
   - “What role does the NNCI currently play in workforce development and how can a future infrastructure improve upon and scale these efforts?"
   - “How can an NSF-funded nanotechnology program help lead and nucleate the broader national nanotechnology infrastructure ecosystem?"
   - “How does NNCI support national research priorities, and how can this be enhanced in a future nanotechnology infrastructure?”

8. Research communities provided summaries of their past and planned activities:

9. Staff awards were presented with details provided in Section 10.5 below.

10. A meeting between the site directors and the coordinating office, to discuss plans for ongoing and Year 9 activities.

11. A private meeting of the External Advisory Board. These discussions resulted in a written report to the Coordinating Office which is attached here as Appendix 14.1.

The Coordinating Office presentations, site reports, and research community summaries are provided, along with the full meeting agenda, on the NNCI website https://nnci.net/nnci-annual-conference-2023.

The next NNCI Annual Conference is scheduled to be held at University of Louisville (KY Multiscale) on October 28-30, 2024.

10. Network Activity and Programs

10.1. Cooperative Network Activity

The NNCI sites and Coordinating Office have continued to make a concerted effort to develop and engage in activities that demonstrate the network "whole being greater than the sum of its parts." These activities include the following: (1) activities where all (or nearly all) NNCI sites participated, (2) activities between sites or with multiple NNCI site partners, and (3) activities where a single NNCI site acted on behalf of the entire network. Below are provided examples of such activities during this past year of the NNCI program.

Network-Wide Activities

1. Participation in monthly NNCI site director meetings
2. Participation in monthly NNCI education and outreach coordinators call
3. Chairing and membership of Subcommittees
4. Leading and membership of Working Groups resulting in shared reports and best practices
5. Participation in National Nanotechnology Day Activities. Eleven NNCI sites submitted 28 entries for the "Plenty of Beauty at the Bottom" image contest in 2023.
6. Attending NSF Nanoscale Science and Engineering Grantees Conference. The December 2023 conference was held in person and virtually, and included organizing committee members Dan Herr, Eric Josephs, and Nancy Brown from UNC-Greensboro (SENIC).
7. Attending NNCI Annual Conference (October 2023)
8. Participating in NNCI REU Convocation (Hosted in Aug. 2023 by MONT)
9. Participating by sending students to attend the "Winter School on Responsible Innovation and Social Studies of Emerging Technologies" and students/faculty to attend the "Science Outside the Lab" program
10. Participating in the NNCI Nanotechnology Entrepreneurship Challenge (NTEC) competition and showcase event
11. Providing content for the NNCI website
12. Participation in the NNCI Outstanding Staff Awards program
13. Discussions between site staff on equipment repair and maintenance issues
14. Dissemination and promotion of NNCI, network events, and opportunities (webinars, workshops, job postings, etc.) through electronic communications and other marketing
15. User referrals to other sites, via NNCI email list or responses to NNCI website contact form
16. Leadership of and participation in the NNCI Research Communities
17. Participation in the NNCO "Nanotechnology Infrastructure Leadership Summit" (September 2023)
18. Organizing, speaking, and participating in the NNCI "Workshop on Nanotechnology Infrastructure of the Future" (September 2023)

<u>Multi-Site Activities</u>

1. Hosting and participation in NNCI supported or sponsored workshops and technical events (host site in parentheses), not including individual seminars and webinars:
    a. Nanotechnology Convergence Research Community virtual event "Help Identify Critical Nanotechnology Opportunities for Addressing Climate Change", February 21, 2023 (hosted by RTNN). Inspired and informed by the NSF Engineering Research Visioning Alliance (ERVA) report, "The Role of Engineering to Address Climate Change" and the Nano4EARTH Challenge, this community event targeting the basic science, fundamental research, and convergence needs was held a few weeks after the complementary commercialization-focused NNCO-organized Nano4EARTH Kick-off Workshop.
    b. Nanoscience in the Earth and Environmental Sciences Research Community (Nano EES-RC) Workshop, April 5-6, 2023 (virtual, hosted by NCI-SW). This workshop was the third in a series. The program included presentations and Q&A with world class experts, a panel discussion on outdoor versus indoor airborne particles, and ability to sign up for "ask an expert" on how to prepare and analyze your own samples.
    c. NNCI Nano+Additive Manufacturing Summit, July 25-26, 2023 (University of Louisville/KY Multiscale). This is an annual event dedicated to bringing together researchers in the advanced manufacturing fields of additive manufacturing and micro/nanotechnology to discuss new findings, share results, showcase capabilities, generate ideas, debate the future, and network with one another.
    d. NNCI Advanced Lithography Symposium, October 24, 2023 (nano@stanford) featuring talks by vendors about new developments in lithography tools, materials, and techniques. The Photolithography Working Group used this opportunity to meet in person.
    e. NNCI Education Symposium, November 11 2023 (SDNI) with the theme "K-12, Community College, and Universities: Building the Next Generation of US Nanotechnology Workforce." The meeting included presenters from NNCI sites (SDNI, nano@stanford, NanoEarth, CNF), NNCO, MNT-EC, Penn State/NACK network, UCSD MRSEC, SEMI Foundation, and local middle and high schools. In the 1-day virtual event, people exchanged ideas and collaboration plans to promote STEM in K-12 and integrate nanotechnology to the current science curricula.
2. User project support: User projects continue to be triaged and referred to and between NNCI sites where work can be done more efficiently. This process, driven and aided by direct cross-network staff technical interactions, an email listserv, and NNCI website contact form, has become an important dynamic within the network which allows for maximizing the network's resources for the nation's benefit. Examples include:
    a. Using the NNCI website, RTNN directs users to other facilities when their work necessitates capabilities outside of the RTNN. This includes several Coursera learners; when another NNCI node may be closer to their home, RTNN directs students there for more information and potential training. During Year 8, RTNN referred a user for MBE deposition to Arizona State and EMSL and users for wafer bonding and parylene coating user requests to Georgia Tech.

   b. NNI's WNF has been involved in remote projects with UCSB, OSU, Virginia Tech, University of British Columbia, and Montana State University.
   c. MONT had user/technical interactions with NNI, NNF, NanoEarth, CNS, CNF, MiNIC, and SDNI.
   d. CNF collaborates with other sites on project support, particularly MANTH and CNS.

3. Staff technical interactions:
   a. The Cornell Nanoscale Facility and the UPenn Singh Center for Nanotechnology have organized a staff exchange in order to enable an improved coordinated partnership and comprehensive understanding of each other's capabilities and best in class methods. The exchange of staff, partly funded through the NNCI coordinating office, provides a hands-on experience that allows each site to share best practices, compare data and help identify areas of improvement. Three MANTH staff members visited the Cornell CNF facility for 3 days in 2023. This followed a visit from 2 CNF staff engineers who met at MANTH the previous year.
   b. Georgia Tech (SENIC) continues to collaborate with Montana State University to implement facility management software at the MONT site, leveraging the extensive application development and applying it to the much smaller installation there.
   c. MONT and NNI are continuing to collaborate on managing the NorthWest Nano Lab Alliance.
4. NSF-funded Research Experience for Teachers (RET) program. Georgia Tech, (lead institution), Northwestern, Univ. Minnesota, and Univ. Nebraska. These four universities from across the NNCI network support 20 high school/community college faculty each year in a 6-week summer research experience, with follow-up support during the school semesters.
5. Partnership in the NSF AccelNet project "Global Quantum Leap" (GQL) (MiNIC is lead, with CNF, SENIC, SHyNE). GQL establishes an international network-of-networks linking the NNCI to quantum networks in Asia and Europe. The GQL has launched a webpage (www.globalquantumleap.org), Twitter, and LinkedIn pages. The GQL has two international exchange programs: an International Research and Training Experience (IRTE) program at NIMS in Tsukuba, Japan and a summer internship program with the ML4Q network in Germany. The GQL also sponsored research-specific student/postdoc exchanges coordinated between members of the US and international partner networks. GQL is also organizing a Quantum Technology Infrastructure Roadmap (QTIR) and plans to have a follow-up Workshop on Quantum Engineering Infrastructure (WQEI2) in 2024.
6. North Carolina Collaborations: To support outreach efforts in rural areas, RTNN collaborates with volunteers from JSNN, part of the SENIC site. Carolina Science Symposium is an annual joint symposium organized by RTNN facilities and staff with considerable collaboration/participation from JSNN (SENIC). RTNN also hosted a booth at the Greensboro Science Center's Science Extravaganza! with the help of 4 JSNN student volunteers. RTNN and JSNN are both active members of the North Carolina Center for Innovation Network (NC COIN). RTNN and SENIC users have used each other facilities, when their tools have been under repair/maintenance, and JSNN staff and users have participated in RTNN and industry co-organized instrument and/or technical workshops. JSNN is a collaborative partner in the DOD Microelectronics Commons Hub "Commercial Leap Ahead for Wide Bandgap Semiconductors (CLAWS)," led by NC State University and RTNN, in the NSF STC "Science

and Technologies for Phosphorus Sustainability Center (STEPS)" led by NC State University, and in the Duke University-led NSF AccelNET program, "International Network for Researching, Advancing, and Assessing Materials for Environmental Sustainability (INFRAMES)."

7. Sharing of best practices:
    a. Regional facility networks have continued and expanded and a working group (led by Ron Olson, CNF) was created to enable sharing of ideas, challenges, and solutions.
    b. Nano Summer Institute for Middle School Teachers (NanoSIMST): This weeklong workshop, originally developed by Stanford, was implemented in 2023 at more than half of NNCI sites, virtually or in-person. Stanford continued to support the in-person programs at SENIC, NNF, and SDNI, and also lead the effort to develop a nationwide virtual NanoSIMST program, which extends the reach to more low resource communities where there is an increased diversity in the student population. Seven NNCI sites (CNS, NanoEarth, RTNN, MiNIC, and NCI-SW, KY Multiscale, SDNI,) sponsored teachers from their local areas.
    c. 4-H Outreach: CNF, NNF, NanoEarth, and MONT are collaborating on 4H outreach initiatives, sharing activities and best practices. Material to engage 4-H Youth already exists within NNCI; using the 4-H mechanism to deliver content and training is a scalable opportunity.
    d. Research and Entrepreneurship Experience for Undergraduates (REEU) seminars (led by Matt Hull).
    e. NNF continued to collaborate with Montana Nanotechnology Facility (MONT) and the Northwest Nanotechnology Infrastructure (NNI) by sharing synchronous lessons and activities and partner contact information, respectively.
8. Participation in SEI Programs:
    a. The SEI program hosted a half day workshop shortly before the NNCI annual conference in 2023 to share best practices, and the SEI leaders at the different sites have met to discuss issues and give each other feedback.
    b. Jamey Wetmore coordinates the efforts of the four primary SEI sites at NC State, Georgia Tech, UT-Austin, and ASU, to maximize the benefits of their work across the network. Each has agreed to develop a program that other NNCI sites, who may have less access to SEI expertise, can plug into. NC State and Georgia Tech are both developing complementary toolkits for assessing the impacts of NNCI sites, UT-Austin will be hosting and sponsoring an SEI engagement workshop designed to help get participants from across the NNCI up to speed on SEI efforts, and ASU is redesigning the Science Outside the Lab program to train each participant as SEI ambassadors who can take what they've learned in the program back to their home institutions.
9. NCI-SW, RTNN, NNF, SDNI, nano@stanford, and SENIC participate in the Nanotechnology Applications and Career Knowledge (NACK) Network's Remote Access Instrumentation in Nanotechnology (RAIN) coordinated by Penn State University.
10. Several sites (ASU, Georgia Tech, and UC San Diego) collaborated with Penn State's Nanotechnology Applications and Career Knowledge (NACK) in the Microelectronics and

Nanomanufacturing for Certificate Program. Designed specifically for US military personnel and veterans, this program was funded by an NSF Advanced Technological Education (ATE) grant. The program is developing and offering a 12-week program, where each site provides laboratory access to students from a local community/technical college.

11. Several sites participate in education programs and meetings organized by MNT-EC (Micro Nano Technology Education Center), NACK (Nanotechnology Applications and Career Knowledge) network, and MNTeSIG (Micro Nano Tech Education Special Interest Group).
12. Activities in computation, modeling and simulation have been organized by Coordinating Office Associate Director Azad Naeemi (SENIC) in collaboration with faculty at NCI-SW, TNF, and other NNCI sites.

Site Activity on Behalf of the NNCI

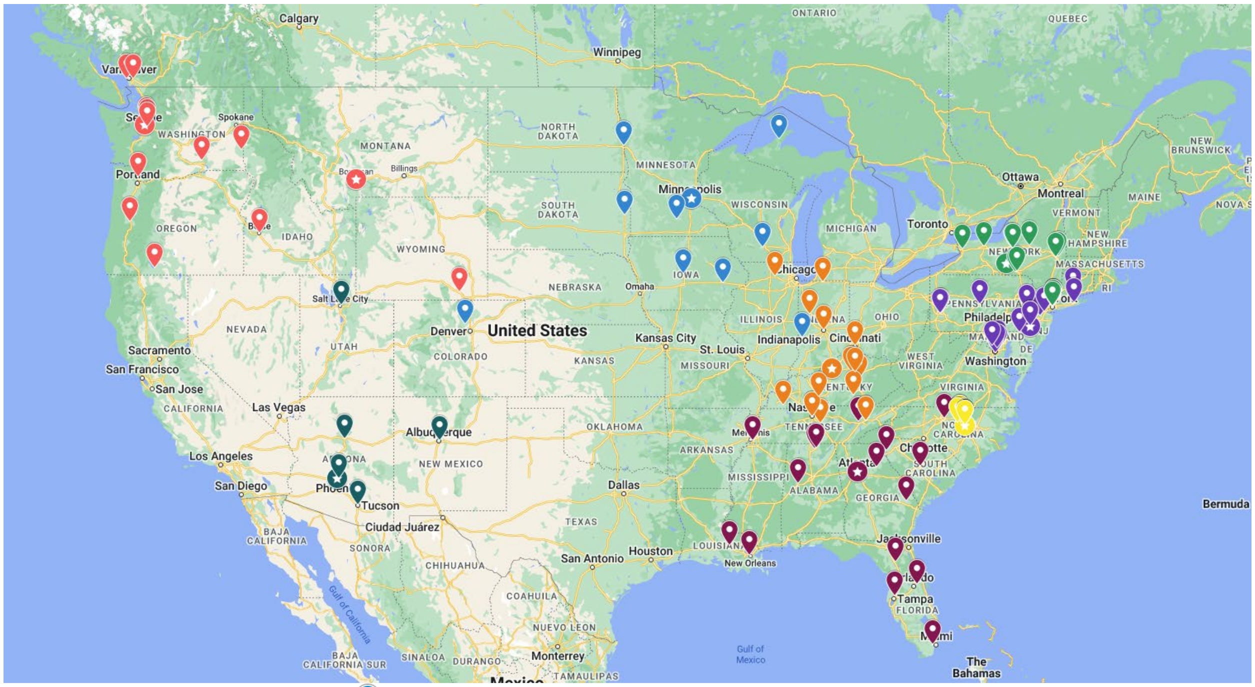
1. CNF publishes "Nanooze", and, in addition to direct distribution to classrooms, distributes it to all NNCI sites for use in their outreach activities.
2. Georgia Tech (SENIC) maintains the current NNCI website. RTNN receives requests from the Spanish language "Contact Us" form and responds to all inquiries made via this method.
3. CNF manages the iREU program that affords a second-year research experience abroad from among the highest rated REU interns from the previous summer.
4. CNF organizes the iREG program, which provides for graduate students from Nanotechnology Platform Japan to spend time in NNCI labs during a summer research experience.
5. NanoEarth continued its partnership with radio producer Jim Metzner who produced a NanoEarth-sponsored "Pulse of the Planet" long form podcast for the eighth year. To date, 61 NanoEarth-sponsored shows have been produced. These episodes are built for public consumption and highlight the most interesting projects from external users, impactful research at other NNCI sites, and local site researchers, with those individuals personally interviewed for each episode. A new episode featuring Dr. Michael Hochella discussing the potential use of engineered nanoparticles in ocean fertilization for large-scale atmospheric carbon dioxide removal was released in April 2023. "Pulse of the Planet" is heard on over 265 NPR radio stations by 1.1M listeners per week and is available as a podcast on Stitcher and iTunes.
6. Tonya Pruitt (NanoEarth) collaborated with Jessica Hauer (NCI-SW) to lead the Innovation and Entrepreneurship Working Group's Economic Impact Survey in 2023. Initial survey responses demonstrate the positive impact that access to NNCI-supported facilities have on industrial users. The survey is still ongoing, and a report will be prepared after its conclusion.
7. Hosting of NNCI REU Convocation by MONT (August 2023)
8. nano@stanford took the lead organizing and implementing the 2023 Workshop on Nanotechnology Infrastructure of the Future. The workshop was chaired by Debbie Senesky (nano@stanford), and co-chaired by David Gottfried (SENIC), Yuhwa Lo (SDNI), and Sara Ostrowski (nano@stanford). The organizing committee was comprised of faculty and staff from seven additional NNCI sites (MONT, NanoEarth, NNI, RTNN, MiNIC, CNS, and NCI-SW). The event was widely attended by the NNCI network, as well as external participants, with a total of nearly 300 virtual and in-person participants. The committee also

collaboratively drafted a white paper with recommendations for the next national nanotechnology infrastructure resource which was provided to NSF.

9. Hosting of NNCI Annual Conference by nano@stanford (October 2023). Planning activities included arranging logistics, soliciting sponsors, creating communications materials, and developing technical content. In addition, S. Ostrowski (nano@stanford) and M. Hull (NanoEarth) created a special topic session on technology translation and entrepreneurship,
10. KY MMNIN hosts the UGIM website and several NNCI staff are members of the UGIM Steering Committee (Aebersold (KY Multiscale), Cibuzar (MiNIC), and Tang (Stanford)).
11. Daniella Duran (nano@stanford) presented at and provided organization support for the NNCO-Nanoeducators Forum. She also coordinates the network-wide list for educators called "NNCI Educators" to highlight nano resources across the network and beyond to K-14 educators.
12. Washington Nanofabrication Director Dr. Maria Huffman (NNI) is a member of the external advisory board of Myfab (www.myfab.se), the Swedish Research Infrastructure for micro and nanofabrication.
13. Steve Wignall (NNF) attended a meeting conducted by the QED-C to help develop ideas to increase employees in the Quantum Workforce.
14. Mikkel Thomas (SENIC) meets monthly with Jared Ashcroft, Director of the NSF-supported Micro Nanotechnology Education Center, to discuss mutual interests.
15. David Gottfried (SENIC) has a monthly meeting with the Director and Associate Director of the National Nanotechnology Coordination Office.

10.2. Regional Facility Networks

Initiated by efforts at MiNIC and MANTH, a number of sites within the NNCI have established informal networks of regional fabrication and characterization facilities to provide mutual assistance, develop best practices, and provide staff networking opportunities. The map below (Figure 19) shows the updated geographic distribution and regional clustering of these networks, along with a brief description of each. The Ohio Valley Nano+AM Regional Network was newly added in 2023. During 2023, a new working group to communicate and share best practices among those sites which support regional networks was formed and has begun meeting (Section 6.4).



Northern Nano Lab Alliance (NNLA)

Southeastern Nano Facility Network (SENFN)

Southwest Nano Lab Alliance (SW-NLA)

Northwest Nanotechnology Laboratory Alliance (NWNLA)

Ohio Valley Regional Network

Mid-Atlantic Region Cleanroom Managers Workshop

RTNN Affiliates Network

New Yok State Nanotechnology Network (NNN)

Figure 19: NNCI Regional Facility Networks

MiNIC: The **Northern Nano Lab Alliance (NNLA)** is a regional network of university fabrication facilities. Its mission is to help each member improve their support of academic research in applied nanotechnology.

SENIC: The **Southeastern Nano Facility Network (SENFN)** was created in 2018 as a regional network of nanoscale science and engineering user facilities located in the SE United States. The objectives of this network are to share information on capabilities and events at each facility, discuss best-practice solutions to common challenges, and begin a process for informal staff-level technical exchanges.

MANTH: The **Mid-Atlantic Region Cleanroom Managers Workshop** began as a gathering of lab managers from the academic and government cleanroom facilities located in the triangle formed between Washington DC, Brookhaven National Laboratory in NY, and Pittsburgh, PA. The Singh Center for Nanotechnology Quattrone Nanofabrication Facility staff at MANTH created these semi-annual meetings in 2016 to share best practices for research cleanroom operations throughout the region.

NCI-SW: The **Southwest Nano-Lab Alliance (SW-NLA)** will disseminate best practices in cleanroom management, equipment purchasing/maintenance, and user training across the partner schools across the southwest. The association will meet annually for a one-day workshop that will rotate amongst the participating labs. The workshop will bring together at least two participants from each lab to discuss best practice for managing cleanrooms and associated multi-user facilities, on-going challenges, and future opportunities.

NNI and MONT: The **Northwest Nanotechnology Laboratory Alliance (NWNLA)** is a joint effort between the NNI and MONT sites to create a regional platform for exchange of laboratory experiences and best practices. Members of NWNLA include nanotechnology facilities in Idaho, Montana, Oregon, Washington, Wyoming, Alberta and British Columbia.

RTNN: The **RTNN Affiliates Network** connects RTNN facilities with other nano-focused university and government facilities in the Triangle. The goals of Affiliates Network are to (1) allow regional facility managers/directors to more readily connect researchers to complementary facilities needed to complete their nanotechnology research, (2) enable facility leadership and staff from across the Triangle to communicate timely information efficiently and effectively about instrumentation and other opportunities, and (3) develop strategic partnerships on emerging opportunities and technical needs that support the facilities or user base.

KY Multiscale: The **Ohio Valley Regional Network** is a coordination of universities, colleges, and community colleges in the Midwest region of the US with state-of-the-art research and educational facilities in the converging fields of micro/nanotechnology and additive manufacturing (AM). The purpose of the network is to exchange information on facilities operation and to highlight the exciting research occurring at each location. The signature event of the network is its annual NNCI Nano+Additive Manufacturing Summit which is held in Louisville in the summer.

CNF: The **New Yok State Nanotechnology Network (NNN)** is focused on bringing together NY state universities and industry to help build local relationships, solve common problems, and grow awareness of the state's capabilities as they pertain to micro and nanotechnology. This network allows universities/colleges and industry to partner and expand technology skills and capabilities while providing synergies that are strengthening technology and the workforce in New York state.

10.3. NNCI Seminar Series

While initially created in 2021 to share technical content about computation, modeling, and simulation with the greater NNCI community, the NNCI Seminar Series quickly expanded to a semi-monthly series with speakers selected by the Coordinating Office Associate Directors to highlight their specific topical areas. Information about the videos is shared with NNCI sites, posted on the NNCI website, and disseminated on social media as well as by external organizations such as the NNCO. Typical attendance during the live events in 2023 averaged around 25 (range:8-57). Video recordings are then posted on the NNCI YouTube channel (see below). The schedule of 2023 seminars is provided in Table 11.

Table 11: NNCI 2023 Monthly Seminars

Date (Topic*)	Speaker(s)	Affiliation	Title
February 15 (C)	Prof. Evgeny Tsymbal	Univ. Nebraska-Lincoln	"Antiferromagnetic Tunnel Junctions for Spintronics"
April 19 (E)	Quinn Spadola, Deputy Director	National Nanotechnology	"The NNCO: Supporting the NNI (That Means You)"

		Coordination Office	
May 3 (I)	Hannah Murnen, Managing Director, Activate Anywhere Karin Lion, Chief Growth Officer Austin Hickman, Activate Fellow	Activate	"Activate Fellowships – Empowering Scientists and Engineers to Bring Their Research to Market"
May 24 (S)	Moriah Locklear, Federal Research Engagement Manager, Arizona State University in Washington, DC Stephanie Mitchell, CCST Science Policy Fellow, California Assembly Committee on Water, Parks, and Wildlife Sawyer Morgan, Research Scientist, New Jersey Board of Public Utilities Community Solar Program Jacob O'Connor, Assistant Consultant, California Senate Committee on Transportation		"Scientists and Engineers in State Governments"
August 23 (C)	Eric Guichard, SVP and GM of TCAD	Silvaco	"Silvaco Technology CAD, Background, Overview & Future"
November 16 (C)	Prof. Stephen Goodnick	Arizona State University	"Particle Based Simulation of Wide Bandgap Devices"

*C=Computation, S=SEI, E=Education, I=Innovation

10.4. NNCI YouTube Channel

The NNCI YouTube Channel was created in April 2018 to host the NNCI Introduction Video created that year. During 2021, the channel was expanded to include additional Playlists for Education Videos, Seminar Series, and Training Videos. Education videos include careers in nanotechnology content created by Jim Marti (MiNIC) and Matt Hull (NanoEarth), which are public, as well as an RET information session (which is unlisted, but used by the RET program). The NNCI seminar series (see above) videos since May 2021 are all archived on the channel and are public. Finally, the Training Video playlist was created for future content and currently holds a video on Evaporative Deposition (unlisted) which is being tested internally. Overall, the channel has 260 current subscribers (nearly 100 new added in 2023) and 2,680 views during 2023, less than that in 2022. Analytics of the top video content during 2023 is shown in Table 12 below, with newly-added videos in bold. Since the start of the channel, there have been more than 9,000 total views with the top 5 videos including those discussing careers, "What is the NNCI", and computation videos from Shela Aboud (Synopsys) and Dragica Vasileska (ASU).

Table 12: NNCI YouTube Video Analytics (2023)

Video*	Views	Average View Duration
Careers in Nanotechnology: Opportunities for STEM Students (Jim Marti, MiNIC)	690	2:58 (21.8%)
The Evolution of Process TCAD in Semiconductor R&D and Manufacturing (Shela Aboud, Synopsys)	370	5:41 (9.6%)
What is the NNCI?	232	1:28 (40.4%)
Antiferromagnetic Tunnel Junctions for Spintronics" (Evgeny Tsymbal, Univ. Nebraska-Lincoln)	**210**	**5:07 (8.0%)**
X/Nano: The Enabling Potential of a Career in Nanoscience (Matt Hull, NanoEarth)	201	5:28 (18.8%)
Silvaco Technology CAD, Background, Overview & Future" (Eric Guichard, Silvaco)	**171**	**3:37 (6.4%)**
Activate Fellowships – Empowering Scientists and Engineers to Bring Their Research to Market (Panel)	**134**	**2:37 (4.4%)**
Simulation Software Next Door (Dragica Vasileska, ASU)	81	5:24 (8.8%)
Scientists and Engineers in State Governments (Panel)	**64**	**4:25 (7.3%)**
Theoretical Exploration of Energy Efficient Spintronics Devices (Tony Low, Univ. Minnesota)	61	4:28 (6.8%)

*Videos added in 2023 are bolded.

10.5. NNCI Outstanding Staff Awards

During 2023, the NNCI Coordinating Office organized the sixth year of the "Outstanding NNCI Staff Member" awards. This award acknowledges the significant efforts by NNCI site staff who endeavor to provide excellent service and support to all network users in three categories: Technical Staff, Education and Outreach, and User Support. In June 2023 nominations consisting of a 500-word narrative were solicited from site directors (maximum of one nomination in each category) and these were reviewed by the NNCI External Advisory Board. Nominations were evaluated based on the individual's activities that align with site/NNCI goals of providing facility access and/or education and outreach, as well as their impact on their own site and the NNCI network. Each winner received an engraved desktop plaque and was recognized at the 2023 Annual Conference, with travel support provided to attend. Some awardees from 2020-2022 were also recognized at this event.

Education and Outreach

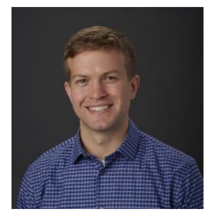
- Emily Moreno-Hernandez (Program Coordinator, Duke University, RTNN)

"... exceptional leadership and contributions to the Duke and RTNN Outreach team over this past year has led to significant growth in the number of outreach activities and participating students, educators, and researchers…"

- Heather Rauser (Program Director, Montana State University, MONT)

"…led our MONT/Empower Scholars program… serving students underrepresented in engineering)… making a difference in these students' lives."

Technical Staff



- Andrew Lingley (Montana Microfabrication Facility Manager, Montana State University, MONT)

"Andy really is the heart, soul and face of the MMF, having built an ethos of service excellence throughout the facility…established a culture of regular and open communication between the staff, users and stakeholders, emphasizing customer service as the top priority."

- Jim Marti (Senior Scientist, University of Minnesota, MiNIC)

"... highly involved in the conception and set up (of NanoBio and Nanomaterials Laboratories) as a broader initiative to support the fields of life sciences in a way that integrates their capabilities with the fabrication facilities of the MNC."

User Support

- Amar Kumbhar (Research Associate, UNC-Chapel Hill, RTNN)

"…broad knowledge of characterization techniques, material types, and specimen preparation techniques has enables him to interface with and provide exceptional support to a wide range of institutions and departments, thereby facilitating convergence in the RTNN."

- Karlis Musa (IT Engineer, Cornell University, CNF)

"... demonstrates continual commitment to the NNCI goals by providing state-of-the-art technology and hands-on education for a diverse group of academic and industry users from around the world."

11. NNCI Network Usage

Individual NNCI site performance, and that of the network as a whole, can generally be assessed based on four major criteria: (1) ability to serve the greatest number and broadest set of researchers from academia, industry, and government, while keeping in mind site's capabilities and focus, (2) impact on the research enterprise and its economic importance in the commercial realm, (3) societal impact based on improved public awareness, diversity, and workforce development for nanoscale activity, and (4) contributions of sites to the NNCI network. Given these broad criteria, each site determines the set of metrics for their annual site report to NSF that best fit their own technical specialization (if any), regional user base and commercial interests, and any partnership arrangements. A non-exhaustive list of examples of potential metrics, many based on experience from NNIN, has been provided in previous reports.

NNCI sites collect statistical data about their users in an effort to assess the strength and success of the internal and external user programs. Research disciplines can be used to help track usage in non-traditional areas. Productivity is implied from annual assessment of user research publications, patents, and presentations that rely on use of the shared facilities and the research budgets enabled. It is more difficult to quantify the productivity of industrial usage, where publications are not the norm, but data on numbers of start-up companies, their financial well-being, patent applications and personnel hiring can be used as indirect measures. In addition, sites may decide to conduct regular user and/or PI satisfaction surveys as a means of assessing site quality and making adjustments to operations as needed (see Section 8.3 above). Education and outreach evaluation plans will provide assessments to guide program improvement as well as impact and effectiveness of programs. Finally, each site's contributions to creating a unified network that surpasses the sum of its parts can be assessed by participation of site personnel in network activities (see Section 10 above).

That being said, it is important that a common set of data for the NNCI network sites, as well as aggregated data for the network as a whole, be regularly collected. The NNCI Coordinating Office has established a *Metrics and Assessment Subcommittee* that has agreed upon a common set of site and network metrics, and the collected data are consistent with the user statistics developed under the NNIN program. The following are the definitions provided to all sites for creating a uniform set of metrics.

1. An on-site user is someone who physically comes to a site facility (or partner facility) to access the tool set. A remote user is someone who contracts to have processing and/or characterization done for them by site staff. In general, there should only be one remote user for any given piece of work. Faculty (both internal and external) and industry PIs, unless they actually do hands-on work themselves, should not be counted as users – only the students/researchers who do the work are users. Site staff should not be counted as users, unless they have a dual role and act as a student/researcher as well. All included facilities are OPEN, SHARED, USER facilities, where the tools are available to all researchers (internal and external) for hands-on use. Purely service facilities or individual PI labs should not be included. It is also important to not count users more than once for using multiple facilities of a single NNCI site. In short, every user in the cumulative user count corresponds to a single, unique individual. Even though summer interns/REU students are typically paid with internal funding and working on internal projects, these users are counted as EXTERNAL users as their home institution is another university/college, which is the primary factor that governs affiliation.

2. Stats are broken down by Affiliation, meaning the type of institution, and Discipline, meaning the area of research. Local Site Academic refers to users who are either students or employees of a site (or its partners). All other Affiliations are for external users. A Small Company is defined as one with <500 employees. Disciplines are often self-selected by the user, or perhaps by site staff. In the Discipline category "Educational Lab Use" is NOT intended to count students in a regular university class which uses the NNCI site facilities. Rather, this category is applied to users who attend workshops or short courses, created as part of a sites NNCI education and outreach, where hands-on work (attendees actually go into the lab) is part of the program.
3. Lab Time refers to actual time in the cleanroom OR tool time for all users during a given month. These should not be double counted. In other words, if a student is using multiple tools in the cleanroom, only the time in the cleanroom should be used. If a student is outside the cleanroom, but a process is still running, the tool time can still be counted. Most characterization tools, outside the cleanroom, are counted as straight tool usage time. For cases when users are logged into a cleanroom tool, but he/she is not inside the cleanroom (for example, during extended furnace runs), tool time is recorded.
4. Monthly Users are the total number of unique individuals who access a site in a given month. In this case, the total number may be different than the sum of On-Site + Remote if a user accesses the site via both methods in a given month.
5. Cumulative Users is the running total of all users since the beginning of the NNCI year on October 1. Each year on October 1, the cumulative count starts over with all users counted again.
6. Fees data are the revenue from all user fees for use of a site's facilities. This data does not include indirect charges (if they are assessed). If a site uses a cap on charges after a certain hour limit, only the actual fees charged are reported, but the actual hours used over the cap limit are reported in Lab Time.
7. New Users Trained refers to those users who are first time users (and typically attend a site's orientation program) in that month. In this section all users should only be included ONE TIME during the entire life of the NNCI program.

11.1. NNCI Aggregate User Data (Oct. 1, 2022 - Sept. 30, 2023)

Since each site provides its own usage data as part of their annual report and a subset of this data is provided in the site reports below (Section 12), we have not included exhaustive sets of individual site data here, but rather the aggregate for the NNCI network. In Table 13 below, we provide the NNCI totals, along with the average for the 16 sites, as well as the minimum and maximum values for the sites as an indication of the wide variation among the sites.

Table 13: Summary of NNCI Aggregate Usage Data (Year 8)

	NNCI Network	NNCI Sites Mean (Min - Max)
Unique Facility Users	13,722	858 (250 – 1,781)
Unique Internal Users	10,079	630 (183 – 1,528)
Unique External Users	3,643 26.6%	228 (67 – 579) 26.8% (14.2% – 50.1%)
External Academic	1,300	81 (13 – 313)
External Industry	2,044	128 (23 – 376)
External Government	238	15 (0 – 149)
External Foreign	61	4 (0 – 27)
Average Monthly Users	5,296	331 (68 – 815)
New Users Trained	5,115	320 (12 – 754)
Facility Hours*	1,095,931	68,496 (9,548 – 200,070)
Facility Hours – External Users	256,767 23.4%	16,048 (1,667 – 66,198) 22.8% (7.4% – 49.1%)
Hours/User*	78	74 (33 –144)
User Fees Internal Users External Users	 $26.0M $19.7M	 $1.63M $1.23M

*Hours were collected as lab usage hours (time in the cleanroom), tool usage hours (when operated while not in the cleanroom), and tool usage hours for non-cleanroom tools. While we have conveyed this definition to the sites (see above), we have not attempted to standardize the data collected.

The data ranges presented above also need to be considered with some nuance and context as to the nature of the individual sites and their sometimes unique roles within NNCI. As has also been discussed previously, sites with large numbers of internal users and total users may have a lower external user percentage while still serving large external user populations.

A comparison of the network aggregate usage data for Years 1-8 is shown in Table 14 below. As can be seen, most metrics show modest percentage increases from Year 7 to Year 8. Of course, this needs to be taken with the context that some site facilities are still recovering from reduced operations and usage due to the COVID-19 pandemic, particularly with external academic users. In fact, many metrics have increased to the levels seen in Year 4, just prior to the pandemic and the "best" year for NNCI. The exception to this recovery remains the level of external usage, with these users in Year 8 still approximately 5% lower compared to Year 4, and even more specifically in the external academic user metric, which remains 15% lower than Year 4. We can speculate that the return to normal operations is easier for internal users who have the benefit of proximity to their home facilities that external users do not. Still, it is encouraging that external usage has continued to grow since Year 4, just not at the same pace as internal users. The changes in internal and external users and usage hours over the first seven years of NNCI are illustrated in Figures 20 and 21. These further illustrate the slight improvements in Year 8 compared to Year 7, and the slower rate of usage growth since the pandemic recovery when compared to the first four years of NNCI. Finally, it should be noted that, with the start of the second 5-year funding period, i.e. in Year 6, a few facilities have been dropped and others have been added to the network sites (see Section 1.2).

Since re-opening of NNCI facilities during the June-August 2020 timeframe, sites have continued to grow operations so that they are near normal (pre-pandemic) usage capacity, with no limits on external usage and regular training opportunities. The effects of the pandemic are most striking for external users (and training). Nevertheless, the fraction of users and hours from external sources, 27% and 26% respectively, remained relatively constant over the course of Year 5 compared to Year 4 (see Table 14) but showed a slight decline in Year 6 (25% external users and external hours), the first full 12-month pandemic period, and remained reduced (25% external users and 24% external hours) in Year 7 before showing signs of recovery in Year 8.

Table 14: Comparison of Years 1-8 NNCI Aggregate Usage Data

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	ΔYear 7 - 8
Unique Facility Users	10,909	12,452	13,110	13,355	10,501	11,242	13,348	13,722	+2.8%
Unique Internal Users	8,342	9,276	9,731	9,503	7,668	8,449	9,967	10,079	+1.1%
Unique External Users	2,567 23.8%	3,176 25.5%	3,379 25.8%	3,852 28.8%	2,833 27.0%	2,793 24.8%	3,381 25.3%	3,643 26.6%	+7.8%
External Industry Users	1,413	1,669	1,870	1,961	1,529	1,619	1,882	2,044	+8.6%
External Academic Users	1,060	1,295	1,365	1,531	1,064	964	1,238	1,300	+5.0%
Average Monthly Users	4,429	4,911	5,001	5,292	3,654	4,381	5,112	5,296	+3.6%
New Users Trained	4,116	4,563	4,981	5,194	2,813	4,414	5,151	5,115	-0.7%
Facility Hours	909, 151	939,230	1,006,764	1,149,788	767,255	967,297	1,072,332	1,095,931	+2.2%
Facility Hours – Ext Users	173,511 19.1%	191,494 20.4%	228,441 22.7%	298,986 26.0%	197,368 25.7%	242,926 25.1%	253,667 23.7%	256,767 23.4%	+1.2%
Hours/User	83	75	77	86	73	86	80	78	-2.5%
User Fees									
Internal	$20.6M	$23.0M	$23.6M	$23.2M	$16.3M	$21.9M	$24.4M	$26.0M	+6.6%
External	$13.5M	$14.5M	$16.9M	$20.5M	$13.1M	$17.8M	$20.1M	$19.7M	-2.0%

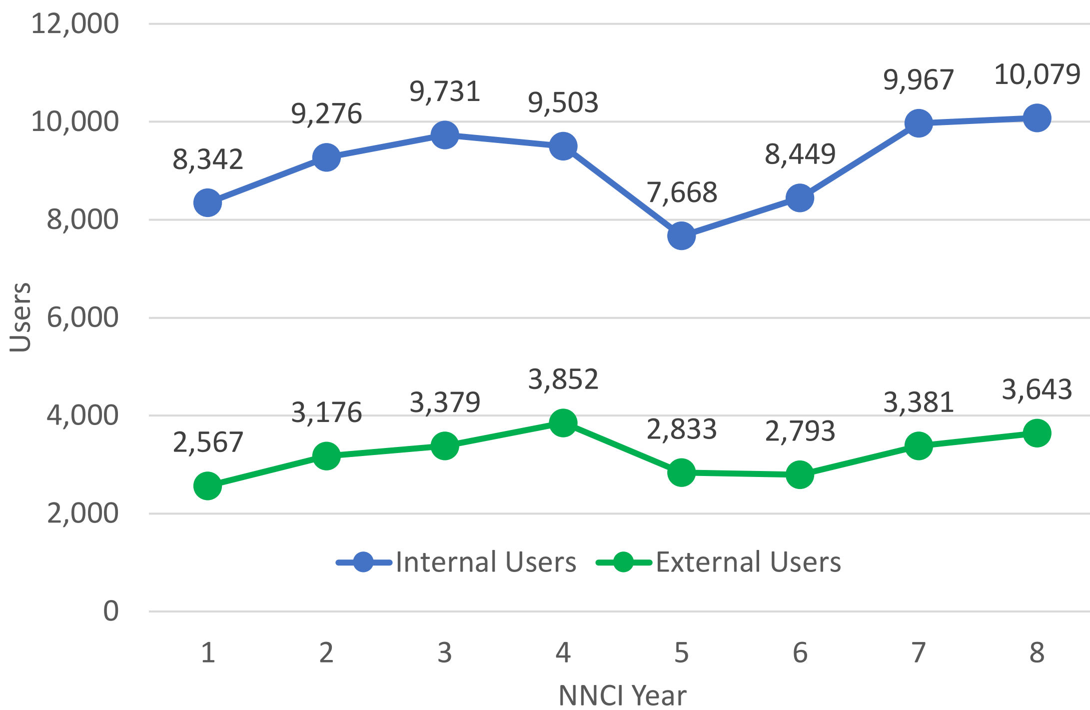


Figure 20: NNCI Users by Year

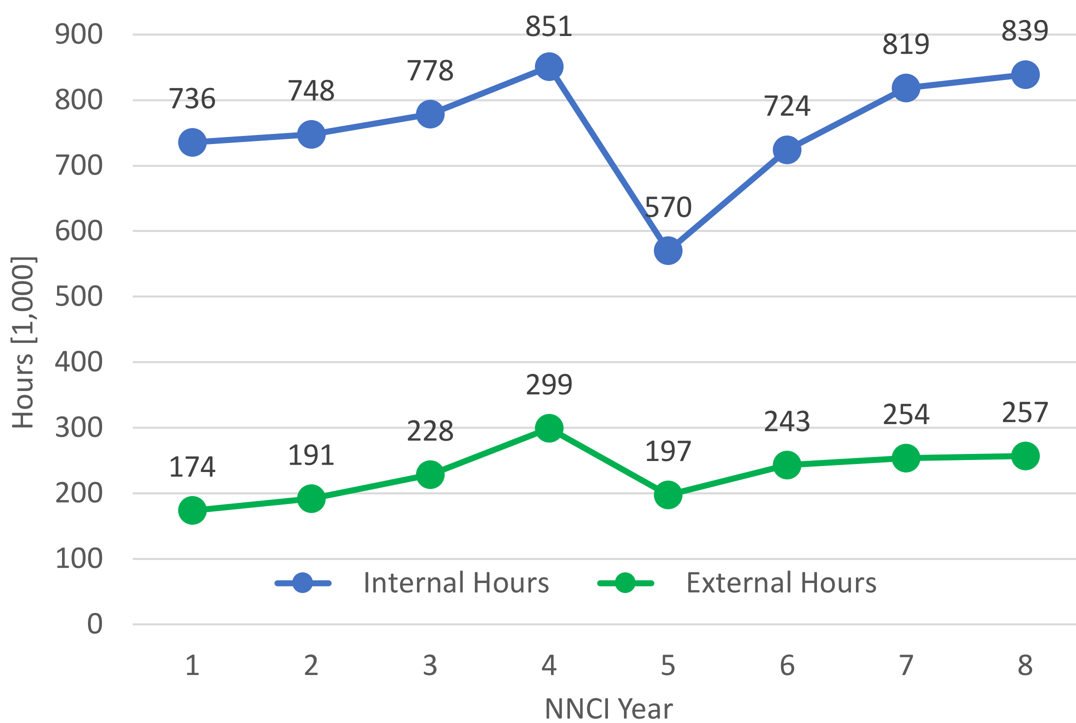


Figure 21: NNCI Usage Hours by Year

A deeper analysis of the annual usage growth, the effects of the pandemic closures, and recovery of usage is explored in the figures below. Figures 22 and 23 show the Years 4-8 monthly change in cumulative users and lab time, respectively, across all NNCI sites. It is clear that usage at the beginning of Year 5 was on a pace to match or exceed that of Year 4, but plateaued suddenly when facilities were shut down in March 2020 and only began to recover partially beginning in June 2020. The number of users began Year 6 at a lower level and grew over that year at a slightly reduced pace and were unable to reach pre-pandemic totals. However, in Year 7, total cumulative users matched that of the pre-pandemic period and growth continued with a 3% increase in Year 8. Recovery in usage hours also appears robust, although not complete, with a 5% decrease in Year 8 total hours compared to Year 4. The effect on cumulative external usage is further illustrated in Figure 24 which shows the percentage of cumulative external users by month for Years 4-6. This figure indicates that in Year 4 (and previous years) the fraction of external users increases throughout the year, with an enhanced rate during the summer months likely benefited by REU students and other summer researchers. During Year 5, of course, this summer effort was curtailed and the overall decrease in external usage is obvious. This effect has continued into Years 6-8.

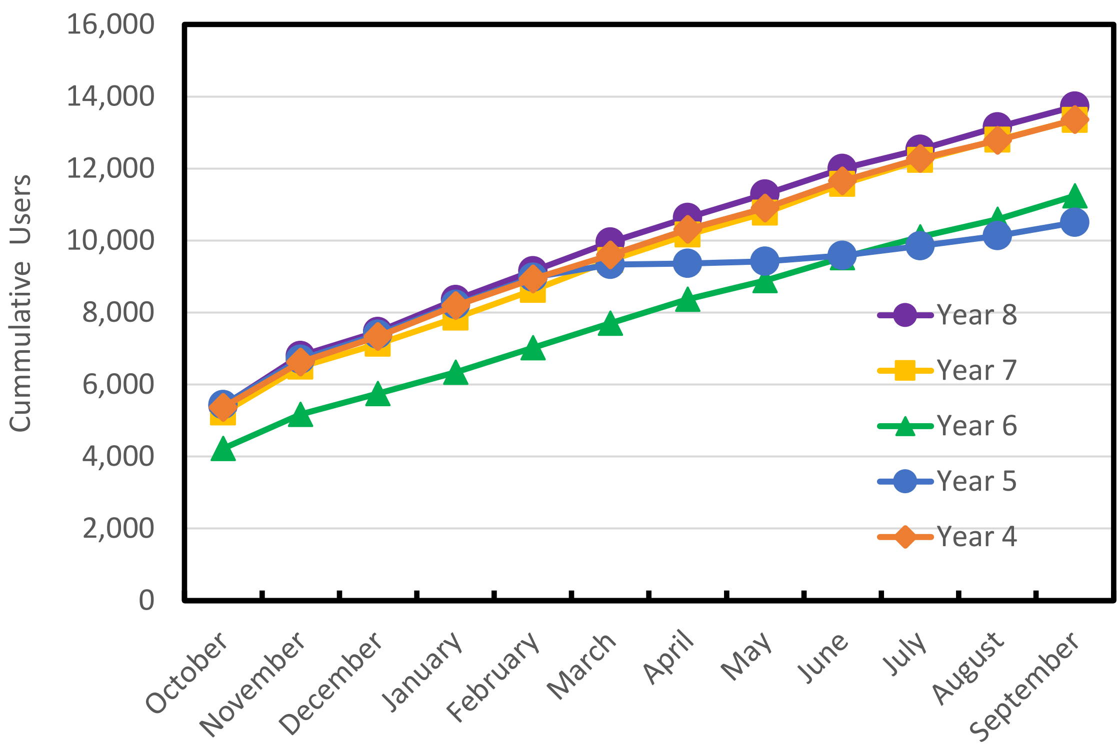


Figure 22: NNCI Cumulative Total Users by Month for Years 4-8

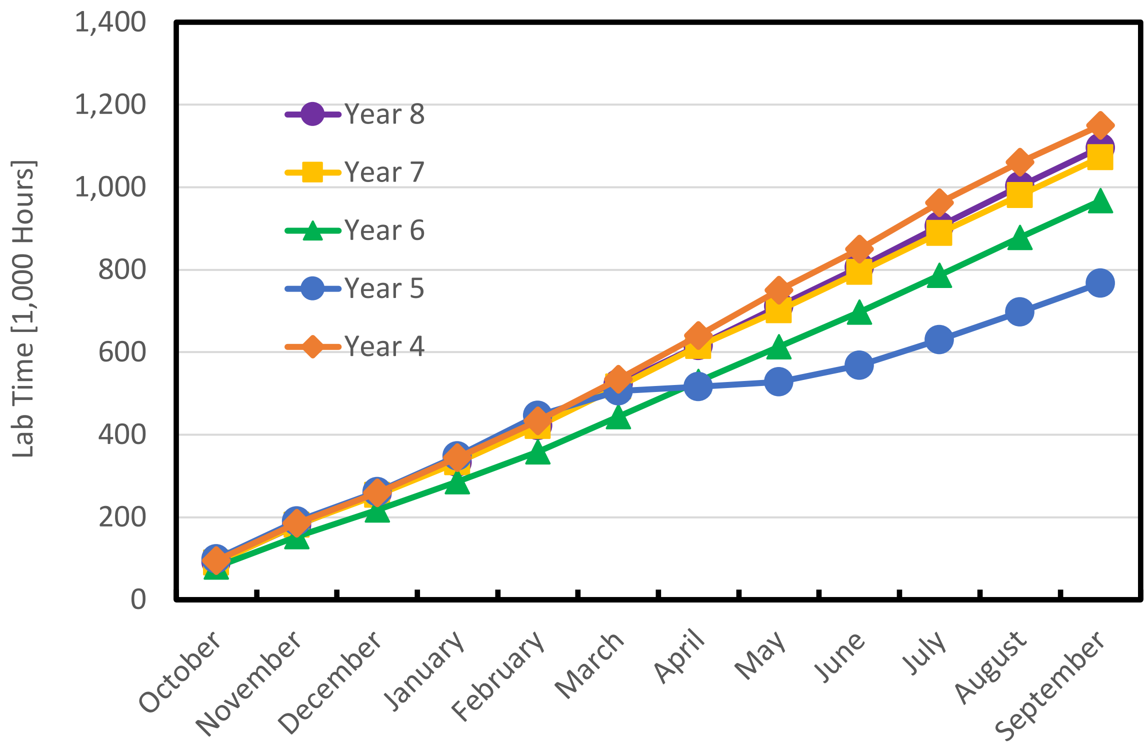


Figure 23: NNCI Lab Usage Time (1,000s of Hours) by Month for Years 4-8

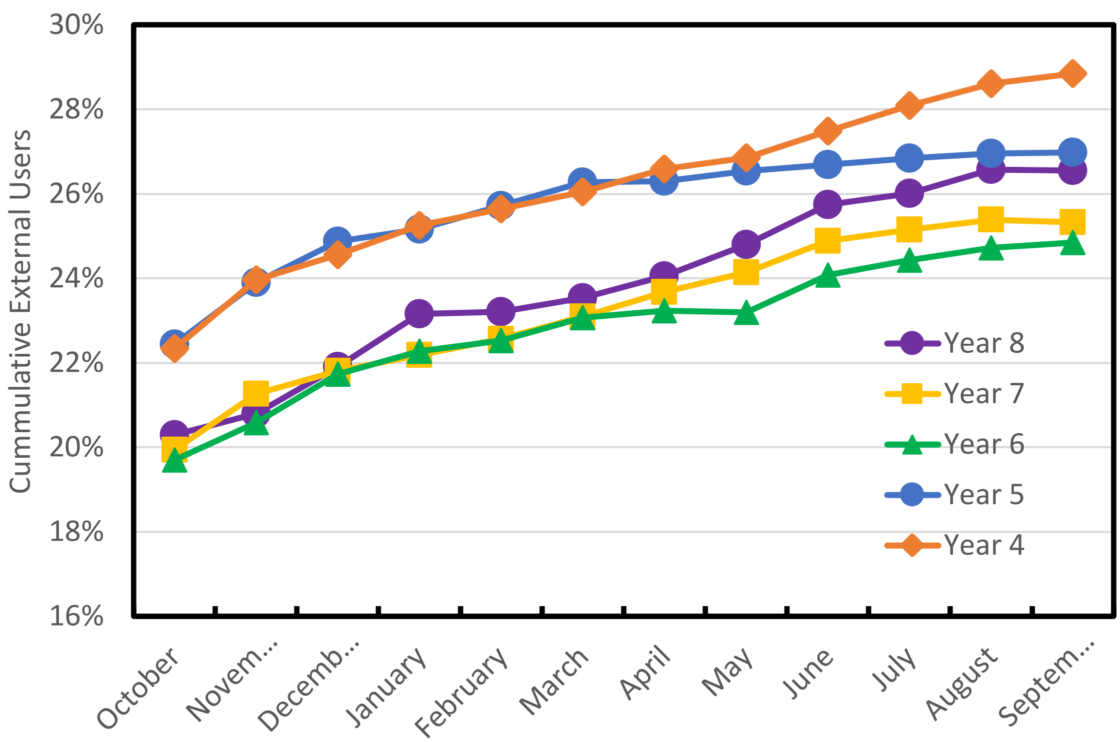


Figure 24: NNCI Cumulative External Users (%) by Month for Years 4-8

As can be seen in the figures above, at the start of Year 6 the overall external usage started off lower than pre-pandemic and failed to recover fully even with robust month-over-month increases. While in Year 7 the total usage achieved near full recovery, external usage continued to be depressed, and this was the case in Year 8 as discussed above. These differential pandemic effects on usage are amplified in Figures 25 and 26, which shows the number of monthly internal and external users across the NNCI, and indicates that, during NNCI Years 7 and 8, monthly internal users reached values seen in Year 4 and the beginning of Year 5. Monthly external users at the end of Year 8 have returned to 95% of pre-pandemic levels, although they started the year at 9% below so improvement over the 12 months was observed, continuing the trend seen last year. Monthly internal users in Year 8 averaged 4,168 which is 2% better than the Year 4 average (4,102), while monthly external users in Year 8 averaged 1,127, which is 5% less than the Year 4 average (1,190) but 7% improved compared to last year.

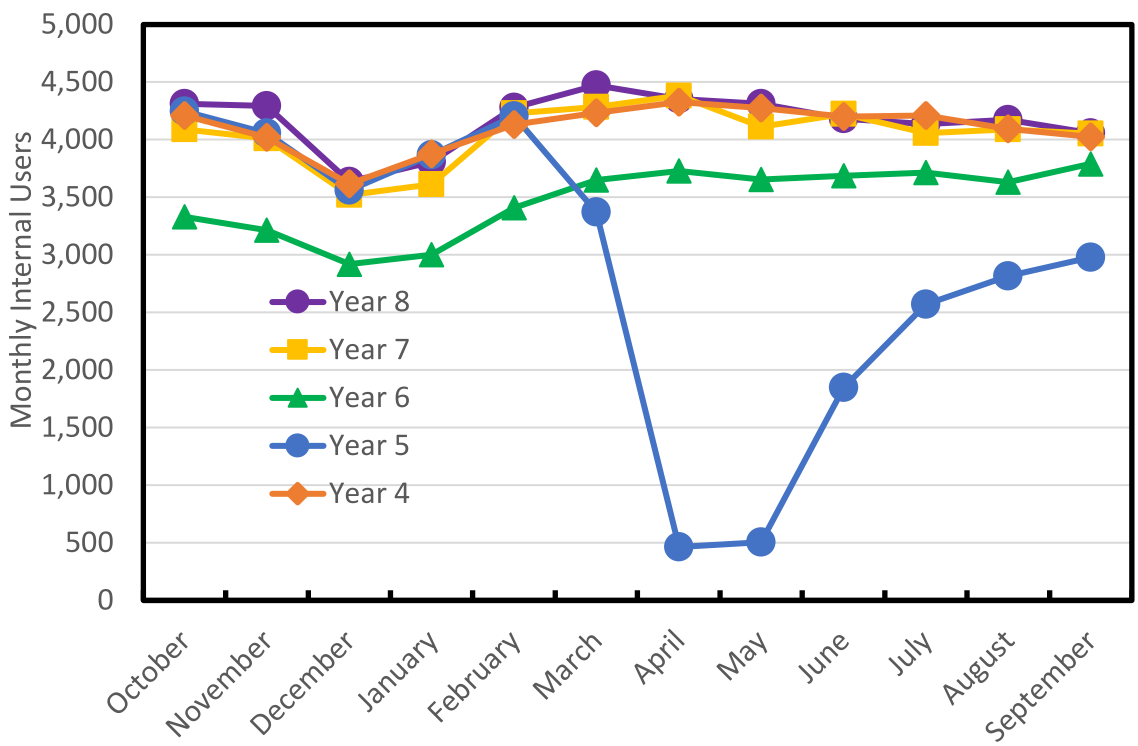


Figure 25: NNCI Monthly Internal Users for Years 4-8

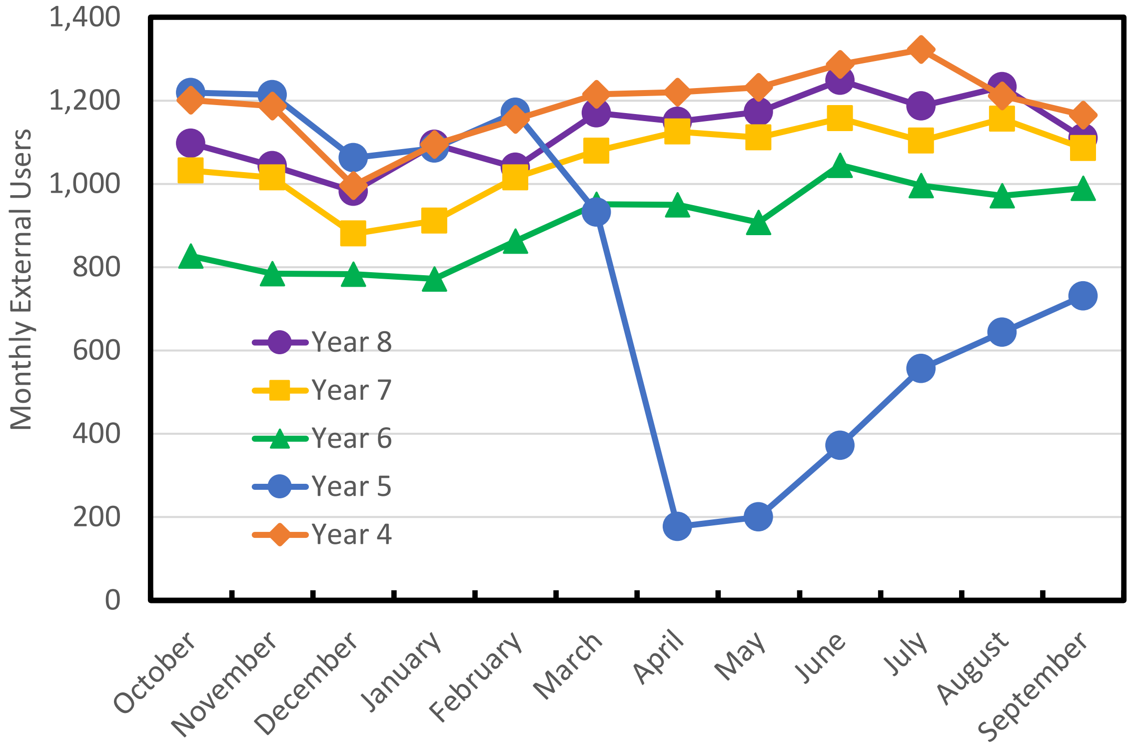


Figure 26: NNCI Monthly External Users for Years 4-8

Finally, the pandemic accelerated a shift to remote usage as can be seen in Figures 27 and 28 for remote users and hours, respectively, begun in Year 6 and continued in Year 7. The assumption is that this mode of access, while more costly for users and labor intensive for facilities, avoided the hurdles associated with travel and training. What can now be seen is that the remote access modality for Year 8, in terms of both users and hours, has returned to pre-pandemic levels, especially for remote hours which is well below what was typical in Year 4.

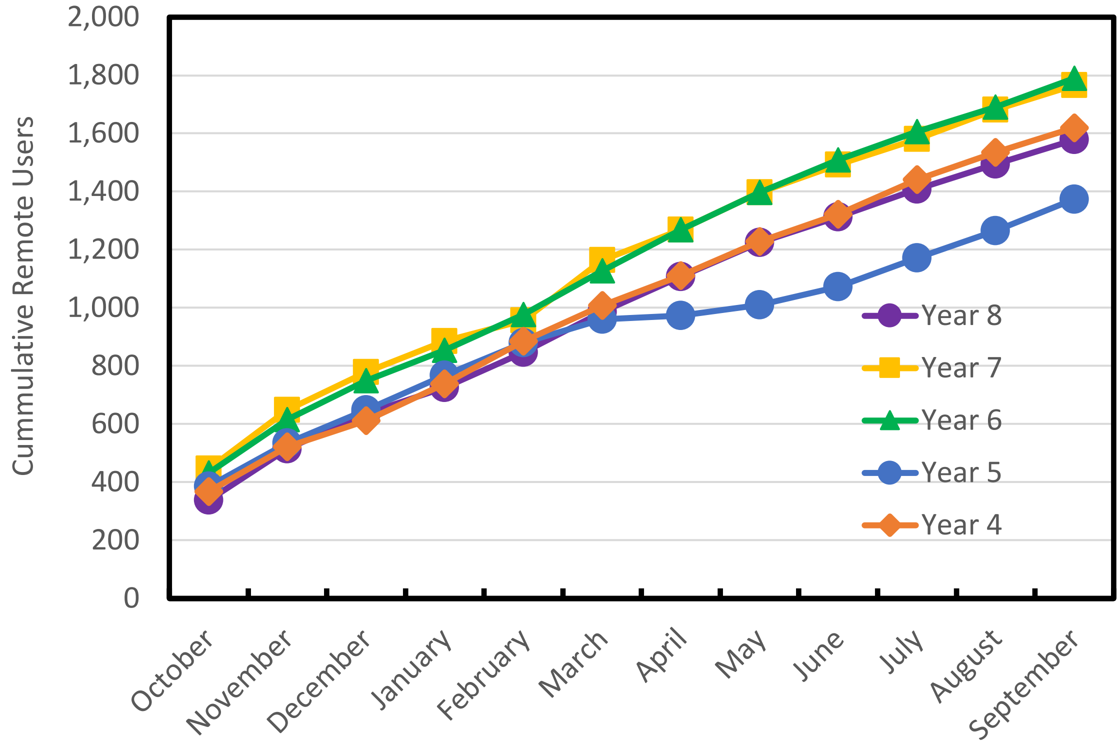


Figure 27: NNCI Cumulative Remote Users for Years 4-8

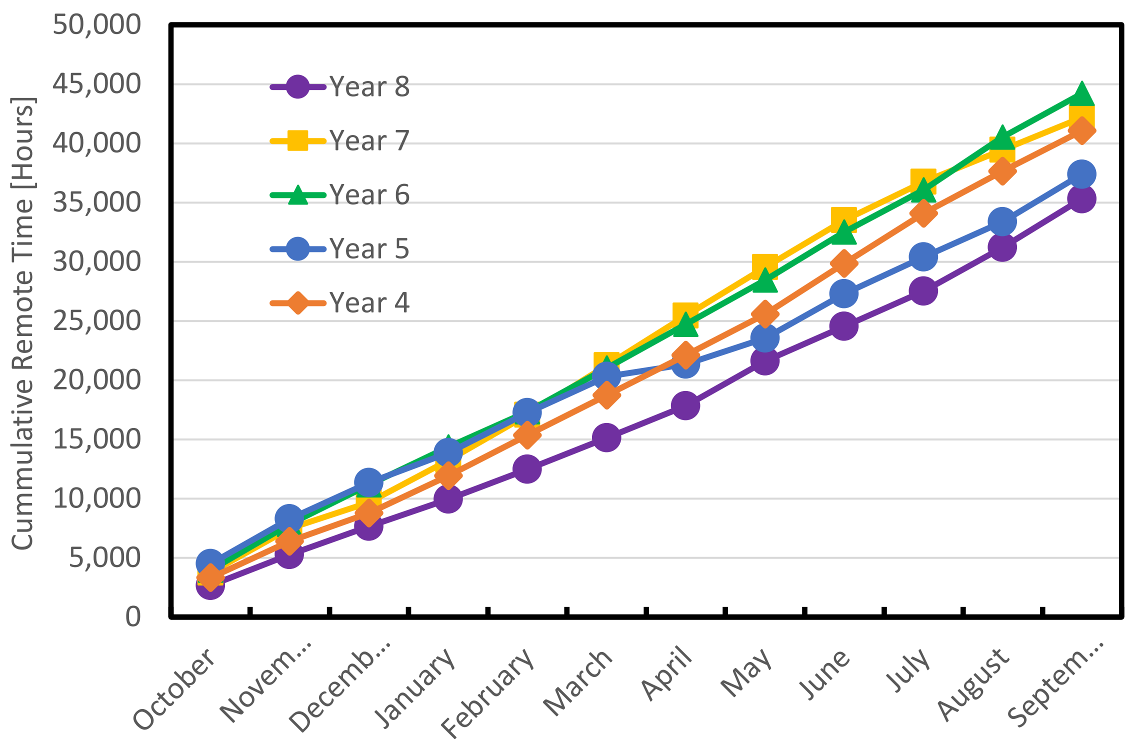


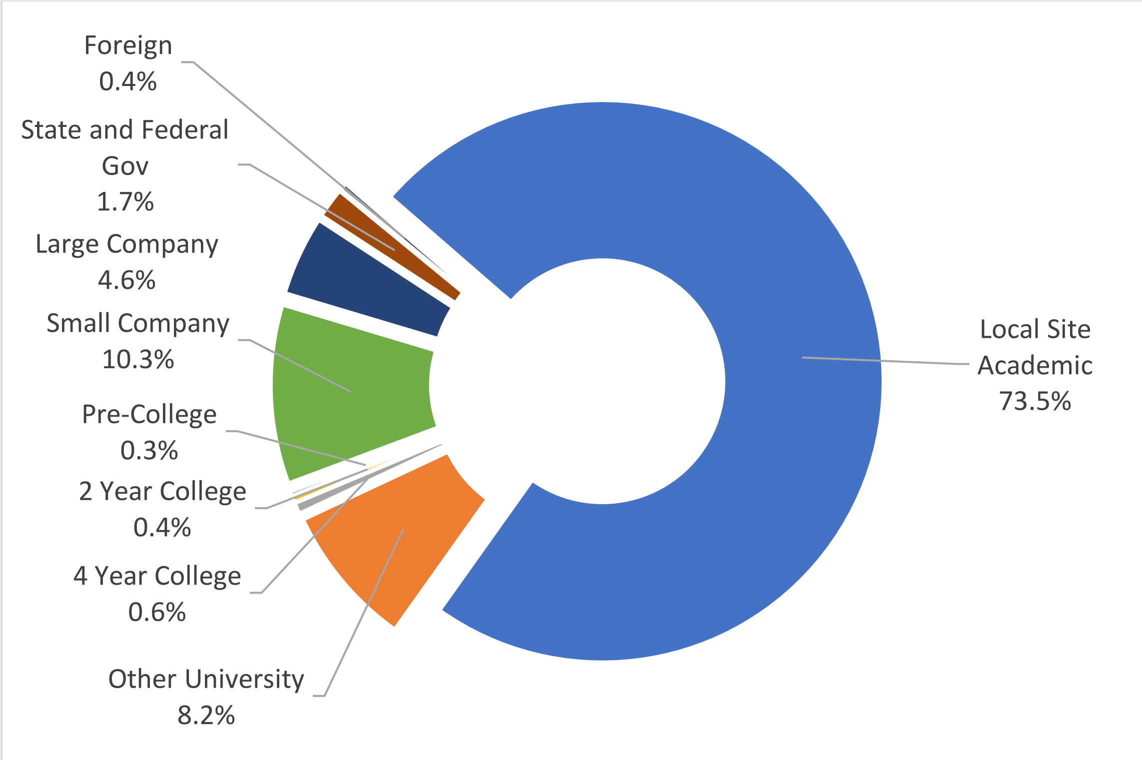
Figure 28: NNCI Cumulative Remote Hours for Years 4-8

The more than 3,600 Year 8 external users come from 1,099 distinct external institutions (full list shown in Appendix 14.2), including 222 US academic institutions from 47 states and Puerto Rico (Figure 29), 594 small companies, 199 large companies, 25 US local/federal government organizations, 37 international institutions (from Europe, Asia, North America, South America, and Australia), and 22 other institutions (museums, hospitals, K-12 schools, and other non-profits). This number does not include cases where an external institution (not necessarily the same PI or user) is working at multiple NNCI sites. It also does not include 119 companies that remain anonymous due to contractual requirements with an NNCI site and may or may not overlap with those listed in the appendix.

Figure 29: NNCI Year 8 US Academic Institutions (222 External)

Figure 30 shows the distribution of users and lab hours by affiliation for the entire network. Individual affiliation plots are shown for each site in the data of Section 12 below. External users make up 26.5% of total users and external hours are 23.4% of total hours. This difference between external users and hours (3.2%) has continued to grow since Year 6. The greater fraction of external users compared to their hours has been ascribed as likely due to the proximity and ease of access of internal users to the facilities, which provides them opportunities for greater overall use. This difference between percentage of external users and external hours was trending downward since the start of NNCI (see Table 16 above), with the smallest difference observed during pandemic Year 6 and has been reversing ever since in parallel with the rise and fall in remote usage.

External Academic Institution



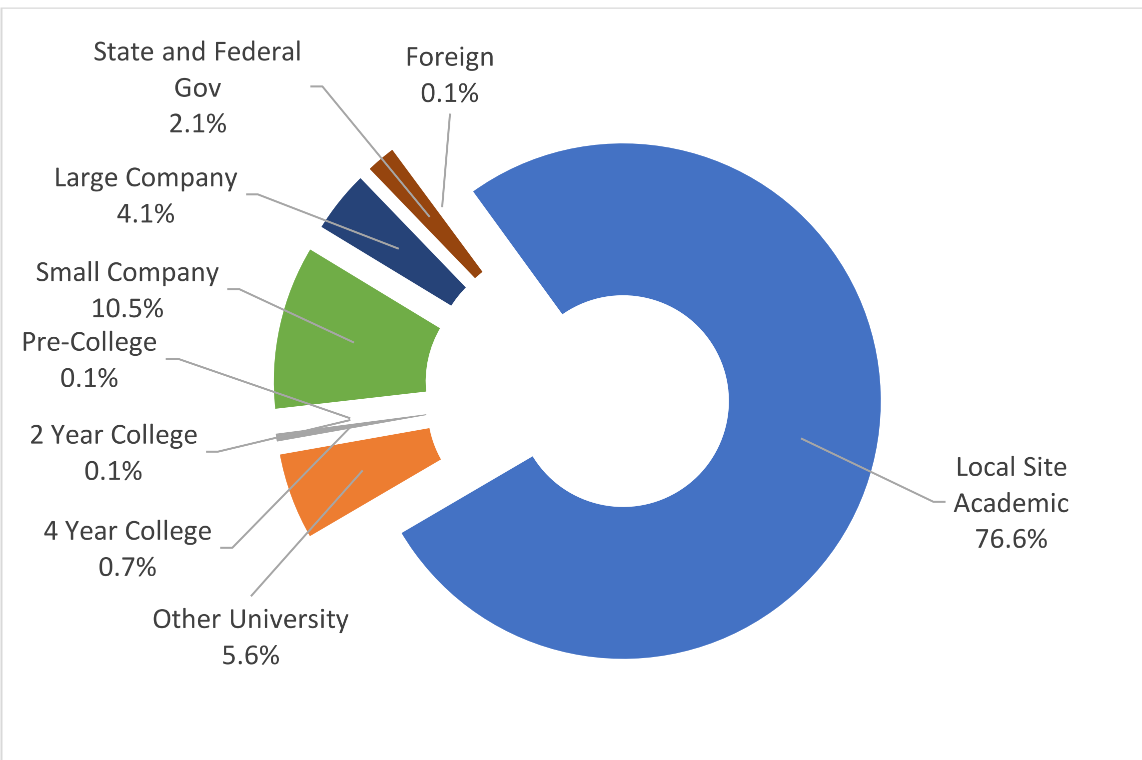


Figure 30: NNCI Users (top) and Usage Hours (bottom) by Affiliation (Year 8)

A comparison of Year 8 cumulative users (by affiliation) by site is provided in Figure 31 for all users and Figure 32 for external users only. Care should be taken when analyzing these data and particularly when comparing different sites. The NNCI sites are diverse: some are located in "nanotechnology" hub areas, others are not; some serve a general NSE user base with a broad tool set, others have a particular research focus; some were part of the NNIN program, others were not; some have a large number of facilities, tools, and staff, others do not. Thus, it can be difficult to draw conclusions from a site-to-site statistical comparison.

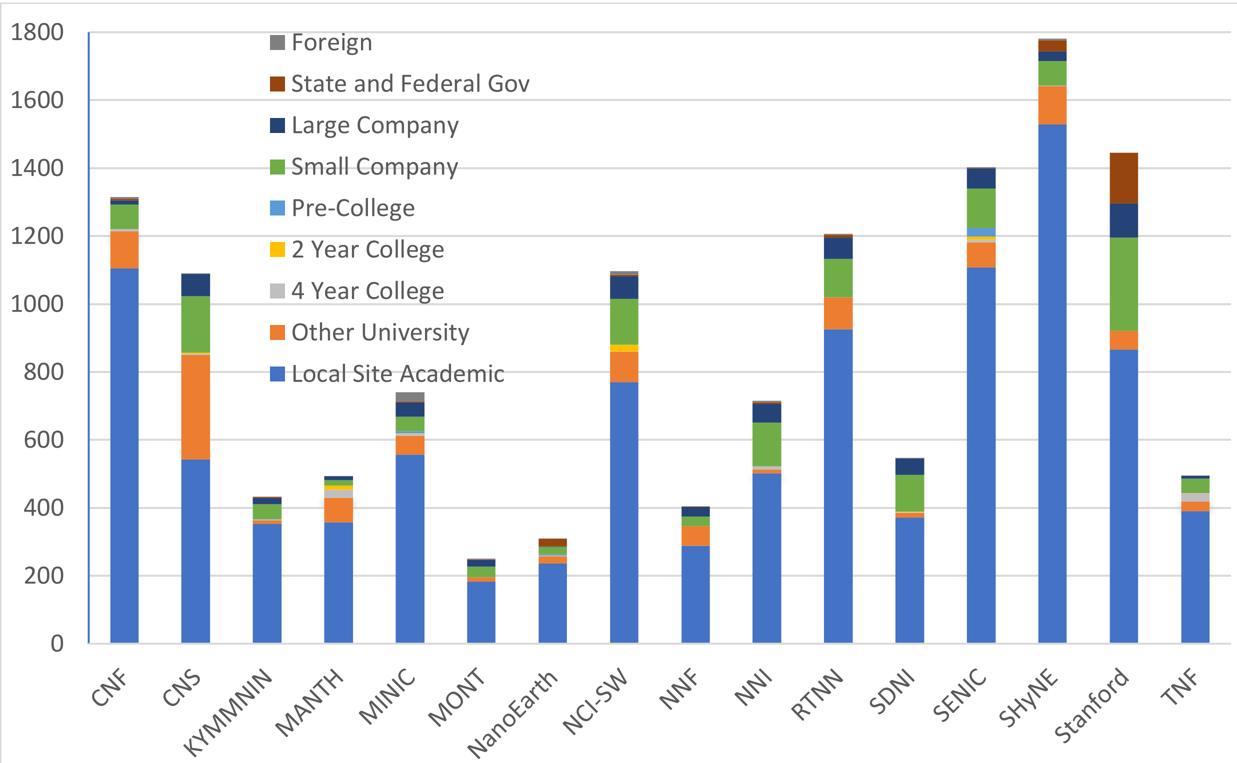


Figure 31: NNCI Cumulative Users by Site (Year 8)

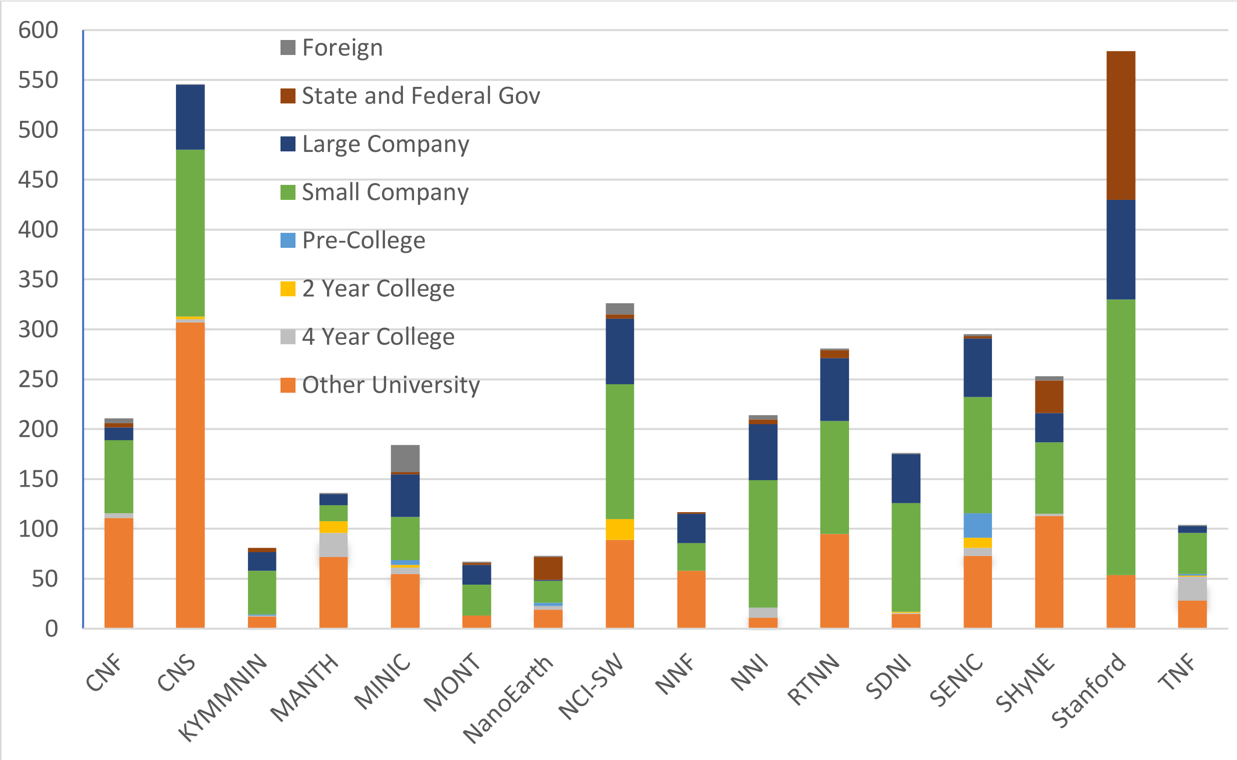


Figure 32: NNCI Cumulative External Users by Site (Year 8)

For academic institutions a network map showing the NNCI nodes and associated US colleges and universities (from 47 US states and Puerto Rico) is shown in Figure 33 below. The size of the NNCI node (blue circle) is proportional to the number of unique academic entities it has as users. Universities with connections to 4 or more NNCI sites are labeled in Figure 33; University of Illinois at Urbana-Champaign had users at 5 NNCI sites, while Columbia University and Massachusetts Institute of Technology each had users at 6 NNCI sites. In Year 1 there were 296 linkages between institutions, and this increased each year reaching 395 in Year 4, but fell to 307 in Year 5 due to the pandemic-related decrease in usage and has risen to 360 in Year 8. In addition to the academic usage depicted by the figure, it was also observed that approximately 45 companies, government agencies, or foreign entities accessed facilities at multiple NNCI sites, although it cannot be determined if these resulted from the same or unique users or projects.

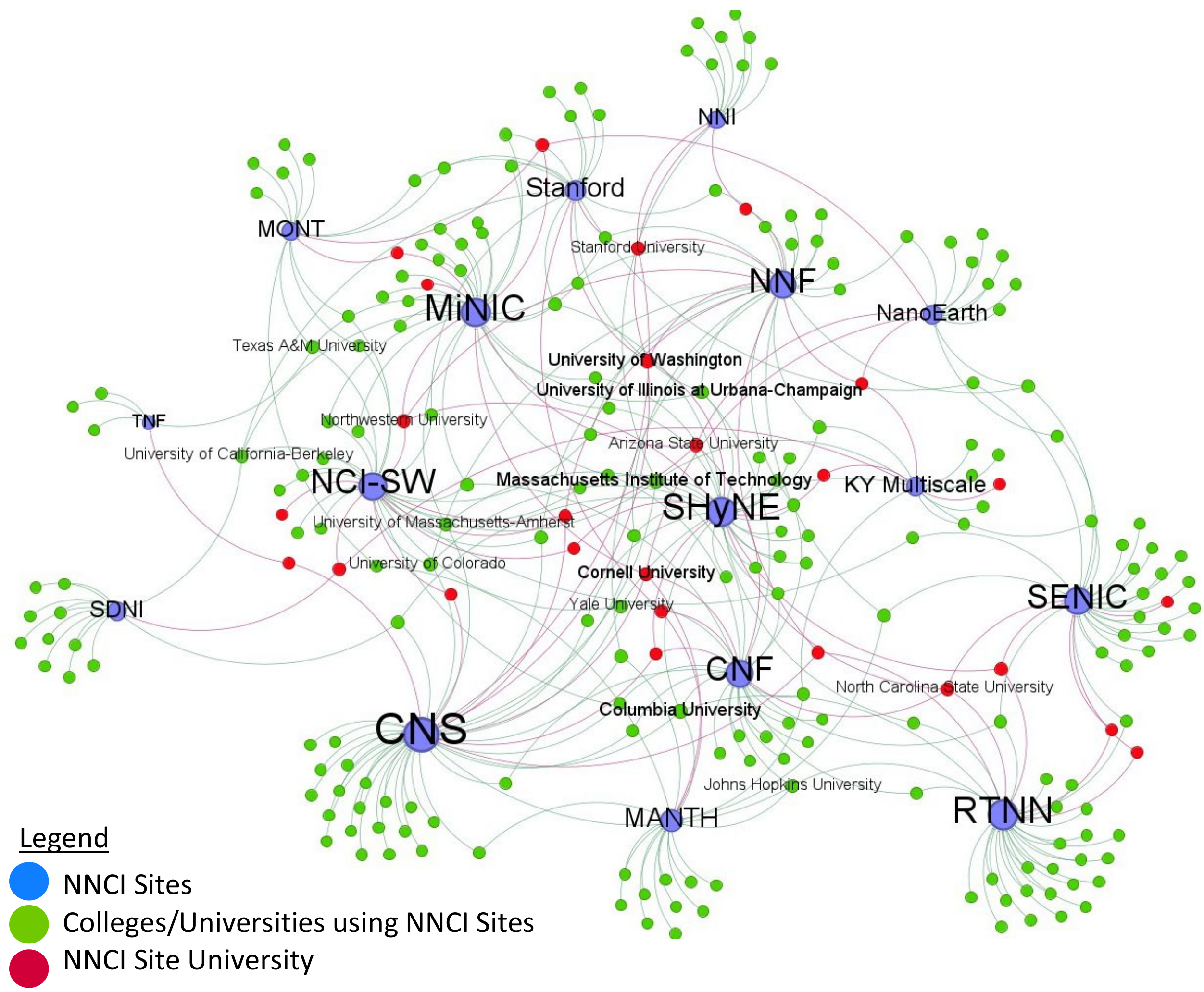


Figure 33: NNCI Academic User Network Map (Year 8)

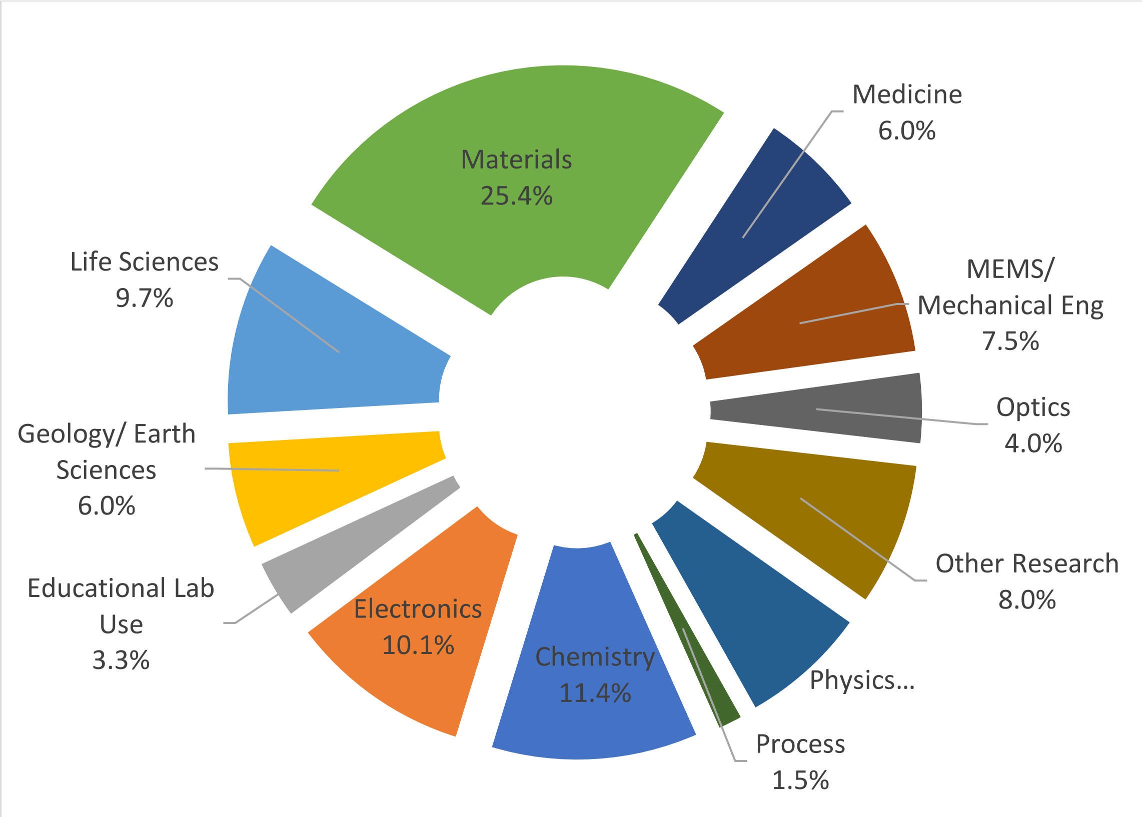
11.2. Non-Traditional Users

One important, though difficult to define, metric is how well NNCI reaches and assists non-traditional users. In order to determine the best way to assess this aspect of NNCI activity, a breakout session on this topic was held at the 1st NNCI Annual Conference (January 2017), and a summary of that discussion was included as part of the Year 1 NNCI Annual Report (March 2017). In addition, the Building the User Base subcommittee has indicated that non-traditional users may come from the following categories:

1. Research areas that do not typically use nanotechnology facilities; these are identified using the disciplines described in more detail below.
2. Demographic groups, such as women and under-represented minorities; information on minority serving institutions is provided below.
3. Users from non-Research 1 educational institutions; data on 2-year and 4-year colleges are provided in the affiliation statistics above.

4. Small companies; data on small company users are provided in the affiliation statistics above.
5. K-12 students, community college students, and teachers; affiliation data is provided for pre-college users and more information about outreach to this category is provided in Section 4.1.

The charts below illustrate the usage of the NNCI network by users in specific disciplines (internal and external). It is worth noting that in many cases these disciplines are self-selected, may reflect the user's home department or their specific area of research, and these may be different from each other. Figure 34 illustrates the distribution by number of users and usage hours in specific disciplines. Furthermore, Figure 35 illustrates the average number of hours/user across the network based on the user's discipline, illustrating that the fabrication-heavy disciplines of electronics, MEMS, optics, physics, and process development tend to require more lab usage by researchers, but with the Geology/Earth Sciences (primarily characterization activities) also among the hours/user leaders. The usage distributions by discipline are similar to previous years, continuing the rapid growth in Geology/Earth Sciences users (6.0% in Year 8 compared to 2.4% in Year 1) and usage hours (7.6% in Year 8 compared to 1.2% in Year 1), and this is also reflected in the hours/user for that discipline. Overall, users from Geology/Earth Sciences, Life Sciences, and Medicine now comprise nearly 22% of all NNCI users. The annual changes in number of users in each discipline are graphically displayed in Figure 36 (with "Educational Lab Use", "Process", and "Other" removed for clarity).



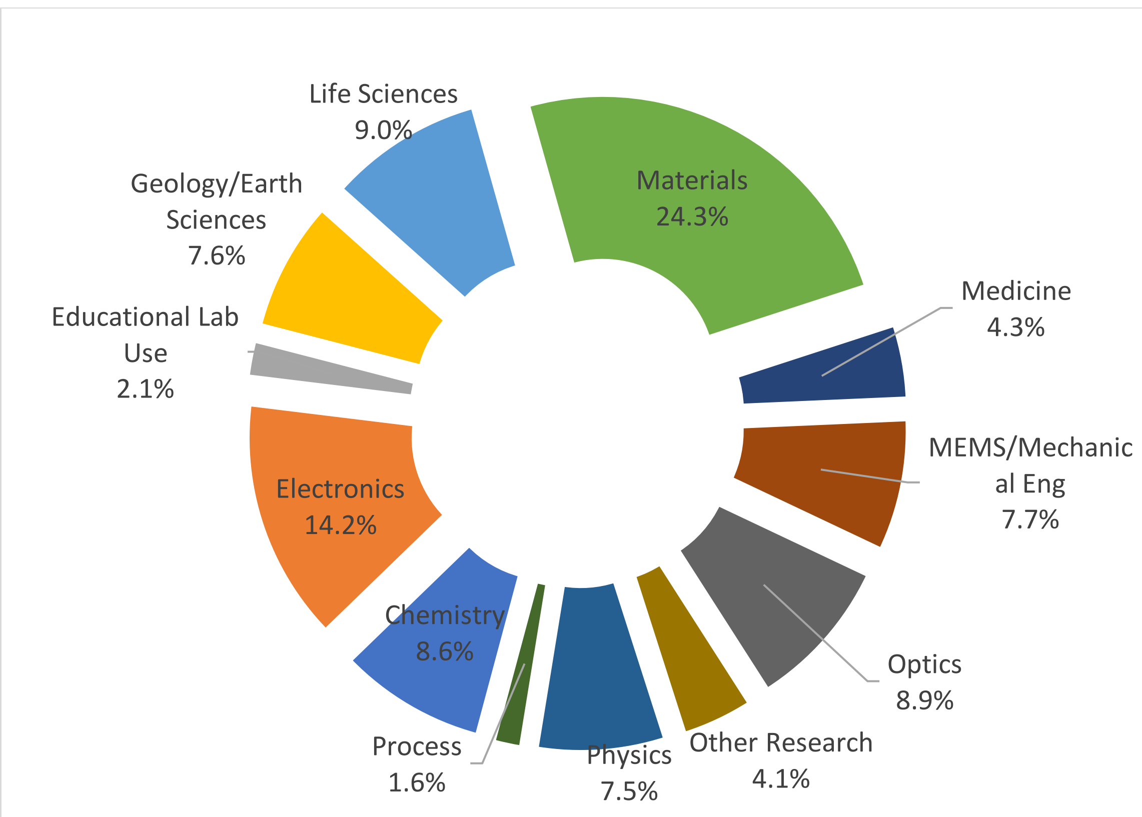


Figure 34: NNCI Users (top) and Usage Hours (bottom) by Discipline (Year 8)

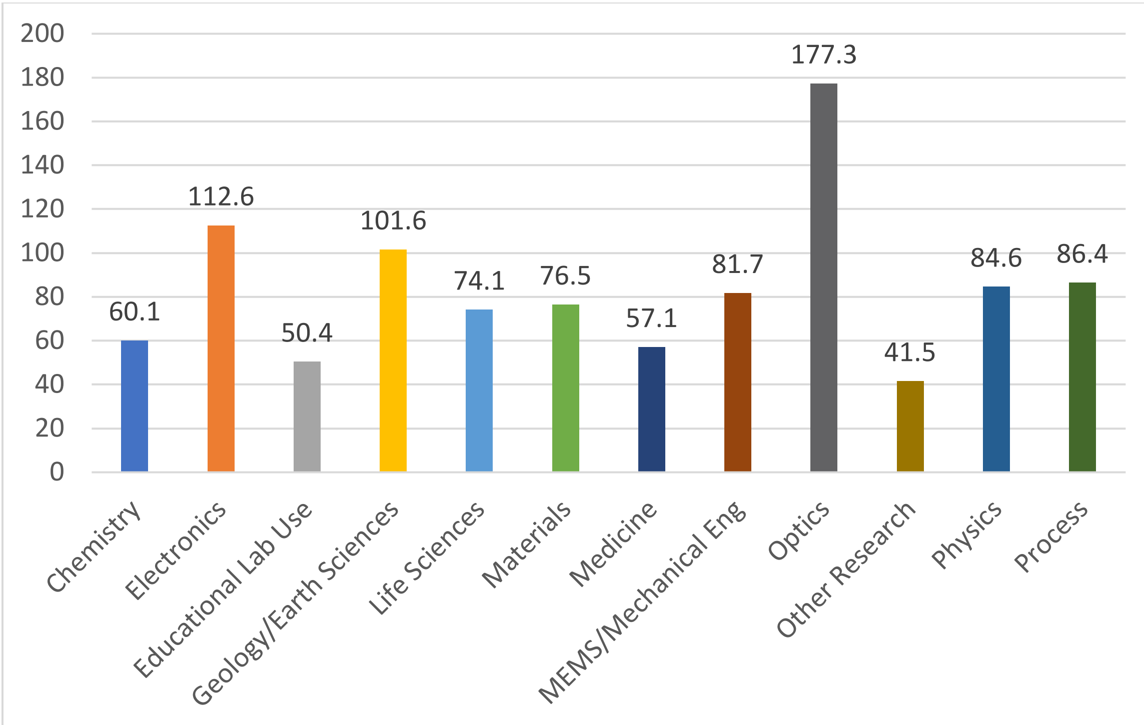


Figure 35: NNCI Hours/User by Discipline (Year 8)

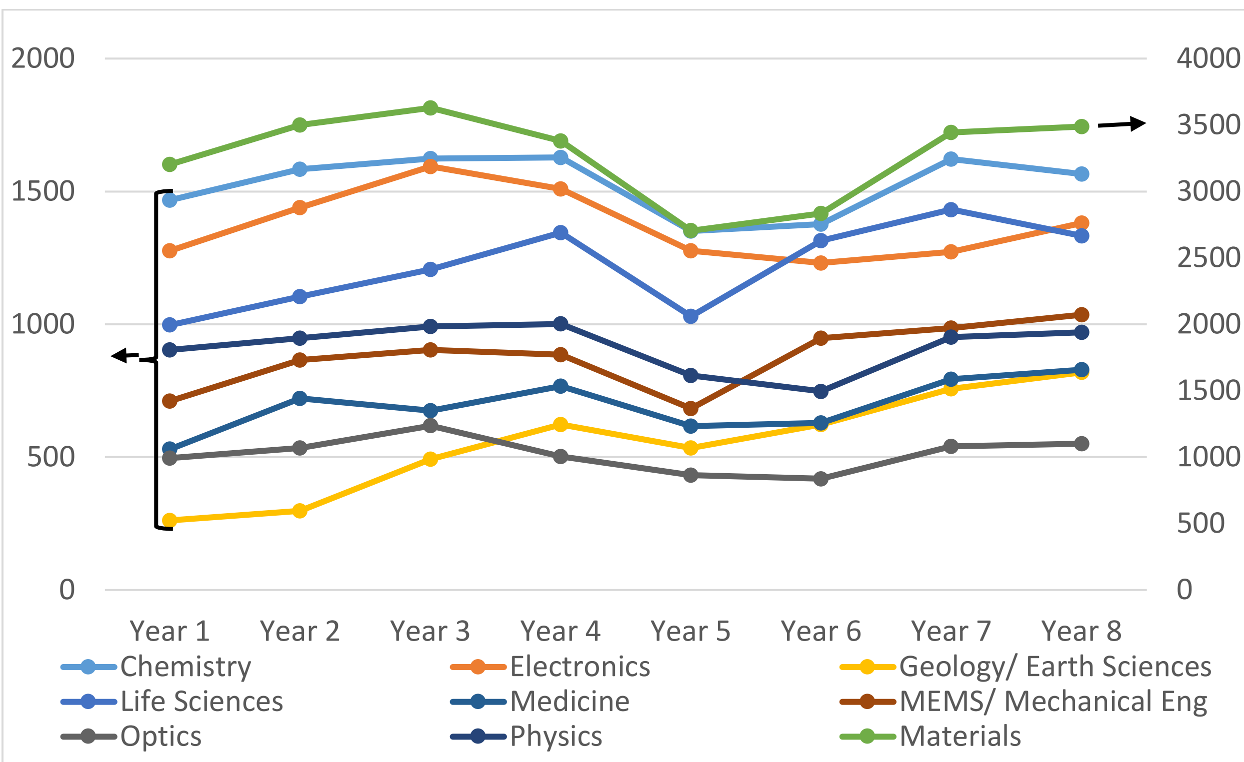


Figure 36: NNCI Yearly Users by Discipline ("Materials" indicated by the right Y-axis for comparison purposes.)

Beginning with the Year 1 annual report, and as a matter of convenience, we have defined "traditional" disciplines to include the engineering-related electronics, materials, MEMS, and process development disciplines, whereas "non-traditional" contains everything else (Educational Lab Use is excluded in this tabulation). Table 15 below compares the relative usage breakdown by number of users and hours for each year of NNCI. Using the above definition, the number of users was split evenly between traditional and non-traditional during the first three years, with a measurable shift in the usage hours from traditional to non-traditional during that same time period. However, during Year 4 usage by non-traditional users increased significantly and has continued to be the dominant population of users, although the relatively proportion of non-traditional usage hours decreased temporarily during pandemic Years 5 and 6.

Table 15: Usage by Traditional and Non-Traditional Disciplines

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
# of Users								
Traditional*	5,386 (51%)	6,063 (50%)	6,384 (50%)	5,997 (47%)	4,791 (47%)	5,148 (47%)	5,893 (46%)	6,110 (46%)
Non-Traditional**	5262 (49%)	6044 (50%)	6383 (50%)	6750 (53%)	5408 (53%)	5,804 (53%)	7,046 (54%)	7,157 (54%)
Hours of Usage								
Traditional*	495,215 (55%)	506,393 (54%)	510,180 (51%)	543,838 (48%)	374,934 (50%)	474,876 (50%)	516,803 (49%)	524,643 (49%)
Non-Traditional**	409,935 (45%)	424,855 (46%)	490,992 (49%)	588,980 (52%)	382,140 (50%)	476,194 (50%)	544,732 (51%)	548,349 (51%)

* Electronics, Materials, MEMS/ME, Process

** Chemistry, Physics, Optics, Medicine, Life Sciences, Geo/Earth Sciences, Other

Since NNCI Year 2, sites have collected PowerPoint slides highlighting individual research activities at their sites during the year, and these are provided separate to this report and archived on the NNCI website (https://nnci.net/nnci-annual-report). Beginning in NNCI Year 4, each slide was tagged with a national research priority, typically one of the NSF 10 Big Ideas, National Academy of Engineering Grand Challenge, or another federal agency (DOE, DOD, White House) research initiative. These annual highlight slides (typically 130-140 each year) provide a glimpse at what research topics are trending at NNCI sites, and the distribution can be seen in Figure 37 below. Between Years 4 and 8 there is relative consistency with approximately 50-60% of highlights tagged with the NSF Big Ideas of *Quantum Leap*, *Understanding the Rules of Life*, and *Growing Convergence Research*. A further 10% of slides address other NSF Big Ideas, although this decreased to 5% in Year 8 as did those associated with NAE Grand Challenges. Over the past two years, highlights related to *Advanced Materials* and *Microelectronics* (DoD Critical Technologies) have been tagged. Finally, this year includes several highlights in *Advanced Photonics* and another group connected to *Energy and Environment*. The remainder are either associated with other priorities or are not indicated.

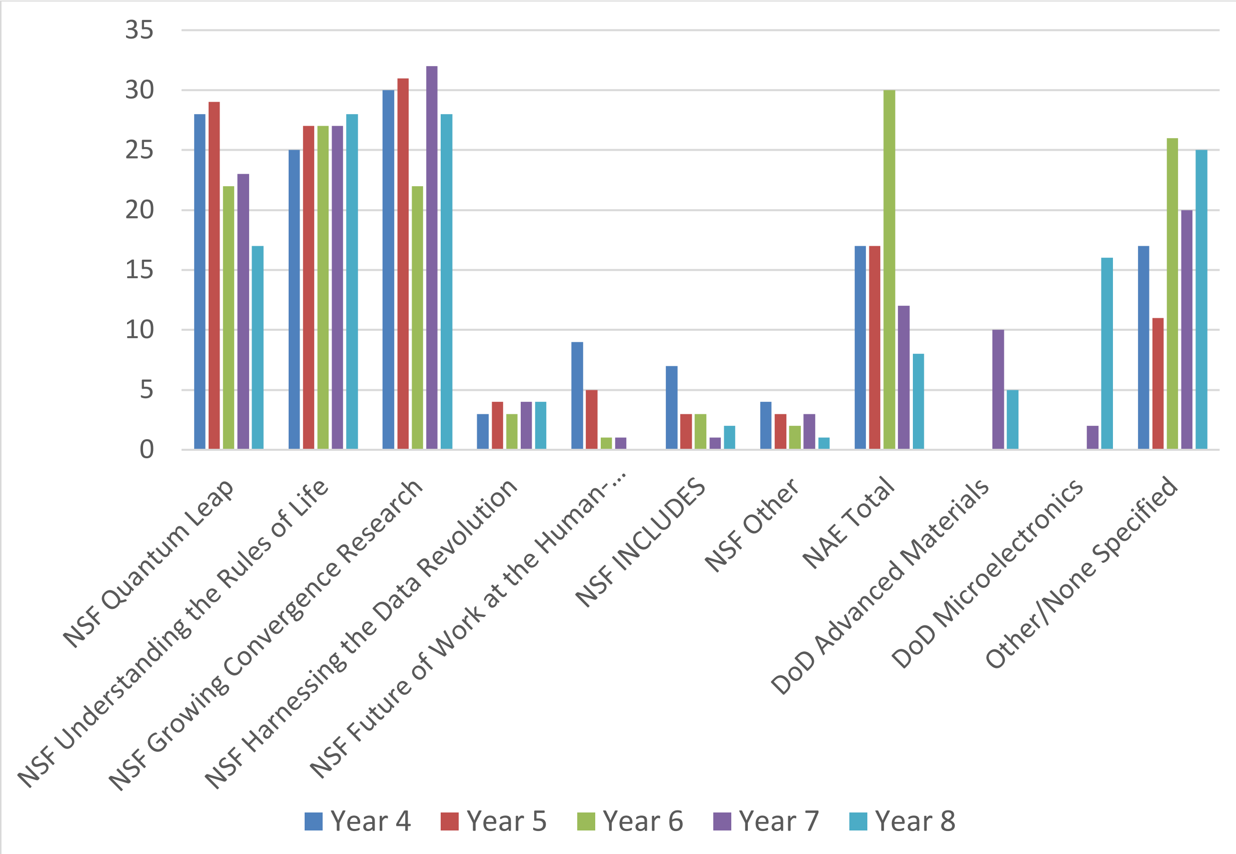


Figure 37: NNCI Highlight Slides Research Priorities (Years 4-8)

As indicated above, another measure of non-traditional usage within NNCI is to examine the diversity of users' home academic institutions, particularly those that serve under-represented minority populations as defined by the US Dept. of Education and the Hispanic Association of Colleges and Universities.

- As constituted, NNCI primary sites and partners consist of the following minority serving institutions:
    - North Carolina A&T State Univ. (SENIC), *Historically Black College and University* (HBCU)
    - Northern Arizona Univ. (NCI-SW), Rio Salado Community College (NCI-SW), and Univ. Texas-Austin (TNF), *Hispanic-Serving Institution* (HIS, 25+% Hispanic undergraduate students)
    - Community College of Philadelphia (MANTH), *Primarily Black Institution* (PBI)
    - Stanford University (nano@stanford), *Emerging Hispanic Serving Institutions* (EHSI, 15+% Hispanic undergraduate students)
    - Univ. California-San Diego (SDNI), Univ. Texas-Austin (TNF), Community College of Philadelphia (MANTH), and Virginia Tech (NanoEarth), *Asian-American and Native American Pacific Islander Serving Institution* (AANAPISI)
- During Year 8, external academic users came from 76 institutions serving minority students: 25 HSI, 25 EHSI, 13 HBCU, 2 PBI, 23 AANAPISI, 1 *Tribal Colleges and Universities* (TCU), and 1 *Native Hawaiian-Serving Institution* (ANNH). This total is more than 76, because 14

institutions have multiple designations. Thus, 34% of the US academic institutions using NNCI facilities serve under-represented populations. This is a significant increase from the 21% observed during Year 6.

  - Examples of these institutions are: Alabama A&M University, Clark Atlanta University, Florida International University, Navajo Technical University, Portland State University, San Jose State University, University of Miami, University of Hawaii-Manoa, and University of Puerto Rico.

- Based on the Carnegie Classification of research universities, where R1 are doctoral universities with very high research activity and R2 are doctoral universities with high research activity, we find the following for the 222 Year 8 US institutions:
  - 104 R1 Universities (out of 146 in the Carnegie list)
  - 51 R2 Universities (out of 133 in the Carnegie list)
  - 67 Non-R1/R2 Universities or Colleges
  - More generally, the fraction of users from non-research academic institutions (4-year colleges, 2-year colleges, and pre-college) has remained steady throughout the life of the NNCI at approximately 1% of all users.

11.3. Publications

The publications data shown below (Table 16) was collected by sites for the calendar year 2022. Due to the challenge in getting compliance from users for this requested information, this should only be considered a lower limit of the actual publications data. In addition, no attempt was made to remove duplicates, where authors might have been from multiple NNCI sites. The 4,213 publications collected for CY 2022 are the smallest number collected since the start of NNCI, but only slightly less than the previous two years (2020 and 2021). Whereas previously most of the decline since 2019 resulted from fewer conference presentations (approximately 50% of peak value in 2020 and 2021, compared to 2019), in 2022 there is a slight decline in journal publications and an uptick in conferences. We ascribe this to a resumption of in-person attendance by researchers to present their work at conferences, although some of the change may also be due to differences in how sites are collecting this data. Publications reported by each site range from 77 to 622. Patents/applications/invention disclosures decreased in 2022, down from the peak in 2019. These trends can be observed in Figure 38.

Table 16: NNCI 2022 Publications

Publication Type (CY 2021)	
Internal User (Site) Papers	2,586
External User Papers	379
Internal User Conference Presentations	728
External User Conference Presentations	73
Books/Book Chapters	11

Patents/Applications/Invention Disclosures	436
Total	4,213

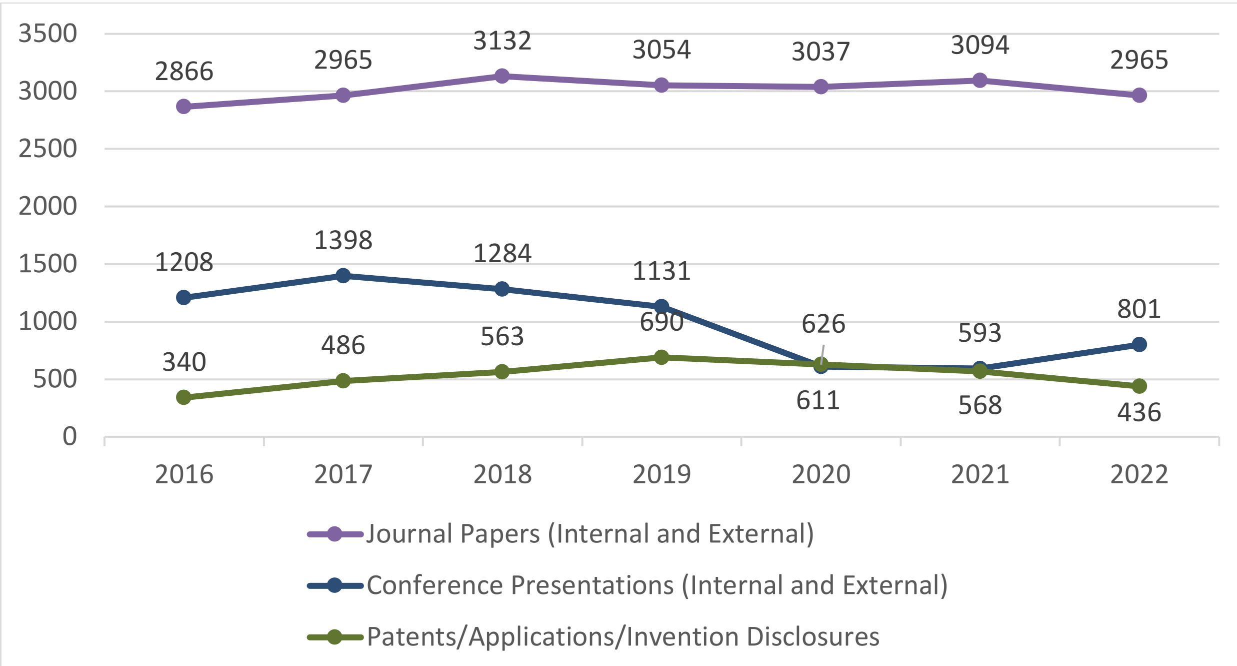


Figure 38: Number of NNCI-enabled Publications by CY.

In addition, due to extra efforts in improving compliance among users and PIs to properly acknowledge NNCI and NSF in publications using the appropriate grant numbers, Figure 39 below shows continued improvement in this metric. Finally, a further detailed search reveals that the work carried out in the NNCI facilities heavily supports industries of tomorrow, as is highlighted by a keyword search among the more than 11,600 journal articles published between 2018-2023 that acknowledge the NNCI 2015 or 2020 award numbers (Figure 40). "Semiconductor" is found in 26-32% of publications over that time frame while "quantum" is mentioned by 30-35% of these publications. An earlier version of this analysis, with additional search terms, was featured in the *2021 National Nanotechnology Initiative Strategic Plan*.

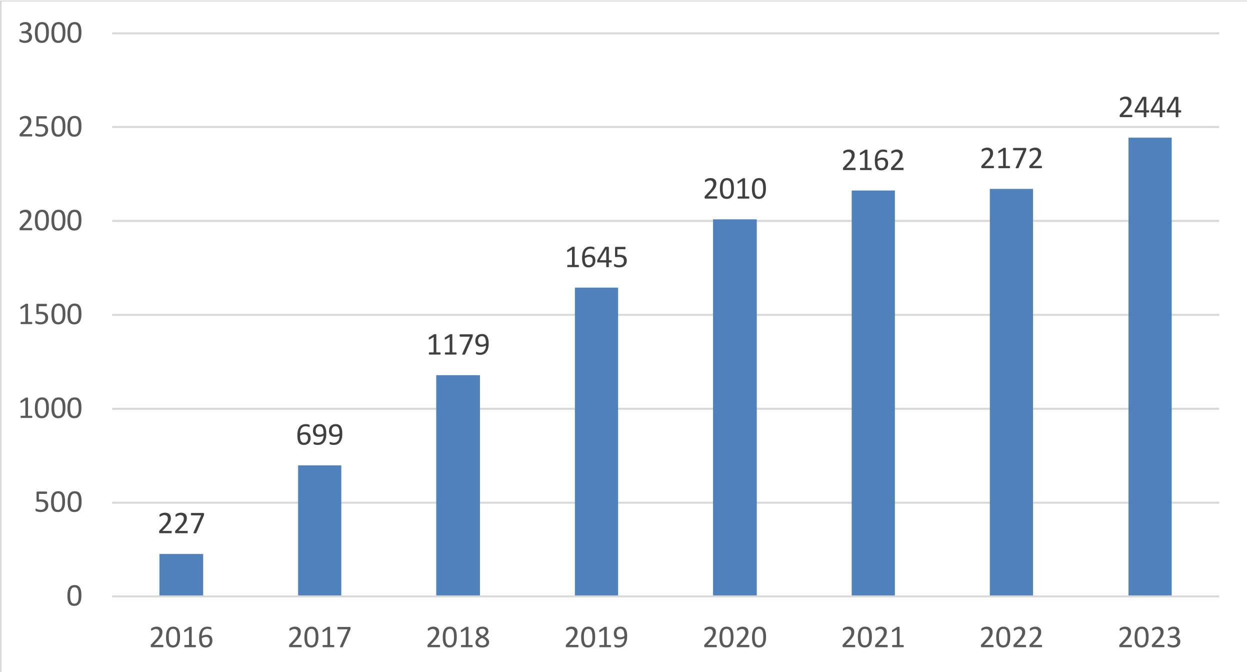


Figure 39: Number of Publications with NSF NNCI Award Numbers based on Google Scholar (NNCI-Award # <u>or</u> ECCS-Award #). Both 2015 and 2020 award #s were used. Search conducted 1/12/2024.

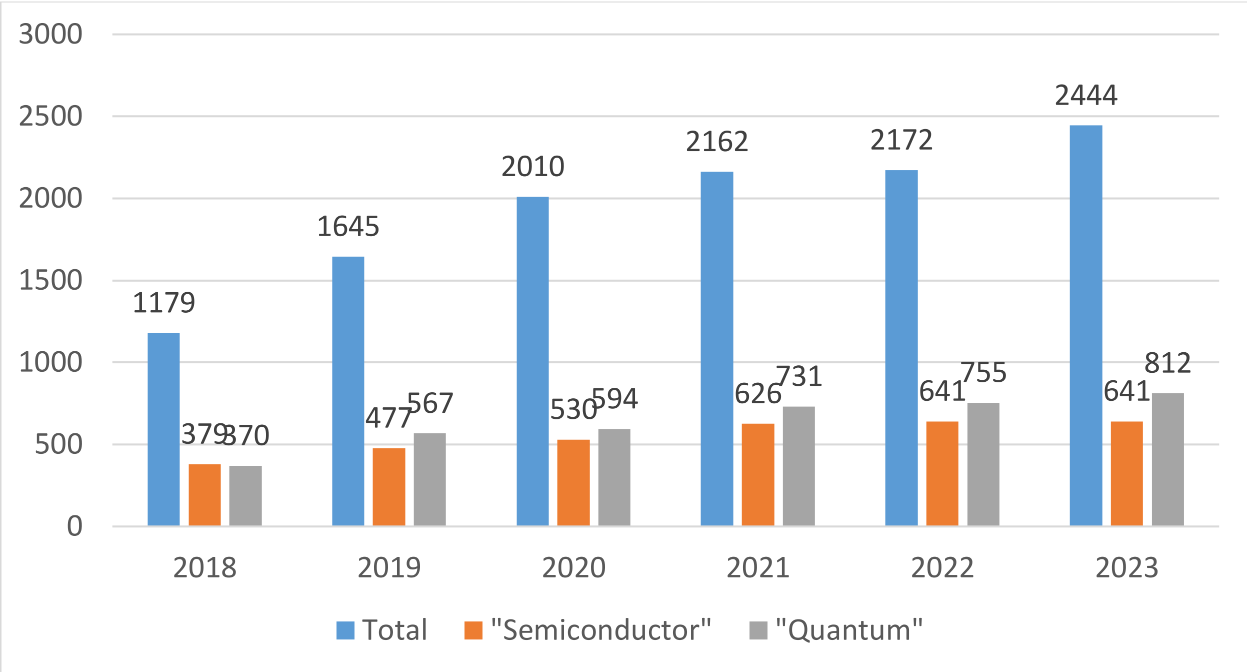


Figure 40: Number of NNCI publications (which cite the NSF award #s) on Google Scholar that also contain search terms "Semiconductor" or "Quantum" (2018-2023). Search conducted 1/12/2024.

11.4. Supported Research Centers

During 2020, the Coordinating Office asked NNCI sites to provide a list of large, multi-PI and/or multi-institution research centers supported by their facilities as a way of demonstrating some of the academic (and even economic) impact of the NNCI program. The list provided in the Year 5 Annual Report included 41 such centers, and this was supplemented in Years 6 and 7 with 29 additional centers, including 3 of the 6 new NSF Science and Technology Centers awarded in 2021. Table 17 below provides a Year 8 update, indicating 18 *new* (and 1 renewed) centers supported by NNCI sites during the previous year. The host and supporting site are provided, but in many cases other sites are also participants in these centers. Most notable this past year was the awarding of 8 hubs for the Microelectronic Commons, *all* of which have at least one NNCI site associated with them.

Table 17: NNCI Supported Research Centers (New in Year 8)

Research Center	Supporting Site	Funding Source
Center for the Co-Design of Cognitive Systems (CoCoSys)	SENIC	SRC JUMP 2.0
Center on Cognitive Multispectral Sensors (CogniSense)	SENIC	SRC JUMP 2.0
Chan Zuckerberg Biohub – Chicago	SHyNE	Chan Zuckerberg Initiative
Commercial Leap Ahead for Wide Bandgap Semiconductors (CLAWS)	RTNN/SENIC	ME Commons
FUSE: Interconnects with Co-Designed Materials, Topology, and Wire Architecture	CNF	NSF FUSE
National Institute for Theory and Mathematics in Biology (NIMTB)	SHyNE	NSF/Simons Foundation
NSF Convergence Accelerator Track I: Toward Water Circularity: Mining Green Hydrogen and Value-Added Materials from Hypersaline Brines.	NNI	NSF
NSF Engines Development Award: Advancing semiconductor technologies in the Northwest (OR, ID, WA)	NNI	NSF Regional Innovation Engines
NSF Engines Development Award: Advancing mass timber technologies (OR, WA)	NNI	NSF Regional Innovation Engines
Precise Sequence Specific Block Copolymers for Directed Self-Assembly - Co-Design of Lithographic Materials for Pattern Quality, Scaling, and Manufacturing	CNF	NSF FUSE
Southwest Advanced Prototyping Hub	NCI-SW	ME Commons

Superior Energy-efficient Materials and Devices (SUPREME)	CNF	SRC JUMP 2.0
The California Defense Ready Electronics and Microdevices Superhub Hub (CA DREAMS)	SDNI	ME Commons
The California-Pacific-Northwest AI Hardware Hub	nano@stanford/NNI	ME Commons
The Center for Dynamics and Control of Materials	TNF	NSF MRSEC (renewal)
The Midwest Microelectronics Consortium Hub in Ohio	KY Multiscale	ME Commons
The Northeast Microelectronics Coalition Hub	CNS	ME Commons
The Northeast Regional Defense Technology Hub (NORDTECH)	CNF	ME Commons
The Silicon Crossroads Microelectronics Commons Hub	SHyNE	ME Commons

11.5. Research Funding Sources

In 2019, at the request of NSF, the NNCI Metrics Subcommittee discussed the collection of data detailing the sources of funding used to support NNCI users and research. The first set of data (grants and users) was collected in 2019 from all 16 NNCI sites for usage during NNCI Year 3 (Oct. 2017 – Sept. 2018). Due to COVID-19, this data set was not collected in 2020. In 2021, a revised set of the data (grants information only) was collected for the time period of NNCI Year 5 (Oct. 2019 – Sept. 2020) and reported in the Year 6 Annual Report (Feb. 2022). A separate report of this data was provided to NSF and the highlights are presented below.

The collected data excludes any sources of internal funding, such as state funding for most of the public universities. Grants data are used to assess the number and type of funding sources as well as the level of financial support (new in this iteration) for research at NNCI facilities as well as the academic disciplines that received the funding (by grant PI). This data is not completely exhaustive, but the general trends presented here provide some indication as to how NSF's NNCI funding is used to support the broader scientific community.

<u>Research Funding</u>

The number of grants from each external funding source (NSF, DoD, etc.) which were used to pay for NNCI facility user fees and/or stipends for students performing the work in the facility were counted (Figure 41). To the largest extent possible, data included both internal and external users (but not staff), although external user data can be more difficult to collect.

In total, 2,609 Principal Investigators (PIs), internal and external faculty as well as industry researchers, were included in the counting with a total of 3,899 grants. These metrics (for NNCI Year 7) are similar to those collected in 2021 for NNCI Year 5 usage but remain slightly lower compared to Year 3. An average PI used 1.5 grants/awards to fund research conducted at NNCI facilities, which is slightly less than the previous Year 5 average (1.8).

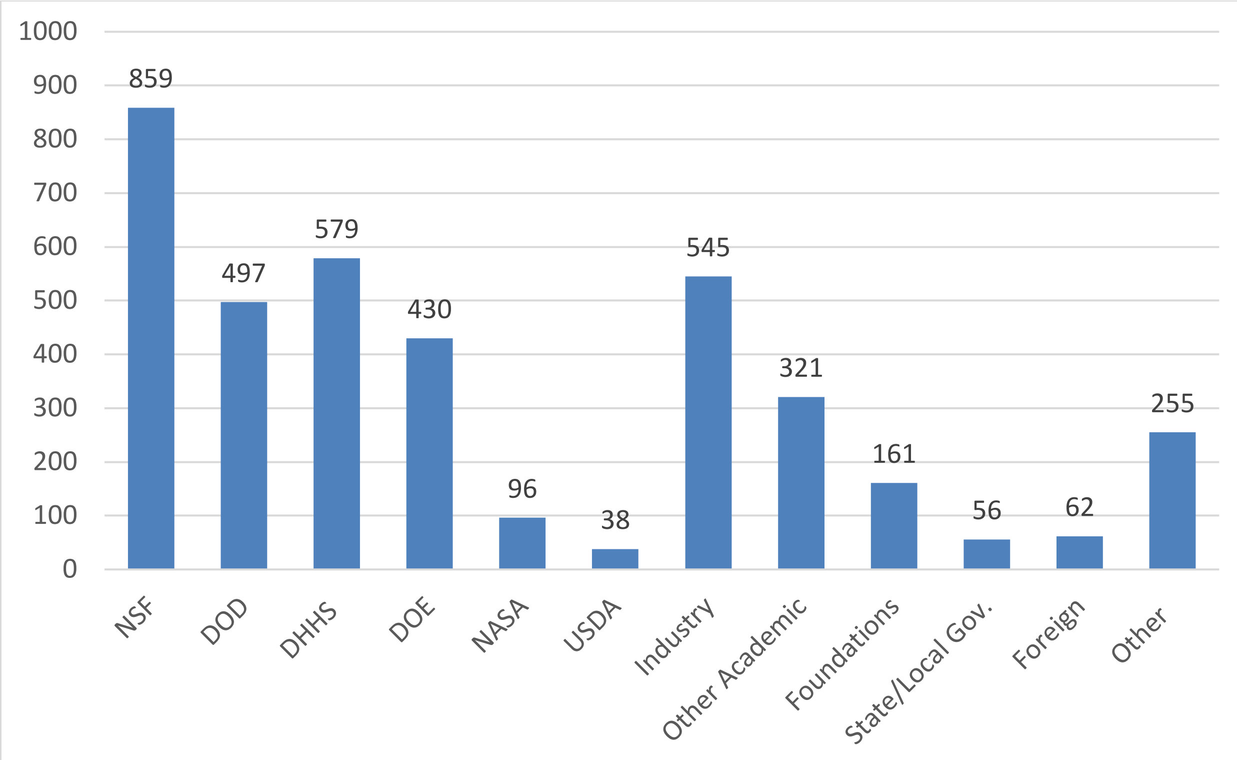


Figure 41: Number of grants by external funding source providing funding for NNCI facility access and research user support (Oct. 2021 – Sept. 2022).

NSF continues to be the largest single external funding source with 22.0% of awards, a greater fraction than the 19.7% recorded in 2021. In addition, 29% of PIs had at least one NSF grant funding their research at NNCI-supported facilities. DoD, DHHS and DoE are the other federal funding agencies with a large number of awards that are supported by the NNCI, with all continuing to show increases in fraction of awards compared to the 2021 and 2019 data collection. DOE had the largest change, from 8.5% of awards in 2021 to 11.0% in this year's data. Industry accounts for 14.0% of grants and other academic sources account for 8.2%. Compared to the 2021 data collection, this represents an increase in industry support and a decrease in other academic support. In both cases, it is likely that some of the industry and academic sources include flow-through of federal funding, so the actual number of NSF (and other funding agency) awards is likely higher than indicated.

For the first time in this metrics data collection, sites were asked to provide the value of the grants that were used for facility access (Figure 42). It should be noted that in many cases only the funded amount to date is available, rather than the full value of the grant, award, or contract. Thus, the values shown are very likely to be underestimations of the total funding amounts. Nevertheless, the total funded amount ($5 billion) is significant, with average amounts of $0.5-2.0 million/award, depending on funding source. NSF awards used for NNCI access totaled more than $1 billion with an average of $1.3 million/award.

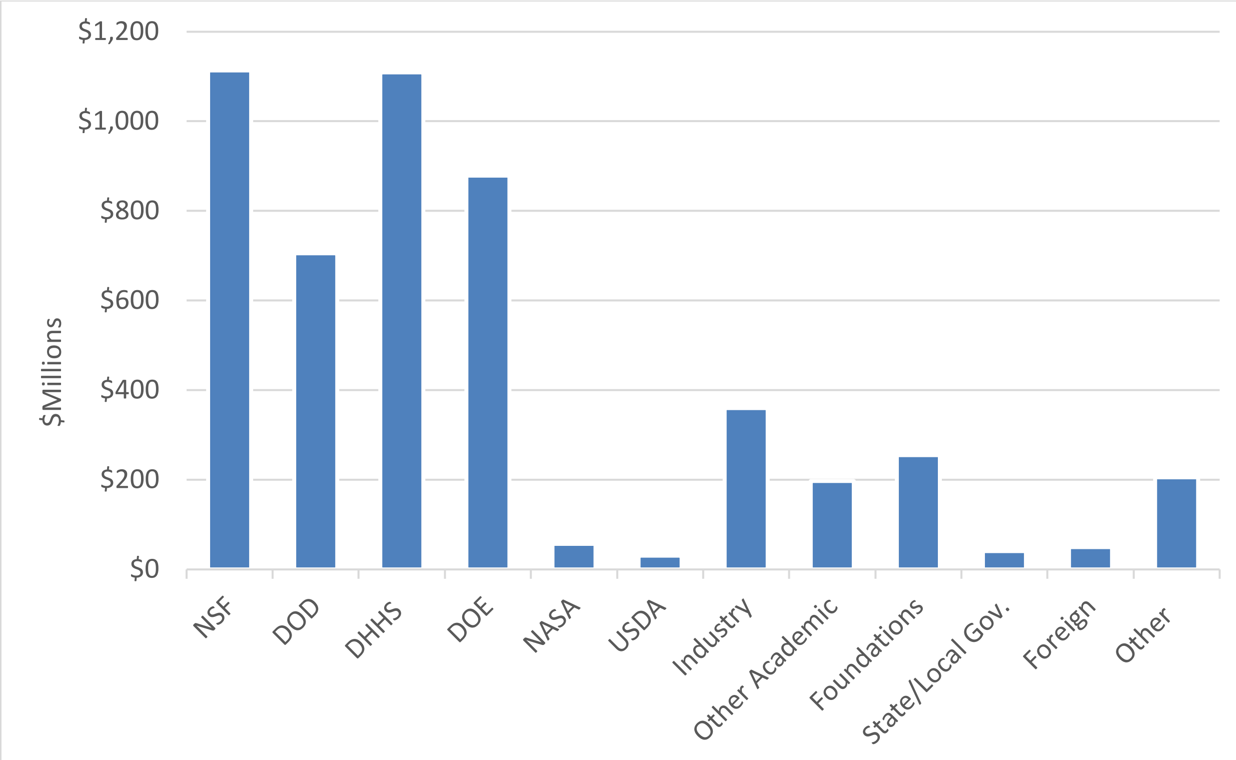
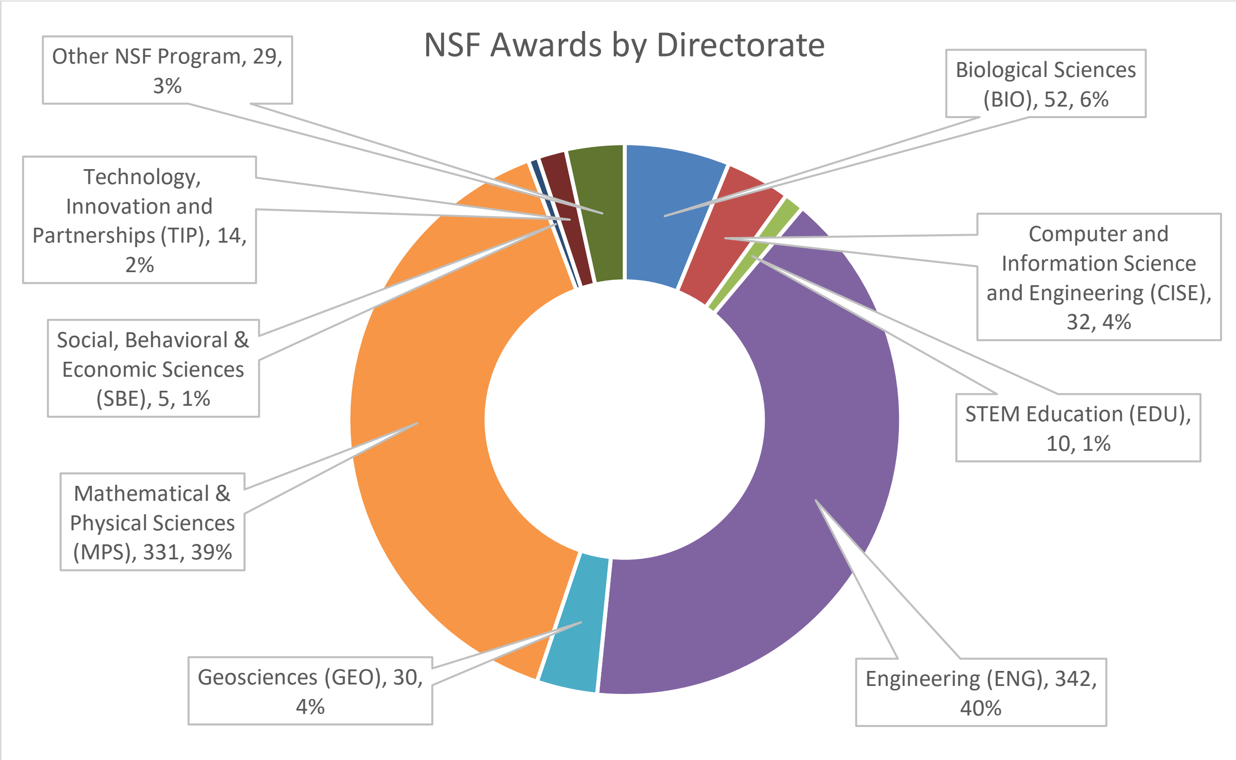


Figure 42: Value of grants by external funding source providing funding for NNCI facility access and research user support (Oct. 2021 – Sept. 2022).

The distribution and values of NSF grants by directorate is shown in Figure 43. Within NSF, the Directorate for Engineering (ENG) provided the largest number of total awards (342) with a funded amount of $488 million, while Mathematical and Physical Sciences (MPS) has 331 awards with a value of $404 million. These two directorates comprise 79% of awards and 84% of funded value of total NSF support. While TIP is a new NSF directorate, NNCI is already estimated to support $5 million of TIP funding.

The Directorate for Engineering (ENG) provides the largest number of NSF research grants (342) to NNCI researchers, with roughly equal distribution of grants from the Division of Electrical, Communications & Cyber Systems (ECCS, 106), the Division of Civil, Mechanical & Manufacturing Innovation (CMMI, 115), and the Division of Chemical, Bioengineering, Environmental and Transport Systems (CBET, 89). The Directorate for Mathematical & Physical Sciences (MPS) is the second largest source for grants (331), dominated by the Division of Materials Research (DMR) which provides 224 grants (67% of MPS awards) supporting NNCI research (the largest number of any NSF division) followed by the Division of Chemistry (CHE) with 74 grants.



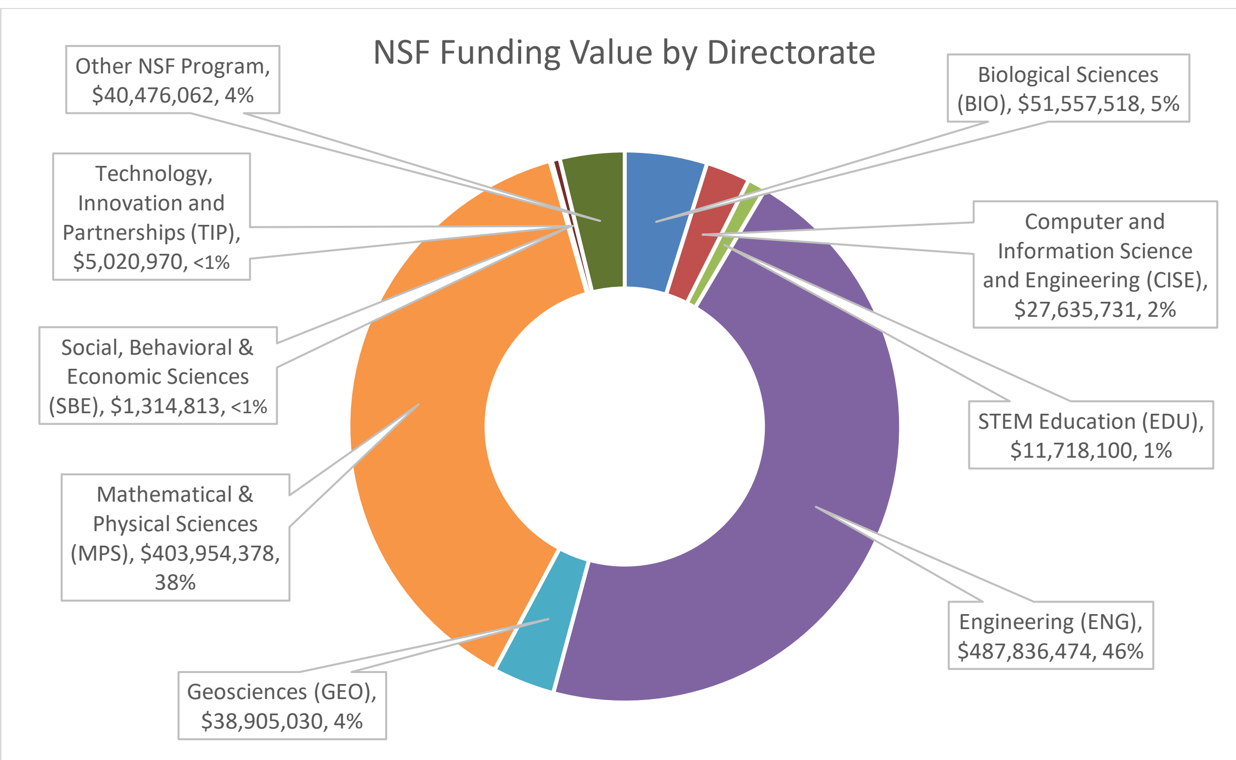


Figure 43: Number (top) and funded value (bottom) of reported NSF grants providing funding for NNCI facility access and research user support by NSF directorate (Oct. 2021 – Sept. 2022).

Academic Disciplines

The 2021 data request combined the information on academic departments with the funding information by soliciting the primary departments of award PIs and assuming the resulting distribution to be indicative of users overall, and this approach was continued for the 2023 data collection. All funded awards are distributed by their academic department as shown in Figure 44. Since industry users do not have an academic department, funding of those users is included in the "Other" category. By total number of awards, the top academic departments (excluding "Other"), representing approximately 65% of awards, are:

1. Electrical and Computer Engineering
2. Materials Science and Engineering
3. Chemistry
4. Physics
5. Chemical Engineering
6. Mechanical Engineering

These are also the top departments for NSF awardees (representing 74% of awards), although in a slightly different order.

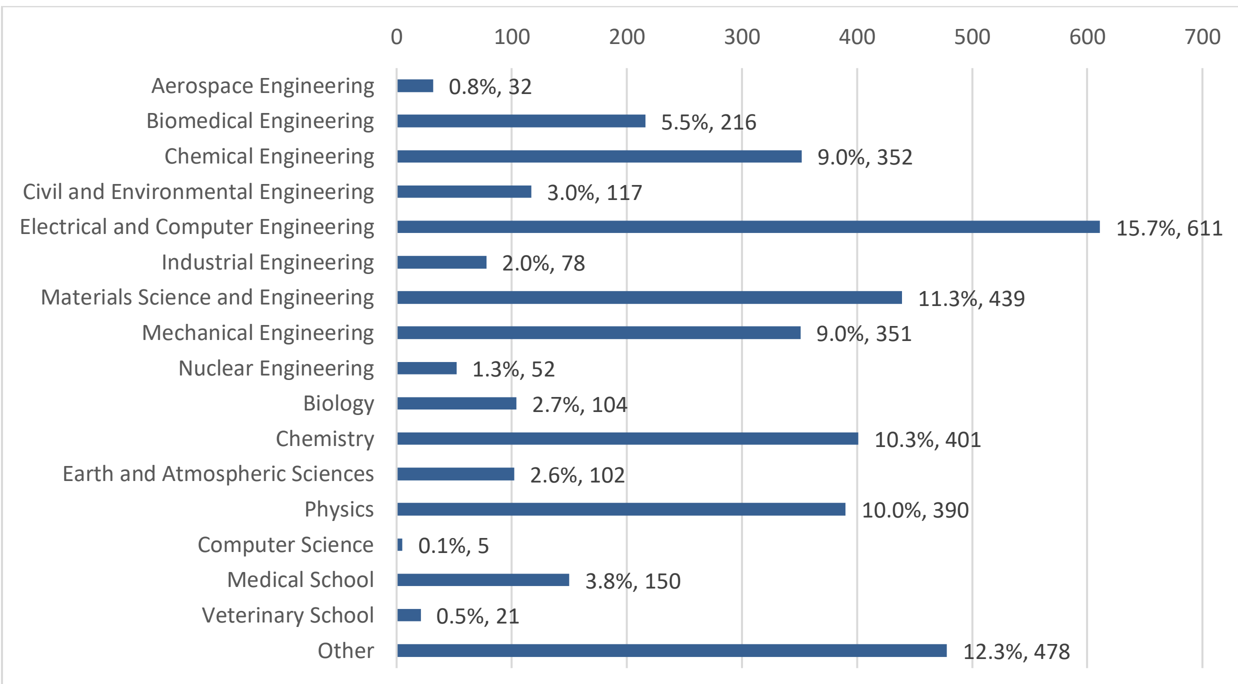


Figure 44: Academic departments of award PIs for grants summed across all funding sources, with funding provided for NNCI facility access and/or research user support (Oct. 2021 – Sept. 2022). The total number of awards included in this chart is 3,899.

Comparing value of all awards by PI's academic department (data not shown) to the number of awards in Figure 44 above demonstrates the differences in average grant value by discipline, ranging from \$0.46 million/award for Nuclear Engineering to \$2.22 million/award for Physics. The average for all awards is \$1.24 million/award.

Non-traditional users of NNCI facilities are supported by a variety of funding sources. Based on the number of research grants (not funded amounts), the largest number of awards to Earth

Sciences or Environmental Engineering PIs (219) are provided by NSF (24%) with significant contributions from Industry (11%), NASA (9%), and Other Academic sources (9%). Similarly, for those PIs in Biomedical Engineering, Biology, or Medical Schools, awards (470 total) are primarily from DHHS (50%), as expected, with additional funding from NSF (13%) and Other Academic sources (8%).

Summary

While there are additional pieces of information and trends that can be gleaned from the raw aggregate data provided in the full report, major findings can be summarized below:

- NNCI facilities during the 12-month period of October 2021-September 2022 (Year 7) supported *at least* 2,609 Principal Investigators (PIs) with a total of 3,899 grants valued at more than $5 billion.
- The top academic departments of primary award PIs (approximately 65% of awards) were: Electrical and Computer Engineering, Materials Science and Engineering, Chemistry, Physics, Chemical Engineering, and Mechanical Engineering.
- The average PI uses 1.5 grants valued at $1.2 million/grant for support of NNCI access.
- NSF remains the largest single external funding source with 859 grants (22.0%), an increase from 19.7% in 2021.
- For federal funding agencies, DOE had the largest change in number of awards supported, from 8.5% of awards in 2021 to 11.0% in 2023.
- The NSF Engineering (ENG) and Mathematical and Physical Sciences (MPS) directorates comprise 79% of awards and 84% of total NSF funded value supported by NNCI.
- Within ENG, the support is distributed among most of the divisions, while in MPS it is dominated by DMR and CHE.
- Non-traditional users are primarily supported by NSF, DHHS, NASA, and Industry.

11.6. Courses Supported

The primary mission of the NNCI is to provide training, support, and physical infrastructure for nanotechnology research. At the same time, most NNCI universities also use their core facilities in support of academic courses by providing laboratory experiences and/or expert instructors. While the students in these courses are not included in the user statistics reported above, it was the recommendation of the Metrics and Assessment subcommittee (Section 5.2) that information on these courses and students be collected to demonstrate the impact NNCI has on traditional education and workforce development. The information below was provided by all sixteen of the NNCI sites for the academic year Fall 2022-Summer 2023 (corresponding to NNCI Year 8).

More than 130 individual courses were supported from 28 different academic departments listed below. Similar department names were combined for simplicity. Each individual NNCI site supported a range of 1-29 individual courses during this time frame with total course enrollment of 3,609 students (site range: 25-1,525). A word cloud of the course titles is shown in Figure 45.

Bioengineering
Biological Mechanical Engineering
Biology
Biomedical Engineering
Biotechnology Program
Chemical and Biomolecular Engineering
Chemical Engineering
Chemistry
Chemistry & Biochemistry
Civil and Environmental Engineering
Earth and Planetary Sciences
Education
Electrical and Computer Engineering
Electrical and Systems Engineering
Electrical Engineering
Engineering
Engineering and Applied Sciences
Engineering Summer Academy at Penn
Fiber Science
Industrial Engineering
Macromolecular Science and Engineering
Materials Science
Materials Sciences and Engineering
Mechanical Engineering
Nanoengineering
Nanoscience
Physics
Sustainability

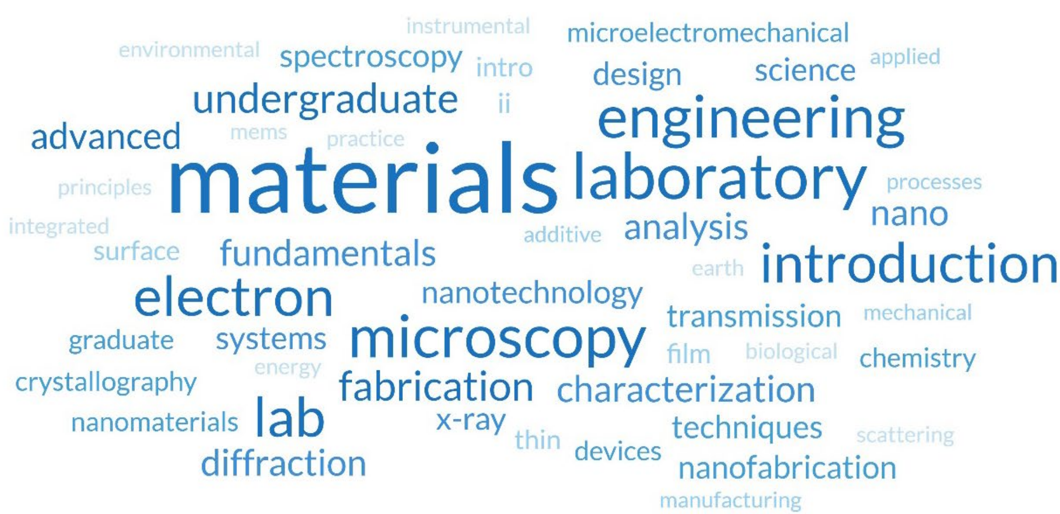


Figure 45: Word Cloud for Course Titles Supported by NNCI Facilities

11.7. Degrees Granted to NNCI Users

One of the biggest impacts that an NNCI site can have is through its training of students, since in most cases the majority of facility users are graduate and undergraduate students. Beginning with NNCI Year 6, the Coordinating Office asked sites to provide information on the number of degrees, and their academic disciplines, granted to (internal) users of the facilities. Fourteen of the NNCI sites were able to obtain that data, and some only in a limited fashion, so this reporting should be considered a lower bound only for degrees granted. The degrees awarded for Fall 2022, Spring 2023, and Summer 2023 (corresponding to NNCI Year 8) are shown in Table 18.

Table 18: Degrees Awarded to NNCI Users (Fall 2022-Summer 2023)

Academic Department	BS Degrees*	MS Degrees*	PhD Degrees	Other Degrees**	Total
Aerospace Engineering	5	5	5	0	15
Biomedical Engineering	22	35	37	1	95
Chemical Engineering	26	38	63	2	129
Civil and Environmental Engineering	1	12	27	0	40
Electrical and Computer Engineering	32	163	77	5	277
Industrial Engineering	0	0	1	0	1
Materials Science and Engineering	45	142	115	0	302
Mechanical Engineering	26	64	67	1	158
Nanoengineering	0	16	16	5	37
Nuclear Engineering	0	5	7	0	12
Biology	9	7	13	2	31
Chemistry and Biochemistry	28	30	133	1	192
Earth and Atmospheric Sciences	3	4	6	0	13
Physics	24	23	62	0	109
Nanoscience	8	5	10	0	23
Computer Science	3	14	2	0	19
Medical School	7	5	12	4	28
Veterinary School	0	0	1	0	1
Other	18	10	17	21	66
Total	**257**	**578**	**671**	**42**	**1548**

*May also include other bachelor's or master's degrees, such as BA or MA.
**May include certificates or professional degrees such as MD.

Note that departments vary across universities and degree data was adjusted to the closest fit department when necessary. Those which did not fit the departments listed above are included in the "Other" category.

Overall, a total of 1,548 degrees were awarded by the 14 sites (mean=110, range=20-284). NNCI users were awarded 671 doctorates, 578 masters, 257 bachelors, and 42 other degrees (including MD or other graduate certificates) during this NNCI Year 8. These values are similar to the previous year. By comparison, the NSF "Survey of Earned Doctorates (2021)" indicates that US institutions awarded 10,240 doctorates in Engineering and 4,693 doctorates in Physical Sciences. For NNCI users, 68% of all degrees (71% for PhD degrees) were awarded by engineering departments, although Chemistry/Biochemistry is the top PhD granting department, followed by Materials Science and Engineering, Electrical and Computer Engineering, Mechanical Engineering, Chemical Engineering, and Physics. Electrical and Computer Engineering is the top discipline for Masters degrees, while Materials Science and Engineering is the top grantor of Bachelor degrees. Disciplines in the "Other" category include Mining Engineering, Economics, Forestry and Forest Products, Food Science and Technology, Psychology, and Translational Biology, Medicine and Health among many others.

11.8. Industry Success Stories

NNCI typically supports the research efforts of 700-900 companies each year, some for a single process step or measurement at an NNCI site, and others with multi-year ongoing relationships. Identifying and collecting quantifiable metrics that demonstrate the importance of access to NNCI facilities and experts on these companies, their success, and the impact they have had on their local and regional economies is difficult. Below we illustrate this success with selected anecdotes from NNCI-affiliated companies during the past year.

CNF has supported 143 different companies (36 Large and 107 Small) for research/prototyping under NNCI, including 17 new start-up companies. **Odyssey Semiconductor**, which offers R&D, wafer fabrication, and foundry services, set up its global headquarters in Ithaca, NY.

CNS supports start-up companies through several incubators and accelerators: Greentown Labs, Harvard Innovation Lab, The Engine, and BOLT. CNS has established a Quantum Networking Alliance with **Amazon Web Services (AWS)**.

Since the beginning of the NNCI program, over 70 small companies and startups have utilized MANTH to create new nanotech products and services. More than one-third of these small companies have received external support, tying overall small company engagement to almost $80M of funding, of which more than 40% is attributed to SBIR/STTR grants. **Sonnest** has developed a silicon/glass microfluidic chip for producing an electrically sensitive ultrasound enhancing agent, that allows clinicians to evaluate the function of the heart quickly and cost-effectively at the point of care.

MiNIC is a critical resource for local start-up companies to develop initial prototypes and to scale-up new nano-scale concepts. **Himax IGI** develops lenses and other optical elements using grey-scale lithography, **Zeptolife** uses GMR sensors and a microfluidic environment with magnetic particles to create a fully-automated, extremely high sensitivity assay, and **Grip Molecular** develops next generation graphene biosensors for lab quality diagnostics at home..

MONT served the needs of 24 industrial partners (16 small businesses), and all are based in or have satellite locations in Southwest Montana and employ over 500 people. Recent SBIR/STTR Phase I and Phase 2 grants, totaling $5.3M, were recently awarded to **AdvR**, **Resodyn**, **NWB Sensors**, and **GlyderTech**.

NCI-SW supports economic development with 19 large business and 42 small business users. Small business spinout companies **Advent Diamond** and **SwiftCoat** continue to grow with new awards from DARPA, DOE, NASA, and NSF.

RTNN demonstrates the value of its facilities to small businesses and economic development with 69% of their industry users from companies with less than 50 employees and more than 200 patents filed or awarded in 2022.

SENIC user company **Absolics, Inc.** broke ground on a new $600 million semiconductor manufacturing facility in Covington, GA. The company developed its semiconductor packaging technology in collaboration with Georgia Tech's Packaging Research Center, **Saras Micro Devices** expanded its research and development presence in the Atlanta area with a new 5,000 sq. ft. cleanroom/laboratory facility, and medical device company **Artelon** secured $20 million in Series B funding to support the growth of its bio-textile for surgical joint repair and moved into new laboratory space.

12. NNCI Site Reports

NNCI sites were asked to provide summary information as part of this Year 8 report. Specific information requested included:

1. A brief narrative corresponding to the NNCI Year 8 (Oct. 1, 2022 - Sept. 30, 2023).
    a. Facilities, tools, staff updates during the year
    b. User base – marketing, outreach and support activities, including any specific research strengths or focus of the site
    c. Research highlights and impact – include brief mentions of any significant user accomplishments as well as scholarly and economic impact. Note: Research and education highlight slides are provided as a separate document.
    d. Education and outreach activities summary
    e. Societal and ethical implications activities (if applicable)
    f. Computation activities (if applicable)
    g. Innovation and entrepreneurship activities (if applicable)
2. A listing of all external user institutions for NNCI Year 8, separated as follows: Academic, Small company (<500 employees), Large company, Government, International, Other. See Appendix 14.2 for the complete listing. Due to disclosure limitations, some external users asked that their information not be shared, and the number of these are indicated in the appendix.
3. A list of site-site or network-wide activities, including proposals, facility operations, education/SEI programs, staff interactions, or other events. This is provided in Section 10.1 above.
4. For this Year 8 report, all sites were asked to provide information that contribute to understanding the impact of NNCI.:
    a. The number of publications in each category for calendar year 2022. The list of publications may have been part of each site's Year 8 report to NSF, but the data presented here (Section 11.3) are only aggregate numbers of publications for the NNCI network.
    b. New centers awarded and supported by the NNCI site during Year 8 (Section 11.4)
    c. Student degrees granted – Number of degrees awarded to facility users during Year 8 (Fall 2022-Summer 2023) per academic department (Section 11.7)
    d. Academic courses supported – Number of academic courses taught enabled by NNCI facilities (lab courses or lab portions of courses) as well as the total number of students enrolled in those courses during the Year 8 period (Fall 2022-Summer 2023). This data does not include courses which are merely taught by site faculty/staff, but only those where students perform lab work in the facility. Note that some of these students may also be research users (Section 11.6).
5. User survey data, if the site did not participate in the common NNCI user survey for 2023. This data was added to the survey results presented in Section 8.3.

In addition, the user statistics for NNCI Year 8 (Oct. 2022-Sept. 2023) were collected from the sites and used by the Coordinating Office to generate both the aggregate network user activity described in Sections 11.1 and 11.2 above, as well as the individual site usage information shown after each site narrative below.

The reports below are presented as provided by the sites, with only minor editing for format.

12.1. Center for Nanoscale Systems (CNS)

This has been an interesting year for the Center for Nanoscale Systems as our usage paradigm evolves. We continue to define a *new normal mode of operation*. The residual effects of the Covid-19 shutdown are still impacting all research operations indirectly, during this period from October 2022–December 2023. Our labs are not back to the full *"pre-covid"* capacity, but more importantly, indications are that we are establishing a bit of a *"New Normal"*. Research groups are working differently and seemingly there is still a bit of lag in the graduate students training window from which we are still recovering. PI Westervelt and co-PI Wilson, the Operational Director of the center, have been continuing the assessment, revamping, and augmentation of the tools and instrumentation available at CNS for advancing transformative Nano and Quantum science. This is being in part driven by our expanding Quantum Networking and Integrated Photonics focus. Our staff have adapted a number of operational changes advancing these efforts. Currently, we are experiencing new user training levels that are near or above, *"pre-pandemic"* levels. In addition, we've continued to establish a new footprint with a satellite unit at our New Harvard Science and Engineering Center (SEC). These labs were opened during the pandemic and now lab operations, on the Allston campus, are beginning to stabilize. We've added new staff to support operations in both facility locations.

Importantly, we've broadened our Quantum Networking partnership with Amazon Web Services (AWS). Amazon has established a local advanced technology effort devoted to device development for Optical Quantum Networking. The team members have become extensive users of a wide variety of CNS tools and instrumentation. To help us accommodate the additional traffic and bandwidth, *AWS has provided ~$5M in equipment and operations support for the New Joint effort.* We are using these funds to future-proof the lab. This "**QLab"** activity has as its mission both device development, workforce development, and teaching. Details of the purchased equipment and staffing support provided is discussed and listed below. We've rolled out our newly developed VR model of CNS which allows for virtual tours of the lab, (*directly accessible from our website* https: //my.matterport.com/show/?m=hcTD1ZqpsKu).

Facility, Tools, and Staff Updates

We continue to evolve the new facilities on the new Engineering campus in Allston, MA. CNS manages three spaces at the Harvard Science and Engineering Complex (SEC). While the preliminary research focus at the SEC has been *soft materials* the actual workflow and research directions are still in flux. Early indications suggest that many of our Harvard Medical School users as well as others in the Harvard hospital system have moved their imaging work to our Allston labs. The labs are fully open, staffed and as of this spring more the 200 Users had been trained on the new instrumentation. We two several new staff members to support efforts on the new campus. Two new staff were added last year to help support, both in Allston and Cambridge.

New CNS Tools/ Instruments: As mentioned above, this year we've begun a strategic partnership with Amazon Web Services (AWS) on Quantum Networking. *As part of this relationship, we are adding tools to increase the operational bandwidth for nanofabrication facility, the **QFab** is a key new lab activity, allowing us to future-proof our nanofabrication resources.* Through this collaboration we will acquire several new tools listed below. In addition, we continue to augment tools and instrumentation both in our Fab and imaging facilities. Finally, new tools and/or instrumentation support have been provided by the Harvard provost's office to allow us to evolve our Scanning Electron Microscope platforms as well as allow us to purchase tools to support our teaching activities. More details on our new teaching efforts are detailed below.

Instrumentation/Tool additions (*acquired with AWS support)

- Elionix ELS-Boden 150*
- Sentech SI-500 ICP-RIE (dur 8/2023)*
- AJA Sputtering/E-beam evaporator system for Complex oxides (due 7/2023)*
- Lesker High-T High Vacuum Furnace (6/2023)*
- Disco DAD-3221 Dicing Saw
- Nikon LV-150N Microscopy system (for 2D materials inspection)
- HQ Graphene Motorized 2D Materials Stacking System (for Glove-box bases assembly platform)
- EMS-plus Sputtering system (for teaching lab)
- Samco RIE-10NR system (for teaching)
- Heidelberg micro-MLA Lithography system (for teaching)

These tools were added to enhance our ability to support device development in two key Quantum materials efforts and to enable us to teach more effectively in our laboratories.

2D Assembly Platform Effort: We are continuing to build up platforms enabling 2D heterostructure Van der Waals materials assembly. The first system, (*ambient condition operation*), is up and running and available to users. Last year we added the 2D system design resource with NNCI support, as noted above, we've now added Danial Haei as a new Nanofabrication Staff Member. Danny became permanent CNS staff this past February. We've also begun assembly of a second 2D assembly system enclosed in a glovebox to enable handling of air sensitive materials.

Imaging Core Additions: This year we turned over our SEM technologies and added a JEOL F200 field emission TEM/STEM. The F200 TEM has a resolution spec is 1 angstrom at 200kv 1.6A for STEM. This system now serves as our basic training tool and is located in the new labs in Allston. We have refreshed our Scanning Electron Microscopes. The legacy systems were nearly 20 years old, and support and maintenance was becoming burdensome. With provost office support, we have added 3 new Zeiss Gemini systems. The two Gemini 360 Field Emission Scanning Electron Microscopes (FESEM) enable high resolution surface examination and analysis. We placed one Gemini 360 both in our imaging suites in Cambridge and one at the SEC in Allston. We also added a Gemini 560 Field Emission Scanning Electron Microscope (FESEM) which enables *ultra-high* resolution surface examination and analysis. An airlock chamber with integrated navigation camera enables rapid sample loading. This SEM has a cross-over free Zeiss Gemini 3 column, featuring the updated Nano Twin lens for *ultra-low* magnetic field, permitting high resolution imaging at low voltage. The Gemini 560 uses a low to moderate beam energy (0.02 to 30 keV) to image samples in *high-vacuum* with 0.5 nm resolution at 15 keV and 0.8 nm at 1 keV. All systems are fully installed and open for training. In addition, we have ordered a system that will enable our users to make *Graphene Wet Cells* allowing liquid imaging in our TEMs. This fully automated system should be online by year's end.

User Base

This year, our accumulated userbase topped 1230 active users (as of 9/30/2023). (*Note: active users are users that have accessed CNS resources during the reported grant period.*). Importantly

~49% of our user base is non-Harvard, 34% being external academic users and ~21% industrial users, (~72% of which are from small companies).

Research Highlights and Impact

Diamond Mirrors for High-Power Continuous Wavelasers: *Haig A. Atikian, Neil Sinclair, Pawel Latawiec, Xiao Xiong, Srujan Meesala, Scarlett Gauthier, Daniel Wintz, Joseph Randi, David Bernot, Sage DeFrances, Jeffrey Thomas, Michael Roman, Sean Durrant, Federico Capasso & Marko Lončar;* ***Peak Power Electronics, INC. and Harvard University;*** High-power continuous-wave (CW) lasers are used in a variety of areas including industry, medicine, communications, and defense. Yet, conventional optics, which are based on multi-layer coatings, are damaged when illuminated by high-power CW laser light, primarily due to thermal loading. This hampers the effectiveness, restricts the scope and utility, and raises the cost and complexity of high-power CW laser applications. Here the Peak Power Team demonstrated monolithic and highly reflective mirrors that operate under high-power CW laser irradiation without damage. In contrast to conventional mirrors, these optics are realized by etching nanostructures into the surface of single-crystal diamond, a material with exceptional optical and thermal properties. We measure reflectivities of greater than 98% and demonstrate damage-free operation using 10 kW of CW laser light at 1070 nm, focused to a spot of 750 μm diameter. In contrast, we observe damage to a conventional dielectric mirror when illuminated by the same beam. Their results initiate a new category of optics that operate under extreme conditions, which has potential to improve or create new applications of high-power lasers. ***Nature Communications*** 13: 2010 (2022); https://doi.org/10.1038/s41467-022-30335-2.

Laser writing of spin defects in nanophotonic cavities; *Day, Aaron M. M. [1] ; Dietz, Jonathan R. R.) [1]; Sutula, Madison [2]; Yeh, Matthew [1] ; Hu, Evelyn L. L.) [1]; [1] Harvard Univ, John A Paulson Sch Engn & Appl Sci, Cambridge, MA 02138 USA; [2] Harvard Univ, Dept Phys, Cambridge, MA USA.* High-yield engineering and characterization of cavity-emitter coupling is an outstanding challenge in developing scalable quantum network nodes. Ex situ defect formation systems prevent real-time analysis, and previous in situ methods are limited to bulk substrates or require further processing to improve the emitter properties. Here we demonstrate the direct laser writing of cavity-integrated spin defects using a nanosecond pulsed above-bandgap laser. Photonic crystal cavities in 4H-silicon carbide serve as a nanoscope monitoring silicon-monovacancy defect formation within the approximately 200 nm cavity-mode volume. We observe spin resonance, cavity-integrated photoluminescence and excited-state lifetimes consistent with conventional defect formation methods, without the need for post-irradiation thermal annealing. We further find an exponential reduction in excited-state lifetime at fluences approaching the cavity amorphization threshold and show the single-shot annealing of intrinsic background defects at silicon-monovacancy formation sites. This real-time in situ method of localized defect formation, paired with cavity-integrated defect spins, is necessary towards engineering cavity-emitter coupling for quantum networking. ***Nature Materials 22****, 696–702 (2023). https://doi.org/10.1038/s41563-023-01544-*

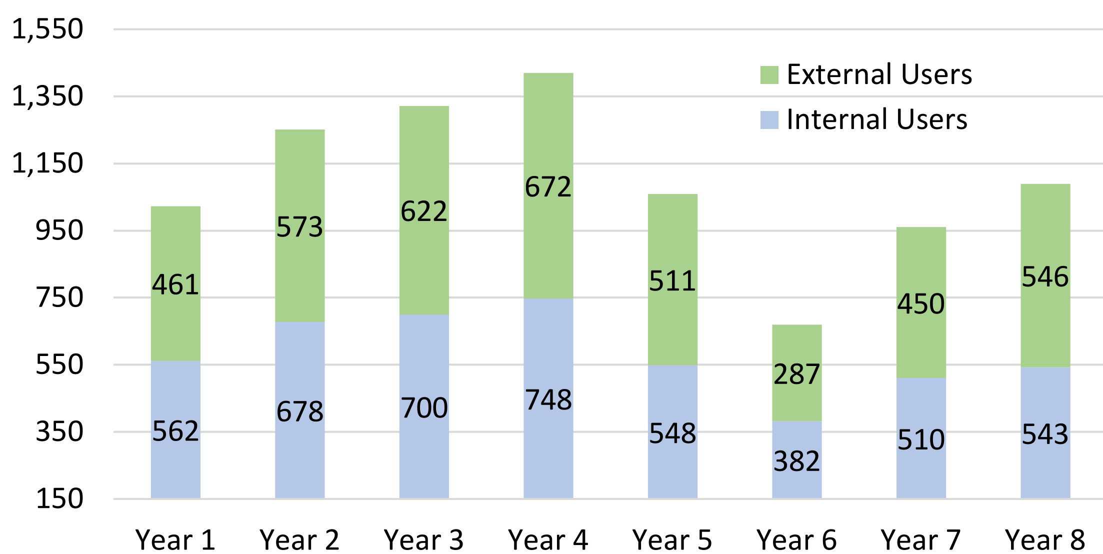
In-sensor Optoelectronic Computing using Electrostatically doped Silicon; *H. Jang, H. Hinton, W. Jung, M. Lee, C. Kim, M. Park, S. Lee, S. Parl, and Dohnee H. Ham;* ***Samsung Advanced Institute of Technology, Samsung Electronics, and Harvard University.*** Complementary metal–oxide–semiconductor (CMOS) image sensors allow machines to interact with the visual world. In these sensors, image capture in front-end silicon photodiode arrays is separated from back-end image processing. To reduce the energy cost associated with transferring data between the sensing and computing units, in-sensor computing approaches are being developed where images are processed within the photodiode arrays. However, such methods require electrostatically doped photodiodes where photocurrents can be electrically modulated or programmed, and this is challenging in current CMOS image sensors that use chemically doped silicon photodiodes. Here Samsung and Harvard Researchers reported in-sensor computing using electrostatically doped silicon photodiodes. They fabricate thousands of dual-gate silicon p–i–n photodiodes, which can be integrated into CMOS image sensors, at the wafer scale. With a 3 Å ~ 3 network of the electrostatically doped photodiodes, they demonstrated in-sensor image processing using seven different convolutional filters electrically programmed into the photodiode network. ***Nature Electronics*** **5**, 519–525 (2022). https://doi-org.ezp-prod1.hul.harvard.edu/10.1038/s41928-022-00819-6

Education and Outreach Activities

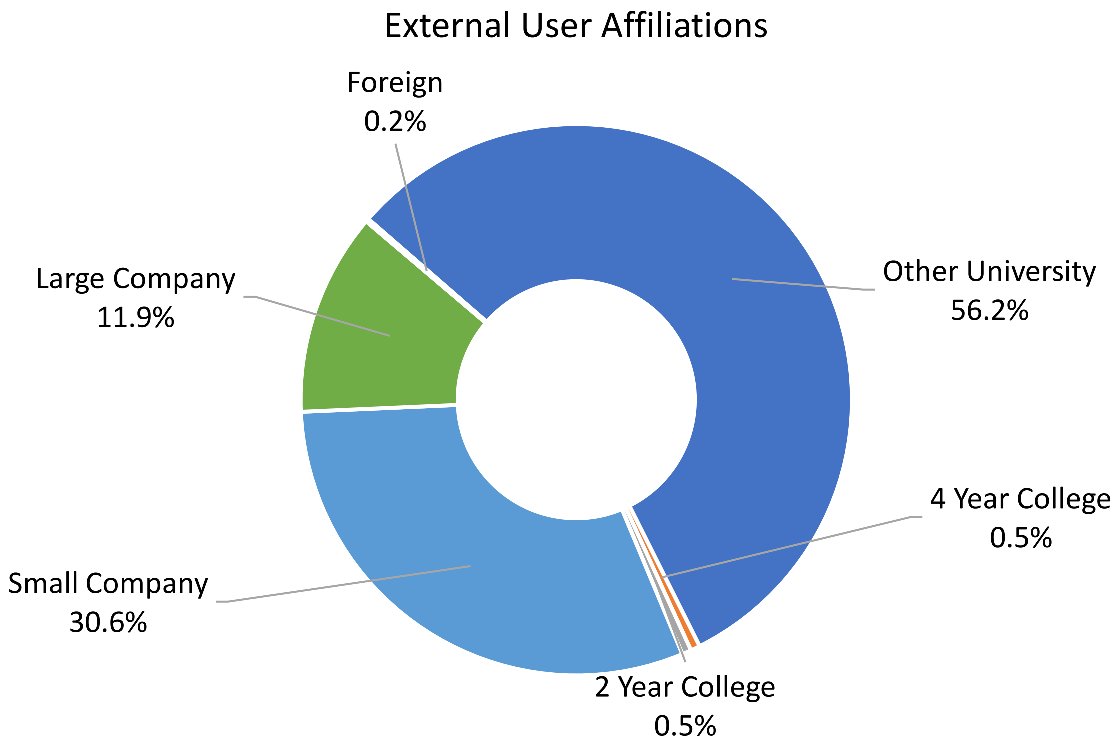
This year we've begun to expand the educational efforts in the lab. We now support two advanced processing courses in our cleanroom. The classes ES 177/277 and ES 176/276 are advanced undergraduate and graduate offerings where students get direct "hands-on" training as they process devices for the class projects. The entire experimental curriculum was developed with CNS staff input and support. The goal has been to offer comprehensive nanofabrication training with minimal disruption to the research mission of the lab. We have been successful thus far in striking the proper balance between class size, training burden, and cleanroom traffic. These new academic offerings are part of our efforts to expand workforce development activities at CNS. The students and their devices are featured in the engineering students design fair held each spring. We note that in general we support a variety of academic offerings in our lab spaces, including Advanced Electron Microscopy (AP 291) and Advanced instrumentations classes (Chem 165). Finally, we continue to evolve our Master Class Lecture series and this year we Sponsored a *Quantum @Harvard* Lecture series, the videos of which are hosted on our website. Last Summer we re-booted our CNS NanoFab summer school and have been "re-connecting" with our CNS scholars as they again begin the "spin-up" of their research activities, *post-pandemic*. This year we plan to recruit more broadly for our CNS Scholars program at HBCUs with the goal of adding at least two new scholars. I have a recruiting trip to Spellman, Morehouse, and Clark Atlanta University planned for this fall. In addition, we plan to finish our "*Glove-box*" based 2D Assembly system with the hope to have it open for users this fall. We have ordered a New High-resolution Flip-Chip bonder to enable heterogeneous integration, particularly integrated photonics in thin film $LiNBo_3$. Again, we expect this system to be available to users by fall. These tools are part of our expanding tool based being optimized to enable fabrication of high-end integrated photonics. Finally, with new support from a DURIP award, Our NNCI-supported postdoc will begin development of a Low-Temperature Scan-Probe Spectroscopy tool. The postdoc, Dr. Ibrahim Abdelwahab, is also finishing work exploring Exciton-polariton dynamics is both 2D Janus TMDCs and an array of 2D perovskites using Scan-probe Near-field Microscopy.

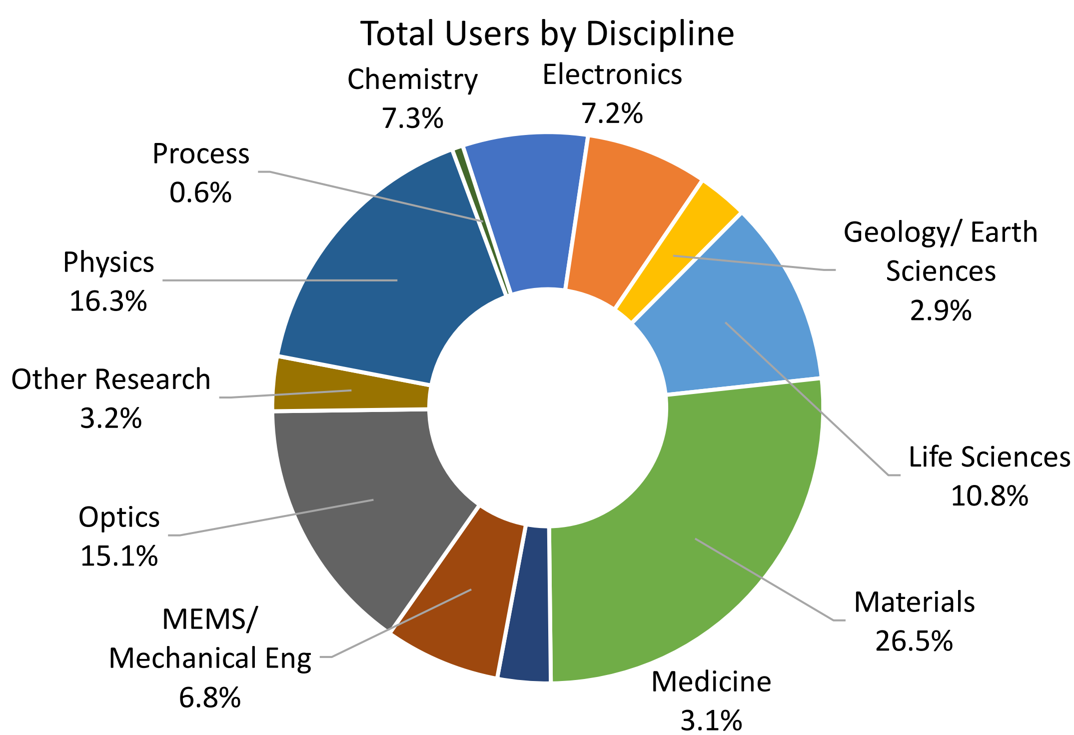
CNS Site Statistics

Yearly User Data Comparison								
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	1,023	1,251	1,322	1,420	1,059	669	960	1,089
Internal Cumulative Users	562	678	700	748	548	382	510	543
External Cumulative Users	461 (45%)	573 (46%)	622 (47%)	672 (47%)	511 (48%)	287 (43%)	450 (47%)	546 (50%)
Total Hours	174,710	181,826	185,288	204,221	114,523	116,357	142,332	157,121
Internal Hours	124,256	133,020	126,662	117,615	69,904	66,051	75,954	90,924
External Hours	50,454 (29%)	48,806 (27%)	58,626 (32%)	86,607 (42%)	45,519 (40%)	50,307 (43%)	66,378 (47%)	66,198 (42%)
Average Monthly Users	511	514	538	565	317	260	379	442
Average External Monthly Users	201 (39%)	196 (38%)	218 (40%)	250 (44%)	137 (43%)	102 (39%)	160 (42%)	192 (43%)
New Users Trained	415	404	452	483	191	116	366	352
New External Users Trained	196 (47%)	200 (50%)	233 (52%)	240 (50%)	89 (47%)	43 (37%)	183 (50%)	207 (59%)
Hours/User (Internal)	221	196	181	157	126	173	149	167
Hours/User (External)	109	85	94	129	89	175	148	121



CNS Year 8 User Distribution





12.2. Cornell Nanoscale Science and Technology Facility (CNF)

Facility, Tools, and Staff Updates

The Cornell NanoScale Science and Technology Facility (CNF) enables rapid advancements in science, engineering, and technology at the nanoscale by providing efficient access to nanotechnology infrastructure and expertise. CNF operates as a flexible open user facility and is proud to be a member of the National Nanotechnology Coordinated Infrastructure (NNCI). CNF has consistently demonstrated the ability to bridge disciplinary boundaries, providing innovative solutions to challenging, multi-step, micro- and nanofabrication processes.

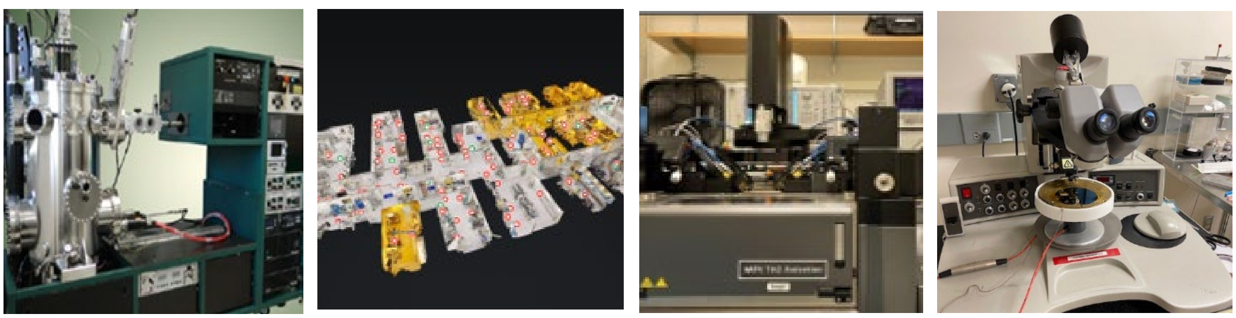
The CNF prides itself on its 46-year history of proven experience as a national and international user facility. The CNF staff is comprised of over 23 dedicated experts committed to the needs of the user community. Their extensive knowledge ensures optimal equipment performance, comprehensive training, and invaluable technical guidance. CNF offers an affordable hands-on 24/7 facility with over 180 tools and capabilities advancing nanoscale research, process development, and prototype fabrication.

CNF possesses one of the most comprehensive selections of nanotechnology fabrication and characterization equipment to support Electronics, Organic and Flexible Electronics, Spintronics, Magnetics, Quantum Computing, MEMs/NEMs, Photonics, Life Sciences, Agriculture, and Nanomedicine. CNF's expansive toolset provides unique capabilities and the flexibility to process a wide range of materials without cross-contamination. CNF has the most advanced e-beam and photo lithography facilities in the network including its only DUV stepper; nanoimprint; contact aligners; 20 dry etcher chambers; 11 CVD and 10 atmospheric tubes, graphene and carbon nanotube deposition, CMP; physical and chemical vapor deposition; plasma-enhanced CVD deposition; atomic layer deposition; molecular vapor deposition; in-house mask makers; rapid thermal processing; electron microscopy; atomic force microscopy; advanced packaging; high frequency electrical testing; and an extensive suite of CAD and modeling software. Through partnership with the Cornell Institute of Biotechnology, users have access to 18 advanced 3-D characterization and imaging tools. A partnership with the Mechanical Engineering Department's Rapid Prototyping Lab (RPL) provides all users with access to a dozen modern 3-D printers and laser cutters.

Continuously enhancing the user experience is an ongoing process. Acquisition of new cutting-edge tools is guided by discussions with the advisory committees and incoming Cornell faculty members. CNF is in the process of replacing its 20-year-old lab management software with NEMO, an intuitive and easy to use laboratory logistics software suite designed by NIST. NEMO manages tool reservations, enables and disables tools, tracks usage, and provides billing of user charges. A state-of-the art superconducting film deposition system has been ordered with an anticipated arrival in spring of 2024. This specialized AJA system is designed specifically for quantum technology. Existing furnace tubes have been updated and reconfigured to deposit LPCVD silicon carbide and high temperature LPCVD silicon nitride for III-V materials. These upgrades are pivotal steps toward enhancing our capabilities and positioning ourselves at the forefront of groundbreaking research and innovation. Menlo Micro is a local company specializing in the production of micro switches, and has generously contributed an Ultratech 602 mask cleaner, K&S 4522 Ball Bonder, a Nikon IR inspection scope, and a Tencor M gage 200 to the CNF. The following tools/capabilities have been acquired or installed/qualified during the past year (Table and Figure below).

Tools/capabilities that have been acquired or installed/qualified over the past year at the CNF

Recent Capital Equipment Acquisitions and Capabilities	
AJA UHV Multi-Technique Deposition System	Terahertz Probe Station
LPCVD silicon carbide	High temp LPCVD silicon nitride for III-V materials
3D Virtual Cleanroom Experience	NEMO Lab Management Web Application
UT 602 Mask Cleaner	Nikon IR inspection tool
Tencor M Gage 300	K&S 4522 Ball Bonder



Newly added capabilities at CNF: AJA UHV Multi-Technique Deposition system, 3D Virtual Cleanroom Experience, Terahertz Probe station, K&S Ball Bonder

CNF has a dedicated technical management team (2 FTE + Faculty Director), supported by an administrative staff (2.75 FTE), and a laboratory technical staff of 20 (18.5 FTE). The main purpose of CNF is to support the user program, provide instruction, and to maintain equipment to ensure the operational success of the CNF.

Dr. Judy Cha

On August 21, 2023, Dr. Judy Cha, a Cornell Ph.D. '09 in Applied Physics and a professor of Materials Science and Engineering, became the ninth Lester B. Knight Director of the Cornell NanoScale Science and Technology Facility (CNF). An expert in topological and two-dimensional nanomaterials with quantum properties, she joined Cornell's faculty in 2022 after postdoctoral research at Stanford University and a faculty position at Yale University.

<u>User Base</u>

In the eighth year of the NNCI, CNF hosted 1,315 users, with 17% representing external users. The inclusion of data from new Biotech and RPL partnerships revealed a shift towards heavier usage for life science projects and a decrease in the percentage of external users. Cornell users utilized 47,544 hours, while external users accounted for 14,523 hours (23% of total usage hours). External user fees accounted for $1.5 million of the total $3.0 million in user fees.

Cleanroom hours exceeded 62,000, with an average monthly user count of 397, consistent with the previous year. Additional user statistics are available in the NNCI coordinating site's report.

Research Highlights and Impact

CNF compiles annual technical research reports in the *CNF Research Accomplishments* available online at https://cnf.cornell.edu/publications/research_accomplishments/2022-2023.

The impact of technical reports generated by CNF users is gauged through their inclusion in respected scientific journals such as *Science*, *Nature, Cell,* and others as well as patents filed and granted. Research highlights from recent user projects are included in this report's appendix.

In 2022, CNF-supported research resulted in a minimum of 234 publications, 84 presentations, and 73 patents/patent applications. Efforts are made to ensure proper crediting of CNF and the NSF award number in publications. Users are encouraged to report their publications, and CNF compiles these outputs annually, acknowledging that reporting could be further improved for accuracy.

Economic Impact

CNF is a key resource for advancing nanotechnology to the market. One hundred fifty-three companies, comprising 112 small/startups and 41 large businesses, have utilized CNF for substantial research, development, and prototyping under NNCI. CNF actively contributes to the growth of small businesses, with an average of two new startup launches annually since the beginning of NNCI.

Startup companies that used the CNF to develop technology.

White Light Power	Kanvas Biosciences	Odyssey Semiconductor	OWIC Technologies	Esper Biosciences	Halo Labs
Inso Bio	CyteQuest	Logrus,	Jan BioTech	Heat Inverse	FloraPulse
Xallent	Ultramend	JR2J	GeeGah	Soctera	

CNF influences major companies including Pacific Biosciences, Applied Materials, ASML, JOEL, Wolfspeed, Corning, GE, Google, BAE Systems, MACOM, Facebook/Oculus, Samsung, and others by offering access to advanced materials and instruments in a flexible environment conducive to rapid technology development. In the past year, 34 small U.S. companies and 9 large U.S. companies benefitted from this access.

Cornell is a founding member of The Northeast Regional Defense Technology Hub (NORDTECH), a coalition of public and private sector experts in the Microelectronics Commons region around New York State. In this partnership, CNF plays a pivotal role in supporting a range of research and development activities. The collaborative program integrates Department of Defense (DoD) selected research and development projects, while expanding CNF's micro-nanotechnology equipment and user base. This initiative positions CNF at the forefront of advancements in microelectronics and nanotechnology, further reinforcing its strong commitment to training the next generation workforce.

Education and Outreach Activities

CNF actively supports diverse education and outreach initiatives across K-12, post-secondary, professional, and public domains. This year, CNF engaged in 116 events, attracting a total of 4054 participants.

CNF continues to lead the establishment of the New York State Nanotechnology Network (NNN). Following the success of the initial student showcase in May 2022 (88 participants), the 2nd Annual NNN Student Showcase/Career Fair focused on "Advances in the Semiconductor Industry" was held at the University at Albany in April 2023, drawing 143 participants. Binghamton University hosted the 3rd NNN symposium at the Albany Nanotech Complex in September 2023, alongside the 34th Annual Electronics Packaging Symposium, with a total of 250 participants. These events spotlighted student talent, fostering collaboration among New York colleges, universities, and industries for networking and promoting technology research. Given the CHIPS & Science Act, the forthcoming Micron fabrication complex in Syracuse, and associated New York State initiatives, workforce development gains increased prominence in the region, underscoring the NNN's vital role in uniting regional industry and universities.

At the CNF Annual Meeting, Dr. Sophie V. Vandebroek, founder of Strategic Vision Ventures, shared career insights, and Dr. Robert Simmons, Head of Social Impact and STEM Programs for Micron, discussed workforce development. The annual meeting provides an opportunity to showcase research excellence demonstrated by users and research groups utilizing the resources offered at the CNF. The meeting proceedings can be found at https://www.cnf.cornell.edu/events/past/annual_meetings/2023.

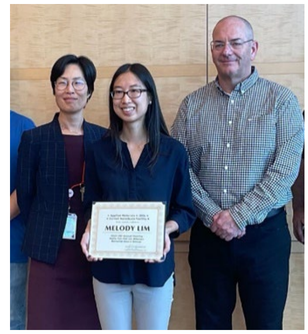
The CNF actively engaged in the 2023 Workshop on Nanotechnology Infrastructure of the Future. Led by Stanford, the workshop sought input on various topics to guide future planning. The result of the workshop was a public-facing white paper submitted to NSF with future recommendations for presentation to U.S. government agencies.

CNF REU Participants

In the summer of 2023, the CNF hosted a Research Experience for Undergraduates (CNF REU) program. The CNF REU program is sponsored in coordination with programs at other participating NNCI sites. Seven undergraduates and one graduate student from Japan participated in this year's program. (Figure 3).

CNF and the National Institute of Material Science (NIMS), Tsukuba, Ibaraki, Japan hosted the Global Quantum Leap International Research Training Experience (GQL IRTE) Program and the International Research Experiences for Undergraduates (CNF iREU) Program. Five former NNCI REU students participated in this year's IREU program. A major part of the Global Quantum Leap program is its IRTE program which is largely managed out of CNF for GQL. IRTE is modeled after the IREU program, however with a narrower technical focus (quantum IT) and a broader recruitment (not limited to NNCI REU). In 2023, GQL/NNCI sent 3 students to NIMS in Japan for quantum related projects. All final reports and a list of participants are online at https://www.cnf.cornell.edu/education/reu/2023.

Annually the CNF presents the Whetten Memorial Award in recognition of women scientists whose work and professional lives exemplify a commitment to scientific excellence, interdisciplinary collaboration, professional and personal courtesy, and exuberance for life. The 2023 award was presented to Melody Lim of the Laboratory of Atomic and Solid-State Physics, Cornell University (Figure 4)



2023 Whetten Award winner

CNF continues to offer the Technology and Characterization at the Nanoscale (TCN) short course virtually each January and in-person each June. This course is integral to community college micro-credential and ATLAS (Advanced Training for Labor Acceleration in Semiconductors) programs.

Collaborating with Micron, CNF participated in workforce development activities like the Northeast University Semiconductor Network and Micron "Chip Camps." The Northeast University Semiconductor Network is tasked to modernize and enhance curriculum, expand access (DEI) and experiential learning programs. Three Chip Camp events (Figure 5) were hosted in 2023, engaging more than 100 junior high students per event in nanotechnology exploration and cleanroom activities.

Micron Chip Camps

CNF continues its annual outreach events, including Tompkins County Expanding Your Horizons, 4-H Career Explorations, alumni reunion tours, Junior First Lego League, Kangaroo Math, and various science classroom visits. High-impact youth outreach events included a virtual cleanroom experience at the New York State Fair, reaching over 400 visitors.

Nanooze is the CNF's kid friendly publication (also @ http://www.nanooze.org). The magazine is intended to excite kids about nanoscience and nanotechnology. CNF distributes Nanooze to NNCI sites, schools, and museums for use in classrooms, libraries, and extracurricular camps. Over 100,000 copies have been distributed this year.

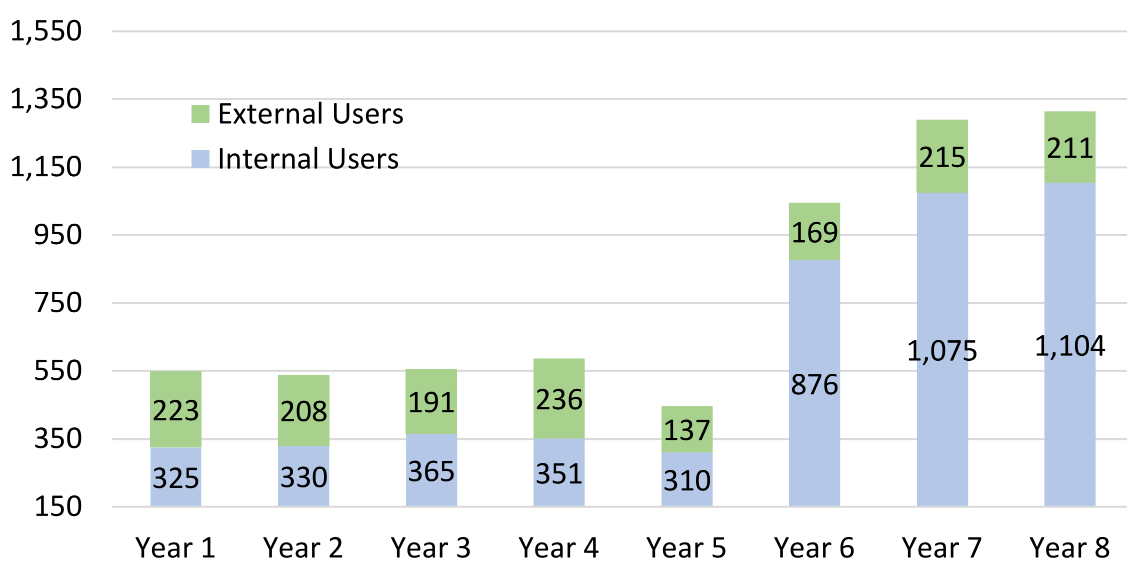
CNF has made significant progress on the workforce development front by launching several new programs in collaboration with local partners. One noteworthy initiative involved working closely with Tompkins Cortland Community College (TC3) to establish micro-credentials. Additionally, CNF is actively involved in assisting with the procurement and identification of equipment. This support aims to enable TC3 to expand its micro-nano educational capability assisting the high-tech workforce in our area. CNF and TC3 have also been working with Penn State to become a new partner site for their Microelectronics and Nanomanufacturing Certificate Program for veterans. We anticipate this project being funded in early 2024 with our first cohort of veteran students coming to the facility in fall of 2024.

CNF is actively expanding its partnerships with regional Board Of Cooperative Educational Services (BOCES). The ATLAS program, initiated in 2022 through collaboration with Tompkins Seneca Tioga (TST) BOCES' New Visions Engineering program, is set to welcome a new cohort of students visiting CNF in January 2024. This program serves as a cornerstone for our workforce educational initiatives, with a strategic focus on program expansion across the central New York region and beyond, extending its reach nationally.

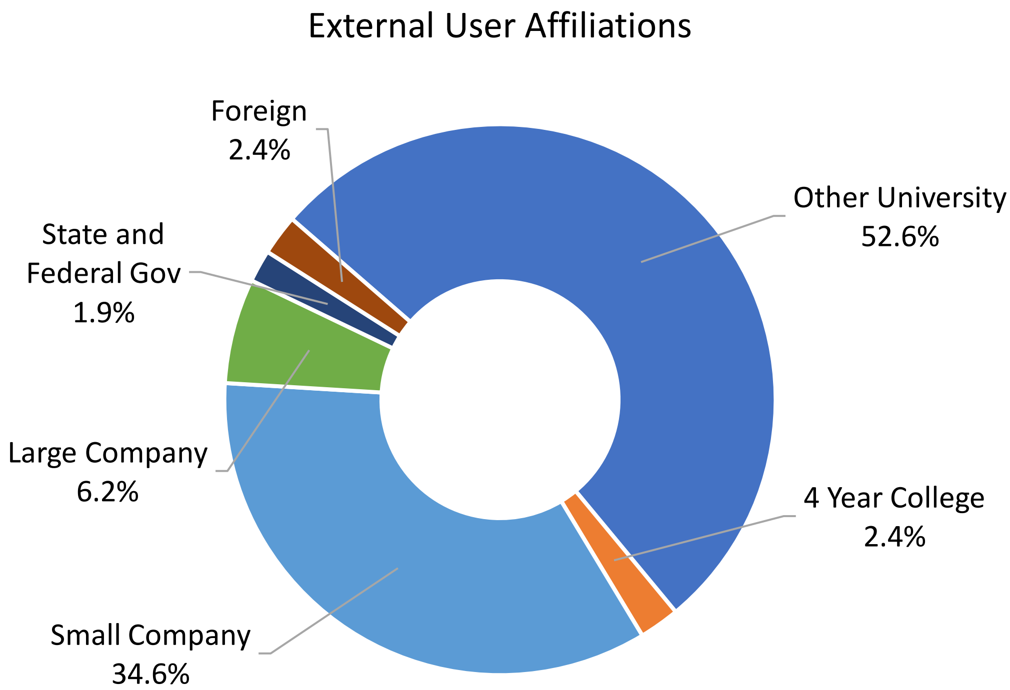
CNF is committed to being a leader in education and outreach and workforce development in the field of micro and nanoscience. We are thankful for the opportunity to innovate and form new partnerships to meet the needs of this expanding industry in the United States and look forward to continued growth in this area.

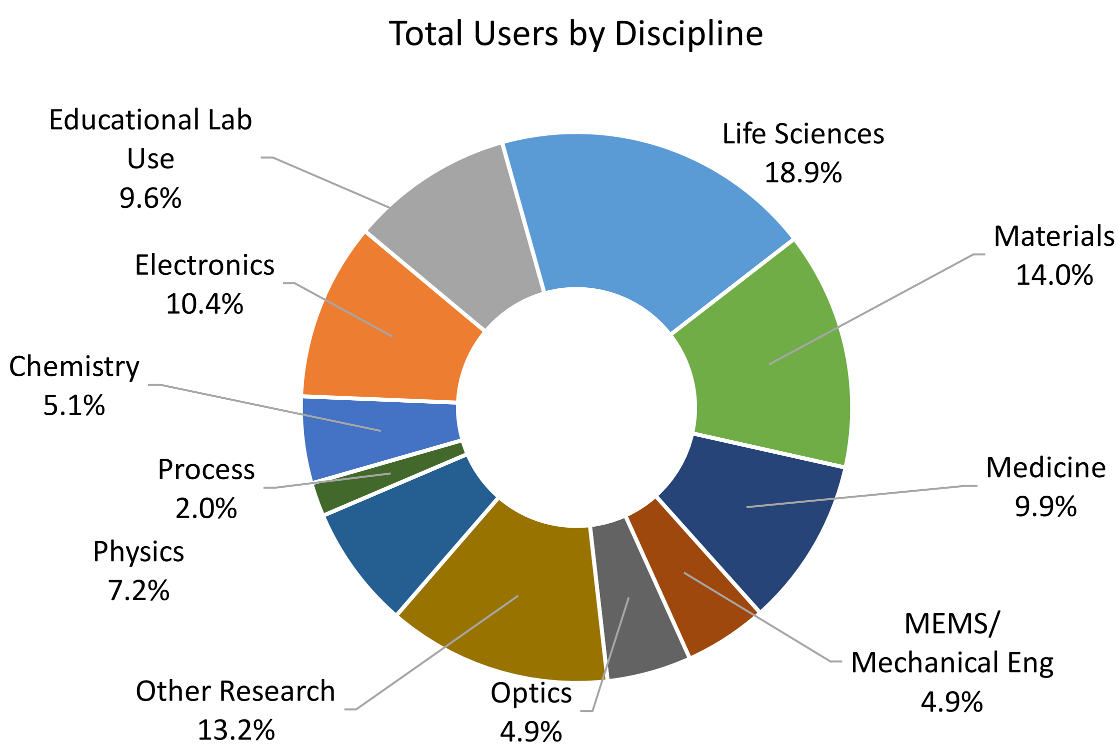
CNF Site Statistics

Yearly User Data Comparison	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	548	538	556	587	447	1,045	1,290	1,315
Internal Cumulative Users	325	330	365	351	310	876	1,075	1,104
External Cumulative Users	223 (41%)	208 (39%)	191 (34%)	236 (40%)	137 (31%)	169 (16%)	215 (17%)	211 (16%)
Total Hours	40,544	45,340	53,680	56,668	31,415	53,688	63,421	62,069
Internal Hours	22,965	25,201	31,143	34,627	20,446	38,571	46,695	47,544
External Hours	17,579 (43%)	20,139 (44%)	22,537 (42%)	22,041 (39%)	10,968 (35%)	15,117 (28%)	16,726 (26%)	14,525 (23%)
Average Monthly Users	210	204	225	235	149	332	396	397
Average External Monthly Users	67 (32%)	66 (32%)	68 (30%)	71 (30%)	39 (26%)	59 (18%)	65 (16%)	55 (14%)
New Users Trained	131	161	174	208	77	355	361	338
New External Users Trained	46 (35%)	51 (32%)	42 (24%)	91 (44%)	12 (16%)	42 (12%)	77 (21%)	72 (21%)
Hours/User (Internal)	71	76	85	99	66	44	43	43
Hours/User (External)	79	97	118	93	80	89	78	69



CNF Year 8 User Distribution





12.3. Kentucky Multi-Scale Manufacturing and Nano Integration Node (KY Multiscale)

<u>Facility, Tools, and Staff Updates</u>

Facilities – UofL began construction this year on a new $100M Engineering Building. The new 120,000 sq ft building will provide a central location for our Conn Center for Renewable Energy Research core facilities, as well as a new, greatly enhanced, state-of-the-art makerspace, which is being named the <u>Innovation Hub</u>. The building will also house academic classrooms, a café, engineering study/recreation spaces, and support offices for advising, recruiting, admissions student success, RSO teams, competition teams, career services, summer camps, and Engineering Information Technology (IT).

UofL New Engineering Building.

Tools and Equipment - Our NNCI site made several important equipment acquisitions during this reporting period. The UofL Micro/Nano Technology Center (MNTC) took out a $1M loan to purchase a new DRIE system to replace our outdated and aging 27-year-old system. **The new Oxford DRIE System** was installed, characterized, and made available to users in year 8. This new system has enhanced features **unique to the NNCI network** and is capable of much faster etching. It can etch pieces along with wafer diameters of 4”, 6” and even 8”, which is critical for industry users. In addition, the UofL Additive Manufacturing Institute of Science and Technology (AMIST) purchased a new metal powder atomizer. **The Amazement rePowder Metal Powder Atomizer** is a unique capability to have at a university research center. This system allows users to create metal powder from any alloy in any feedstock form, even in small quantities. Raw elements or scrap material can be used to prototype new alloying systems in the form of cast powder. Failed printouts, unused powder, scrap from other processes can be recycled back into fine powder. AMIST also acquired a new **XiP 3D Printer**. This printer combines a compact footprint with a large build volume and fast print speed to deliver high-quality prototypes. In addition to an open material platform, it has a broad range of validated rigid and elastomeric materials for prototyping and desktop manufacturing processing.

Staff Updates - In this reporting period, we had several personnel changes. **Dr. Dilan Ratnayake** transitioned from a postdoc position to a permanent nanotechnology research scientist. Dr. Ratnayake was previously at the nanotechnology center at George Washington University in DC. As a research scientist at UofL, Dr. Ratnayake focuses his efforts in 2 areas: 1) developing smart materials to function as the building blocks for No Electrical Power (NEP) Bistable MEMS Sensors, and 2) using aerosol jet printing to directly write conductive, semiconductive, and insulating materials on non-planar surfaces. **Dr. Chuang Qu** also transitioned from a postdoc position to a permanent research staff scientist. Dr. Qu did his PhD in Mechanical Engineering from the Missouri University of Science and Technology. His research is developing novel self-assembly nano-processes for the MNTC and its user base. Presently, he is using glancing angle deposition (GLAD) to deposit a variety of interesting nano-structures using different materials.

Dr. Chuang Qu won the 1st Place Research Staff Award at the 2023 Research Louisville

His most recent accomplishment is using GLAD to mimic the hydrophobic and antibacterial properties of the nanostructures found in nature, such as those on the wings of the Cicada insect. Dr. Qu was honored to win 1st place in the Research Staff Category at the 2023 Research Louisville Conference (see photo). In addition, Dr. Qu also took 1st place in the NNCI network-wide 2023 Nano-Image Contest in the ***Most Unique Capability*** category.

Faculty Updates - Dr. Philip (Sanghyun) Lee, Toyota Engineering Technology Distinguished Professor, Director of Undergraduate Study, Computer Engineering Technology joined the University of Kentucky semiconductor professionals. Dr. Lee is from Indiana State University's Department of Electronics and Computer Engineering Technology where he served as an Assistant Professor and CET Program Coordinator for the department.

User Base

Growing our user base has continued to be one of our top priorities in Year 8. As recovered from the harsh pandemic, more and more users slowly returned to the cores to conduct their research face-to-face. In Year 8 we continued several activities that were initiated in Year 7 to keep encouraging that positive trend.

KY Multiscale Newsletter, Email Campaigns, and Social Media - The main reason we have been able to grow our contact list so rapidly is because of our targeted efforts to identify regional contacts who are in the micro/nano/AM spaces. This way we are able to tailor our email marketing campaigns to reach a specific audience, while focusing on information aligned with their interests. *We are proud to now have* ***over 16,000 recipients*** *of our monthly KY Multiscale Marketing Campaigns!* In Year 8, we had much success reaching out to new audiences via social media using LinkedIn, Facebook and Instagram. We added posts (pictures with captions and/or sort video clips) about our new equipment and their capabilities. We also utilize social media to share event flyers (such as workshops, seminars, and our Nano + AM Summit), program announcements (such as REU, NanoSIMTS Summer Program, etc), seed funding opportunities, and more. We are constantly trying to reach new users while reminding existing users of our excellent capabilities. This has proven to be a great way of reaching out to new contacts via the portals' sharing capabilities. Our social media activity in Year 8 was as high as it has ever been.

2023 Nano + AM Summit, Seminars, & Workshops - In Year 8, our signature event continued to be our ***Annual Nano+Additive Manufacturing Summit***. In Year 8, we brought together over 150 participants to this highly interdisciplinary conference, dedicated to bringing together researchers/users in the advanced manufacturing fields of additive manufacturing and micro/nanotechnology to discuss new findings, share results, showcase capabilities, generate ideas, debate the future, and network with one another. The 2023 NNCI Nano+AM Summit brought together 4 amazing keynote speakers highlighted in the figure at right - Dr. Ilke Arslan (Argonne National Lab), Dr. Mark Poliks (Binghamton University), Dr. Carlos Portela (MIT), and Dr. Ed Herderick (NSL Analytical).

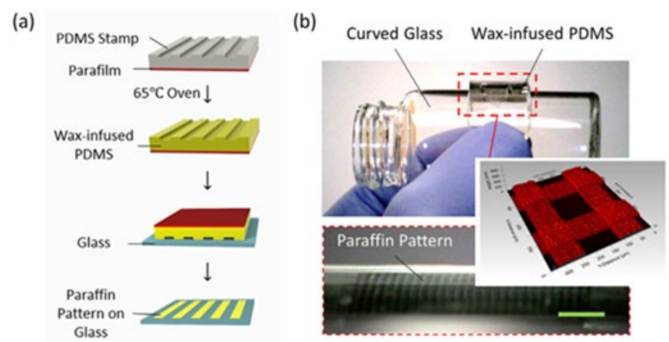
Keynote Speakers for the 2023 NNCI Nano+Additive Manufacturing Convergence Summit.

KY Multiscale also advertises, coordinates, sponsors, and hosts in-person and virtual seminar series and workshops for our user base, as well as prospective clients. We experienced more participation with our Year 8 in-person events since COVID is declining, and we intend to keep pushing this trend forward. For example, on April 11, 2023, we hosted an IN-PERSON ONLY full-day workshop by Plasma Therm on the *Fundamentals of Plasma Processing (Etching and Deposition)*. We had 62 university and industry guests attend this event. Some attendees came from as far away as New York!

Outreach Programs - In Year 8, we continued our **two Internal Seed Programs** which funded new micro/nano/additive/materials users from under-represented populations and/or non-traditional users. Other outreach events included our "Research Exposition (E-Day)" and Core Facility Tours open to the public, which continued to drive new visitors to our NNCI site.

Research Highlights and Impact

Our complete annual report presents several research projects that made extensive use of the KY Multiscale core facilities. Here we present one interesting project entitled "Hydrophobic Surface Patterning with Soft, Wax-infused Micro-stamps". A team led by Prof. Christine Trinkle (UK Mechanical and Aerospace Engineering) recently developed a new approach to nanoscale printing in which PDMS is infused with paraffin that can be subsequently transferred to a target substrate. The researchers showed that patterns with variable thickness and sub-micron resolution can be produced, and the process is readily adaptable to curved surfaces. In addition, the stamp replenishes the surface in less than one-second without re-inking. As a result, multiple stamping and multilayer patterning processes can be realized quickly, as shown in the figure. The technique holds promise for creating small hydrophobic regions that control wetting and for biological patterning. This research was performed at the University of Kentucky CeNSE and EMC core facilities and was supported by NSF Award #1849213. Its results were published in the Journal of Colloid Interface Science, v. 615, p. 494 (2022).



Nano-printing using a paraffin infused PDMS stamp. (a) The stamp is infused with paraffin from a Parafilm sheet at a slightly elevated temperature, and the pattern can be transferred to a target substrate. (b) Stamping can be conducted on both flat and curved substrates (scale bar = 1 mm). Inset: The stamp surface replenishes itself in less than 1 second for multilayer stamping

Education and Outreach Activities

Our NNCI site was involved in many educational and outreach activities during this reporting period. We highlight a few of our most popular and successful E&O activities below.

REU Programs – The UofL MNTC and AMIST core facilities hosted 9 outside undergraduate STEM students for an exciting NSF REU program entitled – IMPACT (Interdisciplinary Micro/nano/additive Program Addressing Challenges Today). The students received hands-on micro/nano/additive manufacturing training in our state-of-the-art core facilities, professional development, and a personalized research experience. This was the last year of our NSF grant renewal (our 6^{th} year for this program), but we have a renewal proposal pending into NSF for continuation. In addition, UK's CeNSE, EMC and CAM core facilities hosted 2 REU programs in the areas of Engineered Bioactive Interfaces Devices and Material Symmetries. Our REU students presented their research results at 2 different conferences - The 2023 NNCI Nano+AM Summit in Louisville and the 2023 NNCI REU Convocation celebrated at Montana State University.

RET Programs – The UofL Conn Energy Center core facility hosted 10 teachers to learn about and develop educational modules related to energy storage/transfer/conversion/efficiency/renewables. This program was led by Prof Brian Robinson of the Department of Engineering Fundamentals. In addition, Profs Faisal Aqlan and Li Yang of the UofL Industrial Engineering Department ran a second RET program that focused on Manufacturing Automation and Simulation, which leveraged the UofL AMIST core facility.

NanoSIMSTs – KY Multiscale joined forces with Nano Stanford and sponsored 1 Middle School Teacher to participate in the virtual NanoSIMSTs program. Dr. Kevin Walsh, Director of the KY Multiscale site, presented a talk about *"MEMS Technology and Sensors"* to program participants during the workshop. KY Multiscale will continue to partner with Stanford on this program and is planning to sponsor up to 6 MS teachers in the summer of Year 9.

Industry Outreach **-** On March 8, 2023, a group from SK Blue Oval visited the MNTC and AMIST core facilities at KY Multiscale. SK Blue Oval is a joint venture between Ford in the United States and SK Industries in South Korea focused on the manufacturing of next-generation batteries for electric vehicles (EV). SK Blue Oval is in the process of building a $5.8B manufacturing and research facility in Glendale, Kentucky, just outside of Elizabethtown. KY Multiscale research cores are exploring opportunities to collaborate.

Educational Initiatives – With the announcements of the CHIPS Act and Intel building a $20B fabrication facility in our adjacent state of Ohio, there will be the need to train engineers in the Midwest region with the technological skillsets needed for the semiconductor industry. Additionally, Skywater is building a $2B fabrication facility in our neighboring state of Indiana. Experts predict we need an additional 10,000 processing engineers and technicians in the Midwest alone (i.e. the Silicon Heartland). In response to that demand, the UofL ECE Department is creating a Concentration Track in Semiconductor Manufacturing as part of its MSEE degree, which should be available for students in the Spring or 2023. In addition, KY Multiscale at the University of Kentucky continues the undergraduate Nanoscience Course partnership with Transylvania University. Currently 24 students are enrolled in the course. CeNSE and the EMC at UK provide two-photon lithography, conventional photolithography, atomic force microscopy, and electron microscopy capabilities for the students to fabricate 3D nanostructures.

Training Courses - The AMIST Core Facility is used as a learning laboratory fully equipped with the latest AM technologies, machining, metrology and powder handling systems. AMIST staff offers on demand, one-day AM metal safety trainings in the center and on-site. These courses cover PPE (person protection equipment), material handling, facility development, and other safety topics in metal AM. Upon completion, participants receive a training certificate and copies of training materials. Additionally, AMIST also offers a 4.5-day metal AM production course. This course covers a full one-day safety training along with build set up, design practices, machine set up/breakout, post-processing and hands-on machine time with machines like EOS M290 and Kurtz Ersa Alpha140. Upon completion, participants receive a training certificate and copies of the training materials.

Summer Camps – Due to the overwhelming response in summer camp registration from previous years, AMIST expanded its offerings and coordinated 3 camps for youth groups (grades 7^{th}-12^{th})

with of total of 55 school participants this past year. The camp called *"Nuts, Bolts, and Thingamajigs"* is a 3-day hands-on experience that introduces participants to additive manufacturing design and fabrication.

KY INBRE Partnership **-** UofL MNTC is currently involved in a strategic partnership with KY INBRE (Kentucky IDeA Networks of Biomedical Research Excellence). KY INBRE is an NIH-supported collaborative network of biomedical researchers within the state of Kentucky. The goal of KY INBRE is to develop a network of support for biomedical researchers and educators within the Commonwealth of Kentucky. The purpose of the network is to develop infrastructure and capacity for biomedical research and training in the state. The MNTC took over operation of a TEM (Transmission Electron Microscope) facility located in the heart of the UofL medical campus. The MNTC staff provides training, remote processing, sample prep, scheduling, invoicing, billing and marketing services to TEM users (internal and external). This has increased our user base, as well as our collaborations with faculty and researchers in the Medical School.

Nano Image Competition – KY Multiscale participated in the NNCI Image Contest "Plenty of Beauty at the Bottom" in celebration of National Nanotechnology Day. In addition, we hosted our own image competition. All submissions collected from our core facilities were framed and permanently displayed in our own Nano-Gallery that we created in the Shumaker Research Building, home of the Micro/Nano Technology Center. In the 2023 Nano Image Contest, we are happy to report our very own Dr. Chuang Qu, using the MNTC facilities, won 1st Place in the **Unique Capability Category** in this year's contest.

Computation Activities

The following software packages are available to educational users at our KY Multiscale site: ConventorWare 2018.0, Silvaco TCAD 2015.0, Tanner Tools V16.2, Xilinx Vivado with SDK Win 2014.2, Autodesk Netfabb, Materialise with Magics, Structures, SG+, Mimics and 3Matic, HP Build Setup & Farsoon Buildstar, Simplify 3D, Ultimake Cura, Chitubox, Leche, 3D Slicr, Amber, ANSYS, FieldView, Fluent, Gaussian, Matlab, MolPro, NAMD, and VASP.

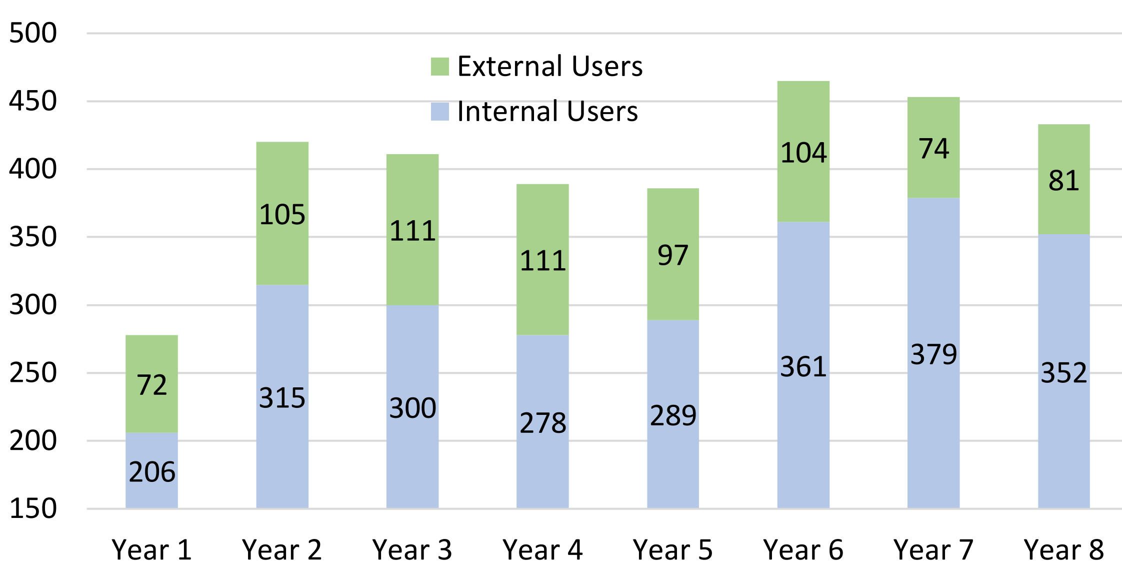
Innovation and Entrepreneurship Activities

Partnership with Kentucky MEP - This year, KY Multiscale entered into a partnership with the Kentucky Manufacturing Extension Partnership (MEP) Program, which recently moved from Bowling Green KY to Louisville. The KY MEP program is part of the MEP National Network, which is led by the National Institute of Standards and Technology (NIST). The MEP Network is composed of 51 Centers located in all 50 states and Puerto Rico. The goal of the national network is to help small and medium-sized companies boost productivity, retain and create jobs, and compete in new markets here and abroad. The KY MEP helps to market our KY Multiscale unique services and prototyping capabilities to industries in the Commonwealth.

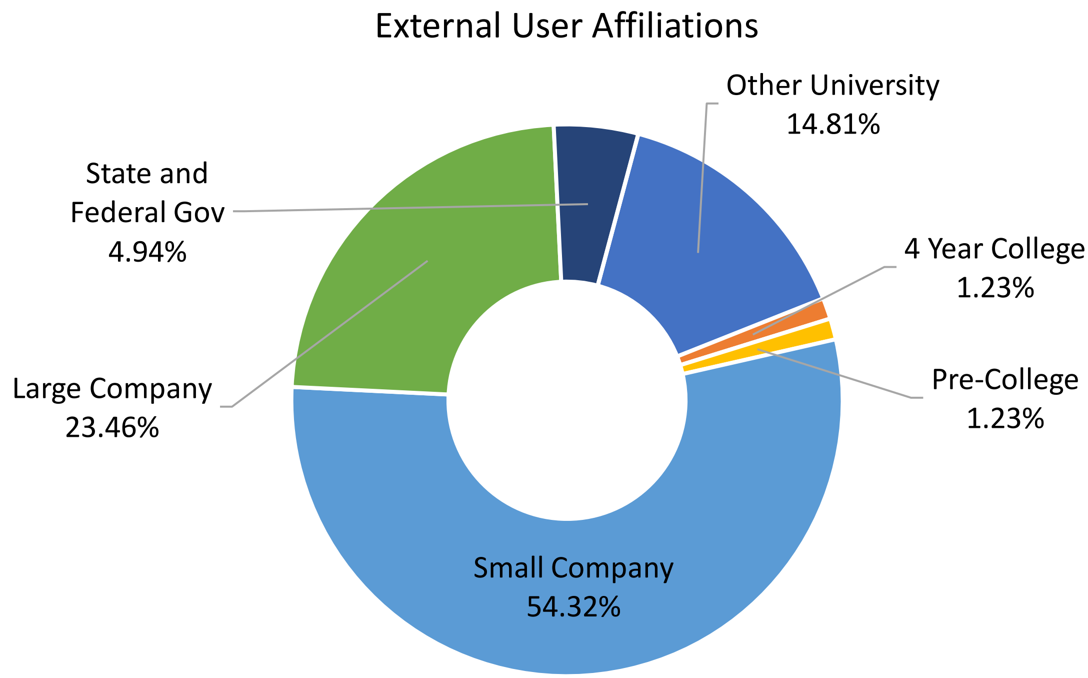
PowerTech Water - PowerTech Water/ElectraMet is a successful start-up company that grew out of the University of Kentucky and has used KY Multiscale facilities in their R&D efforts. Specifically, CeNSE facilities have been used for development of electrode material processing techniques that have supported their intellectual property portfolio. Imaging and microanalysis in the EMC helped PowerTech Water better understand how metals are immobilized on their carbon electrodes. Their KY Multiscale work has been supported by both SBIR grants and private investment, and they are currently evaluating the CAER dry room facility for work on a new DOE SBIR award. To date, PowerTech Water has commercialized two products based on novel carbon electrodes: a membrane-free water softening system (INCION) and an electrochemical filter for metals in industrial wastewater (ElectraMet^{TM}). The devices use activated carbon electrodes and small applied voltages to precipitate metals from solution and trap them in the porous electrode matrix. The company is currently targeting removal of lead, chromium, and copper in industrial applications ranging from semiconductor manufacturing to mining. They have demonstrated that their system can achieve >90% lead removal and >97% copper removal from industrial waste streams. These successes led the company to recently close a $6 million Series B financing round led by HG Ventures. They discussed their challenges and successes on the path to commercialization in an invited presentation at the 241st ElectroChemical Society Meeting in Vancouver.

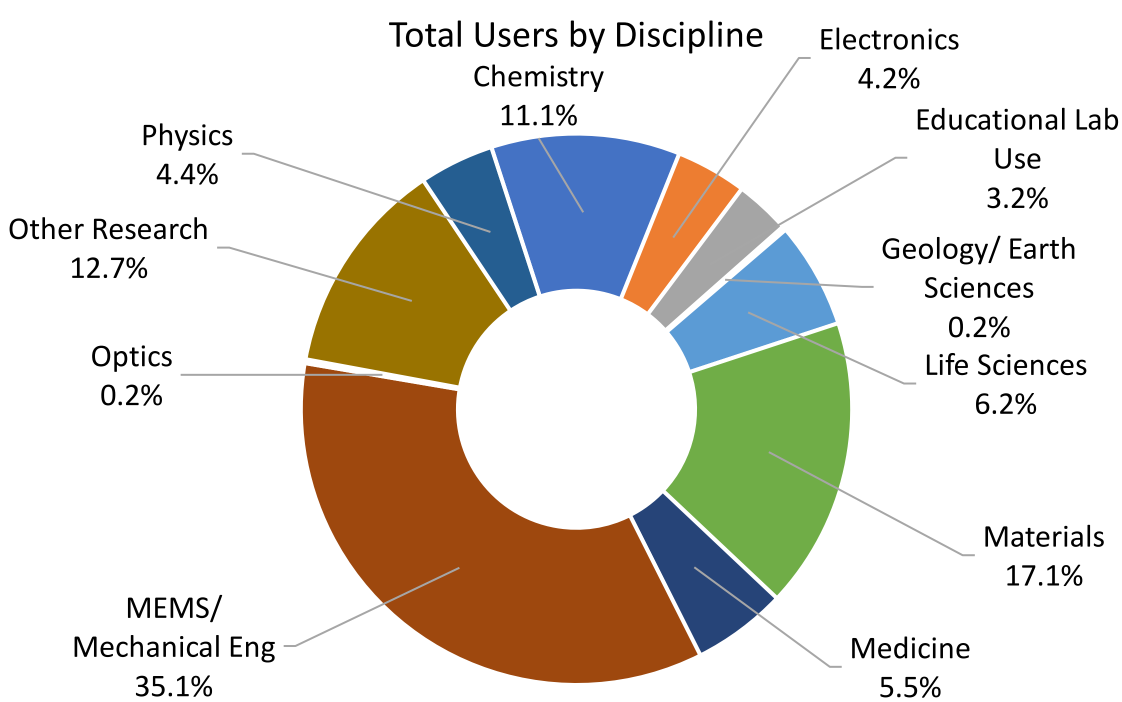
KY Multiscale Site Statistics

Yearly User Data Comparison	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	278	420	411	389	386	465	453	433
Internal Cumulative Users	206	315	300	278	289	361	379	352
External Cumulative Users	72 (26%)	105 (25%)	111 (27%)	111 (29%)	97 (25%)	104 (22%)	74 (16%)	81 (19%)
Total Hours	14,629	17,151	17,301	15,651	12,895	14,220	12,387	14,440
Internal Hours	9,726	12,166	10,960	11,869	9,032	10,282	10,128	11,884
External Hours	4,903 (34%)	4,986 (29%)	6,341 (37%)	3,782 (24%)	3,862 (30%)	3,938 (28%)	2,259 (18%)	2,557 (18%)
Average Monthly Users	104	141	120	140	97	127	121	137
Average External Monthly Users	22 (21%)	25 (18%)	25 (21%)	25 (18%)	20 (20%)	25 (20%)	17 (14%)	22 (16%)
New Users Trained	111	251	164	223	118	165	151	125
New External Users Trained	26 (23%)	43 (17%)	28 (17%)	22 (10%)	18 (15%)	19 (12%)	17 (11%)	10 (8%)
Hours/User (Internal)	47	39	37	43	31	28	27	34
Hours/User (External)	68	47	57	34	40	38	31	32



KY Multiscale Year 8 User Distribution





12.4. Mid-Atlantic Nanotechnology Hub (MANTH)

The Mid-Atlantic Nanotechnology Hub (MANTH) is a partnership between the **University of Pennsylvania** (Penn) and the **Community College of Philadelphia** (CCP). Nanotechnology facilities are housed at the Singh Center for Nanotechnology at Penn. The Singh Center includes: the 11,000 ft^2 class 100/1000 Quattrone Nanofabrication Facility (QNF) supporting a spectrum of diverse materials from silicon to soft materials and the 10,000 ft^2 Nanoscale Characterization Facility (NCF) and Scanning Probe Facility (SPF).

MANTH provides open access to leading-edge R&D facilities and expertise for academic, government, and industry researchers who work within all disciplines of nanoscale science, engineering, and technology. Thirteen professionals staff the center.

The collaboration between Penn and CCP on workforce development and curricula provides opportunities for community college students to learn more about nanotechnology, including nano-related courses and a paid summer technician internship program at the Singh Center.

<u>Facility, Tools, and Staff Updates</u>

New Staff: *Ana Cohen* is a new member of the process team at MANTH QNF cleanroom. Ana supports users through equipment training and process troubleshooting. Her primary focuses are lithography, metrology, and wet chemical processing, with a specialization in photolithography/laser writing. She also is passionate about introducing fellow underrepresented minorities to nanofabrication and championing them within the field.

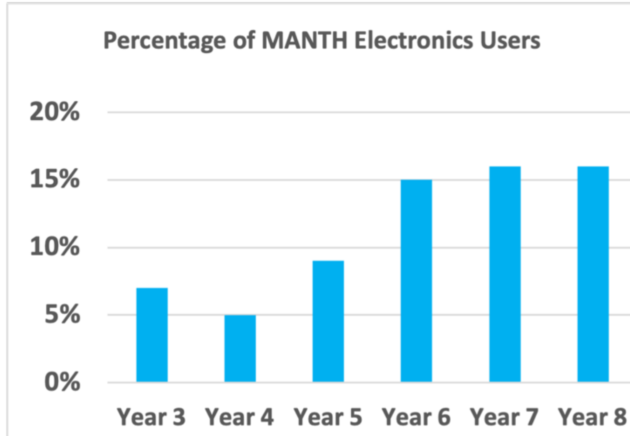
Nicole Bohn is an Electron Microscopy Trainer and Support Specialist in the Nanoscale Characterization Facility. Nicole supports electron microscopes and related equipment in the NCF through user training and troubleshooting. She earned her BA in Science, Technology, and Society with a background in Materials Science and Engineering from the University of Pennsylvania in 2019, where she began supporting electron microscopy users and equipment in 2018. Before her return to Penn, Nicole spent 4 years at MIT specializing in electron and x-ray microscopy at the Institute for Soldier Nanotechnologies and MIT.nano.

Expansion and New Equipment: The Singh Center has invested in a significant series of upgrades of the SPF confocal microscope. A 532 nm solid state laser has been installed. Also acquired are quarter wave plates operating at 405 nm to conduct circular polarization experiments using the existing 405 nm laser. In addition, a new InGaAs IR detector has been added to the confocal system which has the capability to measure wavelengths as long as 1700 nm. Together with the current Si detector, the optical measurement wavelength capability now ranges from 405-1700 nm. In addition, the system has been upgraded with supporting IR compatible optics/filters for all types of optical measurements.

The QNF cleanroom has just installed a new Raith EPBG 100 keV electron beam lithography system and users are now being trained to operate this tool. The QNF continues to build out an entirely new process bay, bringing the total number of bays to 6. The soft lithography facility is being moved to this new bay, making way for a new back-end processing facility that will house our dicing saw and new HBT advanced wire bonder.

<u>User Base</u>

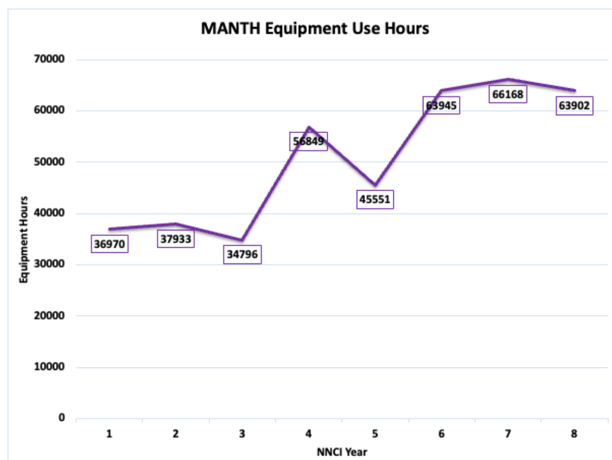
Total Use: Laboratory use statistics show the solid return of internal users; in some use cases exceeding pre-pandemic values. However, we have not yet seen the complete return of our external user base. Significant equipment acquisitions in tools that deposit 2D, piezoelectric, and magnetic films support an increasing number of users who investigate nano-IoT (Nanoscale Internet of Things), quantum, and 2D devices. Of note, supporting the growing importance of these fields, the number of users who identify themselves as electronics device researchers has now climbed to 16% in NNCI Year 8 (October 2022-September 2023), from as low as 5% at the beginning of the NNCI program (see figure at right)



The fraction of MANTH users who self-identify as electronics researchers has increased dramatically from about 5% in the early days of the program to 16% in Year 8.

MANTH served 493 users in NNCI Year 8, the highest number since the pandemic, but below the pre-pandemic peak. In spite of fluctuations in the user base, equipment use hours continue to exceed earlier years. The total hours of lab use in Year 8 reached nearly 64,000 hours (see figure). The average number of monthly users, another indication of the activity in our labs, has never been higher at 212 users per month.

Additionally, 213 new users (internal and external) were trained in Year 8, steadily increasing from the low in Year 5, when the labs were shut down for part of the year due to COVID restrictions.



Equipment use at MANTH approached 64,000 hours in Year 8.

Internal/External Use Breakdown: In NNCI Year 8, the number of external users continues to rise since the pandemic, to 146 researchers, making up 30% of our user base. Small companies continue to lead the way in external use, logging in over 55% of the equipment hours of external research. Although small companies used our equipment more, external academics made up most of the external user count (74%).

Disciplinary Breakdown: MANTH users conducted research in a wide range of fields; 19% of the users were involved in life science or medicine, as in previous years. Those who associate their field with materials research comprised 27% of MANTH users, and 41% identified as working in all fields of physical sciences or engineering including those who self-identify as electronics researchers, at 16%.

<u>Research Highlights and Impact</u>

Publications: Over the calendar year January 1 - December 31, 2022, MANTH enabled 263 unique scientific publications, 49 conference presentations, and 39 patents by our users. The MANTH NNCI contract (ECCS-1542153 or NNCI-1542153 or NNCI-2025608) was acknowledged 85 times in 2022 and 358 times in total (since 2018), according to Google Scholar statistics. 30 PhD and 32 MS student users graduated last year (F'21 to Su'22).

Many research programs fall under the NSF 10 Big Ideas, particularly in the *Rules of Life* and *Quantum Leap*. Other research in nano-robotics, energy storage, and electronic materials showcase work related to the Nanoscale Internet-of-Things (Nano-IoT), an area of special interest at MANTH.

Penn Professor and MANTH researcher Nader Engheta received the Benjamin Franklin Medal in 2023.

Awards: MANTH researcher Nader Engheta, the H. Nedwill Ramsey Professor in Electrical and Systems Engineering at Penn, was awarded the Benjamin Franklin Medal in April 2023 (photo at right). Past winners include Albert Einstein, Enrico Fermi, and Thomas Edison.

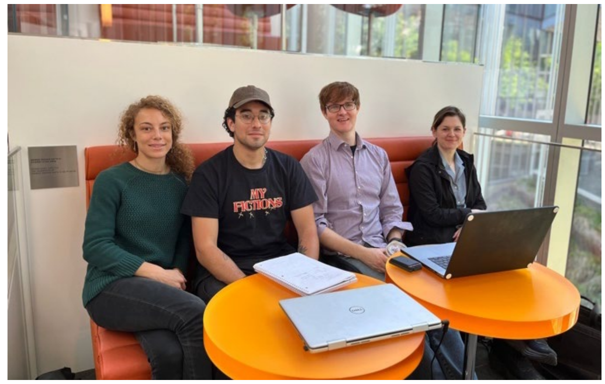
Economic Impact: Since the inception of MANTH, over 70 small companies (defined as 50 or fewer full-time employees) have utilized our resources either on site or remotely. To date, over a third of our small companies have received external support, leveraging their engagement with MANTH to yield nearly **$80M** of funding, including approximately 40% from SBIR/STTR grants. In the year 2022 small companies received nearly $10M in grants (see table below).

MANTH small company funding sources. Funding tabulated in $1000s.

Funding	2015	2016	2017	2018	2019	2020	2021	2022	Grand Total
CrowdFund	$ -	$ -	$ -	$ -	$ 1,070	$ -	$ -	$ -	$ 1,070
Grant	$ -	$ -	$ -	$ -	$ -	$ 15	$ -	$ 221	$ 236
In-Kind	$ -	$ -	$ -	$ -	$ -	$ -	$ 6	$ -	$ 6
Other	$ -	$ -	$ -	$ -	$ -	$ 260	$ -	$ -	$ 260
SBIR	$ 300	$ 3,075	$ 681	$ 1,291	$ 4,861	$ 5,508	$ 11,687	$ 5,567	$ 32,971
Seed	$ -	$ -	$ -	$ -	$ -	$ 755	$ 1,488	$ -	$ 2,243
Series A	$ -	$ -	$ -	$ 6,000	$ 8,000	$ -	$ -	$ -	$ 14,000
Series B	$ -	$ -	$ -	$ -	$ -	$ -	$ 20,500	$ -	$ 20,500
STTR	$ -	$ 233	$ 223	$ -	$ -	$ 420	$ 840	$ -	$ 1,716
VC	$ -	$ -	$ -	$ 1,250	$ -	$ -	$ -	$ 4,060	$ 5,310
Grand Total	$ 300	$ 3,308	$ 904	$ 8,541	$ 13,931	$ 6,957	$ 34,522	$ 9,848	$ 78,312

Education and Outreach Activities

Nanotechnology Training Collaboration with the Community College of Philadelphia (CCP): CCP and Penn have continued to partner to identify and provide educational opportunities for community college students in the field of nanotechnology. This partnership resulted in a program for CCP students – an internship that allows them to experience day-to-day operations in a research cleanroom. The second cohort of 4 CCP students was selected and participated in a 20-hour/week, paid internship in the MANTH nanofabrication facility in the summer of 2023.



The 2023 cohort of CCP interns. Two women were among the 4 who took part in the 14 week program.

Over the 14 weeks of the program, the interns moved through basic safety and nanofabrication training. Interns shadowed staff, developed nanofabrication skills, and presented their results in meetings with other MANTH researchers and staff in periodic meetings.

At meetings that include Singh Center staff and Master's degree students, CCP interns present progress on their assigned projects.

REU Program: The 2022 cohort of 6 students began on May 31, 2022. The three women and three men came from Indiana University, North Carolina A&T State University, Mount Holyoke College, University of Scranton, Cornell University, and University of Notre Dame. Two of the students identify as White/Caucasian, two as Asian, and two as Black or African American. Their undergraduate majors are Chemistry, Chemical Engineering (N=2), Electrical Engineering, Bioengineering, and Intelligent Systems Engineering.

As of 2022, MANTH has hosted a total of 34 REU students (program canceled in 2020). Of these alums, 15 are pursuing PhDs or an MD/PhD, 1 is a postdoctoral fellow, 9 are in STEM positions, and 7 continue their undergraduate programs.

The 2023 cohort of 6 consisted of 2 women and 4 men from Rowan University, Howard University, the University of Oklahoma, Hendrix College, Haverford College, and Auburn University. Five of the 6 attended the Convocation at Montana State University in August 2023.

Singh REU students and their mentors at Orientation on May 31, 2022.

Nanoday@Penn: In the past, several Penn research labs presented aspects of their research to visiting middle/high school students at the Singh Center at MANTH or via Zoom on Nanoday@Penn. In 2023, MANTH collaborated with Drexel University, Temple University, and Jefferson University to provide 12 in-person, hands-on laboratory sessions at the local middle/high schools instead. These presentations enabled students to attend NanoDay in their classroom without a field trip.

In-person NanoDay hands-on lab session at the Swenson Arts & Technology High School, led by MANTH staff member Mohsen Azadi.

The NanoDay @ Penn in the classrooms was particularly helpful amid a nationwide shortage of school bus drivers. For students who are far from Philadelphia, 11 online synchronous sessions were provided. The topics include energy, MEMS, nanomaterials, quantum dots, neural devices, electron microscopy, and career development.

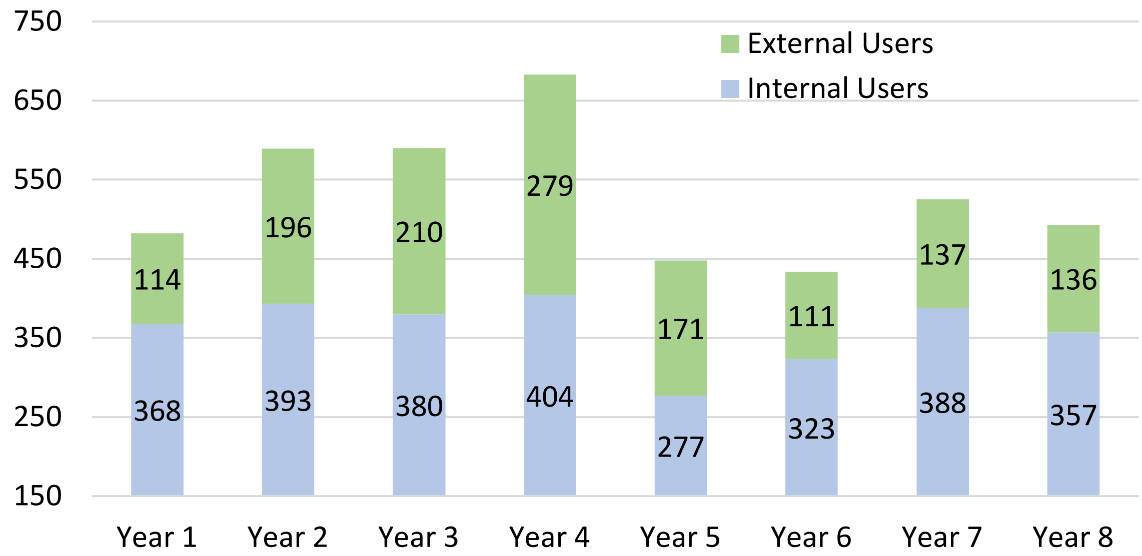
This year the event was scaled up so that whereas about 100 students attended in the past years, over 400 students attended this year. According to the post-survey, 42.9% of students answered that NanoDay elevated their interest in pursuing a STEM career in the future (N=119). Meanwhile, 54.6 % and 2.5% of students answered they have the same and less interest in STEM career, respectively.

<u>Innovation and Entrepreneurship Activities</u>

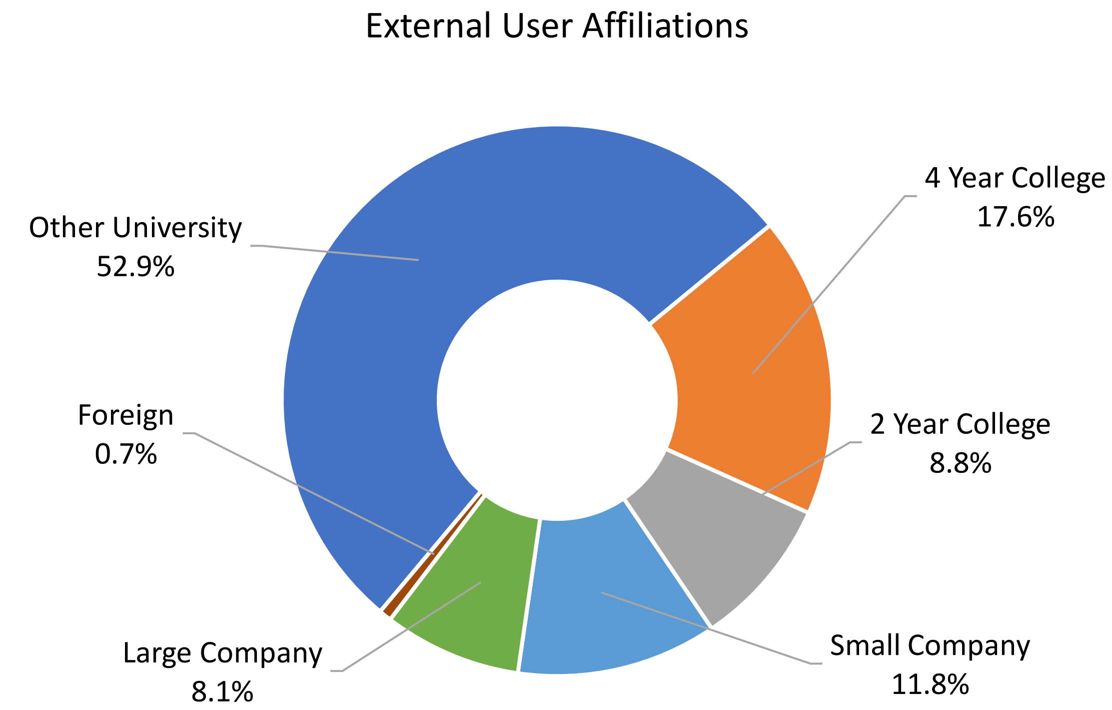
Since 2016, the MANTH Innovation Seed Grant (ISG) Competition has attracted the brightest minds in nanotechnology within the Mid-Atlantic region, offering grants of a few thousand dollars to area researchers and entrepreneurs to access MANTH equipment. Last year, the ISG Competition committee granted funds to 11 entries from academia and from one local startup. The academic applicants range from undergraduate students to faculty, and came from the University of Delaware, Rowan University, Temple University, Saint Joseph's University, Drexel University, and the New Jersey Institute of Technology.

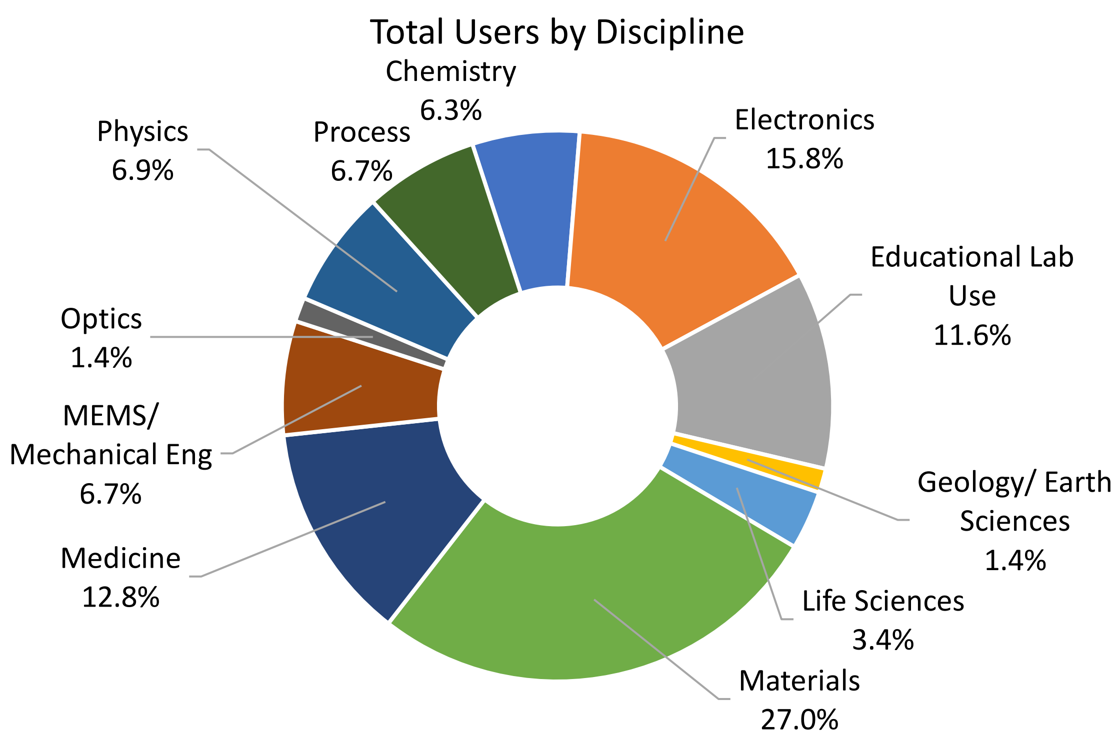
MANTH Site Statistics

Yearly User Data Comparison								
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	482	589	590	683	448	434	525	493
Internal Cumulative Users	368	393	380	404	277	323	388	357
External Cumulative Users	114 (24%)	196 (33%)	210 (36%)	279 (41%)	171 (38%)	111 (26%)	137 (26%)	136 (28%)
Total Hours	36,970	37,933	34,796	56,849	45,551	63,945	56,729	63,902
Internal Hours	34,545	31,542	27,436	43,673	39,379	58,094	50,921	56,042
External Hours	2,425 (7%)	6,409 (17%)	7,360 (21%)	13,176 (23%)	6,172 (14%)	5,851 (9%)	5,807 (10%)	7,860 (12%)
Average Monthly Users	171	194	186	210	142	180	216	212
Average External Monthly Users	29 (17%)	44 (23%)	45 (24%)	61 (29%)	31 (21%)	25 (14%)	37 (17%)	36 (17%)
New Users Trained	270	339	270	418	180	186	215	213
New External Users Trained	73 (27%)	138 (41%)	104 (39%)	203 (49%)	95 (53%)	52 (28%)	72 (33%)	79 (37%)
Hours/User (Internal)	94	80	72	108	142	180	131	157
Hours/User (External)	21	33	35	47	36	53	42	58



MANTH Year 8 User Distribution





12.5. Midwest Nanotechnology Infrastructure Corridor (MiNIC)

Facility, Tools, and Staff Updates

The Midwest Nano Infrastructure Corridor (MiNIC) is based at the University of Minnesota–Twin Cities and provides a broad suite of capabilities to support a wide variety of research on micro- and nano-scale technology. The core facilities of MiNIC include the Minnesota Nano Center (MNC), which consists of two cleanrooms located in Keller Hall and the Physics and Nanotechnology Building (PAN) on the East Bank of the Twin Cities campus. The cleanrooms occupy over 15,000 ft^2, with roughly 7,500 ft^2 being class 100 space. These facilities provide a full suite of cleanroom equipment consisting of over 100 tools with a replacement cost exceeding $10M. The equipment includes a state-of-the-art Raith EBPG 5000+ electron beam lithography system plus several other tools for performing pattern transfer at various dimensional scales. The facility also includes numerous etch and deposition tools, and a wide range of characterization instruments. Advanced capabilities include several atomic-layer deposition systems, unique capabilities for growing and manipulating 2D materials, and an ultra-high-vacuum (UHV) deposition system for quantum materials. The MNC also has BioNano and Nanomaterials Labs specializing in creating and characterizing materials for use in biological applications. MNC has a total of 16 full-time staff members, as well as numerous undergraduate part-time staff and interns.

The second MiNIC core facility is the Characterization Facility (CharFac), which offers broad capabilities to support nanoscale materials characterization. CharFac consists of over 13,000 ft^2 of lab space located in three sites, and offers a wide range of materials characterization tools, including X-ray scattering instruments; spectrometers; scanning tunneling microscopes and other surface/thin-film analytical tools; state-of-the-art electron microscopes and scanning probe microscopes; cryo-enabled electron microscopy; atomic force microscopes; and a high-contrast cryo-TEM. CharFac's scientific staffing includes nine full-time professionals and one shared professional, all of whom have advanced degrees, plus two grad students.

The MiNIC node has two focus areas that are well aligned with two of the current NNCI Research Communities. The first focus area supports the Quantum Leap research area, by providing capabilities for deposition and processing of a variety of materials for use in quantum information sciences. These include tools for growth of two-dimensional (2D) materials such as graphene and transition metal dichalcogenides. The node also supports automated assembly of 2D materials, including precision rotational alignment. In addition, MiNIC has specialized deposition capabilities for ultra-high purity superconducting films, enabling the integration of multiple materials with clean, hyper-abrupt interfaces. The second focus area supports the Rules of Life Research Community. Here, our Nanomaterials Lab provides all the facilities and equipment needed to make and characterize nanoparticle dispersions, adjacent to a fully equipped BioNano Lab with specialized equipment such as fluorescence microscopy, cell culturing, particle size and zeta potential analyzers, and biosafety cabinets. The BioNano Lab also has a state-of-the-art analytic ultracentrifuge for characterizing proteins, nucleic acids, and other biomolecules.

Tool Updates: MNC

In the previous year, MNC acquired a Solaris 150 Rapid Thermal Processing (RTP) tool produced by Surface Science Integration. This tool replaced a failed RTP600 unit that was in service at the MNC for more than 15 years. The new RTP tool can accommodate wafer sizes up to 150 mm, has a maximum operating temperature of 1200 °C, and is plumbed with nitrogen, argon, oxygen, and forming gas. In this year, the tool was placed fully into service and made available to users.

A low-power oxygen plasma cleaner (Harrick Plasma PDC-001-HP) was added to the PAN cleanroom. This tool primarily accommodates users needing to clean organic residue from research samples between processing operations. Prior to this addition, it was common for users to exit the PAN building cleanroom and take their research samples to the Keller Hall cleanroom for de-scumming or simple dry etch cleaning. Users have provided feedback that this tool's addition has had a large positive impact on the usability of our facility. The plasma cleaner has a maximum power of 45 W, is compact, user-friendly, can accommodate individual 150-mm wafers, piece parts, or full cassettes of 100-mm wafers. The chamber is 100% quartz and provides a pristine, low-contamination environment for cleaning operations.

Last year, the MNC commissioned a new AJA ATC series 1800-HY UHV multi-technique deposition system. The system has 6 sputter guns, a 6-pocket electron beam evaporation source, an ion source for substrate preclean, SIMS end-point analysis capability, a load lock for *in-situ* oxidation, and substrate tilt and rotation control. During the past year, this tool has been brought up to full operational condition and has consistently been operating at approximately 3×10^{-10} Torr. It has seen significant use for fabricating superconducting thin films using both Al and Nb, Josephson junctions, and ultra-high-quality Ti/Au contacts.

In mid-2023 the MNC was awarded a substantial grant from the University's Office of the Vice President for Research to obtain a new direct-write lithography (DWL) tool. The new tool will help bridge the gap between optical photolithography and electron beam lithography by allowing users to pattern features as small as 300 nm on a variety of substrate sizes, up to 200 mm, using a high-speed vector scanned laser. The DWL tool also allows the creation of novel 3D structures for advanced applications such as meta-optics and complex fluidic devices. MNC staff are considering several options for the new direct write tool, with installation targeted for the first quarter of 2024.

Tool Updates: CharFac

In March 2023, CharFac completed installation of a new Thermo Fisher Apreo 2 S LoVac, a Schottky field emission scanning electron microscope (SEM), which was funded through the UMN Research Infrastructure Investment (RII) program. This SEM, which replaces a 20+ year old tool that was recently decommissioned, combines ultra-high resolution (< 1 nm) capabilities with an electrostatic lens design together with a low vacuum mode for charge compensation, that provides unprecedented contrast and versatility to a wide variety of MiNIC users.

During the reporting period, CharFac brought online a Thermo Fisher Talos F200C, a high-contrast cryo-capable FEG transmission electron microscope (TEM) optimized for soft materials and *in-situ* liquid studies. The system boasts 40 fps full-resolution imaging for *in situ* analysis using a Thermo Fisher Ceta CMOS camera and dedicated storage network, advanced software for data collection and processing, and specialized 3D software packages for tomography data collection and volumetric reconstruction.

CharFac also purchased a new Oxford Instruments Ultimax 100-mm^2 EDS detector and the symmetry speed boost for the EBSD detector. Both of these can enable rapid characterization of a wide range of materials. The system features beam precession which can be used to rotate samples to a zone axis and perform electron channeling contrast imaging, thereby enabling the visualization of dislocations and other defects in materials.

In June 2023, CharFac expanded its capabilities for microanalysis of solids by adding the Electron Microprobe Laboratory, which houses a JEOL JXA-8530FPlus electron probe microanalyzer (EPMA). This system combines micron-scale elemental and chemical analyses with scanning electron microscopy and is capable of large- and small-scale mapping of specimens. It utilizes an EDS and four WDS detectors, the latter providing much finer spectral resolution. It also includes a novel wavelength-dispersive soft X-ray emission spectrometer (SXES), the first in an academic institution in North America. The addition of the EPMA expands CharFac's research capabilities for the analysis of materials containing many elements including trace quantities.

New MNC and CharFac Staff

In June of 2023, Jennifer Mitchell joined CharFac as the manager of the electron microprobe laboratory. Jennifer is an electron microscopy specialist with a background in planetary geology and is working with both CharFac and the Department of Earth and Environmental Science. In her CharFac role, Jennifer supports researchers who require high precision compositional analysis. Also in June, the MNC hired Matthew Johnson as a full-time lab support specialist for the BioNano labs. In this role, Matthew trains lab users, maintains instrumentation, and has taken the lead technical role supporting MNC's analytical ultracentrifugation capabilities.

User Base

User recruitment and outreach: During this reporting period, MiNIC continued its successful user incentive program, Explore Nano, which seeks to recruit new users or those returning after an absence of over two years. The program offers a $2000 credit against fees for lab and tool use and training. During the current reporting period, MiNIC received 10 applications for the Explore Nano program and awarded grants to 8 researchers from industry and/or external academic institutions. Other outreach efforts by MiNIC staff during this reporting period include:

- Jim Marti presented a talk on the biomedical applications of nanotechnology at the Medical Devices and Materials (MD&M) conference in Minneapolis. This event led to several new contacts with potential external clients.
- The MNC exhibited for the 2023 Design of Medical Devices conference and the MD&M conference. Both events enabled our staff to market MiNIC capabilities to local and national companies working with medical devices and pharmaceuticals.
- We continued outreach using our LinkedIn page and newly redesigned newsletter.

New training short course: Responding to the need for an expanded microelectronics workforce, MiNIC staff were actively involved in the development of a 10-week training course for workers in the microelectronics and microfabrication industries. This intensive short course combines online modules with hands-on training in our cleanrooms, and is intended for technical staff in microfabrication environments, such as integrated circuit and MEMS manufacturing. MiNIC is developing this course in consultation with prominent local microfabrication companies, including Skywater Technology, Polar Semiconductor, Collins Aerospace, Honeywell, and Seagate.

MiNIC also continued to provide a training course on the health and safety aspects of working with micro- and nanomaterials. Intended for lab instructors at the postsecondary level, the course outlines the potential hazards of aerosol and colloidal nanomaterials that may be present in undergrad teaching labs. The course was offered in June 2023 and will be offered again in 2024.

Research Highlights and Impact

Below are brief summaries of notable research projects performed during the past year. More details and figures are found in the accompanying slides.

S-Shaped Configurational Magnetic States in Mesoscale Square Permalloy Particles

This work was performed by members of **Costanzi group at Carlton College**, a small liberal arts college in southern Minnesota. In this work, the researchers used the EBL, sputter deposition and ion mill systems in the MNC to detect the magnetization configuration in individual magnetic nanoparticles, which is highly contingent on particle shape, size, and symmetry.

Near-Perfect Light Absorbers Using 2D Materials

A unique feature of 2D transition metal dichalcogenides (TMDC) is called "band nesting" which allows extremely high optical absorption to be achieved. In this work, a collaboration between the **Koester and Low groups at UMN** and the **Hinkle group at the University of Notre Dame**, TMDCs were used to demonstrate near-perfect light absorption using only two or three uniform atomic layers of these materials. The researchers stacked monolayer TMDCs in such a way, either by twisting or inserting a graphene buffer layer, so as to minimize their interlayer coupling, thus preserving their strong band nesting properties. Through this strategy, absorption as high as 95% was demonstrated.

Optical Control of Neuronal Activities with Photo-Switchable Nanovesicles

In this work, led by the **Zhenpeng Qin group at UT Dallas**, researchers used the MNC and CharFac to develop and characterize photoswitchable nanovesicles for neuromodulation applications. Precise modulation of neuronal activity by neuroactive molecules is essential for understanding brain circuits and behavior. However, tools for highly controllable molecular release are lacking. In this work, photoswitchable nanovesicles with azobenzene-containing phosphatidylcholine (azo-PC) were used for neuromodulation. Irradiation with 365-nm light triggers the trans-to-cis isomerization of azo-PC, resulting in a disordered lipid bilayer with decreased thickness and cargo release. Irradiation with 455-nm light induces reverse isomerization and switches the release off. The researchers demonstrated that SKF-81297, a dopamine D1-receptor agonist, can be repeatedly released to activate cultures of primary striatal neurons.

Surprising Size-Independent Swimming Speed of Peritrichous Bacteria

In this international collaboration between researchers at the **University of Minnesota**, **University of Cincinnati**, and researchers in **S. Korea** and the **UK**, the team showed that the general positive size-speed correlation of swimming objects may not hold at microscopic scales for bacteria, where viscous dissipation overwhelms inertia in their swimming. By combining experiments, simulations, and theory, the team showed that the swimming speed of bacteria with multiple flagella is constant across the natural range of bacterial lengths, settling a long-lasting debate over the size–speed relation of bacterial swimming. This analysis could provide a useful guide for designing artificial micro-swimmers.

Flexible Graphene Sensor Arrays for Electrocorticography

In this collaborative effort between Neuroscience and Engineering researchers at the **University of Minnesota**, graphene electrocorticography (ECoG) electrode arrays conforming to the cortical surface of a mouse were used to record surface field potentials from multiple brain regions. The results were used to provide unique insights into how computations occurred in distributed brain regions to mediate behavior. The arrays were fabricated using a conductive ink produced via liquid exfoliation graphene, and then stencil-printed onto flexible polyimide substrates. The implanted ECoG devices were shown to remain fully functional for up to 180 days.

Education and Outreach Activities

Microfabrication Technology Short Course

MiNIC is actively supporting workforce development for the microelectronics industry. In May 2023, MiNIC began working with the University's Technological Leadership Institute (TLI) to launch the Minnesota Semiconductor Manufacturing Consortium, an initiative aimed at upskilling Minnesota's technical workforce for careers in semiconductor manufacturing. This consortium is supported by stakeholders including Honeywell, Collins Aerospace, Polar Semiconductor, and the Minnesota Department of Employment and Economic Development (DEED). A 10-week short course on CMOS and MEMS-based device manufacturing is being developed and the short course is on track to be offered beginning in January of 2024.

Research Experience for Teachers (RET) Program

MiNIC completed the third year of its Research Experience for Teachers (RET) program. During this RET round, six science teachers from the Twin Cities metro area were recruited for the program and were paired with University of Minnesota faculty that included the teachers as members of their research group. An important part of the RET program has the teachers develop a classroom lesson/unit/activity on some aspect of nanotechnology for their own classes. The teachers have been testing their lessons during the fall semester and will attend the 2024 annual conference of the National Science Teachers Association. The RET program is professionally evaluated by Dr. Mary White of ASU, and Dr. White's report for the 2023 cohort is in preparation.

Lab Internship Program

MiNIC continued to offer its popular laboratory internship program during the current reporting period. This program offers students from two-year community and technical colleges the chance to work in a nanoscience lab, gaining experience that can be applied to their job search or support their transition to a four-year program. During the fall of 2022 and spring of 2023, MiNIC staff supported three students whose research projects explored the effects of nanoparticle exposure on living cells, synthesizing fluorescent nanoparticles for biomedical imaging, and transfecting human cells with genetic markers.

Facility Tours and Classes

MiNIC continued its post-COVID return to offering regular cleanroom tours and classes for visiting student groups, and we collaborated with the Northstar STEM Alliance and the Minnesota Academy of Science to engage students from underrepresented groups. In all, over 900 K-12 students and teachers were reached by our outreach effort during the reporting period.

Quantum+Chips Program

In the summer of 2023, MiNIC hosted the "Quantum+Chips" program, designed to introduce early undergraduate students to key topics in quantum phenomena and computing devices. The program offered lectures, computer labs, experimental lab demos, company visits, and talks by industry and academia experts on the frontiers of quantum computing devices and technologies.

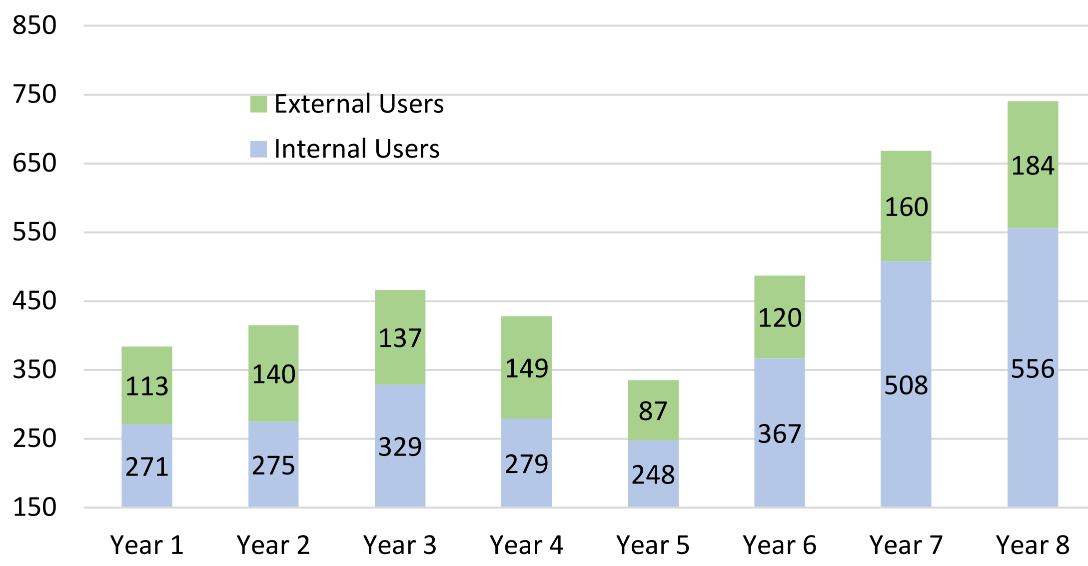
Innovation and Entrepreneurship Activities

During year 8 of the NCI grant, MiNIC actively worked with local start-up company Superior Nano LLC, under an SBIR subaward to develop new methods of nanoparticle drug delivery. The Phase 1 SBIR grant supported the development and optimization of lipid nanoparticles for dermal and oral delivery of drugs, including insulin and dasatinib (an anti-leukemia treatment). In addition to scientific collaboration, MiNIC is providing lab space, sample preparation, and analytical services for Superior Nano. A Phase 2 proposal is in preparation.

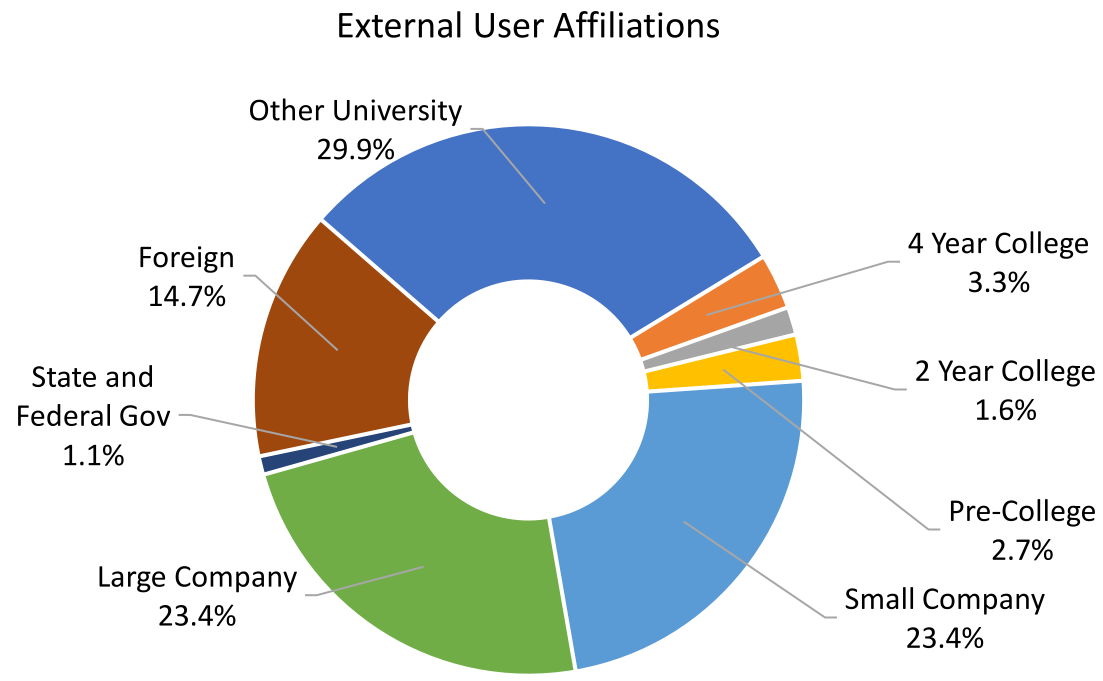
Another small firm supported by MiNIC is Grip Molecular Technologies, a Twin-Cities-based startup developing a multiplexed biosensing platform that could be used for an at-home upper respiratory virus panel test. Grip has extensively used the MNC to develop graphene field-effect transistors, and also uses CharFac for Raman and XPS characterization. In these ways, MiNIC provides such fabrication and analysis capabilities for small business that otherwise could not invest in the equipment maintained by the node.

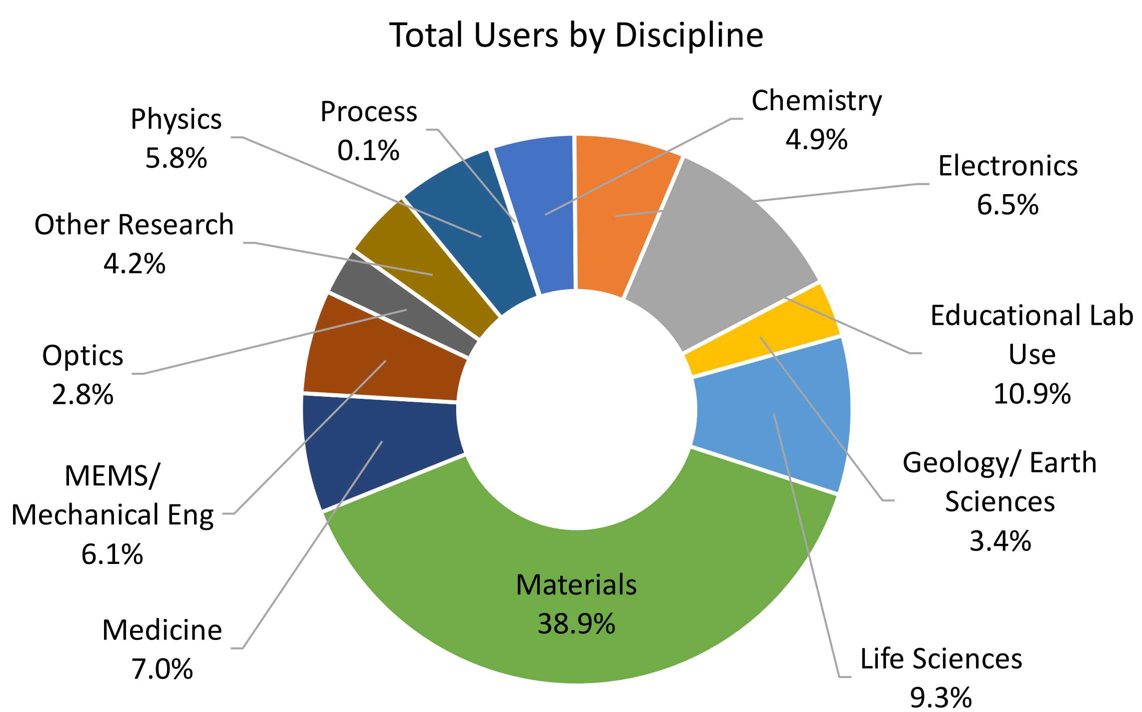
MiNIC Site Statistics

Yearly User Data Comparison								
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	384	415	466	428	335	487	688	740
Internal Cumulative Users	271	275	329	279	248	367	508	556
External Cumulative Users	113 (29%)	140 (34%)	137 (29%)	149 (35%)	87 (26%)	120 (25%)	160 (24%)	184 (25%)
Total Hours	27,002	26,443	26,851	27,782	17,682	27,317	31,916	32,707
Internal Hours	20,495	19,733	21,324	17,780	11,491	21,303	27,384	26,540
External Hours	6,507 (24%)	6,710 (25%)	5,527 (21%)	10,002 (36%)	6,191 (35%)	6,014 (22%)	4,532 (14%)	6,167 (19%)
Average Monthly Users	156	156	161	161	116	165	235	254
Average External Monthly Users	26 (17%)	33 (21%)	30 (18%)	37 (23%)	27 (23%)	31 (19%)	36 (15%)	38 (15%)
New Users Trained	151	150	189	136	101	213	280	298
New External Users Trained	57 (38%)	59 (39%)	48 (25%)	45 (33%)	17 (17%)	39 (18%)	87 (31%)	118 (40%)
Hours/User (Internal)	76	72	65	64	46	58	54	48
Hours/User (External)	58	48	40	67	71	50	28	34



MiNIC Year 8 User Distribution





12.6. Montana Nanotechnology Facility (MONT)

MONT Facilities include Montana Microfabrication Facility (MMF), Imaging and Chemical Analysis Lab (ICAL), Center for Biofilm Engineering (CBE), Mass Spectrometry Facility, cryo-EM facility; Partner site Science Education Resource Center (SERC) at Carleton College. Some facilities within the NSF MonArk Quantum Foundry are now available to MONT users.

Facility, Tools, and Staff Updates

The facilities have added roughly $1.8M in equipment supported outside of NNCI funds (MonArk equipment not included in total).

ICAL has installed and is running equipment introduced during this reporting period: a second Zeiss Ultra 55 field emission scanning electron microscope; an XYZ stage on the XRD instrument for GID and XRR capabilities; new computer operating systems for our FESEMS, an integrated EDS and EBSD detector system, a new BSE detector, and a cathodoluminescence detector in June, 2023. Together, these represent over $675k in improvements, with funding coming from MSU-VPRED (Vice President for Research and Economic Development), NSF EAR-IF, DOE, and ICAL User Fees.

In April 2023, **CBE** installed an Inverted Leica DMI8 Stellaris CSLM with Digital Light Sheet and Stimulated Raman Spectroscopy (SRS) capabilities equipped with a white light laser. This instrument was funded primarily by DoD with about 10% of the $1.1M cost contributed by NIH.

New Leica Stellaris SRS Inverted Digital Light Sheet CSLM in the CBE microscopy facility.

MMF has added about $60,000 in new equipment:

The MMF applied for the VPRED Core Facility Grant Program, and we were awarded funding for a new electroplating system. We also purchased an option to plate with ultrasonic agitation, which can be used as a tool for researching new films.

The MonArk Quantum Foundry added to the new **2D Quantum Materials and Nano-optics Characterization Lab** with a suite of new tools available to MONT users:

- 2D sample preparation and device fabrication with ~10 nm lithography capabilities (Heidelberg NanoFrazer)
- 1.9 K optical cryostat with a 7T external magnetic field with optical imaging and spectroscopy capabilities
- Low-temperature (4K) combined AFM and optical microscope for low-temperature scanning probe and nano-optical measurements
- Suite of four superconducting nanowire single-photon detectors

All MONT staffing remained stable, no changes to report.

User Base

We are pleased that the Y8 user count has again reached an all-time high. MONT served 250 users, which is a 7% increase from the Y7 user count of 233 users. MONT served 67 external users (27% of user base).

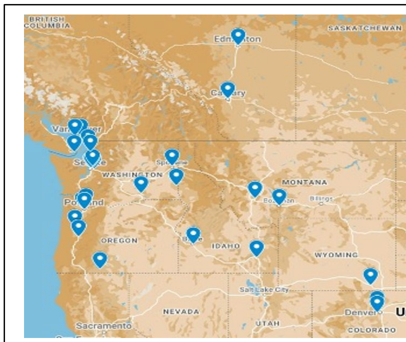
MONT awarded 9 user grants to seed new projects in Y8.

Five internal user grants were awarded to:

- Dr. Roberta Amendola, Development of PVD High Entropy Coatings to Prevent Microbially Influenced Corrosion
- Dr. Yaofa Li, (2 awards) Fabrication of Calcite-Based Micromodels for the Study of Reactive Dissolution in Porous Media and Liquid Film Characterization in Oscillating Heat Pipes Using Combined Velocimetry and Thermometry
- Dr. Stephan Warnat, Two Layer PDMS for Microbial Studies
- Dr. Emma Loveday, Quantification of viral RNA using single cell PCR

Four external user grants were awarded to:

- Dr. Marie D. Jackson, University of Utah, Characterization of Roman Cements
- Dr. Lynn George, MSU-Billings, Investigating the Molecular Mass of Neuronal Titin
- Dr. Zach Adams, University of Wisconsin-Madison, Chemical and Structural Characterization of Prebiotic Compartments Generated from Ammonium Thiocyanate and Formaldehyde
- Dr. Sarah Lukes, Agile Focus Designs, Feasibility of Profilm3d for surface profiles of large deflection, micromachined mirrors



Map of participating NWNLA institutions.

Northwest Nano Lab Alliance (NWNLA): MONT and NNI hosted the first in-person meeting at the University of Washington in August. The NWNLA is a regional network for staff of fabrication, imaging, and analysis facilities in the northwest. Over fifty attendees from universities, government institutions, small companies, and equipment manufacturers participated over the two days. The agenda consisted of invited presentations, breakout sessions for discussions on relevant topics, and vendors presenting laboratory equipment. The NWNLA committee worked to increase the number of participating institutions to nearly 30 (up from 17 at the first meeting).

Research Communities: A third NNCI *Nanoscience for Earth and Environmental Science* Virtual Workshop was held in April 2023. The event was hosted by NCI-SW with co-leads MONT and nano@Stanford. MONT's education partner SERC handled the web hosting, workshop materials, registration, logistics, and marketing for the event. The goals of the workshop were to introduce the audience to environmental nanoscience research using examples from water and agricultural research, to discuss sustainable nanotechnology topics, and hear about new directions in federal nanotechnology A post workshop assessment found an average rating score of 9.4/10, where 10 is extremely satisfied and 1 is extremely dissatisfied.

In conjunction with SHyNE, MONT hosted a *Rules of Life* webinar in November 2022, The Convergence of Biology and Earth Sciences. This virtual event explored the intersection between biology and geological sciences and explored how microbial communities interact with and shape their environment, and how we can use tools from nanoscience to better understand these interactions. About 40 people attended the event; 10 responded to a post event survey. 10/10 would recommend MONT events and felt the goals of this event were met.

In June, David Dickensheets (PI) and Andy Lingley (MMF Manager) traveled to **M**icron Headquarters in Boise, ID for the announcement of the new Northwest University Semiconductor Network, a partnership between 15 universities and community colleges who are educating the next generation of students who will work in the semiconductor industry. The announcement was attended by NSF Assistant Director of the TIP Directorate Dr. Erwin Gianchandani and leaders from Micron and more than a dozen university and colleges. The establishment of this partnership marks a concerted response by northwest regional universities to the National priority targeting US Semiconductor Manufacturing as articulated by the White House and U.S. Secretary of Commerce Gina Raimondo.

Research Highlights & Impact

Scholarly impact: During 2022, MONT researchers produced 37 journal papers and 61 other products.

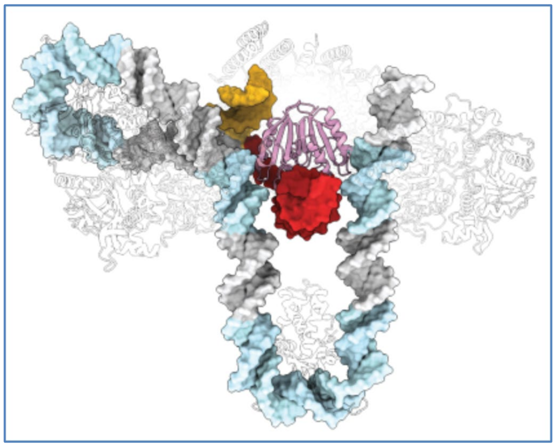
MONT users had several outstanding accomplishments during the reporting period.

Dr. Cecily Ryan received a $700,000 NSF grant to advance 3D printing so it can be used to produce a range of innovative materials that incorporate biological and biodegradable components. Ryan's research combines 3D printing and sensors to create biodegradable sensors made of electrically conductive but easily biodegradable biochar. At the center of the project will be an effort to develop new 3D printer heads that integrate microfluidics devices, then testing the combinations with a variety of different printing materials. Dr. Ryan uses MONT's ICAL facility to support this work.

Cecily Ryan has received a $700,000 National Science Foundation CAREER grant.

Dr. Robin Gerlach received a $1.2M NSF grant for continuing algae research. Gerlach's work focuses on exploring ways to optimize the use of algae combined with other microbes for making biofuel and other products. By cultivating algae in the lab and then carefully introducing one or more strains of bacteria, the Gerlach lab can study how the different organisms exchange nutrients. This work could make significant contributions using algae to make fuel, plastics and other products while helping reduce carbon emissions. Gerlach conducts the majority of this research in the CBE facility.

Grad students examine tubes of algal biomass.



Andrew Santiago-Frangos 'snapshot' of CRISPR enzymes making a DNA-based memory of a viral infection. The American Society for Biochemistry and Molecular Biology selected the image to appear in ASBMB Today and its 2024 calendar.

Andrew Santiago-Frangos, a postdoctoral fellow, is the lead author on a new paper, which appeared in the journal **Nature Structural and Molecular Biology** this September. "Structure reveals why genome folding is necessary for site-specific integration of foreign DNA into CRISPR arrays" explains how CRISPR systems record exposures to viral infections. Santiago-Frangos and team used a the new Cryo-EM Facility to take images of these changes in real time which helped determine the three-dimensional structure that explains how the DNA is bent and inserted into the CRISPR. This work reveals new DNA-binding surfaces that are critical for DNA folding and site-specific delivery of foreign DNA into a CRISPR array.

MONT continues to impact regional companies. During Y8, MONT served the needs of 27 external companies (51 individual users from 8 large and 19 small entities). Notable successes for our industrial users include 10 new SBIR/STTR Awards granted in 2022, totaling over $5M.

Education and Outreach Activities

NNCI REU 2023 Convocation Attendees.

MONT hosted the 2023 NNCI REU Convocation in August. The largest cohort of attendees (87 undergraduate students) from 12 of the 16 NNCI sites gathered in Bozeman, Montana to share their research experiences; each student presented a talk and poster. Students were able to connect with several MONT researchers in areas including neuro engineering and quantum devices. There was a plenary session devoted to science communication for varying audiences and a panel of MONT user entrepreneurs to help inspire and guide students in entrepreneurial workforce endeavors. We also took a field trip for a day of exploration and research overview in Yellowstone National Park. From extremophiles to geology, discoveries in Yellowstone have deep connections to nanoscience and nanotechnology.

SKC high school students at Mammoth Terraces in Yellowstone National Park.

We have been working with the Salish Kootenai College (SKC) middle/high school programs to incorporate nanoscience/technology education on the Flathead Reservation in northwestern Montana. After many years of building this relationship, SKC brought 35 students for a three-day nano camp with MONT. The visit included a day in Yellowstone National Park, making connections with the natural world and nanoscience. Graduate students from several disciplines lead the excursion framing different aspects of small-scale research within the Park. Co-PI Mogk also included several highlights of the importance nano plays in earth research.

The SKC students spent another two days on campus in MONT facilities. They were able to make silver nanoparticles then look at their particles in the SEM. The students engaged with MONT student users, PIs, and staff in several departments. We were also able to show the students other aspects of campus life, spending some time at the new MSU American Indian Hall and learning about support and resources for Native students.

The **MONT Empower Scholars program** awarded three scholarships to place underrepresented undergraduate students with MONT researchers for a research experience and tool training. Two previous MONT Scholars awardees, Diego Armstrong and Aspen Burke presented their work at the 2023 National Conference on Undergraduate Research (NCUR) at the University of Wisconsin-Eau Claire. The students' work is included in the Research Highlights attachment.

We trained 13 students from different MSU REU programs in our facilities and 11 of the students participated in the NNCI REU Convocation.

MONT hosted 20 high school students in our labs during the **4-H Summer Congress**. Lessons included Become a Nano Engineer and Become a Nano Scientist in a two-part, hands-on course.

MONT sponsored and helped to organize MSU Science Day for 170 5th graders. The event features NanoLand where students are "shrunk to 5 nanometers" and perceive how they would interact with everyday objects that represent a virus, bacteria, atom, or other particle at the nanoscale. MONT PIs also have interactive displays on their research involving nanoscience and nanotechnology.

MONT also participated in several additional MSU outreach events including STEAM Day, a 2-day camp for middle school girls, MSU Shadow Day in which high school students shadow an undergrad, several lab tours for school groups (8th -community college), and other events.

Teacher support includes our Solar Cells for Teachers course; MONT PIs also hosted 4 RET teachers who worked in MONT facilities.

Societal and Ethical Implications Activities

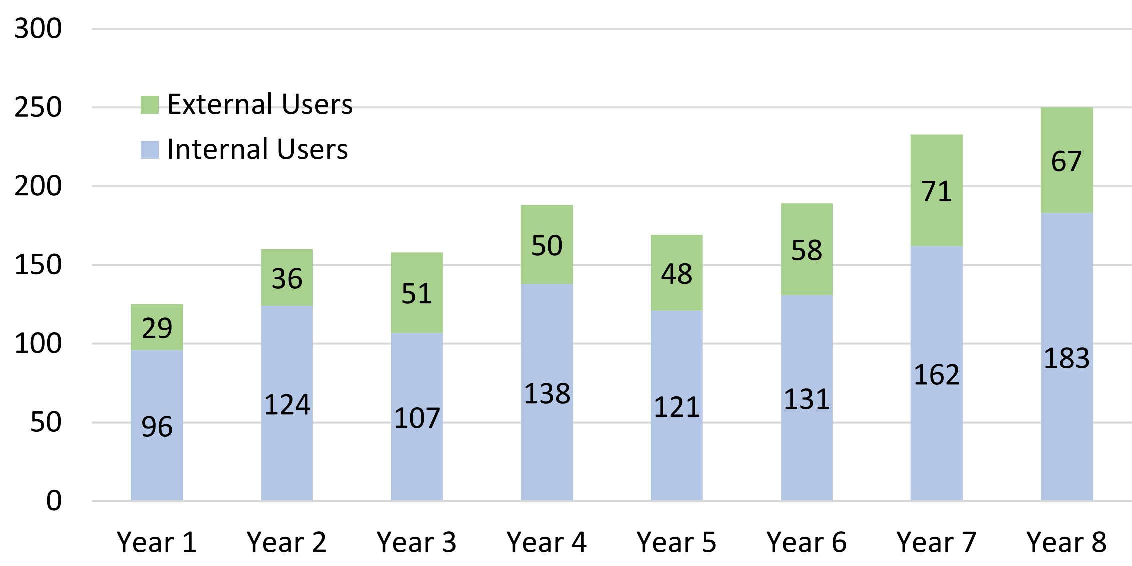
Co-PI Mogk continues to participate with the NNCI SEI working group. Continued website development includes an expanded resource collection of journal articles and books related to ethics and nanotechnology/science, and societal issues related to nanoscience. These references can be accessed at: https://serc.carleton.edu/msu_nanotech/ethics.html

Innovation and Entrepreneurship Activities

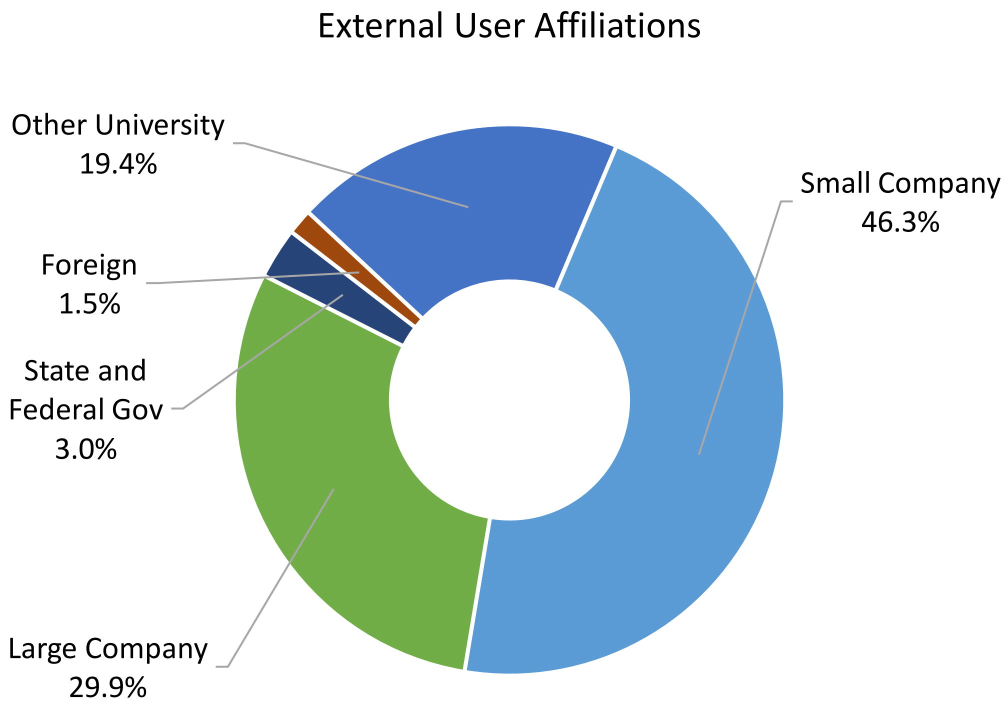
MONT organized and hosted an NNCI webinar for the I&E group in October 2023: "Lab-to-Fab, Transitioning from Cleanrooms to Industrial Prototyping and Low Volume Production," with Miguel Urteaga, Director of Foundry Productions at Teledyne Scientific.

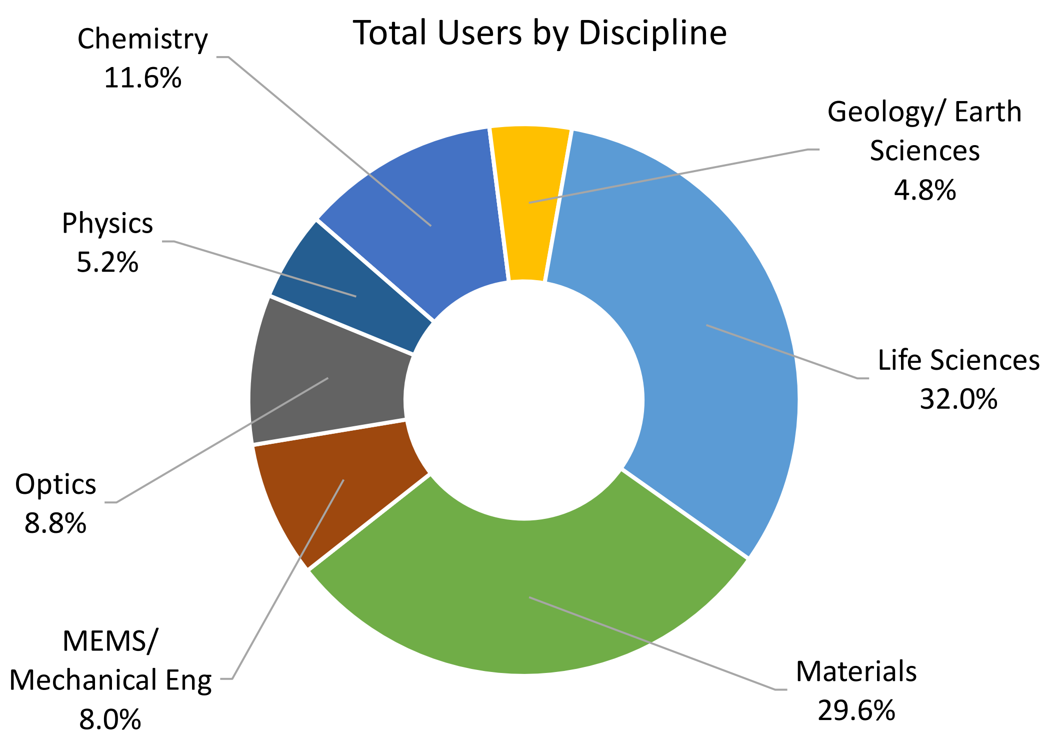
MONT Site Statistics

Yearly User Data Comparison								
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	125	160	158	188	169	189	233	250
Internal Cumulative Users	96	124	107	138	121	131	162	183
External Cumulative Users	29 (23%)	36 (23%)	51 (32%)	50 (27%)	48 (28%)	58 (31%)	71 (30%)	67 (27%)
Total Hours	3,599	4,713	5,420	6,398	4,858	7,735	9,142	9,548
Internal Hours	2,842	3,901	4,541	5,332	3,395	6,550	7,512	7,881
External Hours	747 (21%)	812 (17%)	879 (16%)	1,066 (17%)	1,463 (30%)	1,185 (15%)	1,630 (18%)	1,667 (17%)
Average Monthly Users	46	51	43	62	48	57	75	68
Average External Monthly Users	8 (17%)	10 (20%)	7 (17%)	10 (16%)	9 (19%)	13 (23%)	17 (22%)	14 (20%)
New Users Trained	36	58	58	76	70	86	86	87
New External Users Trained	1 (3%)	9 (16%)	8 (14%)	6 (8%)	7 (10%)	20 (23%)	17 (20%)	8 (9%)
Hours/User (Internal)	30	31	42	39	28	50	46	43
Hours/User (External)	26	23	17	21	30	20	23	25



MONT Year 8 User Distribution





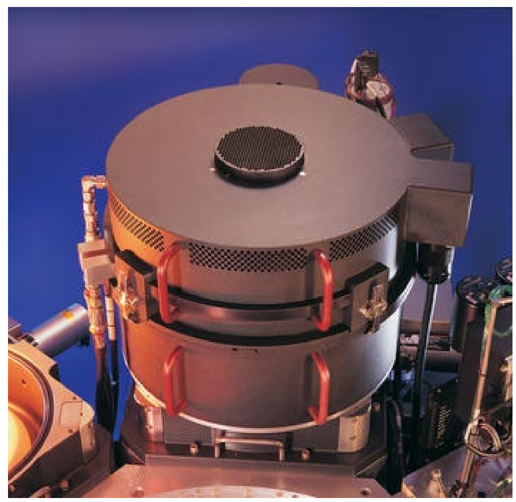
12.7. Nanotechnology Collaborative Infrastructure Southwest (NCI-SW)

Facility, Tools, and Staff Updates

With funding from the Arizona New Economy Initiative (https://neweconomy.asu.edu/) several new tools have been acquired for the ASU core facilities under the NCI-SW umbrella. The ASU Nanofab will commission a ELS-BODEN direct-write electron beam lithography tool from manufacturer Elonix. The new capability will replace the existing JEOL JBX-6000 which is no longer supported by the manufacturer. The ELS-BODEN can pattern 12” substrates as well as small pieces and supports high speed writing as well as high resolution < 10 nm.

The ELS-BODEN allows for pattern stitching with high resolution across large diameter wafers.

The Advanced Electronics and Photonics (AEP) core facility is housed at ASU’s Macrotechnology Works research park and caters to low volume manufacturing and prototype development. New investments in the AEP core include a Centura reactive ion etch capability from Applied Materials. The Centura is a single-wafer, multi-chamber system that supports processing of wafers ranging in size from 5", 6", or 8". The multi-chamber design allows for individual processes in each of the chambers.



Applied Materials Centura system is designed to etch silicon, metal, and dielectric materials.

A new TEM-Talos F200i TEM has been acquired for the NAU Flagstaff campus and is now operational and accessible by NCI-SW users. The TEM is managed by NCI-SW co-PI Prof. Miguel Yacaman, and lab director, Dr. Gregory Uyeda. The instrument has been accessed by internal users and we will begin access for the external community this year. We will focus on regional partners that do not have TEM capabilities.

The new Talos F200i TEM instrument in the ¡MIRA! Center on the NAU campus is available to support users in the Four-Corners region of the US Southwest.

User Base

The Eyring Materials Center regularly hosts an annual electron microscopy winter school that combines theoretical classes with hands on sessions for scientists and engineers who need more advanced transmission electron microscopy training. The workshops serve as a useful recruitment tool to attract users. The 2023 Winter School was held January 9-13. The attendance was capped at 40, with the majority of attendees being graduate students and postdocs, with three participants from National Labs, and nine from abroad.

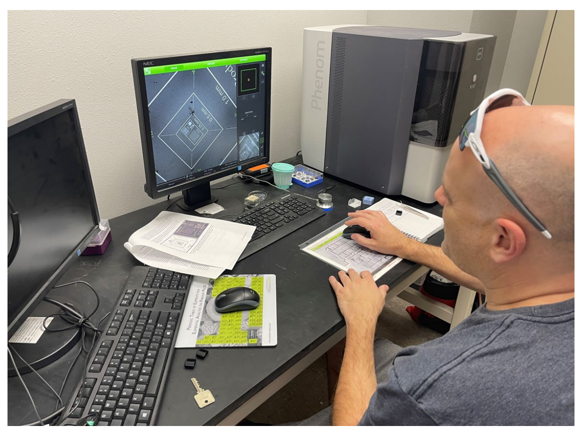
In Year 8 we continued our seed funding program to recruit new users. Academic users not affiliated with ASU can apply for up to $5,000 in laboratory fees to offset the costs of using the ASU Nanofab and/or Eyring Materials Center. During Year 8 we supported Venkata Chava, a research scientist in Prof. Sreeprasad Sreenivasan's group at the University of Texas, El Paso. Dr. Chava is working with our aberration corrected TEM staff scientist to image nanoribbons.

Research Highlights and Impact

The research focus of the NCI-SW is to provide general R&D micro- and nano-fabrication support across a broad range of disciplines including the life and health sciences; environmental nanotechnology; geological nanoscience; and renewable energy. The NCI-SW also established a user facility for the Societal and Ethical Implications (SEI) of nanotechnology that develops tools for the broader social science community to explore the social aspects and implications of nanotechnology. The ¡MIRA! Center at Northern Arizona University brings expertise and infrastructure related to materials science and quantum information.

During Year 8 the NCI-SW supported user projects on 2D and other nanomaterials that were published in Nature, Nano Letters, and ACS Nano, with 20 journal publications by external users in 2022 and 110 by internal users. We supported non-traditional external users from the geosciences and environmental sciences, culminating in the third Nano-EES (Environmental and Earth Sciences) workshop hosted virtually by the NCI-SW on April 5-6. The Nano-EES workshop was a collaboration with MONT, nanoEarth, and nano@stanford with a total of 71 participants over the two days. Our former REU student, Marian Jimenez, a first-generation college student and 2022 graduate from Pima Community College, completed the 3rd semester of her biomedical engineering degree at the University of Arizona.

The NCI-SW impacts workforce development through our partnership with Rio Salado College (RSC) to graduate nanotechnology technicians with AAS degrees. The partnership with RSC is supported with a "New to ATE" award from the NSF Advanced Technological Education (ATE) program. The ATE award enables Rio Salado College to offer a six-course certificate, as well as a 2-year associate degree in Nanotechnology. New in Year 8 the NCI-SW is working with Penn State University and RSC to offer a 12-week certificate program in semiconductor manufacturing for US veterans. The first cohort of veterans started in February, and 20 have completed the program.



One of the veteran participants in the new Micro and Nanoelectronics Certificate Program gains hands-on experience with the NCI-SW scanning electron microscope.

Education and Outreach Activities

Broadening Participation in STEM: ASU's Center for Broadening Participation in STEM (CBP-STEM) supports the NCI-SW outreach model by providing wrap-around services to ensure K-14 students have the opportunity to explore Science, Technology, Engineering & Math (STEM) in an open and safe environment. In Year 8, CBP-STEM organized participation in the Arizona Hispanic Serving Institutions (AZ HSI) Summit at Estrella Mountain Community College with a session titled *Arizona Universities Collaborating to Increase Diversity in STEM at All Levels*. This session focused on the collaborative efforts of Arizona's three research universities ASU, NAU, and the

University of Arizona to enhance access to STEM education and employment possibilities inclusive of all Arizona students through interventions that connect children, families, and communities to one-on-one science experiences in their own towns and surroundings. During the summit, NCI-SW and CBP-STEM illustrated how these outreach efforts instill a "sense of belonging" and foster STEM identities in participants. CBP-STEM has also joined the leadership group of the Micro Nano Technology Education Center (MNT-EC) Business Leadership Team monthly meetings to support inclusive workforce development of Community College students in the nanotechnology space. Another impactful activity in year 8 was CBP-STEM's leadership in a culturally relevant session facilitated by Anna Tanguma-Gallegos, Research Program Manager for CBP-STEM, and Jessica Hauer, Educational Outreach Coordinator for NCI-SW with the Arizona Indian Education Association in the fall of 2022 titled, *Biomimicry: Nature's Talents Among Us,* which examined the process of biomimicry in nature.

NCI-SW Co-PI Dr. Ines Montano (left) and other NAU volunteers at Estrella Mountain Community College for the Arizona Hispanic Serving Institutions Summit.

Research Experiences for Undergraduates (REU): The NCI-SW hosted nine undergraduate students for the summer 2023 REU program. As in previous years, this was a diverse cohort selected from 2- and 4-year colleges and representing first generation and/or underrepresented groups in STEM research and careers. All the REU students had valuable summer research experiences as evidenced by their successful presentations at the NNCI convocation at Montana State University. One of the students received a travel scholarship to attend the SACNAS Diversity in STEM conference, held in Portland, OR, on Oct 26-28, 2023.

Public Events: The major public outreach activities supported by the NCI-SW are in collaboration with the Arizona SciTech Institute, whose vision is to establish a prosperous and equitable world where STEM is within reach of every human. NCI-SW outreach team helped over 17,980 attendees of public events better understand the latest developments in nanoscience. Special attention has been paid in this last year to informing the public of workforce development opportunities that support Arizona and national economies in semiconductor manufacturing. Notable community events included: Indigenous Peoples' Day Phx Fest; Mall of America's "STEAM Event"; City of Flagstaff 4th of July Parade; SciTech "Innovation Summit"; ASU "Open Door"; City of Tempe's "Geeks Night Out"; Super Bowl LVII Host Committee's "100 Yards of Education: A STEM Playbook for Youth"; Barrett-Jackson STEM FEST "Gearing Towards the Future"; Cottonwood Vortex Festival; and Flagstaff STEM City Celebration.

Students, staff and faculty at public outreach events hosted by the NCI-SW in Year 8.

K-14 School Events and Teacher Professional Development: Partnerships between ASU's Center for Broadening Participation in STEM and NAU's MIRA center allowed us to expand the in-person K-14 impact, reaching over 2500 students at ten schools across metropolitan Phoenix and Flagstaff. With the goal of educating students and teachers, NCI-SW students, faculty, and staff demonstrated principles of nanomaterials engineering through the use of an optical microscope to view patterned wafers, real-time remote access to a scanning electron microscope to image samples with micro- and nanoscale features, as well as demonstrations such as illustrating the use of nanotechnology in paper money and stain resistant fabric. The NCI-SW also supported four middle school teachers' participation in the 2023 Nanoscience Summer Institute for Middle School Teachers (NanoSIMST) professional development workshops with NNCI host nano@Standford.

Societal and Ethical Implications Activities

Dr. Jameson Wetmore leads the NCI-SW SEI user facility with support from NNCI funded research assistant Martin Perez Comisso. The unit works one-on-one with visiting scholars and facilitates workshops, resources, course development, events, and in-depth training focusing on the social dimensions of nanotechnology and emerging technologies. The flagship activity of this SEI user facility is Science Outside the Lab (SOtL), a week-long training program traditionally held in DC every June. Dr. Wetmore also leads Societal and Ethical Implications activities across the NNCI as one of two non-Georgia Tech members of the NNCI Coordinating Office.

Since the creation of NCI-SW, the SEI team has led a Science Outside the Lab (SOtL) program every year except for the pandemic disrupted year in 2020. The program brings together a cohort of students, drawn largely from NNCI sites, to Washington, D.C. for a crash course in how science influences policy and how policy influences science. SOtL has proven to be a very powerful way to train young scholars in the social and ethical aspects of their work. For Year 8 SOtL was held June 4 -10 and included 15 participants from 12 NNCI sites. And for the first time a SOtL program tailored for faculty was hosted May 31 – June 2, with 12 faculty from nine NNCI sites participating.

Alumni of the SOtL program have proven very successful in making the transition from PhD student to science policy professional including: three Mirzayan S&T Policy Fellows at the National Academies; four AAAS S&T Policy Fellows; one AAAS Mass Media Fellow; two State of California S&T Policy Fellows; one Eagleton Science and Politics Fellow for the State of New Jersey; one intellectual property lawyer in DC; and one currently working for ASU's government research liaison office.

We have worked to share SEI ideas beyond the NNCI and ASU. For instance, Dr. Wetmore has presented an NCI-SW REU/RET webinar to introduce those participants to science policy. He also moderated the panel discussion between past SOtL participants on 24 May 2023, entitled "Scientists and Engineers in State Governments". And Dr. Wetmore presented the SEI work of NCI-SW and the Coordinating Office at the NSF Nano Grantees Conference: Nanotechnology for Sustainable Society on December 8, 2022.

Dr. Wetmore also manages the NNCI CO SEI efforts with the Winter School on Emerging Technologies being the flagship activity. During Year 8 the Winter School was led by a team including Ira Bennett (ASU), Nich Weller (ASU), Rider Foley (U. Virginia), Lauren Keeler (ASU), Vasiliki Rahimzadeh (Baylor College of Medicine), and Martin Comisso Perez (ASU). The Winter School was held 3-10 January 2023, and hosted 11 participants including 9 students from 6 NNCI universities (Stanford, NC A&T, ASU, NC State, UNC Greensboro, and Texas).

Computation Activities

Prof. Vasileska coordinates the computational activities for the NCI-SW. Working with the Georgia Tech node, she is redeveloping the tool-based curricula ACUTE on nanoHUB. Voiced presentations that describe concepts of semiconductor device modeling and simulation and first-time user guide for Victory Device (Silvaco TCAD device simulation framework) have been completed and installed on nanoHUB. ACUTE, ABACUS and AQME are popular tool-based curricula which allow students, via modeling and simulation (utilizing tools deployed on nanoHUB), to understand semiconductor device theory and applied quantum mechanics, respectively. Up until now, ACUTE has been accessed by 409 users, AQME by 2005 users, and ABACUS by 19,167 users. Note that Prof. Vasileska is the 3rd largest contributor of tools, tool-based curricula, and educational materials out of 2681 contributors on nanoHUB.

Prof. Vasileska also introduced on nanoHUB.org more than 300 teaching materials in the form of written materials on a given topic, corresponding presentations, and a series of exercises. These additional materials in calendar year 2022 alone were used by 77,097 users. In terms of classroom teaching, 7,516 users in 480 courses from 47 institutions worldwide used the tools and the educational materials on nanoHUB co-authored by Prof. Vasileska.

Innovation and Entrepreneurship Activities

The NCI-SW supports small business users including SBIR and government funded ‘spin-out’ companies, most notably iNanoBio and Advent Diamond. Both companies benefit from user access to NCI-SW core facilities at the non-profit rate that is considerably lower than the standard industrial rate.

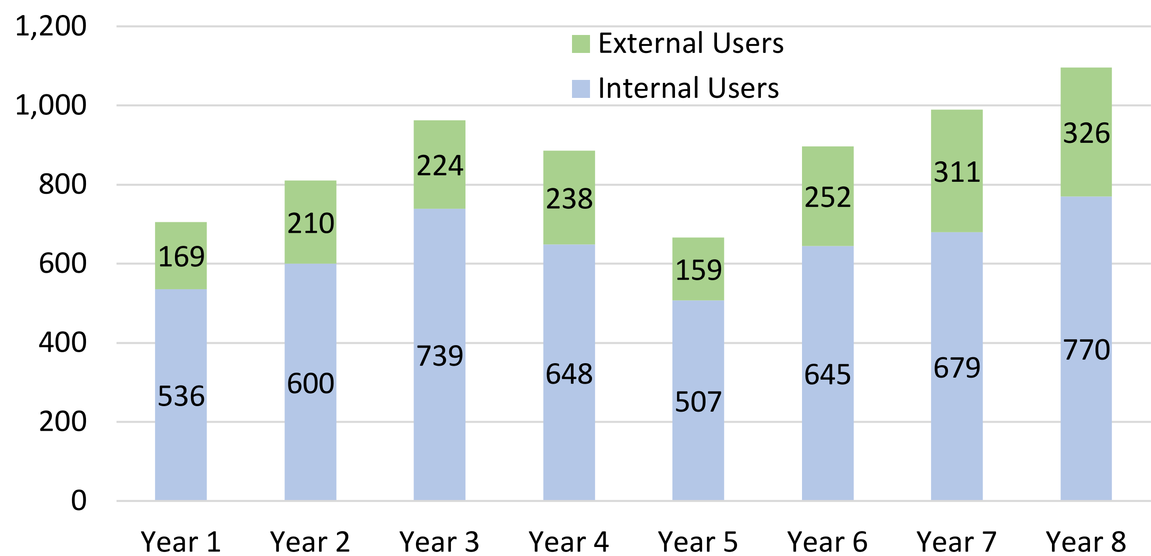
iNanoBio is a startup based out of Scottsdale, AZ and Menlo Park, CA. The company’s mission is to develop high-accuracy early-stage disease diagnostics using transformative nano-biotechnology platforms and machine learning. They have received $5.4 Million over four years as part of the Defense Advanced Research Projects Agency contract to a consortium led by the Icahn School of Medicine at Mount Sinai New York. They are also implementing a longitudinal, non-randomized study to evaluate the utility of their protein arrays in detecting unique antibodies in COVID-19 patients.

Advent Diamond has received more than $4M to develop diamond-based radiation detectors and high-power RF components, including a $750k NSF SBIR Phase II award. Dr Manpuneet Benipal, the CEO and Founder of Advent Diamond is a member of the NCI-SW External advisory Board.

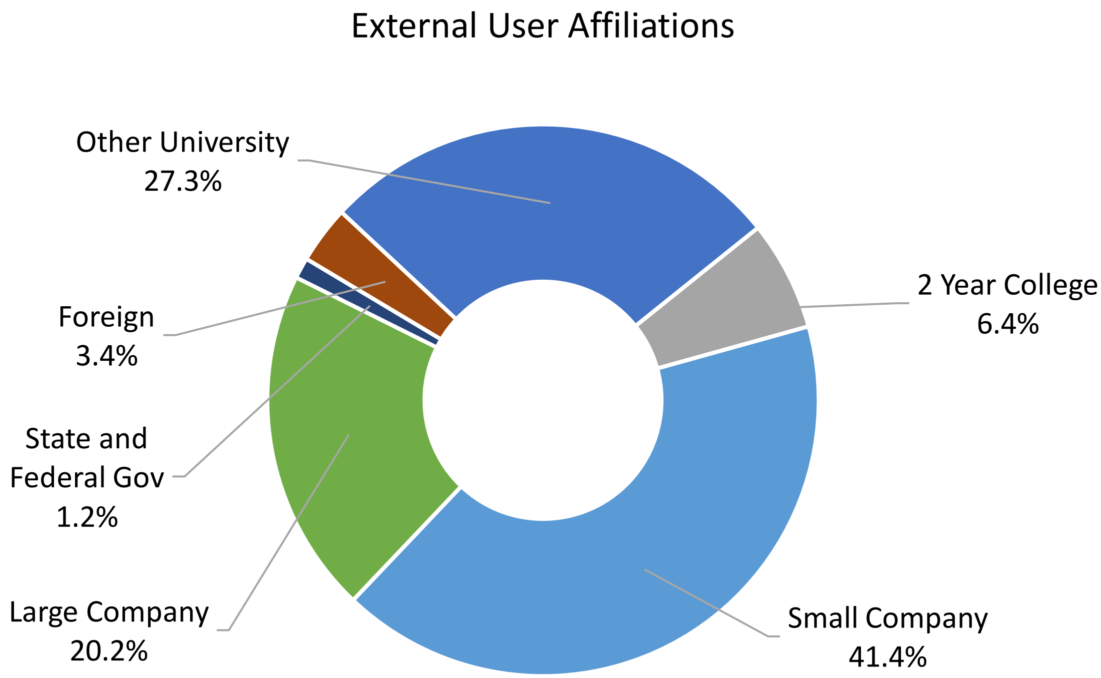
Because we have been using the annual Winter School on Emerging Technologies to help graduate students better understand how their research can have a lasting impact beyond academia, we have been including a significant emphasis on entrepreneurship. In 2023 we invited NNCI Coordinating Office associate director Matt Hull to meet with the student participants and he spent several days working with and coaching them over the course of the Winter School.

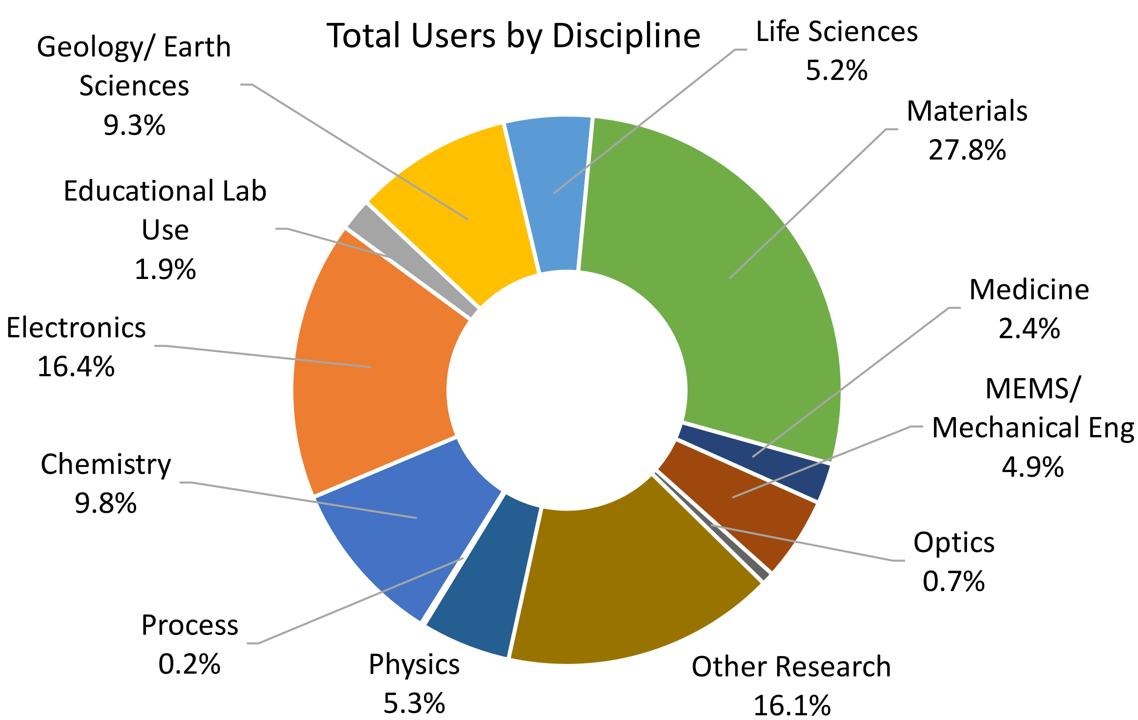
NCI-SW Site Statistics

Yearly User Data Comparison								
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	705	810	963	886	666	897	990	1,096
Internal Cumulative Users	536	600	739	648	507	645	679	770
External Cumulative Users	169 (24%)	210 (26%)	224 (23%)	238 (27%)	159 (24%)	252 (28%)	311 (31%)	326 (30%)
Total Hours	43,098	49,370	46,647	50,630	30,206	51,029	71,372	76,759
Internal Hours	32,883	38,270	37,954	37,996	23,997	43,124	60,568	63,214
External Hours	10,215 (24%)	11,100 (22%)	8,693 (19%)	12,834 (25%)	6,209 (21%)	7,904 (15%)	10,804 (15%)	13,545 (18%)
Average Monthly Users	271	313	284	312	272	311	328	386
Average External Monthly Users	43 (16%)	49 (16%)	47 (17%)	56 (18%)	45 (17%)	68 (22%)	86 (26%)	98 (25%)
New Users Trained	275	333	675	700	375	692	628	754
New External Users Trained	47 (17%)	53 (16%)	102 (15%)	143 (20%)	35 (9%)	187 (27%)	180 (29%)	193 (26%)
Hours/User (Internal)	61	64	51	58	47	67	89	82
Hours/User (External)	60	53	39	54	39	31	35	42



NCI-SW Year 8 User Distribution





12.8. Nebraska Nanoscale Facility (NNF)

Facility, Tools, and Staff Updates

The enhancement of NNF facilities has proceeded through funds received from the University of Nebraska (UNL), U.S. Army Research Office, NSF:NNCI and NSF MRI. The Physical Properties Facility received an advanced Dynacool PPMS system through EPSCoR EQUATE grant. SMCF Facility placed an order for a Qnami ProteusQ - LT Nitrogen Vacancy (NV) Microscope because of a successful NSF MRI proposal led by NNF/NCMN Director Prof. Binek. The Qnami ProteusQ – LT system is a complete quantum microscope system. The system combines the Nitrogen Vacancy magnetometry and scanning probe microscopy into a single instrument and enables the simultaneous acquisition of surface topography and its surface magnetic fields with nanoscale resolution. A closed cycle cryostat enables low temperature measurements at T <2K. NNF wants to play an important role in workforce development for the semiconductor industry and lab-to-fab projects which bring prototype device concepts to production. To do so, NNF seeks to update its nanofabrication tools, notably by replacing the outdated 30kV e-beam lithography with a state-of-the-art 100kV system. In this regard, Prof. Binek and colleagues submitted a proposal to NSF MRI for procuring an advanced 100 kV Reith E-beam Lithography system for the NCMN – Nanofabrication Cleanroom Facility. Staff members supported wholly or in part by NNCI:NNF include: NNF Coordinator and User Contact: Dr. Jacob John; NNF Staff Scientists: Dr. Andrei Sokolov, Dr. Wen Qian, Dr. Ather Mahmood, and Bibek Tiwari; NNF Education-Outreach Coordinators: Steven Wignall, Dr. Hanh Phan, and Jenna Huttenmaier.

User Base

The NNF organized in-person events this year aimed at expanding external usage. The NNF Facility Coordinator/User contact reached out to potential users from other universities, colleges and industries in the region and neighboring states to recruit new users. The NNF was able to communicate with several industries during the last six months and a few of them visited NNF facilities for tour and dicussion. Some of them are currently using our facilities. Companies like Wilson Case, Hastings, NE, Hydrograph, Manhattan, KS, General Dynamics, Lincoln, and SLD Photonics, Wyoming are some of them.

Minicourse: Free Equipment Training for External Students and Industry Engineers: Our annual 3-day Minicourse for external users was held on November 1-3, 2022. The NNF provided free hands-on operational training on instruments of their choice for almost 28 external participants during the 3-day free equipment training. Each participant received training on 2 or 3 instruments of their choice during the Minicourse. The Minicourse attendees were graduate students and industry engineers from neighboring states such as SD, WY, KS and OK. The NNF also covered the accommodation expenses of all the Minicourse participants from neighboring states.

NNF Seed Grant/Free Usage Program for External Universities/Companies During Campus Visits: The NNF Facilities Seed Grant program aims to provide resources to small companies, start-up companies, and students from smaller regional universities and colleges for facilitating development of new nanotechnology enabled products, proof-of-concept development that involves characterization of nanomaterials, fabrication of devices, and testing that require access to the instrumentation facilities.

Research Highlights and Impact

Research Focus Areas in NNF: In 2021, the NSF awarded $20M funding for the EPSCoR proposal on "Emergent quantum materials and quantum technologies" lead by the NNF Director Prof. Christian Binek. Since then, the interdisciplinary research by a team of 20 PIs and 4 universities in the state of Nebraska adds to the pool of NNF users and transforms NE into an internationally recognized hub in the field of quantum materials. The NNF facilities play a critical role in facilitating, supporting, and enabling advanced quantum materials and technology research of the EPSCoR EQUATE Center. EQUATE includes 20 faculty members from the University of Nebraska-Lincoln, the University of Nebraska at Kearney, and Creighton University. It leverages existing partnerships with Little Priest Tribal College and Nebraska Indian Community College. The UNL hired four faculty in QMT in the Departments of Physics, Chemistry, Electrical and Computer Engineering, and Mechanical and Materials Engineering. These new faculty, along with several present faculty, will form a strong research group in the NSF Big Idea: Quantum Leap. In 2021, UNL's Chancellor selected Quantum Science and Engineering as one of seven grand challenge themes which see significant $40M funding over the next five years. The team led by NNF/NCMN Director Prof. Binek received a $4.8M UNL internal grand challenge award from an internal competition. There are 21 investigators in this project and most of them are NNF users. This new award will continue to strengthen NNF's transitioning to quantum materials science. The NNF also supports major sponsored research programs at the NCMN, an institutional Nanoscale Science and Technology Program of Excellence, the Nebraska Innovation Campus, UNL's new Voelte-Keegan Nanoscience Research Center, the NSF-MRSEC, the SRC-NIST Center for Nanoferroic Devices, the DOE-EERE Collaboration on Magnetic Materials, and several other research centers and programs in other universities and colleges in the western region of the US Midwest.

Example Projects of External Users:

- *Hydrograph, KS*: Hydrograph produces ultra-high purity graphene at an industrial scale with optional chemical modifications that allow the graphene to react more readily to a chosen material. Hydrograph's plant located in Manhattan, Kansas uses NNF Facilities for characterization and analysis of their products. The NNF supports Hydrographs with XRD, XPS, Raman, SEM, and FTIR of their samples on a regular basis.
- *SLD Photonics, WY*: NNF supports SLD Photonics, an SBIR award recipient, in the R&D and fabrication of a new detector device. This small company is developing a broadband detector that can capture visible light and near-infrared light and the detector can be used in unmanned vehicles and defense-related devices. The detector can also be paired with diagnostic tools for improved healthcare. The company uses device fabrication facilities in NNF for its R&D work.

Economic Impacts: The NNF critically supports all research in materials and nanoscience at the Univ. of Nebraska. NNF also supports the manufacturing economic sector of Nebraska's economy and Midwestern states. The NNCI grant enables NNF to provide critical resources necessary for many companies, smaller universities, and colleges in the Midwest region. The NNF supported more than 40 regional institutions in more than 7 states in the Midwest region during NNCI Year 8 in terms of R&D, innovation, product development and testing, quality control, solving and identifying problems in product lines and identifying reasons of product failures in the field, etc.

Education and Outreach Activities

NNF-Sponsored Events:

National Nanotechnology Day Celebrations in October included a couple of different events: 1) NNF submitted images by graduate and postdoc students to the national NNCI 2022 **"**Plenty of Beauty at the Bottom" image contest. 2) NNF recognized Nano Days in Nebraska by providing a booth at both the State Teachers of Science Conference (NATS) and at our annual Astronomy Day at UNL. Teachers from around the state at all levels were exposed to this event and nanotechnology. In addition, at-risk students at 6 of our middle schools in Lincoln, in their after-school programs, benefitted by exposure to the event. Total attendance at the events were approximately 500.

Junior/Senior High School Tours: We resumed in person tours exclusively this year. Estimated number of participants in 2023 tours were 150-200. We continually try to suggest this activity at educational events to increase this number in the future.

Partnerships: Nano and Discover Engineering Days: NNF continued to partner with the UNL College of Engineering to introduce hundreds of rural and urban middle-school students and their teachers to the various fields in engineering and nanoscience at the UNL throughout the year. Events were filled with hands-on activities that applied math, science, and creative thinking skills. October 2022 through September of 2023, 680 junior high students from 20 schools throughout Nebraska received nano lessons using hands-on materials provided for the lesson.

Family Science Night: We expanded our presence this year with the collaboration between us and the Southeast Community College system for Family Science Night. We set up a table with demonstrations and activities for children and their family to experience the wonders of Nano and Quantum Physics. We attended this event at the Beatrice and Lincoln campuses in the spring and fall with approximately 1000 in attendance between the two events.

Family Forestry Day: We attended this event for the first time this year. It attracted 1400 people from around the states of Nebraska and Iowa. We set up multiple tables and presented activities and lesson pertaining to "Nature in Nano." The attendees were mostly families with younger children, and surprisingly a large amount of "Home Schoolers".

Workforce Development:

Nanotech Lab Course for Student Users: This one-credit-hour per semester course provided graduate students with an introductory, but yet comprehensive, view into the large variety of instruments available at the NNF. The purpose of this course was to help students master experimental skills in their own research area and to broaden their horizon in experimental nanotechnology methods, complementary to that area. The course spans two semesters and covers theoretical introduction and demonstration of technical capabilities in areas such as: Thin film fabrication, X-ray and TEM characterization, Nanofabrication and SPM surface analysis.

Research Experience for Undergraduates (REU): Two undergraduate students were selected regionally to work in research labs 8-10 weeks as part of NNF's REU program during the 2023 summer. We were also honored again this summer to represent the NNCI as one of the Host schools for the Japanese exchange program. Kota Aono selected "3D Tissue Fabrication for Skin Regeneration" with Prof. Ruiguo Yang. All 3 presented their research at the NNCI REU Convocation. NNF has committed to hosting the NNCI REU Convocation in August 2024.

High School Intern Program: NNF hosted 22 high school interns in-person from June-August 2023. Faculty from Chemistry, Physics, and Engineering provided the high school students the opportunity to work in research labs for 8-10 weeks with the help of a graduate student mentor to guide and train them in research techniques.

Rural Workforce Development: To support the development of our workforce, we provided undergraduate student cohorts from Central Community College (CCC), Columbus, NE, first-hand opportunities to use our NNF Facilities, which included Electron Nanoscopy Instrumentation, Nanofabrication, Surface & Materials Characterization, X-Ray Characterization, and Nano Materials and Thin Films. Students have regularly performed research in NNF labs along with CCC faculty on a regular basis.

NNCI Site Collaboration: Two community college undergraduates, Central Comm. College (CCC) using our facilities during the school year were chosen for the 2023 NNCI REU's program. This great connection between NNF's community college partner and us will help to bring future collaboration between CCC and hopefully other community colleges in the state to have further collaboration with the NNF. This could be very beneficial if training for Semiconductor processing becomes a reality in our state.

Teacher Conferences/Workshops: This year we were able to attend 4 in person Conferences and one conference virtually. These included the Nebraska Association of Teachers of Science (NATS) Oct 6th-8th, and the state AAPT meeting and Astronomy Day on (Oct 22nd). We also did presentations on Nano and Quantum at two other teacher conferences this year, one in Grand Island for 100 Vocational Ag teachers for their state conference, and one with CCC for 20 Northeast Neb Science teachers. The virtual conference was the South Dakota State Science teachers meeting where we presented on Zoom to a group of teachers with the collaboration of Professor Larry Browning of SDSU Physics Dept. Attendance was ~250-300 for all sessions.

Research Experience for Teachers: Five teachers were selected to participate in NNF's 2023 Summer RET Program scheduled from June 19 - July 28. Teachers worked in nanoscale science and engineering labs to gain hands-on experiences in the techniques and tools used within NNF facilities, with follow-up support during the school semesters. This RET Program is in partnership with three other RET sites throughout the US (Georgia Tech, Minnesota, and Northwestern).

Nanoscience Summer Institute for Middle School Teachers in Partnership with Stanford: Last summer nine teachers participated in the NanoSIMST four-day virtual workshop at the end of June. The goals of the workshop were to: 1) excite teachers about nanoscience, 2) equip middle school teachers with content knowledge and empower them with pedagogy to teach their students; and 3) effectively teach thousands of students about nanoscience. Teachers from across NE will learn about quantum, nanoscience and engineering through lectures, hands-on activities, facility video tours, and guest speakers.

K-12 Diversity Programs:

NNF's After-School programs for diverse elementary through high school populations expanded during this year. 1) NNF's partnership with Educational Talent Search (ETS) which serves eligible low-income, first-generation students in grades 6th through 12th remained at 6 middle schools. NNF created lessons, and gave presentations to 90-100 junior high, for a total of almost 200 students. 2) Thirty diverse Upward Bound high school students were given two 2-hour nano workshops during the summer with career information and hands-on activities. 3) Twenty-five diverse Girls

Inc. high school students were given a 2-hour nano workshop during the school year with tours of nano-related research in NNF Facilities, career information and hands-on activities. (4) 50 Rural 2-7 grade students came to NNF with their teachers as part of a Summer STEAM camp at the Columbus NE. school.

Traveling Nanoscience Exhibit:

Our two 400-sq.-ft. hands-on exhibits are still active and making their rounds in museums in the Midwest. During this report's time span the exhibit was viewed at the Grout Museum in Iowa, and the Hastings Museum in Nebraska. Our second traveling exhibit, the Sun, Earth, Universe Exhibit, was hosted by the SAC museum in Nebraska, and Hastings Museum. The exhibits were created by NISE Net, funded by NSF, and sponsored by NNF and Morrill Hall at UNL.

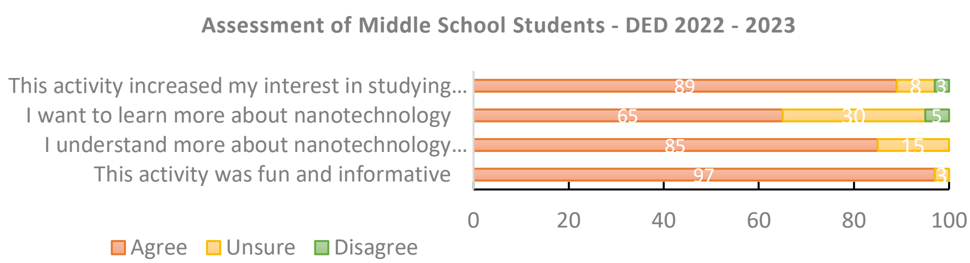
Resources:

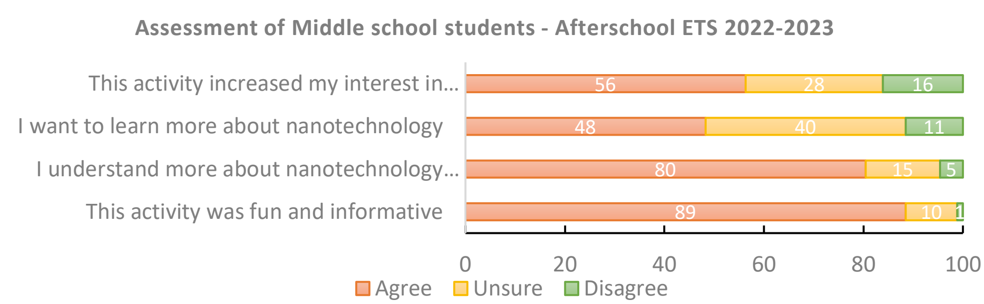
Nano/STEM Kits: We provided Nano/STEM activity kits (developed by NISE Net, a NSF-funded organization) to teachers in the area. The kits contain hands-on activities to support a variety of science concepts at the middle school level. Kits can be adapted for different ages, contain reusable hands-on activities, and include digital files, training videos, scripted lesson plans, and national science standards about nanoscience topics.

Training Modules: Equipment training videos provided new facility users with an effective and efficient method of learning information needed to work in NNF labs. New users can access "how to" information by facility specialists before and after real-time training, which increases efficiencies and level of learning. Several video tutorials for users have been prepared for introducing instruments, their functions, and overall capabilities. Also, K-12 teachers benefited from some of these videos as part of our online nanoscience teaching modules.

Assessment Activities:

The Nebraska Nanoscale Facility (NNF) evaluated efforts to promote nanoscience among diverse, underrepresented groups, and urban and rural middle-school students by surveying participants at the completion of the After-School programs for Educational Talent Search (ETS) and Nano and Discover Engineering Days participants. ETS students responding said they understood more about nanotechnology after the activities (89%) and (56%) of the ETS students had become more interested in studying science and engineering. Students in





our fall 2022/spring 2023 Discover Engineering outreach events to 21 Nebraska schools were assessed and 97% of the 680 students agreed that the DED hands on activities were fun and informative. Among the respondents, 85% understood more about nanotechnology and 89% of them responded that the activities had increased their interest in studying science and engineering. This resulted in 65% of the students surely wanting to learn more about nanotechnology. NNF is a member of the NNCI Evaluation Working Group which continues to provide information and advice on how to 1) define and follow an evaluation plan, 2) include consideration for the population involved and measurement methodology, 3) assess and analyze data, and 4) apply the results to planned and future activities and share lessons learned with others. Quality assessment practices will be an integral part of the learning processes and activities.

Computation Activities:

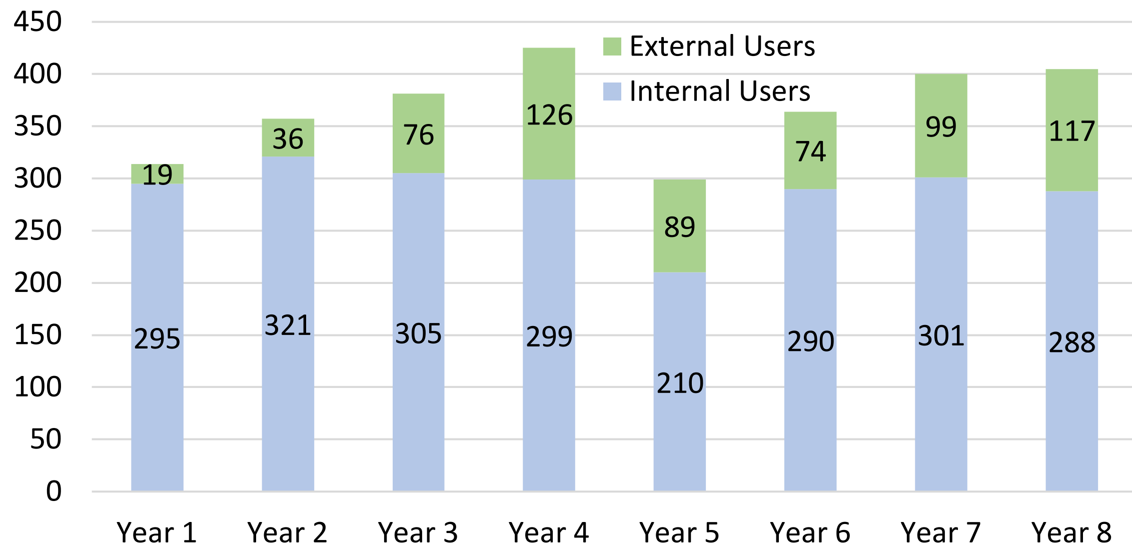
NNF/NCMN is considering adding computational support to the center. Specifically, we explore the need among users for machine learning support and try to find ways to finance such a position. It is increasingly obvious that artificial intelligence in general and machine learning in particular, will play an ever-increasing role in materials science and significantly support experimental approaches which often rely on educated guesses with trial and error approaches which are costly and slow. To this end multiple speakers have been invited in the framework of the combined EQUATE/NCMN seminar series (https://equate.unl.edu/seminars#2022). Those include Prof. Arti Kashyap from the School of Physical Sciences, IIT Mandi, India with a presentation entitled "DFT and DFT based Material Databases in the Era of Machine Learning" and Arun Mannodi-Kanakkithodi from Purdue University with a presentation entitled "Multi-Fidelity Machine Learning for Perovskite Discovery". NNF also utilized NNCI's expertise. In fact, it was NNCI Coordinating Office Associate Director Prof. Azad Naeemi (Georgia Tech) who suggested to contact Prof. Mannodi-Kanakkithodi. NNF is currently in the process of evaluating if such a position can be realized and find sufficient use.

Innovation and Entrepreneurship Activities

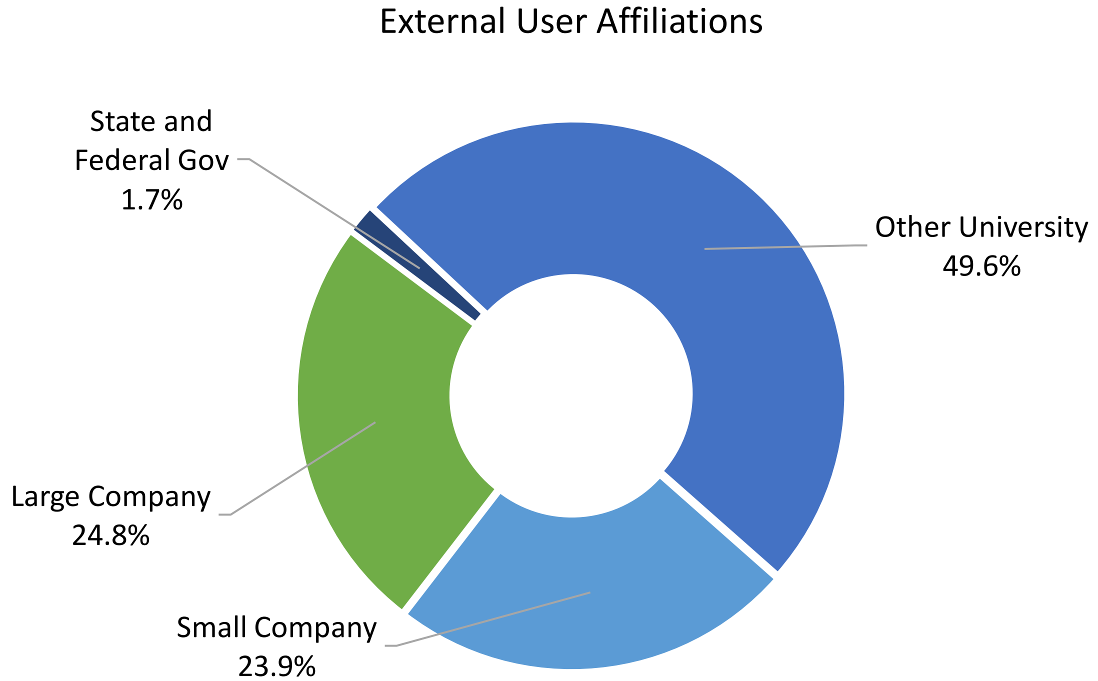
Entrepreneurship success by NNF faculty user Prof. Ravi Saraf: Vajra Instruments, INC, a small startup and recipient of several federal government grants including SBIR, was founded by UNL faculty and NNF User Prof. Ravi Saraf. Vajra Instruments, Inc. is focused on an inexpensive screening tool for pancreatic cancer. Recent research indicates that less than hundred microRNA (miRNA) sequences specifically generated by tumors are sufficient for early detection of PaC and other cancers for effective intervention with excellent prognosis MiRNA can be extracted from urine and blood using standard kits. Vajra Instruments is a regular user of the NNF facilities. Access to the NNF Nanofabrication Cleanroom facility is critical for the success and operations of small startup company Vajra Instruments. The NNF Nanofabrication Cleanroom facility is providing Vajra Instruments with high quality electrochemical microarray chips for screening pancreatic cancer. Chip fabrication is based on laser lithography using a Heidelberg DWL66 direct laser writer and depositing Cr/Au metallic thin films using a sputtering system. The firm is working to directly measure the tumor specific miRNA extracted from about ml of serum or plasma using a disruptive technology called SEED. Measurement by SEED is virtually blind to non-specific binding with consistency. The binding time of targeted miRNA to the probe will reduce from hours for conventional microarray methods to below one hour.

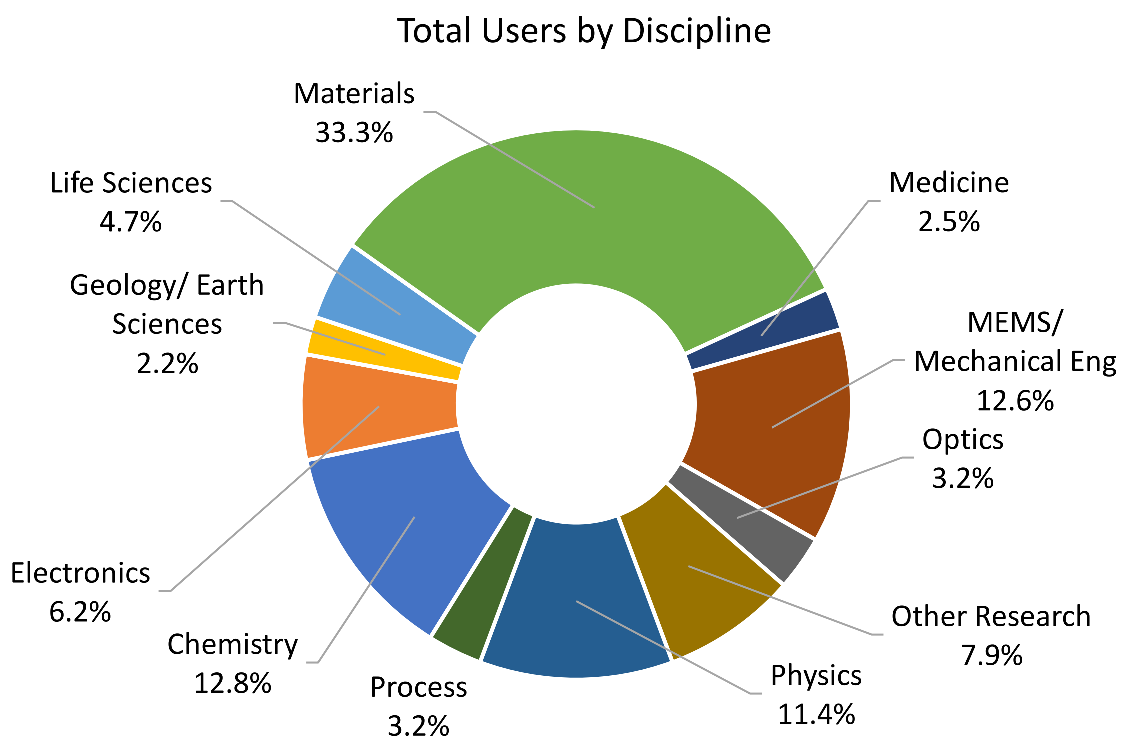
NNF Site Statistics

Yearly User Data Comparison								
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	314	357	381	425	299	364	400	405
Internal Cumulative Users	295	321	305	299	210	290	301	288
External Cumulative Users	19 (6%)	36 (10%)	76 (20%)	126 (30%)	89 (30%)	74 (20%)	99 (25%)	117 (29%)
Total Hours	23,445	20,102	24,008	31,037	24,002	23,422	27,262	23,297
Internal Hours	23,123	19,278	22,260	27,468	20,809	20,382	23,388	19,779
External Hours	322 (1%)	824 (4%)	1,748 (7%)	3,569 (11%)	3,192 (13%)	3,040 (13%)	3,874 (14%)	3,518 (15%)
Average Monthly Users	40	120	132	137	90	120	134	128
Average External Monthly Users	3 (8%)	7 (6%)	19 (15%)	18 (13%)	14 (15%)	15 (12%)	17 (13%)	18 (14%)
New Users Trained	47	54	124	98	150	215	278	211
New External Users Trained	0 (0%)	1 (2%)	6 (5%)	7 (7%)	5 (3%)	16 (7%)	26 (9%)	14 (7%)
Hours/User (Internal)	78	60	73	92	99	70	78	69
Hours/User (External)	17	23	23	28	36	41	39	30



NNF Year 8 User Distribution





12.9. NNCI Site @ Stanford (nano@stanford)

The NNCI site at Stanford University (**nano@stanford**) provides **access to world-leading facilities and expertise** in nanoscale science and engineering for internal users and external users from academic, industrial, and government labs. We also seek to **develop and propagate a national model for educational practices** that will help students and visitors become knowledgeable about the nanoscale and proficient users of the facilities. nano@stanford prides itself on its **entrepreneurial ecosystem**, which is facilitated by auxiliary laboratories with less stringent particle count requirements that can function as flexible maker spaces as well as entrepreneurial resources available on campus. Another unique strength of nano@stanford is its **high-impact, scalable, education and outreach programs**: a community college internship program and a middle school teacher professional development program. Both programs strategically target underrepresented groups, minority serving institutions (MSIs), and Title 1 schools to provide more equitable opportunities.

nano@stanford facilities include **Stanford Nano Shared Facilities (SNSF)**, **Stanford Nanofabrication Facility (SNF)**, **Stanford Mineral Analysis Facility (MAF)** and **Stanford Isotope and Geochemical Measurement & Analysis (SIGMA) Facility.** The facilities offer an extensive suite of advanced nanofabrication and characterization tools, including capabilities rarely found at shared facilities (e.g., MOCVD, two Raith EBPG 5200 electron-beam lithography systems, a diamond deposition system, a nanoSIMS, and a scanning SQUID microscope). The facilities occupy ~30,000 sq. ft. of space, including 16,000 sq. ft. of cleanrooms, that are all located in convenient proximity on Stanford's main campus. Not only do the facilities offer access to state-of-the-art equipment, but they also provide the expertise of ~35 technical staff members (including 18 Ph.D.s) who support the lab community's research endeavors.

<u>Facility, Tools, and Staff Updates</u>

During year 8 of the award, nano@stanford added several new capabilities:

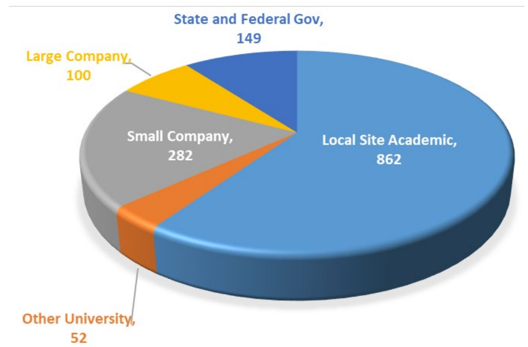
1. Physical Electronics VersaProbe 4 XPS, featuring airless sample transfer, a heating/cooling stage, an Ar+ GCIB, REELS, UPS, and LEIPS.
2. Thermo Fisher Spectra 300 (S)TEM with aberration corrected image resolution down to 0.5Å and 30meV energy resolution; EDS; EELS; and TEM, STEM, + EDS tomography.
3. Filmetrics F20 Film Thickness Measurement Instrument.
4. Zeiss Merlin® SEM.
5. KLA Instruments™ Alpha-Step® stylus profilometer.
6. MicroMLA Direct Write System
7. TWO Raith EBPG 5200 electron-beam lithography systems for high-resolution lithography.
8. Kurt Lesker Evaporator.
9. Hitachi -4000PlusE Tabletop SEM (for Education & Outreach and user research).

SNSF is making swift progress on a planned, significant expansion that will include an additional 10,000 sq. ft. of facility space and new characterization capabilities thanks to an investment from the Vice Provost and Dean of Research, including $30M for construction and an estimated $16M for new instrumentation.

In year 8, nano@stanford **increased staffing with 4.5 new positions** including Grace Hsieh (nano@stanford Program Communicator), Gabriel Catalano (Senior Operations Engineer), Chloe Goings (MOCVD Engineer), Quynh Nguyen (1/2, Financial Accountant), and Paul Wallace (Senior Microscopist).

<u>User Base</u>

In year 8, nano@stanford served a total of 1445 users, the **highest number of cumulative annual users** for the duration of the award and an 18% increase compared to year 7, indicating recovery from the pandemic.



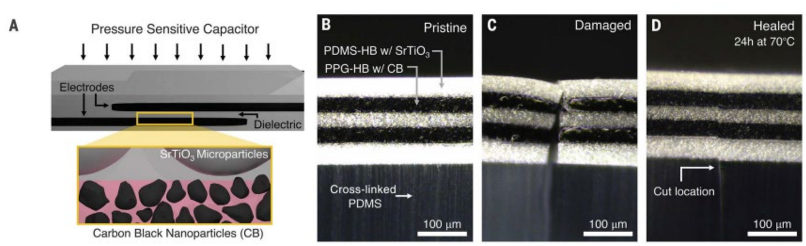
Year 8 cumulative users by affiliation.

Several program changes were implemented to help grow the user base. First, we hired an additional staff member for the newly created role of Program Communicator, who will help improve the visibility of nano@stanford, enhance communications with lab members, and collaborate with staff to develop additional on-line training content to further streamline the onboarding process for new members. Secondly, to augment the user experience, we started sending a "nano@stanford Weekly Update" to our users to keep them informed about facility-related news, events (e.g., workshops, help clinics, seminars), and opportunities (e.g., E&O volunteer activities, fellowships, job openings). Finally, we formed a user advisory board (the "Lab Member Collaborative"), and the board's mission is to help improve the user experience, to act as conduit between users and nano@stanford leadership, and to build a sense of community and belonging.

<u>Research Highlights and Impact</u>

The following are three representative research highlights from an internal user and two external users. A comprehensive list of research publications is provided in our year 8 Annual Report and additional research highlights are available in the supplemental PowerPoint file. During 2022, we captured 221 published journal articles from internal users, 51 articles from external users, 53 conference presentations, and 3 book chapters.

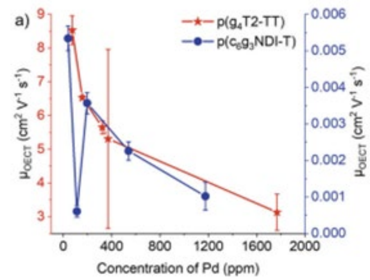
As featured on NSF Foundation News, **Stanford Professor Bao's group** developed several multi-layer, self-healing devices with modified polymers having similar dynamic bonds but immiscible backbones. Using characterization techniques available at nano@stanford (e.g., rheometry, mechanical testing, nanomechanical imaging by AFM), theoretical models, and computers simulation, the researchers developed a field-theoretic description to explain the interfacial self-healing behavior between modified PDMS and PPG layers. Importantly, they hypothesized that reduced interfacial healing enabled autonomous realignment of alternatively stacked films after damage. Furthermore, they embedded stacked films with conductive micro- and nano-particles or flakes and demonstrated the functional self



Demonstration of a self-healing, realigning pressure capacitor.

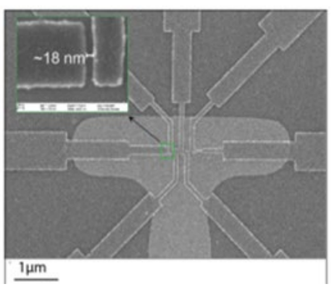
healing of the films in a pressure-sensor capacitor, magnetically assembled soft robot, and an underwater LED circuit (https://www.science.org/doi/10.1126/science.adh0619).

External users from **Professor McCulloch's group at the University of Oxford** made strides towards optimizing organic electrochemical transistors (OECTs), which are attractive devices for biological sensing applications. The authors demonstrated an alternative method for purifying organic mixed ionic-electronic conductor (OMIEC) materials using preparative gel permeation chromatography (GPC) to minimize the presence of reaction by-products (e.g., palladium (Pd)) and to separate polymer batches into discrete molecular weight fractions. The ICP-MS, performed at nano@stanford's SIGMA facility, indicated that Pd contamination was reduced by between 54-97% using this new method. The electrical performance of OECT devices fabricated with purified OMIEC exhibited an increase in the charge carrier mobility (mOECT) of 60% - 80% (figure above). ***A portion of this work was also performed at the SHyNE site and is an example of cross-network research*** (https://doi.org/10.1038/s41467-022-35573-y)



Pd concentration (measured at nano@stanford) vs. OECT electrical performance (measured at SHyNE).

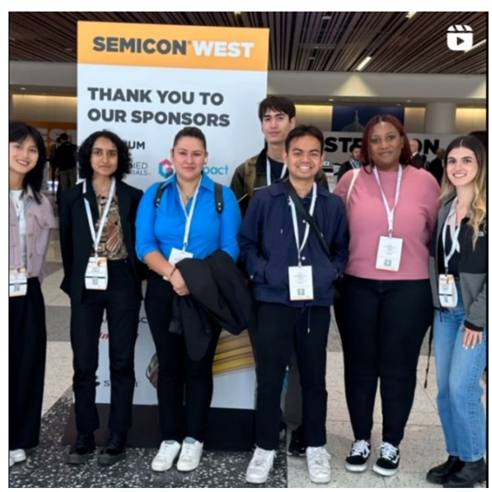
In another external research example, **Professor Bokor from UC Berkeley, Dr. Ruffieux from Empa, and colleagues** developed a novel synthesis method to grow 45-nm long, 5-atom wide graphene nanoribbons (5-AGNRs) and demonstrated their successful incorporation into Field Effect Transistor (FET) devices. This advancement was remarkable, because previously 5-AGNRs had only been synthesized to be a few nm in length making them unusable as alternative channeling materials in FETs. With this development it could be possible to replace traditional doped silicon with 5-AGNRs and reduce transistor sizes to below 7nm (https://doi.org/10.1002/smll.202202301).



SEM of a FET fabricated with 5-AGNR.

Education and Outreach Activities

Our year-round, **community college internship program** provides hands-on, paid experience in nanotechnology for students from local colleges. The program has undergone substantial growth in year 8, increasing from 9 to 21 interns. We have intentionally targeted MSIs when recruiting interns, which has resulted in 88% of our interns have been from underrepresented groups. Additionally, 69% of our interns have been female. This year we started to overlap new interns with senior interns, who assist with training to reduce staff time for onboarding, and this facilitates scaling. Out of the 25 interns that we have hosted since 2018, 10 transferred to 4-year institutions, 1 accepted a full-time job, and 1 participated in a REU at Harvard's NNCI site.



nano@stanford sponsored an intern field trip to SEMICON West.

NanoSIMST is a **middle school teacher professional development workshop** during which participants learn about nanoscience and prepare classroom lessons. Since 2017, NanoSIMST has grown to become a network-wide activity, led by nano@stanford. Last summer, we partnered with 9 other NNCI sites which either adopted the in-person program or provided financial support to sponsor teachers from their areas. The agenda this year included guest speakers from our sister sites at CNS and KY Multiscale, exemplifying the power of a network. To date, NanoSIMST has trained 145 teachers, impacting an estimated 7000 students. We strategically target diverse cohorts of teachers based on subject matter expertise and school location/demographics. The addition of a virtual format increased the participation of Title 1 schoolteachers from an average of 48% over previous years, to 71% in year 8. This year we hosted a field trip for 150 eighth graders from a Title 1 school where a NanoSIMST alumna teaches. During the last two years of the award, we plan to both increase the number of teacher participants and to enhance the program content with industry guest speakers and career resources.

Field trip for 150 8th graders to visit nano@stanford, led by a NanoSIMST alumna. This demonstrates the impact of a single teacher.

To further augment the internship program and NanoSIMST, we plan to incorporate career-oriented content (e.g., industry speakers, career resources, industry opportunities) and have begun building connections with industry towards this goal. For example, we have been working with the SEMI Foundation to share and leverage the resources they have developed for educators and career explorations for both NanoSIMST and the intern program.

Other E&O activities included a mini grant for Stanford graduate students to create DEI-targeted STEM experiential learning content, along with numerous facility tours, demos, workshops, curriculum support etc., reaching a total of 2445 participants this year alone. In year 8 we have continued to create content for our edX courses, reaching 10,228 learners since 2019. While most learners are based in the US (26%) and India (23%), the course has a truly global reach.

<u>Societal and Ethical Implications Activities</u>

nano@stanford staff have served as guides and proponents for a SEI Student Working Group, comprised of six alumni from NNCI's Science Outside of the Lab (SOtL) program. With support from a seed grant from Stanford's McCoy Family Center for Ethics in Society, the working group has tackled three primary projects. (1) The first project was the development of an online training module called "Ethical Considerations for nano@stanford Researchers", to help familiarize the nano community with nanotechnology ethical concepts and provide recommendations for communicating science, data processing, data management, and authorship. (2) The second project was the creation of an ethics infographic to educate lab members about reporting research misconduct, which is now posted around the nano@stanford facilities and available on our

SEI Student Working Group's book club.

website. (3) Lastly, the SEI Student Working group launched a SEI Book club, in collaboration with Stanford's Science Policy Group (SSPG). The group read "The Code Breaker (Walter Isaacson): Biography of the CRISPR inventor" by Jennifer Doudna, which discusses the ethics of genetic coding. nano@stanford has provided funds for coffee, snacks, and 20 copies of "The Code Breaker" to encourage and facilitate participation. The SEI book club affords a sense of community and belonging for like-minded, SEI-interested individuals in the nano@stanford lab community.

Innovation and Entrepreneurship Activities

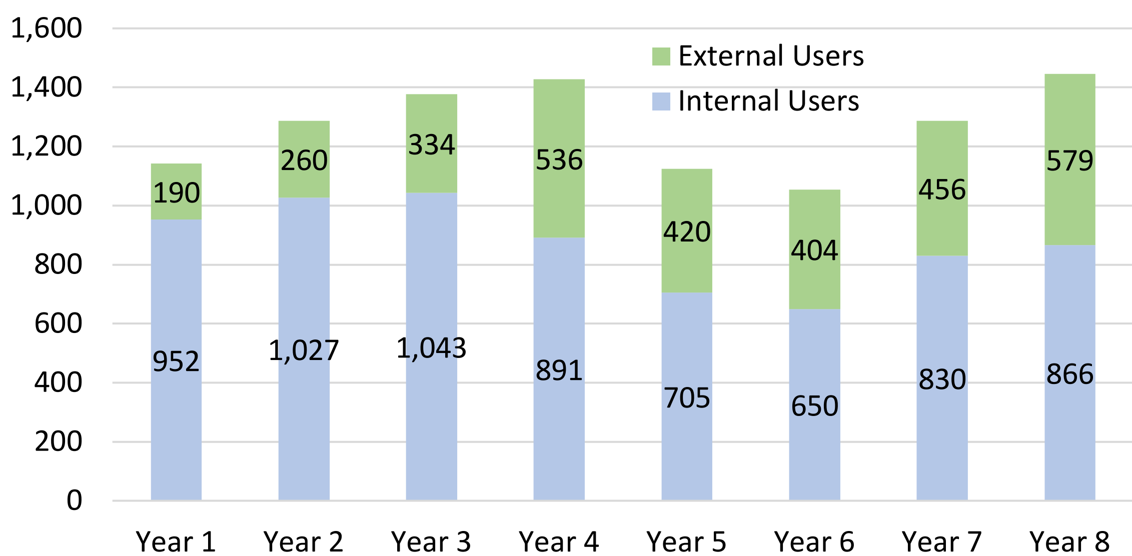
Dr. Schneider presenting at the Workshop on Nanotechnology Infrastructure of the Future.

In 2023, nano@stanford planned two major NNCI events: the Workshop on Nanotechnology of the Future and the NNCI Annual Conference. Both the workshop and conference featured entire sessions devoted to innovation and entrepreneurship in nanotechnology. Given the healthy entrepreneurial ecosystem at Stanford and the surrounding Bay Area, we have strong connections with relevant translation experts and invited them as guest speakers. For example, Dr. Rick Schneider (co-Founder and Chief Development Office for Raxium) presented at the workshop about his experiences developing successful startups, such as and Raxium, which were facilitated by access to CNF and nano@stanford, respectively. In preparation for the October conference, we invited speakers to showcase some of the valuable entrepreneurial resources available at Stanford, such as Stanford Ignite, Activate Berkeley, Silicon Catalyst, and the new Applied Material's EPIC Center. Additionally, co-founders from two start-up companies were invited to present about their translation journeys and how access to the nano@stanford facilities and Stanford's entrepreneurial resources helped in their success.

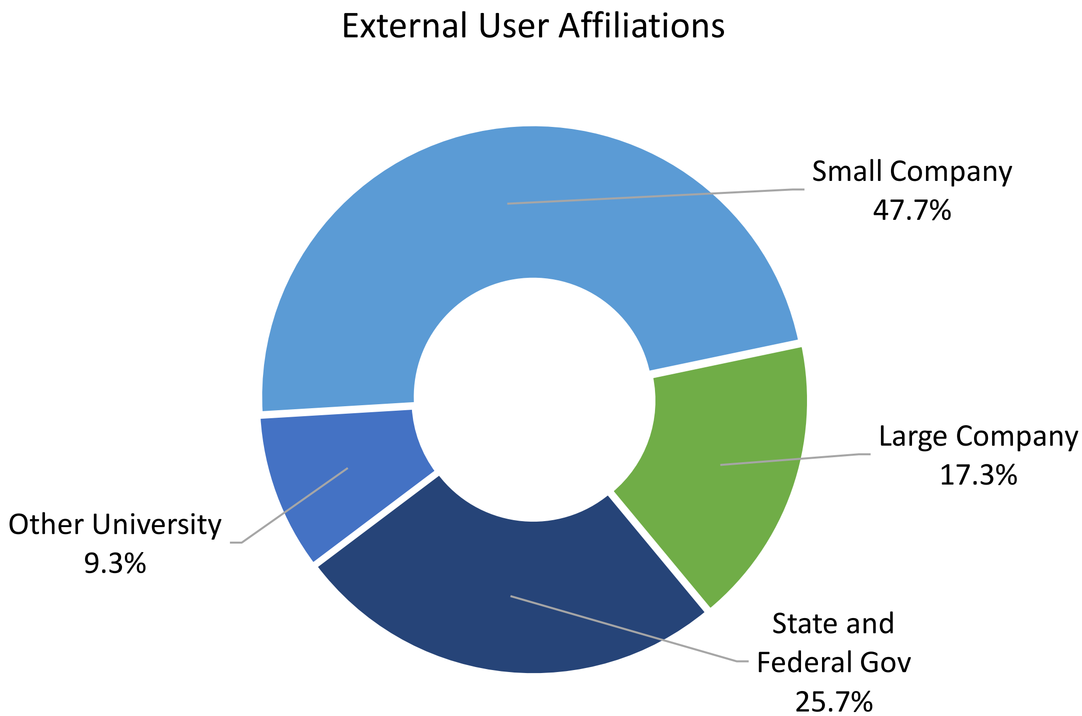
nano@stanford Site Statistics

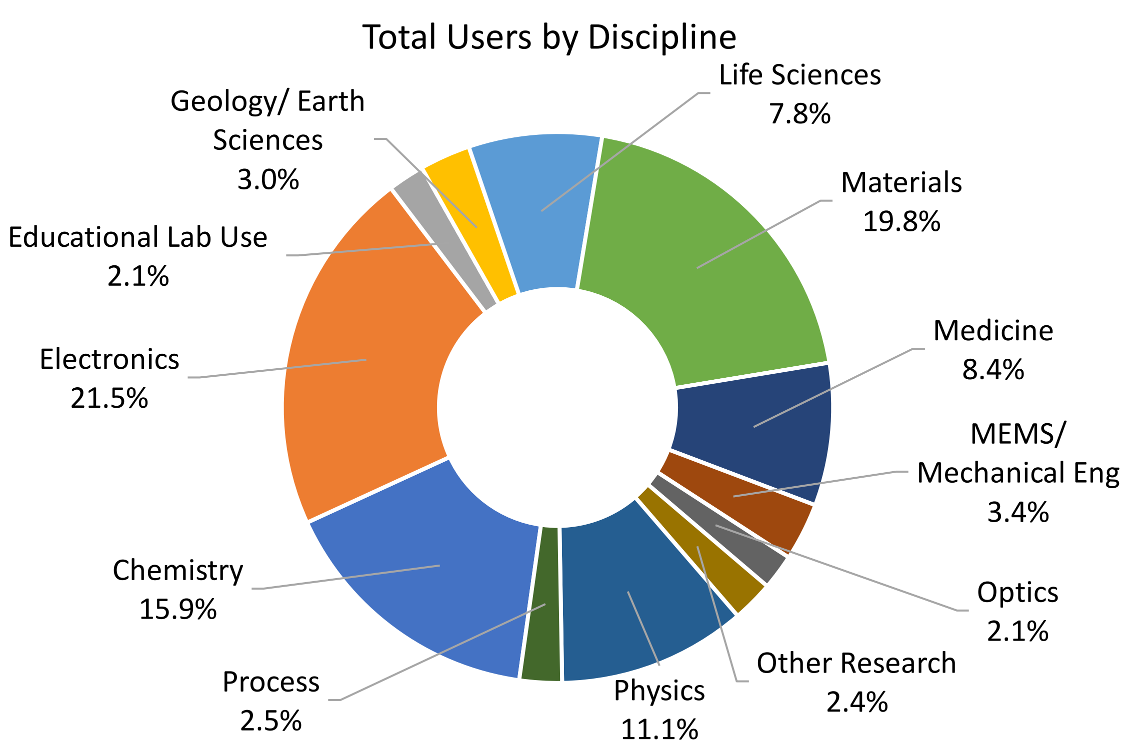
Yearly User Data Comparison								
	Year 1	**Year 2**	**Year 3**	**Year 4***	**Year 5**	**Year 6**	**Year 7**	**Year 8**
Total Cumulative Users	1,142	1,287	1,377	1,427	1,125	1,054	1,286	1,445
Internal Cumulative Users	952	1,027	1,043	891	705	650	830	866
External Cumulative Users	190 (17%)	260 (20%)	334 (24%)	536 (38%)	420 (37%)	404 (38%)	456 (35%)	579 (40%)
Total Hours	113,089	113,193	135,054	119,877	78,663	104,536	108,702	109,649
Internal Hours	94,996	91,248	105,083	72,408	47,856	63,013	69,230	66,599
External Hours	18,093 (16%)	21,944 (19%)	29,971 (22%)	47,469 (40%)	30,807 (39%)	41,523 (40%)	39,472 (36%)	43,050 (39%)
Average Monthly Users	520	572	601	615	405	470	548	589
Average External Monthly Users	74 (14%)	92 (16%)	115 (19%)	213 (35%)	136 (34%)	162 (34%)	176 (32%)	198 (34%)
New Users Trained	550	579	584	596	359	491	581	579
New External Users Trained	97 (18%)	143 (25%)	194 (33%)	262 (44%)	159 (44%)	186 (38%)	197 (34%)	212 (37%)
Hours/User (Internal)	100	89	101	81	68	97	83	77
Hours/User (External)	95	84	90	89	73	103	87	74

*Starting in Year 4 the Stanford site began to categorize users from the SLAC National Lab as federal government (external) users instead of internal users.



nano@stanford Year 8 User Distribution





12.10. Northwest Nanotechnology Infrastructure (NNI)

The Northwest Nanotechnology Infrastructure (NNI) site, the Pacific Northwest node in NSF's NNCI network, includes world-class facilities at the University of Washington (UW) in Seattle, Washington and at Oregon State University (OSU) in Corvallis, Oregon. These publicly accessible facilities provide researchers and engineers in the region, across the country and around the world, with access to both workhorse and cutting-edge tools, advanced training opportunities, and other specialized resources. NNI leverages collaborations with academic, industry, and government partners, such as the Department of Energy's Pacific Northwest National Laboratory (PNNL), to expand NNI capabilities. By linking together characterization and fabrication capabilities across the Pacific Northwest, NNI streamlines and expands the breadth of equipment and expertise available to scientists with diverse research interests and needs. The growing and distributed user base of NNI facilities includes academic and industrial users as well as nontraditional users in clean energy and biotechnology. NNI also plays an important role in educating and training the highly skilled workforce of engineers, researchers, and technicians needed by industry. NNI continues to be key to affirming the Pacific Northwest's leadership in research and innovation for nanotechnology, photonic and quantum devices, advanced energy materials and devices, and bio-nano interfaces.

Facility, Tools, and Staff Updates

Infrastructure Investments

In recent years, the NNI site undertook major infrastructure expansions and upgrades, including a complete renovation of the WNF cleanroom and a new Nano Engineering & Sciences building on the UW campus, as well as an expansion of the MaSC facility, a renovation of the ATAMI business development space, and completion of the new Johnson Hall on the OSU campus. The renovation of Graf Hall at OSU is nearing completion, and dedicated laboratory space will be available for Oregon Process Innovation Center (OPIC) research equipment. Significant planning is underway at OSU on the design and construction of the new Collaborative Innovation Complex (CIC) building, and on putting together a 10-year plan for renovating several engineering buildings.

Major New Tools and Capabilities

University of Washington:

- Electron beam lithography (JEOL JBX-6300FS) received a major workstation and software update, now operating with LINUX. The tool also underwent a major PM including a new emitter.
- New Disco wafer grinder has been installed.
- A new ICP etch tool from Oxford (Plasma Pro 100, Cobra 300) with ALE capabilities as well as chlorine etch will be installed in early 2024.
- An Intel donated goniometer (contact angle measurements) will arrive in early 2024.
- An expanded TEM sample prep area in NanoES G66 now houses the current TEM sample prep tools and a new data processing station for TEM analysis (purchased by UW Student Technology Fund).
- The Bruker Icon AFM computer has been updated to provide more reliable service and expand capabilities (funded by Clean Energy Institute, CEI).
- 2 new Nikon stereo microscopes (one with digital camera) were added thanks to funds from CEI.

- The electron microscopy sample preparation has been upgraded with a new MiniMet1000 grinder/polisher.
- UW Student Technology Fund provided the MAF with 6 new data processing stations.
- New Apreo II SEM has been ordered thanks to funds from CEI.

Oregon State University:

- Ocean Insight UV/VIS spectrophotometer.

Staff Updates

During this period, the WNF had a successful recruitment effort. We hired Steven Spalsbury, who came to us from Texas Instruments with 10 years of experience. Steven is an equipment engineer. Two hires in 2022 are now also fully up-to-speed: Sarah Yarbrough, our administrative assistant, and Doc Daugherty, who came to us from ASML and replaced Brant Hempel, who left the WNF due to a family relocation. Doc, in the past, was a WNF undergraduate research assistant (URA). The WNF staff is an excellent and cohesive team of 11 engineering professionals, many with industry experience, and together with our administrative assistant and the WNF director we are 13 full time professionals. Currently, we also employ 13 URAs, 3 of whom have Intel sponsored research projects covering their time in the WNF. This is a new activity for our URAs sponsored by industry.

At the MAF, Dr. Heather Niles left to work at a local branch of SpaceX. Dr. Dan Graham has expanded his duties to take on the job of covering the AFM tools and assisting in managing the MAF. A new hire in the student staff team assists with TEM and general MAF duties.

At OSU, Greg Herman took on a new position as Division Director of Chemical Sciences and Engineering at Argonne National Labs. Joe Baio has taken over the NNI leadership at OSU.

User Base

Academic research at NNI spans a wide range of topics including the principal research areas of integrated photonics and quantum devices, advanced energy materials and devices, and bio-nano interfaces and systems. This work is complemented by users from government and industry, with regional startups and small businesses representing the largest portion of external users.

During Year 8, all COVID-19 restrictions in the NNI labs were lifted. NNI facilities have seen usage patterns return to, and in some cases exceed, pre-pandemic averages. Encouragingly, there has been a notable uptick in cumulative users by approximately 10%, and the number of new users in the WNF has doubled. However, some other NNI facilities observed a decline in new user engagement, leading to an overall decrease of about 10% in user-generated revenue. These fluctuations in user numbers are likely attributable to residual effects of COVID restrictions, while a substantial decrease in activity from our largest industrial user disproportionately impacted the overall revenue.

Research Highlights and Impact

This year, we want to highlight small businesses that rely on NNI facilities for their R&D efforts.

RenewCat, Inc., a burgeoning startup located in Oregon, is focused on significantly enhancing pharmaceutical production yields by revolutionizing the design of new catalysts. Central to their efforts is the management of the oxidation state of copper (Cu) in various heterogeneous catalyst compositions. The company is leveraging the characterization facilities within the NNI to explore diverse preparation techniques for synthesizing heterogeneous copper catalysts. Their goal is to establish correlations between the support material, preparation conditions, and the resulting oxidation state of Cu. This research is aligned with the National Research Priority in energy and convergence research, which encapsulates NSF's 10 big ideas. RenewCat was supported by the University Venture Development Fund at OSU.

SBIR/STTR Grants to NNI Users

Currently we are aware of at least nine small businesses with active SBIR/STTR grants performing part or all of their R&D work at NNI facilities. In Washington state, these include Hummingbird Scientific, a Lacey, WA based business building products for electron, X-ray and ion microscopy with an emphasis on transmission electron microscopes (TEM); Taproot Medical Technologies, a Bothell, WA based business developing patient-focused products including a state-of-the-art ventricular shunt, which promises to dramatically improve the lives of children with hydrocephalus; and Tunoptix, a leader in broadband meta-optics imaging that enable thin, lightweight computational vision systems. At OSU, SBIR/STTR recipients include Arcaea, a Boston, MA, based startup focusing on benign and sustainable beauty products; NanoVox, a developer of nanocomposites and high performance optics in Beaverton, OR; and NexTC Materials, an OSU spin-off creating state-of-the-art processes for manufacturing thin film coatings.

Education and Outreach Activities

NNI's E&O portfolio continues to emphasize workforce development, K-12 outreach, underrepresented populations in nanotechnology (including women and communities farthest from educational justice), and engagement of Regional First Nation Tribes. We regularly offer lab tours for courses, prospective students and faculty, middle and high school students, and the UW Youth and Teen Program.

Workforce Development and Industry Engagement

WNF director Maria Huffman is the PI for an award through the ME Commons hub led by Stanford (and Berkeley as co-lead), providing $2,066,095 over 5 years for workforce development. Huffman and WNF Engineering & Business Development Manager Darick Baker are attending regular meetings with several staff members of the WA Department of Commerce, which is giving the WNF additional pathways for Workforce Development activities and funding opportunities. They are also both participating in the OSU-led NSF Regional Innovation Engine focusing on workforce development.

We have cultivated strong relationships with both Intel and Micron, and we are also part of the NW University Semiconductor Network that the WNF launched with Micron. Meanwhile, 14 academic institutions have become members of this network.

A new activity has been the Intel-supported URA research activity in which 3 URAs undertake a project to be carried out at the WNF with financial support by Intel. The URAs receive mentorship from WNF staff as well as Intel engineers. At the end of their projects (lasting up to an academic year) they present the work to Intel. Another exciting activity, again Intel-supported, is a day-trip to Intel in Hillsboro, OR, for a site visit and interactions with their staff. Two WNF URAs also participated in the annual UW-wide undergraduate research symposium, and the undergraduate OSU-Intel research experience continues to be hosted by NNI facilities.

First Nations Engagement - Nespelem Middle-Schoolers Visit the UW

Excerpt from a trip report: "From April 20th to 22nd, a group of eleven excited 8th graders from Nespelem School on the Colville Reservation woke up early, boarded a school bus, and crossed the state to spend three days exploring the UW [and] meeting Indigenous students and faculty. [On April 21st] … the group attended, at the invitation of the department of American Indian Studies, the Willapa Spirit canoe awakening at the ASUW Shellhouse. The day continued with an afternoon visit to MolES labs, where NanoES/MolES faculty and staff demonstrated how scientists learn from nature and how to build materials using atoms and molecules… These life-changing trips are organized by Professor Stroup [Classics; Program Director, *Humanities First*] in consultation with her close friend in Colville, 8th grade teacher Barb Quintasket. All expenses for this visit were fully covered thanks to the extreme generosity of the Department of Classics and the National Nanotechnology Coordinated Infrastructure grant (funded by the NSF; Prof. Daniel Ratner, Co-PI)."

Seminars, Workshops and Short Courses

With the help of the UW external relations office, the WNF hosted representatives from the offices of Senators Cantwell and Murray in an open house. That event was attended by senior administration from the College of Engineering, the Vice Provost of Research and key faculty.

Staff from NNI and MONT planned and hosted the 2nd Northwest Nanolab Alliance (NWNLA) meeting at the UW, which attracted about 50 participants from institutions and companies. This biennial event provides a regional platform for exchange of laboratory experiences and best practices.

The WNF launched a Micron-funded nanofabrication workshop for underrepresented undergraduate students. The weeklong course was so successful that we have secured funding from Intel and Micron for future courses. The workshop included a "Talk with an Engineer" event featuring Micron engineer Brenda Kraus.

The School of Chemical, Biological, and Environmental Engineering at Oregon State University hosts the annual Summer Experience in Science and Engineering for Youth (SESEY) program for high school students in the summer, this camp brings about 40 high school students from diverse backgrounds for a week-long on-campus engineering experience every year, 75% are female. In addition to providing opportunities for students of different ethnicities and gender identities, the cost is kept at a minimum and scholarships are provided for students to provide opportunities for economically-challenged students which has attracted students from across the country to the camp.

The WNF hosted a PlasmaTherm Technical Workshop on plasma processing (deposition and etch) and a Woollam Short Course on thin film characterization. The MAF held an in person workshop "Characterization of Materials at the MAF" (August 7-8, 2023), which sold out before the registration deadline. Workshop attendees were a combination of students and users from local industry.

UW mechanical engineering professor Lucas Meza is helping community college students explore nanotechnology in his seminar on Nano-Engineering of Materials and Structures (NEMS), a four-week intensive summer program within the Path to UW Program.

WNF Director Maria Huffman was invited by the National Nanotechnology Coordinating Office to give a virtual presentation about science and nanotechnology to 7th grade students at Hyde Middle School in Cupertino, CA in celebration of Women's History Month in March 2023.

Undergraduate and Graduate Courses

The University of Washington and Oregon State University offer comprehensive curricula with both conventional graduate courses and evening classes for professional master's program (PMP) students. Currently, several courses utilize the NNI facilities: EE 527 Nanofabrication Techniques, EE/ME/MSE 504 Introduction to Microelectromechanical Systems (MEMS), EE/MSE 486/528 Integrated Circuit Fabrication, ME 461/561 Mechanics of Thin Films, BioEn 492/592 ChemE 458/558 Surface Analysis, BioEn 315 Molecular and Biochemical Engineering, and OSU's CHE 444/544 Thin Film Processing, ECE 418/518 Semiconductor Device Processing, CHE 417/517 Instrumentation in Chemical, Biological and Environmental Engineering, and BioE445/545 Surface Analysis. WNF Senior Research Engineer Darick Baker provided lectures and hosted lab sessions for EE504, EE527, and the PMP version of EE527.

Intel is supporting a curriculum development plan to integrate semiconductor learning modules on all levels in undergraduate education at OSU and will help bring diverse speakers from Intel into the classroom to help increase and promote diversity in the semiconductor industry workforce.

Innovation and Entrepreneurship Activities

Working Group and Seminar on Innovation & Entrepreneurship

The NNI site has renewed its efforts in innovation and entrepreneurship activities on several fronts. We are actively participating in the newly created I&E working group. One of its activities is an approximately quarterly seminar series with leaders in I&E.

PI Böhringer served as a panelist for the NNCI virtual NanoTechnology Entrepreneurship Challenge (NTEC) Showcase on May 4, 2023. NTEC is a program created to support student entrepreneurs interested in translating nano-enabled innovations from the lab to society.

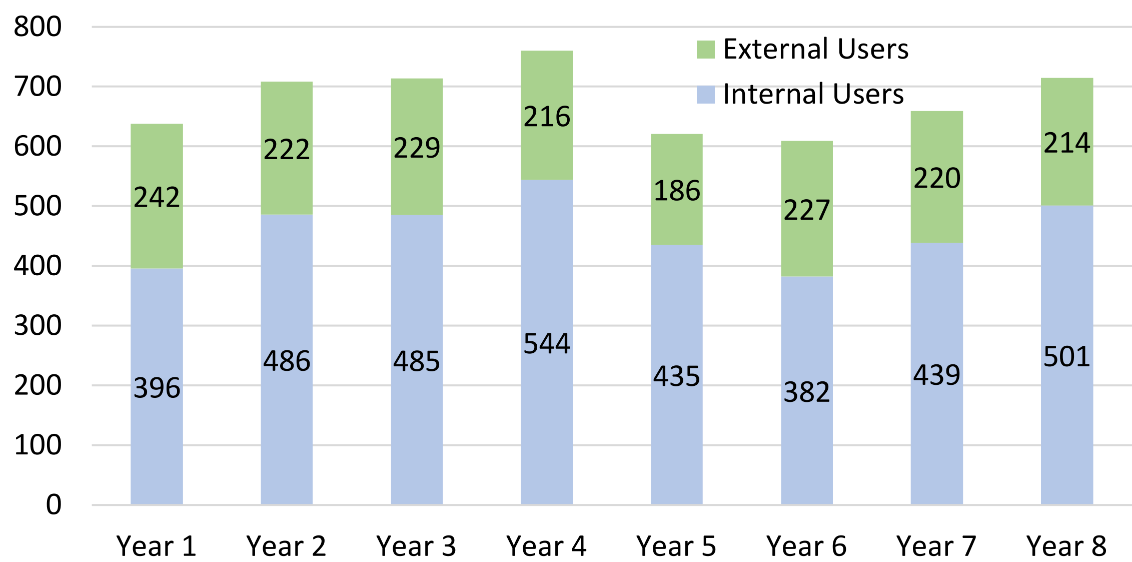
Other I&E events include a virtual presentation and discussion on "Micro-optics for Endoscopy and Bioimaging" on April 25, 2023, featuring two UW faculty-entrepreneurs and speakers from NNCI-MONT and the University of Nottingham.

Regional Technology and Innovation Hubs (Tech Hubs)

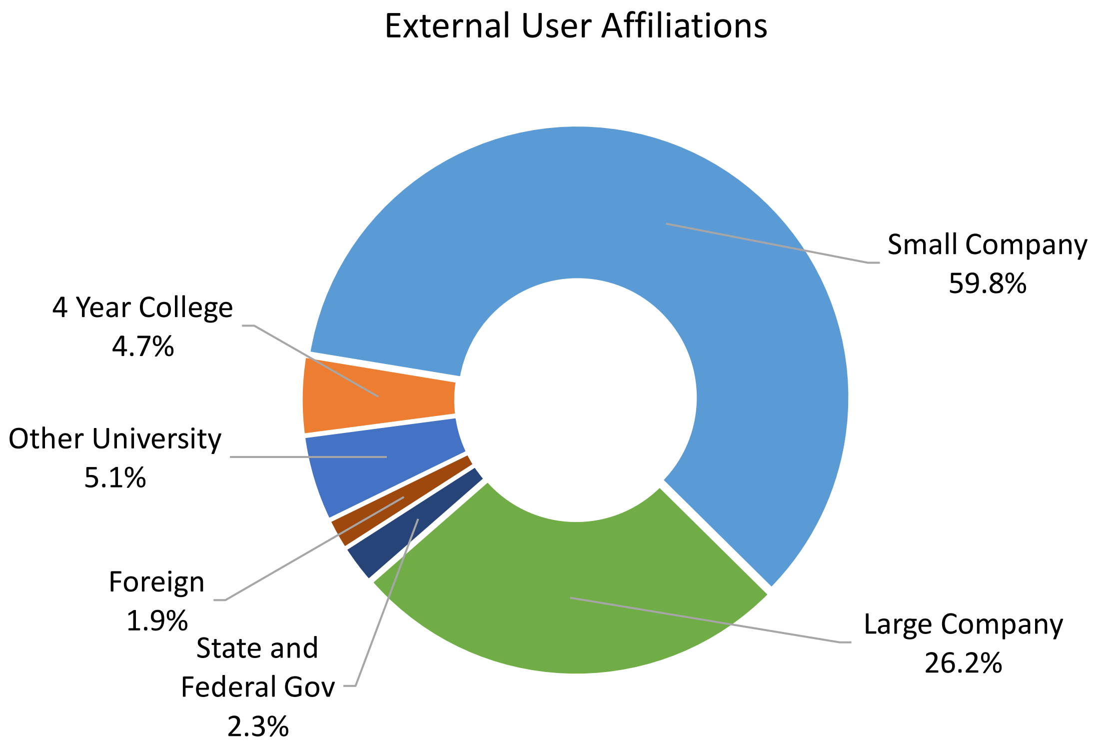
- Corvallis Microfluidics Tech Hub aims to establish global leadership in the development, scaling, and commercialization of microfluidics technology for use in semiconductor and electronic cooling.
- Pacific Northwest Mass Timber Tech Hub aims to be a global leader in mass timber design and manufacturing to lower the construction industry's carbon footprint and increase housing affordability.

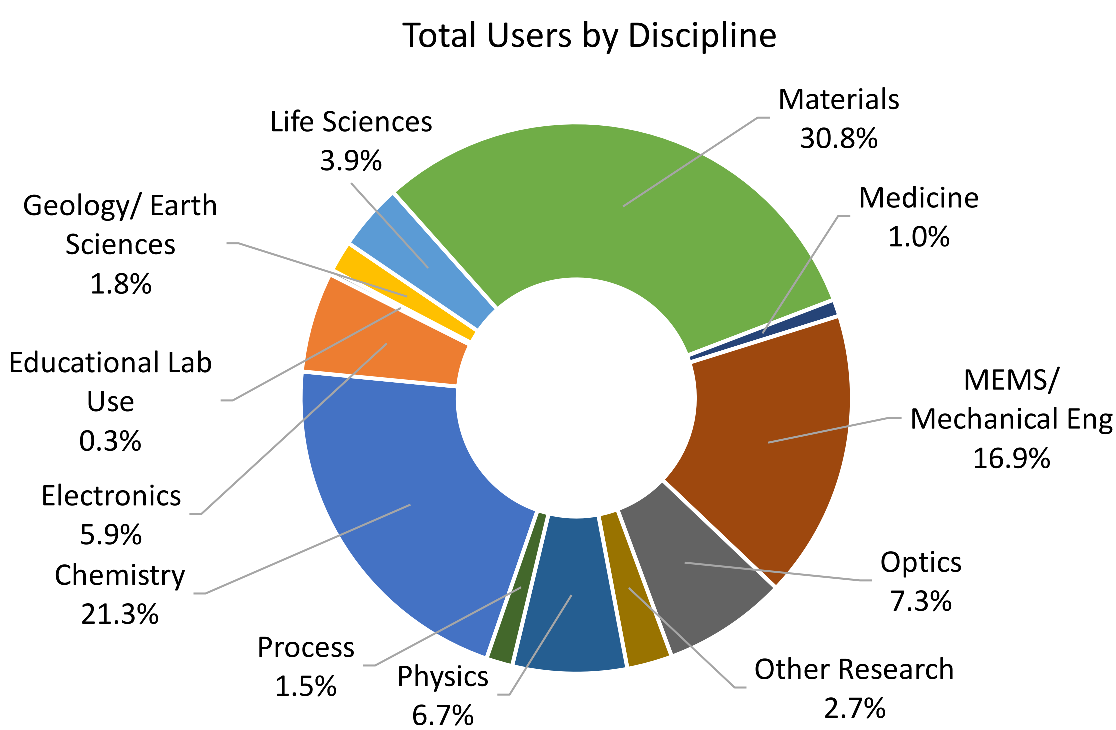
NNI Site Statistics

Yearly User Data Comparison	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	638	708	714	760	621	609	659	715
Internal Cumulative Users	396	486	485	544	435	382	439	501
External Cumulative Users	242 (38%)	222 (31%)	229 (32%)	216 (28%)	186 (30%)	227 (37%)	220 (33%)	214 (30%)
Total Hours	38,350	46,562	55,925	65,032	55,939	72,122	60,027	52,784
Internal Hours	21,822	30,600	27,695	35,564	22,262	26,740	29,379	26,864
External Hours	16,528 (43%)	15,962 (34%)	28,230 (50%)	29,468 (45%)	33,677 (60%)	45,382 (63%)	30,648 (51%)	25,920 (49%)
Average Monthly Users	267	277	266	304	226	252	265	282
Average External Monthly Users	103 (39%)	98 (35%)	93 (35%)	93 (31%)	77 (34%)	88 (35%)	85 (32%)	87 (31%)
New Users Trained	126	159	206	134	64	115	186	170
New External Users Trained	41 (33%)	37 (23%)	57 (28%)	31 (23%)	18 (28%)	31 (27%)	56 (30%)	45 (26%)
Hours/User (Internal)	55	63	57	65	51	70	67	54
Hours/User (External)	68	72	123	136	181	200	139	121



NNI Year 8 User Distribution





12.11. Research Triangle Nanotechnology Network (RTNN)

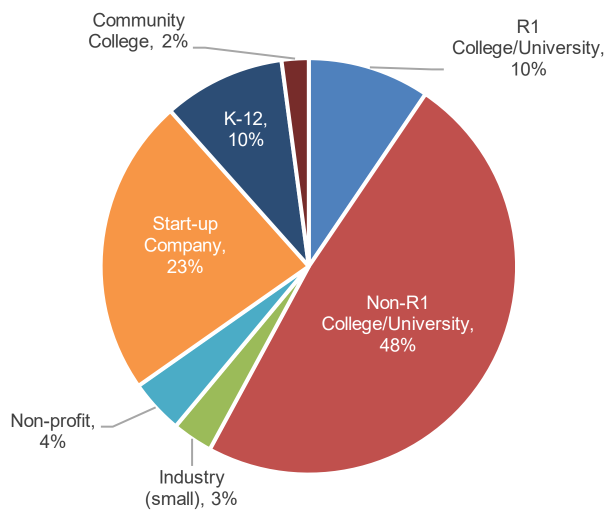
Facility, Tools, and Staff Updates

Tools: In Year 8, 25 new instruments valued at >$4 million were acquired, including 2 Hitachi Scanning Electron Microscopes (SU8700 Field Emission and FlexSEMIII thermionic), Rigaku Supermini200 X-Ray Fluorescence (XRF) Spectrometer, Heidelberg Direct Write Lithographer (DWL), Keyence VK-X3050 Optical/Laser Confocal Profilometer, LPKF ProtoLaser R4 Laser Cutter, Leica Stellaris 5 Confocal Microscope, Zeiss Axio Imager.M2 Light Microscope, Fisher Scientific Cryostar NX50 Cryostat, Leica Plunge Freezer (EMCPC), Anton Paar XRDYnamic 500 X-Ray Diffractometer (XRD), Oxford PlasmaPro Cobra Inductively Coupled Plasma (ICP) etch tool, Woollam M-2000 Ellipsometer, Frontier Semiconductor FSM 128NT film stress and wafer bow mapping system, Dektak XT Profilometer and a new video-rate imaging module (VRS1250) for Atomic Force Microscopy (AFM). A Hummink NAZCA Capillary Precision Capillary Printer is currently on trial via lease with intent to own but is available to facility users as normal. There is current momentum in building out soft materials characterization labs at separate RTNN universities which includes 2 TA Instruments Differential Scanning Calorimeters, 2 rheometers (Anton Paar MRC302 and TA Instruments DHR-2), a TA Instruments RSA-G2 Dynamic Mechanical Analyzer, and TA Instruments Thermogravimetric Analyzer (TGA 5500). **Techniques:** Much of the new equipment described in the Tools section allows new techniques or capabilities, i.e., video-rate AFM at SMIF (VRS1250), laser-cutting in NNF (Protolaser R4), and expanded biological sample preparation bandwidth or capabilities in AIF provided by the Leica EMCPC Plunger Freezer and the Fisher Scientific Cryostar NX50 Cryostat. CHANL now has a new Cressington 108 Sputter Coater available for preparing SEM specimens, as well as an Agilent G-8610 Helium leak detector to allow leak detection in vacuum instruments. **Staff:** Dr. Inno Shuro, with a PhD in Materials Engineering from Toyohashi University of Technology (Japan) and an MBA from North-West University and experience as a Senior Specialist in Electron Microscopy at North-West University (South Africa), has been hired as a Characterization and Outreach Scientist at CHANL where he will lead outreach efforts as well as supporting SEM and AFM instrumentation. Emily Snell, previously a high school chemistry teacher, was hired as a Program Coordinator at SMIF to help with multiple programs including outreach, REUs, and more. Dr. Lydia Skolrood, who recently graduated from NC State University, was hired as an Engineer at SMIF and will help manage TEM labs as well as help with outreach activities. Dr. Sameera Pathiranage was hired as AIF's Surface Analysis Postdoctoral Researcher where he manages the XPS instrument as well as other surface analysis techniques. NNF has hired two new Semiconductor Research Engineers (Erik Vick – Etch Specialist, Borys Kolasa – Lithography Specialist). In addition to full-time positions, RTNN labs hired many new student assistants. NNF hired graduate assistants (Travis Elmore and Lucas Pupillo), and multiple undergraduate assistants (Kyle Koesters, Crystal Goecke, Will Allion and Adam Davis) who all assist with various operation requirements and techniques. Caitlyn Obrero (undergraduate) was hired at AIF to assist in the X-Ray CT labs. PCOST hired Graduate Research Assistant Folasewa Olatunde to assist with assessment metrics as well as two undergraduates, Charles Smalls and Nate Shorter, to assist with ongoing work related to Nanotechnology for Food Security.


AIF Staff member Toby Tung trains an undergraduate assistant on advanced nanoCT use and maintenance.

User Base

The overarching goal of the RTNN is to build the user base. We make a concerted effort to reach out to users from underrepresented demographic populations, rural areas without access to Research 1 (R1) institutions, non-R1 institutions, and industry. As identified in our proposal, three barriers to engaging new users are distance, cost, and awareness. To address these barriers, we have implemented targeted, innovative programs and activities. **Satisfaction***:* RTNN continually assesses its facility users and programs. The RTNN Assessment team is associated with PCOST (Public Communication of Science and Technology) at NC State. Unique surveys are used for collecting demographic and user satisfaction data from various RTNN programs. Surveys are hosted on Qualtrics, the analysis was done on SPSS with some original SAS coding, and all surveys are IRB-approved. Overall, facility users who responded to the survey were very satisfied with their experiences in the facility they used in Year 8 (6.31 ± 1.13 on a 7-point Likert scale where 7=very satisfied, n=238). This level of satisfaction was consistent with responses from previous RTNN years (Year 7: 6.36 ± 1.09, n=239). 100% of users (n=112) indicated that they would return to the lab they utilized if further work was necessary. **RTNN Kickstarter Program:** This program supports use of the facilities by new, non-traditional users by providing free initial access. To date, 95 projects have been awarded (Year 8: 8 projects). The figure at left shows the affiliations of the program participants. Most participants are from non-R1 colleges/universities (48%), start-ups (23%), while K-12 students/classrooms make up about 10%. The RTNN strives to retain the participants as long-term RTNN users and to highlight their successes via social media campaigns to recruit new users and solicit proposals. Of the projects who completely used their time in the program, >40% subsequently continued to use facilities spending >$318,000 of their own funding in facility use. The program brings in new users and provides a pathway to facility sustainability. Several recipients utilized data generated with the Kickstarter program to publish as well as propose and secure additional funding such as SBIR Awards. Ongoing assessment and interviews of Kickstarter recipients reveal that respondents continue to be happy with the overall program, indicate that they will return to the facilities, and have positive interactions with RTNN staff.



Affiliations of participants in the Kickstarter program (n=95).

Online Coursera Course: "Nanotechnology, A Maker's Course," introduces nanotechnology tools and techniques while providing demonstrations within RTNN facilities. The course targets students who have a high school or higher science background and limited exposure to these facilities. **Since the course launch, over 300,350 (Y8: 33,150) people have visited the course website, over 38,850 (Y8: 4,950) have engaged with course components, and over 12,090 (Y8: 2,180) have completed the course**. Several participants have engaged with RTNN outside the course (e.g., Kickstarter program, workshops, newsletter subscription). *Assessment:* Students were highly satisfied (7=very satisfied) with the course materials on all five measures (6.37). Students were also highly satisfied with the course instruction on all five measures (6.34). Similarly, students were also highly satisfied with the multimedia content of the course (6.55). Over 91% of respondents noted they were "likely" or "very likely" to recommend the course to others. 72% of respondents noted they had a better knowledge of the capabilities of RTNN's facilities.

Screenshot of a video filmed for "Nanotechnology, A Maker's Course" with a demonstration of TEM sample preparation.

Workshops, short courses, symposia: In Year 8, RTNN held >9 short courses with over >125 participants. Standard-instrument-focused short courses introduce tools and techniques to provide a foundation for subsequent training on a specific tool. Most short courses are now fully in-person, while some special topics may be virtual or recorded, edited, then uploaded to facility YouTube accounts. The RTNN also helps to plan and execute the Carolina Science Symposium on an annual basis with collaboration from the Joint School of Nanoscience and Nanoengineering (JSNN), which is part of SENIC. This event is student-focused, giving many early career students their first opportunity to present research in a professional setting. In 2022 (Year 8), this event returned to a one-day in-person format, drawing over 105 participants.

Communication: One of our main methods to disseminate information to stakeholders is via the RTNN website (www.rtnn.org). The website describes RTNN events, programs, and opportunities (e.g., nanotechnology jobs board). It also highlights recent nano-related news and provides an overview of research being pursued by principal faculty. We also maintain two subscription lists to share information and opportunities: one to principal faculty (>260 PIs) and one to other stakeholders (>3,800 subscribers). The RTNN actively promotes activities, events, and opportunities on multiple social media platforms including X (formerly Twitter), Facebook, and LinkedIn.

Research Highlights and Impact

Core technical capabilities and specialized expertise and facilities in the RTNN span the following areas: Low dimension and layered nanomaterials; materials for energy efficiency and sustainability; nanomaterials for biology, medicine, and environmental assessment; and advanced materials and interfaces: metamaterials, nanomaterial and nanostructure interfaces. **Scholarly and Economic Impact:** Work performed in the RTNN led to >227 publications in 2022 by our users (176 of which cited the NNCI award number). 41 of these publications were authored by external users (27 cited the NNCI award). Work performed in the facilities led to >175 patents filed and >26 patents awarded in 2022.

Education and Outreach Activities

The RTNN's educational and outreach activities are a focal point of RTNN's goal to build the user base; the table below gives an overview of RTNN's educational and outreach activities. In Year 8, a combination of added staff and a spike in demand for our programs due to the return of large-format community events lead to a record-setting year for RTNN Education and Outreach efforts.

In-Person Programs: Year 8 maintained strong momentum for in-person outreach programs, including new/resumed outreach events. The success of these programs is a direct result of two new dedicated Outreach Coordinators and the addition of more RTNN Student Ambassadors. At least 110 outreach events were in-person this year with a total of >18,000 participants reached. This is largely a result of large-format events, including booths at museums, libraries, Science Olympiads, and many more.

Community Engagement: "Building the user base" activities optimally have an important long-term component, which we emphasize with community and K-12 engagement, particularly for under-represented groups in STEM and rural and/or indigenous communities. Many events engage directly with diverse communities, i.e., Girl Scouts STEM Day @ Duke (>600 participants, ~95% URG), Community STEM Day with a Waccamaw-Siouan Tribal community (95 participants, 100% URG). Large format events and travel-friendly activities are critical in reaching as many communities in our area as possible e.g., a traveling tabletop SEM and nano activities to the NC Science Olympiad (>3k participants), and the Greensboro Science Center (>3.6k participants). A strong relationship with the local NC Museum of Life and Science allows us to engage multiple times each year, including hosting a geology-themed microscopy activity titled "*Rocktober*" and an educator networking event (sciREN), where teachers gather to see demonstrations and collect lesson plans including RTNN-developed lesson

Year 8 RTNN Education & Outreach Events

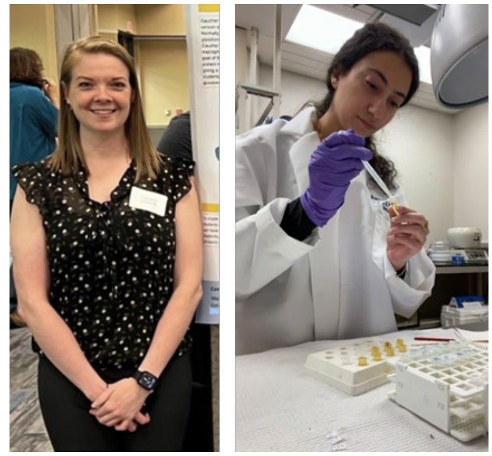
Evaluated programs are highlighted.

	Participants
Kickstarter Program	8
Engaged learners in Coursera course on nanotechnology	>4,950
In-Person Outreach Events	>3,850
Large-Format Events (e.g. Booths)	>7,770
Remote outreach events (e.g., SEM demonstrations in classrooms)	>1,200
Short courses, workshops	>125
Conferences	106
Total	>18,000

Left: New RTNN Student Ambassador Kohen Goble (UNC) demonstrates photolithography at a community science night at Scroggs Elementary in Chapel Hill, NC. Middle: Young Waccamaw-Siouan kids learn how and why to put on a cleanroom suit as part of nano-themed activities hosted on tribal land Right: Multiple RTNN Staff host a booth with nano-themed activities at Greensboro Science Center's Science Extravaganza.

plans on pollen, surface area, and many more. Virtual Outreach options remain valuable in reaching larger audiences, especially with rural and indigenous communities, including virtual SEM sessions through RAIN, remote activities, Community Science nights, and more.

Education and Experiential Learning: RTNN staff and facilities are a powerful enhancement to courses available in our network including Class-Based Explorations, Advanced Physics Laboratory Experiences, and the availability of staff and facility access to supplement topical courses like Wide Bandgap Semiconductor Device Fabrication/Technology or Biological Electron Microscopy techniques. A concerted effort is also made to maintain a strong connection to local community colleges in the Triangle ecosystem: NNF Director Phil Barletta continues to teach a lecture series at Durham Tech for Wolfspeed/Cree Technicians seeking requisite training and knowledge for a promotion to Engineer roles. In Year 8, RTNN welcomed the first two participants in its Community College Internship program, which supports two students actively enrolled at local community colleges to work in an RTNN core facility with professional staff and other undergraduate assistants during the academic year. These students are continuously supported, if desired, as they progress through the transfer and matriculation process. RTNN staff and facilities are also leveraged considerably in other NSF programs, including a collaborative Research Experience for Undergraduates (REU) site focused on hybrid perovskites that welcomed 12 new participants and a Research Experience for Teachers program that hosted 8 teachers in Year 8.



RTNN Interns Val Haller presenting at a poster session (Left) and Marielise Ishak preparing biological samples for imaging (Right).

Societal and Ethical Implications Activities

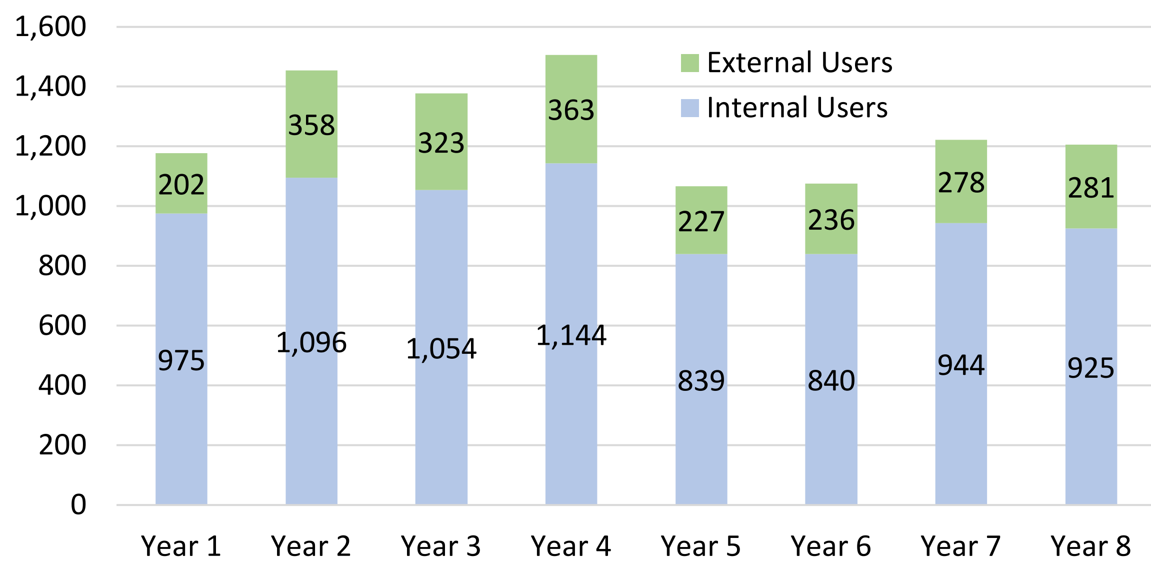
The RTNN's research in Social and Ethical Implications (SEI) of nanotechnology leverages the RTNN team and user base to enhance the instruction and understanding of how humans engage with nanotechnology. The SEI team is currently engaged with the NNCI Research Community on Convergence Research to determine how nanoscience and availability of lab support contributes to some facets of geoengineering that may be able to impact concerns regarding climate change (presented at Oxford and SNO-Marine del Rey to date). The SEI team is also testing a metanalysis and a meta-synthesis of the first 7 years of user data from the RTNN labs before our anticipated final report. The RTNN SEI team is also trying to define the range of societal and ethical issues pertinent to different investment portfolios in NNI associated governmental spending, e.g., funding infrastructure networks, career grants, centers, etc. Additionally, the SEI team is trying to determine the best predictive algorithm for evaluating the contribution of time spent with an infrastructure network and the likelihood of starting-up a new company, licensing patents, hiring from the workforce, and more.

Innovation and Entrepreneurship Activities

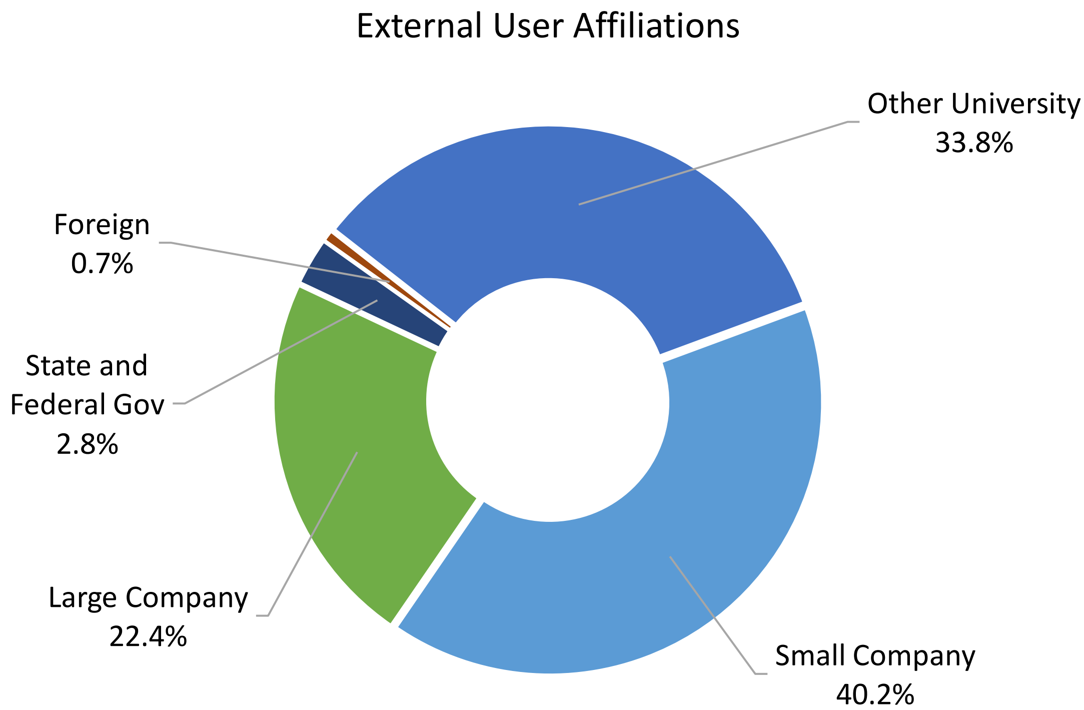
The RTNN serves a critical role in innovation and entrepreneurship through facilities, expertise, and programs. The majority (>69%) of companies in Year 8 that used the facilities have less than 50 employees. The Kickstarter program was designed in consideration of small companies without extensive research funding who may need a proof-of-concept experiment to then enable progress to larger funding, i.e., SBIR/STTR programs – about 23% of all Kickstarter recipients are either start-up or small companies.

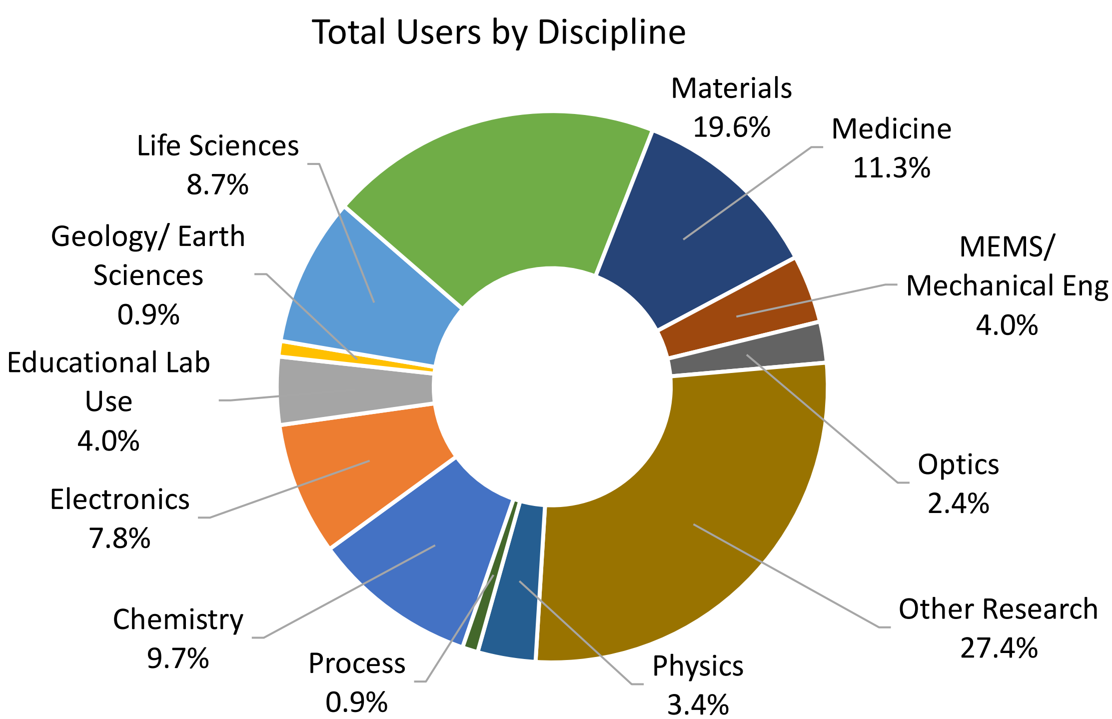
RTNN Site Statistics

Yearly User Data Comparison	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	1,177	1,454	1,377	1,507	1,066	1,076	1,222	1,206
Internal Cumulative Users	975	1,096	1,054	1,144	839	840	944	925
External Cumulative Users	202 (17%)	358 (25%)	323 (23%)	363 (24%)	227 (21%)	236 (22%)	278 (23%)	281 (23%)
Total Hours	53,044	51,747	55,684	61,404	43,099	53,491	51,211	50,150
Internal Hours	46,908	43,053	46,422	49,685	33,636	43,209	40,837	40,958
External Hours	6,136 (12%)	9,694 (17%)	9,263 (17%)	11,719 (19%)	9,463 (22%)	10,282 (19%)	10,374 (20%)	9,192 (18%)
Average Monthly Users	395	422	420	445	308	352	396	397
Average External Monthly Users	50 (13%)	63 (15%)	71 (17%)	74 (17%)	53 (17%)	67 (19%)	78 (20%)	80 (20%)
New Users Trained	433	527	695	627	288	435	492	449
New External Users Trained	71 (16%)	69 (13%)	82 (12%)	102 (12%)	54 (19%)	74 (17%)	60 (12%)	75 (17%)
Hours/User (Internal)	48	39	44	43	40	51	43	44
Hours/User (External)	30	24	29	32	42	44	37	33



RTNN Year 8 User Distribution





12.12. San Diego Nanotechnology Infrastructure (SDNI)

Facility, Tools, and Staff Updates

Facility: SDNI's open-access user facilities include the Nano3 Facility for nanoscience, nanoengineering, and nanomedicine, the Microfluidic Medical Device Facility, the Chip-Scale Photonic Testing Facility, the CMRR Materials Characterization Facility that supports research in the areas of magnetics, energy, and quantum devices, and the Electron Microscopy Facility which includes a 200kV transmission electron microscope (TEM) with state-of-the-art Energy dispersive X-ray spectroscopy (EDS) and electron energy loss spectroscopy (EELS) capabilities. The operation of all the SDNI facilities is managed by the Facility Online Manager (FOM) system, which streamlines the operation, record keeping, and accounting processes.

SDNI continues to operate using two service modes for the convenience of our users. For users who wish to perform the fabrication and characterization independently, they can access the lab on their own. For users who cannot access the lab or do not wish to fabricate and characterize their devices, SDNI staff can do this for them as a service. This extra mode of remote service work addresses the limitations of companies to hire and train their own nanofabrication engineers. It also overcomes the geographic limitations, greatly expanding the regional coverage of our service.

The first six months of data from Year 8 showed increased usage mostly in the areas related to small and large businesses. Cumulative users and remote cumulative users were both near all-time highs for the first six-month totals. Internal user reporting statistics dropped from the previous reporting period and an investigation into the reasons for low internal lab use and internal user numbers is underway. A final encouraging statistic is the number of new users trained in Year 8, which was 96% of the all-time high during any October to March reporting period.

Tools: The upgrade of the EBPG 5200 electron beam lithography tool was completed. The general pattern generator has been upgraded to the universal pattern generator (UPG). The UPG has a processing speed five times faster than the GPG as well as the following additional benefits. The maximum clock rate is now 125 MHz which increases system throughput and can use smaller address grid sizes for better pattern resolution without increases in exposure time. This can significantly broaden the process parameter window and overcome issues with clock rate limits on fast resists. The increased system memory allows basic shapes to be held in system memory for repetitive patterning. This can substantially reduce the overall data transfer in specific cases like periodic patterns. The additional memory also provides enhanced buffering of shapes for reduced data transfer and can use intelligent settling time algorithms for adjoining shapes to reduce machine writing time. Finally, the upgrades improve system calibration times by up to 30% and allow integration of future planned system improvements over the next few years. With this investment, SDNI users can continue to use the in-demand electron beam lithography services with equivalent hardware to newly installed machines.

The previous AFM was increasingly unable to meet the requirements of SDNI users. The limited sample size of 15 mm in diameter severely limited what could be measured on the tool and support for the tool was becoming increasingly difficult to obtain. To increase sample size and capabilities, a state-of-the-art AFM from Park Systems was purchased and installed. During a 3-month evaluation period, users were trained on the various imaging modes by Park engineers and evaluated the system using their samples. A second workshop was offered by SDNI and Park Systems. The workshop focused on Piezoresponse Force Microscopy (PFM) and imaging in liquid, two areas important to SDNI users. The workshop was very helpful for users and staff to increase the imaging expertise and improve the tool operation. The AFM system includes 16 measurement modes to cover a wide range of research needs: contact mode, non-contact mode, tapping mode, dynamic contact EFM (EFM-DC), electric force microscopy (EFM), conductive AFM, I-V spectroscopy, scanning capacitance microscopy (SCM), Kelvin probe force microscopy (KPFM), scanning ion conductance microscopy (SICM), force-distance spectroscopy, magnetic force microscopy (MFM) under variable fields, force modulation microscopy (FMM), lateral force microscopy (LFM), nanoindentation, and scanning thermal microscopy (SThM). These additional measurement modes have helped to double the AFM equipment usage since installation.

SDNI has purchased another maskless lithography tool, NanoFrazor, in 2022 and the tool is scheduled to be shipped in June 2023. The NanoFrazor Explore from Heidelberg Instruments combines thermal scanning probe and direct-write lithography into a single tool. An ultra-sharp heatable probe tip can write and inspect complex nanostructures. A heated tip produces high-resolution nanostructures by local sublimation of the resist while the cold-tip can acquire information about the recently written features. For larger micron-scale features such as contact pads and wires, a direct-write laser can sublimate the resist. Having these two size scales available in a single tool will allow users to bridge the fabrication space between our photolithography and electron beam lithography tools and expose sensitive samples where electron beams can damage the sample.

The recent proliferation of photonics foundries offering multi-project wafer services has significantly reduced the cost and fabrication time of integrated optical devices. In contrast, photonics packaging is highly idiosyncratic, and no equivalent facilities are available. The only notable development on this front is expensive, offers limited availability, and is tied to a specific silicon photonics foundry that has a limited run schedule. Therefore, photonics packaging remains largely unavailable to researchers and small businesses. This is a significant limit to technological innovation. To remedy this situation, we are constructing a general semi-automated optical packaging system as part of SDNI's Chip-Scale Photonics Testing Facility. This will greatly enhance the research and prototyping capabilities of the facility.

Staff: Staff turnover continues to affect personnel at the SDNI facilities. In July 2022, the technical director retired after 15 years at the nanofabrication facility. Dr. John Tamelier assumed the Interim Director position. Dr. Tamelier had spent the previous five years at SDNI as a Process Engineer, External Service Manager, and Assistant Director. Dr. Tamelier continues as the Interim Director. In March 2023, a job posting for the Technical Director was posted. The final selection of the new Technical Director for the facility was completed in August 2023, and Dr. Fubo Rao became the new Technical Director of the SDNI cleanroom facility. Before joining SDNI, Dr. Rao was the cleanroom manager at Argonne.

Student assistant positions in SDNI have returned to normal levels before pandemic and there are currently approximately 25 student workers helping staff and users in the laboratories. Students are involved in most areas of operation including fabrication assistance, characterization assistance, packaging assistance, training users, equipment maintenance, and facility operation. The student assistants receive valuable training in the semiconductor field while employed at SDNI. Local users of the facility recognize the value of these experienced student assistants and often hire the students during and after their undergraduate education.

User Base

Usage statistics for many total usage categories appear satisfactory. Increases in external usage are often balanced with a decrease in internal usage. Except for lab hours and monthly remote users, all changes in the reporting categories in Year 8 were either positive or less than 5% when compared to the same time in Year 6 or 7.

Most encouraging among the reporting categories is external usage, particularly with small and large companies. Small companies have seen the largest increases among any type of user in most categories. These small companies are an important component of the economy and drive technologies with large disruptive potential.

Large companies have reporting totals near the maximum amounts reported in most categories. This increase in usage by industrial users shows the value of providing well-maintained tools and fabrication expertise for businesses in Southern California and across the nation.

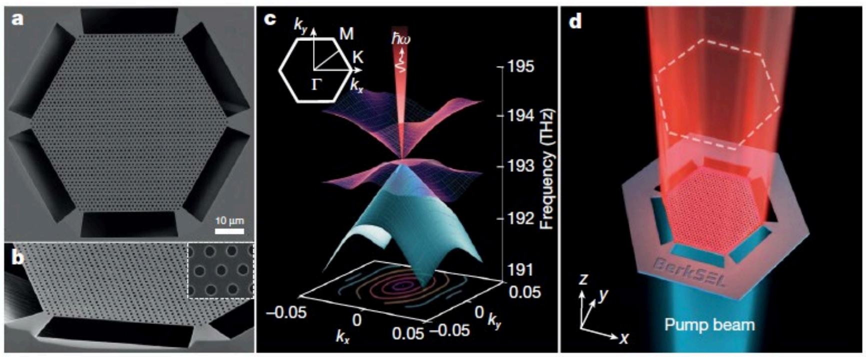
Also encouraging for the future is the number of new users trained, reaching almost the all-time high amount. For the 4-year college, small company, and large company affiliations, the total number of users trained also exceeded the all-time high for any previous years.

Research Highlights and Impact

SDNI continues to be the central place that enables groundbreaking fundamental and applied research in nano/meso/metamaterials, nanophotonics, nanobiomedicine, and nanomagnetism. By expanding our tool sets and processing capabilities, we have equipped ourselves to support broader science and technology areas including fundamental and translational research in biomedicine, semiconductors, energy, communications, and quantum materials/devices/systems. Our facility has also contributed, in a significant way, to the development and commercialization of innovative technologies. In the past 12 months, the SDNI facilities have supported over 200 peer-reviewed scientific publications from approximately 80 groups from academic institutes, government labs, and companies.

The fundamental and applied research, cutting-edge technology development, and translational research SDNI has supported in the past year demonstrated significant impact and was in alignment with the nation's initiative in semiconductors and NSF Big Ideas, particularly in the areas of convergence research, quantum leap, and laying the foundation for the midscale infrastructure to support science beyond 2026. In each case, the SDNI facility and its staff have played crucial roles in the success of the research endeavors. We either became the primary site where the proof-of-concept devices were fabricated, or our staff carried out critical tasks of material/device fabrication and characterization.

For quantum leap, SDNI has supported the groundbreaking research of achieving single-mode surface emitting laser via open-Dirac singularities to overcome the previously considered fundamental limit for lasers (i.e. loss of the single mode characteristics with the increase in the laser aperture). For convergence research, SDNI has played a crucial role in several breakthroughs in the areas of semiconductors and energy. One of the best performing compute-in-memory chips based on resistive random-access memory was demonstrated by post processing of commercial CMOS chips in university facilities with unique technologies developed by university labs. The multiscale, multi-modality electron imaging capabilities offered by SDNI allowed the first quantitative studies of cathode degradation of lithium batteries under high energy density. The study unveils the myth of cathode degradation and points out promising directions to solve this vital issue that is not only scientifically interesting but also significant for our society since improved battery performance, reliability, and safety is closely related to sustainability, energy, and environment as well as a trillion dollar EV industry. In 2022, SDNI also helped establish several enabling technologies of profound impact in biotechnology. There is an intention of expanding these capabilities into a new midscale infrastructure so the capabilities can be offered to the broader scientific and medical communities. The two examples we did in 2023 are (i) transistors over the tips of a 3D structure for intracellular and intercellular electrophysiological studies and (ii) ultrahigh throughput microfluidic cell imaging and sorting hardware to produce 1000 3D cell tomography per second, coupled with Omics data and AI image analysis engines to unveil the rule of life.



Scalable open-Dirac electromagnetic cavity and the Berkeley surface-emitting laser.

<u>Education and Outreach Activities</u>

We have been working diligently to integrate nanotechnology contents to K-12 NGSS-aligned science curricula as well as community college programs in California. We continued to network with the other NNCI sites to make an impact nationwide.

Scanning Electron Microscopy remote hands-on sessions:

Nanostructure visualization is an effective means to introduce STEM subjects to K-12 and community college students. SDNI is currently the top performer of the nationwide RAIN (Remotely Accessible Instruments for Nanotechnology) network that includes 28 institutions across the nation. In Year 8 we continued to perform remote scanning electron microscopy sessions with K-12 and community college students as well as on-site sessions. During these sessions, students were introduced to the basic principles of microscopy and the difference between optical and electron microscopy. A large library of specimens including nanoparticles, nanophotonics, semiconductor chips, MEMS, metallic/ceramic structures, and a large variety of biological samples including pollen, phytoplankton and zooplankton from deep sea sediments, butterfly wings, gecko feet were studied. When performing outreach SEM sessions, we also suggest follow-up assignments and thought-provoking questions about image analyses and feature/function correlations.

Hands-on Kit for Nanophotonic Education:

SDNI's Chip-Scale Photonics Testing Facility (CSPTF) facility has made improvements to its pilot Integrated Photonic Education Kit (IPEK). CSPTF successfully established a full production line for the IPEK Kit, including photonic packaging. This enables SDNI to produce enough demo kits to accommodate the growing needs for college and graduate level education, convergence research training projects, and SDNI's workforce development efforts.

The IPEK is the first plug & play didactic toolkit that enables hands-on experimental integrated photonics for education institutions. Hands-on experience in photonics is often lacking in college and technical school programs due to the prohibitive cost of test equipment. The IPEK solves this gap in learning by offering a user-friendly and cost-effective solution. It allows students to experimentally analyze the basic building blocks and concepts used in all integrated photonics devices and will encourage them to participate in STEM education and careers.

To further the development of the IPEK, SDNI-CSPTF has completed a full curriculum for the device, ECE 184: Optical Information Processing and Holography class. The curriculum includes five modules and covers topics ranging from waveguide and component basics to more complex devices such as ring resonators and Mach-Zehnder modulators. This pilot program has generated valuable feedback, and fundamentally vindicated the IPEK concept. Grant applications are being fielded to enable the program to be implemented at a large scale.

Workforce Development: Microelectronics and Nanomanufacturing for Veterans

SDNI has provided a 12-week hands-on training program to teach veterans the principles and operation of the micro/nano fabrication and characterization tools in its state-of-the-art nanofabrication and characterization facility. The program will continue for a period of 3 years and train 24 veterans every year (6 cohorts for a total of 72 veterans). This program aims at preparing the participants for jobs in the nanofabrication and semiconductor industry which is now booming in the United States amid the US CHIPS Act.

Workforce Development: Collaborative Efforts for Nanofabrication and Characterization

Capitalizing on the success of the Microelectronics and Nanomanufacturing for Veterans Consortium program and lessons learned, SDNI is working with Southwestern College to develop a nanotechnology collaborative education program. The program will enable SWC to provide both a technician-oriented program for students aiming to enter the marketplace after their 2-year graduation from SWC as well as a general education program for students aiming to transfer to UC San Diego as part of their academic and career paths.

Workforce Development: Expansion of the Internship Programs

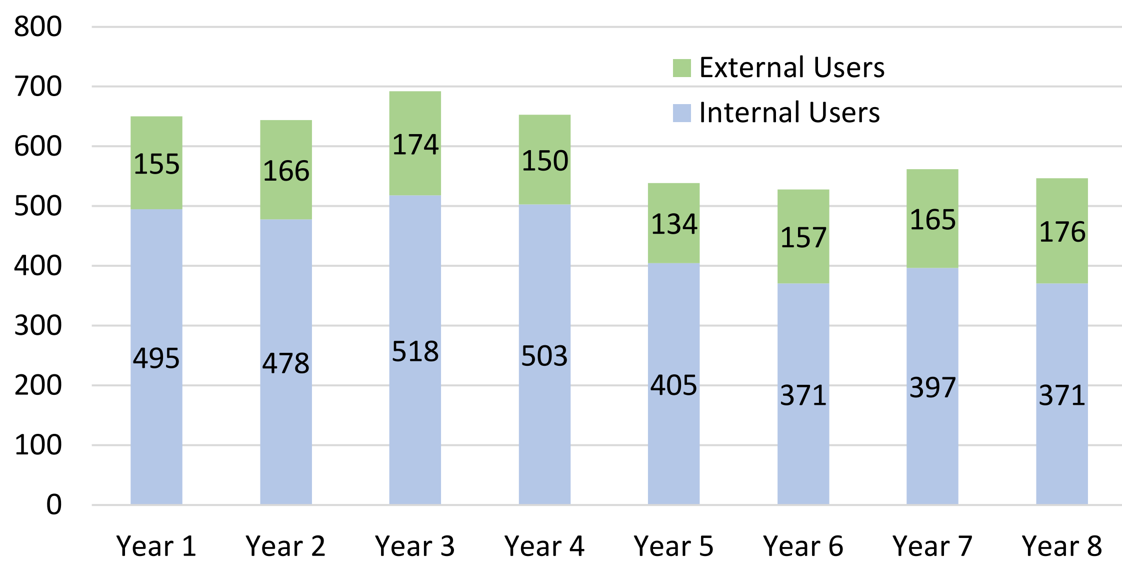
From the inputs of industrial advisors, relevant work experience is one area our training program should be focused on. In response to this feedback, we have garnered the university support to create 25 internship positions over a period of 5 years. In parallel with our internal workforce training program, we also helped create a channel between student trainees and industry trainers. Many participating companies are SDNI industrial users, including Illumina, Intel, Qualcomm, ASML, TSMC, Becton Dickinson, nanoComposix, Skyworks Solutions, General Dynamics, AMD, ThermoFisher, RASIRC, Eurofins, Applied Materials, and EMD and several other smaller companies.

More Workforce Development-Driven Programs

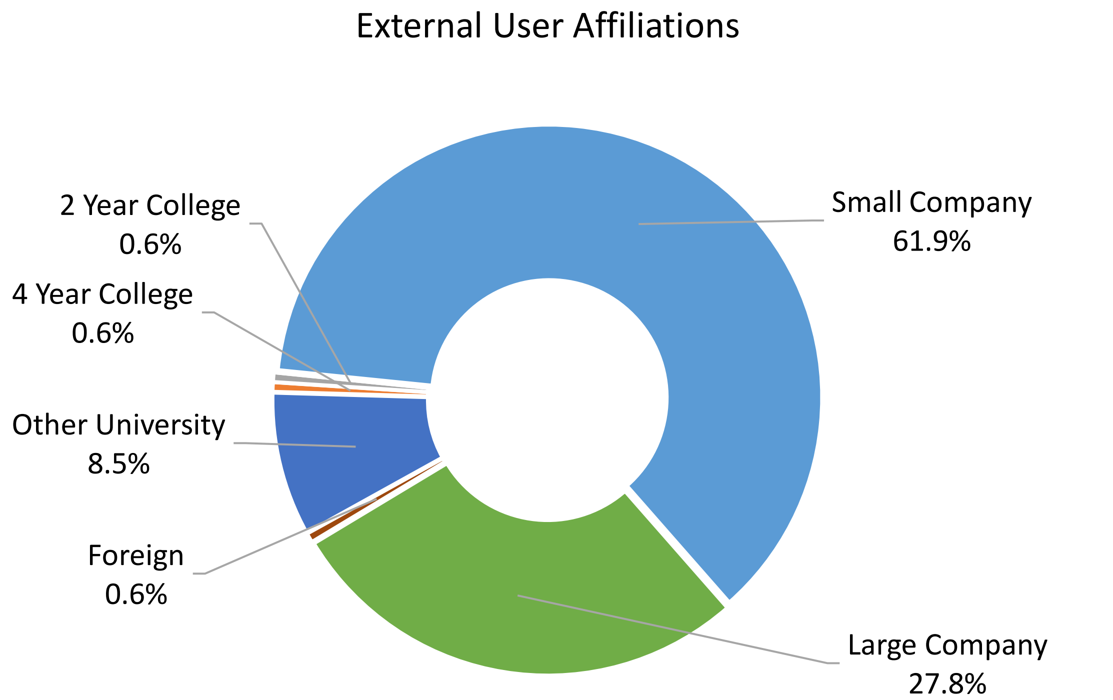
We promoted STEM education by working with middle and high school science teachers via remote SEM sessions, the REU/RET efforts, and the summer institute for middle/high school science teachers. All these efforts led by SDNI have contributed to building the pipeline of talents in science and technology.

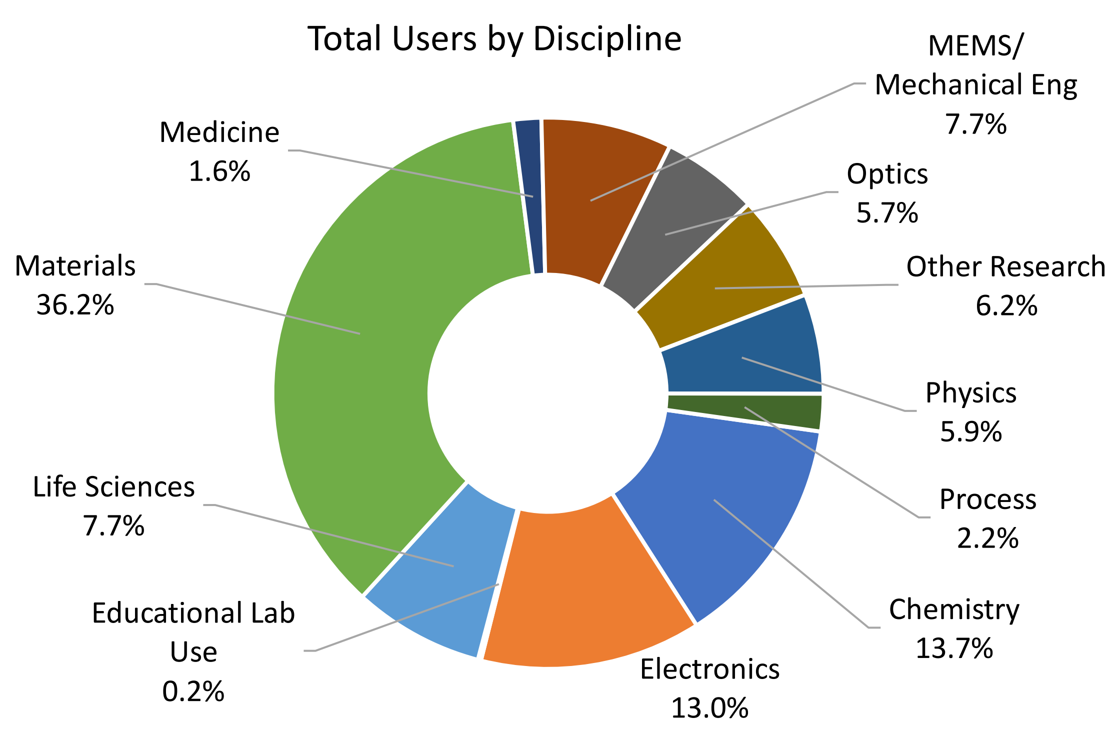
SDNI Site Statistics

Yearly User Data Comparison								
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**
Total Cumulative Users	650	644	692	653	539	528	562	547
Internal Cumulative Users	495	478	518	503	405	371	397	371
External Cumulative Users	155 (24%)	166 (26%)	174 (25%)	150 (23%)	134 (25%)	157 (30%)	165 (29%)	176 (32%)
Total Hours	47,893	50,497	49,519	69,367	53,667	61,111	65,051	58,521
Internal Hours	40,890	38,890	39,372	56,393	41,316	44,969	45,279	38,781
External Hours	7,003 (15%)	11,607 (23%)	10,147 (20%)	12,974 (19%)	12,352 (23%)	16,142 (26%)	19,773 (30%)	19,740 (34%)
Average Monthly Users	290	285	300	296	229	234	260	248
Average External Monthly Users	49 (17%)	56 (20%)	54 (18%)	50 (17%)	46 (20%)	53 (23%)	63 (24%)	68 (28%)
New Users Trained	183	210	225	202	169	152	152	152
New External Users Trained	34 (19%)	50 (24%)	46 (20%)	40 (20%)	36 (21%)	18 (12%)	18 (12%)	18 (12%)
Hours/User (Internal)	83	81	76	112	102	121	114	105
Hours/User (External)	45	70	58	86	92	103	120	112



SDNI Year 8 User Distribution





12.13. Soft and Hybrid Nanotechnology Experimental (SHyNE) Resource

A joint venture between Northwestern University and University of Chicago, SHyNE Resource represents the Midwest within the NNCI, providing researchers from academia, non-profits, government, and companies large and small with access to world-class user facilities with leading-edge fabrication and characterization tools, instrumentation, and technical expertise within all disciplines of nanoscale science, engineering, and technology. Under the leadership of site director, Professor Vinayak Dravid and co-director Professor Andrew Cleland, SHyNE Resource coordinates the integration of a diverse group of open-access nanoscale fabrication and characterization facilities across Northwestern University (NU*ANCE*, SQI, NUFAB, IMSERC, NUCAPT, JB Cohen XRD, PLD) and the University of Chicago (PNF).

Facility, Tools, and Staff Updates

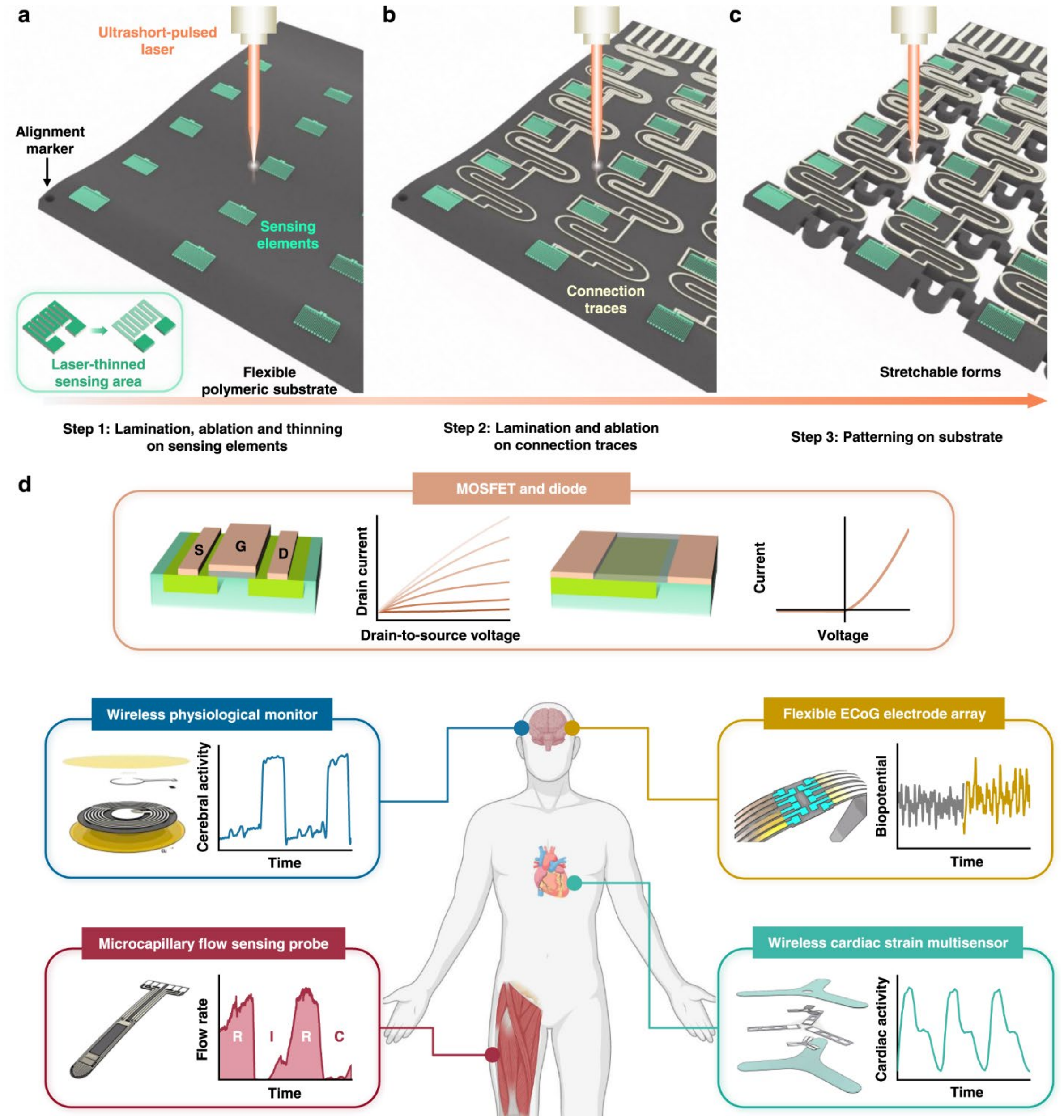
SHyNE facilities are actively engaged in acquiring and upgrading key equipment within the facilities through a combination of internal and external funding mechanisms. More than 20 new instruments and tool upgrades valued at over $10M were acquired in Year-8. NUFAB: AJA Niobium Sputtering system; Plassys Tilt-Angle Evaporator system; SAMCO Deep RIE system; SAMCO PECVD system; Osiris Acid Bench; Air Control Acid Bench; Toho FLX 2320-S Thin Film Stress Measurement System; Keysight Semiconductor Device Parameter Analyzer. NU*ANCE*: Gatan liquid Helium TEM holder; Thermo/FEI Helios 5 Hydra Plasma FIB; Cryo Industries Cryogenic Stage for TERS-AFM system; Protochips Cathodoluminescence (CL) TEM holder; Thermo NEXSA G2 XPS UV source upgrade; Malvern Zetasizer Advance Series - Ultra (Blue Label); Oxford EDS for FEI Helios FIB; JEOL 3200FS "in-lens filter" TEM; IMSERC: High pressure attachment for single crystal diffractometer for using Diamond Anvil Cells; Cohen XRD: Xenocs SAXS system upgrade, Rigaku Ultima 3; NUCAPT: Synology NAS RackStation 168TB server; Thermo Fisher cryoMat cryo stage; Leica EM VCT500 base station and cryo-vacuum shuttle. PLD: Annealing Furnace for substrate preparation; PNF: new high-speed direct-write optical lithography installed, with plans for two new instruments.

Maintaining an active and engaged user base for SHyNE facilities is contingent upon the successful recruitment and retention of high-quality staff. SHyNE supports over 60 staff members annually, and several new staff joined the SHyNE team in Year-8, two of whom are in newly created positions. NUFAB: Scott Kreager, Core Engineer; NU*ANCE:* Kelly Parker, BioCryo Research Associate; Stephanie Torres, Financial Coordinator; Nicholas Gogola, EPIC Assistant Core Scientist; Krysten Villalon, EPIC Core Scientist; Cohen XRD: Sumit Kewalramani, XRD facility director; PNF: three new staff members; SQI: Hiroaki Sai, Director of ANTEC; Kasandra Lee, Assistant Core Technician, PS Core and ANTEC.

User Base

SHyNE facilities in Year-8 served 1781 unique users who logged nearly 200,070 hours of instrument time generating $6.2M in revenue. Northwestern and UChicago shut down in the spring of 2020 for nearly 3 months in response to COVID-19; Year-8 utilization numbers indicate a full return to pre-pandemic activity. External users this year represented 14% of total users and revenue, a significant increase over Year-1 and another step toward hitting our steady-state goal of 20%. PNF, which began operations in Year-1, had 30 external users in Year-8.

SHyNE actively engages local and regional companies, colleges, universities, non-profit research organizations and governmental agencies to recruit new users. This is accomplished by several communication strategies including: exhibitions at conferences and trade shows, production of web portals, highlight videos and promotional materials, networking with alumni, coordination with university-wide corporate engagement and media relations offices, and an active social media presence. In Year-8, SHyNE continued managing a SEED (SHyNE External Experiment Development) funding program to recruit new external users by providing start-up grants for up to $2500 in facility usage. Three proposals were funded for new users from University of Alabama,



Laser ablation fabrication procedures for bioresorbable electronics, including patterning of sensing elements and structuring of alignment markers (a), patterning of connection traces (b), and structuring substrates into stretchable forms (c). Inset in a: laser thinning process on the sensing elements. (d) Illustrations of a representative collection of bioresorbable electronic systems fabricated using these procedures, such as Si-based semiconductor devices and a series of sensors of pressure, cardiopulmonary activity, thermal transport, fluid flow, biopotential, and mechanical strain, for various organs and biomedical applications. Quansan Yang, John Rogers, et al. Nature Communications, Volume 13, 6518 (2023).

Cal Tech, Woods Hole Oceanographic Institute, and early-stage startups, Fonase and Caporus. In Years 9-10, SHyNE will continue to focus on recruiting additional external academic, industry, and government users through an active engagement campaign including our SEED program.

Research Highlights and Impact

Soft-Hard interfaces have become ubiquitous in many emerging technologies, especially those which connect microelectronics with biology. Physically transient forms of electronics enable unique classes of technologies, ranging from biomedical implants that disappear through processes of bioresorption after serving a clinical need to internet-of things devices that harmlessly dissolve into the environment following a relevant period of use. John Rogers group developed a sustainable manufacturing pathway, based on ultrafast pulsed laser ablation, that can support high-volume, cost-effective manipulation of a diverse collection of organic and inorganic materials, each designed to degrade by hydrolysis or enzymatic activity, into patterned, multi-layered architectures with high resolution and accurate overlay registration. The technology can operate in patterning, thinning and/or cutting modes with (ultra)thin eco/bioresorbable materials of different types of semiconductors, dielectrics, and conductors on flexible substrates. Component-level demonstrations span passive and active devices, including diodes and field-effect transistors. Patterning these devices into interconnected layouts yields functional systems, as illustrated in examples that range from wireless implants as monitors of neural and cardiac activity, to thermal probes of microvascular flow, and multi-electrode arrays for biopotential sensing. These advances create important processing options for eco/bioresorbable materials and associated electronic systems, with immediate applicability across nearly all types of bioelectronic studies.

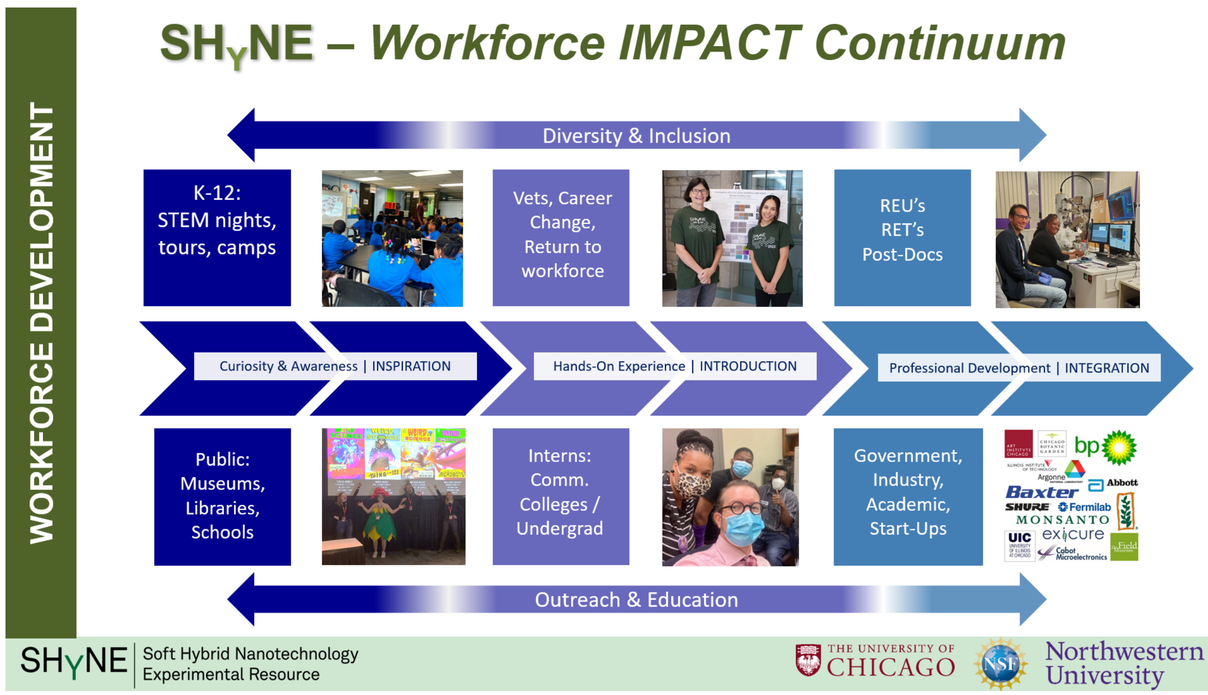
This work introduced a new manufacturing process for biomedical devices based on the laser ablation technique utilizing LPKF laser cutting tool in NUFAB. The device performance was evaluated with electrical test probe station, also in NUFAB cleanroom. This new pathway has immediate application across nearly all types of bioelectronic studies.

Education and Outreach Activities

Education and outreach are a critical part of SHyNE's mission and include academic courses with laboratory components, monthly user meetings, REU & RET programs, hands-on workshops, seminars, vendor symposia/demos, facility tours/demos (K-12, higher-ed, public), nano-journalism and related web and social media communications. In Year-8 we held several major workshops and lectures, assisted with 25 courses, hosted 30+ seminars and exhibitions and provided tours for academic, international, and industry participants. SHyNE sponsored five REU students in a unique, facilities oriented REU program that exposed undergraduates to advanced instrumentation as a key component of their projects. SHyNE also participated in a 10-week paid internship with Chicago State University and the Office of Research and hosted an undergraduate intern. Over 20 workshops and demos were held, including a Special Topics in SEM and Microanalysis 2-day Workshop with Oxford Instruments and Hitachi.

SHyNE continued its partnership with Science in Society (SiS), a Northwestern University research center dedicated to science education and public engagement, through the collaborative Magnifying Minds Program. The program partners with urban K-12 teachers, administrators, and youth development agencies to create high-quality, long-term, high-impact science learning opportunities for underserved youth. SHyNE also hosted the Midwest Microscopy & Microanalysis Society Spring meeting, iNano Spring Meeting, Career Day for Girls, and the 3rd Annual Women in Microscopy Conference. This event, hosted virtually by SHyNE and the MSA

Student Council, highlighted the work of female researchers, product specialists, and laboratory managers from universities, national labs, and microscope vendors with 600 registrants from 36 different countries. To extend our presence in social media and engage with the broader community, SHyNE has launched successful campaigns including our “Women in Nano” campaign which occurs annually in addition to a new Earth Day week-long campaign highlighting SHyNE facility users who focus on environmental research.



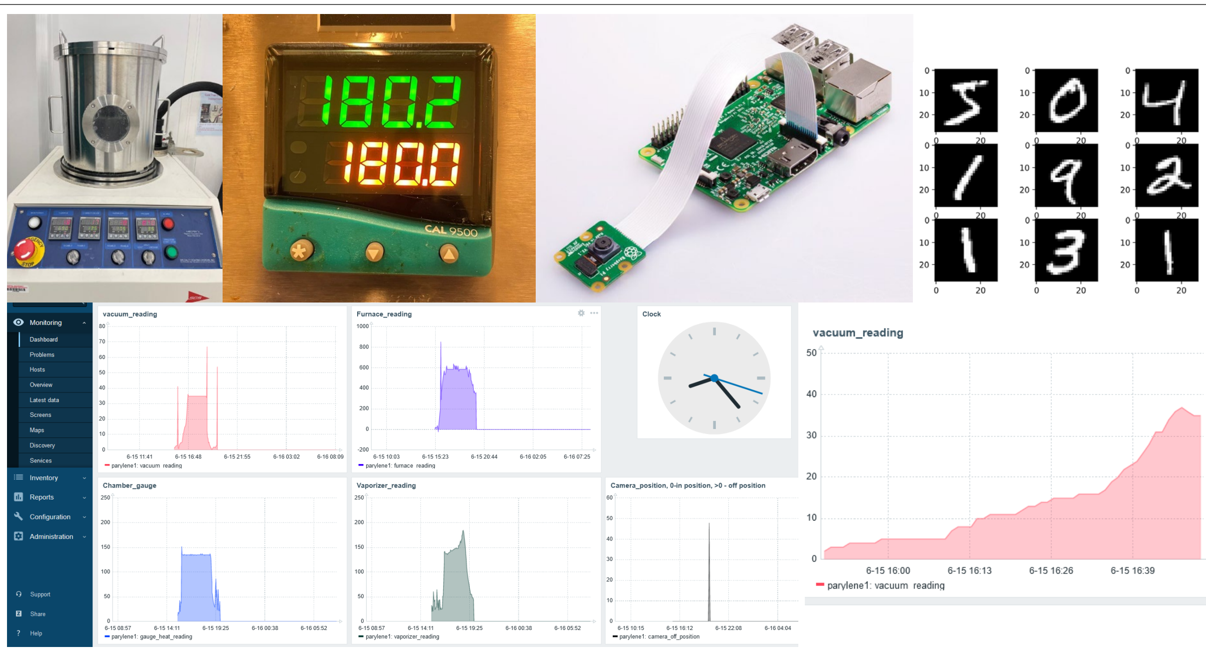
Schematic of SHyNE approach to workforce development across the K through ‘Gray’ education spectrum.

SHyNE Resource, collaborating with Northwestern’s Medill School of Journalism and the School of Communication, has established a novel Nano-Journalism focus within the existing Health, Environment and Science Journalism program. In 2019, we were excited to Mohammad Behroozian join the team! Mohammad is a PhD student in Northwestern University’s School of Communication working with Dr. Ellen Wartella’s Children, Media and Human Development Lab, Mohammad studies educational media for wartime to inform productions for children living in warzones. He joins SHyNE as a Nanoscience journalist and content producer, responsible for creating educational content to excite youth about nanoscience and nanotechnology. Mohammad is currently producing two videos to highlight the OHM (Oleophilic, Hydrophobic Multifunctional) sponge with great potential for managing oil spills and environmental remediation, more broadly. He also began a series of short video interviews created for social media to discuss and highlight NU*ANCE*’s “Art of Science” Image contest winners and the science and thought behind winning entries. This series will also be expanded to include educational content for outreach to middle-school students. SHyNE leadership in the Global and Regional Interactions (GRI) sub-committee is underscored by its emphasis on international and intra-network staff exchange, as well as workforce development initiatives on both a global and local scale. To this end, SHyNE hosted an undergraduate intern from Chicago State University, an HBCU, and is working with Oakton Community College to establish an internship program for their Nanotechnology Certificate students.

Computation Activities

***Computational Imaging Efforts in S/TEM at* NU*ANCE*:** The large amount of data produced by novel direct-electron detectors (Gatan K2-IS, K3-IS) recently installed, ~4Tb/hr, can no longer be effectively analyzed by human intuition and experience alone. NU*ANCE*/SHyNE staff are implementing strategies to improve experiment design, execution, analysis, and data sharing. We have substantially reduced the collection time or radiative dose of conventional electron microscopy experiments. A significant need exists for improved methods of collecting spatially resolved spectroscopic signals at electron doses low enough for the preservation of sensitive structures or subsequent investigation with a correlated technique, and/or for the acceleration of conventional spectrum images for the investigation of spatially confined biological-inorganic complex structures, engineered hybrid soft/hard ordered materials. Through development of "smart" sampling algorithm, we accelerate a low-dose experimental analytical imaging of materials that is applicable to arbitrary S/TEM imaging. In contrast to static sampling schemes or denoising, our method can produce spatially accurate spectrum maps at high speeds/low doses with weakly informative prior information, and no direct processing or manipulation of spectral data (no sparsity constraints). By maximizing the application of electron dose to areas with meaningful information or contrast on-the-fly, this approach may allow for the efficient characterization of radically larger regions of interest or materials/interfaces that are sensitive to accumulated dose.

***Equipment and facility predictive maintenance system with artificial intelligence*:** With the continued advancement of sensor technology, equipment manufacturers are integrating more sensors into the systems to improve their reliability. Recording and interpreting the sensor readings are key when it comes to equipment maintenance and troubleshooting. However, the sensor data is not always accessible and usually can only be understood by well-trained technicians. Based on years of equipment/facility maintenance experience, artificial intelligence and cloud technology, NUFAB's Dr. Ying Jia has developed a central facility management system to store, display, and



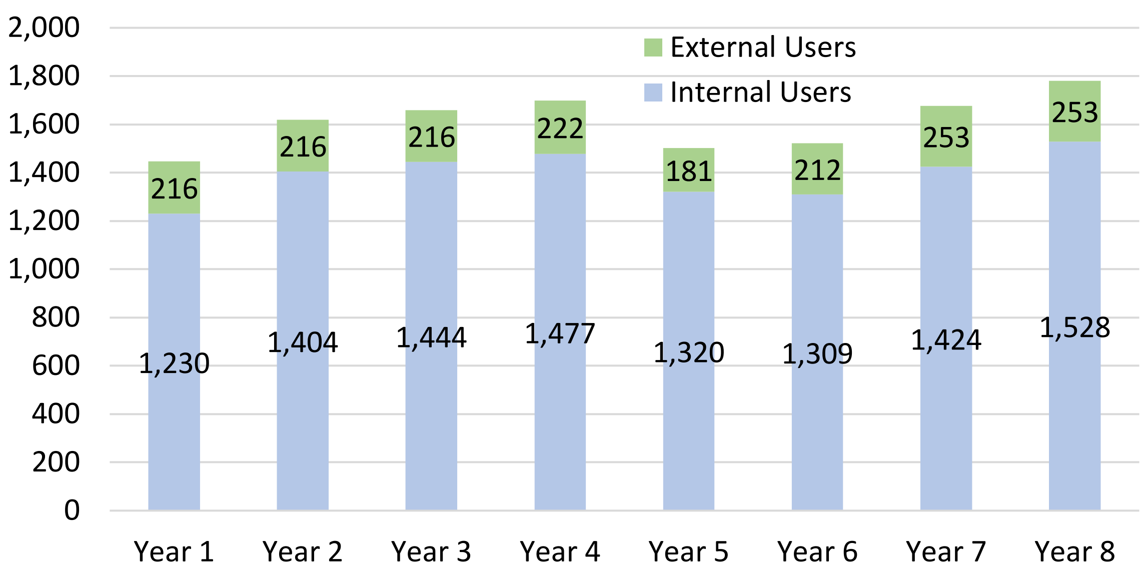
Raspberry Pi with camera feed into Zabbix dashboard and server. Applies Tensor Flow multi-classification image processing algorithm to read vacuum output numbers on tools that cannot be monitored inline.

analyze the sensor data in real time. This system evaluates the equipment's condition, predicts the future trends, toward maintenance recommendations, and can be monitored remotely, with push notifications to designated facility managers.

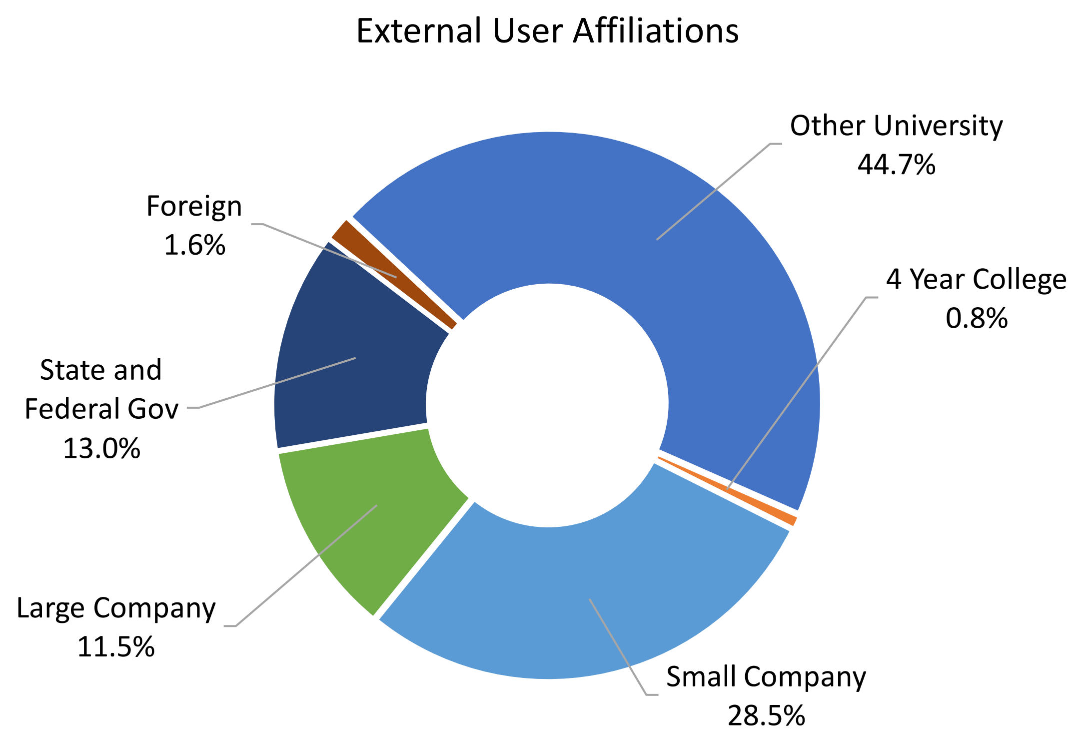
In summary, SHyNE/NU*ANCE* implementations are synchronized with the rise of artificial intelligence ecosystems and associated machine learning algorithms to accelerate innovation in a wide variety of scientific disciplines. We expect that in the coming years, the latest data analysis tools and techniques will gain a greater foothold into facility environment and revolutionize this environment in ways that leave it better positioned to address major scientific challenges.

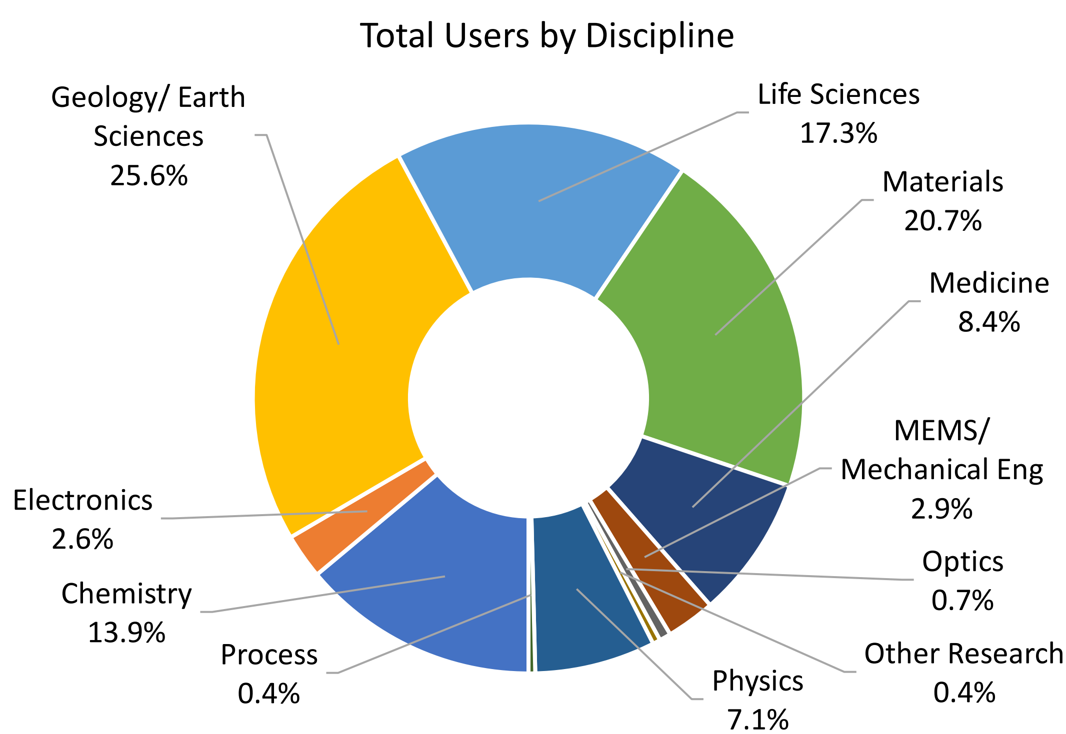
SHyNE Site Statistics

Yearly User Data Comparison	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Total Cumulative Users	1,446	1,620	1,660	1,699	1,501	1,521	1,677	1,781
Internal Cumulative Users	1,230	1,404	1,444	1,477	1,320	1,309	1,424	1,528
External Cumulative Users	216 (15%)	216 (13%)	216 (13%)	222 (13%)	181 (12%)	212 (14%)	253 (15%)	253 (14%)
Total Hours	138,000	132,673	137,375	202,844	139,175	159,720	179,802	200,070
Internal Hours	128,838	127,127	131,206	192,434	132,177	150,425	167,794	185,264
External Hours	9,162 (7%)	5,545 (4%)	6,169 (4%)	10,410 (5%)	6,998 (5%)	9,294 (6%)	12,008 (7%)	14,806 (7%)
Average Monthly Users	679	802	797	829	606	693	759	815
Average External Monthly Users	54 (8%)	54 (7%)	52 (7%)	61 (7%)	41 (7%)	54 (8%)	61 (8%)	72 (9%)
New Users Trained	699	698	605	649	340	597	649	653
New External Users Trained	152 (22%)	140 (20%)	86 (14%)	120 (18%)	66 (19%)	121 (20%)	137 (21%)	132 (20%)
Hours/User (Internal)	105	91	91	130	100	115	118	121
Hours/User (External)	42	26	29	47	39	44	47	58



SHyNE Year 8 User Distribution





12.14. Southeastern Nanotechnology Infrastructure Corridor (SENIC)

Facility, Tools, and Staff Updates

SENIC continues to facilitate the "3 universities, 2 locations, 1 site" mindset and partnership between the Georgia Tech Institute for Electronics and Nanotechnology (IEN) and Joint School of Nanoscience and Nanoengineering (JSNN). Our strategic goals, as developed with the help of our advisory board and stated in our NSF renewal proposal, are to (1) develop and serve a diverse user base, (2) develop strong synergies between partners, (3) expand capabilities based on future research trends, (4) develop education and outreach and societal and ethical implications programs targeting the SE, and (5) assist the NNCI network in becoming more than the sum of its parts.

During Year 8, the IEN Micro/Nano Fabrication Facility added 7 new positions: (1) Laboratory Technician to support cleanroom operations, equipment installation, and maintenance, (2) Web Developer to support SUMS operations and function development, (3) Lab & Facility Coordinator to support the cleanroom daily operations, user orientation training, inventory management and equipment maintenance, (4) Senior Research Engineer to support the Laser Lab, (5) Process-Equipment Engineer to support equipment installation and maintenance, (6) Research Engineer I to support operations of the Packaging Research Center, and (7) Research Scientist I to support the educational lab operation, undergraduate lab teaching, and research projects.

Several projects are scheduled for completion by the first quarter of 2024 in the Pettit Microelectronics building. Two new dry abatement systems were installed to replace the current wet scrubber systems, and this change is expected to reduce power and water consumption, leading to significant cost savings. Nine gas cabinets are scheduled for upgrades, which will improve operational efficiency and safety. IEN also replaced the Dangerous Gas Monitoring System (DGMS) with the campus-adopted Honeywell Midas system.

The Materials Characterization Facility (MCF) at Georgia Tech purchased several new instruments, as listed below. Collectively, these instruments allow users to examine the crystal structure, electronic structure, and elemental and chemical composition of samples with submicron features, temperatures of 77-2400 K, and concentrations down to parts-per-trillion levels. Planned and current personnel additions expand our expertise in surface science, scanning probe analysis, and mechanical testing instrumentation, in particular, and provide useful backup for other analytical instruments.

During the past year, SENIC has continued to add new tools/upgrade existing tools at both Georgia Tech and JSNN. Decisions regarding tool purchases/upgrades are informed by annual NNCI user survey, dedicated equipment need surveys and questionnaires, as well as input from conferences and workshops. University support of core facility equipment benefits the goals of SENIC and NNCI in making state-of-the-art nanofabrication and characterization tools accessible to a broad and diverse user base.

New Tools/Upgrades:

OAI 808E Mask Aligner	Raith Voyager E-Beam Lithography System
Nabity NPGS E-beam patterning	Nanoscience Spinbox Electrospinning
Exaddon CERES Metal 3D Printer	Suss-ACS200 Gen33M Coater, Develop and Bake
Bruker TriboLab CMP System (2)	Lesker Pro Line PVD75/200 (2)
TPT Thermosonic HB16 Wire Bonder	CiphercoNTM 1500 Gas Cabinets (2)
WiTec 300R Confocal Raman Microscope	Rigaku Smartlab XRD

Evident FV3000 Confocal Microscope	Micromeritics ASAP 2060 BET
Agilent 1290 UHPLC	ThermoFisher is50 FTIR with RaptIR Microscope
Agilent Cary 7000 UV-Vis-NIR Spectro	Agilent 8890-5977B GC-MS
Agilent 7900 ICP-MS	TA Instruments 5500 TGA
Beckman Coulter CytoFlex Flow Cytometer	Leica UC7 Ultramicrotome
Evident BX53 Materials Microscope	Keithley 4200A Semiconductor Parameter Analyzer
PowerWulf ZX1R HPC Cluster	Bruker Icon-IR AFM-IR
Bruker μ-focus X-Ray Fluor Spectrometer	Bruker TI-980 triboindenter
Thermo Fisher NEXSA XPS/UPS system	Gatan Cathodolumin detector (SEM upgrade)

User Base

User growth, particularly from non-traditional areas that have not used nanotechnology core facilities in the past, requires dedicated marketing and outreach programs. Since the start of the NNCI, SENIC has streamlined its user recruitment efforts based on feedback from the annual user survey on how users learn about SENIC and sharing of best practices among sites. In 2018, the NNCI subcommittee on "*Building the User Base*" identified awareness, accessibility, and affordability as the three key limitations for growing the user base. To create SENIC **awareness**, we use websites, SENIC newsletter, social media presence, and visits to universities and companies in the southeast, particularly along the I-85 corridor. To facilitate these visits, we recruit current and past users at these institutions as "*SENIC Ambassadors*" who assist with organization and local promotion. To target the **accessibility** challenge, we continue to provide remote work capabilities, where staff perform the work on behalf of the user rather than the user doing the work on site. Seed grant programs seek to address the **affordability** challenge, and SENIC continues to support the IEN Facility Seed Grant Program and the Catalyst Program.

Marketing of SENIC continued through the website as well as promotional and communication efforts through email and social media, with SENIC-specific efforts on Facebook, LinkedIn, and Twitter. A quarterly SENIC newsletter, initiated in 2018, is emailed to over 3,000 current and potential users along with other stakeholders. Year 8 issues were sent in December 2022, and March and June 2023. The SENIC website (http://senic.gatech.edu/) was updated with new content, including the latest information on education and professional development activities such as the SENIC Undergraduate Internship in Nanotechnology, RET program, Summer Institute for Middle School Teachers, seminars, and hands-on user short courses.

In support of its vision to strengthen and accelerate discovery in nano-related fields across the US, the SENIC Catalyst Program provides researchers limited (up to $1K) free access to the SENIC facilities to aid in research, obtain preliminary data, conduct proof-of-concept studies, or for education. During Year 8, new Catalyst awards were made to researchers from Fort Valley State Univ., Univ. of the West Indies, Berry College, Morehouse School of Medicine, North Gwinnett High School, Johnson C. Smith Univ., High Point Univ., Spelman College, and Episcopal School of Jacksonville. Since the start of the program in 2019, 39 projects have been awarded.

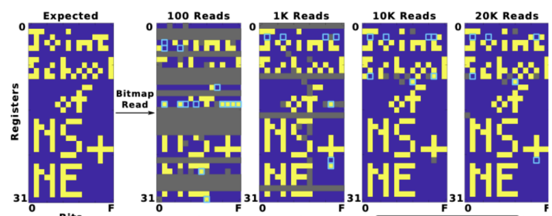
As stated in our renewal proposal, SENIC expanded its relationship with the Center for Nanophase Material Science (CNMS) at Oak Ridge National Lab (ORNL). In particular, we have developed a pathway for joint user/project support, where a SENIC user can obtain expedited access to ONRL resources not available in SENIC facilities and vice versa.

During this past year of the NNCI (Oct. 2022 - Sept. 2023), SENIC facilities have served 1,403 individual users, including 295 external users (43% growth since Year 5) representing 85 companies, 27 colleges/universities, and 13 other institutions, including pre-college schools. Several users have accessed capabilities at both SENIC locations with minimal difficulty. Most users access the facilities on-site, although 166 users obtained services remotely, and some users were served both on-site and remote. Monthly users averaged 603 (a 62% increase compared to Year 5), and on average 48 new users/month were trained (571 total during the reporting period).

Research Highlights and Impact

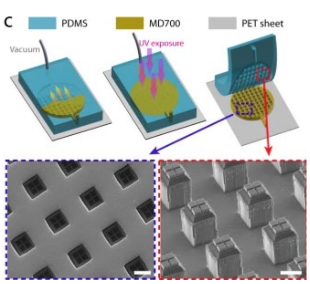
Notable new academic users of the SENIC facilities this past year come from University of Cincinnati, University of Missouri, Guilford Tech, Berry College, Alabama A&M, while new industry users include Exponent, General Dynamics, Milwaukee Electric Tool, Guerrilla RF, Silicon Dynamix, CarbonMeta, to name a few. Some example research highlights include:

Digital Data Storage on DNA Tape using CRISPR Base Editors (R. Zadegan, NC A&T, D. R. LaJeunesse and A. Josephs, UNCG)



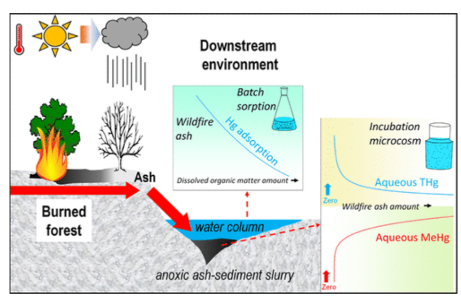
Researchers created a molecular digital data storage system called "DNA Mutational Overwriting Storage" (DMOS) that stores information by leveraging combinatorial, addressable, orthogonal, and independent in vitro CRISPR base-editing reactions to write data on a blank pool of greenly synthesized DNA tapes. The work was funded by the National Science Foundation and published in *Nature Communications*.

Chip for Treating Metastatic Cancer (F. Sarioglu, Georgia Tech)



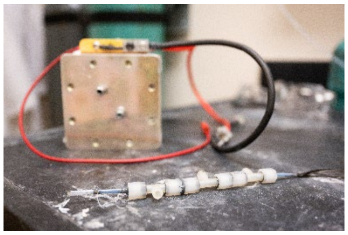
Circulating tumor cells (CTCs) that travel via the bloodstream are one way that cancer spreads in the body, but they are difficult to track and measure. Researchers at Georgia Tech School of Electrical and Computer Engineering have developed a device for characterizing CTC which could lead to earlier and more targeted treatments. The Cluster-Well, combines microfluidics and membrane filtration to find CTC clusters. The research was supported by Prostate Cancer Research Program (DoD) and was published in *Nature Communications*.

Impacts of Forest Fire Ash on Aquatic Mercury Cycling (H.H. Li, UNCG, R. A. Dahlgren, UC Davis, T. C. Hoang, Auburn U and A. T. Chow, Clemson U)



Researchers compared the differences of wildfire ash with activated carbon and biochar on the sorption of aqueous inorganic Hg and sedimentary Hg methylation. This study indicated that while wildfire ash can sequester aqueous Hg, the leaching of its labile organic matter may promote the production of toxic MeHg in anoxic sediments, which has an important implication for potential contamination in downstream aquatic ecosystems after wildfires. This project was funded by NSF published in *Environmental Science & Technology*.

Flow Batteries for Clean Energy (N. Liu, Georgia Tech)



Flow batteries provide a solution for clean energy, with consistency needed for a reliable power grid. In this type of rechargeable energy storage and delivery, electrolytes from storage tanks flow through electrochemical cells. Existing flow battery techno are too expensive for practical application, but a team has developed a more compact design that reduces size and cost. This work was supported in part by GT faculty start-up funds and was published in *Proc. Natl. Acad. Sci*.

Scholarly impact can be measured indirectly with more than 620 publications, presentations, and patents benefiting from SENIC facilities in CY 2022. Using a Google Scholar search, more than 200 of these 2022 publications (and more than 1000 publications 2015-2022) acknowledged the SENIC NSF award number. Furthermore, the SENIC SEI program produced an analysis of 1500+ publications (2016-2020) demonstrating diverse collaborations and enhanced research.

SENIC facilities supported multiple lab courses from Fall 2022 to Summer 2023. GT teaching cleanroom and Materials Characterization Facility supported 8 courses from 6 schools in the Colleges of Engineering and Science. JSNN facilities support an additional 8 courses for graduate students in Nanoscience and Nanoengineering. These courses had nearly 400 students enrolled. Over the academic year from Fall 2022 to Summer 2023, more than 270 degrees were awarded to current/former SENIC users at GT and JSNN: 50 Bachelors, 106 Masters, 118 Doctorates.

Additional impact of SENIC is indicated by centers and other large programs that are enabled by the supported core facilities. In 2022-2023, Georgia Tech was selected by SRC/DARPA to lead two new JUMP 2.0 centers, **Center for the Co-Design of Cognitive Systems (CoCoSys)** and **Center on Cognitive Multispectral Sensors (CogniSense)**, while the Assoc. Director for a third center, **Center for Heterogenous Integration of Microelectronic Systems (CHIMES)**, led by Penn State, is also at Georgia Tech. In 2023, JSNN joined NC State University and RTNN as a collaborative partner to be selected as one of the hubs for the DOD Microelectronics Commons - "**Commercial Leap Ahead for Wide Bandgap Semiconductors (CLAWS).**".

While economic impact can be difficult to quantify, select examples from Year 8 indicate that SENIC-supported startup companies are achieving success:

- **Absolics, Inc.** broke ground on a new $600 million semiconductor manufacturing facility in Covington, GA. The company developed its semiconductor packaging technology in collaboration with Georgia Tech's Packaging Research Center.
- DOE awarded **Sila Nanotechnologies** (a Georgia Tech startup) $100 million to support a new battery factory in Washington.
- **Saras Micro Devices** expanded its research and development presence in the Atlanta area with a new 5,000 sq. ft. cleanroom/laboratory facility.
- Medical device company **Artelon** secured $20 million in Series B funding to support the growth of its bio-textile for surgical joint repair and moved into new laboratory space.

<u>Education and Outreach Activities</u>

SENIC's vision for education and outreach is focused on the development of a strong workforce capable of meeting the needs of a growing nanotechnology-enabled economy. This year through our programs, we reached more than 5,000 individuals from young children to adults.

JSNN is home to the NIH Maximizing Access to Research Careers (MARC) Undergraduate Student Training in Academic Research (U-STAR) Fellowship program. This program annually offers two students underrepresented in biomedical sciences a research opportunity, focused workshops, and courses to prepare them for graduate school. With support from Intel, JSNN established a microelectronics training program – "*Intel-NCA&T Partnership in Broadening Research and Experiential Learning Pathways in Semiconductors*." Five community college students (Guilford Tech and Forsyth Tech), six undergraduates (NC A&T, Winston Salem State, North Carolina State and UNC Chapel Hill) participated in the 8-week summer internship program. In addition, JSNN provided research training to four incoming NC A&T undergraduates in microfluidics and biomedical applications, as part of the NIH-funded ESTEEMED program. Georgia Tech, inspired by JSNN's programs, started their own paid, technical college internship in spring 2020, with the first students participating in 2022. IEN has established a strong relationship with the Technical College System of Georgia and has hosted visits by faculty and students. IEN's summer internship program had students from three colleges from the state of Georgia. Three students came from Dalton State University (non-R1/R2), one from Georgia State University (R1 institution), and two from Kennesaw State University (R2 institution). IEN also hosted five REU students in 2023. In addition to internships, SENIC also provided opportunities for high school students and undergraduates to work in the facilities as student assistants.

Each academic year, JSNN hosts a weekly seminar and IEN hosts a bi-monthly seminar series entitled Nano@Tech, held in-person with live streaming on YouTube. JSNN also hosts a virtual journal club. Georgia Tech's NanoFANS Forum, a biannual symposium at the intersection of life sciences and nanotechnology, was held in October 2022 ("Micro-Nanotechnology Commercialization") and June 2023 ("Trends in Machine Learning for Biology").

SENIC has been active in providing outreach to K-12 students, educators, and the general public. SENIC at Georgia Tech is the lead site of the NSF-supported Research Experiences for Teachers across the National Nanotechnology Coordinated Infrastructure collaborative program. The last cohort of this program was held during summer 2023 for four teachers from the metro Atlanta area and one teacher from the Macon area. This program provided these high school and community college faculty with an opportunity to engage in hands-on research for six weeks, implement lesson plans they created in the classroom, and travel to the National Science Teaching annual meeting (Mar 2024) to share their results and experience with the broader teaching community. The summer 2023 Nanotechnology Summer Institute for Middle School Teachers (NanoSIMST) program was held in-person at JSNN with a cohort of 15 teachers from North Carolina. Teachers participated in a week of instruction that introduced them to nanotechnology and learned about classroom lessons that meet North Carolina standards. The teachers also participated in cleanroom and lab tours, used the portable SEM, and participated in a careers panel. Through an ongoing partnership with the Guilford County School System, JSNN provided professional development sessions to middle school and high school science teachers.

In July 2023, JSNN hosted the ExPlorers Program for 16 underrepresented high school students and 4 high school teachers. This was a week-long program involving interactive hands-on experiences with the nanoscale, applications of nanotechnology, phosphorus sustainability, agriculture, and ethics in science. JSNN also hosted nineteen high school students for 6 weeks, as part of the Draelos Science Scholars Program where students gained mentored lab experiences in chemistry, nanoscience, biology, and bioengineering. IEN is continuing to offer virtual class trips to schools throughout Georgia. The virtual program covers similar information as the original

"*Intro to Nano*." IEN staff ship kits to schools so students can continue to do hands-on activities while being guided through a virtual visit. IEN partnered with Micron for Chip Camp, a three-day event for middle school students, with a specific focus on microelectronics. Over 60 students had facility tours, tried on a cleanroom suit, and view the "Intro to Nano" presentation. During Year 8, IEN hosted five short courses - three on Microelectronics Fabrication (one specifically for new hires at Northrup Grumman) and two on Microfluidics.

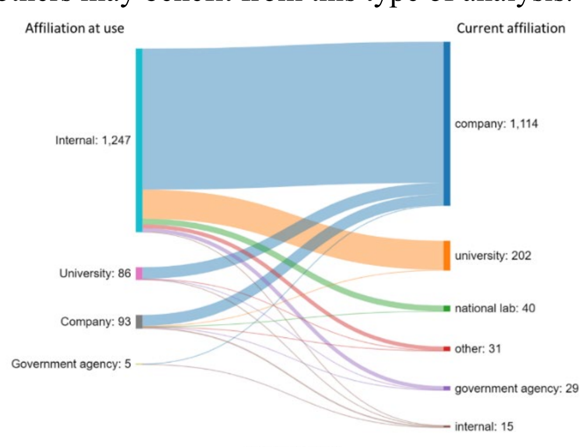
<u>Societal and Ethical Implications Activities</u>

The aim of SENIC's SEI activity is to develop tools and techniques to measure the impact of SENIC on societal sectors. The results are designed to provide SENIC with information about its impact and facilitate replicability across the NNCI network by forming the basis for toolkits that other sites or facilities can use to replicate this work.

Research Impact: Youtie and Shapira examined the research outputs of SENIC resulting in a journal publication [Pelaez, S., Youtie, J., & Shapira, P. (2022). *Analyzing research outcomes and spillovers at a US nanotechnology user facility*. Journal of Nanoparticle Research, 24(12), 243] The article was based on a new dataset built from the 1,644 journal articles listed in SENIC annual reports between 2015 and 2020. The paper finds that SENIC works across a broad range of fields, emphasizing materials science, chemistry, physics, and nanotechnology with activity also in biosciences and energy.

Strengthening the Workforce: Year 8 was a time of transition for the SEI work at SENIC as Prof. Diana Hicks of the Georgia Tech School of Public Policy assumed the role of SEI Coordinator. Hicks and Pelaez conducted an analysis of the job outcomes of past SENIC users. Analyzing the career trajectories of past users provides insights into the societal impact of these facilities, in particular, their enhancement of the workforce. When users move on from NNCI facilities, they take their newfound skills into their jobs. Examining where people take the high-tech skills they developed at NNCI facilities will reveal career paths influenced by the facilities and thus the facilities' contributions to a highly skilled workforce. The methodology developed was written up in a toolkit circulated to all NNCI facilities so that others may benefit from this type of analysis.

Using LinkedIn, 2,360 past SENIC users were identified. Individuals who did not relocate and those still in education were excluded to highlight the contribution of SENIC to enhancing the workforce. The results showed that Intel is by far the largest employer of past SENIC users. Academia employs the most past SENIC users, followed by the semiconductor industry. The results of the study were presented at the NNCI annual conference and are available [online](#).



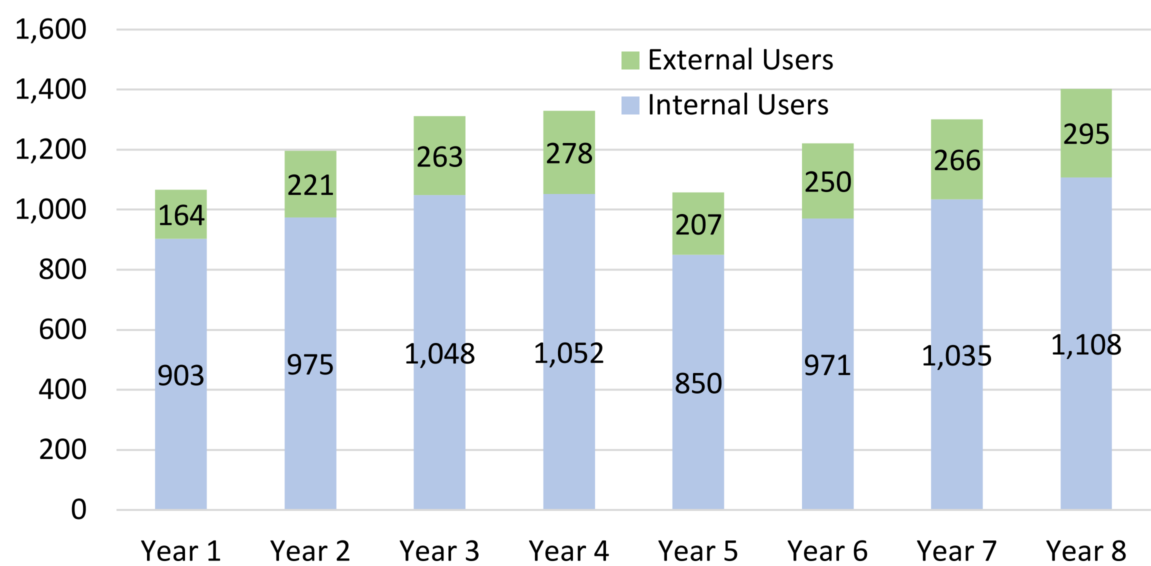
<u>Innovation and Entrepreneurship Activities</u>

In 2023, a project from SENIC (JSNN) led by Hunter Holden (Mentor: Dennis LaJeunesse) was one of nine teams selected to participate in the NNCI NTEC cohort. Paul Joseph offered additional mentorship to the students during the weekly virtual touch-base meeting during the seven-week program. SENIC representatives Paul Joseph (Georgia Tech IEN) and Sherine Obare (JSNN) participated in the NNCI I&E Working Group quarterly meetings.

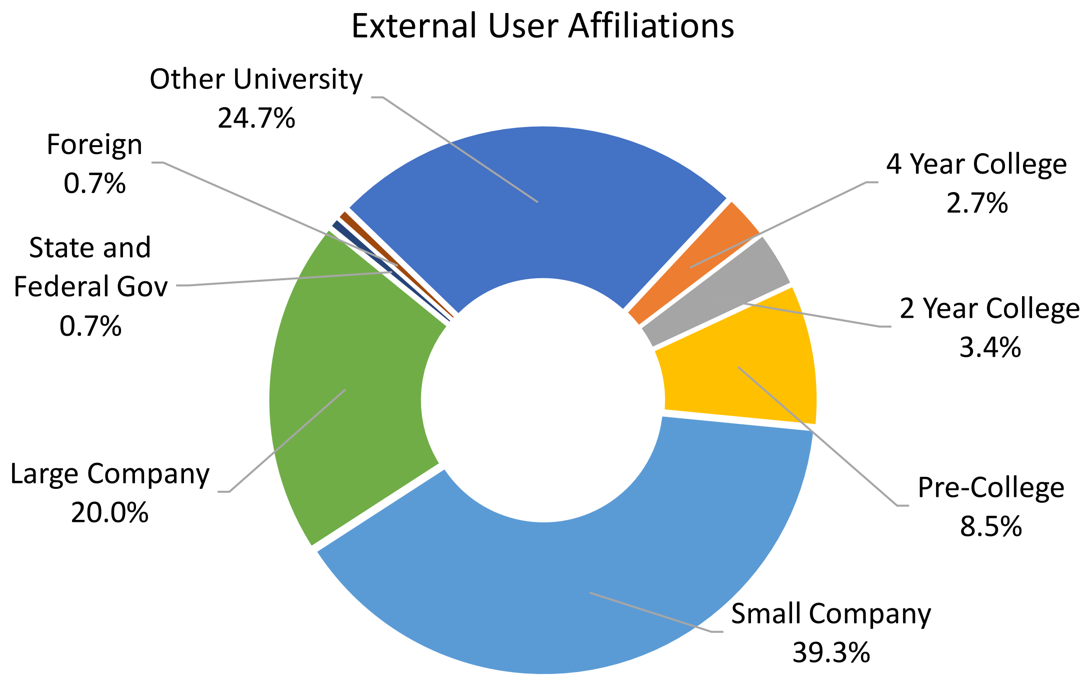
SENIC Site Statistics

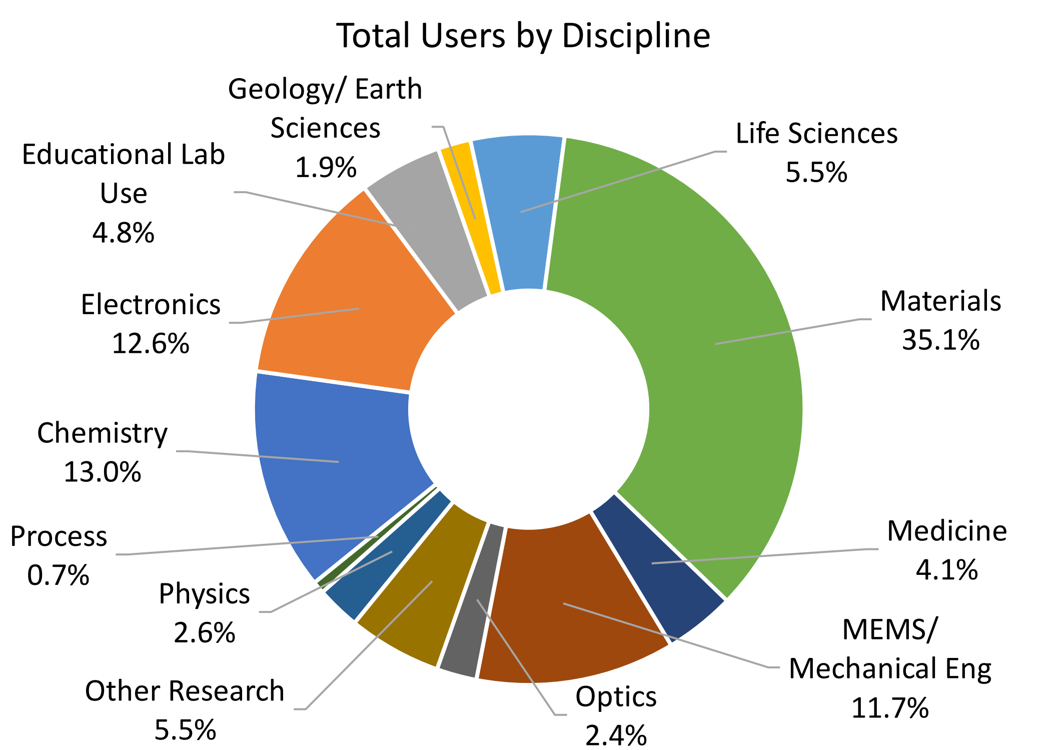
Yearly User Data Comparison								
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**
Total Cumulative Users	1,067	1,196	1,311	1,330	1,057	1,221	1,301	1,403
Internal Cumulative Users	903	975	1,048	1,052	850	971	1,035	1,108
External Cumulative Users	164 (15%)	221 (18%)	263 (20%)	278 (21%)	207 (20%)	250 (20%)	266 (20%)	295 (21%)
Total Hours	79,581	85,275	99,118	101,571	66,611	92,998	109,049	127,584
Internal Hours	71,659	73,499	85,730	88,282	58,620	80,751	96,276	112,755
External Hours	7,922 (10%)	11,733 (14%)	13,388 (14%)	13,289 (13%)	7,991 (12%)	12,247 (13%)	12,773 (12%)	14,829 (12%)
Average Monthly Users	447	498	546	576	373	499	563	603
Average External Monthly Users	60 (13%)	63 (13%)	83 (15%)	89 (15%)	51 (14%)	75 (15%)	73 (13%)	83 (14%)
New Users Trained	313	313	386	502*	248	453	505	571
New External Users Trained	67 (21%)	110 (35%)	123 (32%)	132 (26%)	45 (18%)	80 (18%)	124 (25%)	142 (25%)
Hours/User (Internal)	79	75	82	84	69	83	93	102
Hours/User (External)	48	53	51	48	39	49	48	50

*Starting in Year 4, SENIC began adding new users of the Materials Characterization Facility to this metric.



SENIC Year 8 User Distribution





12.15. Texas Nanofabrication Facility (TNF)

Facility, Tools, and Staff Updates

The Texas Nanofabrication Facility (TNF) at the University of Texas at Austin (UT) is composed of the Microelectronics Research Center (MRC, the Texas Materials Institute (TMI), and nanomanufacturing fab (nm-Fab). NNCI-TNF (composed of MRC, TMI and nm-Fab facilities) has 22,000 sq. ft. cleanroom space (class 100 and 1000) and 20,000 sq. ft. of labs.

The MRC cleanroom provides extensive nanofabrication capabilities, TMI provides state-of-the-art metrology tools, while the nm-Fab has developed and provides novel nanomanufacturing tools in the areas of roll-to-roll manufacturing (deposition and etch), and high speed, large area nanoimprinting. TNF is well positioned geographically in the Austin high-tech hub, within the Dallas/Fort Worth-Houston-San Antonio triangle, with no competing universities having comparable infrastructure in nanotechnology in this region of the country. Since Texas, in general, and Austin in particular, have a strong industry base in nanotechnology, TNF has a large external user cohort, especially in terms of small companies. We also serve academic institutions in Texas, and the neighboring states. We also have users from other parts of the US, and the rest of the world. We have enabled and fostered breakthrough nano-innovation in the areas of electronics, healthcare and energy – all of which have significant presence in the South West; while establishing educational activities in nanotechnology directed at engaging underrepresented minorities (URM), particularly Hispanics and women. We have added two staff members in our cleanroom to assist with new user training and equipment maintenance in the area of plasma and reactive ion etching.

TNF has recently invested heavily in advanced plasma etching, deposition, and metrology tools. The nmFab has installed a novel roll-to-roll atomic layer deposition system on flexible substrates, and a roll-to-roll etch system. A Scios Dual beam Focused Ion Beam and a JEOL Aberration Corrected TEM funded by Univ. of Texas have been installed. A new JEOL E-Beam lithography 8100 FS system funded by Univ. of Texas was installed during Summer 2023. **The State of Texas has provided $550M to upgrade and expand the TNF cleanroom. We will add 10,000 sq. ft. of cleanroom space to the facility by 2024. Facilities are being added for heterogeneous integration of CMOS +X devices. We are also upgrading our fabrication tools to be 8" compatible.**

User Base

Sanjay Banerjee participated in the Metrics Subcommittee, and the Increasing User Base Subcommittee. S. Banerjee also co-led the "Microelectronics Research Community" with Philip Wong from Stanford, Trevor Thornton from ASU and Shyam Aravamudhan from NCAT. A two-day Workshop was held in Sept. 2022. Issues such as increasing the user base were discussed. A report was prepared in December, 2022.

Research Highlights and Impact

Work done at TNF has led to multi-institution, and multi-NNCI site high impact papers. NNCI has also enabled technology development by small companies, many supported by SBIR and STTR grants from NSF, DoD, etc. Some of these examples from the past year are described below. Several of these address the NSF 10 Big Ideas, or other federal initiatives.

Small Company User (2010 - present): Nanohmics

This company is illustrative of the wide range of programs that small companies run through TNF, funded by various government SBIR and STTR programs.

- ***Compact Hyperspectral Imager Using Tunable Metasurfaces***

  This work is supported by a Navy SBIR Phase II, N6893622C0002. PI. Dr. Mark Lucente

  Nanohmics, Inc. is developing a battery-operated, low-SWaP HSI system by combining a metasurface tunable spectral filter with a COTS LWIR camera. This system will fit aboard small mobile platforms, achieve full focal plane array (FPA) resolution and be capable of detecting targets in cluttered environments.

- ***Chip-scale Hyperspectral Imaging MISSE (CHIMP) for International Space Station***

  This work was supported by a Nanohmics IRAD program and a cooperative agreement with the International Space Station National Lab, Agreement No. 80JSC018M0005. PI. Dr. Chris Mann

  Through a User Agreement with the ISS National Lab, Nanohmics built and launched a low-SWaP video-rate spectral imager that was installed on the ram-facing side of the MISSE flight facility on the exterior of the International Space Station.

- ***Nonreciprocal optical metasurfaces for photonic systems***

  This work is supported by OSD STTR Phase I grant W911NF22P0025. PI. Dr. Karun Vijayraghavan

  The overall goal of this program is to develop passive, solid-state, magnet-free optical isolators in the near-infrared spectrum (120 – 300 THz). The devices are designed on the principles of metasurface 'flat optics' in which the optical properties of light can be manipulated by sub-wavelength scaled patterns on a wafer. The isolators are designed using novel Fano-metasurface technology and the goal is to demonstrate better optical isolation performance per size, weight, power and cost than Ferrite-based devices employed in applications such as directed energy laser systems or photonic integrated circuits.

Small Company User (2011-present): Applied Novel Devices (AND)

A new class of Si power MOSFET technology (ANDFET) with sub-30um substrate has been developed by AND with some of the development work carried out at the NNCI facility in UT-Austin. ANDFET has 2x lower Qoss and superior specific on-resistance at gate drive as low as 2.5V compared to state-of-the-art low-voltage (<60 V) MOSFETs. ANDFET also has near-zero reverse-recovery charge/losses for all voltage applications. ANDFET is manufactured with self-aligned and low-complexity process in a high-volume 8-inch Si foundry. Thin-Crystalline Technology is utilized to yield mechanically handleable sub-30um substrate. Finally, the ANDFET architecture is well-suited for SiC and GaN-like wide-bandgap (WBG) devices as it inherently yields enhancement-mode WBG MOSFETs.

Small Company User (2010-present): Sheetak Inc.

This company is illustrative of the wide range of programs that small companies run through TNF, to enable commercialization of emerging technologies in Texas. The research was supported earlier by DOE ARPA-E and DoD grants.

- ***Efficient Integrated Thermoelectric Devices***

Sheetak has developed efficient monolithically integrated thin-film Bi-Sb-Te-Se thermoelectric technology on Si and SiC substrates. These high figure-of-merit zT device structures exploit non-equilibrium transport of electron/phonon systems in nanostructured thin films. The thermoelements operate at high fields ~10^5 V/m resulting in local cooling flux exceeding 7kW/cm^2 , and exhibit zT ~1.5, that is 2× better than commercial thermoelectric coolers. The integrated chips are solder-free, hermetic, with densities >1000 couples/cm^2, making it a compelling proposition for optoelectronics, 5G wireless, thermal cyclers in genomics, wearables, and battery-free IoT. Sheetak fabricates structured Si substrates at the UT MER, and the follow-on processes at its fabrication facilities in South Austin. The work performed at UT Austin Microelectronic Research cleanroom facilities, including the LPCVD SiN, thermal oxides, ALD alumina and Pt, KOH etching, mask lithography, and scanning electron microscopy.

Internal Academic User: Prof. Deji Akinwande (Univ. of Texas)

- ***Comparative Study between Sulfurized MoS_2 from Molybdenum and Molybdenum Trioxide Precursors for Thin-Film Device Applications***

Molybdenum was sulfurized under different temperatures using e-beam evaporated Mo metal and MoO_3 on Si/SiO_2 substrates. As-grown samples showed relatively high-quality growth with thicknesses ranging from a few layers to monolayers based on spectroscopic and AFM characterizations. XRD and XPS depicted the 2H-MoS_2 structure along with the successful sulfurization of MoO_3. Electrical measurements revealed p-type behavior featuring an Ohmic contact to Au source and drain electrodes, with mobilities in the range of 21–41 $cm^2\ V^{-1}\ s^{-1}$. Furthermore, the switching phenomenon showed that sulfurized thin films successfully behaved as an active material for bipolar resistive switching with an on/off ratio of 10^4 at an operating voltage of ±1 V. The successful sulfurization using the reported CVD route can further be implemented on different substrates for scalable growth and device realization.

Internal Academic User with another NNCI site: Prof. Dan Wasserman (Univ. of Texas, TNF) and Prof. Monica Allen (SDNI)

- ***High-speed mid-wave infrared holey photodetectors***

A high-speed mid-wave infrared detection using InSb photoconductive material was developed. InSb pixels were patterned with nano-scale hole arrays, integrated into a coplanar waveguide structure. The addition of the hole arrays provides a significant additional surface area for surface recombination, reducing the average lifetime of photoexcited carriers in the detector. The hole-array samples show a dramatic improvement in the photoconductor time response, with approximately a 10× decrease in the detector impulse response time and a similar increase in the bandwidth when compared to the control, unpatterned pixels. With a hole diameter of D=480 nm and an array period of 600 nm, a ∼10× improvement in detector temporal performance is achieved, resulting in a detector bandwidth of ∼7 GHz. This drastic improvement in bandwidth is achieved with a commensurate penalty in the signal amplitude of 3×, when compared to the unpatterned pixel, primarily a result of the decrease in the absorber material fill factor.

Internal + External National Lab User: Prof. Incorvia (Univ. Texas) with Sandia National Labs

- ***Shape-Dependent Multi-Weight Magnetic Artificial Synapses for Neuromorphic Computing***

  In neuromorphic computing, artificial synapses provide a multi-weight (MW) conductance state that is set based on inputs from neurons, analogous to the brain. Herein, artificial synapses based on magnetic materials that use a magnetic tunnel junction (MTJ) and a magnetic domain wall (DW) are explored. By fabricating lithographic notches in a DW track underneath a single MTJ, 3-5 stable resistance states that can be repeatably controlled electrically using spin-orbit torque are achieved. The effect of geometry on the synapse behavior is explored, showing that a trapezoidal device has asymmetric weight updates with high controllability, while a rectangular device has higher stochasticity, but with stable resistance levels. The device data is input into neuromorphic computing simulators to show the usefulness of application-specific synaptic functions. Implementing an artificial neural network (NN) applied to streamed Fashion-MNIST data, the trapezoidal magnetic synapse can be used as a metaplastic function for efficient online learning. Implementing a convolutional NN for CIFAR-100 image recognition, the rectangular magnetic synapse achieves near-ideal inference accuracy, due to the stability of its resistance levels. This work shows MW magnetic synapses are a feasible technology for neuromorphic computing and provides design guidelines for emerging artificial synapse technologies.

<u>Education and Outreach Activities</u>

TNF initiated a technical seminar/workshop series.

1. Workshop on Advances in Etch and Materials Growth Processes at Oxford Instruments
   Craig Ward, Oxford Instruments, January 2023.
2. Workshop on Nanoindentation organized with KLA Instruments, April 2023.
   This was a two day workshop which included presentations from KLA as well as student presentations from UT. A part of the workshop included demonstrations on the iNano nanoindenter as well as data analysis. The workshop was attended by 27 students from UT and included students from Iowa State
3. Workshop on Electron Microscopy, June 2023.
   This workshop included lectures by TNF staff and UT faculty on electron microscopy techniques, data collection and data analysis. The workshop also included practical sessions on our SEMs, aberration-corrected TEM and dual beam.
4. Workshop on Surface science techniques in June 2023.
   This workshop includes lectures by TNF staff and UT faculty on surface analysis techniques. The workshop also included practical sessions on our XPS and TOFSIMS instruments as well as data analysis.

We have a year-round REU program for 5 student from Austin Community College where students are trained at the TNF MRC cleanroom. We are targeting women and URMs. The students get academic credit at ACC, and graduates are highly sought out by industry.

Societal and Ethical Implications Activities

Prof. Lee Ann Kahlor, a risk and science communication expert at the University of Texas at Austin has led the social and ethical implications (SEI) team at NNCI-TNF for the last eight years.

SEI@TNF Website

Over the past year, Kahlor has implemented several improvements to enhance the user interface and navigability of the SEI@TNF Website (http://sites.utexas.edu/nnci-sei/). First, she revised existing content on the SEI@TNF website to ensure its relevance with recent developments. She also verified that all hyperlinks embedded within the SEI@TNF website are fully operational. Second, she updated the team members' current academic appointments and contact information. Third, she incorporated the SEI team's recent research output and streamlined the formatting style across all journal publications, conference presentations, as well as student theses and dissertations. Finally, she re-organized the resources about nanotechnology implications, such that it better reflects the individual-level impacts (i.e., health) to larger-scale and collective-level impacts (i.e., societal, environmental).

Research Highlights

Determinants of Nanotechnology Knowledge Gaps

Information regarding technological developments have consistently been distributed inequitably among individuals with varying education and household income. However, individuals' information behaviors — seeking, avoidance, and processing — have also increasingly determined their knowledge acquisition. Thus, she conducted an online survey questionnaire with 408 U.S. residents to investigate how these variables predicted their factual knowledge and perceived familiarity with nanotechnology.

Individuals' education and household income failed to predict their factual knowledge and perceived familiarity with nanotechnology (upon controlling for their age, gender, and ethnicity). Compared with these socioeconomic indicators, individuals' information behaviors played a greater role in predicting their factual knowledge and perceived familiarity with nanotechnology. Notably, information behaviors were related to these knowledge dimensions differently. Notably, information behaviors also had different impacts on the gaps in factual knowledge and perceived familiarity with nanotechnology among individuals with varying socioeconomic status.

Benefit and Risk Perceptions of Sunscreens formulated with Nanoparticles

While nanotechnology researchers have increasingly examined the environmental impacts posed by sunscreens formulated with nanoparticles, extant literature has often overlooked consumers' awareness and perceptions in this regard. To address this research gap, Kahlor conducted an online survey questionnaire with 408 U.S. residents to investigate how consumers' perceived information need determined their perceived benefits and risks of sunscreens formulated with nanoparticles. We also evaluated how information behaviors — seeking, avoidance, and processing — served as underlying mechanisms that affected consumers' perceived benefits and risks.

Consumers with greater information need also perceived greater personal benefits provided by sunscreens formulated with nanoparticles. This effect also occurred indirectly through consumers' information behaviors and their perceived familiarity with the environmental impact of sunscreens formulated with nanoparticles. Meanwhile, consumers' information need affected their perceived environmental risks of sunscreens formulated with nanoparticles indirectly.

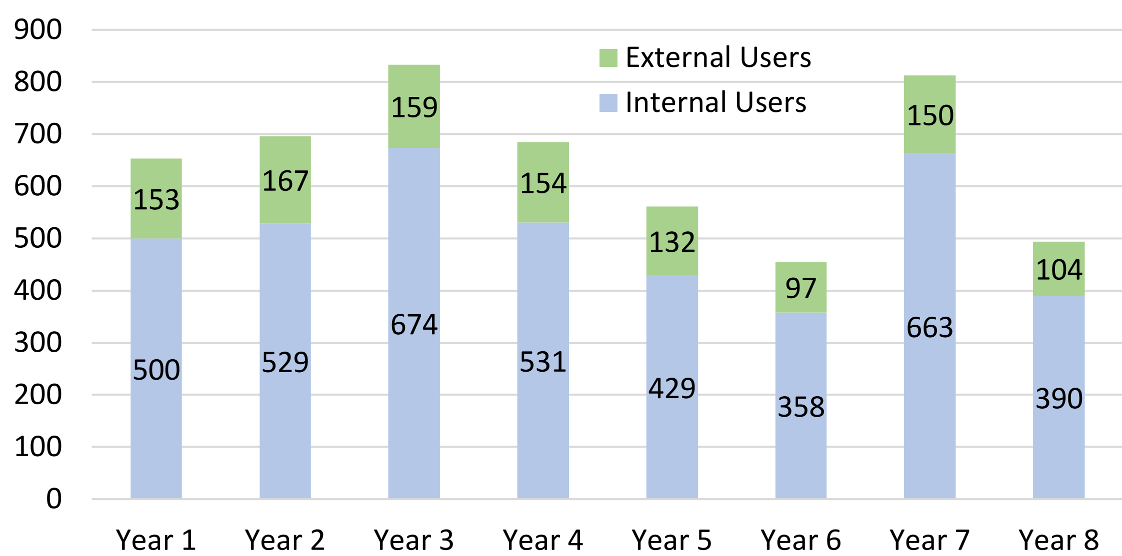
Computation Activities

Modeling and simulation efforts performed with NNCI support have focused on understanding and guiding subsequent experimental efforts planned within our NNCI facilities, and in collaboration with colleagues at sister sites to present a series of seminars on modeling and simulation of interest to the NNCI community.

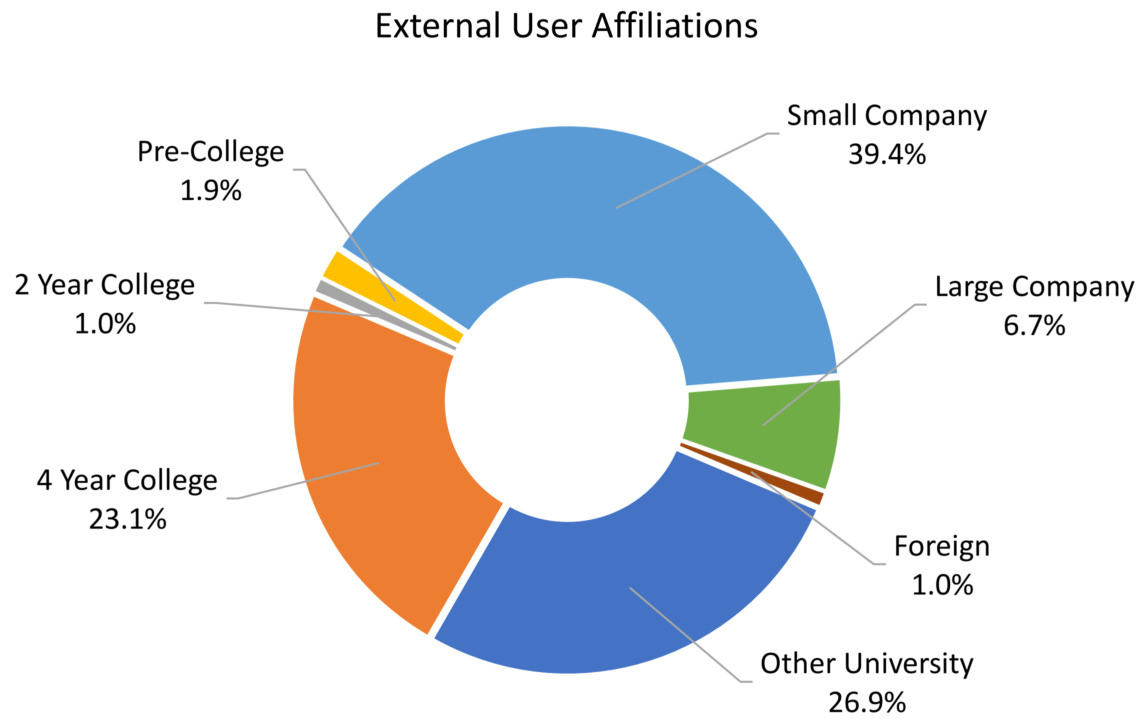
Prof. Register, who leads the Computation effort, has worked on aspects of the band alignment properties of 2D material heterostructures beyond the electron affinity rule, which results from charge redistribution in real space between the layers. Such alignments are relevant for, e.g., 2D material based optoelectronic and tunneling devices, or simply channel confinement in 2D material-based field effect transistors (FETs). Specifically, these works focus on black phosphorous (BP) to transition metal dichalcogenide (TMD) heterostructures. Perhaps most significantly, charge redistribution among the layers has been found to shift the band alignment expected away from the expectations of the Electron Affinity Rule by up to almost 1 eV for some systems, and in all cases considered, at least several tens of meV. Work has also been done on semi-classical Monte Carlo transport studies in FETs made in such 2D materials.

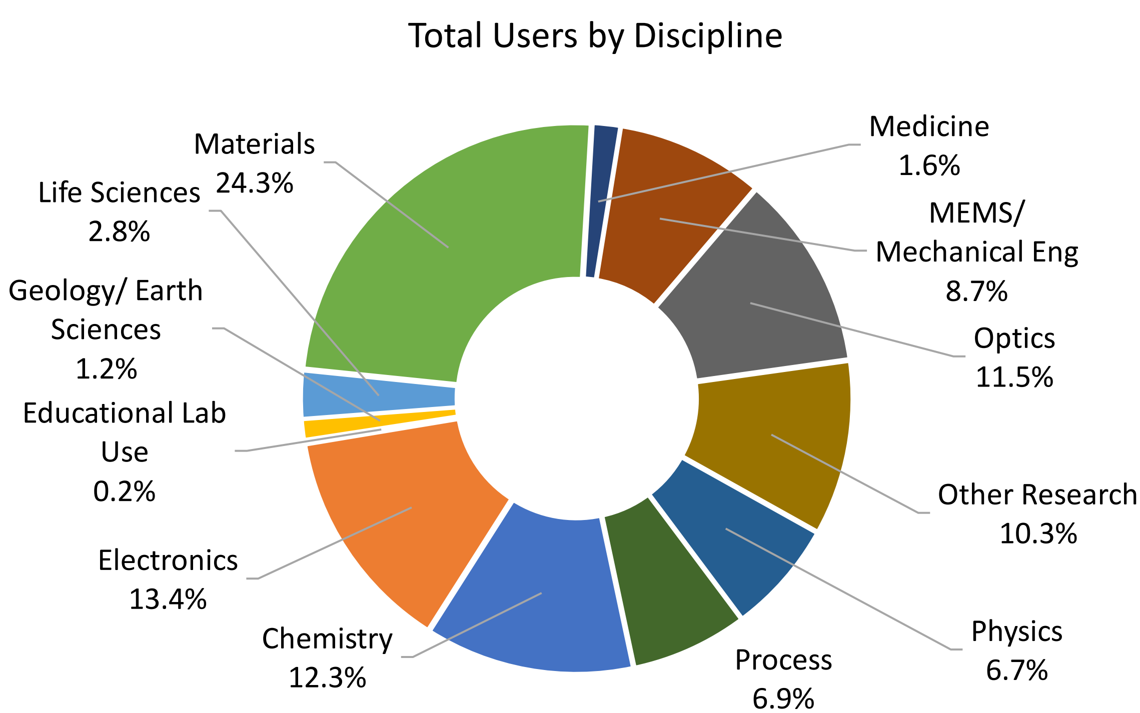
TNF Site Statistics

Yearly User Data Comparison								
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**
Total Cumulative Users	653	696	833	685	581	455	813	494
Internal Cumulative Users	500	529	674	531	429	358	663	390
External Cumulative Users	153 (23%)	167 (24%)	159 (19%)	154 (22%)	132 (24%)	97 (21%)	150 (18%)	104 (21%)
Total Hours	67,570	58,354	63,645	65,166	38,229	53,901	65,193	41,445
Internal Hours	53,484	45,952	46,464	48,254	28,263	41,159	51,438	30,537
External Hours	14,084 (21%)	12,402 (21%)	17,181 (27%)	16,912 (26%)	9,966 (26%)	12,742 (24%)	13,755 (21%)	10,908 (26%)
Average Monthly Users	244	272	287	315	216	246	337	245
Average External Monthly Users	45 (18%)	50 (19%)	59 (21%)	65 (21%)	45 (21%)	53 (22%)	66 (20%)	51 (21%)
New Users Trained	99	193	80	62	34	38	54	12
New External Users Trained	48 (48%)	45 (23%)	33 (41%)	29 (47%)	16 (47%)	10 (26%)	18 (33%)	5 (42%)
Hours/User (Internal)	107	87	69	91	66	115	78	78
Hours/User (External)	92	74	108	110	76	131	92	105



TNF Year 8 User Distribution





12.16. Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth)

As the NNCI approaches the end of performance period, NanoEarth and the NNCI have been very forward looking this reporting period. Many examples are included throughout this brief report, but a couple of highlights not included elsewhere are 1) Marc Michel represented NanoEarth at the National Infrastructure Leadership Summit at the White House's Eisenhower Executive Office on Sept. 11, 2023 and 2) Matthew Hull and Tonya Pruitt joined him to participate in the subsequent Workshop on Nanotechnology Infrastructure of the Future.

Facility, Tools, and Staff Updates

Facility & Tools: The facility acquired a Helios 5 UC Scanning Electron Microscope (SEM)/Focused Ion Beam (FIB). The PHI Quantera SXM Scanning Photoelectron Spectrometer Microprobe (XPS) and Malvern PANalytical Empyrean XRD received significant upgrades. A dedicated data analysis laboratory has been added and facility renovations have expanded space available to accommodate new tools.

Staff: NanoEarth/NNCI Associate Director for Innovation and Entrepreneurship Matthew Hull was named director of the Nanoscale Characterization and Fabrication Laboratory (NCFL), NanoEarth's primary facility. With one technical staff member joining and two departing, the facility has been reduced to three technical staff members while an on-going search looks to fill the open positions.

User Base

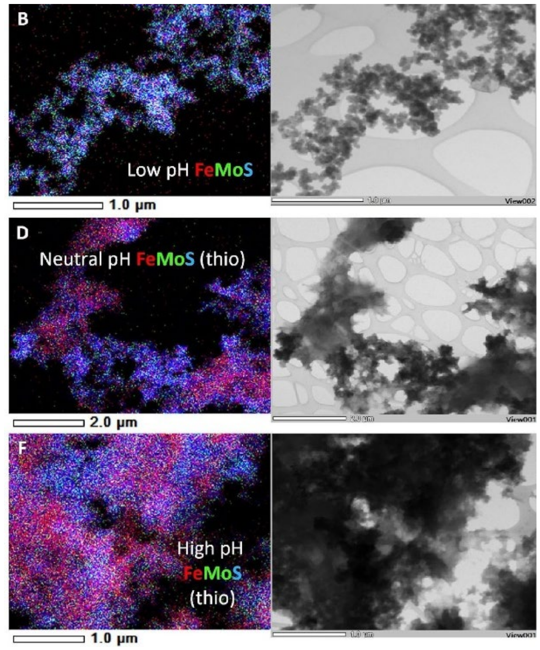
NanoEarth is designed for users in the Earth and environmental sciences and engineering fields, but many other scientists and engineers accomplish important research in related fields using our labs and instrumentation. In the case of NanoEarth, Earth and environmental science and engineering related users have included those in the fields of chemistry, mechanical engineering, civil engineering, medicine, materials, electronics, and physics.

Our Multicultural and Underserved Nanoscience Initiative (MUNI) continues to support diverse populations through research support and educational opportunities. In addition to our continued collaboration with VT's Institute for Critical Technology and Applied Science (ICTAS) Diversity and Inclusion Seed Investment program and the VT Office of Recruitment and Diversity Initiatives HBCU/MSI Research Summit, this year we began working with the VT Chapter of Minorities in Agriculture, Natural Resources, and Related Sciences (MANRRS).

Research Highlights and Impact

Discussed below are one academic and one industry highlight from this year. Additional highlights are described in the included PowerPoint slides.

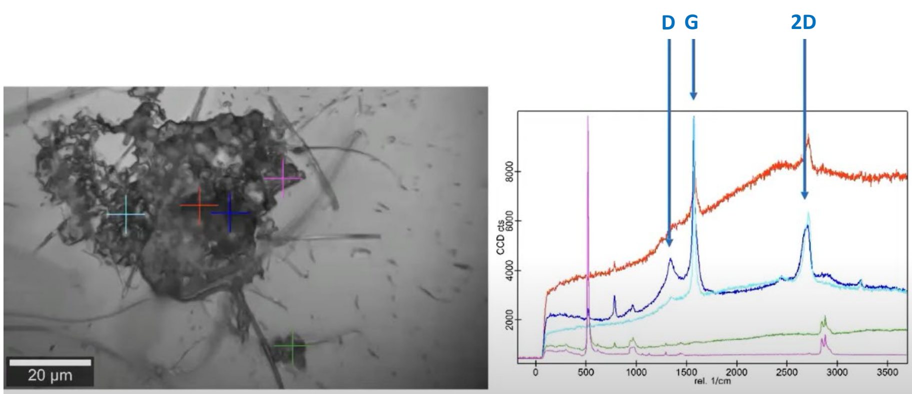
Academic Highlight – Significance of pH and iron-sulfur chemistry for molybdenum sequestration under sulfidic conditions: Molybdenum (Mo) records ancient changes in Earth's redox conditions. Mobility and reactivity of Mo are closely tied to the chemistry of reduced sulfur and iron species, but it is not clear what external conditions control formation of Fe-Mo sulfides in past environments. NanoEarth scientists are collaborating with researchers at Arizona State University and University of Texas at El Paso to characterize the (nano)mineralogy of samples containing nanosized and amorphous Fe-Mo sulfides. The findings suggest that changes in pH and Fe^{2+} concentrations may be responsible for the sulfide-independent variations in Mo behavior observed in euxinic basins.



EDS composite X-ray maps of representative MoS and FeMoS precipitates showing distribution of Fe, Mo, and S.

This work was published in: Phillips, R., Singerling, S., Leng, W., & Xu, J. (2023). Significance of pH and iron-sulfur chemistry for molybdenum sequestration under sulfidic conditions. *Chemical Geology*, 638(2023), 121702. Funding for this research was provided by DOE award DE-SC0023251, NSF/Geological Society of America (NSF/GSA) grant 13124-21, and NSF-NNCI NanoEarth awards ECCS-1542100 & ECCS 2025151.

Industry Highlight – Investigating graphene content in commercial gloves using Raman spectroscopy and scanning electron microscopy: NanoSafe Inc. is a small local start-up focused on managing emerging nanotechnology environmental health and safety (EHS) risks. The study aimed to determine if the graphene content in commercial gloves was consistent with the manufacturer's claims. The study found that Raman spectroscopy is the most effective tool for identifying the presence of graphene in gloves. We concluded that some commercial gloves did contain graphene oxides, but most of the time the manufacturer's claims were false. Carbon materials are extremely allotropic materials used in industry, however, graphene is a specific family of carbon materials. Some false claims can be made intentionally to profit from the popularity of "graphene" as an additive, and some can be made unintentionally when material provided from a supplier is a non-graphene material or when the material is ambiguous (i.e. similar but not within the accepted definition of graphene). This study suggests that a rigorous independent test is needed to ensure integrity of the "graphene-enabled" market.



Single Raman spectra reveal different carbon materials are contained in the glove sample.

The results of this research were shared via "The Graphene Council" online webinar and published on its YouTube channel. https://www.youtube.com/watch?v=Qw7vn8SjxPA.

Education and Outreach Activities

With the reduction in pandemic restrictions and the addition of Diversity and Outreach Coordinator Sylvianne Velasquez, we have ramped up our engagement, outreach, and social media activities. Not including social media engagement and *Pulse of the Planet* listenership, we interacted with over 3,100 individuals during this reporting period. A few highlights include:

- NanoEarth continued its partnership with syndicated radio producer Jim Metzner (multiple radio media major-award winner, plus multiple NSF, Grammy Foundation, and Fulbright grants recipient), who produced a NanoEarth-sponsored *Pulse of the Planet* long form podcast for our eighth year. This brings our total up to 61 NanoEarth-sponsored shows. NanoEarth's *Pulse of the Planet* episodes are built for public consumption and highlight the most interesting projects from external users, impactful research at other NNCI sites, and local site researchers, with those individuals personally interviewed for each episode. These episodes are available as podcasts on Stitcher.com, iTunes, and many other sites. The new episode featuring Dr. Michael Hochella discussing the potential use of engineered nanoparticles in ocean fertilization for large-scale atmospheric carbon dioxide removal was released in April 2023. A full list of episodes with links to each program, which credit the National Science Foundation by name, are available on the NanoEarth website.
- NanoEarth participated in the Arctic REU Greenland lead by Concord University in partnership with Montana State University. The REU is focused on developing skills in arctic geoscience research by integrating studies of bedrock geology with records of environmental change in a remote, international setting. The 4 REU students spent a week at NanoEarth analyzing their samples with our team. Students finished the REU at MSU and attended the NNCI REU Convocation.
- NanoEarth has participated in many broad scoping outreach events engaging students and the general public at science festivals, libraries, and schools. During the outreach activities, NanoEarth frequently draws on resources developed and vetted by other organizations including the NSF-funded Nanoscale Informal Science Education Network (NISE) Network NanoDays Activities (DR-0532536 and DRL0940143), Cornell University's Nanooze Magazines (CHE-1104799, ECCS-0335765, ECCS-1542081, and ECCS-2025233), and coloring sheets from MIT.nano. Events include hands-on activities for participants to explore how a material behaves on the macroscale is affected by its structure at the nanoscale including activities with ferrofluid, kinetic and magic sand, nano-fabric, heat transfer, and nitinol.
    - The impact of these outreach activities goes beyond the participants. Virginia Tech undergraduate and graduate students serve as volunteers for many of these events. Through their service, volunteers learn how to interact with the general public, convey scientific information to individuals at different levels of understanding, and explain their research at a non-academic level.
- In addition to the off-site outreach, NanoEarth also regularly hosts events at our facilities. Events including tours, workshops, talks, and demonstrations, are tailored to the level, needs, and interests of the visiting group and often include demonstrations and guided hands-on experience on our instruments including our Transmission Electron Microscope (TEM), Focused Ion Beam (FIB), Scanning Electron Microscope (SEM), and Scanning Photoelectron Spectrometer Microprobe (XPS).

- To highlight the wide breadth of individuals who use our facilities, we initiated a "Meet the User" article series in the fall of 2022. Articles focus on both the research and background of the users including the user's academic background, current research interests, personal interests, and advice they would like to share with young researchers. The articles are shared broadly through our website, X/Twitter, and LinkedIn. The series was shared during a NNCI Education Coordinators meeting and was well received by many sites who indicated an interest in starting their own version of the article series.

Societal and Ethical Implications Activities

NanoEarth participates in Societal and Ethical Implications (SEI) activities that are coordinated across the NNCI under the direction of Jamey Wetmore of the Nanotechnology Collaborative Infrastructure Southwest (NCI-SW). SEI activities initiated within NanoEarth include: 1) engagement with diverse and underrepresented groups, 2) empowerment of individuals and social change through nanotechnology entrepreneurship, and 3) earth and environmental nanoscience in the service of society.

Innovation and Entrepreneurship Activities

NanoEarth continued to operate its core innovation and entrepreneurship (I&E) programs including the industry seminar series, the NanoTechnology Entrepreneurship Challenge (NTEC), and the Entrepreneur-in-Residence (EiR) program. Additionally, NanoEarth supported multiple ongoing collaborative projects with industry partners. Following is a summary of NanoEarth I&E highlights in this reporting period:

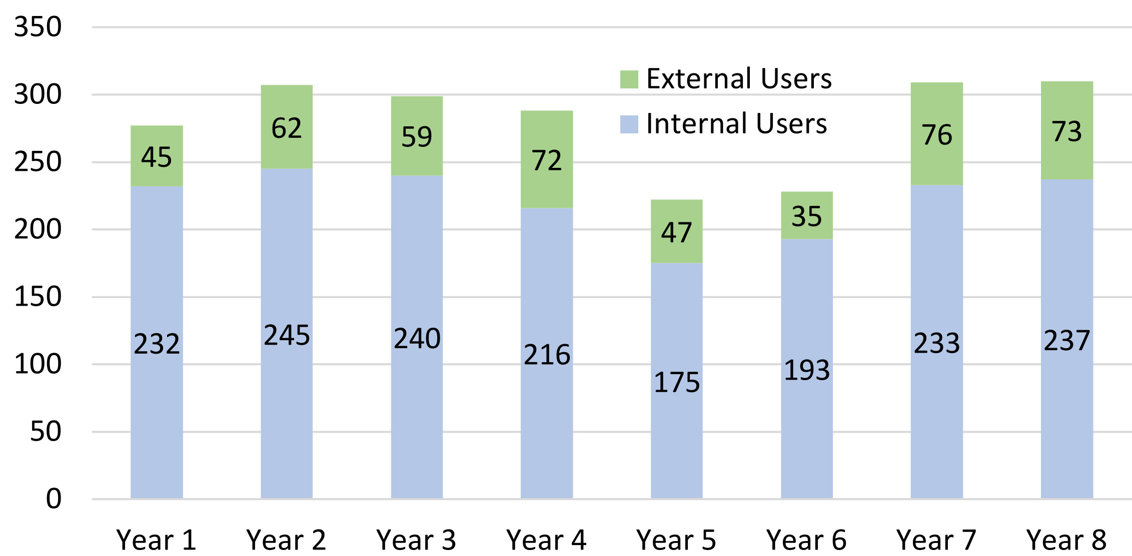
- NanoEarth hosted Darren Anderson, CEO and Co-Founder of Vive Crop Protection for a NanoEarth Industry Seminar on December 5, 2022. Dr. Anderson discussed nanotechnology in agriculture.
- M. Hull served as co-instructor for the ASU Winter School on Emerging Technologies. The title of Hull's lecture/activity was "Pain-to-Pitch 180". Hull attended the winter school and interacted with faculty and students from 1/3/2023 to 1/6/2023. Approximately 15 students participated.
- M. Michel and M. Hull served as co-instructor for a course focused on helping students in the Virginia Tech Nanoscience major secure rewarding careers in nano-enabled fields. The title of the course was "Careers in Nanoscience" and the class met weekly from 1/23/2023 to 5/3/2023. The course included 10 undergraduate students within the VT Nanoscience program.
- M. Hull served as a panelist at the Nano4EARTH event organized by the US National Nanotechnology Coordination Office (NNCO). The event included over 400 combined in-person and online attendees. As a follow-up to this event, M. Hull served as an invited speaker at a virtual RTNN event focused on identifying critical nanotechnology opportunities for addressing climate change. The title of Hull's presentation was: NNI's Nano4EARTH Kick-Off Workshop – Key Takeaways and Opportunities for the Nano Community. 40 virtual attendees participated in the follow-up RTNN event.
- M. Hull served as an invited speaker to the Federal Foresight Community of Interest (www.FFCOI.org). This audience reaches across the US Government – mostly foresight advocates in government, as well as contractors supporting the government. The title of Hull's

talk was: Dirty Nanotech: Confronting Nano-Enabled Threats in Complex Matrices. The event included 100 virtual attendees.

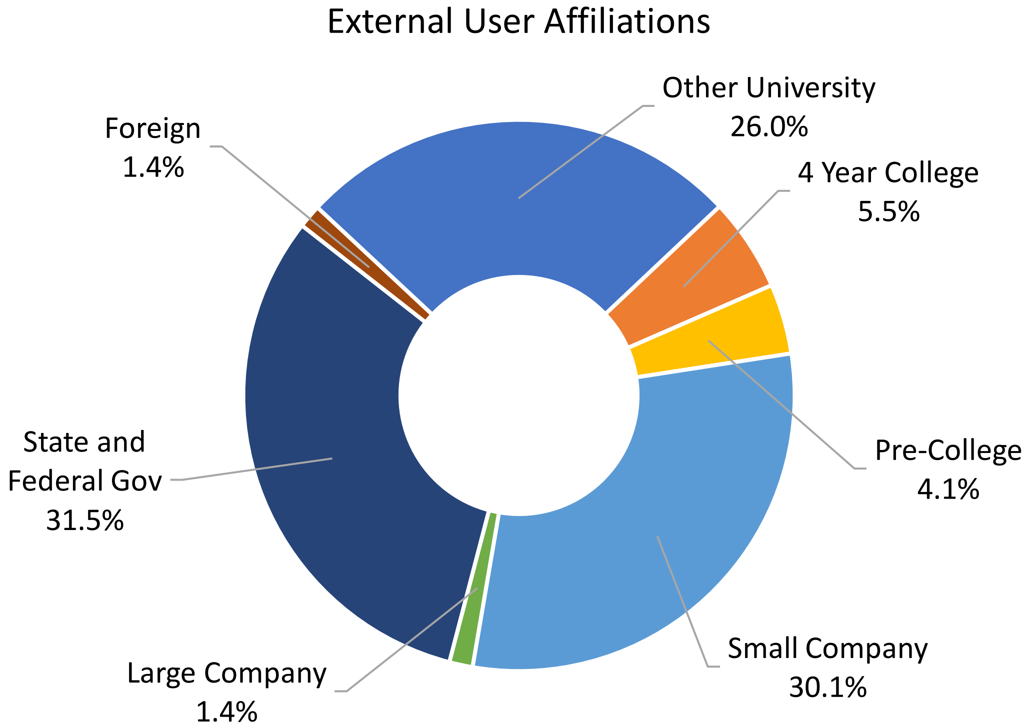
- Ongoing industry engagements included Hoover Color (Hiwassee, VA), GeoMat LLC (Columbia, SC), EAM Consulting LLC (Spring Green, WI), AcumenIST (Belgium), CSI: Create. Solve. Innovate. LLC (Blacksburg, VA), Micronic Technologies (Bristol, VA), GP Nichols & Company (Knoxville, TN), Natural Immunogenics (Sarasota, FL), and ITA International (Blacksburg, VA).
- Through his role as EiR, Dr. Hull mentored two faculty members who are considering start-ups and contributed to the mentorship of 14 entrepreneurial students via the NTEC challenge.
- The 2023 NanoTechnology Entrepreneurship Challenge (NTEC) cohort consisted of seven NanoEarth teams, a team from MANTH (UPenn), a team from SDNI (UC San Diego), and a NTEC-MUNI team from SENIC/JSNN (UNC Greensboro). Ivonne Gonzalez-Gamboa of UCSD won the top overall NTEC project and the top diversity project for her work on protein-based nanoparticles as bioengineered platforms for pesticide delivery. As winner, NanoEarth sponsored her attendance to the Student Leaders Conference at TechConnect where she served on the Nano4EARTH panel.
- M. Hull resumed his annual presentation at the Contaminants of Concern: Chemistry, Toxicity and Treatment short-course led by VT's Continuing and Professional Education program (virtual). The lecture was entitled: Engineered Nanoparticles: Contaminants of Concern or Building Blocks for a Sustainable Future – Considerations for public and environmental health professionals. There were 17 registered attendees in 2023, which included a mix of industry, academic, and government professionals.
- NanoEarth's Associate Director for Innovation and Entrepreneurship Matthew Hull continues to take what he developed at NanoEarth to establish and grow the NNCI Innovation Ecosystem in his role as Associate Director, I&E for the entire NNCI.

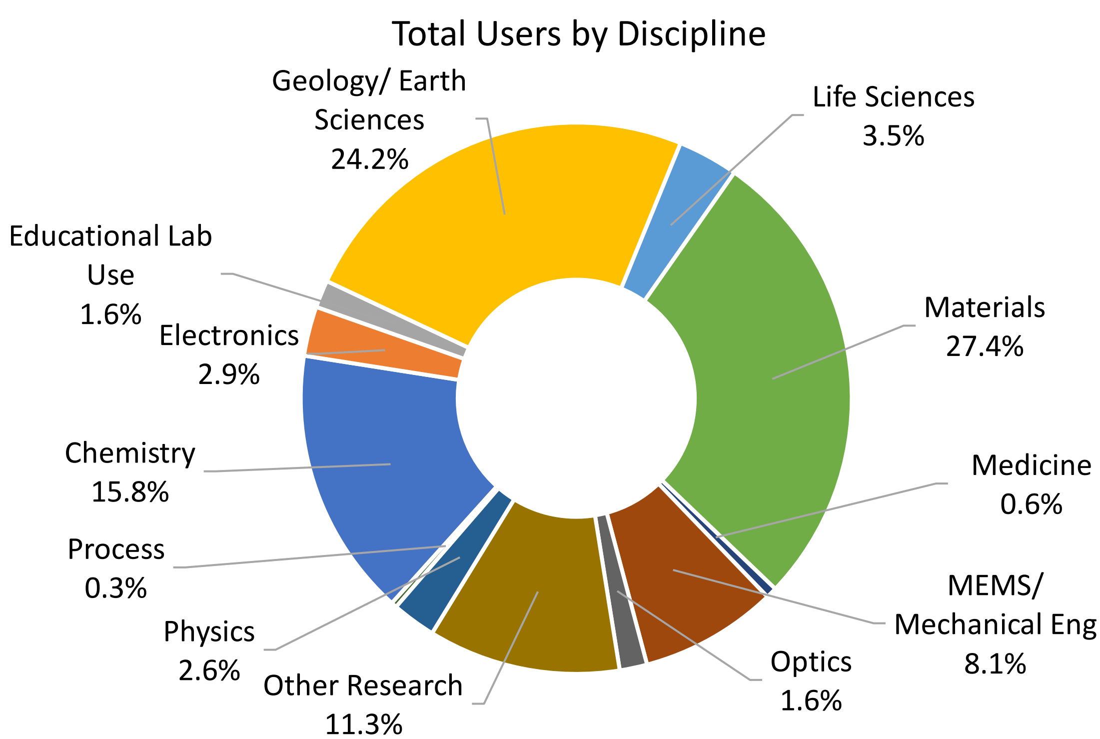
NanoEarth Site Statistics

Yearly User Data Comparison								
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**
Total Cumulative Users	277	307	299	288	222	228	309	310
Internal Cumulative Users	232	245	240	216	175	193	233	237
External Cumulative Users	45 (16%)	62 (20%)	59 (20%)	72 (25%)	47 (21%)	35 (15%)	76 (25%)	73 (24%)
Total Hours	7,627	18,056	16,455	15,291	10,710	11,706	18,736	15,884
Internal Hours	6,196	14,277	14,073	11,622	8,174	9,748	15,882	13,597
External Hours	1,431 (19%)	3,779 (21%)	2,382 (14%)	3,669 (24%)	2,536 (24%)	1,958 (17%)	2,854 (15%)	2,286 (14%)
Average Monthly Users	78	90	93	91	61	83	100	92
Average External Monthly Users	9 (12%)	14 (15%)	13 (14%)	18 (20%)	10 (16%)	13 (16%)	20 (20%)	15 (17%)
New Users Trained	277	134	94	80	49	72	123	99
New External Users Trained	45 (16%)	27 (20%)	0 (0%)	0 (0%)	0 (0%)	3 (4%)	10 (8%)	10 (10%)
Hours/User (Internal)	27	58	59	54	47	51	68	57
Hours/User (External)	32	61	40	51	54	56	38	31



NanoEarth Year 8 User Distribution





13. Program Plans for Year 9

Year 6 marked the start of the 5-year renewal of the NNCI. However, many of the programs for the Coordinating Office (see Section 2 for details) remain the same as in the first five years. The Coordinating Office will continue to: (1) promote and market the NNCI and its sites, (2) assist users in finding appropriate resources across the network and beyond, (3) coordinate site activities and share best practices across the network and beyond, (4) assist the sites wherever possible, and (5) serve as the main interface with the NSF. Thereby, the overarching goal remains to ***make the network greater than the sum of its parts*** to the benefit of our user communities.

The roles of the Coordinating Office (CO) were defined in the NSF program solicitation:

- "The Coordinating Office will be responsible for establishing a comprehensive web portal to ensure close linkage among the individual facility websites such that they present a unified face to the user community of overall capabilities, tools, and instrumentation."
- The Coordinating Office "will also work with all sites in ways to guide users regarding which site or sites, which instruments, and which processes would enable users to complete their projects most successfully."
- "The Office will help to coordinate and disseminate best practices for national-level education and outreach programs across sites, as well as the instruction and study of social and ethical implications of nanotechnology."
- The CO "will seek to harmonize capabilities for modeling and simulation in nanoscale fabrication and characterization across sites, and provide effective coordination with the NSF-supported Network for Computational Nanotechnology (NCN)."
- "The Office will work with the individual sites to establish uniform methods for assessment and quantifiable metrics of overall site performance and impact, including those for educational and outreach activities."
- The CO "will help to share best practices and laboratory safety and training procedures across all sites. It will engage all sites in a planning process to explore emerging areas of nanoscale science, engineering, and technology that can lead to future growth of the external user base."
- The CO "will coordinate the acquisition needs for specialized instrumentation across all sites to enhance new areas of research growth."
- "The Office will also coordinate data management across all sites"
- The CO will coordinate "the dissemination of shared knowledge to research, education, and technology communities"
- The CO will enhance "connections with other nationally funded academic centers or networks and facilities supported by government, the private sector, and international partners."

Starting in Year 6, the CO added a fourth Associate Director, Dr. Matt Hull from Virginia Tech, to initiate and coordinate network wide activities in the area of innovation and entrepreneurship. The other three Associate Directors of the CO will continue to coordinate activities in Education & Outreach, Societal and Ethical Implications, and Computation across the network.

In Year 9, the CO will continue to support Subcommittees and Working Groups, the NNCI website, the NNCI Annual Conference, as well as the Research Communities, which are a new network-wide effort for Years 6-10. In prioritizing its programs in view of the limited resources, the CO considers recommendations from the NSF, the NNCI Advisory Board, the NNCI Executive Committee, as well as the NNCI Subcommittees, Working Groups and Research Communities. The CO appreciates the strong support from all sites in making the network more than the sum of its parts and counts on continued site support for Year 9.

A number of specific activities planned for Year 9 are highlighted below:

- *NNCI Website*: The CO will continue to add new and revise existing content to the nnci.net webpage.
- *NNCI Annual Conference:* The 9th NNCI Annual Conference will be hosted by KY Multiscale and held at University of Louisville, October 28-30, 2024. The current plan is that this year's conference will be a hybrid event with in-person events for those who can travel accompanied by live streaming for those who cannot.
- *REU Convocation*: The Year 9 REU Convocation will be hosted by NNF and held at University of Nebraska-Lincoln, August 4-6, 2024, as an in-person event.
- *Research Communities*: The CO will continue to support the current six Research Communities: "Transform Quantum", "Understanding the Rules of Life", "Growing Convergence Research", "Nano Earth Systems", "Nano for IoT" and "Microelectronics/Semiconductors". These research communities are described more fully in Section 7.
- *Coordination with Microelectronics Commons Hubs:* All of the newly-funded Microelectronics Commons Hubs have some affiliation with an NNCI site university. At the end of 2023, the CO created a working group, led by Trevor Thornton (NCI-SW), to help establish and coordinate the relationship between NNCI and the Hubs, and this effort will continue during Year 9.
- *Staff Exchange Program*: Originally proposed by the Global & Regional Interactions Subcommittee, the CO will continue to support a staff exchange program in Year 9. While staff exchanges were not possible in Years 5 and 6 because of the pandemic-related travel restrictions, some use of this mechanism occurred in Year 8 and was described above. Funds to support this program have been included in the CO renewal budget.
- *NNCI Staff Awards:* The CO plans to continue the successful NNCI-wide staff awards program started in Year 3 to promote staff and recognize excellence in areas of user support, technical activity, and education and outreach.
- *Workshops*: The CO will continue incentivizing sites to collaborate via symposia and workshops. A budget has been established to financially support workshops that involve and benefit multiple NNCI sites (see also Subcommittees and Working Groups).
- *User Survey:* The CO will administer this survey again in summer 2024.
- *Data Collection and Reporting:* The CO will continue to collect statistical data on network usage and report these data to the NSF as part of the annual reporting. The collection of data on funding sources supporting research done at NNCI facilities was done in 2023 and will be

skipped in 2024. We will continue the collection of information on courses supported (started in Year 7) and degrees awarded to NNCI users (started in Year 6).

- *NNCI Impact:* The CO will continue to work with the Metrics and Assessment Subcommittee to define NNCI societal and economic impact metrics, collect those metrics and disseminate them as appropriate. The goal is to better showcase, using quantitative and qualitative data, the societal and economic impact of the NNCI and, thus, complement the data collected on the scientific and scholarly impact of the network.
- *NNCI National and International Connections:* As a focus effort for Years 6-10, the CO will work with NNCI sites and the Global and Regional Interactions Subcommittee to connect with other nationally-funded as well as international "nano" networks and facilities supported by government, the private sector, and international partners. The goal is to promote capabilities, improve user support, share best practices and develop strategies for future infrastructure programs.
- *Prioritization of NNCI CO Funds:* With more and more requests for financial support from the CO, the CO will review how it spends its annual budget and, together with the Executive Committee, prioritize its resources to impact the programs that help the network be more than the sum of its parts.