Report to the National Science Foundation on

The Workshop on Nanotechnology Infrastructure of the Future

Held September 12-13, 2023, at the National Academy of Sciences, in Washington DC and Online

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National Nanotechnology Coordinated Infrastructure

EXECUTIVE SUMMARY

Nanotechnology is everywhere. And, our ability to engineer and examine at the nanoscale will become more advanced over the next 10 years (and beyond). Today, we have the opportunity to harness the potential of nanoscience and nanoengineering to address the nation's most critical challenges in energy, Earth's environment, healthcare, defense, and more. In addition, the government aims to bring semiconductor jobs back to the US but we face a skilled workforce shortage. Building upon a four-decade long legacy of shared nanotechnology infrastructure support, a future national nanotechnology infrastructure can address these challenges and is a critical resource for our nation.

In response to the nearing end of the 10-year, NSF-funded National Nanotechnology Coordinated Infrastructure (NNCI) program, subject matter experts convened in Washington, D.C. to identify opportunities for a future nanotechnology infrastructure. This white paper summarizes and details the input from the participants (~200 virtual and ~80 in person) and organizing committee of "The Workshop on Nanotechnology Infrastructure of the Future." More specifically, major takeaways and future recommendations related to the identification of key nanotechnology research priorities; education and workforce development; technology translation; research ecosystem and social responsibility; and organizational structure, governance, and assessment are provided. 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 to image, fabricate, and control nanoscale systems.**
- **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.**

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1 INTRODUCTION

The National Nanotechnology Coordinated Infrastructure (NNCI), supported by the National Science Foundation (NSF), hosted "The Workshop on Nanotechnology Infrastructure of the Future"—a two-day workshop held on September 12 and 13, 2023 in Washington, D.C. The workshop was hybrid in format. There were approximately 80 in-person participants at the National Academy of Sciences (NAS) and approximately 200 participants joined virtually (via Zoom). A detailed agenda can be found at the end of this white paper.

The current NNCI program, which ends in 2025, is the latest in a four-decade long legacy of NSF-supported user facilities for nanotechnology research. To make recommendations for the next iteration of this national resource, NNCI and NSF sought input from hundreds of researchers, educators, government officials, industry leaders, site users, and other partners, seeking a clearer understanding of the nanotechnology community needs and priorities over the next ten years. This critical input was used to develop this white paper that will inform and make recommendations about the direction of a future network and align its priorities in service of advancing existing and emerging technologies, including domestic semiconductor research and manufacturing, through 2035 and beyond.

At the workshop, which held three sessions each day, participants heard from keynote speakers and distinguished panelists, as well as participated in question and answer sessions. In addition, brainstorming activities via a digital collaboration tool (XLeap) were held. Professional facilitators (Nexight Group) and workshop organizers guided both in-person and virtual participants in discussing focus questions related to the session talks. Both in-person and virtual participants populated the digital collaboration tool (XLeap) with their answers, inputs, and responses to specific prompts.

The result of the workshop activities was a robust dialog related to five nanotechnology infrastructure focus areas that the NNCI identified as critical to this ecosystem prior to the workshop:

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

A high-level, cross-cutting summary of the participant and workshop committee recommendations as related to the five critical nanotechnology infrastructure focus areas are outlined below.

- **Advance the frontiers of research for the nation by providing the necessary tools, facilities, expertise, and collaborative spaces to image, fabricate, and control nanoscale systems.** Our ability to visualize and manipulate the behavior of systems is progressing to smaller sizes. We can harness this ability to better understand our environment, engineer advanced materials, and uncover new phenomena. This can lead to major breakthroughs in energy, medicine, climate, space exploration, and more.
- **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.** Such partnerships would broaden opportunities for a diverse pool of future researchers and technicians, expose students in other disciplines to the uses of nanotechnology in their field, and give the research infrastructure community a better understanding of the skills needed for a future workforce. Industry would also be able to help guide the training and education programs developed to ensure that the recent graduates join the workforce with skills that the industry needs.
- **Partner radically with industry, government agencies, and related academic disciplines to maximize the impact of our nanotechnology infrastructure on the US technology ecosystem.** Strong collaborations with industry and government agencies (e.g., NSF TIP) can help accelerate the translation of nano-enabled technologies for societal, economic, and national security benefits. Such partnerships are also essential for realizing effective and scalable workforce development programs. In addition to industry partnerships for workforce development, government agencies can provide additional research opportunities and successful programs to emulate. Access to nanotechnology facilities is especially critical for startups and academics outside R1 universities. Disciplines outside the traditional areas in nanotechnology (electronics, MEMS, materials) will both benefit from specialized tools and expertise and will be able to contribute to a wide range of applications.
- **Be intentional about increasing access across geographical regions and social barriers with a focus on rural communities, underrepresented individuals, and women.** Broad geographic access and a high diversity of participating institutions are important to advance the field. There are realistic constraints on site location and how many can be funded, but there are still opportunities for broadening access within those constraints. Partnering with organizations that work toward equitable access to science and engineering resources and opportunities will allow the network to better understand and address the barriers that underrepresented communities and women face. Partnerships with ethicists, social scientists, and STEM professors at liberal arts schools can help inform the development of consistent ethics and social responsibility standards of practice.

- **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.** Each site has specific strengths (e.g., technology domains, regional advantages, established programs) that should be harnessed for the benefit of advancement and the nation. For common practices, develop recommended resources that can be shared among sites, and develop guides on best sharing practices to enable sites to independently collaborate with each other. A balance between coordination and autonomy is ideal to spark and maintain growth.

These themes and more were considered and discussed as participants reflected on the event's speakers and focus questions. Key observations in each of these critical focus areas based on the participants' verbal discussions and digital inputs (via XLeap), along with specific recommendations, are outlined and described in the sections below.

1.1 Strong Nanotechnology Infrastructure Is Essential to the Nation's Future

Nanotechnology (defined as technology with feature sizes of 100 x 10^{-9} meters and below) is the key to a broad range of scientific fields, including materials science (crystal growth), geology (imaging interior of rocks), biology (cells and proteins), chemistry (synthesis of new materials), and many others. The application space for nanotechnology is even broader, with applications in microelectronics, geosciences, nanomedicine, energy production, transportation, to name a few. Nearly all of these fields continue to advance nanotechnology to even smaller dimensions, and with more complex materials and structures utilized. Hence, it is of national importance to stay at the forefront via investments in nanotechnology infrastructure across the nation.

Nanotechnology also represents a strategic national security priority for the United States. For instance, advanced microelectronics, which relies heavily on nanotechnology, has been designed as a key national priority for the US, since a large portion of the national defense and commercial infrastructure rely upon microchips. Solving some of the world's most pressing crises, such as climate change, ecosystem diversification, and freshwater availability, all rely upon nano-scale science and engineering. Therefore, having a physical infrastructure to support research in these fields is critical.

One of the key aspects of nanotechnology research that is important to understand is that it is **capital intensive**, which generally means that the infrastructure is **expensive**. It is well documented that a commercial extreme ultraviolet (EUV) lithography system is > US$100 million, and while such equipment is generally not used in R&D, an electron beam lithography system for research purposes that can achieve comparable dimensions can often cost as much as US$5 million. In general, the start-up costs of a good university cleanroom are around US$30 million, with the cost rising quickly due to supply chain disruptions. Many advanced research experiments require such equipment and cannot be performed without it. For this reason, **resource sharing in R&D, particularly at the university level and for start-up companies is not only preferred, but essential.**

Nanotechnology infrastructure has benefits in other ways as well. Through its support of cutting-edge basic and developmental research, it acts as one of the nation's most important resources for training the next generation of skilled engineers, scientists and technicians. Through NNCI, training has reached ~5000 new researchers every year. This training is greatly enhanced by the sharing of physical infrastructure (tools and equipment), as well as the knowledge that goes along with use of this equipment. The workforce development provided by a shared infrastructure spans all levels from M.S. and Ph.D. students working on advanced projects, to K-12 students. In fact, many K-12 students get their first introduction to the nano-scale through programs provided by, or in coordination with, the national nanotechnology infrastructure network. Such early introductions are critical to excite and engage the youth across the nations at an early stage, before they are swept into different fields before even having the chance to consider nanoscience and engineering as a career option. The shared infrastructure is also critical for reaching out to a diverse range of communities that have historically been left behind and would otherwise not gain exposure to these emerging technology fields.

1.2 The Power of the Network Model

One of the great successes of the NSF's investment in nanotechnology infrastructure over the past several decades has been the network model. A network model for infrastructure provides funding support to a group of separate facilities, whose use of those funds is coordinated in some way. This high-level coordination has several advantages.

Most importantly, the network model accelerates access to nanotechnology resources geographically across the nation. This is enhanced by a common access model that the network structure provides. For instance, in the current NNCI, all funded facilities must be open to any qualified academic, industry, or government user, subject to usage rules and regulations.

The network model not only enables sharing of physical infrastructure (e.g., tools and equipment), but also knowledge. Once again, in the current NNCI, such sharing occurs through the numerous interactions, both online and in person, of the center directors, staff members, and users. Process recipes are exchanged and best practices for equipment maintenance and upkeep are shared within the network. The combination of improved access and knowledge sharing has the net effect to accelerate innovation within the research community, leading to an enhancement in US competitiveness in nanotechnology.

A networked nanotechnology infrastructure provides additional benefits to enhance innovation—it builds a cohesive community or ecosystem that feels a sense of shared ownership in the overall mission of the network. We learn from each other's successes and failures. Successes can be quickly amplified and replicated across the nation. A network also helps to make connections between unexpected partners: researchers who otherwise would not have crossed paths, creating radical collaborations that can lead to unexpected new outcomes. Such a community is inherently multi-disciplinary, allowing the different "pieces of the puzzle" of a difficult engineering problem to be assembled together. Such a network can also be empowered to look at larger societal issues of a problem, such as sustainability and climate impacts, problems often overlooked or de-emphasized in individual institutional facilities. Finally, a network has more "bargaining" power than individual sites, and can be represented advantageously in multiple venues.

In summary, the benefit of the network model is that it truly builds the technology of tomorrow with a sense of shared ownership in the future outcome. The community that is created through such a structure helps to define what may emerge a decade later, and how big problems and challenges can be tackled. In addition, the network is a test bed for the industrial-scale facilities that will emerge from a diverse range of facilities with different strengths and geographic areas sparking new forward-thinking technology and manufacturing approaches.

1.3 Statement of Purpose

Why a network of nanotechnology infrastructure now? Nanotechnology is everywhere and we have yet to harness its full potential to solve the nation's greatest challenges in energy, Earth's environment, healthcare, defense, sensing, communication, computation, and more. In addition, the government aims to bring semiconductor jobs back to the US, but we are faced with a skilled workforce shortage.[1] The skilled, high-tech workforce of the future needs academic environments that enable experiential learning and exposure to cutting-edge research. In response to this need, technology hubs and institutes (e.g., Microelectronics Commons, Manufacturing USA) have been supported by the government to create new pathways to commercialization, as well as for workforce development. These hubs are complementary to the NSF-supported nanotechnology infrastructure; both are key parts of the US technology ecosystem that will accelerate technology transfer for US competitiveness. Continued support of national nanotechnology infrastructure in universities will catalyze and enhance these efforts.

It is critical that we capitalize on the decades of work that the current nanotechnology infrastructure ecosystem has built—this is a juncture in US history that calls for greater support of shared facilities. For example, established education, outreach, and workforce programs can

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[1] https://www2.deloitte.com/us/en/pages/technology/articles/global-semiconductor-talent-shortage.html

be expanded upon to reach more learners to address the skilled workforce shortage; start-ups will continue to have access to unique prototyping facilities; the industrial sector will use our infrastructure as pilot-scale testbeds for emerging manufacturing processes; and major research breakthroughs will be made.

The major takeaways and recommendations from the workshop participants are outlined in detail in the sections below. The following sections are organized by the five critical areas that were identified prior to the workshop—(1) key research priorities; (2) education and workforce development; (3) technology translation; (4) research ecosystem and social responsibility; and (5) organizational structure, governance, and assessment. Again, the aim of this white paper is to identify opportunities and, potentially, a broader mission for a continued NSF-funded national nanotechnology infrastructure. To quote one participant from the workshop,

"*It could be more efficient to market a coalition of user facilities nationally than to have every university develop their own nationwide strategy*."

2 KEY RESEARCH PRIORITIES

2.1 Introduction to Key Research Priorities

National nanotechnology infrastructure enables research that is addressing our most critical national priorities. As nanoscience and nanotechnology continue to penetrate diverse disciplines and become established as essential research tools, our facilities will evolve to support new research needs. That evolution will be driven by a combination of technology "push" by facilities and application "pull" from users with unique requirements. For example, as facilities upgrade both capability and capacity for emerging fabrication and characterization techniques, the availability and accessibility of those methods to diverse groups of researchers will stimulate new approaches to solving important problems. Also, many of our facilities add specialized capabilities in response to specific user needs, often partnering with users to write proposals for new equipment, and then taking on the responsibility for maintaining and training new users on that equipment and making it accessible to all. This user "pull" can lead to localized specialization at supported sites. A well-functioning network can then communicate and facilitate broader awareness and access to those specialized capabilities. A future nanotechnology infrastructure program can continue to foster this fertile research ecosystem, to maximize the impact of our evolving national shared-use nanotechnology capacity to help address our most pressing research questions.

2.2 How the NNCI has Previously Addressed Research Priorities

Infrastructure users are independently funded by many federal agencies (e.g., NSF, DoD, DoE, NIH, NASA). As such, their research will align with agency priorities, which in turn align with articulated national research priorities. The NNCI and prior infrastructure programs clearly understood the importance of availability and access to nanofabrication and nanocharacterization capacity in order for our nation's researchers to accomplish their goals. Nanotechnology has become a key component in many fields across the disciplines addressing research questions critical to national priorities. Nevertheless, these prior programs, NNCI included, have not had an explicit mechanism to drive new nanotechnology capability or capacity to meet a specific national research priority. Rather, these networks offered access to comprehensive nanotechnology facilities, upgrading those facilities primarily according to user demand (number of users or number of hours), without clearly linking those decisions to user research goals.

There may be mechanisms to make the linkage between infrastructure and research priorities more explicit. One way that the current NNCI infrastructure program has evolved since it was conceived is the creation of several "research communities" of users and facility personnel, as well as non-user researchers, that are organized around priority research themes rather than technological capability. Member sites in a particular research community have "users" who are applying nanotechnology to advance research in that topical area. Participating sites in the current NNCI have self-organized into these communities, according to the makeup of their users and local specialization of both equipment and staff to support those needs. Starting in 2020, research communities were organized around "Understanding the Rules of Life," "Transform Quantum," "Nanoscience in the Earth and Environmental Sciences," "Nanoscience Convergence," and "Nano-enabled Internet of Things." Recently another community organized itself around "Microelectronics/Semiconductors" to reflect the re-emergence of microelectronics as a national research priority. Through technology-focused meetings and workshops these research communities are both informing researchers about methods and capabilities offered in our facilities and listening to users about what the next needs will be in order to advance the field. This is an example of one mechanism that a new infrastructure program might employ to promote a stronger linkage between broadly used core nanotechnology facilities and specific national research priorities.

2.3 Workshop Takeaways on Research Priorities

Based on participant feedback from our two-day workshop that broadly solicited input on the nanotechnology infrastructure of the future, we derived the following takeaways that reflect recurring themes and important perspectives.

- **Broaden the scope of network research to include emerging fields where nanotechnology could be applied.** Broaden the applications of nanotechnology tools to manipulate and examine small systems over a broader range of fields such as bioengineering, molecular biology, geosciences, and earth and environmental sciences, as well as materials science, electronics, and photonics. Many grand challenges facing humanity are nano-related: climate change, energy issues, water and food security, geohazards, critical minerals, pathways of toxins and pathogens that impact human health, and much more. The future nanotechnology infrastructure should be more inclusive of all STEM disciplines that are positioned to contribute.
- **Establish collaborations between sites within the nanotechnology infrastructure and large-scale user facilities supported by the NSF, the DOE Office of Science, and other agencies.** University-based nanotechnology fabrication and characterization facilities play a distinct role that is complementary to specialized large-scale facilities (e.g., the Laser interferometer Gravitational-wave Observatory, the National High Magnetic Field Laboratory, the Advanced Photon Source, the Molecular Foundry). Specifically, the NSF nanotechnology infrastructure sites (i) offer a low barrier to entry with broad geographic reach; (ii) allow independent research by users including industrial users (with IP accruing to those users which promotes technology transfer); and (iii) are typically

co-located with universities allowing engagement with workforce development efforts that are also critical to a future infrastructure program. Strong collaborations between NSF infrastructure sites with these other specialized facilities will promote and enable impactful cross-cutting nanoscale research.

- **Nanotechnology infrastructure is essential for quantum science and engineering and other emerging national research priorities.** Nanotechnology provides the tools needed to make and characterize nanoscale systems. It is now a foundation for many technologies and areas of scientific research that are CURRENTLY emerging, including quantum information science, 2D materials, nanomedicine, neuroscience, precision agriculture, smart textiles, and biomedical devices. And, it remains central to the semiconductor industry. Researchers in all of these fields rely on the infrastructure for fabrication and characterization at the nanoscale. Quantum research studies quantum states, and nanoscale structures are required to observe quantum states.

2.4 Recommendations for Research Priorities

Based on the takeaways from our comprehensive two-day workshop and the experience gained as an NNCI network, we make the following recommendations to ensure that our national nanotechnology infrastructure keeps pace with and evolves to enable the acceleration of research on national priorities.

- **A national nanotechnology infrastructure should facilitate a broad scope of research, including national research priority areas where nanotechnology can be applied to accelerate progress.** Nanotechnology tools can be used to create, manipulate, visualize, and characterize in a broad range of fields such as Bioengineering, Molecular Biology, Biochemistry, Geosciences, Earth and Environmental Sciences in addition to Materials Science, Electronics, and Photonics. Many grand challenges[2,3] facing our world will implement nanotechnology as critical parts of their solutions: climate change, energy issues, water and food security, geohazards, critical minerals, pathways of toxins and pathogens that impact human health, and much more. Future nanotechnology infrastructure should be inclusive of all STEM disciplines that are positioned to contribute and to benefit. Participating sites should be aware of their current users' research and the site capabilities that can enhance research advancing national and global priorities. They should articulate a plan to grow user engagement to help inform decisions about new tools or methods that will address the needs of future researchers applying nanotechnology to address our most important questions.
- **Nanotechnology infrastructure should provide broad access to the tools needed to create and characterize nanoscale systems.** Nanotechnology is foundational to current and emerging national priorities, and rapid progress in those priority areas depends on

[2] NAE. 2017. NAE Grand Challenges for Engineering

[3] NSF. 10 Big Ideas. https://www.nsf.gov/news/special_reports/big_ideas

nation-wide access to nanotechnology infrastructure that is flexible and provides a high level of training and support. Nanotechnology tools are essential for many technologies and areas of scientific research including quantum information science, 2D materials, nanomedicine, neuroscience, precision agriculture, smart textiles, and biomedical devices. It remains central to the semiconductor industry. Researchers in all of these fields rely on the infrastructure for fabrication and characterization at the nanoscale. It is imperative that US researchers retain broad access to both basic and specialized nanofabrication and nanocharacterization capacity in order to accelerate progress in these fields.

- **A nationally coordinated infrastructure program of university sites can and should cooperate with other specialized large-scale user facilities supported by the NSF, the DOE Office of Science, and other agencies.** The National Nanotechnology Coordination Office (NNCO) has recently initiated conversations among many of the national nanotechnology infrastructure groups (e.g., DOE-funded Nanoscale Science Research Centers (NSRCs), light source facilities, National Institute of Standards and Technology). Those relationships should expand opportunities for users without duplicating efforts and should be encouraged in a future program. An open-access, flexible national nanotechnology infrastructure with a high level of user training has a key role to play in the ecosystem with other large-scale user facilities to advance research, education, and workforce development.

3 EDUCATION, OUTREACH & WORKFORCE DEVELOPMENT

3.1 Introduction to Education, Outreach, & Workforce Development

Over the past 40 years, NSF has provided support for a network of facilities where education, training, experimentation, innovation, and outreach have been at the forefront. As advancements in nanotechnology are made, new skills and expertise are needed to keep up with new technology and maintain a robust and well-trained workforce. A future nanotechnology infrastructure network would play a crucial role in how nanotechnology is taught and experienced at the K–12 through the university level, potentially creating a pipeline to careers in nanotechnology and other STEM fields across the nation. A future national nanotechnology infrastructure will also play a crucial role in training the new nanotechnology workforce. By partnering with educators and industry members, we can better assess the resources and strategies needed to develop and grow a domestic nanotechnology workforce.

3.2 Previous Education, Outreach, & Workforce Development Activities

During the tenure of the NNCI, a particular strength of the education, outreach, and workforce development program has been the diversity of the programs offered by the various sites. The original program solicitation did not specify what activities should be included in an EWD program. Due to this, no two sites had an education and outreach profile that was identical with each other. The programs offered by the NNCI sites covered from “K to gray,” allowing the NNCI to address current and projected workforce shortages. For K-12, the NNCI sites offered significant educational experience for students in nanotechnology that complemented or was in addition to traditional educational experiences. These experiences were offered in a variety of delivery models, including: NNCI educators going into the classrooms, some with hands-on activities (for example, with a portable SEM), engaging students in hands-on activities at a specific NNCI site, and presenting material virtually, allowing sites to increase the footprint of their outreach programs. Student training was not the only avenue used for K-12 education. Teacher professional development was also a key component of many sites’ educational programs. One significant teacher development program of the NNCI was the Nanoscience Summer Institute for Middle School Teachers (NanoSIMST). This program was originally developed at the nano@stanford site and has been adopted by numerous NNCI sites. The program has been presented both in-person and through virtual programs. The virtual version of NanoSIMST is supported by eight NNCI sites. In 2023, the program reached 24 teachers from 11 different states, with 70% coming from Title I schools. The NNCI also hosts multiple RET programs across the network with the main collaborative effort being the RET Across the NNCI programs hosted by four NNCI sites. This program is for high school and community college teachers. Each site can sponsor up to five teachers, with a total of 20 teachers hosted in 2023. Virtual education was particularly significant during the pandemic, and the free online Coursera course, "Nanotechnology: A Maker's Course," logged over 60,000 active learners. Undergraduate education has also been a point of emphasis within the NNCI. Twelve of 16 sites participate in the NSF-funded Research Experience for Undergraduates (REU) program. Through this program, students are given the opportunity to spend 10 weeks working on a research project with a faculty member at the host institution. At the conclusion of the research period, all sites come together for a joint convocation at one of the host sites. One site targets incoming freshmen (or first-year students) that are in a high-risk group for failing at college. Using admissions data, these students are identified and offered a spot in a nano-based program designed to keep these students in college. The program has seen a 98% retention rate. Several sites also have robust internship programs for college students. Two sites have large programs focused on undergraduate students at two-year colleges, while a third site has a robust internship program focused on four-year college students. These internship programs provide students with access to and experience in a nanotechnology facility that they would normally not have access to. Several sites offer short courses, so individuals can learn about various topics in nanotechnology. Students can experience hands-on instruction in areas such as microelectronics fabrication, characterization, and microfluidics devices. Most sites are participating in STEM-related activities offered to the general public. Work has been done with organizations such as the girl and boy scouts, the Atlanta Science Festival, 4-H (America's largest youth development organization), and the Boys and Girls Club of America. Several sites have also held workshops at local libraries and museums with hands-on activities to engage the public in nanotechnology activities.

3.3 Workshop Takeaways on Education, Outreach, & Workforce Development

During the workshop several themes were repeated regarding education and workforce development in a future nanotechnology infrastructure program. Below are the key takeaways from the discussion that occurred in-person and online during the workshop.

- Traditionally, universities are focused on training students to obtain B.S., M.S., and Ph.D. degrees in many subject areas. To succeed in attracting and retaining talent for the future workforce needs in everything "nano" that intersects numerous disciplines we must:

  - **Engage with communities and with younger students and better explain to them what it is that nanotechnology enables.** An excellent way to achieve this is to offer teachers short courses that can give them the basic tools and materials to transfer what they learn to their students. Presentations to students highlighting the benefits of nanotechnology and the prospects of the job market will also be useful.
  - **Engage with community colleges and veteran's offices to offer experiential learning and upskilling opportunities.** Partnerships with these entities will be essential to a new network, especially community colleges.
  - **For university students, collaborate with industry so that they can provide industrial mentors to interact with students so that they understand what it is that a job in the nanotechnology sector is all about.** It is important to try to engage with and excite students who are currently not in the pipeline.
  - **A "Talk with an engineer/scientist/technician" program** would be very helpful and could be tailored to the appropriate audience.
- **Close networking with industrial partners** is key in understanding industry needs and thus better preparing the future workforce. There needs to be a unified industrial checklist for workforce needs.
- **Experiential learning should take advantage of augmented and virtual reality (AR/VR) in any way possible to enable a range of access and potentially enhance training**. All technology available must be leveraged in order to bring the lab to the public.
- **Together with industry partners, develop ways that engage, excite, and educate the general public and the potential future students** about nanotechnology and its far reach into so many fields. Reaching to underrepresented groups must be a priority since there is so much untapped talent.
- Ensure that in everything we do, we **keep diversity, equity, inclusion, accessibility and belonging (DEIAB) in focus.**
- **Work on ways to present material to the general public**. Make sure this information is digestible and engaging. It is important to create a recognizable identity with regards to nanotechnology.
- **Enable access to additional workforce & outreach funding** via program enhancements (e.g., NSF REU) and emerging industrial workforce programs. An infrastructure network can help bridge potential programs with infrastructure.

3.4 Recommendations for Education, Outreach, & Workforce Development

Overall, we recommend providing different options for sites to choose that are appropriate for their specific site. The recommendations are outlined below.

- **Collaborate with educators, industry, and academia** to define needs, skills, degrees, certificates and career paths.
  - Through this collaboration, support pertinent hands-on training and include new teaching methods to attract and keep students interested in pursuing STEM careers.
  - Develop a workforce development curriculum that is created in **partnership with industrial partners**.
- **Collaborate with community colleges, veteran-focused outreach groups, and K-12 teachers** to provide them with pathways for potential students that lead to careers in "nano."
- **Support and offer REU and RET programs** tailored to expose as many students as possible to nanotechnology, both at the University but also at the K-12 levels through teachers. These programs should be funded through the future nanotechnology infrastructure grant for sites that want to have them.
- **Encourage participating sites to have a community\technical college partner (e.g., regional)** or some equivalent on the proposal to be part of the workforce development effort. These institutions should be full partners and are critical to developing a workforce training plan.
- **An optional activity for the sites could be a two-year college/ 4-year college (non R1) paid internship program.** This would be funded through the grant and would provide hands-on experience and training for students in fabrication techniques and equipment maintenance. This can easily be facilitated with the technical/community college partner and can potentially be part of a larger **certificate program**.
- **Emphasize engagement of women and underrepresented individuals.** To create the workforce of the future, all individuals must feel that they have opportunities and that they belong. This has not been the case historically, and the engagement of women and underrepresented individuals must be intentional at every site.

4 TECHNOLOGY TRANSLATION

4.1 Introduction to Technology Translation

Technology translation is essential to realize the societal benefits and economic impacts of nano-enabled innovations across many domains that include not only semiconductors and microelectronics, but also medicine and the life sciences, agriculture, energy storage, carbon sequestration, and many others. NNCI plays a critical role in technology translation through its support of companies, particularly small businesses, which comprise up to half of the external users at a majority of NNCI sites. Despite NNCI's success supporting technology translation, the requisite staffing, resources, and associated best practices have generally not been incorporated into the core functions of NSF-funded nanotechnology networks. Participants at the NNCI Futures Workshop appreciated the critical role that NNCI facilities already play in supporting technology translation but indicated that a future network could do more to support translation, especially for startups, small businesses, and faculty, staff, and students seeking to positively impact society through their nano-enabled innovations. A national nanotechnology infrastructure network's organizational structure and its relationships should allow it to serve as a bridge between academia and industry, regional and national innovation hubs, flexible R&D spaces, and pilot-scale manufacturing facilities. Further, a national network helps lower access barriers and catalyze nanotechnology translation across diverse and geographically distributed innovation ecosystems.

4.2 Previous Technology Translation Activities

NNCI provides robust support for technology translation as evidenced by industry usage , particularly small businesses. User data show that 562 small companies and 189 large companies used NNCI facilities in 2022-2023 and represented more than 55% of external users (Figure 1). On a cumulative basis, small businesses comprise one-third to one-half of annual external users across all NNCI sites (Figure 2). In response to strong usage by entrepreneurs and more established companies, NNCI has adapted (in years 6-10) to develop and implement programs focused on supporting technology translation and fostering a diverse and inclusive NNCI-wide innovation ecosystem. To date, 18 student- or post-doc-led teams from six NNCI sites have participated in the NNCI Nanotechnology Entrepreneurship Challenge (NTEC), a seven-week pre-I-Corps™ Virtual Accelerator program for training nano-savvy entrepreneurs. NNCI I&E seminars have included talks on topics ranging from "Lab to Fab", "Lab to Market" and "What Investors are Looking for in Early Stage Start-Up Companies" to translational fellowship programs like Activate. The NNCI Research and Entrepreneurship Experience for Undergraduates (REEUs) entered its third year and includes REEU seminars available for participation across all NNCI sites. The program has reached 98 students across eight NNCI sites who regularly participate in REEU activities including, SDNI, MANTH, NNF, KY Multiscale, NCI Southwest, and SENIC. In January 2023, a new "Pain to Pitch 180™" experience was developed and introduced 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. NNCI sites continue to lead critical I&E activities like CNF's NNN Symposium (hosted at Cornell on May 19, 2022 and at the University at Albany SUNY on April 25, 2023), SENIC's NanoFANS Forum (hosted bi-annually at Georgia Tech), and NNF's Commercializing Quantum Technologies event (hosted at the University of Nebraska on April 14, 2022). The NNCI Nano + Additive Manufacturing Summit hosted annually by KY Multiscale remains a key forum for discussing technology translation in the context of nanotechnology's convergence with additive manufacturing. Since small companies are often the path to technology transfer, particular emphasis has been placed on enabling small company access to sites, through such programs as the RTNN Kickstarter program, which awards $1000 of free use to companies and non-R1 users, of which many have returned with funding acquired through the preliminary results obtained through free use. Other NNCI sites offer similar programs to help support technology translation efforts by small businesses.

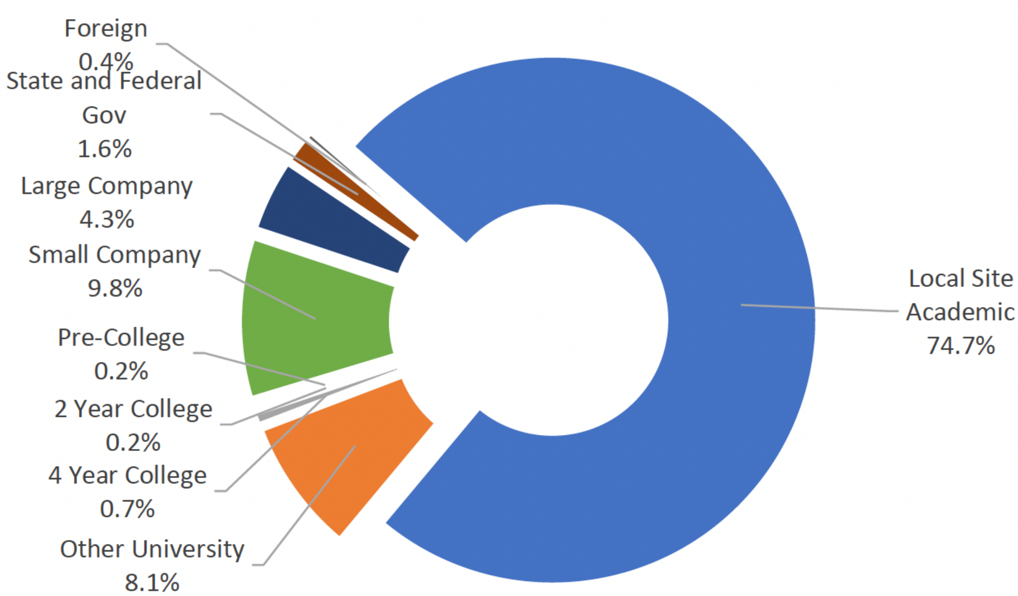

Figure 1. Nearly 10% of NNCI users come from small companies. More than 4% come from large companies. (*Source: Fig. 26 - top - from pg. 126 of 2023 NNCI Annual Report*)

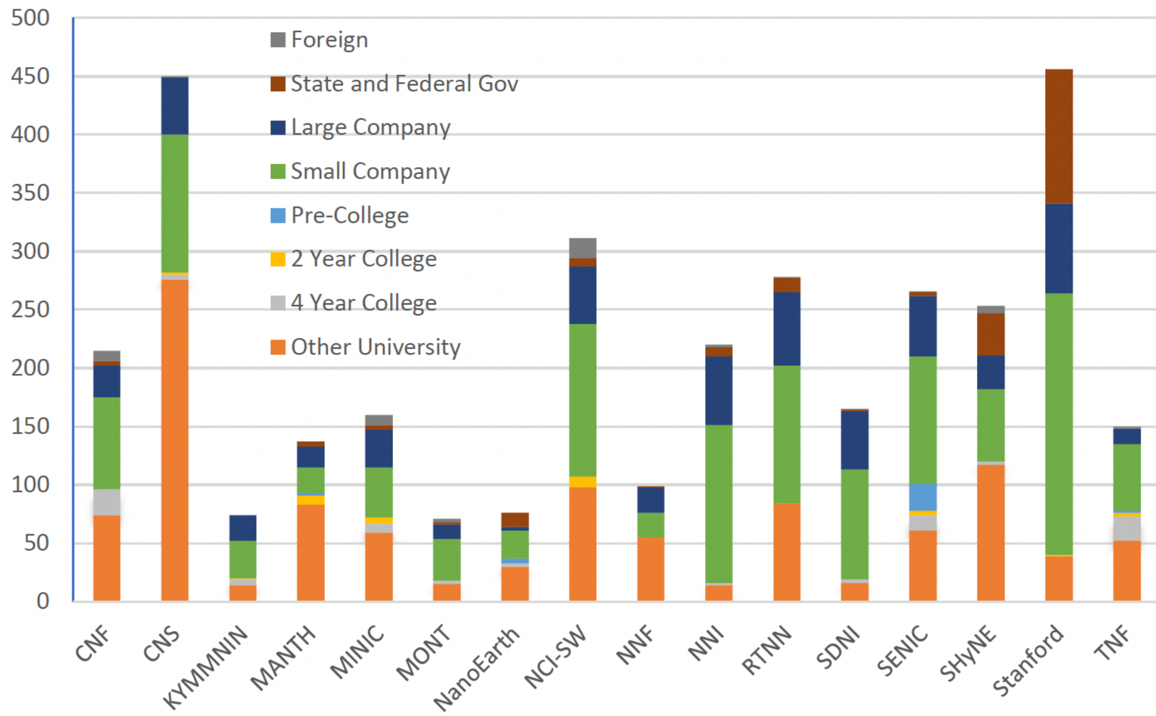

Figure 2. Small companies comprise one-third to half of the annual external users at most NNCI sites. (*Source: Fig. 28 from pg. 128 of 2023 NNCI Annual Report*)

4.3 Workshop Takeaways on Technology Translation

A summary of the workshop participant's takeaways in the area of technology translation can be found below.

- **Facilities in the network promote and enable technology translation in multiple ways – for some startups, NNCI is the ONLY path for translation.** Some facilities already provide startups valuable and highly accessible tools, knowledge, and technology they do not have, which enables them to test, create, and advance ideas more rapidly than through other means, and at some sites, with free access. Many participants indicated the success of the NNCI website, which has a database that provides information on the tools and resources available at sites. This website and staff connections across NNCI sites allow startups to quickly identify sites with capabilities they need. More streamlined access to labs is helpful when startups are on a short timeline.
- **Relationships between network facilities and industry users can create reciprocal funding benefits for all parties.** The NNCI enables a nationwide innovation ecosystem around nanotechnology and helps establish a "critical mass" of high-tech small companies. Seed grants and other funding from NNCI facilities help lower barriers for

startups and stimulate technology translation. This relationship, in addition to government funding in the form of programs like SBIR/STTR, give startups the resources they need to sustain operations and pursue new nano-enabled innovations. In turn, commercialization success enables industry users to subsidize academic usage fees and supports valuable training and research that may lead to new startups and industries.

- **The resources (entrepreneurial and technical) that some facilities provide to scientists and engineers prepares them to move their research projects from the lab to commercialization**. Examples of this include entrepreneurial mentorship, the seven-week NNCI NanoTechnology Entrepreneurship Challenge (NTEC) and linkages to NSF's I-Corps programs, which demonstrate a shared commitment to training and supporting entrepreneurs skilled in nano-related fields. The network can catalyze the rate of research and increase the impact that innovations can have on the market. Building on the successes of the programs and scaling them up will be crucial to move forward.

4.4 Recommendations for Technology Translation

It is clear from the participant response during the workshop that technology translation to commercial practice will be a great benefit to and potential outcome of the future national nanotechnology infrastructure. A summary of the major recommendations in the area of technology translation can be found below.

- **Prioritize diverse, flexible, and accessible innovation.** The shared NNCI infrastructure must pursue innovation and translation beyond CHIPS and microelectronics. Nano-enabled innovations spring from diverse areas such as life sciences, agriculture, energy storage, CO_2 capture, textiles, and beyond. Thus, NNCI facilities should remain flexible and provide space for innovation and translation across all nanotechnology-enabled domains. Participants felt strongly that a diversity of independent but collaborative and coordinated sites based on geographic location, materials, areas of specialization, problem focus, unique programming strengths, and beyond offered the greatest opportunities for translational impact. Metrics and incentives should be aligned to help prioritize innovation and translation. Resources should be included for a robust assessment of NNCI economic impact.
- **Establish a collaborative hub for supporting start-ups and translation.** NNCI sites bring together nano-enabled start-ups and established companies. The next NNCI could do more to support them locally as well as nationally. Expanded offerings could include rentable cleanroom and office space, increased staff assistance, start-up seed-funding, and prioritized tool access. As a collaborative hub, the NNCI could help connect innovators and entrepreneurs with translational resources such as local incubator networks, investors, and national programs like NSF TIP, I-Corps, SBIR/STTR, and many

others. Resources could be added to help increase staffing at NNCI sites for positions to serve as entrepreneurs-in-residence or to assist with implementing programs such as commercialization bootcamps, pitch competitions, faculty and student "innovation" workshops, and intellectual property (IP) best practices. Such programs could help create rather than simply recruit new users of NNCI facilities. The future NNCI should offer companies low barriers to entry, streamlined access requirements transferable across sites, and favorable IP terms.

- **Complement commercial-scale manufacturing and workforce development with an emphasis on leveraged resources and funding support.** NNCI facilities serve as an incubator of ideas, providing resources to help with small-scale, proof-of-concept of innovative ideas. NNCI does not replace commercial-scale facilities, but rather, should serve as a "bridge" to help entrepreneurs and companies identify and connect to more specialized resources for commercial-scale manufacturing. Limited pilot-scale manufacturing facilities could be included in the NNCI in collaboration with leveraged support from government, trade organizations, industry, and OEM tool manufacturers, where such relationships may be mutually beneficial in terms of, for example, workforce development and beta testing of new tools. Such "win-win" relationships could be fertile ground for student traineeships, internships, community college certificate programs, engaging veterans, industry mentorship, and other forms of specialized vocational training. In particular, the NNCI could help innovators and entrepreneurs connect with commercial-scale manufacturing facilities beyond the semiconductor industry, which is already heavily resourced through the CHIPS and Science Act. Outside of the semiconductor industry, the path from nascent innovation to commercial-scale manufacturing becomes much more challenging and uncertain. A future NNCI can go further to help clarify and support translational paths for a broader range of nano-enabled technologies.

5 THE RESEARCH ECOSYSTEM & SOCIAL RESPONSIBILITY

5.1 Introduction to Research Ecosystem & Social Responsibility

The NNCI has deliberately worked to reshape the research ecosystem of the nation by lowering barriers of entry to the world of nanoscale research and fabrication and cultivating social and ethical reflection amongst its participants. State-of-the-art nanotechnology tools and processes are often prohibitively expensive and require specialized expertise. Creating access to these tools, and staff who know how to use them, for researchers across the country has secured gains in knowledge and applications. As the NSF looks to the next ten years, it is important to consider how that access can be expanded even further, how other barriers to entry can be lowered, and how it can cultivate a diverse community that understands, communicates, and discusses its social and ethical responsibilities.

5.2 Previous Activities in Research Ecosystem and Social Responsibility

Addressing Societal and Ethical Implications (SEI) has been an important part of the NNCI since its creation and was similarly important in previous NSF nanotechnology programs. Carrying out SEI work within these programs has been an important way to get social scientists, natural scientists, and engineers to work alongside each other and to develop knowledge and programs that have proven beneficial for the infrastructure and beyond.

In response to the NSF call that created the NNCI, four sites – TNF, SENIC, RTNN, and NCI-SW – proposed a significant SEI component as part of their programs. These sites included scholars with PhDs in the social sciences and humanities to carry out SEI activities. The results of these efforts include quantitative and qualitative studies of site user satisfaction (including some IRB-approved assessment); social science research into the impacts of NNCI sites on academic publishing and local economies; educational materials that bring SEI concepts to scientists and engineers; and training programs in the social aspects of science and engineering. For instance, nearly every year since 2016 the NNCI has sponsored an intensive science policy immersion program for graduate students called Science Outside the Lab (SOtL) that trained participants in how to consider and engage with the broader implications and social complexities of science and engineering. In 2023 the NNCI ran a successful version of the SOtL program for faculty across the infrastructure. When the coordinating office was created it included an associate director who supported efforts at the four sites and worked with the SEI scholars to disseminate their work and further their impact across the NNCI as a whole.

Steps to increase the diversity of those who work at and use NNCI facilities have been steadily taken since the creation of the NNCI. Much of the work done in this area for the NNCI as a whole has been carried about by the NNCI Diversity Subcommittee. This subcommittee drew upon members from across the NNCI on a volunteer basis and was formed in an effort to broaden participation in the NNCI and nanotechnology nationally by positively impacting culture, developing assessment strategies, identifying strategies to overcome common obstacles, collaborating with sites to share and disseminate best practices, and inspiring and challenging each other. The NNCI Diversity Subcommittee carried out a number of programs including creating and sharing a statement of diversity across the NNCI hosting an online "Anti-Racism Town Hall," gathering and sharing a variety of definitions of diversity that different host universities use to facilitate broader reflection, and pulling diversity information from NNCI user statistics to boost awareness of the diverse user base that was being served. During Year 7 of the NNCI, nearly one-third of all external users came from academic institutions that serve under-represented populations, such as Historically Black Colleges and Universities and Hispanic-Serving Institutions. The NNCI also developed a user survey for use across the infrastructure that asks about the level of civility (professional engagement and mutual respect) in interactions at the NNCI facilities they used with the results and comments provided to sites for follow-up action.

5.3 Workshop Takeaways on Research Ecosystem & Social Responsibility

One panel at the workshop brought together experts in SEI; sustainable innovation; and Diversity, Equity, Inclusion, and Belonging. Additionally, the SEI annual meeting, held during the NNCI annual meeting, was also used as an opportunity to gather feedback from across the NNCI. Takeaways from these events include:

- **Individual facilities need to better define and communicate their values and their commitment to social responsibility.** Training sessions, seminars, and workshops about social responsibility already exist, but these could be expanded and consolidated. While universal training requirements might be too inflexible, facilitating discussions around goals and values could be an important part of user engagement within a future infrastructure.
- **The future model should strive to better engage local and underrepresented communities**. Public engagement is needed to connect nanotech research and researchers with communities. This could be done through outreach to local schools, community colleges, and community organizations. Such engagement could result not only in better community outcomes, but also attract underrepresented students to the field.

- **Disparities in participation and awarding will require intentional and pervasive strategies to counteract in a future model.** Attempts to engage with and meet the needs of diverse communities will be significantly strengthened through a future infrastructure that deploys proven approaches to better engage with, listen to, and recruit a set of students, users, researchers, and administrators that better reflect the diversity of the country and local regions served.
- **A greater sense of community and high levels of interaction can catalyze innovation, cross-pollinate ideas, and encourage information sharing**. Collaborative tools and platforms are already being used in the research community, but regular events such as workshops and professional meetings could enhance a sense of community and belonging and allow for more professional development.
- **Collaboration can spur innovation, encourage best practices, and facilitate the application of knowledge in ethics and social sciences to nanotechnology research**. Within the fields of nanotechnology research, mentorship or staff exchange programs would both foster a greater sense of community and allow for professional development. Reaching beyond the field, collaboration with ethicists, social scientists, and liberal arts colleges could assist in cultivating social responsibility and incorporating ethics into the practice of research.

5.4 Recommendations for Research Ecosystem and Social Responsibility

We would strongly recommend that SEI activities continue under the next nationwide nanotechnology infrastructure and that considerations of diversity be a required component of anyone seeking to be a part of such an infrastructure. The following are a series of specific items we believe would be useful to consider.

- **Foster engagement with local communities**. There is an opportunity for a future nanotechnology infrastructure to work to repair some of the distance that has been created between the general public and research scientists through community engagement. Social scientists have repeatedly shown that teaching the public about science does not lead to an increase of trust. If we want to strengthen science's position as a trustworthy source of knowledge in the United States and increase the diversity of people that it serves, efforts must be made to build relationships between researchers and their local community. One future path for Nano SEI could be to refine, promote, and train others in the tools necessary to build community engagement and partnerships. A nanotechnology infrastructure that can respond to community needs would greatly enhance its effectiveness as well as strengthen public trust in science.
- **Rethink how SEI is organized across the infrastructure**. There were some calls at the workshop to require SEI at every site. If there is sufficient funding and desire this could

be successfully done if: 1. The call for proposals includes some minimum level or general guidelines for the funding of SEI endeavors to ensure that they are robust enough to attract the necessary talent to carry out valuable work; 2. The call makes clear that the SEI aspects of a given proposal will be taken seriously in the evaluation process; and 3. The NSF offers an SEI development program for candidate sites that are strong in other ways, but have not addressed SEI in a significant way. The alternative is to develop centralized or regional SEI expertise and then create ways for that expertise to be shared across and engage with the infrastructure, as was largely done in the NNCI.

- **Facilitate higher levels of engagement between members in the network community**. Facilitating regular meetings, mentorship pairings, staff exchange programs, subfield-specialty groups, and professional groups for underrepresented populations would help establish strong relationships and create a sense of community. This should also include a component specifically addressing the creation of a culture of respect within the labs and user communities.
- **Expand outreach to K–12, community college, and minority serving institutions.** Broadening awareness of a future network and nanotech will require reaching out to students that may not be aware of the facilities, conferences, or even of the field. That outreach, and funding to make participation possible, is one way to reduce barriers and expand diversity and equity of access. Nationwide resource groups for underrepresented groups could assist with this. Additionally, a future network should coordinate and expand the REU programs of its sites.
- **Consider program changes that other organizations have used to reduce inequity and increase social responsibility.** Sites could choose to make a social responsibility score part of its publicly available annual report. Facilities could conduct periodic review of projects, procedures, and operations to evaluate users’ experiences in the labs and to ensure that shared facilities are advancing the public good. There may also be a benefit to making multilingual support available at sites.
- **Partner with existing programs and engagement experts to better engage underrepresented communities and increase awareness of the field in local communities**. Professional associations such as the National Society of Black Engineers, the Society for the Advancement of Chicanos/Hispanics & Native Americans in Science, Society of Hispanic Professional Engineers, and Student Veterans of America are already doing good work in increasing participation of underrepresented communities in STEM fields. Partnering with those organizations would help a future network design programs that address the barriers they have identified. Collaborating with two-year college programs could yield similar benefits.

6 ORGANIZATIONAL STRUCTURE, GOVERNANCE, & ASSESSMENT

6.1 Introduction to Organizational Structure, Governance, & Assessment

An effective and efficient organizational structure for shared facilities needs to focus on providing access and use to a geographically, intellectually, and demographically diverse US population while building a supportive, engaging, and respectful community for all users and staff. In addition, this structure should provide a central point for organization-wide activities such as a database for metrics, assessment, annual meetings, and collaboration with other US facilities in the translational ecosystem. Key to effective use of shared facilities are knowledge, distance, and cost, which strongly affect the use of shared facilities for research, education and outreach, workforce development, and technology transfer. An organizational structure needs a focal point for information that includes facility instrument and access information, databases, training information and videos, and contacts for common research methods, best practices, and shared press releases that provides the external and internal knowledge necessary to support the facilities and the users in the US community. Consideration of the geographic distribution of sites, as well as the inclusion of a wide array of characterization and fabrication capabilities, addresses the challenges of travel, distance and cost, and fosters community through individual belonging and multidisciplinary collaboration. The organizational structure should encourage site autonomy and flexibility to engage and support regional communities, which will likely result in some diversification between sites, while ensuring that all sites share some common goals of the overall organization. The organizational structure should strategically position the shared infrastructure as an integral partner with other parts of the national research, educational, and development ecosystem to leverage and provide foundational support for technologies, especially revolutionary advances, moving quickly to products. Sharing best practices, common data, and strategies for research, education, outreach, workforce development, and technology translation that are successful as measured through formal assessment are all key attributes of an effective organizational structure that supplies feedback for efficient use of resources. The organizational structure has the potential to have a transformative effect upon the shared facility use and governance, the effectiveness of the shared university facilities in the US technology innovation and tech transfer ecosystem, and the efficient utilization of the NSF funds.

6.2 Previous Organization, Governance, and Assessment Strategies

The National Nanotechnology Coordinated Infrastructure (NNCI) is a 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 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). The NNCI network is funded by the NSF through cooperative agreements with the individual sites. The Coordinating Office (CO) for the network was awarded to the Georgia Institute of Technology through a separate proposal process limited to the awarded NNCI sites. The NNCI sites are located in 16 states and involve 29 universities and other partner organizations 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.

All of the NNCI facilities, most of which have partners and/or multiple locations, are available for use by students and professionals from around the country and globally. The sites and facilities within NNCI support research and development for academic education and research purposes, as well as product and process development for commercial purposes. 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 facilities, their tools, and staff expertise. All sites use the resources provided by NSF to support a variety of education and outreach activities, and many also offer programs or research in societal and ethical implications (SEI) of nanotechnology and simulation and modeling. With the NNCI renewal in 2020, the Coordinating Office also began to coordinate network activities that promote and support innovation and entrepreneurship.

The Coordinating Office 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) composed 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 tackle high-level issues related to the NNCI network as a whole. Leveraging the distributed expertise at the network level, 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. After the 2020 renewal, 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.

6.3 Workshop Takeaways About Organizational Structure, Governance, and Assessment

NNCI's organization as a coordinated infrastructure rather than a centrally managed institution has several advantages that workshop participants appreciate. Site autonomy and flexibility are important values to the user community. The "coordinating not commanding" approach fosters cooperative collegiality and friendly competition. While participants were overwhelmingly protective of NNCI's governing model, many expressed a desire for tighter coordination between sites on several shared tasks. Additionally, they identified several promising opportunities for collaboration with other organizations.

- **There may be benefits and efficiency to coordinating some common resources and tasks.** Centralized coordination was suggested for activities such as education and outreach, metrics and assessment, communications, marketing and user recruitment, user onboarding procedures, environmental safety and health standards, backup tools and processes, resources for DEIAB and social responsibility training, and other best practices. However, this level of coordination is not always possible with the diversity and individuality of facilities and universities, nor should it be heavy-handed. A "federal model" that collects, moderates, and shares best practices and offers resources while respecting the autonomy of individual sites would strike the right balance between coordination and autonomy. Some sites already share some of this information, but many participants claimed that current sharing practices are too haphazard and ad-hoc. A future network could establish and communicate best practices for information and resource sharing, and act as the clearing house for collection, moderation, and sharing.

- **There is much to be gained in partnering with other government agencies, infrastructure programs, industry groups, and private initiatives.** NNCO has initiated an effort in this direction, and a future nanotechnology network could benefit from collaborations and partnerships with the broader nanotechnology ecosystem. Those relationships should expand opportunities and access for users without duplicating efforts. Collaboration with DOE infrastructure or coordination with CHIPS recipients could make new tools and capabilities available. It is important to understand that the NNCI sites, located at universities, offer infrastructure primarily for research and early prototyping, and, as a result, are typically flexible in nature. These NNCI site facilities typically do not have dedicated fabrication lines for specific materials and device processing or dedicated characterization equipment for specific targeted high-throughput characterization. Integrating the future nanotechnology infrastructure into the ecosystem continuum of resources for research, high level prototyping, and scale-up product development is an important aspect of the partnerships that could be formulated (e.g. with Microelectronics Commons sites). Participants also noted the value of informal relationships and communication with other networks and scientific communities, stating that simple awareness of purpose and function can inspire improvements within a future nanotechnology network.

- **Organizational structure of the infrastructure.** Competing needs should be balanced. Successful facilities require a critical mass of local/regional users and distributing them too widely hinders that, as most university research operates on tight budgets that do not include substantial travel for students for fabrication or characterization, thus funding more sites enables broader and more diverse access. Some workshop attendees requested that a future infrastructure include more facilities at a more diverse range of universities. Note, however, that opening facilities to shared outside use is something that some smaller universities have indicated that they do not have the administrative or support staff bandwidth to accommodate.
- **Metrics and assessment need to be incorporated into a future infrastructure.** It is vital that the future nanotechnology network collect user data, staff data, and workforce development and outreach data, and that the data is shared to move forward with best practices. Some standard assessment across all sites should include the numbers and types of users, user satisfaction, staff experiences/satisfaction and outreach attendee outcomes and satisfaction across multiple variables. For example, user satisfaction should be assessed across variables that include staff interactions, training, lab tools, safety, and overall satisfaction. As necessary, some of these assessments would be IRB-approved. There should be some standard assessments across all sites complemented by additional assessments that are site-specific. Optimally, a full range of data collection tools should include surveys, semi-structured interviews, yearly and exit interviews for all our staff, and outreach analysis. The data should be analyzed by multiple demographics, and, to the extent possible, utilize socioeconomic background data. This can help to establish if there is equitable access and satisfaction in the user base and in workforce development/outreach programs, and if the culture and practices are welcoming to all. It is extremely important for the success of the next nanotechnology infrastructure that the program be assessed, and that the results are shared across the network and with NSF. Some of the attendees indicated that this assessment should be performed by an external evaluator or team.

6.4 Recommendations for Organizational Structure, Governance, and Assessment

- **Organization and governance of the infrastructure locations.** The geographically-distributed consortium developed under the NNCI has worked well and is emulated by other programs. The organization and governance allows site autonomy to develop activities that fit best with their capabilities and local needs, while providing a headquarters to coordinate network activities and share best practices. There are several key factors regarding the organization of the infrastructure that are recommended:
  - Wide geographical distribution of the sites is critical, as overnight travel cost is a major factor that inhibits use, as has been the case in the current NNCI network. Regional use, within approximately 4-5 hours of the facility, enables users to access the facilities easily. Successful facilities require a critical mass of local and regional users, and distributing them too widely hinders that, as most university research operates on tight budgets that do not include substantial travel for students for fabrication or characterization, thus funding a larger group of sites, from a range of universities, will enable broader and more diverse access. Other suggestions for navigating between competing demands included a hybrid model—a few regional centers with higher funding along with satellite sites for broader access (hub and spoke model).
  - A balance between fabrication and characterization is critical to increase the intellectual diversity of the user base. Historically, fabrication was the impetus for the early nanotechnology shared infrastructure grants. However, the current NNCI has seen a growth in the interest in more balanced infrastructure support between characterization and fabrication, with the addition of many users who lie outside of the more traditional materials, electronics, optics, and chemistry fields, including biology, geosciences, textiles, and medicine. In fact, some workshop attendees requested that a future infrastructure include a greater spectrum of facilities beyond traditional cleanrooms and characterization, to include imaging, surface analysis, chemical analysis, materials synthesis, modeling and simulation, prototyping, and others. It is important, however, that the funding of the infrastructure facilities not become too diffuse to have impact, thus the expansion into other types of facilities should be made cautiously, and with assurance that the facilities are open to outside use, and that they have staff support and user training.
  - Creating groups that foster community is essential to building a strong user base and workforce, and enables facilities to form links with regional companies. Emphasizing linking of sites that lie within a geographic region enables users and staff to more easily move between sites without long distance travel. This builds regional

relationships and affiliations that are valuable for research and workforce development, which has also been the case with the current NNCI network.

- Creating a cross-linking of sites around technical topics is a new idea that could accelerate innovation and strengthen relationships across the nation. Across the funded sites, each site could participate in a few technical networks, that is groups of sites that focus on support of a common technical discipline (quantum science, earth science, microelectronics, etc.). This would be an extension of the current Research Communities established by the NNCI, but with funding attached specifically to foster interchanges across sites in the technical areas. Metrics and assessment methods should be included that demonstrate the benefit and impact of the network (magnifying effect) so that programs and effort can be evaluated for greatest return on investment. A clear statement of goals and an assessment methodology to measure the progress toward those goals is key to improvement of the ongoing programs.
- An External Advisory Board (EAB) is an important feedback mechanism for the next program, and should be continued, with an emphasis on including different fields of study among the board members.

- **Create and communicate a national repository of resources.** Resources and processes that are applicable to all sites should be managed and maintained by a future network and used by individual sites as needed. Examples could include common user application paperwork and IP agreements, safety training resources, responsible onboarding procedures, fundamental concepts for common tools, access protocols and user agreements, resources for DEIAB and social responsibility training, and workforce development or outreach and education materials. However, it is crucial to understand that individual university facilities may have requirements and procedures that supersede any nationally mandated processes or documents.
    - These common resources should be available to staff and users alike, via a web portal or other mechanism. The infrastructure should develop common communications, organized by the coordinating office (resources and personnel required), for sharing of information among site staff and with users.
    - Common user recruitment marketing strategies should be developed and shared among the sites.
    - A future set of infrastructure sites should create committees, working groups, and other structures to collaborate across the sites, share best practices, and disseminate information, as outlined above in the cross-linking of sites around technical areas.

  - The sites (leadership and staff) should meet regularly, online and/or at an -in-person annual meeting, to foster communications, networking, and collegiality among the program participants.

- **Form and further partnerships with regional, national, and international nanotechnology organizations and networks.** The National Nanotechnology Coordination Office (NNCO) has recently initiated conversations among many of the national nanotechnology infrastructure groups such as the DOE-funded Nanoscale Science Resource Centers (NSRCs), our national light source facilities, Network for Computational Nanotechnology (NCN), National Institute of Standards and Technology (NIST), and others. Those relationships should expand opportunities for users without duplicating efforts and should be encouraged in a future program. In addition, a future program should pursue partnerships with other nanotech networks—from the smaller regional ones to the larger national (such as the UGIM group and meeting) and international networks. Finally, participants also noted the value of informal relationships and communication with other networks and scientific communities, stating that simple awareness of purpose and function can inspire improvements within a future nanotechnology network.

  - Sites should cultivate connections with prototyping facilities, incubators, small scale manufacturing, and other entrepreneurial support opportunities (e.g., Activate Fellowship) to better support start-ups and other commercial users.

  - Connections should be made with other government agencies, such as the National Institute for Occupational Safety and Health (NIOSH) for safety concerns or USDA/FDA labs for support of non-traditional users in agriculture or medicine.

  - Education and outreach partnerships should be encouraged, such as connections with other organized REU/RET programs, perhaps including joint events such as the REU Convocation developed under the NNIN/NNCI.

  - Mechanisms to support staff, faculty, or student exchanges within the infrastructure network and with other domestic and international networks should be developed.

- **Assessment toward stated goals should play a key role in program initiation and development**

  Assessment is key to enhanced user and staff research/educational enablement and satisfaction, optimizing the impact of workforce development and outreach programs, and the organizational performance of any site-to-site relationships (e.g., groupings or network(s)).

  - Setting clear goals for the overall program, any regional programs, and for each site helps the sites focus on activities that promote progress toward the goals. Just as important, encouraging innovation and new goals as the program develops and matures should be encouraged.

- o Data is essential to making data-informed decisions regarding which efforts are producing progress toward the goals of the site/region/network/technical area. It is vital that the future nanotechnology infrastructure sites and any larger network collect site data, user data, staff data, and workforce development/outreach data in a manner that is consistent across sites to the extent possible, and that the data is shared to move forward with best practices.

- o Assessment should include many variables that impact the efforts and goals, which can include both simple to collect data and data that is more based upon satisfaction.

  - § Data which is more simple to collect includes the number of engaged individuals and how often they return to the facility, including: the number and demographics of users, number and demographics of staff, number of users per staff member, each of these prior three as a function of technical area or instrument or characterization vs fabrication, number of teachers and students engaged and at what levels of education and engagement, etc.

  - § Data which is more nuanced to collect and will likely warrant an investigation into whether or not IRB approval is needed include: user satisfaction, staff experiences/satisfaction, outreach attendee outcomes and satisfaction across multiple variables, including demographics. For example, user satisfaction could be assessed across variables that include staff interactions, training, lab tools, safety, and overall satisfaction.

- o Assessment should have common questions across all sites, with each site able to individualize, based upon their goals, with additional assessment questions or activities. Optimally, the list of individuals assessed and the assessment variables should be identified at the onset of the next nanotechnology infrastructure program, and an assessment research instrument should be developed and applied across all members of the network. A full range of data collection tools should include surveys, semi-structured interviews, yearly and exit interviews for all our staff, and outreach analysis.

- o The data should be analyzed by multiple demographics, that should include, but are not limited to, region (urban vs rural), race, ethnicity, gender, sexual orientation, and veteran status. To the extent possible, utilizing socioeconomic background data should also be included. This can help to establish if there is equitable access and satisfaction in the user base and in workforce development/outreach programs, and if the culture and practices are welcoming to all

- o Some of the attendees indicated that this assessment should be performed by an external evaluator or team. However, this would require significant resources.

7 CONCLUSIONS

There is an opportunity to capitalize on the decades of work that the current nanotechnology infrastructure ecosystem has built. More specifically, established education, outreach, and workforce programs can be expanded upon to reach thousands more students; start-up companies can continue to have access to unique prototyping facilities in a broad range of disciplines; the industrial sector can use our infrastructure as pilot-scale testbeds for emerging manufacturing processes; and major research breakthroughs can be made via radical collaborations. The established network is an asset to the nation and is supported by an ecosystem of subject matter experts, staff, interns, and budding leaders.

The response and input from the participants of "The Workshop on Nanotechnology Infrastructure of the Future" were summarized and discussed in detail in this white paper. The major takeaways and future recommendations related to the five major focus areas: (1) identification of key research priorities; (2) education and workforce development; (3) technology translation; (4) research ecosystem and social responsibility; and (5) organizational structure, governance, and assessment are provided to guide the design of a future follow-on nanotechnology infrastructure program. More specifically, the high-level and cross-cutting recommendations are to:

- **Advance the frontiers of research for the nation by providing the necessary tools, facilities, expertise, and collaborative spaces to image, fabricate, and control nanoscale systems.**
- **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.**

We have yet to harness the full potential of nanotechnology to address the nation's most critical challenges in energy, climate, healthcare, defense and more. A shared nanotechnology infrastructure can provide the space to conduct radical collaborations and address these grand challenges via state-of-the-art facilities and unique partnerships across the nation. In addition, a future nanotechnology infrastructure can help prepare and inspire the next-generation workforce.

8 ACKNOWLEDGEMENTS

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List of in-person participants:

James Adams (National Institutes of Standards and Technology)

Aixa Aleman-Diaz (Copenhagen Business School)

Mark Allen (University of Pennsylvania)

Kiana Aran (Keck Graduate Institute)

Nava Ariel-Sternberg (Columbia University)

Joe Baio (Oregon State University)

Elijah Belayneh (CAID)

Yvonne Bennett (National Institutes of Health)

David Berube (North Carolina State University)

Cosima Boswell-Koller (National Science Foundation)

Konrad Bussmann (Naval Research Laboratory)

Maria Fernanda Campa (National Nanotechnology Coordination Office)

Binek Christian (University of Nebraska - Lincoln)

Khershed Cooper (National Science Foundation)

Luisa Dempere (University of Florida)

Vinayak Dravid (Northwestern University)

Andrew Dreyer (Mitsubishi)

Daniella Duran (Stanford University)

Paul Eason (University of North Florida)

Brystol English (National Academies of Sciences, Engineering, and Medicine)

Arthur C. Evans III (Georgia Piedmont Technical College)

Ilse Feitshans (Georgetown University)

Jonathan Felbinger (Quantum Economic Development Consortium (QED-C))

Michael Filler (Georgia Institute of Technology)

Darrin Frye (United States Special Operations Command)

Kevin Funkhouser (Unaffiliated)

Rob Gandy (Nexight Group)

Tom Gearty (Massachusetts Institute of Technology)

Kuan-Tsae Huang (Asia University, Taiwan)

Jacob Jones (North Carolina State University)

Jack Judy (University of Florida)

Aju Jugessur (University of Colorado - Boulder)

Alamgir Karim (University of Houston)

Hanseup Kim (University of Utah)

Sung Jin Kim (University of Louisville)

Tiffany Kimoto (Kavli Nanoscience Institute at Caltech)

Gerhard Klimeck (Purdue University)

Matthew Levy (AE Blue Capital)

Feng Li (University of Idaho)

Mo Li (University of Washington)

James Liddle (National Institutes of Standards and Technology)

Yigal Lilach (George Washington University)

Florence Lucey (University of Maryland - Baltimore)

Anthony Maciejewski (National Science Foundation)

Sandrine Martin (University of Michigan)

Moneck Matthew (Carnegie Mellon University)

Marc Michel (Virginia Polytechnic Institute and State University)

Karren More (Oak Ridge National Laboratory)

Vladimir Murashov (Centers for Disease Control and Prevention - National Institute for Occupational Safety & Health)

Richard Nash (National Science Foundation)

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Shashi Poddar (Euclid Techlabs)

Tonya Pruitt (Virginia Polytechnic Institute and State University)

Victor Pugliano (Department of Defense)

Luke Qi (Stanford University)

Sahar Rabiei (University of California - Berkeley)

Manijeh Razeghi (Northwestern University)

Matteo Rinaldi (Northeastern University)

Raymond Samuel (North Carolina A&T State University)

Martin Sandrine (University of Michigan)

Nora Savage (National Science Foundation)

Vishal Shah (Community College of Philadelphia)

Rishiit Sharma (Hume Nanotech)

Mark Sherwin (University of California - Santa Barbara)

Tolou Shokuhfar (University of Illinois - Chicago)

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William Wilson (Harvard University)

Dalia Yablon (TechConnect)

Zhenrong Zhang (Baylor University)

9 APPENDIX (WORKSHOP AGENDA)

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)