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Democratizing Science Through Advanced Cyberinfrastructure

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Democratizing access to cyberinfrastructure is essential to democratizing science. This article explores knowledge, technical, and social barriers to accessing and using cyberinfrastructure and explores approaches to addresses them. It also highlights recent activities and investments at the National Science Foundation that implement some of these approaches.

Science and engineering (S&E) research in the 21st century, powered by the growing availability of computation and data, continues to explore new frontiers, generating discoveries and innovations with the potential to transform our lives, our environment, and our economies. Examples of such S&E research enabled by computation and data include fundamental discoveries about our solar system and the universe, understanding and modeling climate change and potential strategies for mitigating these changes, understanding the nature and progression of diseases and how to cure illnesses, changing the way we farm and deliver food and other natural resources to consumers, and responding to and managing the impacts of natural disasters, such as hurricanes, earthquakes, and wildfires. Researchers today have unprecedented amounts of data from diverse sources, including sensors, instruments, and computational simulations, as well as an equally unprecedented need for computing to allow them to extract meaningful insights from the data to drive understanding, predictions, and decision making.

Digital Object Identifier 10.1109/MC.2022.3174928
Date of current version: 29 August 2022

The essential role of computation and data in 21st century science has been highlighted in several recent reports, including a 2021 National Academies of Sciences, Engineering, and Medicine (NASEM) report, "Global Change Research and Opportunities for 2022–2031,"[1] which identified the critical need for computing research and computing resources that can advance the nation's understanding of and response to climate challenges, as well as the 2021 NASEM "Decadal Survey on Astronomy and Astrophysics,"[2] which summarized the tremendous impacts of data from multiple observatories. It is therefore imperative, now more than ever, that all researchers benefit from the opportunities for scientific exploration enabled by computation and data. As a result, ensuring broad, fair, and equitable access to advanced cyberinfrastructure (CI), including computing, data, networking, software, and expertise, that is, democratizing access to CI, is essential to democratizing science.

Recognizing this growing role of computation and data across all areas of scientific research, there have been significant investments around the globe in advanced CI resources, services, and expertise. In the United States, the National Science Foundation (NSF), through its Office of Advanced Cyberinfrastructure (OAC) and predecessor offices, has, over the past four decades, funded the development and provisioning of advanced CI resources and services toward an overarching vision[3] of ensuring the broad availability and innovative use of an agile, integrated, robust, trustworthy, and sustainable CI ecosystem that can drive new thinking and transformative discoveries in all areas of research and education. Investments include acquisition, integration, coordination, and production operations associated with shared data, secure networking, advanced computation, scientific software and data services, and the design and development of computational and data-enabled S&E.

The OAC also nurtures the computational and data skills and expertise needed for next-generation S&E research, and it promotes innovative, robust, secure, and interoperable CI as well as sharing and collaboration among academic research infrastructure groups, other federal agencies, international research funders, and the private sector. A recent road map by the National Science and Technology Council Subcommittee on Future Advanced Computing Ecosystems[4] highlights that these investments are complemented by investments at the national, regional, and local levels; by other U.S. federal agencies, academic institutions, and industry; and in other countries.

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BARRIERS TO CI ACCESS AND USE

However, despite these global investments and the growing availability of an advanced CI ecosystem, significant barriers still limit broad and equitable access to this ecosystem, especially for individuals and institutions that are resource constrained and for communities that have been traditionally underrepresented. These knowledge, technical, and social barriers were explored in a recent study,[5] and they span several key areas, as summarized in the following.

Knowledge barriers

As a result of increasing national, regional, and institutional investments in the CI ecosystem, researchers typically have access to a range of resources and services. However, researchers often lack a broad awareness of this availability, and perhaps even more importantly, even when they are aware of the available resources, they may not understand how to use these resources (for example, determining which resources are relevant to a researcher's specific needs and how to gain access to these resources can be challenging). Effective use of advanced computing and other CI resources requires significant support structures to help researchers determine the most appropriate resources, obtain allocations, train practitioners once they have allocations, and support application migration and execution. Such support structures are often missing at the local level, especially at underresourced institutions that often need the most help. The lack of access to necessary support has been noted as the most significant barrier to broad access to the CI ecosystem.[5] National and regional entities and institutions do provide support structures, but scaling these structures to meet the needs of a growing and diverse community is challenging. Current efforts often focus on domains and communities that have traditionally used advanced CI resources rather than on integrating new and developing communities that are not as able to adapt to specific needs.

A related barrier is associated with the recruitment, retention, and cultivation of a highly capable, adaptive, and agile workforce, for example, system administrators, software developers, and data curators. Developing and sustaining such a CI workforce presents challenges, including initiating effective institutional and on-the-job training to keep up with evolving software, technologies, platforms, and application requirements. Furthermore, there remains a lack of recognized job titles for the CI workforce, and skilled CI workers often face career uncertainty and a lack of recognition, as their valued services are in positions not visible to the research community and they have titles that are neither consistent nor meaningful. Providing creative incentives, reward mechanisms, and career paths will be essential to sustain this workforce. Whereas the formal educational pathway is critical, providing on-ramps for nontraditional students (for instance, those who are older and/or seeking reskilling and upskilling opportunities) requires thoughtful educational practices, mentoring, and support to promote success and advancement.

> Specific efforts and incentives focused on increasing awareness and access by, for example, integrating and embedding CI, CI expertise, and CI best practices within communities, must be a priority.

Technical/procedural barriers

The number and diversity of researchers using CI resources has continued to evolve over the past few decades. However, the mechanisms used to allocate these resources have largely remained the same. Most national and regional resources and many institutional resources use proposal-based mechanisms for allocating resources: once their research is funded, researchers must submit a second proposal requesting resources. These proposals are then periodically evaluated, and if selected, the researchers are given an allocation that they can use to access the resources and conduct their research. This approach works well for certain classes of users and types of usage modes, but it can prevent broad usage of the resources for a multitude of reasons. For example, users often face "double jeopardy" by having to get their proposal and resource requests through two separate processes. Users must have a certain level of expertise and experience to appropriately articulate their needs and put together a competitive proposal. The latency of the proposal process presents additional barriers. Furthermore, proposal review criteria tend to be skewed toward more experienced users, requiring prior results for performance and scalability. Although many systems provide small "start-up" allocations, these are limited and cannot support extended research needs. Alternate access models, such as on-demand and urgent access as well as the integration of access into popular science tools, are not typically supported.

The ability of researchers to use growing national and regional CI capabilities is often limited by local infrastructure, which is typically needed to allow them to have access and effectively use these resources. These limits include a lack of adequate local capabilities for securely connecting to advanced computational resources, accessing relevant data resources, and integrating these resources into their application workflow. Perhaps most importantly, local resources are not equitably available across the full range of institution types, preventing certain segments of the research community from accessing the on-ramps that would pave the way toward their engagement in computational and data-enabled S&E.

Social barriers

In addition to the technical and procedural barriers noted in the preceding, there remain social barriers at the institutional and regional levels that impact how research CI is viewed, funded, and supported. For example, the unique nature of research CI, how it is used, the needs of its user community, and how it differs from more typical IT infrastructure and services are often not appreciated at an institutional level, resulting in a lack of mechanisms and structures needed to support researchers and, more importantly, to expose them to the potential benefits of CI to their research. This lack of appreciation also makes it harder to attract and retain the necessary talent and can lead to the deployment of CI solutions that do not match user needs. Furthermore, these adverse impacts often disproportionately affect underresourced institutions and communities. The resulting lack of engagement of underresourced institutions and communities can further result in the downstream exclusion of certain communities and their contributions from the scientific research enterprise and the propagation of bias. Specific efforts and incentives focused on increasing awareness and access by, for example, integrating and embedding CI, CI expertise, and CI best practices within communities, must be a priority.

DEMOCRATIZING ACCESS TO CI

Democratizing access to the CI ecosystem is essential to democratizing science and ensuring that every researcher has fair and equitable access to the resources that support his or her work. As the needs for and opportunities from CI grow and broaden, eliminating the barriers listed previously is becoming critical. This approach requires strategic investment in a broad set of CI resources, services, and expertise that can systematically address barriers to CI access while, at the same time, providing adequate training and support structures. Specifically, such investments should consist of the following:

- integrated and user-friendly portals and gateways for discovering and accessing resources, supported by flexible allocation and access mechanisms that sustain a wide spectrum of users and their needs
- access to local CI resources as part of a shared fabric of national CI resources connected and reachable through high-speed frictionless data networking
- diverse and flexible allocation and access modes (for example, on-demand, urgent, and coordinated access) that support a diversity of users and application needs
- agile, easily accessible, and scalable networks of experts that integrate embedded expertise and user support that is responsive to local needs
- broadly accessible training targeting the spectrum of CI users and skills as well as support for exchanges among communities and the dissemination of best practices.

Collectively, the preceding steps can be transformational in broadening and democratizing access to CI and the research opportunities CI provides.

NSF investments toward democratizing CI

The broad requirements for democratizing CI listed in this article are fundamental to the NSF's CI vision[3] for a national CI ecosystem and underlie many of the agency's recent investments that implement this vision. They are also integral to the NSF's blueprint for future national CI coordination services.[6] For example, the NSF recently announced[7] a suite of awards through its Advanced Cyberinfrastructure Coordination Ecosystem: Services and Support (ACCESS) program. This program is aimed at improving the accessibility and usability of the national CI ecosystem and increasing its integration with systems and research communities on campuses across the nation. ACCESS services build on the NSF's past CI investments and activities as well as more recent explorations, such as a high-throughput computing allocation pilot.[8]

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Complementing the ACCESS services are the NSF's sustained efforts to foster and nurture a diverse, recognized, and skilled CI professional (CIP) workforce.[9] *CIP* refers to the community of individuals who provide a broad spectrum of skills and expertise to the scientific and engineering research enterprise by inventing, developing, deploying, and/or supporting research CI and CI users. Examples of CIPs include CI system administrators, CI research support staff, CI research software engineers, data curators, and CI facilitators, and it may also include computational research scientists and engineers who are not in traditional academic paths. The NSF uses the broadest definition of CIP, including researchers who use CI, CI developers, and CI operators—all workforce categories required to effectively leverage and utilize current, emerging, and future CI capabilities and amplify the transformative impact of CI across S&E research fields.[10,11] These individuals and the highly valued services they provide to S&E deserve more institutional recognition, support as a community, and clearer pathways for their professional/career development. Specific NSF activities to support CIPs include the Training-Based Workforce Development for Advanced Cyberinfrastructure (CyberTraining) program,[12] which supports innovative, scalable training, education, and curriculum/instructional materials along with deeper incorporation of CIPs into the research enterprise.

CyberTraining seeks to broaden CI access and adoption by 1) increasing adoption of advanced CI and computational and data-driven methods by a broader range of S&E disciplines and institutions; 2) enhancing the incorporation of CIPs into the research enterprise, highlighting the value of those professionals in S&E research; and 3) effectively utilizing the capabilities of individuals from a diverse set of underrepresented groups. The program includes a track for funding CIPs at the institute and regional levels and their integration into a national computational science support network managed by one of the services that are part of the ACCESS program. Importantly, CyberTraining and other programs supporting CIPs require a mentoring and/or professional development plan to encourage research proposals to explicitly consider and support this important but often neglected aspect of CI.

A related support activity is the Research Computing and Data Nexus Cyberinfrastructure Center of Excellence,[13,14] which aims to advance research computing and data infrastructure through the strategic development of tools, practices, and professionals. Overall, the NSF envisions networks of connected and coordinated hubs that recognize and connect CIPs, support communications and training, share best practices, and foster mobility and synergies across projects and organizations. Finally, the NSF recognizes the importance of diversity in driving scientific innovation and discovery. The NSF is thus committed to enabling the broadest access to its CI ecosystem and continues to make investments to support this commitment. For example, the recently funded Minority-Serving Cyberinfrastructure Consortium[15] envisions a transformational partnership to promote advanced CI capabilities on the campuses of historically Black colleges and universities, Hispanic-oriented institutions, tribal colleges and universities, and other minority serving institutions.

To harness the full potential of research discoveries and the resulting impacts on science and society, all researchers must be able to avail themselves of the opportunities for scientific exploration provided by advanced CI. Ensuring broad, fair, and equitable access to advanced CI resources, services, and expertise will be essential for democratizing science in the 21st century. This article described some of the barriers to achieving this objective on the basis of experiences at the NSF and highlighted the NSF's recent activities and investments to address these barriers. However, the democratization of science and its benefits requires not only continued investments by the NSF but also broader and more coordinated local, national, and global efforts and investments. The NSF intends to continue to look at more effective ways to reduce barriers to CI access and explore new approaches to ensure broader participation and equity. For example, the NSF is coleading the congressionally chartered National Artificial Intelligence (AI) Research Resource Task Force,[16] which is seeking to address the "resource divide" in AI research and has been developing a plan to democratize access to AI R&D for America's researchers and students and providing them with critical computational, data, and training resources through a broadly accessible shared CI.

ACKNOWLEDGMENT

The author is grateful for discussions with and thoughtful feedback from NSF colleagues about drafts of this article.

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Digital Object Identifier 10.1109/MC.2022.3195393