The Missing *Millions*

Democratizing Computation and Data to Bridge Digital Divides and Increase Access to Science for Underrepresented Communities

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We acknowledge the traditional owners of the lands where Washington, Maryland, and Virginia now stand–the Pamunkey, Chickahominy, Upper Mattaponi, Rappahannock, Monacan, and Nansemond. We pay respect to their Elders past, present, and emerging.

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Executive Summary

Research computing infrastructure—one component of what the National Science Foundation (NSF) terms *cyberinfrastructure* (CI)—has led the world in transformational ways, but with considerable gaps in services for software and data capabilities. Moreover, the composition of the people supporting and utilizing the cyberinfrastructure does not sufficiently represent the diversity of society. The scale of the challenge is reflected in what the NSF leadership and National Science Board (NSB) terms the "missing millions"—those who are yet to be engaged for the science, technology, engineering, and mathematics (STEM) workforce so that it reflects the racial, ethic, and gender representation in the general population. Broadening the accessibility of CI investments to reach the missing millions promises tremendous gains for the national research enterprise and its impacts on society (https://www.nsf.gov/nsb/committees/vision2020cmte/NSB-missing-millions-figure-063021.png).

The grant supporting this research, "EAGER: Democratizing the Use of Advanced Computational Resources (NSF OAC 2127459)," comes at a time when there is growing support to increase societal investments in science and technology. This report complements the White House Executive Order 13985 on "Advancing Racial Equity and Support for Underserved Communities Through the Federal Government," which highlights the central role of improved data in order to achieve greater equity across government agencies. This report also complements the White House Memo (27 August 2021) entitled "Multi-Agency Research and Development Priorities for the FY 2023 Budget" and addresses several R&D priorities. The 1950 founding legislation establishing NSF (Public Law 507) cautioned against "undue concentration of such research and education," and this report is designed to help deliver on this requirement. At stake are not just increased equity in science and engineering (S&E) investments, but also the new knowledge and beneficial impacts that will be possible when the missing millions are fully contributing to and supported by both the S&E enterprise and CI investments.

This study began with a long-term motivating question:

- ▶ How can NSF and other relevant stakeholders significantly expand, diversify, and support the development of new cohorts and communities of scientists and researchers to address pressing research, social, and global issues in 2030?

The research was supported by the Office of Advanced Cyberinfrastructure (OAC) at NSF, which has implications across the agency because all research directorates depend on cyberinfrastructure in many ways and because democratization of the cyberinfrastructure will have broader impacts across the S&E enterprise, including an increased ability to tackle research questions around equity. The study involved a total of 15 focus groups, and 6 additional individual interviews were conducted with 88 key stakeholders of research CI investments to more fully identify opportunities to democratize computation and bridge digital divides in ways that would better reach the missing millions.

Key findings in this report begin with the identification of many barriers that limit access to research data and computing, including cyberinfrastructure being undervalued and a culture that is not sufficiently inclusive. While there is a history of NSF efforts to increase access to high-performance computing (HPC) resources, the focus groups called for broader engagement and increased investment beyond traditional HPC. Institutions serving underrepresented communities need to be more fully included in NSF processes and CI investments. Focus groups consistently observed the need to continue support for computing innovations and to expand investments in services for software and data. This response includes capabilities reaching nontraditional fields and disciplines, as well as expanded support for facilitation services, both of which are necessary to achieve the awareness, interest, and ability of target groups to make use of these investments. Important innovation is happening in the way edge computing enables S&E, representing an important opportunity for community engagement. Focus groups called for NSF to experiment with bold ways to achieve broader impacts that include specific and long-range measures of CI engagement across target groups because incremental change will not be sufficient.

Taken together, the findings and paths forward in this report point to a mix of incremental changes and broader, systemic changes in the S&E enterprise. These include both shorter term (2–4 years) and longer term (5–10 years) suggestions, beginning with a commitment to inclusive access and experiments in how NSF operates. Data and software investments ought to be comparable to investments in computing. This means that the scope of funded CI research and capabilities will need to expand, and this includes investments in distributed data and edge technologies. Further, there is a need to foster dialogue, learning, and action to address forms of underrepresentation in those engaged in and by NSF's investments in

CI services. The results will involve accelerating what the NSF terms *broader impacts,* including advances in social and environmental sustainability and longer-term, inclusive approaches for community building as well as increased capacity to align common and competing interests of relevant stakeholders. Paths forward point to a need to more effectively bridge across NSF directorates and federal agencies as well as fostering multistakeholder consortia and partnerships.

A "Stakeholder Alignment and Action" template is provided in the appendix, along with guidance on relevant change management principles. These are designed to help support implementation of paths forward for which there is sufficient support. As one participant noted, the change will require early gains to build momentum, given the scale of the challenges: "There are so many things to work on—small steps are needed *because* the obstacles are huge." At the same time, this same individual urged a long-term commitment to achieve more than incremental change: "Our goal is to increase computing usage by an order of magnitude. We are focusing on the rate of change—focusing on the derivative. This is key for broader impacts."

Reaching the Missing Millions

The computing infrastructure for science and engineering (S&E) has advanced in world-leading ways over the past several decades, yet the composition of the faculty, staff, and students providing and utilizing this infrastructure does not sufficiently reflect society. Moreover, the needed infrastructure must include new, more distributed *edge* services for data engagement and computation, sustained investment in software and data sets, and vast arrays of capability-building services and capabilities that are broadly accessible in society. The leadership of the National Science Foundation (NSF) refers to this challenge as bringing in the "missing millions," whose voices and perspectives are missing from the S&E enterprise. On 4 March 2021, the National Science Board (NSB) passed a resolution to address the missing millions. In the field of economics, matching societal representation in the field of engaged professionals is seen as integral to addressing an expanded set of economic questions.

In the context of the cyberinfrastructure for science, addressing the missing millions includes racial and gender diversity as well as diversity in fields and disciplines served, inclusion of tribal communities, expanded access for citizen scientists, and applications of the cyberinfrastructure in ways that more extensively address broader impacts in society. All of this will take a concerted effort—democratizing computation and bridging digital divides.

Computing and data infrastructure—part of what the NSF terms *cyberinfrastructure*—is relevant to virtually all fields and disciplines and is essential for 21st-century science and research. Thus, progress (or lack of progress) in this domain is integral, impactful, and informative to any efforts to address the missing millions across the science, technology, engineering, and mathematics (STEM) workforce.

There is urgency in addressing these matters. We are in a postindustrial, digital era in which the pace of change with technologies is accelerating. At the same time, the COVID-19 pandemic has thrown into sharp relief social disparities and societal divides. Simply put, overall social institutions and broader engagement with diverse researchers, educators, and students in science and engineering (S&E), are not keeping pace with technology, and the gaps are widening.

The challenges are global, as reflected in the 17 Sustainable Development Goals articulated by the United Nations, the Ten Big Ideas articulated by NSF, the 14 Grand Challenges for Engineering in the 21st Century presented by the National Academy of Engineering, and other bold commitments across society. Together these commitments signal challenges that cannot be fully addressed by any one organization or societal institution. It is with these major challenges in mind that proposals are before the U.S. Congress to increase investments in NSF, with an expectation that science investment will deliver value on the major challenges facing society. Concurrently, on January 20, 2021, the White House issued Executive Order 13985 on "Advancing Racial Equity and Support for Underserved Communities Through the Federal Government." A key finding in the initial report to the President under Executive Order 13985 is the importance of using data to assess equity in the work of all federal agencies. The White House memorandum entitled "Multi-Agency Research and Development Priorities for the FY 2023 Budget" (27 August 2021) highlights the importance of developing measurable strategies to promote diversity, inclusion, equity, and accessibility across all R&D focus areas.

Taken together, the implications for NSF are clear—investments in S&E have to deliver more results, and they have to do so in ways that leverage the value made possible through increased diversity, equity, and inclusion.

From its founding, the 1950 enabling legislation for NSF (Public Law 507) called for a balance of research and educational activities but with a caution that the NSF should "avoid undue concentration of such research and education." In this context, the missing millions may be found in parts of research-intensive universities (classified as R1 institutions), as well as in R2 institutions: historically Black colleges and universities (HBCUs), tribal colleges and universities (TCUs), Hispanic-serving institutions (HSIs), and others. Without full engagement of the missing millions, there are fundamental questions for the S&E enterprise, including the following:

- What research questions are not being pursued?
- What talent is not achieving its full potential?
- What new technologies are not being advanced?
- What societal impacts are not being achieved?
- What innovation is happening but is not widely visible?

To identify the paths forward on reaching the missing millions and to democratize computing and bridge digital divides, we conducted 15 focus groups and 6 additional individual interviews with a total of 88 leading researchers, cyberinfrastructure professionals, and university executive leaders. Participants spanned engineering, mathematics, the sciences, the social sciences, the humanities, and other domains. The sessions were all lively and highly engaging, with participants posing questions about deeply embedded assumptions in S&E, including the following:

- What do we mean by "democratization of data and computing"?
- Who are the "missing millions" in data and computing, and what are their interests?
- Who is currently being served and how do they compare to the missing millions?
- Who is responsible for data and computing infrastructure?
- What is proper balance between "scientific merits" and "broader impacts"?
- How long should NSF funding last to achieve transformational change?
- What is the role of an NSF program officer in achieving broader impacts?
- What are the role and responsibilities of NSF review panels to advance broader impacts?
- How are investments in high-impact innovation different than investments in incremental science?

While many participants talked about the existing NSF programs or initiatives, such as the Extreme Science and Engineering Discovery Environment (XSEDE), the OSG (formerly Open Science Grid), the Campus Research Computing Consortium (CaRCC), and others, the sessions were not an assessment of current programs. Focus group participants did note that programs oriented around high-end research cyberinfrastructure were very useful and valuable in serving those researchers who need high-performance computing (HPC) capabilities. This is important, but the participants felt that the digital gap can only be effectively addressed by expanding beyond HPC and making the full spectrum of research cyberinfrastructure capabilities available to all users. Participants also pointed favorably to NSF programs such as Smart and Connected Communities (S&CC), Campus Cyberinfrastructure (CC*), Big Data Hubs, and the more recent Convergence Accelerator initiative, all of which explicitly seek broader impacts with diverse stakeholders. In this spirit, this report focuses on the entire data and compute spectrum, going beyond a traditional view of CI, advancing the infrastructure and the associated communities for science and engineering capabilities over a 5- to 10-year horizon.

To reach the missing millions, focus groups observed that NSF and other key stakeholders would need to experiment with alternative approaches, such as establishing small multiyear grants that would be given directly to HBCUs, TCUs, HSIs, and others to enable campuses to establish research initiatives that meet the research needs of the campus and their communities. These grants would combine planning, community building, and research coordination and enable these institutions to establish and develop new science efforts for their respective campus. Some focus groups used the concept of "block grants" in this context to signal the idea of investing in a campus in the same way that the NSF will invest in an early career scholar—providing a block of funds, with flexibility on its use (within certain bounds). This reflects the view that there may be talent that will not come forward to a traditional review process but that has great potential and is worthy of seed funding.

These *block grants* would shift much of the responsibility to the campus to identify and develop new science efforts. Similarly, focus groups pointed to the need to give greater weight to broader impacts for appropriate solicitations and a need for greater expertise in broader impacts on all review panels. This is consistent with the recommendation of NSB to include broader impacts experts on the Committees of Visitors. Note that achieving broader impacts involves greater engagement with diverse stakeholders, who will have common and competing interests (including distrust, by some stakeholders, of science itself). This is an expertise that needs to be fostered within NSF and in the research community.

Looking out a decade or further, some key elements of a success vision highlighted by the focus group participants included the following:

- **Ubiquitous Access:** Anyone would have access to the research cyberinfrastructure from anywhere—including ubiquitous compute, software, and data capabilities.
- **CI Spectrum:** The cyberinfrastructure would feature a broad spectrum of hardware, software, data, and community engagement capabilities, matched to diverse research needs, with supporting facilitation and capability-building services.
- **Advancing the "Edge":** Advances and innovations in what some term as *edge computing*—distributed entry points to hardware, software, and data for use in labs and in the field—will transform the conduct of S&E.
- **Data Leadership:** Research data would be treated as a "first-class research object," with digital object identifiers for citation, formatting standards, and supporting infrastructure approaches that support sustained accessibility and future interoperability.
- **Communities:** Diverse communities in society will be advancing research topics important to them while also building the next-generation cyberinfrastructure workforce—representing new sources of value in society.
- **Recognized Expertise:** Under-resourced colleges and universities lead innovations in outreach and inclusion as well as addressing research needs of their communities, and they partner with research-intensive institutions to broaden their scope and capabilities.

- **CI Careers:** There will be clear career paths for the human side of cyberinfrastructure—within universities, public agencies, and the private sector (commercial and not for profit).
- **Collaboration:** Collaboration around cyberinfrastructure would increase across NSF, among federal agencies, and with a wide range of consortia and public-private partnerships.
- **Broader Impacts:** The role of broader impacts would expand for appropriate NSF solicitations and include specific metrics that can be measured and evaluated for their impacts on society.
- **Success Indicators:** Gains and innovations in outreach and inclusion are visible and valued as strongly as technical innovations and investments in new "shiny objects."
- **Documented Results:** There would be documented evidence of millions of researchers from diverse communities—including researchers in nontraditional CI fields and disciplines, those at HBCUs, TCUs, HSIs, and other MSIs, citizen scientists, and others—engaged in the S&E enterprise who would not otherwise have been engaged, working on research topics that would not otherwise have been pursued.

With this vision in mind, many of the focus group participants indicated an interest in continuing and expanding the dialogue begun in the sessions. They saw reaching the missing millions not as a single event or initiative but instead as a long-term undertaking, and they indicated a willingness to help.

Findings

The findings reported here represent promising themes for democratizing computation and bridging digital divides in ways that will reach the missing millions. These themes emerged from multiple focus group sessions. One overarching finding is a call for systemic change. Incremental change was not seen as sufficient to reach the missing millions. In many cases, focus groups called for increased investments of one kind or another. In this context, it is important to avoid such investments being seen as redividing a fixed pie. Instead, achieving broader impacts has the real potential for expanding the proverbial pie as an increasing array of societal needs are addressed.

Overall findings are listed, along with supporting text and selected illustrative quotes, though discussion around each finding was brought up across multiple focus groups and interviews. Think of the quotes as being in dialogue with the text and not just as supporting evidence. There is increased supporting evidence in the field notes. Also, many of the findings are interrelated, so there are important connections to be found across them.

Finding 1
There are substantial barriers to access

Focus group participations pointed to many barriers to the democratization of computation and data, making it harder to bridge across digital divides and bring in the missing millions. This begins with limited infrastructure for internet connectivity, particularly for TCUs, HBCUs in rural locations, and other small colleges.

> " [Example of TCU with] considerable connectivity on campus but major connectivity problems trying to work with commercial deliverers of broadband on branch campuses in New Mexico and Arizona—one has no connectivity at all beyond a modem with telephone."

Beyond physical infrastructure, representatives from HBCUs, TCUs, and other underserved communities pointed to barriers further "upstream" in the K–12 system.

> " The larger issue is the STEM workforce that is not mathematically competent coming out of high school—there is not the teaching support at middle and high school, so there is a problem by the time that they get to an HBCU."

For the people who make up the cyberinfrastructure, focus groups pointed to the lack of clear career paths for research cyberinfrastructure professionals and a lack of rewards for research that informs key aspects of cyberinfrastructure, including data and community engagement.

> " There are institutional barriers—people are not rewarded for investments in data infrastructure."

A further barrier cited by many focus groups involves a cultural context about programs and initiatives that are relatively new because they are lacking long-term funding and institutional standing.

> " Cultural barriers are the hardest, and that has to be the primary focus. Campuses relegate programs to data science institutes that are in a start-up phase, sorting out resources and power. Anything that requires resources from people who have them will face barriers."

Finding 1—continued

There is also an unfortunate history of researchers extracting data from communities without returning value or, in deeply troubling cases, causing harm. Focus groups observed that this makes trust a challenging barrier.

> "There is a history in social science of 'using' communities and leave nothing—or, worse, we leave trauma and damage in the wake."

The issue of trust cannot be addressed easily or quickly. It is rooted in relationships built up over time, with follow-through on commitments. What is key for NSF is to support principal investigators (PIs) in this relationship-building work.

> "We started to work with one of the tribal colleges and learned we can help them with a GIS cluster. They have a challenge in even attracting basic IT people. We said we can support a GIS classroom. There were many challenges that emerged that we didn't expect. It was all Windows computers, for example, which is a barrier when it comes to HPC. Ultimately, getting the needed hardware was not the problem, and we are still meeting with them to overcome the gaps we have encountered. The key is building a trust relationship—that we are there, we care, and we will not go away. The Native Americans have a long history of disappointment with people coming in and making promises that are not kept. We will make a difference, and it is for the long-haul."

In society, science has been at the core of social progress while also being in the middle of social divides; this is perhaps the deepest barrier of all cited by some of the focus groups.

> "People have to care. Much of society doesn't care about what we do and at times doesn't even believe in what we do. This has to be addressed."

Finding 2

Accessibility = Access + Ability

Virtually all of the focus groups envisioned a future where access to compute and data resources was ubiquitous. At the same time, focus groups also observed that access alone was not sufficient.

> "It wouldn't matter what institution you are at to access resources for research computing and data."

Also essential are the skills and capabilities to utilize access. As one member of the research team noted, it even goes beyond "teaching people to fish" because many first need to know what fishing even is.

> "For scientists, the focus needs to be on training and building capability rather than just making access ubiquitous."

Focus groups pointed out that reaching the missing millions involved increased capability to work with data and software, which may involve coding skills. As we will see in Finding 8, there is a call for more accessible user interfaces for some forms of research so that coding ability is not a barrier.

> "Breaking down the divide between scientists who code and those who don't—the carpentries are helping, and new students are coming in with coding skills and the ability to sling data around, but there is still much work needed to build skill sets to work with data and many types of software."

Finding 3

Racial, gender, and other forms of underrepresentation in data and CI need to be studied, socialized, and addressed

All of the focus groups observed that underrepresentation by race, gender, and other categories was real and needed persistent and comprehensive attention to broaden the uptake and impact of CI.

> "In quantum computing, we are building an industry with a few companies, and the recruiting is not diverse, so we are building an ecosystem that will not look different from computing in general."

Finding 3—continued

Many of the comments on race and gender were strongly worded, pointing to deep and long-standing concerns, including the compensation and career pipelines for people using and providing CI for S&E.

> "The pipelines are broken in science. By contrast, we have a very effective pipeline from school to prison."

Not only did the focus groups talk about the barriers facing people in the science and engineering workforce, but they also pointed to disparities integral to big data. These disparities include various biases that are found in the data used to support machine learning.

> "Big data too often supports systemic racism, and something needs to change in order for this to change—data is not apolitical."

Finding 4

Insufficient engagement with underrepresented institutions

Many of the missing millions can be found in HBCUs, TCUs, HSIs, and other institutions with minority-serving populations and missions. Although examples of NSF engagement with these institutions do exist, participants in the focus groups reported the experience of mostly being on the outside, looking in—not finding the wording of solicitations, the dialogue in review committees, and other aspects of NSF operations as sufficiently welcoming and inclusive.

> "Think about alternative pathways—people are not getting access to computing resources because they don't go through the sanctioned doors."

Focus group participants observed that advances in the cyberinfrastructure and funding infrastructures so that they better support and engage minority-serving institutions will serve to democratize computation and broadens the research agenda.

> "If you want people from colleges on Native American reservations, HBCUs, smaller places that don't get grants, you have to develop the infrastructure, which is the long game."

Finding 4—continued

Focus group participants pointed to a wide range of research questions that would likely emerge from broader inclusion of the missing millions. These included issues of food insecurity, community water quality, and many other matters.

> " From Delaware to Texas, where we find most of the HBCUs, we also find food insecurity—so can we use the data to address these issues and move people out of food deserts?"

The missing millions can also be found in universities classified as R2 institutions and even in diverse fields and disciplines in parts of R1 research-intensive universities. This would include the computing, data, and software needed in the digital humanities and across the social sciences. Focus groups even pointed out that a pipeline to engage the missing millions is to be found among high school students and citizen scientists, most of whom do not have access to the cyberinfrastructure for research, even though they may have community-led research questions that would be important to pursue in partnership with well-resourced institutions.

> " Broader citizen science is a piece of this."

Finding 5
It is computing, *and* software, *and* data

Research computing is necessary because research often involves gathering, producing, and drawing insights from digital data. While there have been investments in successive generations of computing hardware to support work with research data, there has been far less investment in the data itself (curation, storage, access, interoperability) and in software sustainability (especially in contrast to National Institutes of Health [NIH] investments in key data, format standards, and software for working with them). In many respects, computing is actually secondary to data and software, but we have not treated it that way. This is, in part, why large-scale computing lacks sufficient on-ramps for researchers and students who have not developed computing, data, and software capabilities. They will not have skills in automatable and scalable practices or tools, such as coded data analysis or beyond-the-desktop data and computing services. These researchers are steps away from utilizing large-scale computing investments, may work with data or methods that do not need them, or may need computing solutions well-outside of traditional HPC.

A partial analogy to strategic shifts at IBM was discussed in focus groups. The company pivoting over time from a primary focus on computing, to software, and then to services. In contrast, many competitors were never able to make the shift and have now become footnotes to history. There are

Finding 5—continued

not exactly comparable dynamics in government, but agencies do become more or less important over time, depending on their ability to pivot in ways that add value in society. In the case of IBM, these transitions have involved considerable and difficult culture changes, which are comparable to the challenges faced by NSF.

> "When there is a need for new hardware, we have an idea how to project ahead—not as much with data and services."

Focus groups were particularly focused on the culture-change challenges associated with research data. These include a complicated mix of challenges including accessibility for proprietary data, Institutional Review Boards (IRBs) mindsets that limit the sharing and reuse of de-identified data, respectful use of sovereign data (such as tribal data), and infrastructure needed for data curation, storage, and reuse that satisfies access concerns. It was noted that industry is racing ahead with commercial applications of data, which provide both an opportunity and a threat to the infrastructure for research data. It is an opportunity, focus groups noted, in that groups of researchers and universities can make the business case for private-sector investments in infrastructure services and data collections. It is also a threat in that commercial applications may only be developed where there is a broad market, crowding out innovations in research software and services for novel data sets and research areas.

> "This is a 'pull the pin' on the grenade moment. A billion dollars a year is needed for the data infrastructure to extract insights from data—that would be pulling the pin on the grenade."

There was also attention given to software, particularly open-source software, as part of democratizing computation. This is a complex domain in which the open-source movement does advance the principles of open access, but open-source software generated through NSF grants does not always achieve usability standards needed for broad use. It is also complex in that the open-source domain is intertwined with commercial business models that represent sustaining support only where it advances commercial interests.

> "There is a need to organize the open-source communities. After grants, there is no support. Google does take care of some open-source software, but it has to match their business model. Universities may or may not have people who can do so. Open-source community support is needed."

Finding 6
More diverse fields and disciplines need support

Many of the focus groups cited increased demand for research data and computing infrastructure beyond the fields and disciplines that have been long-time users of classical HPC (astrophysics, computational chemistry, geosciences, atmospheric research, etc.). These include the increased use of data in the social sciences, the digital humanities, and other societally relevant domains. As a result, the cyberinfrastructure workforce needs to bridge across more diverse fields and disciplines.

> "Beyond HPC to computational diversity. Disciplines that haven't needed computational efforts in the past now do."

This also means that researchers have to anticipate applications of data outside of their primary field and discipline, which places a greater premium on metadata and ensuring findability, interoperability, and other qualities. It also means that there need to be incentives and support for these researchers to invest the time in making their data reusable to others.

> "It is important to understand how communities different than yours might want to use your data."

In smaller colleges and universities, there are less likely to be many researchers with similar research and infrastructure needs, so these parts of the missing millions will need an infrastructure that spans across colleges and universities enabling collaboration across diverse fields, geographies, and institutional boundaries.

> "The community at a smaller institution may be more limited—so how to bridge across multiple institutions?"

Finding 7
Facilitation successes need expansion

There was widespread appreciation across the focus groups for the work of research computing and data facilitation, referring to human infrastructure to provide personalized guidance for researchers in their pursuit of relevant CI services. Awareness of the need for facilitation and facilitators has grown since the national introduction of the term Advanced Cyberinfrastructure–Research and Education Facilitators via the similarly named NSF Advanced Cyberinfrastructure–Research and Educational Facilitation (ACI-REF) project, and with national networks forming around facilitators and other professional CI roles within organizations such

Finding 7—continued

as Campus Champions and the Campus Research Computing Consortium (CaRCC) People Network, among others. Focus groups pointed to the need for facilitation services to be more broadly available across research-supporting institutions, including specific and deliberate investments for HBCUs, TCUs, HSIs, and other minority-serving institutions.

> "A need for more campus champions with HBCUs and other minority-serving entities."

Importantly, research data and computing facilitators include a higher proportion of women than the broader field of computer science, though concerns were also expressed around the lower pay for people doing data consulting and curation, for example, as compared to data analytics, where the gender gap and pay gap remains more significant.

> "Look at the Whiteness of the profession. Look at the opposite gender issues in the library profession, with stereotypes and implications around pay."

A common concern across focus groups was that these professionals often lack well-defined career paths on campuses. As a result, there is high turnover as many are hired away by industry. Focus groups did observe that it is consistent with the mission of the university to provide talent to industry, but the disruption of turnover can be mitigated with better career paths. Further, these careers do not precisely fit in the campus information technology (IT) function or within the purview of many vice presidents of research. As a result, the cyberinfrastructure workforce is hired in through many channels, often with soft funding, resulting in instability on the human side of infrastructure.

> "Career paths with data and computing [need to be] clear and widely evident—especially for community colleges and HBCUs."

In time, focus groups could envision a world where access to research computing and data was so ubiquitous that facilitators would be needed less; for the short and medium term, however, an expansion of facilitation services (especially for more general data and compute capabilities) was required. Focus groups pointed out that practical expertise needs to be more highly valued.

> "Lip service is paid to nontechnical expertise."

Finding 8

Distributed/edge computing is expanding

All focus groups discussed innovations in what some term as edge computing, such as Jupyter notebooks that bring computing and data infrastructure right into the laboratory or the field, where research is being conducted. Another example lies in the cooperative computing ecosystem of the OSG, with contributed computing capacity, data, and access points distributed across numerous campuses. The associated infrastructures and interfaces are very different than those needed for "big iron" HPC and have the potential to reach many of the missing millions.

> "Jupyter notebooks have been a revolution."

Many focus groups highlighted the importance of Graphical User Interfaces (GUIs) that do not depend on command line programming when it comes to reaching the missing millions. They pointed to the ecosystem of apps that emerged when Apple eliminated the command line with personal computers (and noted how many computer science professionals criticized the change at the time). There was comparable debate in focus groups around a more accessible infrastructure, making research choices less visible with a "black box" approach. It was noted, however, that there is a spectrum of applications for research computing and data, some of which will still require command-line control for automation and scale. Other controls are possible, but the key point of the focus groups was that the present research computing and data ecosystems look impenetrable to many of those not yet engaged.

Industry partnerships were highlighted by a number of focus groups as holding great potential to foster innovations in making research computing and data more accessible "at the edge."

> "Go to Raspberry PI and have them build an ecosystem for software tools and technologies in every high school."

Finding 9

There is a need for NSF to be more open to experimentation with pilots and by partnering with existing communities that reach the "missing millions"

All of the focus groups pointed to conservative review panels as a barrier to reaching the missing millions, prioritizing proposals from known sources with known approaches.

> "The money is not there—the people on the review panels say that is not how we do that—they don't want to take a chance with new models. We need innovative research teaming approaches."

Finding 9—continued

With an experimental approach, short-term gains can be demonstrated, which will build trust.

> "Trust has to be built with small steps. It is critical that things happen early on, with clear accomplishments. They have to all stream to a more inclusive society in 5 or 10 years, but we need a few waves to be created before it becomes a full ocean."

In order to reach the missing millions, focus groups observed that NSF might explore and experiment with alternative approaches, such as "block grants" to HBCUs, TCUs, HSIs, and others; seats on review panels focused on broader impacts; and other experiments. The idea behind block grants is to combine planning, community building, and research coordination and to enable these institutions to establish and develop new science efforts for a campus or community. It was noted that this would be an experimental approach consistent with the principles of science, wherein NSF could review to see which funding and engagement approaches are most successful. It would not involve randomized controls in the classical science approach but instead would involve designed innovations, with observation and learning on impacts.

> "A science-based approach [is needed for] science funding."

Finding 10

Systemic change is needed

All of the focus groups indicated that reaching the missing millions will not happen through incremental adjustments alone (which are important, but insufficient). Systematic culture change was highlighted as necessary.

> "We need systemic change."

Focus groups stated that NSF would need to "roll up its sleeves" and "get its hands in the dirt" to achieve the needed change. This will involve not just an "arm's length" administration of grants that focus on helping to reduce the digital divide but will require significant engagement with researchers so that they can achieve the necessary broader impacts and become sustainable efforts. This represents a fundamental challenge for the field of computer science, which has historically focused only on leading-edge challenges rather than on applied tools and

Finding 10—continued

methods. Too often, computer science professionals see cyberinfrastructure as "working on the plumbing" rather than as leading-edge research. Equally, social scientists are too often less interested in helping to lead change as compared to tackling problems that are current in the field. There are researchers who embrace learning from applied challenges; they will be key to reaching the missing millions.

> "Computer science is the worst thing to have happened to computers and to science. There is a profound problem with the de-coupling of computers from the physical world. A need to integrate more deeply in society."

Many of the focus groups pointed to the operation of review panels as a key barrier to achieving the needed broader impacts in society. Review panels tend to focus primarily on scientific merits rather than a balance of scientific merits and broader impacts.

> "Doing broader impacts is work that requires expertise. Example of an NSF panel where everyone was able to assess scientific merits but no one had expertise in broader impacts. There should be a seat on review panels for broader impacts."

There was enthusiasm within the focus groups and a desire to continue this dialogue of systemic change. In this respect, this project has surfaced the initial contours of a community of practice committed to reaching the missing millions across cyberinfrastructure ecosystems.

> "I am hopeful that this will create change. Too often, agencies have these conversations and still do business in the same way—with no change. There needs to be a change in who gets funded and who doesn't. Most review panels haven't heard of many of the HBCUs."

Paths Forward

To make progress in reaching the missing millions, 12 overarching paths forward are provided, each with suggestions and illustrative quotes. The quotes have been selected to motivate the paths forward. They are not offered as complete evidence on these points—though many points were repeated multiple times across the focus groups. Instead, think of these quotations as being in dialogue with the paths forward, selected as thought starters rather than as conclusions.

Many of the paths forward are interrelated. As a result, paths forward could be combined together in various ways for overarching initiatives.

Of course, each of these paths forward and suggestions will involve consideration across various combinations of stakeholders. Toward that end, some change management principles are provided in the appendix. In this sense, the paths forward, suggestions, and quotes are all intended to serve as thought starters, with dialogue, engagement, adjustment, and action to follow. In this context, it may be helpful to consider which opportunities might point to short-term initiatives (2–4 years) and sustained longer-term initiatives (5–10 years). We gleaned suggestions on timing from focus group participants, though some could happen more quickly and some could take considerably longer.

Paths Forward

1. Ensure inclusive access
2. Experiments in NSF and other public and private funding operations
3. Elevate data and software to match computing investments
4. Engage in long-term, inclusive community building
5. Expand the scope of funded research
6. Enable distributed, edge technologies
7. Ensure racial, gender, and other forms of inclusion
8. Accelerate broader impacts
9. Advance social and environmental sustainability
10. Bridge across directorates and federal agencies
11. Foster consortia and partnerships
12. Advance dialogue by NSF and other agencies' leadership

Path 1
Ensure inclusive access

Shorter-term initiatives (2–4 years)

Path 1A: Expand investments in apprenticeships, internships, and training grants to provide underrepresented students with the ability to participate in CI and CI-dependent research efforts.

▶ This in turn may require some funding support to a campus as well as support to individual faculty to mentor these students. It will also involve partnerships with employers, which may be in higher education, in the private sector, in government, and in the nonprofit sector. All are domains where data and computing are of great and growing importance.

> " Four things that need to happen to increase impact with HBCUs: (1) apprenticeship programs (students from HBCUs need to have an experiential component); (2) training grants (experience from the NIH world in biomedical sciences—helping bring students from diverse backgrounds into graduate programs, reduce debt, and provide experiential training); (3) workforce development through internships and job opportunities, so students can get into the marketplace with career-related employment; (4) research (joint research programs with part of the research centered at the HBCU)."

Path 1B: Document and make visible the full spectrum of research data and computing resources that can help researchers to do their science, especially since there is no one size or approach that fits all needs.

> " There might be more clearly defined computing environments for different applications. HPC is needed at the top end for climate models, etc. Are there other configurations of computing that are more accessible for other types of questions—desktop connected to a cluster for computing? A spectrum of options—matching the resources to the research questions."

Longer-term initiatives (5–10 years)

Path1C: While current initiatives providing access to high-end research computing resources are still critical, significant additional investments are required in software, data, and computing services that are easier to use and do not require large-scale resources.

▶ For example, one participant called for a translator into and out of CSV files—something that is needed by vast numbers of researchers but is not seen as the type of investment that federal research funders would make. If there is not a commercial market for such a tool, what should the role of NSF and other funders be? Further, many researcher needs center on software, data, and computing services—expertise on what to do rather than just the hardware to do the research.

> “ Access to technology is less [of] an issue compared to access to expertise.”

Path 1D: Ensure that research investments integrate to achieve a frictionless workflow across the data, software, and computing infrastructures.

▶ For example, in some cases, this may require more attention up front on common approaches and standards to ensure some level of interoperability. Establishing the standard need for a frictionless workflow is not just a matter of announcing standards but of supporting the full process of community engagement and adoptions.

> “ Key is frictionless research computing and data. Look at the entire pathway that data flow. Friction points will be technical and cultural. More generally, [reduce friction in] how we integrate data, compute on data, share data, and store data—all have multiple elements associated.”

Path 1E: Explore investments in research computing and data infrastructure that do not require command-line expertise, while still building in relevant transparency and controls (to avoid it being a “black box” approach).

> “ Lower barriers to entry, but build up the controls at the same time.”

Path 1F: Develop entry-point mechanisms for K–12 students, undergraduates, and educators at these levels to explore what can be done with research data and computing.

▶ This includes discovery as well as applications and tools that may be low technology but high value for the science they want to pursue.

> “ Creating entry points and support systems is key to start. A discovery platform is important, but only if students know what they are looking for. That’s the challenge—helping people to figure out what they are looking for. It is helping people to know what options are there.”

Path 2
Experiments in NSF and other public and private funding operations

Shorter-term initiatives (2–4 years)

Path 2A: Experiment with "block grants" to HBCUs, TCUs, HSIs, and other minority-serving institutions, along with associated consortia, to support innovations and incremental science with research computing and data.

▶ The "block grants" approach gives these campuses the institutional capacity to identify and develop research interests that are germane to their community and to support complementary efforts at the regional and national levels. This approach contrasts with a grant to a specific researcher for a specific study. Instead, it represents support to a campus or community to then distribute the funds for a portfolio of projects.

> "Put money in the hands of minority communities—not insisting on original research propositions but engaging students and faculty, leaving [it] to them to generate the research projects."

Path 2B: Experiment with solicitations, request for proposals, and review processes that give greater weight to broader impacts.

▶ For example, some solicitations might be set up with three-quarters of the weight given to broader impacts (where that is aligned with the aim of the solicitation). Similarly, review panels could have a designated seat for experts in broader impacts. This would be consistent with the NSB decision to add "broader impacts" expertise to Committees of Visitors. Building new vibrant research communities may be the most effective way to improve the science or accelerate innovation and adoption, which would require that greater weight and expertise be given to broader impacts.

> "Experiment with reviews that give greater weight to broader impacts [relative to scientific merits]."

Path 2C: Increase the flexibility provided to program officers with Grants for Rapid Response Research (RAPID), EArly-Concept Grants for Exploratory Research (EAGER), CC*, Research Coordination Networks (RCN), and other grant types focused directly engaging and reaching the missing millions.

▶ For example, the RAPID grant vehicle might be one way to jumpstart research efforts in specific communities where climate impact is a large local issue (e.g., ocean rise for indigenous communities, water resources for arid areas, adverse environmental impacts of zoning laws). The CC* program might be expanded to help campuses with "pre-access" issues and plans.

Path 2—continued

EAGERs may be broadened to include seeding the development of nascent or potential research efforts at small institutions and those that are digitally underdeveloped. Research Experiences for Undergrads may be expanded to include supporting internships for students at underrepresented institutions to engage in research at other federal agencies and labs. Internships could include travel funds to attend conferences and workshops.

> "What is the most important gets the most funding. Look at what the NSF is spending money on as an indication of where the priorities are. The budget should reflect a commitment to the missing millions if that is the priority. People want the outcomes but are not investing the time and money. It takes time, money, and relationships/networks to have impact."

Longer-term initiatives (5–10 years)

Path 2D: Foster an "investment portfolio" mindset within the culture of the NSF and the larger S&E community to include a greater proportion of "high-risk, high-reward" initiatives aimed at reaching the missing millions.

▶ If NSF is explicit about its intent to broaden science engagement, the research community can help ameliorate risk by helping to define what success should look like.

> "Accept some degree of failure. Think of this like a portfolio—not everything will pan out. Move on when something doesn't work or will take 10 times the effort."

Path 2E: Ensure "check and adjust" mechanisms and integrative adaptation so that positive lessons learned can be incorporated into NSF and other public and private funding operations.

▶ This also means that in these cases, program officers will have more responsibility throughout the life of the grant. This is very similar to the approach of the Convergence Accelerator Program.

> "It requires a dependence on people more like the DARPA [(Defense Advanced Research Projects Agency)] model—people are adaptable—[they] will be all over social and technical change faster than the [National Science] Foundation can be."

Path 3
Elevate data and software to match computing investments

Shorter-term initiatives (2–4 years)

Path 3A: Experiment with grant mechanisms that support, develop, and sustain the usability of services for computation, software, and data in cyberinfrastructure, with a focus on reproducibility, interoperability, extensibility, and sustainability of these capabilities.

> "Grants require innovation rather than stabilizing, hardening, and standardizing tools."

Path 3B: Pioneer innovations in the infrastructure for open and consistent sharing and reuse of data and software not only for current research but also for the next generation of researchers and scientists.

- ▶ This may mean much more focus on the tough technical and social issues to make data useful for anyone.

> "We need to be better at sharing digital artifacts—data and software. Better as sharing experiments—reproducibility. People share research by sharing papers, but to share and reuse data, you need infrastructure. Reproducibility is part of democratization."

Longer-term initiatives (5–10 years)

Path 3C: Balance investments in new technology innovations, with investments in sustained services and innovative approaches for the diffusion and adoption of new technologies.

> "Decisions about what is funded and prioritized should reflect interests in a democracy—not limited to the views of academics at the front of their field. It is not the newest thing—shiny objects—what about sustainability of technologies, usability of technologies?"

Path 3D: Ensure that useful and usable data can be found and utilized by anyone, anywhere.

> "Lower barriers to pushing data on many different platforms—big data will be scattered in many different platforms—there will need to be a data network with many different ways to find and combine data."

Illustrative Example as Thought Starter:

Assist with equity data infrastructure supporting efforts of federal agencies under Executive Order 13985, "Advancing Racial Equity and Support for Underserved Communities Through the Federal Government." Promote research with the equity data in ways that are consistent with the mission and legal considerations for each agency.

Path 4
Engage in long-term, inclusive community building

Path 4A: In seeking "community input" on research priorities, define community broadly to include underrepresented voices so that the research priorities reflect their interests.

▶ For example, NSF "Dear Colleague" letters and other forms of outreach by funders may not reach researchers who are not at research-intensive institutions, so more proactive forms of outreach are needed. For many next generation researchers, an emphasis on social impact will be particularly important as that is being given increasing weight in career decisions.

Path 4B: Foster dialogue on aspects of the NSF research data, software, and computing portfolio that would benefit from a longer-term horizon.

▶ The NSF knows how to take a long-term view to major science instruments, such as telescopes, ships, and other long-term investments. Similar thinking is needed for the culture change associated with reaching the missing millions. This includes communities of practice around the sharing and reuse of research data, the community support needed for open-source software generated through NSF grants, and the communities of practice associated with all aspects of research computing.

> "Focus on research that makes a difference in people's lives."

Path 4C: Experiment with longer-term missing millions grant formats like early career awards (investing in the person, or the institution, with flexibility on the research focus).

▶ This connects to Path 2A and other discussions of "block grants."

> "A cultural challenge requires a minimum horizon of a decade."

Longer-term initiatives (5–10 years)

Path 4D: Experiment with the establishment of community IRBs (possibly linked to university IRBs) that are proactive and responsive in governing the use of research data involving human subjects in their community.

▶ This raises a challenge around the FAIR data principles (data that are Findable, Accessible, Interoperable, and Reusable), on the one hand, and issues of data sovereignty in tribal communities and confidential data more generally, on the other hand.

> "Attempts to go into communities to collect data could be met by community IRBs in minority communities so [that] they can control the research about them."

Path 4—continued

Path 4E: Learn from and incorporate the long-term thinking of communities in the research data and computing ecosystem (such as the Long-Term Ecological Research Network [LTER], TCUs, and others).

> " A need for longer time horizons—the Menominee Tribe works on a seven-generation timeline."

Path 4F: Build expertise in participatory research methods for program officers, current grantees, prospective developers of proposals, and other stakeholders.

> " Research methods and deployment methods that are participatory are key—not designing for communities but designing with them. The NSF could fund people to work with communities in this way. A much more substantive approach than what is typically in 'broader impacts.' Agile processes that take into account participatory design."

Illustrative Example as Thought Starter:

Develop a solicitation centered on reaching the missing millions with computer, software, data, and service infrastructure, with additional weight given to broader impacts in the review process.

Consider NSF funding of facilitation roles that can evolve with a community, such as a community data manager or a local data assembly engineer. Once started, these roles may become supported as "local infrastructure."

Path 5
Expand the scope of funded research

Shorter-term initiatives (2–4 years)

Path 5A: Adopt a "clean sheet" approach to identify promising new research computing and data investments.

▶ For example, the compute power of many edge and personal devices (smartphones, laptops, notebooks, smart sensors) have enough capability to analyze and compute data at the local or personal level without requiring access to traditional HPC resources. This opens new paradigms for computing approaches as well as new paradigms on data investments. It also puts a premium on a sufficient networking infrastructure.

> "Increases in computing power have led to expanded capabilities but no change in how we think about computing—how might we rethink this if we were designing computing today?"

Path 5B: Use social impact language in research solicitations to bring in a broader, more diverse set of CI-relevant proposals.

▶ For example, if use of cyberinfrastructure capabilities can be harnessed to help address issues of climate impact or severe weather events on local communities, this opens up new research pathways for students and faculty that want to help their communities and campuses. Further, there is increasing evidence that climate change, the COVID-19 pandemic, and other broad societal challenges are revealing disparities that are deeply felt by the missing millions.

> "There is interest in social justice and climate issues—so the link to computation should be more clear."

Longer-term initiatives (5–10 years)

Path 5C: Expand the scope of research solicitations to more fully take into account the societal impacts of data and computing technologies.

▶ For example, the cost of cooling for major compute and data storage installations continues to rise, and it is important that research efforts to address the total cost (power, environmental, social) be supported. Note that this path is directly linked to Path 8 on social and environmental sustainability.

> "The research community should take into account the environmental impact of computing—can we be on the cutting edge on the impacts of computing?"

Path 6
Enable distributed, edge technologies

Shorter-term initiatives (2–4 years)

Path 6A: Invest in cyberinfrastructure and community laboratories at the "edge," enabling broader and more diverse participation in science and engineering.

▶ For example, what can be done to support research efforts that do not require large-scale computing and data resources? Community robotics competitions, fabrication laboratories (fab labs), and maker spaces have all demonstrated the power of project-based learning as an entry point for STEM. This path raises the idea of comparable forms of engagement for additional aspects of S&E. As was discussed in an early career workshop as part of the NSF EarthCube initiative, could there be an interface like Google Earth with geoscience data available as you zoom in and zoom out around the planet?

> "The interface will be as much of an improvement as was Microsoft Word—not needing to know specific codes to do writing."

Path 6B: Explore investments in research computing and data infrastructure approaches that are easily accessible (such as GUIs, science apps, and field tools).

▶ Not all research computing and data applications can be utilized without command-line programming, although more could, and that would increase access to some of the missing millions. This relates to Finding 8.

> "Are there ways for people to take advantage of computing without having to know programming? A high school student in a well-resourced school today has access to 3D printers in the library, and they have apps that help them with the design work."

Longer-term initiatives (5–10 years)

Path 6C: Build a ubiquitous research data and computing infrastructure (widely distributed and accessible regardless of university or college infrastructure resources).

▶ Drawing on Finding 2, while having access to these resources is critical, unless there is a parallel effort to enable users in how to use these resources, these efforts will never adequately scale. The effort also has to include significant focus and support in how to maintain the software and the data for broad societal research for the next generation.

> "Closing a digital divide implies movement toward equal access. Beyond equal access is equitable access—people needing more help get more help."

Path 7
Ensure racial, gender, and other forms of inclusion

Shorter-term initiatives (2–4 years)

Path 7A: Experiment with language in data- and compute-relevant solicitations and other initiatives that will draw in underrepresented organizations and individuals.

▶ For example, promoting access to and use of the latest scientific instruments works well for researchers already in the club. For students and faculty who do not have experience or existing expertise with the instruments and resources, access and use are meaningless. New initiatives and pilots need to start with helping end users to solve problems in which they are interested. In some domains, the underrepresentation may be based on gender, race, first-generation status, type of institution, or other factors.

> "What brings in people who are underrepresented? The topics need to be of interest to them. If you say 'robotics,' you will draw boys; if you say 'solving global challenges,' more girls will come."

Longer-term initiatives (5–10 years)

Path 7B: Experiment with cross-institutional partnerships to support underrepresented, next-generation scholars along professional development pathways.

▶ For example, what can be done to help support the development of vibrant communities (virtual or otherwise) that will enable students and faculty at underrepresented institutions to find ways to develop relationships with people at other institutions with similar interests?

> "It is really important to support people on the journey so they don't quit. It is easy to think 'I don't belong here' if you don't see people like you, and that is when people are more likely to quit. It is not just about getting them in the door but also about giving them support along the way."

Path 7C: Explore research investments that will deepen understanding of the broader impacts of artificial intelligence (AI) and related technologies in generating and ameliorating racial, gender, and other disparities.

> "Machine learning and access to machine learning models and infrastructure is a big issue. Establishing pathways for access is important. There are commercial machine learning platforms that underpin so much of what is happening and people are not able to understand what is happening. There is not transparency, and how to be sure that bias is not being incorporated."

Path 8
Accelerate the broader impacts

Shorter-term initiatives (2–4 years)

Path 8A: Document and learn from past awards and efforts of all relevant agencies that have done an outstanding job in achieving broader impacts relevant to technology adoption.

▶ For example, agencies that require broader impacts could conduct an internal review of those awards that have had success in achieving broader impacts to learn what has worked well, what sort of broader impact metrics should be encouraged and supported, and what change management processes might be utilized.

> "The global network of over 2,000 fab labs began with an NSF research grant on digital fabrication. The first fab lab in 2002 was part of broader impacts on the NSF grant. It was not a top-down science vision on what should be done with digital fabrication but [was] more practical in providing people with tools and then seeing what can be accomplished. The network grew from there, doubling every 18 months."

Path 8B: Provide technical assistance to prospective PIs on effective ways to address broader impacts in proposals.

▶ For example, as the following quotation suggests, a proposal could begin with broader impacts rather than with scientific merits. This is a small change, but it sends an important signal to review committees.

> "The challenge of with broadening impacts is that it has to be part of the proposal, but that is usually the end of things. There is no accountability. We know that if we start a proposal with the technical aspects, the reviewers will never get to the community aspects. So, we start proposals with broader impacts. Most don't, but if you start with broader impacts, that then becomes the first thing to be discussed in a review."

Path 8—continued

Longer-term initiatives (5–10 years)

Path 8C: Approach broader impacts with the same level of methodological rigor given to scientific merits.

▶ For example, a subset of awards would support a diversity of new and experimental approaches for achieving broader impacts. This would reinforce and extend the commitment by NSB to include broader impacts experts on the Committees of Visitors.

> "Broader impacts should be professionalized on how to do this."

Illustrative Example as Thought Starter:

A Broader Impacts Initiative—Bring together relevant NSF and other agency program officers (possibly in combination with outside experts) to develop guidelines and training on achieving broader impacts. Form a broader impacts resource team within NSF and other agency. Establish broader impacts seats on review panels. Designate certain solicitations as having a greater weight given to broader impacts.

Path 9
Advance social and environmental sustainability

Shorter-term initiatives (2–4 years)

Path 9A: Identify and support sharing of innovations in reducing the carbon footprint of research computing.

▶ This connects to Path 4C, which also concerns research on the environmental impacts of HPC. It is also part of a high priority given to social impact on the part of next generation researchers.

> "The research community should take into account the environmental impact of computing—can we be on the cutting edge on the impacts of computing?"

Longer-term initiatives (5–10 years)

Path 9B: Develop long-term sustainability models for community-building initiatives.

▶ For example, the standard 3-year award that focuses on innovation is at odds with developing communities as awardees are expected to come up with new innovations for the next 3-year award in order to continue to build and develop on what they have started.

> "Community building takes longer than a 3-year or 5 year grant."

Path 9C: Pioneer distributed, environmentally sustainable approaches to research computing.

> "Data clusters need lots of water for cooling, and we have not been able to solve this—it is a real problem for the Navajo, Zuni, and Pueblo Nations."

Illustrative Example as Thought Starter:

Develop solicitations and requests for proposals that look beyond planning, development, and deployment to emphasize long-term adoption and diffusion of innovation.

Path 10
Bridge across directories and federal agencies

Shorter-term initiatives (2–4 years)

Path 10A: Review recent success with cross-directorate or division initiatives in funding agencies to identify implications for solicitations, budgeting, leadership, and other matters relevant to cross-cutting research data and computing initiatives—elevating relevant cyberinfrastructure (social and technical) as a foundational agency-wide resource.

> "There is a great opportunity for interagency collaboration—multiple agencies are funding science in many domains, and there are benefits if the infrastructure is more broadly shared."

Path 10B: Identify policy constraints and enablers associated with interagency collaboration, educating program officers, PIs, and other relevant stakeholders on what is and is not possible.

> "The problems in higher education are very siloed—you have to get rid of the silos. The same is true with government agencies. NSF needs to collaborate more with FAA, NOAA, NASA, NIH, DOD, OSTP—cyberinfrastructure is cross-cutting. Otherwise, you will not have the resources you need—you will only be talking to yourself."

Illustrative Example as Thought Starter:

Coordinate across federal agencies involved in bringing broadband connectivity to rural locations to include use cases around community access to relevant research data (a parallel to public access channels for cable television).

Path 11
Foster consortia and partnerships

Shorter-term initiatives (2–4 years)

Path 11A: Map the ecosystem of consortia associated with research computing and data, and then develop mechanisms for sustaining and coordinating among them.

> "There are many consortia and networks: CaRCC, Campus Champions, etc.—but it takes hard work to sustain."

Longer-term initiatives (5–10 years)

Path 11B: Identify and support innovations in bridging research computing and data services across fields and disciplines.

> "How to build 'porous membranes' across communities? You need something more than getting snippets of code from GitHub—you need a guide and helper when bridging across domains."

Illustrative Example as Thought Starter:

Many of the consortia associated with research computing and data have been launched with NSF Research Coordination Network (RCN) grants, which have been effective as sources of seed funding. Companion sustaining grants could be explored that support innovations in scaling and sustaining the work of RCNs.

Path 12

Advance dialogue by NSF and other agencies' leadership

Shorter-term initiatives (2–4 years)

Path 12: Foster and expand dialogue and action with the OAC Advisory Committee, the Computer and Information Science and Engineering Advisory Committee (CISE AC), NSB, and others.

- Note that NSB has embraced the importance of reaching the missing millions and increasing capability around broader impacts.

> "The National Science Board should advance this conversation. There should also be town halls on the missing millions hosted by professional societies. This will need a broad coalition and a long horizon."

Methods

Research Process:

- Eighty-eight researchers, cyberinfrastructure professionals, and campus leaders participated in 15 focus groups and 6 individual interviews.
- The individuals were selected based on recommendations from the research team, NSF program officers, and participants in some of the sessions.
- The aim was to include early career, mid-career, and long-term career thought leaders from diverse fields and disciplines, as well as R1, HBCU, TCU, and other settings. We sought out tenure track faculty, cyberinfrastructure professionals, university leaders, community leaders, and others.
- The sessions were not recorded so as to foster open discussion. There were two note takers at each session. During the sessions, the notes were periodically shared with subjects for transparency and to prompt additional thoughts.
- The session notes were mined for key themes and illustrative quotes, some of which have been selected for inclusion with this report.

Interview Protocol:

- **Success Vision:** If OAC and NSF more broadly were fantastically successful over the next decade in democratizing research computing and achieving broader impacts, what would be key elements of that success? Focus less on the specific technologies (that is next) and more on what the technologies are enabling? Consider "what if" and "why not" statements. Do not limit your thinking to current NSF funding and priorities—think out of the box on this.
- **Specific Technologies:** What new computing and data technologies will be integral to this vision? What technologies do not exist but might be compelling and impactful? What are new or nontraditional research applications that we might consider?
- **Communities of Practice:** How can we build diverse and inclusive communities of practice associated with advanced computing technologies? How can we make more than incremental advances in terms of democratizing computation? What will it take for innovation to be community driven on a continuing basis?

- **Barriers:** What do you see as organizational, institutional, and societal barriers to the success vision and the technologies? What would be failure modes, deep problems, risk, or unanticipated aspects of potential future computing technologies in society that we should worry about?
- **Anything Else:** Are there any other comments and questions that you would like to share?

Participants in 15 Focus Groups and 6 Individual Interviews:

- Researchers/Scholars and Administrative Leaders in Mathematics, the Sciences, the Social Sciences, the Humanities, and Other Domains
  - For example, Karen Baker (U. Illinois, Urbana-Champaign), Helen Berman (Rutgers U.), Marcus Bond (Southeast Missouri State U.), Karen Camarda (Washburn U.), Joel Christianson (Brandeis U.), K. C. Claffy (U. California, San Diego), Dirk Colbry (Michigan State U.), Alex Feltus (Clemson U.), Kim Fortun (U. California, Irvine), Sandra Gesing (U. Notre Dame), P. Bryan Heidorn (U. Arizona), Laura Jiménez (Boston U.), Kate Keahey (Argonne National Laboratory), John Leslie King (U. Michigan), Julia Lane (New York U.), Kerstin Lenhert (Columbia U.), Jon McKenzie (Cornell U.), Mariofanna Milanova (U. Arkansas, Little Rock), Sarah Nusser (Iowa State U.), Timothy Rogers (U. Wisconsin, Madison), Raj Sampath (Brandeis U.), Namchul Shin (Pace U.), Douglas Thain (U. Notre Dame), Pipps Veazey (U. Maine), Frank Vernon (U. California, San Diego), Susan Winter (U. Maryland)
- Early Career Scholars
  - For example, Kayhan Batmanghelich (U. Pittsburgh), Joao Rebourcas Dorea (U. Wisconsin), Michael Maffe (Penn State U.), Nadya Peek (U. Washington), Benjamin Smarr (U. California, San Diego), Gretchen Stahlman (Rutgers U.), Erik Wright (U. Pittsburgh)
- HBCU Leaders, Faculty, and CI Professionals
  - For example, Cajetan Akujuobi (Prairie View A&M U.), Richard Alo (Florida A&M U.), Venkata Atluri (Alabama A&M U.), Damian Clarke (Alabama A&M U.), Suxia Cui (Prairie View A&M U.), Deborah Dent (Jackson State U.), Jon Gant (North Carolina Central U.), Charles Weatherford (Florida A&M U.), Joseph Whittaker (Jackson State U.)
- TCU Leaders, Faculty, and CI Professionals
  - For example, Chris Caldwell (C. Menominee Nation), Tom Davis (Navajo Technical U.), Al Kuslakis (American Indian Higher Education Consortium [AIHEC]), Russell Hoffman (AIHEC)
- University CI Professionals
  - For example, Martin Andersen (U. North Carolina at Greensboro), Sarvani Chadalapaka (U. California, Merced), Steve Diggs (Scripps Institution of Oceanography), Jacob Fosso Tande (U. North Carolina at Greensboro), Robert Freeman (Harvard U.), Lev Gonick (Arizona State U.), Ken Hackworth (Pittsburgh Supercomputing Center), Bradley Huffaker (U. California, San Diego), Ron Hutchins (U. Virginia), Christine Kirkpatrick (U. California, San Diego), Claire Mizumoto (U. California, San Diego), Michael Renfro (Tennessee Technical U.), Patrick Schmitz (Semper Cogito, formerly U. California, Berkeley), Eric Sedore (Syracuse U.), Subhashini Sivagnanam (U. California, San Diego SC), Dena Strong (U. Illinois, Urbana-Champaign), Mohammed Tanash (U. Northern Iowa), Jeffrey Weekley (U. California, Santa Cruz), Jason Wells (Bentley U.), James Wilgenbusch (U. Minnesota), Elena Yulaeva (U. Califorina, San Diego), Michael Zentner (U. California, San Diego)

- Government and Federally Funded Research and Development Center CI Professionals
  - For example, Michael Fienen (U.S. Geological Survey [USGS]), Sky Bristol (USGS), Jessica Burnett (USGS), Matt Mayernick (National Center for Atmospheric Research)
- Digital Fabrication Ecosystem
  - For example, Neil Gershenfeld (Massachusetts Institute of Technology), Megan Smith (Shift7, formerly Office of Science and Technology Policy [OSTP]), Beno Juárez (Floating Fab Lab Brazil), Rico Kanthatham (Fab Lab Japan), David Lonnberg (Shift7), Nuria Robles (Fab Lab Leon), Pradnya Shindekar (Fab Lab India)
- Industry Experts
  - For example, Dana Brunson (Internet2), Peter Levin (consultant, formerly Intel and Autodesk), Kayla Lee (IBM), Barbara Mittleman (Applied Molecular Transport, formerly NIH)
- Six Individual Interviews
  - Fran Berman (U. Massachusetts, Amherst)
  - George Boateng (ETH Zurich)
  - Kayla Lee (IBM)
  - Miron Livny (U. Wisconsin, Madison)
  - Dan Reed (U. Utah)
  - Cynthia Warrick (Stillman U.)

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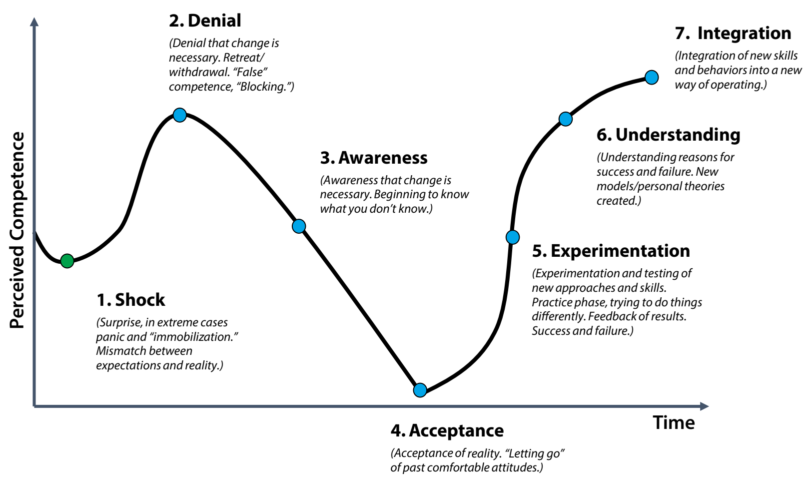
Appendix A:
Change Management Principles

"What is your theory of change?" This question was posed by focus group participants and it is key to making progress on a challenge on the scale of reaching the missing millions. This appendix represents potential elements of a large-scale change process—thought starters pointing toward what could be an implementation plan.

Some of the paths forward in this report can be addressed in the shorter term (2–4 years) and some in the longer term (5–10 years). All need additional immediate action steps to begin the process. None can just be accomplished with just a set of announcements or policy changes, though some announcements and policy experiments will be needed. Ultimately, a long-term, structured change management process is needed.

In managing change, the first principle is that people need to let go of the old before they can embrace the new. Here is a sample change management model from Ford's executive development programs, adapted from the Elizabeth Kubler-Ross model for death and dying. It indicates that key stakeholders will have to experience shock, denial, awareness, and acceptance before any experimentation, understanding, and integration can happen.



In planning for implementation, it is often helpful to locate different stakeholder groups along this curve, then meeting them where they are.

A further principle of systems change is the importance of reducing variability. Efforts to improve highly variable systems do not necessarily produce overall improvements. Too often they just accentuate differences. Thus, some degree of standardization is an essential foundation for improvement. "Bright spots" and successful pilot experiments are valuable only if they can be standardized and diffused across systems. Waiting until all the results are in from pilot experiments is often too long – at that point the pilots have become islands rejected by the larger system. A more agile and adaptable mindset is needed where there is continuous learning from multiple pilots.

At the heart of change management is good storytelling. This is a key principle – knowing how to explain complex science and engineering findings in the form of a compelling story. There is dramatic tension and uncertainty woven throughout the research enterprise and there are compelling examples of triumph against the odds, but these are too often buried in technical terminology so that the vision and impact is lost. Broader impacts depend on both the concrete or tangible impacts of research, as well as the translational or intangible aspects of change.

Thus, achieving broader impacts with science and engineering research requires an appreciation for common and competing interests among stakeholders, understanding that some stakeholders will be letting go of the old, reducing variation, and great storytelling. It also requires a change management strategy.

To achieve systemic change, most initiatives will involve a combination of top-down and bottom-up approaches, and a new category of "middle-across" change. Top-down change involves policies, procedures, and initiatives by leadership. Bottom-up change begins at the grass roots and is emergent. Middle-across change is the process for lateral alignment across stakeholders so that all can accomplish together what cannot be done separately.

Here are some examples of top-down change that come from this report:

- Experimental policy support for review panel innovations (broader impacts, etc.).
- Experimental policy support for increased program officer flexibility (EArly-Concept Grants for Exploratory Research [EAGERs], Grants for Rapid Response Research [RAPIDs], etc.)
- Experimental policy support for block grants to historically Black colleges and universities (HBCUs), tribal colleges and universities (TCUs), Hispanic-serving institutions (HSIs), and consortia.
- Policy support for community Institutional Review Boards (IRBs) linked to university IRBs.
- Technical support unit providing services for broader impacts.

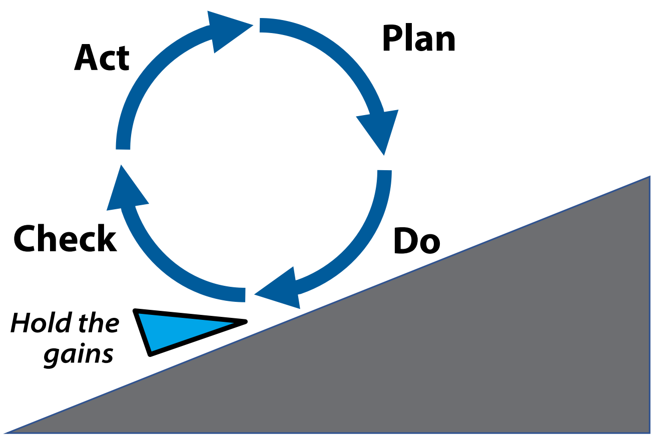
And here is one of many long-standing, top-down change management models; this one is adapted from John Kotter (1995):

Note, in particular, the need for a guiding coalition and the need for some short-term wins on the top-down efforts.

In parallel, here are some examples of bottom-up change associated with this report:

- Outreach to identify computing and data innovations reaching the missing millions to identify policy implications.
- Block grants to HBCUs, TCUs, HSIs, and relevant consortia.
- Pilot experiments with community IRBs.
- Expanded access to research computing and data facilitators.
- Infrastructure support for local public-private partnerships, industry partnerships, and data/ compute initiatives associated with workforce development.

And here is one of many long-standing, bottom-up change management models, this illustration of the Plan-Do-Check-Act (PDCA) model is adapted from W. Edwards Deming (1986):

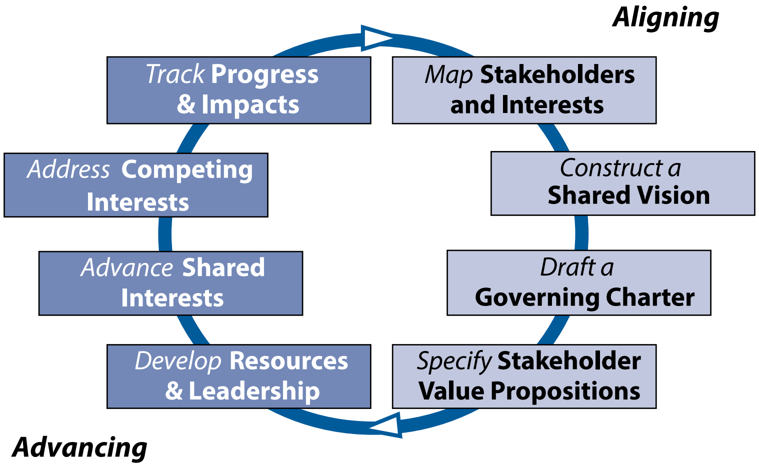


Note, in particular, the infrastructure needed for PDCA change, which includes tracking processes for each initiative, standardized reporting, and maintaining an "accomplishments" listing as projects are complete. Skilled facilitation support is essential as well.

Finally, here are some examples of middle-across change relevant to this report:

- Increased coordination across consortia, communities of practice, professional societies on reaching the missing millions, and bridging digital divides.
- Sustaining support for consortia and communities of practice with demonstrated broader impacts.
- A coalition of cities and towns with community IRBs, linked to university campuses.
- Ethical standards for broader impacts aligned across professional societies.
- Consortia standards for career paths for research data and computing professionals.

For middle-across change here is a sample model from the Stakeholder Alignment Collaborative and WayMark Analytics (2021):



In launching middle-across, multistakeholder initiatives, a *minimum viable consortia* model represents a new development in the change-management literature. The key concept is to begin with the minimum viable structure (and not less), which has a lower activation energy needed and can then allow for iterative adjustments over time based on lessons learned and emergent developments.

Note that this model assumes multiple stakeholders with common and competing interests. Many scientists intend to achieve broader impacts but are not prepared to navigate competing interests among stakeholders.

In the private sector, continuous improvement and systems change initiatives utilize what is termed an *A3 form,* designed to put key aspects of a change initiative on a single (large) page (the A3 paper size is roughly comparable to an 11" x 17" page). The idea is to then literally get relevant stakeholders on the same page. This requires interactive dialogue among the stakeholders. For change management in the National Science Foundation (NSF) (and other federal agencies), a "stakeholder alignment and action" template is provided here (included below). Like the A3, it places key information on one page. Unlike the A3, this is designed for use where there is likely to be a diverse mix of stakeholders with common and competing interests as well as policy and legal contexts that need to be taken into account.

Broadly speaking, the change process involves an initial group producing a draft version of the form, reviewing this with relevant stakeholders, adapting the entries on the form and getting initial alignment, beginning with key activities on the "Action" section of the template, and periodically checking the stakeholders and interests for alignment updates (since both stakeholders and interests can change over time). Note that the "Action" section will likely involve a mix of top-down, bottom-up, and middle-across actions. Further, any change initiative will involve ongoing support for implementation, with periodic check-and-adjust processes.

Ultimately, the change process will involve both many small steps and a commitment to large-scale transformation. As we noted in the "Executive Summary," one participant stated that the change will require early gains to build momentum: "There are so many things to work on—small steps are needed because the obstacles are huge." At the same time, this same individual urged a long-term commitment to achieve more than incremental change: "Our goal is to increase computing usage by an order of magnitude. We are focusing on the rate of change—focusing on the derivative. This is key for broader impacts."

Appendix B:
Stakeholder Alignment & Action Template

[Title}

<table>
<tr><td>Issue</td><td colspan="2">[A statement of the issues or set of issues that are the focus—essentially, a well-posed problem statement.]</td></tr>
<tr><td>Vision</td><td colspan="2">Brainstorming elements of a vision of success on this issue or set of issues, begun with the phrase: Imagine a world where. . . .]</td></tr>
<tr><td>Data, Law, and Policy</td><td colspan="2">[Relevant data, laws, and policies that motivate and provide context for the issue.]</td></tr>
<tr><td>Stakeholders</td><td colspan="2">[A listing of all relevant types of stakeholders.]</td></tr>
<tr><td>Interests</td><td colspan="2">[A listing of what is at stake for the stakeholders—not specific positions, but underlying hopes, fears, concerns, and other matters associated with the value propositions for the various stakeholders. Note that some interests will be widely shared, some will be particular to one or more stakeholders, and some will be competing with others. Key interests are to be copied and pasted in one of the two categories below.]</td></tr>
<tr><td rowspan="2">Alignment</td><td>Misalignment Challenges</td><td>Alignment Strengths</td></tr>
<tr><td>[Interests for which there is considerable misalignment or tensions that need to be addressed—in red.]</td><td>[Interests for which there is considerable alignment on which advances can build—in green.]</td></tr>
<tr><td>Actions</td><td colspan="2">[Milestones for implementation on a quarterly or annual basis.]
1Q 2022
– o
2Q 2022
– o
3Q 2022
– o
4Q 2022
– o
2023
– o</td></tr>
</table>

Example: Stakeholder Alignment & Action Template

Community IRBs: Oversight and Impact with Community Data

Issue	In a postindustrial digital era, data are more important than ever; yet, too often, communities have little input or control over relevant data, resulting in increased risk of harm and lost opportunities. Examples: water data in Flint, MI; internet connectivity data in rural communities; climate data on tribal lands; food desert data in urban communities; social science survey data in all communities; and countless others.
Vision	Imagine a world where communities of all types had Institutional Review Boards (IRBs)—connected, where appropriate, to university IRBs—that assured timely review and oversight of research relevant to the community and involving human or animal subjects. Both community and university IRBs would effectively balance mitigating harm resulting from research while also promoting expanded use of data and next-generation workforce development with data.
Data, Law, and Policy	University IRB policies, adapted for community use. Data privacy principles and standards. Principle of "nothing about us without us."
Stakeholders	Newly formed community IRBs Associated university IRBs Community leaders (formal and informal) Community members Researchers interested in conducting community-level research Next-generation youth in the community open to developing data skills Funders of community-level research
Interests	Mitigating harm due to the misuse of community data. Addressing issues of importance to the community with research data. Advancing protections for privacy with the use of community data. Promoting the sharing and reuse of community data. Building next-generation workforce skills with community data. Avoiding creating overly bureaucratic and overly risk-averse systems. Fostering collaboration between communities and nearby colleges and universities. Commercial organizations and researchers protecting what are seen as proprietary data.

<table>
<tr><td>Alignment</td><td>Misalignment Challenges</td><td>Alignment Strengths</td></tr>
<tr><td></td><td>Advancing protections for privacy with the use of community data.
Promoting the sharing and reuse of community data.
Avoiding creating overly bureaucratic and overly risk-averse systems.
Fostering collaboration between communities and nearby colleges and universities.
Commercial organizations and researchers protecting what are seen as proprietary data.</td><td>Advancing protections for privacy with the use of community data.
Promoting the sharing and reuse of community data.
Avoiding creating overly bureaucratic and overly risk-averse systems.
Fostering collaboration between communities and nearby colleges and universities.
Commercial organizations and researchers protecting what are seen as proprietary data.</td></tr>
<tr><td>Actions</td><td colspan="2">[Milestones for implementation on a quarterly or annual basis.]
1Q 2022
Identify 3–5 pilot communities.
Conduct stakeholder mapping surveys to identify points of alignment and misalignment.
Develop a sample charter for a community IRB.
2Q 2022
Conduct summit dialogue sessions in the 3–5 pilot communities, informed by the stakeholder mapping surveys.
Develop a shared vision of success in each community and adopt a charter for the community IRB (with appropriate review processes by relevant community groups).
3Q 2022
Process community data projects with the IRB.
4Q 2022
Process community data projects with the IRB.
2023
Assess initial experience and impacts.
Review and adjust vision and charter.
Compare experiences with other pilot community IRBs.
Expand use of the community IRB model.</td></tr>
</table>