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DIRECTORATE FOR COMPUTER & INFORMATION SCIENCE & ENGINEERING (CISE)

NSF CISE Vision 2030

A Vision for NSF CISE Opportunities and Challenges Over the Next Decade

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WHERE DISCOVERIES BEGIN

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EXECUTIVE SUMMARY

Taking a long-term, decade-and-beyond perspective, this document looks to identify and understand key opportunities and challenges facing NSF CISE and its community. In particular, we consider several questions:

(1) Where is the computing field going over the next 10-15 years?

(2) What are potential opportunities, disruptive trends, and blind spots?

(3) Are there new questions and directions that deserve greater attention by the research community and new investments in computing research and education? We also consider and discuss

(4) relationships with industry and partnerships more broadly, and, finally,

(5) the experimental research infrastructures that modern CISE researchers need.

EXECUTIVE SUMMARY

Opportunities for CISE impact on society and the world are greater than ever as computing has become embedded into society, scientific discovery, engineering efforts, and more; however, this great potential for impact also comes with great responsibility. CISE has become a socio-technical field and as such CISE researchers and practitioners must consider the impact on society and the world of the technology they produce, including that technology's impact on security, equity, fairness, sustainability, inclusion, and privacy.

Becoming a socio-technical field is one of the key trends identified in this report. Other trends include CISE researchers' ability and responsibility to address pressing humanitarian and environmental challenges; the growing impact of artificial intelligence, machine learning and data science on many endeavors; research opportunities into new hardware and architectures (which now includes quantum computing, robotics, molecular programming, and digital fabrication, among other areas); the increasing dependency on networked, often embedded, cyber-systems in our society, and the challenges it creates to ensure their functioning (hardware and software) under adverse conditions; the increasing complexity and distribution of modern systems, software, and applications; the role accessible computing is playing in engaging the broadest segment of our society; and the need for accessibility to affordable computing to ensure equal opportunities for all.

These trends are affecting CISE research, education, and identity. On the research side, the field is expanding both in terms of foundations and world impact. CISE foundations include traditional areas such as theory, systems, AI, or programming languages, but also novel areas such as molecular programming or computational biology. CISE research today also includes many areas with direct world impact such as accessible computing, misinformation, or technologies for developing and rural communities.

This ongoing transformation also impacts CISE education. Educating our students only in computing methods and techniques no longer suffices. We also need to educate them to always consider the ethics, equity, inclusion, and more broadly the impact of technology on the world. We further need to inspire our students to work on the world's most pressing issues, which will require many to become skilled at cross-disciplinary and cross-cultural collaborations.

The expansion of the field is also changing our identity. Our field is expanding dramatically. At the same time, all fields need to do computing. We must pause and think deeply about the impact on our identity and our field. One area where this identity change visibly manifests is in the sharp increase in the number of standalone schools and colleges of computing that have appeared on university campuses.

These changes are not occurring in a vacuum. International competition is affecting our ability to carry out research openly. The impact and growth of a small number of large tech companies is changing the research landscape. Additionally, feelings toward many large tech companies and CISE more broadly are mixed. We need to ensure that society continues to see the positive impacts of our field. We should also intentionally and purposefully inform policy related to technology research to help mitigate risks and maximize benefits.

Finally, the motivation for making our field more diverse, equitable, and inclusive is stronger than ever, and so is the need to build and maintain productive partnerships between academia, industry, funding agencies, and the National Science Foundation.

In this context, the report has recommendations for NSF and the CISE community:

- Seize the opportunities of CISE's centrality in research, business, and society and its evolution to a socio-technical field, with impact on society, the environment, education, and technical innovation. This fundamental transformation has changed CISE as a field. It is impacting the scope of and approach to CISE research and education, and it is changing the role and position of CISE on university campuses.
- Take a systems approach to addressing opportunities and challenges, especially as it relates to supporting interdisciplinary research, encouraging research on humanity's greatest challenges, accelerating research that requires novel types of infrastructure, and supporting research on today's complex and distributed systems.
- Rethink our approach to CISE research and education given the changing national and international context for research, with special emphasis on partnerships.
- Reimagine and continue to invest in diversity, equity, and inclusion (DE&I) in our field.
- Remember to dive deeply into the many opportunities for research and innovation in the growing and vibrant field of computing

INTRODUCTION

Inspired by the *Vision 2025* report, previously created as a collaborative effort between the NSF CISE Advisory Committee and the Computing Community Consortium (CCC), we develop an updated vision for NSF CISE Vision 2030. From our new point in time, we seek to look out a decade and beyond to understand the key opportunities and challenges facing NSF CISE. We also study what has changed since Vision 2025 and how those changes should impact Vision 2030.

Vision 2025 explored three key questions:

(1) Where is the computing field going over the next 10-15 years?

(2) What are potential opportunities, disruptive trends, and blind spots? and

(3) Are there new questions and directions that deserve greater attention by the research community and new investments in computing research? In the NSF CISE Vision 2030, we start from the key takeaways from the Vision 2025 activity and discuss what has changed.

INTRODUCTION

We observe that the NSF CISE fields are now at a transition point. Opportunities for developing great technology and applying that technology to almost any field of science and engineering, our society, our lives, and our world are greater than ever. CISE continues to grow as a vibrant discipline. Our tremendous past and current successes have brought computing to the point where it is inextricably woven into many facets of society, and deeply influential on essentially all forms of science as well as other intellectual pursuits. Yet, the very centrality that allows the CISE research community to have a huge impact also places us in a position of responsibility, where the systems and techniques we design must offer good results on a range of metrics other than innovation, including newer areas of societal impact: safety, security, reliability, environmental sustainability, privacy, inclusion, equity, and fairness. To add to this challenge, feelings toward many, large, computing-related technology companies and technology in general are mixed. We are facing a "techlash" that we must learn to navigate and counter. We also recognize more than ever the need to make the CISE community diverse, equitable, and inclusive. The competition among nations is also fierce, but CISE research needs to be open and include the best and brightest minds throughout our nation and from around the world. We are thus at a juncture where great opportunities have met a growing responsibility and a changing world-context. In this document, we dive into this challenge and ask how the CISE community should respond.

We argue that, in response to the changes above, we must rethink and reorganize our community, education, partnerships, and funding. We must understand our role and responsibilities in society. We must embrace the need to inform policy. We must deeply think about our broad field: how can we grow and change to become better and more impactful without losing whatever it means to be computing? We need to prepare students as future researchers and contributors to a CISE-based economy and society. We need to invest in research to maintain intellectual lead in novel and broader areas, while retaining a strong core. We need to partner with industry and other agencies that want to work together toward open scientific discovery. We also need to partner with like-minded nations that have a shared commitment to values and practices that support the integrity of the research to accelerate progress addressing global challenges. We need to understand the CISE community's responsibility to society for the technologies we produce and for the research security of the nation while maintaining an open exchange of ideas, people, data, and research products within privacy, security, and other standard constraints.

NSF can play a catalytic role in the goals above through its investment portfolio and priorities, promotion of the benefits of its research, partnerships with other agencies and industries, and by convening the community to begin discussions on the changing landscape.

Putting together this document provided the committee with an opportunity to focus and emphasize long-term, important issues over near-term, urgent ones. We hope that the themes we articulate in the document will be helpful to the NSF CISE Advisory Committee in its future deliberations, to CISE as it is thinking about opportunities to explore and encourage as well as the challenges to anticipate and manage, and to the broader community in discussing the broad issue the role and responsibilities of CISE in the technologies it develops and shares with the world.

In this report we identify seven New and Accelerating Trends in research, often multidisciplinary, all with impact on society; opportunities and challenges in Education and Human Capital including Diversity, Equity, and Inclusion (DEI); challenges regarding CISE's Identity as its impact grows in most other fields of science; how CISE researchers are faced with Changing Context of Scientific Research including research security; and Potential Blind Spots that could result in unforeseen consequences, such as a reduction of students, foreign or domestic, to participate in CISE research.

We view this as a living document that could be looked at annually or every two years to see how we collectively are addressing the opportunities and challenges articulated herein, and to determine whether and how to modify our perspectives. We also hope that if CISE and the CISE Advisory Committee decide to undertake another major visioning exercise, that this document might provide a template for that future effort, although we believe changes to the template are vital. Examples of new sections are those on Education and Human Capital and Blind Spots, which were not clearly laid out before.

CISE's centrality in society and its transformation into a sociotechnical field is the core assertion of this report. Almost daily we can read headlines that support this assertion. Even during the writing of this report, several national events conspired to make this point clear. Here are three.

First, there was a significant software breach into many government agencies, alleged to have been undertaken by a foreign state-actor. This is a clear call to arms for the CISE community to improve its arsenal of software development tools—including bug tracking; modeling and checking tools; and secure software update mechanisms—and to build meaningful partnerships with agencies, and industries, to protect government, financial, and social infrastructures. Second, we have seen the use of social media in spreading misinformation not only across the globe but within the United States, sometimes to devastating effect. Finally, work on this report started before the COVID-19 pandemic, which has upended many aspects of what we consider normal in work, learning, health, and participating with other human beings. For those who have access to technologies, an altered life and living has continued, relatively safely, thanks to the existence of those technologies; however, we know that technology deployment and accessibility are not uniform, rather they are lumpy.

Our society, indeed our science, requires an open exchange of ideas. Being part of the policy debates will be critical for the CISE and academic community. CISE, in partnership with social scientists and lawyers, can help guide input to those discussions, requiring people with expertise and skills to bridge our communities.

VISION 2030 SUMMARY RECOMMENDATIONS

Vision 2030 makes several recommendations. The recommendations are aimed at NSF CISE, individual NSF researchers, universities, professional organizations, and industry. To address the opportunities in light of the transformations mentioned in this report will require NSF and the broader community to contribute, each in its own way, to work together, supporting each other. The report contains many specific opportunities to pursue, some relevant to NSF, others to the community. In this section we highlight some larger, aggregated recommendations that we hope will frame the discussion of CISE's future.

VISION 2030 SUMMARY RECOMMENDATIONS

Seize the opportunities of CISE's centrality in research, business, and society and its evolution to a socio-technical field, with impact on society, the environment, education, and technical innovation.

- We are now required to understand the implications of CISE's growing scope, changing identity, and new responsibilities. This will require many discussions at the NSF, at universities, in professional societies, and in industry. Further, we must engage with all of stakeholders, not just those directly tied to CISE. These discussions may take the form of workshops, idea labs, or activities to develop collaborations.
- We need to re-imagine CISE curricula to include training on ethics; on diversity, equity, and inclusion (DE&I); on responsibility of the discipline; and on collaborating across disciplines.
- We need to inspire the new generation of CISE researchers and practitioners to either work directly on or otherwise become involved with and contribute to humanity's greatest challenges, including policies and laws related to technology.
- We need to reconsider roles and structures of departments, which are increasingly becoming standalone schools and colleges with a broader scope and mission to serve their universities in research and education. All units on university campuses should be encouraged to cross-pollinate with CISE fields in support of their own research and education and in support of CISE's research and education. CISE units should welcome this cross-pollination.
- NSF CISE has an outsize role in the federally funded research in computer science. Used wisely, it can help advise this vision. We can reconsider and adjust, as needed, review mechanisms to better support interdisciplinary collaborations that address the many new facets of CISE; and to revise accordingly metrics for success in academia, among other activities. We should discuss whether we have the optimal set of programs to support the growing, expanding, and changing CISE field.

Take a systems approach to addressing opportunities and challenges. While point solutions are easier to arrive at (e.g., more program funding in technology, or new solicitations in technical areas), optimizing impact will require systems thinking if we are to ensure that appropriate educational, infrastructural, and other partnership opportunities exist to support CISE's broader role in science and society.

- In particular, interdisciplinary research opportunities will often require new CISE research, or application of research in a new way, understanding of how to collaborate, access to infrastructure, perhaps at scales not achievable before, and new ways of engaging students.
- We will need to address constraints, including our reward systems, both in academia as well as in society. How can we encourage more research with direct impact on humanity's greatest challenges? How can we best support this type of, often inter-disciplinary, research? How can we best support collaborations between academia and industry?
- We will need to think of research, education, and infrastructure (including software, hardware, data, and real-world deployments) together, and design programs that reflect these connections.

Examples where systems thinking could be valuable

- To address the trend of being a socio-technical field requires
  - Good interactions with SBE in co-developing key research areas, perhaps at a scale not done before.
  - Strong focus on education within CISE, about profession (ethics), knowledge (some disciplinary concepts), experience (collaboration).
  - Potential new partnerships with foundations, government (including local and state governments) and industry, for research, education and infrastructure.
  - We note that the Smart and Connected Communities program has attempted to create a framework for both research across disciplines as well as translation between academics and local or other governments. Other such models should be explored.
- Similarly, cyber-systems and software could require new research initiatives (e.g., PPoSS, which could be extended and expanded), education, engaging social science and healthcare into development, and experimental systems at scale (in partnership with industry). In addition, new research on the ability to model and understand large and complex systems is required to understand, predict, or remediate the results of infusing computing into almost everything we do and relying on complex systems as fundamental pieces of our infrastructure.

VISION 2030 SUMMARY RECOMMENDATIONS

Rethink our approach to CISE research and education given the changing context of research, with special emphasis on partnerships. Business as usual simply will not suffice to advance the broad CISE vision for 2030. There are many examples of new or enhanced approaches:

- Pursue partnerships broadly for research, education, and infrastructure with a variety of entities, including other government agencies, industry, foundations, and like-minded agencies in other countries. Partnerships can bring talent, expertise, infrastructure and leverage to benefit the vision. It will be incumbent on NSF to streamline its processes to reduce any overhead that makes such partnerships more difficult. We note that a subcommittee is looking at issues associated with public-private partnerships; the JASON's report makes several recommendations in the context of research integrity.
  - We note that the new AI Institute program intentionally built partnerships into the activities, with notions of expanding the type of partners in subsequent years.
- Re-imagine training and education through close partnerships with other disciplines (e.g., to teach ethics) and also based on how students learn (e.g., hands-on or experiential learning), and consider ways to embed training opportunities in practical applications, perhaps via partnerships with government, industry, and other fields.
- As noted above, rethinking the structures of organizations— including universities and government agencies—in addition to relationships to partner entities will be required.
- Rethink how we disseminate research results, ensure their open access and repeatability, and partner with industry, including start-ups in the context of research and technology transfer.
- Encourage partnerships with policymakers and others as technology and human values impact innovation.

Reimagine and continue to invest in diversity, equity, and inclusion (DE&I) in our field:

- Emphasize research, education, and translation work related to accessible computing and the accessibility to computing.
- Rethink and revise university curricula to educate students not only in computing techniques and methods, but also in working toward a more diverse, equitable, and inclusive community.
- Educate our students on ethics and general implications of computing to ensure they consider such implications in their research and development endeavors.
- Work toward building diverse, equitable, and inclusive environments on university campuses and in industry.

Dive deeply into the many opportunities for research and innovation in computing:

- Invest in and pursue research in the core aspects of the computing field, including cross-stack research and research across steps in data science pipelines.
- Acknowledge that the core of the field is expanding and includes novel areas.
- Invest in and pursue research in interdisciplinary and cross-cutting disciplines. Also acknowledge that such opportunities are expanding.
- As CISE contemplates the dual challenge of continuing to invest in its core disciplines while increasing its involvement in interdisciplinary activities, it will need to carefully consider how to distribute its investments across these various opportunities. Managing this challenge is likely to require an increase in funding commensurate with the level of effort required to succeed.

SUMMARY OF THE EARLIER VISION 2025

Trends identified in the previous Vision 2025

The previous Vision 2025 document identified three key trends:

1. Hardware facing the limits of Moore's law.
2. Greater production and customization of programmable goods and services, leading to a prevalence of intelligent objects in a "post mobile" world and software becoming distributed and embedded in the real world.
3. Massive amount of cyber connectivity between people, these intelligent objects, goods and services, and the evolving social contracts surrounding their use and exchange. Application challenges becoming dominated by societal needs in comparison to computing industry tools.

We observe that (1) has come to pass, giving rise to more specialized forms of hardware (e.g., tensor processing units (TPUs) and increasingly large multi-core chipsets) and increasing software-hardware co-design. (2) has accelerated impacting the way we live and also the way we work. (3) has led to positive but also significant negative impacts which have caused CISE to pause and realize that it has become a socio-technical field whose products can have both advantageous and deleterious applications.

Changing Context of Scientific Research Viewed from 2015

In the previous, Vision 2025 report, challenges engaging in modern computing discussed by two panel discussions for the Vision 2025 document included

- the need to publish data as part of the research process;
- the need to deeply engage other fields (e.g., materials, transportation, and healthcare) and the agencies associated with those industries;
- the need to assess the contributions of computing as part of larger scientific agendas; and
- the need to create "sandboxes" that allow for computing explorations in the context of distributed and cloud computing and corresponding Internet of Things.

All these remain valid today. But we have new challenges now, including international competition and in particular research security, increased focus on technology and human values, and increased interactions between academic and industry research work.

Six specific recommendations were presented, many of which resonate with the theme of the growing interplay between computing systems and the social, economic, and physical world. We list those recommendations in the Appendix.

NEW OR ACCELERATING TRENDS

We now turn our attention to the details of our Vision 2030, starting by discussing trends that are either new or ongoing and that deeply affect the CISE community. Our goal is not to be exhaustive and list all trends, but rather focus on important changes that we all must pause to reflect on and react to. We note that many of the trends are inherently interdisciplinary in nature. Thus progress will likely involve making CISE scientists more interdisciplinary (e.g., integrating ethics, social awareness, or other disciplinary knowledge into CISE curricula) or learning how to collaborate with researchers from other areas (e.g., learning about techniques in the science of team science), or even as a CISE community, learning how to partner with other disciplines, or some combination of these approaches. While CISE researchers and the CISE community have a history of interdisciplinary work, the evolution of computing calls for developing even deeper and stronger connections with other fields. We discuss some of these issues in sections on Education and Changing Context of Science. In this section, we focus on the trends themselves.

NEW OR ACCELERATING TRENDS

CISE as a Socio-technical Endeavor

It has long been all but an article of faith among CISE researchers that computing and computer science is important to science, technology, and society. What has changed in the last decade is that it has become almost inarguable that the field has become a central part of essentially all aspects of society and all forms of science and engineering. This centrality both as an intellectual enterprise and as a practical one has meant that the field is now inextricably woven into all our social, political, and intellectual pursuits. Thus, other fields, notably the social and behavioral sciences and economics are increasingly important to—and an important part of—CISE.

There are many ways in which this centrality is evident, but perhaps the most publicly visible ones involve artificial intelligence (AI) (generally, and including data science and machine learning) as well as security and data privacy. Self-driving cars are making their way onto our streets, and some are involved in accidents. Automated surveillance and facial recognition are increasingly discussed among the broader population. The judiciary uses machine learning to determine the advisability of parole while the executive branches use it to determine the application of policing. As more and more data about each of us as individuals are available and our field builds algorithms that use that data to predict and influence behavior, fears about the availability of that data spread throughout the population.

As a (perhaps unwelcome) consequence, the field has increasingly had to wrestle with notions of responsibility, accountability, and transparency among others. We find ourselves discussing not just computer models of diseases, for example, but computing and the law; computing and policy; and even computing and politics. These questions are uncomfortable and difficult. When we build systems that evolve on their own, who is responsible for the decisions and mistakes they may ultimately make? There are significant legal implications for how we answer these questions and we can expect a growing body of work around these ideas. Given these issues have both technical as well as social/sociological/political/economic components, approaches could include developing interdisciplinary initiatives that can set expectations and help develop solutions that meet them.

As a field, we have avoided being a "profession" in the sense that, for example, civil engineers must be certified to be professionals and may be held accountable for the bridges they design; however, we have not been able to resist an increasing call for the field to consider our impact in light of its effects on our politics, our privacy, our security (including our physical safety), and our larger societies' lack of equity and fairness. As it has become more important, the field's lack of diverse perspectives and experiences has become a central problem, both from a sense of morality or fairness, but also in that it blinds us to seeing the consequences of our technology.

This trend can rightly be described as new; however, it is more important to recognize that it can only increase: the consequences on the field will be significant, as will the consequences on society more broadly. It is not an exaggeration to suggest that this trend will not only continue but will accelerate. As such it is incumbent on CISE to take affirmative steps to participate in and shape these conversations on the one hand, and to hold itself accountable on the other:

- CISE should build partnerships with SBE (Social, Behavioral, and Economic Sciences) in NSF as well as agencies outside of NSF.
- It should further strengthen cross-directorate research projects focused on grand challenges such as those from the ACE-ERE cross-directorate committee.
- CISE should encourage responsibility as a central part of research, promotion, and both undergraduate and graduate education, and not as a post hoc add-on to the "engineering" of software.
- It should further increase its existing efforts at diversity, including partnerships with CEOSE (Committee on Equal Opportunities in Science and Engineering). We further discuss diversity in the section on Education and Human Capital.

NSF's efforts in this area need to be embraced, amplified, and extended by the CISE community.

While we focused on AI above, the deep integration of computing into all facets of our society also means that we are increasingly relying on complex systems, which benefit our lives but also raise their own set of challenges and responsibilities for our field. We discuss this issue further in the later section on Cyber Systems and Software.

Pressing Humanitarian and Environmental Challenges

In the past, the CISE community has primarily focused on developing technology in order to make human work easier or faster, or to make possible new and exciting capabilities, with only a fraction of our focus on humanity's greatest problems. Today, however, the challenges that humanity

is facing are greater than ever and they threaten our very existence. They include climate change and sustainability, pandemics, homelessness, drug addiction, and others. The magnitude and impact of today's challenges have been accelerating. Those problems are also inter-connected as one problem worsens (e.g., climate change), other problems worsen as well (e.g., forest fires, hurricanes, pandemics). The unusually difficult and turbulent year 2020 exemplifies this trend.

The implication for the CISE community is several fold:

- Because of our centrality, our impact on all fields of science and engineering, and our growth as a community, we must play a responsible and collaborative role in addressing humanity's greatest challenges. We must increase our attention to the challenges that face our planet and our societies. We must invest in research that actively seeks to develop or improve computing technology to help address those problems.
- This investment will require working with researchers from different disciplines, thus learning how to collaborate across disciplines will be critical to success. In part, this will require all partners in a collaboration to derive appropriate benefit and credit. While some fraction of the CISE community has been working on interdisciplinary and world-focused problems for many years, this type of work and capability is now more important than ever.
- We must inspire the new generations to work on such problems as opposed to focusing on maximizing personal gain.
- It is often surprisingly difficult for investigators to get funding for interdisciplinary research because those projects can come across as somewhere in between research and infrastructure development, and thus a suboptimal fit for either. Except for specific programs (e.g., Smart and Connected Communities), panels most often comprise members of a single community who may not have the background to appreciate the full proposal. We must continue to create interdisciplinary panels and educate panelists in how to evaluate interdisciplinary proposals.
- Collaborators on interdisciplinary projects often need seed grants to explore the potential of their area before being able to submit a competitive proposal. We should facilitate such grants.
- Solving large-scale problems requires deep international collaboration and the recruitment of the best talent, which are currently threatened as we describe in detail in the later section on the Changing Context of Scientific Research.
- Solving humanity's greatest problems may not require the development of the most innovative technologies, but primarily the judicious application of existing technologies making those problems ill-suited for a CISE investigator who needs to write a thesis or publish novel work in prestigious venues. We need to develop an ecosystem that encourages this type of work. Often, to be truly effective, e.g., producing solutions of wide benefits, such efforts may best be pursued in collaboration with non-academic stake-holders, e.g., industry, local governments, other agencies, etc.
- Finally, truly solving existing problems requires embracing the notion of translation of computer science into other areas. The work cannot stop at proof-of-concepts and prototypes. Translation of ideas into practice, however, requires a different skill set and different interests than what most researchers are specialized in.

Artificial Intelligence, Machine Learning, and Data Science

Beyond the increased responsibility toward society and humanitarian problems, CISE is also facing a set of exciting trends related specifically to the technology that it produces. As noted in the section above on "CISE as a Socio-technical Endeavor," perhaps the most public way in which CISE fields are currently capturing the general public's imagination is through artificial intelligence (AI) and machine learning (ML).

We have discussed some of the social implications of the increasing use of ML and AI in the section above, so will not repeat those examples here; however, it is worth noting that the growth of ML and AI are largely driven by a growing emphasis on:

- AI as a part of larger systems involving humans
- AI as the driver of automated data analysis and decision-making

As a result, ML and AI have become prevalent tools within and outside of computing. ML is becoming a default technique for data analysis across multiple fields in the sciences, social sciences, and humanities. In addition, many of the ML and AI systems in use suffer from being relatively opaque, thus limiting their interpretability. There are several implications:

- There is a need for ML/AI experts on university campuses more than ever. At the same time, the demand for ML/AI experts in industry is so high that it is nearly impossible for universities to retain ML/AI talent.

- In the rapid change to moving toward applying ML/AI, practitioners and researchers alike are using these techniques without necessarily having the appropriate education, in particular understanding the limitations of the technique and more general resulting ethics considerations of their use.
- All computer science students today need to be educated in ML and AI, and in general in statistical inference and the general scientific method. At the same time, we should continue to teach a variety of data analysis methods. AI and ML should not become the only approach to data analysis. In the section on Education we argue for a rethinking of core CISE education.
- Students outside of computer science need to at least be facile in ML/AI, data science, and computing.

Even as the United States has invested in these efforts and historically led the world, there has been an even stronger investment from elsewhere in the world with significant implications for national security and national competitiveness. So, given the accelerating trend, we believe that CISE should continue its investment in AI and ML through programs such as the AI Institutes. It is also important to support concerted efforts to identify and fund benchmark projects such as the next ImageNet.

It cannot be said enough that central to the current AI and ML efforts is data. In particular, many fields of academic research, industry, and governments continue to generate data at increasingly large scale and rate. Thinking in terms of data science, there is a great deal of work in understanding pipelines; storing and collecting data; and extracting information at the edge of the cloud; however, access to these data are crucial to improving the state of the art in AI and ML. CISE should continue to support partnerships to ensure that researchers are working with the best data. It should also continue to support research that addresses all aspects of the end-to-end data science pipeline.

Finally, the impact of AI and ML is a result of many advances happening together, including advances in: foundational algorithms; data collection, storage, and management; compute power, including new special-purpose architectures; human computer interaction (HCI); and the ubiquity of data. As such CISE must make strategic decisions about how to distribute its investment between "pure" AI on the one hand, and AI that is a part of other areas on the other. Additionally, both the NSF and researchers should focus on building novel AI methods and techniques as well as develop novel systems that include AI at their core. Finally, as we discussed in the previous section, the community must focus on research in ethics and bias issues in AI and ML.

While AI/ML clearly is having and will have profound impacts on research, the economy and society, modeling and analysis of physical, social, and other processes require a broader palette of tools and expertise. It is essential that NSF CISE management and the research community embrace and promote multiple lines of analytic research and development beyond AI/ML. Further, it is important to remember that large amounts of non-AI/ML software will also be produced and relied upon across all areas of research, economy, and society.

New Hardware and Architectures

It has now been many years since Dennard Scaling reached its limit, putting an end to Moore's Law as we knew it. This has not, however, put an end to innovation in computing hardware, architecture, and systems. On the contrary, innovation has accelerated because of the need to rethink our approach to performance. Modern servers have become highly parallel with large numbers of CPUs and GPUs, large memories, and a variety of data storage options from traditional disks to SSDs, to non-volatile memory. Modern servers also increasingly comprise specialized components such as Tensor Processing Units (TPUs). These changes are accelerating innovation in computer architecture and system design, as well as novel ideas in hardware and software co-designs.

Beyond the traditional desktop or server, we also see significant innovation in novel hardware and systems. The number and variety of sensors deployed in our environment is growing at an unprecedented rate. Modern homes have high levels of automation driven by a variety of sensors. Most cities are instrumented with traffic cameras. Most people have a smartphone and many also wear a variety of sensors to track their health and daily activity. The availability of these devices and sensors as well as increasingly powerful algorithms for analyzing the resulting data are also opening new opportunities for research and industry impact.

We similarly see an explosive growth in robotics research and practice. Companies, such as Amazon, use fleets of robots to service requests. Autonomous vehicles can now be found driving on our streets. Research in human-robot interaction is growing. We see continued growth in automation. Robots and software increasingly replace humans both to accomplish tasks and make decisions. These changes are offering great opportunities for innovative research and practical impact. They also raise important ethical and societal questions that the CISE community should be involved in addressing.

Recent years have also seen an explosive growth in fabrication capabilities. It is now increasingly feasible to manufacture personalized products or parts, democratizing design and manufacturing. This area, however, is still rather

new, and much research must be done in order to leverage the opportunities that fabrication and prevalent maker spaces have to offer.

Beyond the traditional digital technology, quantum computing has transitioned from an area of pure exploration with unclear practicality, to an area of fierce competition and rapid innovation.

Finally, we are seeing increased innovation at the boundary between the digital and organic worlds with growth in areas that include synthetic biology, molecular programming, DNA storage, electro-neural interfaces (e.g., cochlear implants), and more.

These exciting trends and innovations have several implications for the CISE community:

- We must continuously rethink our funding programs to ensure that both traditional research areas, which are undergoing high levels of innovation, are well funded. At the same time, novel research areas that stretch the boundary of our field need to be well funded and may need more specialized panels or calls. Realizing both will likely require an increase in funding levels.
- All the above opportunities expand the CISE community, which has implications on our identity as a field as we discuss further in the section on CISE Identity.

Cyber – Systems and Software

Systems, from networked sensors in a smart city context to systems of networked computers, data centers, and miscellaneous devices are increasingly permeating all facets of society, economy, defense, and research and are being relied on in many daily pursuits (as noted above).
In particular

- Deployments of cyber/info/sensor infrastructure are continuing, with usage increasing, e.g., (commercial) clouds and data centers; connected sensor devices, part of edge computing, to data centers, over a variety of wireless, cellular and physical networking.
- Applications are spanning from sensor to edge to cloud, in diverse areas of manufacturing, power grid, agriculture, smart buildings to smart cities, environmental and ecosystems monitoring.
- Systems components are increasingly heterogeneous, e.g., mix of cpu/gpu, quantum processors, field-programmable gate arrays (FPGA); and component boundaries, e.g. compute/data/communication and hardware/software, are increasingly blurring.
- These systems are increasingly dependent on complex, distributed technology, and the dependency creates fragility, requiring thoughtful and resilient designs.
- Humans are increasingly a factor in systems: systems are changing the way people interact with them and each other.
- Requirements on the systems are also growing, including performance, robustness, efficiency, security, integrity, with "assurances" increasingly difficult to maintain with rapid component changes and larger scale.

Disruptions to software and physical infrastructure (e.g,, public compute clouds, power grids, sensor networks), whether those disruptions are man-made or via natural disasters, can be devastating to life, the economy, defense, and the environment. Changes to both the design of those systems (e.g., increased reliance on AI) and the increasingly distributed underlying infrastructure, are changing opportunities for disruption (e.g., changing the attack surface, including attack on data and its effects on the algorithms). Some research challenges and opportunities include systems approaches to

Security: Systems are increasingly programmable, widely distributed, remotely operable, and thus are more penetrable by malicious actors. We have to re-architect the systems that control our infrastructure. We need ways to audit. We need visibility into the operations of critical systems, including who is accessing such systems. Security also includes physical safety. When systems interact directly with end-users, especially in the case of cyber physical systems, user safety is paramount.

Software Development Tools: The recent, significant software breach into many government agencies, alleged to have been undertaken by a foreign state-actor, is a clear call to arms for the CISE community to improve its arsenal of software development tools—including bug tracking; modeling and checking tools; and secure software update mechanisms—and to build meaningful partnerships with agencies, and industries, to protect government, financial, and social infrastructures and systems.

Privacy: As systems increasingly rely on user data, privacy and data governance (including rules for access to and use of data) play an analogously increasingly critical role, as does the ability to clearly convey choices and their implications to users.

NEW OR ACCELERATING TRENDS

Robustness and Resilience: With increasing sources of disruption, there is increased interest in their ability to sustain damage / partial failure, to ensure survivability of services and their integrity, and return to normal in defined periods of time. Moreover, the fragility of systems requires thoughtful and resilient design. To continue to reap the benefits of our dependence on software, we need research to guide software-based systems developers to more reliable designs.

AI/ML: AI/ML algorithms are increasingly introduced to improve attributes of the system and their services, e.g., data processing close to the edge, monitoring of and responding to system changes, auto-tuning. Understanding risks of misuse of AI/ML, including implications of their statistical nature (e.g., in autonomous systems), and the consequences of bias and legal implications will increase.

Durability: In many systems, in particular those embedded in the physical world, such as smart grid or smart cities, hardware is upgraded slowly, we need software that can evolve and handle obsolete hardware, component software, and new introduced security holes. In other cases, sensors may deteriorate faster than budgets can replace them, yet the system must continue to function and be sustained.

People interact with systems: Understanding the feedforward and feedback loop between people and systems will be a challenge. How should people and their use of and impact on a system be factored into issues such as security, data rights, variability of use and privacy concerns, and robustness?

Systems are increasingly complex, heterogeneous, made of multiple components that are often replaced or upgraded rapidly, and being envisioned at scales beyond current sizes.

Systems Research: The above raises new challenges in fundamental systems research.

Programing Model: This provides research challenges of rethinking/redesigning underlying hardware/software programming models, abstractions to manage complexity, and design flows to improve balance of multiple systems attributes, e.g. security, performance, scale, integrity, robustness, efficiency.

Data Management: The changing nature of today's systems also raises issues related to data management and data governance as most systems leverage heterogeneous data lakes, work with various forms of data, and must manage data that is produced and consumed by different parties.

There are several implications of these opportunities and challenges, and NSF has taken some steps to address them.

- We recognize the recent announcement of the Principles and Practice of Scalable Systems (PPoSS) that "seeks to fund projects that span the entire hardware/software stack and will lay the groundwork for sustainable approaches for engineering highly performant, scalable, and robust computing applications." This addresses one of the challenges outlined above. Although we are concerned that the current funding level is insufficient.
- Loss of sustainability of systems under adverse natural or human-made conditions will increasingly be disruptive to society. Ensuring adequate levels of research funding will be critical.
- The need for experimental systems and testbeds, at scale, will be increasingly important. See discussion of Experimental Research Infrastructure under Changing Context of Scientific Research below.
- As noted before, systems intrude into society and onto personal lives, understanding the individual, societal and policy implications will be important. Here, partnerships with Social and Behavioral Sciences within NSF will be important.
- Working in partnership with industry or other countries who share research values may be a strategy for NSF researchers to gain access to some systems of scale, allowing NSF to reserve funding for unique infrastructure investments for systems research.
- Finally, fundamental research in all aspects of system design, software development, programming languages, data management, architecture, and other fields that contribute to innovation in building modern systems remains critical.

We note that the NSF Workshop Report *Inter-Disciplinary Research Challenges in Computer Systems for the 2020s* – September 2018. A Cohen, X Shen, J Torrellas +49 others, also had a number of interesting recommendations for consideration.

NEW OR ACCELERATING TRENDS

Accessible Computing

According to the world bank, one billion people, or 15% of the world's population, experience some form of disability (*https://www.worldbank.org/en/topic/disability*). When developed with care, technology can dramatically help and enable people with disabilities to experience the world more fully as well as to contribute to that world more easily. If not developed carefully, however, technology can exclude participation by people with disabilities.

Significant advances in technology continue to make the world increasingly accessible to a growing number of people. Text-to-speech and speech-to-text technologies have dramatically improved in quality. Digital fabrication, as we discussed above, makes it possible to design and manufacture personalized parts that can be used in prosthetic devices. Teleconferencing systems have become commonplace and meetings increasingly include remote attendees. In the past ten years, we have seen the emergence of multiple research centers and institutes that focus on accessible computing. Technology companies have also increased their focus on accessibility. For example, Microsoft has had a Chief Accessibility Officer since at least 2016.

An important aspect of the work on accessible computing is not only how to make the world more accessible to people with disabilities, but also how to elevate their voices and bring more of them into the CISE community, so they can contribute their talents to research, education, and development. The CISE community currently often ignores students and researchers who may be different and who do not fit the mold in terms of how they can demonstrate their talent and how they can contribute that talent, and shape future research.

There are several implications for the CISE community:

- Because of the large number of people with disabilities, it is critical for the CISE community to continue and grow its efforts to develop innovative technologies to ensure the full participation of this community in all aspects of education, research, and industry practice.
- We must work to make the CISE community equitable and inclusive to researchers, practitioners, and students with a variety of visible or hidden disabilities.
- Work on accessibility is not only important, it is also exciting and highly interdisciplinary, and is worthy of increased visibility within the CISE community. Supporting that work thus requires supporting and funding a diverse community or a diverse set of specialized, interdisciplinary communities.

Accessibility to Computing

The past years have seen a growing trend in academia and industry, focusing on ensuring that technology be accessible to all. The goal is to make technology accessible and useful to people in remote, rural, often poor communities. This challenge raises issues of feasibility, but also affordability.

While increasingly many people in the world have some type of computing device (often a smartphone), people in rural, often poor, communities continue to have limited or no network access. In actual fact, some communities in large cities also have inadequate network access to meet the requirements of modern work and education. Over the past few years, the CISE community looking into information and communication technology for development has grown. Significant research investigates how to provide cost-effective ways to connect remote communities to the Internet. Other research studies how to leverage computing in these environments (e.g., collect data and upload it assuming that network connectivity is intermittent). Other research yet focuses on the human computer interaction challenges. Many opportunities are available and it is critical for the CISE community to embrace and expand those efforts, perhaps through partnerships with other agencies. Enhancing accessibility to computing throughout the country is essential to ensuring development and recruitment of talent, both to advance our nation's economic future and security, and to increase the talent pool for future research and CISE's global competitiveness.

The concept of accessibility to computing can extend to campuses, to ensure students and researchers are not only able to connect, but able to access diverse data and compute resources across campus, the country and throughout the world. Programs such as the Office of Cyberinfrastructure's (OAC's) Campus Cyberinfrastructure program have helped many campuses upgrade capacity to participate in today's data intensive research. Moreover, the OAC International Research Network Connection Program has helped improve networking and people connections to other parts of the globe, to benefit the US research and education community. These programs would extend the reach of new efforts in enhanced accessibility of computing throughout this country.

EDUCATION AND HUMAN CAPITAL

To fully capture the opportunities described above, we must continue to grow and support diverse talent within the CISE community. We must also ensure a broad distribution of knowledge about the opportunities and cautions of CISE research to all citizens. We need to invest in CISE education innovation and in educating CISE researchers as inter-disciplinary leaders and global citizens. Keeping the door open to the best minds in the world is essential for the US economy and research enterprise. Equally important is to cultivate the minds of our own country. In both cases we need to ensure we sustain that talent to our profession. In this section we discuss several challenges and opportunities in education, several unique to CISE.

Diversity, Equity, and Inclusion (DEI): As noted above, CISE researchers and practitioners build systems that impact all aspects of and everyone in our society, yet the people who build this technology do not represent the diversity of the human population. Similarly, the growth of high tech companies and their impact on society has resulted in computing jobs being very well paid with generous benefits, yet that economic advantage remains limited to only some people. Finally, the work environment in the computing field, whether in industry or academia, remains unwelcoming to women and to people in other underrepresented groups. The result is that the CISE community is missing out on talent and excellence. In order to grow the excellence of the field and make our society more fair, we must welcome and nurture all talent. This need translates into several recommendations for the CISE community:

- We need to educate our faculty in matters of diversity, equity, and inclusion. We all need to work toward changing our institutions and our communities.
- We must educate our students not only in CISE techniques, methods, and tools, but also in how to create a welcoming environment around them, free of biases, where everyone can be themselves, and where everyone can be recognized for their accomplishments and can thrive.
- We must also educate our students in matters of racism and technology, technology and disabilities, etc. Many academic institutions and technology companies claim to be meritocracies, whereas it is quite clear that they are not.
- We should teach our students how to talk with each other respectfully and openly about all these important topics, and how to come together around those topics.
- We should similarly expand the research efforts of the CISE community in topics that include racism and technology, inclusive technology, DEI in CISE fields, fairness, and more.
- We need to encourage the integration of socially relevant data, applications, and questions in our core CISE courses.

We also need to expand our efforts to broaden participation in the CISE field. Thanks in part to NSF's leadership, there is a substantial chance that by 2030, nearly half the undergraduates majoring in Computer Science will be women. While this projection is optimistic, the success of universities guided by the National Center for Women and Information Technology (NCWIT) and the Building Recruiting And Inclusion for Diversity Initiative (BRAID), suggest it is possible and perhaps even likely. We need to continue to pay attention to gender diversity, but we also need to significantly expand our efforts around racial diversity and in bringing people with disabilities (whether visible or not) into the field. Some efforts, such as the FLP (Diversifying Future Leadership in the Professoriate) Alliance, are already underway, but the CISE community needs to do significantly more. As we diversify our field and attract talented students with different backgrounds and different preparations, we need to expand dramatically the support that we offer those students to ensure their success in our field. Feeling overwhelmed and inadequate after the first few computing classes is one of the main reasons students drop out. We should invest in various on-ramp courses, side courses, tutoring, and other methods to expand our support for all students.

Global Citizens: As our world faces unprecedented environmental and societal challenges, we need to educate our students to think about the world around them instead of focusing on maximizing their immediate recognition and compensation. Students, researchers, and practitioners should all work toward making the world a better place. Students need to learn how to build systems with ethics, privacy, security, social, and environmental implications in mind. Students should strive to solve the world's greatest challenges. Too many students become professionals who focus solely on their personal success. Part of the problem is that many jobs are not really amenable to thinking about the world. Everything in the modern workplace in industry is about employee performance, compensation, bonuses, and recognition. The CISE community needs to investigate how to change this. Perhaps the community could create employment opportunities that enable industry practitioners to also be involved in research projects at universities focusing on making the world a better place. We should

expand our support and funding for research that specifically targets the most pressing humanitarian challenges. The CISE community must investigate how to reconcile the need to educate students so they can work on humanity's greatest challenges with the reality that most undergraduates want to major in computer science and get a high-paying job at a tech company.

Working across Disciplinary Boundaries: As computing technology continues to permeate society, policy makers, entrepreneurs, scientists increasingly need to learn about it. All undergraduates on university campuses need to have a basic knowledge of computing. Computational thinking is applicable to a wide range of disciplines. Analogously, undergraduates who specialize in CISE-related majors need to be knowledgeable in topics at the boundary between CISE and society. They also need to be able to communicate effectively with colleagues in other disciplines and with the general public. They need to know how to influence and affect policy. They need to know when and how to make their skills useful in a broader context. In general, tackling the challenges highlighted in the previous sections requires interdisciplinary skills. For this, we need to both change how we educate CISE students to make them more interdisciplinary and cultivate partnerships with experts in other domains. We should educate our students in successfully establishing and participating in such partnerships. We should further leverage partnerships with other fields to cross-pollinate the education in our respective majors. The cross-pollination can take the form of new X+CS or CS+X undergraduate programs, but it should also fundamentally influence core CISE education, bringing important concepts from other fields into undergraduate CISE programs (*e.g.,* ethics, policy, and societal impacts, as well as other ways of thinking from science, engineering, economics, and the humanities, among others).

Next generation of educators: On the topic of education, we need to understand how best to educate the educators. These include CISE professors, but also faculty outside of computational fields, and K-12 teachers. There is research and efforts around the best methods to teach computer science. We must also educate instructors in the above challenges: the societal implications of computing; diversity, equity, and inclusion in computing; computing and humanitarian challenges; etc.

Computer Science Education as a Discipline: On a related topic, as we expand the number of students learning computer science at the college but also K-12 and post-baccalaureate levels, the need for research into effective and inclusive ways to teach this discipline grows. We need to emphasize the importance of this discipline and appropriately include it in departments and support it. We should incorporate the learnings from the research into our classrooms. Modern pedagogy calls for methods such as flipped classrooms, hands-on learning, working on meaningful problems, and more.

Rethinking the core of CISE education: As we discussed above, the CISE field is broadening. CISE education used to focus primarily on theory, system design, and software engineering. Today, CISE includes topics such as molecular programming, computer science for social good, data visualization, natural language processing, human computer interaction, etc. This growing breadth requires us to fundamentally rethink how we teach computer science. Is there still a core that all students should master? How do we cost-effectively teach the breadth of knowledge that is now CISE? How do we find the time to cover both the broadening technical content, the social and global implications of computing, and the diversity, equity, and inclusion aspects? Perhaps there should no longer be a single core but instead we should acknowledge that our students can learn different aspects and components of our field based on their interests and goals.

A related topic is how to teach CISE methods and tools to the global university campus. Everyone needs to be knowledgeable in data science in order to be effective in their chosen career because data science permeates so many professions. Similarly, all students need to have fundamental knowledge in computing and its implications in order to be an informed citizen and technology user.

Many computer science departments have grown into Colleges or Schools. The CISE community needs to reflect on what this transformation means for the

field. These new academic constructs serve a much broader community that may not even see itself as squarely in the CISE fold.

Area Diversity in Face of Changing Demand: Diversity gains aside, the 2020s are likely to be a challenging time in Computer Science education. Demand for Computer Science education continues to grow. Even if we see one of the periodic dips in demand, the dip is likely to be modest. Concurrently, overall university enrollments are expected to drop, especially after 2025. The effects of the enrollment drop will vary substantially by region, and in some regions will be acute (> 10%). Declining enrollments will stress university budgets. As a result, Computer Science departments or schools/colleges are likely to need to grow to accommodate demand, at a time that many universities are cutting back. This is a significant issue, especially as some techniques that universities use to manage such situations (such as limiting enrollments in popular majors) are believed to harm diversity. The current trend is causing humanities departments to shrink and even close while computer science (and several other STEM fields) is booming. It is not desirable for our societies to educate only STEM students. How can we support the humanities, arts, social sciences, and other domains? How do we ensure students continue to be educated in those domains? Should we move toward a model of increasingly many double-majors? Should we create new, joint degrees? Should we explore other models? As we discussed above, most domains today are benefiting from close interactions and collaborations with computing fields and vice-versa. This includes the humanities (e.g., digital humanities), social sciences, and other non-STEM fields. As such, close collaborations and the education of students in both those domains and in computing would likely appeal to students.

Graduate Education: In thinking about computing education, it is crucial to remember that university faculty are a cornerstone of delivering that education. As such, it becomes important to track the health of the PhD pipeline. We are currently seeing a number of noticeable trends: there has been a significant demand for PhDs from industry; a parallel drop in the percentage of PhDs who join academia after finishing (students see academia as increasingly less attractive due to its dramatically lower pay, long hours, at times unreasonable expectations, miscellaneous teaching and service responsibilities, constant fund-raising stress, etc.); yet the total number of faculty in our institutions has grown—45% from 2006 to 2019 according to the Taulbee Survey — leading to a commensurate growth in the number of PhDs who are awarded each year. It is unclear how concerned the community should be, given all of these concurrent pressures. They may balance each other.

On the other hand, there are certainly some troubling statistics. In particular, there has been a leveling off of domestic students going into PhD programs; from 2018 to 2019, enrollment of students from underrepresented groups in CS PhD programs decreased by 16%, also according to the Taulbee Survey. Given both the needs for more students and more diversity among those students, these numbers are troubling to say the least.

Junior and Mid-career Talent: While there is much focus on attracting people to careers in CISE, we also need to focus on issues of retention and sustaining those who start their CISE careers In particular, while there are programs for early career researchers, such as CAREER and CISE Research Initiation Initiative (CRII), there appear to be few programs for mid-career researchers. Given the expected "bubble" introduced by the boom in hiring/growing CS in academia for the last 5-10 years, attention to sustaining active careers and retaining talent will be increasingly important. Assuring that sufficient resources and appropriate mechanisms are in place to support the longer career pipeline will be important for CISE and the community. Similarly, what are programs to help keep faculty up-to-date, especially those at non-R1 schools where there is a danger that faculty members aren't able to easily keep up with changing trends in a field.

CISE IDENTITY

One consequence of a field becoming increasingly central is that the field begins to be owned by so many that it can lose its identity. We want to have our identity, but we do not want to be either insular or stale. The lament might go: Everyone wants to do computer science and partner with us, but we can't become everything to everyone.

There are multiple possible reactions, including distinguishing explicitly between, say, "pure" computer science, "applied" computer science, and so on. One challenge will be felt in teaching courses on topics such as machine learning, data science and security, relevant to many disciplines. What principles will help inform the CISE and other communities to optimize the division of labor and intellectual effort to train these students, so they learn about opportunities and limitations of tools? What has been learned by the development of data science programs today, or the teaching of statistics used by many disciplines, that can help inform us now?

Computer science has undergone three main transformations: exciting transformations within the field itself, exciting new interactions with other fields, and exciting ways through which the field impacts and transforms society. These transformations have led to expanding those fields with which we interact, but have also importantly expanded the boundary of the field itself. This expansion provides a new context that affects the way we do research and the way we do education.

There are many examples one can use to illustrate the point. When computational thinking met biology, the transformation changed the language that biologists use to describe their own artifacts. In genetics, the fact that the information was represented in a manner that could be processed by a computer (DNA, RNA) allowed computing to vastly assist in the complete sequencing of biological genetic codes and in the discovery of matching codes in genetic databases such as the Human Genome Database. To the degree that the sciences admit of representations that can be computer-processed, computing becomes increasingly central to progress in that science. Similarly, one could argue that there are many examples of machine learning that is about adapting mechanisms and modes of thought from other fields, including evolutionary biology.

Today, many advances come from how data and computing are embedded and used in various application areas. Many of those advances are not necessarily fundamental (though some do trigger major CISE advances). One can then ask: What is the role of CISE? How should its researchers contribute to such projects? One key role for CISE researchers in these types of endeavors is to provide depth of thinking in the appropriate CISE tools and techniques to use, and when appropriate, the development of novel such techniques. As such, the CISE community and the NSF should continue to encourage and support partnerships around such projects.

Computing has also been changed by its increasing focus on humans being at the center of our systems. We increasingly depend on human-subject experiments for our research and hands-on labs for our students. As the field shifts in these directions we need to expand both the image and the reality of what makes up the field while retaining what makes computing computing.

As we continue discussion about CISE's Identity, we need to be mindful of the organizational structure that limits or enhances our ability to fulfill our identity, e.g., university structures, funding agency organizations. In addition we need to consider what our key aim in educating the next generation is, especially for those in other disciplines, to teach techniques or to convey mindset.

One piece of evidence of the importance of questions of both the breadth and uniqueness of computing is the sharp increase in Schools and Colleges of Computing and their equivalents. 30 years ago there were perhaps two among the research 1 universities. Now there are at least five just among the top ten, depending upon how one counts.

This move is an important milestone in the development of the field and its ability to contain its breadth on the one hand and to build both intellectual and organizational partnerships with other units at universities. CISE is in a similar situation and would do well to continue building its intellectual and organizational connections to the rest of NSF.

CHANGING CONTEXT OF SCIENTIFIC RESEARCH

Vision 2025 made the following points which are still true today: (1) the need to publish data as part of the research process; (2) the need to deeply engage other fields (e.g., materials, transportation, and healthcare) and the agencies associated with those industries; (3) the need to assess the contributions of computing as part of larger scientific agendas; and (4) the need to create "sandboxes" that allow for computing explorations in the context of distributed and cloud computing and corresponding Internet of Things. While those key points continue to be important as we prepare a Vision 2030, the following important changes must be considered:

CHANGING CONTEXT OF SCIENTIFIC RESEARCH

Science and Security: Knowledge advances through rigorous, open inquiry and debate in science and technology. This is achieved through exchange of ideas, data, expertise and people, with as low barriers as is possible.

As stated by the NSF, "The values that have driven NSF and its global research partners for decades are openness, transparency, and reciprocal collaboration; these are essential for advancing the frontiers of knowledge."[1] The subsequent JASON's Report "Fundamental Research Security [2]" notes that these values help promote US leadership in science, yet not all countries adhere to these values, leading to threats to national security and competitiveness. The JASON's report makes several recommendations in the context of research integrity, e.g., expanding this to include full disclosure of commitments and actual or potential conflicts of interest, and to reaffirm the principles of National Security Decision Directives (NSDD)-189 [3], "which make clear that fundamental research should remain unrestricted to the fullest extent possible, and should discourage the use of new CUI (Controlled Unclassified Information) definitions as a mechanism to erect intermediate-level boundaries around fundamental research areas" rather than other approaches that "erect intermediate-level boundaries around fundamental research areas."

This national discussion should involve the academic community, both to ensure the integrity of the research system as well as to ensure openness (to the greatest extent possible) of ideas, data, results, expertise and people in the conduct of fundamental research. Moreover the community must be ever vigilant of proposed changes to ability of allowing the brightest students to come to study in the United States.

Already, we have seen a shrinking pool of international applicants to certain disciplines, including computer and information science and engineering. This has direct implications for the conduct of near-term research and of long-term collaborations, as well as the source of talent for US industry and government.

Another implication is that there should be a renewed effort to build talent in the country as described above.

In short, all components of the US research community must safeguard research integrity, be vigilant to maintain an open (to the greatest extent possible) ecosystem for fundamental research, and renew efforts to cultivate talent within the United States. These steps are essential to maintain national competitiveness, global cooperation, and ensure leadership in research.

Evaluation and Dissemination of Results: Today, there are multiple approaches to disseminate research results (e.g., social media, arXiv.org). There are also increased opportunities to use technologies to speed publication, which puts pressure on the evaluation process. A recent Computing Community Consortium report [8] drew attention to the trends in disseminating and evaluating research results. The report found that "Trends impacting computing research are largely positive and have increased the participation, scope, accessibility, and speed of the research process," however "Challenges remain in securing the integrity of the process, including addressing ways to scale the review process, avoiding attempts to misinform or confuse the dissemination of results, and ensuring fairness and broad participation in the process itself."

The report includes several recommendations, and underscores some steps the CISE community is taking to ensure research integrity in its community.

We also recognize that technology transfer remains a critical approach to bringing the benefits of innovation into practice, but also as a way to create bridges between practice and innovation that can further spur research projects. Technical transfer should continue to be encouraged. In doing so, we should recognize that technology transfer is usually affected by people-transfer: start-ups, post-docs, internships. Technology transfer strategies should address and facilitate the people transfer, including the ability to move back and forth between academia and industry.

Research Infrastructure: Infrastructure is a key multiplier of research productivity. NSF has long supported the computing research enterprise by investing in infrastructure. The need for continued investment remains and will continue to be important through 2030; however, the nature of that infrastructure is changing in important ways.

In particular, "infrastructure" often evokes hardware: fast, powerful supercomputers that can support scalable computer experiments. Today, this also includes experimental embedded computing infrastructure (e.g., health care, smart cities), where the need is to create a safe place to experiment at scale. A particularly important class of research infrastructure are capabilities for research experimentation across and within the wide variety of emerging technologies and use scenarios. Living in the future also means enabling continuous R&D infrastructure gains. Our highly connected world is growing exponentially in scale and complexity.

Increasingly, in addition to hardware, the research enterprise also depends on *data* and *software*. *Tensorflow* is infrastructure. *ImageNet* is infrastructure. Community data resources, data commons and data trusts, are also important components of infrastructure, especially in our increasingly data-driven world.

CHANGING CONTEXT OF SCIENTIFIC RESEARCH

Furthermore, as computing research continues to broaden and extend its scope, we expect that there will be increased need for even those focusing on basic research to incorporate users.

It will also be important to use these experimental systems for test and benchmark in real-world uses.

All of these trends suggest an even more increased need to support partnerships with industry. Whether we are discussing machine learning or cybersecurity, industry will increasingly have both the computational resources and the data necessary for researchers to extend the state of the art. NSF will need to facilitate these partnerships to support its research mission.

Open and Repeatable Research: Looking forward, it is clear that CISE R&D must be grounded in the same systematic approach to discovery and validation that is routine in other scientific and technological disciplines. To approach these challenging research problems, we must create a paradigm shift in experimental research. Only by enabling demonstrable, repeatable experimental results can we provide a sound basis for researchers to leverage prior work, and create new capabilities not yet imaginable. Tomorrow's researchers must be able to stand on the shoulders of today's researchers, not be consigned to re-treading the same ground.

Key tenets of an experimentation strategy should include the following key principles:

- Support experimentation and testing of hypotheses;
- Enable creation of repeatable, science-based experiments that can be validated by others;
- Generate research results that can be leveraged into broad, multi-component solutions in which components demonstrably support one another, making the whole greater than the sum of its parts;
- Foster methodologies and tools to help guide experimenters toward this new, scientific experimentation discipline; and
- Provide an open environment for researchers in industry, government and academia to build on one another's achievements.

Intersection of technology and human values impacts innovation: One of the key findings of this report is the need for the CISE community to understand the impact of the implementation of its technologies on society. For example, society reacts strongly against fatalities caused by technology such as self-driving cars, against biased decisions made by algorithms, against poor outcomes from automated diagnostic systems, and against other negative outcomes of technology. In addition, we see how bad players can manipulate social media to cast aspersions on electoral processes via amplifying or misrepresenting information. As a third example, the field of Human Computer Interaction (HCI) is one that studies human values. Ensuring broad understanding and diversity of the human factors to design the human-computer interfaces is essential to develop trusted and trustworthy products. We need to factor in that relationship between society and technology. This problem also expands to computing, policy, and law enforcement. Our community must become comfortable working with policy and lawmakers on defining how technology should be regulated. The CISE community must be an integral part of defining new policies and laws related to technology.

Growth and Dominance of Technology Companies and Continued Low Research Funding in Industry: Technologies companies have moved beyond their technology base, using a combination of internal research and development and external acquisitions. Instead of moving computation into application companies, technology companies have started to become application companies themselves. For example, five years ago, Google was not an automotive company, Amazon was not a grocery store, and Microsoft was not a medical research center.

In addition, the level of basic research funding in industrial environments have gone toward zero. Industry fundamentally does more applied research: trying to apply fundamental methods to specific problems and deploying research in applied settings.

These two changes place different stresses on NSF and the research community.

- NSF and its budget, which funds more than 80% of all federal fundamental computer science research in this country, are being stressed as the role of CISE research increases in society. Ensuring the appropriate balance between basic and translational research and promoting increased funding for both will be important for NSF and the larger federal funding activities.
- The scale of issues that the technology companies are addressing increasingly adds to the gulf between resources available to academic researchers and those in the tech industry. This has implications for research and the educational experience offered students and faculty.
- As the size of technology companies increases, so does the demand of technology expertise, adding competition to and stressing universities in their hires (salary).

- Together, under current economic conditions and budget allocations, more demand for NSF's research and the ability to capture, sustain and retain talent in academia creates long-term challenges for the US fundamental scientific research leadership. (See comments in the Education section relative to the entire career pipeline.)

Faculty with deep industry engagements. Traditionally, researchers have had both feet planted in either academia or industry. Since Vision 2025, we have seen an increased flow of researchers leaving academia for industry. There are several reasons for this movement. First, the gap between salaries in academia and in industry has dramatically increased. Second, successful faculty who move to industry often enter into high-level positions where they get to oversee large teams of researchers and engineers. This enables them to have immediate, large-scale impact. Third, industry provides access to extremely large-scale compute infrastructure and unique datasets that are not available in academia.

Successful faculty engagements with industry can bring many benefits to students and universities. They can enhance the student experience by providing faculty with greater knowledge of the needs and research problems that arise in industry. Faculty who engage with industry can bring that experience back into their classrooms. Deep industry collaborations can enable access to resources beyond what academia can provide. Interesting datasets and large-scale or unusual computer resources can become available to faculty members and their graduate students for their research. They can strengthen collaborations with industry experts. Real-world problems can inspire faculty and graduate students to select research problems that have a direct practical impact. Industry experts can be co-advisors to students and even co-authors on papers. Finally, faculty with engagement with industry frequently bring gift funds to the university in support of university research.

Deep engagement of faculty with industry also creates additional, great challenges for universities. Faculty members use their industry engagement as a reason to get out of teaching and academic service. Faculty members also spend much less time on their university campuses, at the detriment of their graduate students and their colleagues. It becomes more difficult to maintain a sense of community and commitment. Faculty become much less attached to their department and much less involved with working toward the good of their department.

Looking into the future, unless academic salaries increase dramatically, faculty will continue to either leave academia or keep one foot in industry. Our recommendation to the CISE community is to use the shared experience already accumulated by different institutions to define models that work, where faculty can have one foot in industry and one foot in academia. Several reports and articles have already been published on this topic and could serve as starting points [**4, 5, 6, 7**]. These models should address issues such as the following: facilitating growth of funding and lab sizes to retain faculty and work on problems of scale; developing standard agreements and standard templates for these types of split roles, especially mindful of intellectual property issues; ensuring the sense of belonging and commitment to both organizations; ensuring that students continued to be taught by the world's greatest experts in their respective domains; managing academic service work; providing fairness to different faculty with different types of external engagements; and ensuring an appropriate level of commitment to the increasingly diverse role of faculty; all while being mindful of faculty in other departments. Overall, this is a critical and difficult problem that requires our immediate attention and our creative thinking. While this problem does not uniformly affect all universities, we can expect this problem to spread and, without good models, it could significantly affect academia.

Industry versus federal research investments: NSF looks at the entire CISE research and education ecosystem, including fundamental long-term research; interactions with other science, engineering and education disciplines; community infrastructure investments; and the growth of human capital.

As part of a healthy research and education ecosystem for computer and information science and engineering, NSF and CISE also use as a consideration the allocation of funding across institutions, geographically and types, and engaging a diverse PI community. In addition, NSF CISE works to ensure the US CISE community plays leading roles with international researchers who share research values, as well as opportunities to interact with industry, where it makes sense.

On the other hand, industry is a consumer of NSF's fundamental research, sometimes a collaborator in its creation, and its human capital via hires. Industry focuses on different scales of problems and implementation of new ideas. In addition, industry may often focus on only segments of CISE's research's intellectual space, often is driven by a different time horizon, and is not intrinsically interested in (or feel responsible for) promoting (i.e., being a steward of) the research and education ecosystem.

Intellectual partnerships between the NSF research community and industry that take advantage of each other's unique attributes may be of mutual benefit.

The United States as well as many other countries have long seen the connection in long-term research investments and

national competitiveness and security. Today, however, investments in research in some countries are on a steeper incline than are those in the United States. This can hurt the competitiveness of our country and it can also cause us to lose talent because opportunities abroad have in several cases become more appealing than staying in the United States.

To maintain our competitive edge, investments are required in basic research and development of human capital that advance our industries. Investments by industries are fundamentally of a different type, with a different purpose.

Concretely, NSF and the community must make clear the value of long-term investments to the broader public.

Partnerships with Industry: We applaud CISE's willingness to explore partnerships with industry and other agencies. We feel there are potential win-win situations in those partnerships. We also understand that there are overheads in any partnership, sometimes administrative, sometimes intellectual. Finally, we understand CISE is undertaking a review of its previous partnership to understand the value of those investments in terms of return on the intellectual, financial and administrative investment.

Given NSF is undertaking a review of its experience, we will only raise some questions that are worth considering in this review:

- What has been the value of the partnerships to the academic community? To industry? In particular, have there been specific successes from any of the participants' viewpoints? What do each member of the partnership bring uniquely to the table?
- Have there been qualitatively different results in this partnership than in non-partnership programs?
- What have been major issues in reaching agreements with industry to support research?
- Have these partnerships been done at a scale to reap a benefit for the community beyond those researchers who are participating?

Hearing about these experiences should inform NSF and the AC as to the question of whether NSF's partnerships co-investments should increase or decrease (presumably when there is benefit and value). We pose the following questions about larger-scale partnerships or a larger portion of NSF's investment portfolio.

- Are there constraints on the mechanisms to partnerships?
- Are there new partnership models used by other agencies (domestic or international) that could be considered?

We see potential advantages to the NSF research community of partnering with industry under circumstances that allow for mutual benefit. Some of these benefits include an understanding of and focus on problems of direct relevance to industry, access to scale of infrastructure and types of data not available to academic researchers, and collaborations with the talent and innovators in industry. Potential benefits to industry is working with a diversity of talent, access to early research directions, and scouting future employees.

One possible drawback when industry partners with the NSF is they may sponsor less research in other ways. As NSF considers partnering with industry, we encourage NSF to proceed in a way to incentivize industry to invest in more research, and the research and education ecosystem. One area to help industry is to increase the size and diversity of their pool of talent when they recruit. Are there opportunities for NSF-Industry to partner in efforts to broaden participation in CISE activities?

Finally, as NSF reviews its own experience, one consideration is how to incentivize collaborations, which may involve lowering barriers to interactions and creating a portfolio of opportunities. Under mutually beneficial conditions, one consideration to initiate collaboration is a lighter weight proposal approach, that might use/prototype and advertise an EAGER-like mechanism or supplements to begin collaborations between PIs and industry.

Final Thoughts on NSF-and-Partnerships: In closing, we encourage CISE to also consider expanding partnerships with industry and beyond! The scale of societal challenges as well as the need for a healthy CISE research community and ecosystem requires a partnership strategy. To this end, NSF has a role to play. First, NSF must continue to articulate the value of its research and education investments that form the foundation for the industries of the future. Second, NSF should consider ways to grow a dialog between academic researchers and industry in a way to grow the academic research enterprise and open communication to allow flow of ideas and expertise and access to unique resources. Finally, NSF should consider ways to invest in infrastructure that would not be available or accessible in industry to ensure CISE researchers work on problems of importance and scale.

POTENTIAL BLIND SPOTS

Finally, we end with a reflection on our potential "blind spots". In this document, we use the term "blind spot" in two senses. The first is where we know where to focus our attention, but there is significant uncertainty of what will emerge; the second, while perhaps not technically a blind spot, is where we are not choosing to focus.

Examples of the former (type 1) are proprietary or national security research directions and results in industry, military and national defense, both domestic and international. Examples of the latter (type 2) are the waning attention to mature CISE fields because of the energy on exciting new areas, the lack of awareness of the use of CISE in other areas, or in not learning the open science in other countries. Risk and risk mitigation approaches differ in each type of blind spot. For example, with the former one approach is to build communication ties as best possible to ensure immediate update when those results are released; in the other is to ensure some ongoing investments as well as to build conduits to new disciplinary or geographical areas of research.

Additional examples of Type 1 Blind Spots include the following.

The area of quantum computing could produce unexpected changes. It is also an area that is unevenly covered in curriculum.

Another example, that we can partially mitigate, are policy, regulations, legislation and enforcement. Current discussions are now happening about social media, and are likely to take place on legislation on automatically driven vehicles, which may impact how technologies are adopted by society. By mitigation, the community could adapt a position of interaction with lawmakers prior to the rush of responding to the most recent events.

As discussed in the education section above, there is also a projected enrollment cliff in undergraduate programs, which will dramatically impact some institutions. This is also coupled and complicated with the questions of affordability. How should the CISE community respond to this looming issue?

Finally, immigration policies that determine the access of students to US research institutions and more broadly the ability to access international talent will have an impact on student populations and the technology workforce. The US population is only a small fraction of the world population. To recruit the best and brightest, we need to draw our students and faculty from our own and from beyond our borders.

Mature Fields (blind spot type 2): Many CISE fields are considered mature, but we must ensure that fundamental research and forward-looking innovations continue in those fields. Without ongoing innovations, we risk losing the competitive edge of some of our mature fields. Consider communications and networking. This field is considered mature for how we have used the work that has come from it in the past, but it will need to continue to adapt and grow to engender future innovation.

APPENDIX

Specific Recommendations from Vision 2025

1. The current Cyber-Human Systems program needs to be invigorated with challenges oriented to technologies that exist in the physical "post mobile and web" world. These explorations will require innovations in programmable matter, distributed systems and cloud computing.

2. Systems-oriented research areas are starting to interact with humans in the loop, and need to formally involve more human-centric research, not only social science research, but variations of human-computer interaction research as well.

3. Overall we face a need for "intra-disciplinary" computing research across multiple, often siloed, areas of computing expertise.

4. Cyber-human systems and cyber-physical systems research activities need to explore greater collaboration and joint exploration. Application-oriented research in healthcare, transportation and smart cities frequently requires robust cyberphysical systems working hand in hand with usable and flexible cyber-human systems.

5. Research activities focused on the merging of the computing-social-physical world require novel testbeds to facilitate collaborative explorations. These investments should mirror and leverage current investments in high-performance computing. One example application area is the growing interest in "smart cities."

6. Research activities focused on the merging of the computing-social-physical world require educational experiences for graduate and undergraduate students that differ substantially from current educational programs. One challenge is how to teach basic computing expertise that incorporates preservation of privacy and security from the ground up. Another challenge is how to expose students to capabilities in mechanical and materialsx engineering.

[1] http://www.nsf.gov/news/news_summ.jsp?cntn_id=298852&org=NSF&from=news

[2] https://www.nsf.gov/news/special_reports/jasonsecurity/JSR-19-2IFundamentalResearchSecurity_12062019FINAL.pdf

[3] National Policy on the Transfer of Scientific, Technical and Engineering Information, https://fas.org/irp/offdocs/nsdd/nsdd-189.htm

[4] Evolving Academia/Industry Relations in Computing Research. CRA Report. June 2019. https://cra.org/ccc/wp-content/uploads/sites/2/2019/06/Evolving-AcademiaIndustry-Relations-in-Computing-Research.pdf

[5] At Tech's Leading Edge, Worry About a Concentration of Power. NYTimes. Sep 26th 2019. https://www.nytimes.com/2019/09/26/technology/ai-computer-expense.html

[6] "When the A.I. Professor Leaves, Students Suffer, Study Says". NYTimes. Sep 6th 2019. https://www.nytimes.com/2019/09/06/technology/when-the-ai-professor-leaves-students-suffer-study-says.html

[7] "AI Academy Under Siege". Inside Higher Ed. Nov 20th 2019. https://www.insidehighered.com/views/2019/11/20/how-stop-brain-drain-artificial-intelligence-experts-out-academia-opinion

[8] Evolving Methods for Evaluating and Disseminating Computing Research https://cccblog.org/2020/07/02/ccc-releases-evolving-methods-for-evaluating-and-disseminating-computing-research-white-paper