Education and Workforce Development in the High End Computing Community

The position of NITRD's High End Computing Interagency Working Group (HEC-IWG)

Overview

High end computing (HEC) plays an important role in the development and advanced capabilities of many of the products, services, and technologies that are part of our everyday life. The impact of HEC on the agencies of the federal government, the quality of academic research, and on industrial competitiveness is substantial and well-documented. However adoption of HEC is not uniform, and to fully realize its potential benefits we must address one of the most often cited barriers: lack of HEC skills in the workforce. Distinct challenges for the development of such a workforce include that: 1) such a workforce needs to have multidisciplinary knowledge spanning areas of computer sciences and other areas of science and engineering; and 2) developing such workforce requires change of the workforce development paradigm to one that bridges academic education, which typically provides little access to HEC platforms, with real-world exploitation of HEC systems. To overcome the present barriers we must pursue approaches to develop both ends of the computational skills spectrum, from HEC Providers to HEC Consumers.

The approach described herein and endorsed by NITRD's High End Computing Interagency Working Group (HEC-IWG) includes a focus on internships, scholarships, graduate and post-doctoral fellowships, and directly-funded research experience for those in traditional undergraduate and graduate university programs, as well as curriculum development, to develop a robust university environment that produces the workforce ready to apply HEC to problems of US interest. The HEC-IWG approach also includes explicit support for in-career professionals, who may be best served by new, more flexible learning approaches.

The HEC-IWG believes it is critical for the development of meaningful workforce development and education programs that our community identify the specific skills needed by HEC Consumers and Providers to ensure successful exploitation of HEC capabilities. Identifying a representative set of career paths within HEC (computer architect, systems administrator, systems software developer, application developer, computational scientist, etc.), as well as the skills and experiences required to successfully pursue those career paths, will facilitate the development of effective workforce development and education programs and encourage recruitment and in-career transitions.

High End Computing and US Leadership

Today US institutions of innovation, discovery, and economic well-being – from industry and academia to the agencies of the Federal government – cannot achieve their goals without high end computing

(HEC)[1]. HEC is used in a remarkably broad array of activities, including: defense and homeland security; scientific research and discovery; the discovery of new drugs and therapeutic approaches; modeling of weather and climate patterns; the design of complex systems from automobiles and airplanes to microprocessors and household appliances; finding and extracting oil and gas; the manufacture of consumer products from diapers to tires; and managing retail inventories. Furthermore, capabilities that are developed in support of HEC have an impact across the spectrum of computing. For example, the ability to reason about and program for a high degree of parallelism began as a HEC challenge, but this capability is increasingly important for data center operation, real-time processing in safety critical environments, and even for full utilization of multi-processor desktop and laptop computers.

HEC, also referred to as high performance computing (HPC), is a cluster of activities that enable the development and application of computer hardware, support software, and advanced algorithms to address highly complex, computationally challenging problems. HEC is distinguished from the general class of computing by its scale: HEC addresses challenges that are either compute-intensive, requiring a very large number of processors working together at one time, or communication-intensive, requiring specialized networks supporting high speed communications among processors and/or distributed systems, or both. Increasingly, large-scale simulations for science and manufacturing depend on ingest of “big data,” both to set the stage for processing and also to bridge between simulations and experimental and observational approaches to design and discovery.

The contributions and potential of HEC have been well documented in a variety of national studies, including those by the National Academies[2], the President's Committee of Advisors on Science and Technology[3], and the Council on Competitiveness[4]. HEC is a critical enabler for computational science, identified in many studies as crucial for the Nation’s prosperity, national and economic security, industrial production, engineering, and scientific advancement. Useful in this regard are the 2005 report from the President’s Information Technology Advisory Council[5] and the 2006 NSF report, *Simulation-Based Engineering Science, Revolutionizing Engineering Science through Simulation*:

> *This much is certain: there is overwhelming concurrence that simulation is key to achieving progress in engineering and science in the foreseeable future. Indeed, seldom have so many independent studies by experts from diverse perspectives been in such agreement: computer simulation has and will continue to have an enormous impact on all areas of engineering, scientific discovery, and endeavors to solve major societal problems.*

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[1] For the purposes of this document, the terms “high end computing,” “high performance computing,” and “supercomputing” are synonymous.
[2] National Academies Press. (2004). *Getting up to Speed: The Future of Supercomputing*.
[3] Report to the President, President's Committee of Advisors on Science and Technology (December 2010). *Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology.*
[4] Council on Competitiveness (May 2008). *Reveal: Council on Competitiveness and USC-ISI Broad Study of Desktop Technical Computing End Users and HPC.*
[5] Report to the President, President's Information Technology Advisory Committee (June 2005). *Computational Science: Ensuring America’s Competitiveness.*

The US Council on Competitiveness describes the impact of HEC on the ability of our Nation's businesses to compete – and win – in the world marketplace this way[6]:

> *During the past three years, a series of pioneering studies and conferences conducted under the Council's High Performance Computing (HPC) Initiative confirmed the vital role this technology plays in driving private-sector competitiveness. Study after study showed that virtually all businesses – large and small – that adopt HPC consider it indispensable for their ability to compete and survive. The reason is simple: HPC is a proven game-changing technology.*

HEC has often revolutionized, or fundamentally enabled, the fields, industries, and institutions where high end computing is a fundamental part of research or product workflow. But there are still many areas that have not yet even started adopting HEC, and for some that have started, the use of HEC is not as widespread as the adopters would like. Why? Scarcity of talent is often cited as the number one barrier to adoption[6]. A recent report from the NSF Advisory Committee for Cyberinfrastructure finds that a lack of computational science and engineering skills, the multidisciplinary bundle of skillsets that utilize and advance the practice of HEC, is creating a workforce without the skills needed to apply our most powerful tools – high end computers – to the most significant challenges we face as a nation[7].

A skilled, computationally savvy workforce is needed in all areas of federal, academic, and industrial endeavor. Meeting this challenge begins with understanding the HEC workforce we have today and anticipating the skills we will need tomorrow.

Characteristics of the HEC Workforce Today

The influence of HEC on the discovery and innovation engines of the United States is very large compared to relatively small portion of the workforce that pursues these activities. Because HEC professionals represent such a small proportion of the much larger IT and STEM workforces, specific and focused workforce data on HEC is hard to come by. However, there are some data.

In 2010 IDC conducted a study of the talent and skillset issues impacting HEC centers for the Department of Energy (DOE) National Nuclear Security Administration (NNSA)[8]. The study surveyed three constituencies:

- DOE national laboratories
- Major HPC data centers
- Academic and training organizations with strong HEC ties

[6] Council on Competitiveness (May 2008). *Advance: Benchmarking Industrial Use of High Performance Computing for Innovation.*
[7] National Science Foundation Advisory Committee for Cyberinfrastructure, Task Force on Grand Challenges (March 2001). *Final Report.*
[8] IDC HPC User Forum: Special Study (July 2010). *A Study of the Talent and Skill Set Issues Impacting HPC Data Centers.*

The study found that nearly all of the centers surveyed (93%) said that hiring qualified staff is among their key challenges, identifying it as either “somewhat hard” or “very hard”, with the majority reporting that it is “very hard” to find qualified staff. The skills that the HPC center respondents considered hardest to find were: scientists with HPC expertise, parallel computing programmers, algorithm developers, and system administrators with high-end computing experience.

Survey: where does the HEC workforce come from?

IDC found that the most fruitful source of qualified candidates for HPC positions from academic programs are “university graduates in mathematics, engineering, or the physical sciences”, followed by “university graduates in computer science.” Importantly, however, the most productive non-academic sources of qualified HPC job candidates are “employees of other HPC centers”, “employees in related positions/areas at our own site”, and “employees of HPC software or hardware vendors.” In other words, a significant source of “new” talent in the HPC centers is not new at all but taken from another part of the HEC community. This is a zero sum strategy that ultimately limits the pace at which the Nation can take advantage of HEC.

HPC centers can, and do, recruit employees with some relevant experiences from other IT-related fields, but the cost of doing so is the amount of time it can take these employees to become proficient in HEC. IDC found estimates of this time can vary from three months to two years, with many responses in the 6-12 month range; anecdotal feedback from the federal HPC community indicates that these responses are in fact on the low end of what is commonly experienced outside of the target community of this study.

Survey: what skills are missing today?

IDC found that the skills most badly needed today include a combined understanding of a scientific discipline and computational science and/or computer science; parallel programming and code optimization, especially for scaling to large processor/core counts; algorithm development; HEC system administration; and understanding of parallel file systems.

Survey: what steps should we take for the future?

When asking how the availability of skilled HEC professionals could be improved, IDC found a variety of answers with some common themes:

- HEC centers focused on encouraging universities to produce larger numbers of qualified graduates
- Academic organizations identified a need to expand coursework in computational science and to integrate computational science methods into the requirements for science degrees
- Academic and training organizations identified a need for more collaboration among government, academia, and industry to increase the number of internship and fellowship opportunities that are available to train and attract students to work in HEC environments

Essential Elements in Developing the HEC Workforce: Elements of a Successful Approach

The HEC-IWG agrees in general with the findings and recommendations of the IDC study summarized above, although we feel the study's recommendations by themselves will not produce sufficient progress to keep pace with the requirement[9].

Traditional approaches to HEC workforce development have focused primarily on the provider side of HEC: those who architect, design, and provision HEC applications and computer systems. In order to successfully develop a workforce that supports the use of HEC to address the challenges faced by federal agencies[10] and the academic and industrial communities, we believe that a successful approach will have a broad span that includes both consumers and providers of HEC capabilities, and encompassing the spectrum of skills across these constituencies. This view is supported by other recent reports; for example, the final report of the National Science Foundation Advisory Committee for Cyberinfrastructure task force on cyberlearning and workforce development observes[11]

> *What has been termed "computational thinking" represents a perspective, an approach, and a set of problem-solving tools that complement those provided by mathematics and scientific logic, and that should be considered essential to students' education and professional preparation, regardless of discipline.*

Realizing the full potential of high end computing to positively impact the missions of the federal government (and the Nation as a whole) will mean that we need to expand the community of domain specialists and computing users who can take advantage of HEC to support their work. This will mean both attracting new graduates from STEM programs who know how to apply HEC as well as augmenting the existing skills of the current workforce. Thus it is important to focus new workforce development efforts on training,career transition, and recruitment and retention, in addition to the more traditional emphasis on university graduate and undergraduate degree programs.

Finally, the HEC community must provide a clear picture of the skills it requires in order to ensure that the education and training community can develop professionals ready to address HEC requirements in the work place. To meet this goal the HEC community must clearly define a set of career paths and skill sets that are critical for success for both ends of the workforce spectrum, drawing on relevant work in other disciplines.

The spectrum of HEC knowledge workers

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[9] This is not a fault of the study, which was designed to capture the sentiment of the communities under study, not to recommend a specific set of strategies or positions.

[10] Although this paper focuses on the HEC community of the federal government, as the Council on Competitiveness and others have pointed out, advanced simulation and high performance computing are playing an increasing role in the industrial competitiveness of the country as a whole. Seen in this light, issues of HEC workforce development are issues faced by the US workforce as a whole.

[11] National Science Foundation Advisory Committee for Cyberinfrastructure, Task Force on Cyberlearning and Workforce Development (March 2001). *Final Report.*

To fully realize the potential of high end computing, we must develop a workforce that is capable of provisioning computational environments and a workforce of HEC-literate professionals that knows when and how to apply advanced computing resources to its problems. The former are *HEC Providers*, and the latter are *HEC Consumers*. In practice these are not discrete end points but opposing extremes on a skills continuum, with individuals moving along the spectrum in both directions as their careers and interests evolve.

In order for the federal agencies that depend upon HEC to accomplish their diverse missions, it is essential to have a stable, regularly refreshed cohort of HEC Providers to provision, maintain, and facilitate use of HEC resources.

This is an important component of a workforce development strategy, but by itself this is not a complete solution for all of the agencies or for the Nation. On the other end of the HEC spectrum are parts of the workforce that own the problems that require HEC in order to reach a solution, the HEC Consumers. In order for organizations to gain full benefit from their investments in computing, these problem owners (or "domain specialists") need to have a basic understanding of HEC and the algorithms and approaches that underpin successful HEC applications so that they can recognize when advanced computing and the expertise provided in agency-funded HEC centers can help them solve their specific problems.

Academic education and workforce development

Traditional undergraduate and graduate programs that educate domain specialists to be effective users of HEC (the HEC Consumer), as well as those programs that build HEC Providers who can architect and implement next-generation hardware and software systems to support HEC, are important parts of the workforce development picture. Although universities have made some strides in this area over the past several decades, there is still work to be done[12]:

> *Universities are not adequately preparing today's students with the right background, skills breadth, and depth to become tomorrow's computational scientists and engineers, able to harness powerful new supercomputers for scientific discovery and engineering innovation.*

Engaging productively with universities, however, requires more than the establishment of degree programs and adding HEC modules into existing courses. Faculty and students need access to meaningful HEC problems to work on that foster the skills needed by federal agencies, and graduate students and post-doctoral fellows, in particular, need funded research opportunities to partner with the federal HEC community in solving the research challenges we face.

As others have recommended[12], we believe that a complete approach to addressing the higher education portion of our workforce development mission should also include a variety of strategies, such as internships, scholarships, graduate and post-doctoral fellowships, and funded research in addition to collaborative curriculum development in order to develop a robust university environment that produces the workforce ready to apply HEC to problems of national interest.

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[12] National Science Foundation Advisory Committee for Cyberinfrastructure, Task Force Grand Challenges (March 2001). *Final Report.*

Additionally, a comprehensive approach to workforce development includes support for transition into HEC professionals trained in other areas as their interests develop and change over time; for example, when an administrator for enterprise IT systems wants to transition full-time to administering HEC systems or when a chemist wishes to augment existing skills by adding HEC skills in order to develop applications that bring HEC to bear on a specific set of problems in their research area.

Where possible, this type of training and skills development should take advantage of the support already offered within agencies of the federal government, such as online modules in career programs, "for credit" courses at universities, and so on. As possible models for extending the reach of HEC training, and development of HEC workforce, the HEC community may also benefit from looking into the feasibility of establishing two-year college-curriculums in high-performance computing, as well as post-graduate programs similar to the certificate and executive MBA programs.

Defining skillsets and career paths

In order to encourage the development of rich training and education programs that produce a workforce ready to address the HEC challenges of tomorrow, we must identify the specific skills that workforce requires to be successful. Although increasingly many technical fields require a broader set of skills in addition to in-depth expertise in a given area; in the high end computing arena multidisciplinary understanding and multidisciplinary training and approaches are an imperative. We believe that identifying a representative set of career paths within HEC (architect, administrator, application developer, computational scientist, etc.), as well as the skills and experiences required to successfully pursue those career paths, will facilitate the development of effective education programs and encourage recruitment and enable in-career transitions by providing prospective practitioners with concrete ideas of what a career involving HEC looks like, along with a template for achieving that career.

Conclusions

The impact of HEC on the effectiveness of the agencies of the federal government in meeting their missions – in space, health, defense, energy, and so on – is well-documented and substantial; HEC today is a technology upon which our Nation is critically dependent for out-competing its geopolitical, industrial, and military rivals. Emerging national priorities in big data, revitalization of US manufacturing, novel drug design, clean energy, and engineered materials all depend upon high end computing, and addressing these priorities will require an expanded community of expert HEC providers and knowledgeable consumers.

Current approaches to HEC workforce development and education are inadequate to address today's needs in HEC centers and scientific disciplines that depend upon HEC; as demands upon HEC increase, this gap will widen. To fully realize the potential of high end computing, we must develop both ends of a spectrum of computational skills that range from the HEC Providers that provision HPC environments to the HEC Consumers who apply HPC to specific problems of interest to the Nation. We must also provide mechanisms that support recruitment of HEC Consumers into the federal workforce and by Federally Funded Research and Development Centers (FFRDCs).

Based on the preceding discussion, the HEC-IWG recommends a multi-faceted approach to developing a workforce of capable HEC Providers and Consumers that includes:

- Development of the next generation workforce in undergraduate and graduate university programs through collaborative curriculum development to establish base skills; and internships, scholarships, graduate and post-doctoral fellowships, and funded research to ensure students and faculty are motivated by rich, real-world HEC problems of interest to government agencies and the private sector (academe and business/industry).
- Support for transition of professionals in other disciplines into HEC, for example by engaging with two-year and certificate programs, utilizing the career development apparatus of the various agencies of the federal government and the private sector (academe and business/industry), as well as self-paced and online instruction.
- The HEC community must identify the specific skills its workforce requires to be successful. Identifying a representative set of career paths within HEC (computer architect, systems administrator, systems software developer, application developer, computational scientist, etc.), as well as the skills and experiences required to successfully pursue those career paths, will facilitate the development of effective education programs and encourage recruitment and in-career transitions.
- Federal agencies with mission drivers for HEC should develop programs that support recruitment and retention of people with critical HEC skills into federal service and/or positions with FFRDCs, for example through support for internships, graduate and post-doctoral fellowships, and support for HEC research.

Next Steps

The NITRD HEC-IWG will take specific action on the conclusions and recommendations above, including but not limited to:

- Defining a set of career paths and skillsets required to leverage HEC to advance Federal missions.

- Working with academic and business sector leaders to describe and develop curricula that will produce new expert HEC Providers and HEC Consumers with the necessary skillsets.

- Working with leaders in the computing and education communities to adapt and test new, more flexible methods of education and workforce development that enable rapid knowledge advancement and in-career transitions to HEC-related positions.

- Engaging the HEC workforce of tomorrow by providing relevant, mission-driven research and application problems, and funding for internships and scholarships.

- Supporting recruitment and retention of the HEC workforce required by federal mission drivers, both in federal service and at FFRDCs, through mechanisms that may include internships, graduate and post-doctoral fellowships, and partnerships with industry and academia.