The BDEC “Pathways to Convergence” Report
Toward a Shaping Strategy for a Future
Software and Data Ecosystem for Scientific Inquiry

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Executive Summary

Although the “Big Data” revolution first came to public prominence (circa 2010) in on-line enterprises like Google, Amazon and Facebook, it is now widely recognized as the initial phase of a watershed transformation that modern society generally, and scientific and engineering research in particular, are in the process of undergoing. Responding to this disruptive wave of change, over the past four years the Big Data and Exascale Computing (BDEC) project organized a series of five international workshops that aimed to explore the ways in which the new forms data-centric discovery introduced by this revolution might be integrated with the established, simulation-centric paradigm of the high performance computing (HPC) community. These BDEC workshops grew out of the prior efforts of the International Exascale Software Project (IESP)—a collaboration of US, EU and Japanese HPC communities, which produced an influential roadmap for achieving Exascale computing early next decade. It also shared the IESP’s mission: to foster the co-design of shared software infrastructure for extreme scale science that draws on international cooperation and supports a broad spectrum of major research domains. However, as we argue in more detail in this report, subsequent reflections on the content and discussions of the BDEC workshops make it evident that the rapid proliferation of digital data generators, the unprecedented growth in the volume and diversity of the data they generate, and the intense evolution of the methods for analyzing and using that data, are radically reshaping the landscape of scientific computing.

At a time when science is, and needs to be, more international and interdisciplinary than ever, this data-driven upheaval is exacerbating divisions, both recent and longstanding, in the cyberecosystem of science; it is thereby raising a host of conceptual, political, economic and cultural challenges to future cooperation. The BDEC community’s sustained examination of these changes focused on the problems in two different divisions in the cyberecosystem of science that the Big Data revolution has either produced or destabilized:

- **The split between the traditional HPC and High-end Data Analysis (HDA):** This divide between HPC and HDA software ecosystems emerged early this century when software infrastructure and tools for data analytics that had been developed by online service providers were open sourced and picked up by various scientific communities to solve their own data analysis challenges. Major technical differences between the HPC and the HDA ecosystems include software development paradigms and tools, virtualization and scheduling strategies, storage models (local vs. Cloud/SAN), resource allocation policies, and strategies for redundancy and fault tolerance. These technical differences, in turn, tend to produce significant contention for technological, economic, and human resources.

- **The split between stateless networks and stateful services provided by end systems:** The division between stateless datagram-delivery networks (e.g., the Internet) and stateful services provided by network-attached end systems (e.g., supercomputers, laptops, sensors, mobile telephones) has been fundamental to the cyberinfrastructure paradigm that proved remarkably successful for well over three decades. However, the exponential growth in data volumes over the same period forced users and service providers to repeatedly find new workarounds (e.g., FTP mirror sites, Web caches, Web cache hierarchies, Content Delivery Networks, Commercial Clouds) in order to manage the logistics of ever larger flows of data. Unfortunately, such workarounds seem to have reached their limits. The most explosive growth in data generation today is taking place in “edge environments,” i.e. across the network from both HPC and commercial cloud machine rooms. These new data sources include major scientific instruments, experimental facilities, remote sensors (e.g., satellite imagery), and the myriad of distributed sensors with which the plans for “Smart Cities” and the Internet of Things (IoT) are replete. The environment in which many of these data torrents originate lack the processing and buffer/storage resources to manage the logistics of such immense flows, and yet the conventional strategy of backhauling all data across a fast link to the Cloud or Data Center is no longer a viable
option for many applications. Hence, the intense commercial and research interest in “fog” or “edge” computing infrastructure, which in one way or another, is supposed to solve this fundamental problem by combining processing, storage/buffering, and communication in a converged distributed services platform.

Looking toward the future of cyberinfrastructure for science and engineering through the lens of these two bifurcations made it clear to the BDEC community that, in the era of Big Data, the most critical problems involve the logistics of wide-area, multistage workflows—the diverse patterns of when, where, and how data is to be produced, transformed, shared, and analyzed. Consequently, the challenges involved in codesigning software infrastructure for science have to be reframed to fully take account of the diversity of workflow patterns that different application communities want to create. For the HPC community, all the imposing design and development issues of creating an exascale-capable software stack remain; but the supercomputers that need this stack must now be viewed as the nodes (perhaps the most important nodes) in the very large network of computing resources required to process and explore rivers of data.

Against that background, we suggest that the prospects for integration of technological infrastructures and research ecosystems needs to be considered at three different levels, or from three different perspectives. First, we discuss opportunities for convergence of research applications and workflows, where, despite the impediments of the ongoing cyberecosystem Balkanization, progress toward a research paradigm that combines both HPC and HDA is already being made. Such success with application-workflow communities both orients and motivates efforts at the other two levels. Second, we offer an account of some of the problems involved in creating a converged infrastructure for distributed edge, or “peripheral,” environments, i.e., shared infrastructure that can be scalably deployed throughout the network to meet the combined data processing, communication, and buffer/storage requirements of massive data workflows. Third, we focus on some opportunities for software ecosystem convergence in large, logically centralized facilities execute large scale simulations and models and/or perform large scale data analytics. Finally, we offer some conclusions and recommendations for future investment and policy review. We briefly summarize each of these parts of the report below.

Emerging Convergence in Large Scale Scientific Applications. Despite the manifest challenges of a converged cyberinfrastructure for multidisciplinary research, the scientific and engineering opportunities are compelling. Many science communities are combining HPC and HDA applications and methods in large-scale workflows that orchestrate simulations, or incorporate them into the stages of large-scale analysis pipelines for data generated by simulations, experiments, or observations. Communities that would benefit substantially from application and workflow convergence are abundant, spanning all of science and engineering. To provide intellectual context for an analysis of application-workflow level convergence, we describe a unified model of the inference cycle for the process of scientific inquiry that locates “computational science” and “data science” as different phases of that process. Next, to capture the complexity of application-workflows, which typically involve changing configurations of software, hardware, and data flows, we structure our discussion around three computational archetypes that provide broader categories than specific traditional formulations and furnish a convenient grouping of collaborations by the “culture” of the users. We illustrate these application-workflow with exemplars that “follow the data.” In that context, we address three modalities of data provenance: (1) data arriving from the edge (often in real time), never centralized; (2) federated multi-source archived data, and (3) combinations of data stored from observational archives with a dynamic simulation. These exemplars make it evident that understanding application-workflows, and especially application-workflows that involve far flung data sources, is pivotal for developing a new application-level convergence paradigm that combines HDA and HPC.
Challenges to Converged Infrastructure in Edge Environments. The proliferation of huge and heterogeneous flows of data generated outside of commercial clouds and HPC centers, i.e. across the WAN in “edge environments,” as well as the need to distribute large data sets from such centralized facilities to the edge, represents a highly disruptive development that makes the way forward in many different areas of research uncertain. At the core of this uncertainty is the fact that the explosive growth of digital data producers at the edge, or in the periphery, creates a collection of highly multi-dimensional problems. Looking at the properties of the data flows being generated, the exhibit a range challenging characteristics, including their volume, velocity, value, variety, variability, and veracity. The most general designation for the field that must study and understand the problems that these data flows present is “Data Logistics,” i.e., the management of the time sensitive positioning and encoding/layout of data, relative to its intended users and the computational resources that they can apply. But problems of data logistics affect not only wide area workflows, but also workflows in the machine room. For example, whether you are talking about the output of a major instrument or a large HPC simulation, some form of data reduction has to be applied locally before any further data movement can be even attempted. Hence, one can think of data logistics as defining a continuum, with I/O issues inside the Internet data center (IDC) or supercomputing facility falling at one end, and data-intensive workflows that begin at remote and/or distributed data sources, possibly scattered across edge environments, falling at the other.

Creating a common, shared software infrastructure that can address the logistical challenges of application-workflows along this entire continuum is a critically important challenge for the scientific community in the coming decade. We use the term distributed services platform (DSP) as a generic characterization of the infrastructure/ecosystem that the community must develop in order to support such compute- and/or data-intensive workflows between the ingress/egress of the IDC or HPC center and the network edge. We present two pieces of common context for this discussion. First we preserve continuity with the traditional TCP/IP + Unix/Linux paradigm by reiterating the importance of the hourglass architecture, and the “spanning layer” at its waist, as the foundation for ecosystem interoperabilty. Second, since these workflows are inherently stateful processes, it is clear that an adequate DSP must be not only wide area capable, but must also offer processing, memory/storage, and communication as shareable resources. Satisfying these requirements in a common, open and interoperable way, which is essential for the broad science and engineering community, but would benefit society as a whole as well, will be no mean feat. We conclude this section by briefly reviewing some of the strategies (e.g., stream processing, content delivery networks (CDN’s), and edge computing) that are currently being deployed to address different problem areas on the data logistics continuum.

Pathways to Convergence for Large, Logically Centralized Facilities. Today, scientific discovery almost universally integrates both advanced computing and data analytics, whose fusion strongly motivates also integrating the associated software with the hardware infrastructures and ecosystems. This raises a number of challenges: overcoming the differences in cultures and tools, dealing with shifting workforce skills, adopting new infrastructure, assuring the co-existence of stream and batch models, computing at the edge, virtualization for sharing, resource allocation and efficiency. We have also identified two major cross-cutting challenges: energy sustainability and data reduction. As far as architectures are concerned, radically improved resource management is indispensable for next generation workflows, and in this context, containerization is a promising candidate for the narrow waist, or spanning layer, of the hourglass model.

As the new era of Big Data and extreme-scale computing continues to develop, it seems clear that both centralized systems (viz., HPC centers and commercial cloud systems) and decentralized systems (viz., any of the alternative designs for edge/fog infrastructure) will share many common software challenges and opportunities. Software libraries for common intermediate processing tasks, need to be promoted and a complete software ecosystem for application development is needed. Finally, the divergence between programming models and languages poses a convergence issue, not only with regard to interoperability of the
applications but also to the interoperability between data formats from different programming languages.

**Conclusions and Recommendations.** Following the above structure of the document, we have divided our findings and recommendations into three categories: global recommendations, recommendations for edge environments, recommendations for centralized facilities. However, our ultimate goal is to prepare the ground for the kind of community-driven “shaping strategy” [43, 44] approach that we believe would be both more appropriate and more successful – see below in Sec. 1.2. Consequently, the conclusions as they appear below, may have to be refactored in order to serve the shaping strategy model.

Our major, global recommendation is to address the basic problem of the two paradigm splits: the HPC/HDA software ecosystem split and the wide area data logistics split. For this to be achieved, there is a need for new standards that will govern the interoperability between data and compute, based on a new, common and open *Distributed Services Platform* (DSP), that offers programmable access to shared processing, storage and communication resources, and that can serve as a universal foundation for the component interoperability that novel services and applications will require.

We make five recommendations for decentralized edge and peripheral ecosystems:

1. Converge on a new hourglass architecture for a Common Distributed Service Platform (DSP).
2. Target workflow patterns for improved data logistics.
3. Design cloud stream processing capabilities for HPC.
4. Promote a scalable approach to Content Delivery/Distribution Networks.
5. Develop software libraries for common intermediate processing tasks.

We make five actionable conclusions for centralized facilities:

1. Energy is an overarching challenge for sustainability.
2. Data reduction is a fundamental pattern.
3. Radically improved resource management is required.
4. Both centralized and decentralized systems share many common software challenges and opportunities:
   (a) Leverage HPC math libraries for HDA.
   (b) More efforts for dense linear algebra standards.
   (c) New standards for shared memory parallel processing.
   (d) Interoperability between programming models and data formats.
5. Machine learning is becoming an important component of scientific workloads, and HPC architectures must be adapted to accommodate this evolution.
1 Introduction

This report, and the series of Big Data and Exascale Computing (BDEC) workshops that it summarizes, is part of the response of the high performance computing (HPC) community to two major inflection points in the growth of scientific computing in the 21st century. The first marks the disruptive changes that flowed from the end of Dennard Scaling, c. 2004 Dennard et al. [24], which gave rise to the era of multicore, manycore, and accelerator-based computing, as well as a variety of other complex and closely related problems of energy optimization and software complexity. The second, occurring nearly simultaneously, was the relatively rapid emergence (c. 2012) of “Big Data” and large scale data analysis as voracious new consumers of computing power and communication bandwidth for a wide range of critical scientific and engineering domains. Because the BDEC community has its roots in traditional HPC, the marked difference in the ways in which this community has struggled to absorb and adapt to these two watershed transitions, with varying degrees of success, provides essential context that informs a reading of this report.

To those who witnessed previous transitions from vector and shared multiprocessor computing, the response to the end of Dennard scaling was comparatively familiar and straightforward. Indeed, the dramatic effects of the end of Dennard scaling on processor and system designs were very much on the mind of the group of HPC leaders who gathered at the annual Supercomputing conference in 2009 to form what would become the International Exascale Software Project (IESP) [27]. Along with the European Exascale Software Initiative (EESI)\(^1\) and a parallel effort in Japan, these grass roots exascale efforts were the progenitors of the BDEC.

Although the challenges that confronted the IESP’s vision of exascale computing were unquestionably formidable—orders of magnitude more parallelism, unprecedented constraints on energy consumption, heterogeneity in multiple dimensions, and resilience to faults occurring at far higher frequencies—they fit within the problem space and the ethos that defined traditional HPC. Participants in that planning effort worked successfully over the next three years to draft a technology roadmap leading to a common, high quality computational environment for exascale systems [5, 27]. What the HPC community did not adequately anticipate was the eruption of interest in infrastructure and tools for doing large scale data analysis in cloud computing environments. In the US, this fact was revealed in the surprise that accompanied the Presidential strategic initiative [29, 30] that emphasized the importance of big data and HPC ecosystem convergence. This has been echoed in recent EC/EU communications on the “European Data Infrastructure” and the “European Open Science Cloud”\(^2\), where HPC has been completely “absorbed” into a broader “Digital Single Market” and only appears as a component in this global system. In Japan, as well as in China, the latest national roadmaps are focused on combining HPC with artificial intelligence, that itself is tightly linked to the big data revolution. The Japanese program provides for a 107.8 billion yen ($1 billion) commitment over the next 10 years on inter-ministry AI-related research that encompasses big data, machine learning and the internet of things. In China’s 5-year plan for exascale systems, big data analytics has been considered as a major application category. As clearly stated in the requirements for their exascale pilot systems, deep learning benchmarks are an important metric for evaluating the capability and efficiency of the proposed new hardware architectures.

The rapid transition of the earlier IESP roadmap activities to the BDEC effort shows how quickly the community recognized that high-end data analytics (HDA) and HPC needed to have equal status in an integrated computing research-and-development agenda. However, although the BDEC effort aims to expand the general mission of the IESP—to foster the co-design of software infrastructure for extreme scale science drawing on international cooperation and supporting a broad spectrum of major research domains—subsequent experience has shown that adding the HDA dimension to the scientific computing

\(^1\)http://www.eesi-project.eu

problem space radically transforms it. As we argue below, it raises a host of conceptual, political, economic and cultural problems and places several of the existing paradigms and assumptions underlying traditional scientific computing and computational science into question.

1.1 Disruptive Partitions in Two Current Paradigms

The BDEC community’s sustained examination of the changes wrought by the ongoing Big Data revolution has revealed at least two different and somewhat orthogonal ways in which the cyberinfrastructure that science and engineering communities depend on is becoming, or has long been bifurcated. One of these splits—between the traditional HPC approach and strategies that leverage or model commercial cloud computing—emerged early this century as an unexpected byproduct of the explosive growth of data online commerce and social media. The second split—between stateless datagram-delivery networks (e.g., the Internet) and stateful services provided by network-attached end systems (e.g., supercomputers, laptops, sensors, mobile telephones)—is fundamental to the cyberinfrastructure paradigm that has been in use for well over three decades. Unfortunately, as we explain below, the Big Data revolution has also rendered an entrenched bipartite cyberinfrastructure paradigm that is highly problematic. As reflected in the analysis given below, we believe that any planning for cyberinfrastructure convergence today has to take the partitioning of both these types into account.

1.1.1 First partition: Recent split in software ecosystems

The former came to the attention of the BDEC community early in the process. The “Two software ecosystems” diagram (see Fig. 1), which was introduced at the second BDEC workshop, quickly became emblematic.
of the ongoing bifurcation in the software ecosystems being deployed for data analytics and scientific computing. The Computational Science Ecosystem developed and flourished over the course of roughly four decades (primarily) to increase the capabilities of scientists to model and simulate, i.e. to enable scientists and engineers to project, in more detail, the consequences of theories that had been or could be expressed mathematically. Meanwhile, the rapid growth of the Data Analytics Ecosystem has occurred largely during the last fifteen years. For the most part, however, it is not being developed by the scientific computing community to explore the rising flood of data from new instruments and sensor systems, but rather by an equally thriving group of academic and commercial software developers to process the torrents of business, industrial process, and social network data now being generated by consumer devices and the burgeoning Internet of Things. The pace of change in the data analytics ecosystem is extraordinary, already rendering obsolete some of the elements in the figure above.

Thus, at least some of the major differences between the HPC and the HDA ecosystems—software development paradigms and tools, virtualization and scheduling strategies, storage models (local vs. Cloud/SAN), resource allocation policies, strategies for redundancy and fault tolerance—can be accounted for by the fact that each evolved during a distinctly different phase of the ongoing digital revolution, driven by distinctly different optimization criteria.\(^3\) For example, it can be reasonably argued that scientific “big data” has existed for more than a decade, but that it remained essentially “dark,” i.e., unavailable for analysis, until commercial cloud technology and content distribution networks began to provide broader access to the computing power and data logistics needed by the communities who wanted to analyze it.\(^4\) By contrast, the HPC infrastructure model—a system of regional and national supercomputing centers, connected together by high performance research networks—was already fully mature at the beginning of the century and serving the needs of the modeling and simulation-centered parts of the scientific community relatively well.

But even the ultimate convergence of the HPC and HDA ecosystems, could it be achieved, would not help with the ongoing breakdown of the other, more basic paradigm, namely, the one in which networks only forward datagrams while all other storage and computation is performed outside the network.

The problem is that much if not most of the explosive growth in data generation today is taking place in “edge environments,” i.e. outside of and across the network from both HPC data centers and commercial cloud machine rooms (Figure 2). This includes not only major scientific instruments, experimental facilities, and remote sensors (e.g., satellite imagery), but even more importantly, the incredible welter of digital data generators with which the plans for “Smart Cities” and the Internet of Things (IoT) [41] are replete. For example, a recent NSF workshop on the future of wireless networking concluded that the ubiquitous deployment of sensor technologies that are a standard element in such plans will “...generate massive data inflows [that produce] as much if not more data and network traffic than the World Wide Web,” and will therefore “...reverse current loads, where most data is produced in the cloud and consumed at the edge” [8]. Likewise, the authors of the 2017 HiPEAC report [28], concluded that “...in order to stem the flood of data from the Internet of Things, we must employ intelligent local data processing on remote devices that use minimal energy ... This may well require us to break away from the traditional von Neumann architecture and to rethink device technology.”

\(^3\)The system and application software of the original dot.com revolution had much in common with then current HPC infrastructure. That is far less true today.

\(^4\)One early exception was data from the Large Hadron Collider experiments in CERN; the global High Energy Physics community had both the organization and the clout to command sufficient government funding to support a content distribution network and distributed computing infrastructure, purpose-built to meet their needs. Astronomy and Astrophysics is another example. The International Virtual Observatory Alliance (IVOA) provides a good example of an international organisation that nurtured web-services standards, data representation standards, such as the Flexible Image Transport System (FITS), and other standards for accessing astronomic data, exchanging data between virtual observatories, tools to communicate and analysis software. The result is that 90% of the world’s astronomy data is reachable and real science can be done by using the tools and software that are being built all around the world. The same is true for Seismology with the international Federated Digital Seismic Network (FDSN) organisation.
Figure 2: Current problem of data logistics: The highest concentrations of computing power and storage are in the “center” (i.e., in commercial clouds or HPC Centers), but much of the rapid increase in data volumes and the dramatic proliferation of data generators is occurring in edge environments, where the processing and storage infrastructure needed to cope with this rising flood of data is \textit{ad hoc} and under provisioned at best.

Thus this remarkable reversal of direction of the data tide, which turns the familiar “last mile problem” into a multidimensional “first mile problem” represents a challenge for which neither cloud-based HDA nor center-based HPC have a solution. In fact, explosive growth in data generation in edge environments seems to clearly indicate that revolutionary innovation in distributed computing systems is becoming an increasingly urgent requirement [17, 21, 37, 62]. As argued below, we believe this represents the breakdown of the bipartite cyberinfrastructure paradigm that has been dominate for nearly three decades, making the problem of “convergence” substantially more complex and momentous.

1.1.2 Second partition: Inherent split in the legacy paradigm

Some historical perspective is required in order to understand the other “divergence,” or paradigm breakdown, that the proliferation of data generators seems to be causing. If one were to try to mark the year in which the two parts of the dominant research cyberinfrastructure paradigm of the last twenty-five years—TCP/IP and Unix/Linux—were first fused together, 1989 would make a very plausible candidate. In June of that year, the Berkeley Software Distribution (BSD) of Unix, including a DARPA-approved version of the TCP/IP protocol stack, was made freely available under an open source license. Their combination in that form was especially well received by the research community:

As the Internet evolved, one of the major challenges was how to propagate the changes to the software, particularly the host software, . . . [T]he incorporation of TCP/IP into the Unix BSD system releases proved to be a critical element in dispersion of the protocols to the research
community. Much of the CS research community began to use Unix BSD for their day-to-day computing environment. Looking back, the strategy of incorporating Internet protocols into a supported operating system for the research community was one of the key elements in the successful widespread adoption of the Internet [54].

Although TCP/IP and UNIX/Linux became complementary parts of one integrated package (i.e., became the “dominant CI paradigm”), they supported two different software ecosystems for two separate but complementary infrastructures. The former laid the software foundation for a globally scalable data network that offered one fundamental service: unicast datagram delivery to move/copy data from one location (buffer/host/end system) to another. The latter, by contrast, was designed to provide an application interface to end systems of all kinds, ranging from personal computers to “middle boxes” to supercomputers; its purpose was to enable applications and services that required the full complement of basic resources—processing power, storage, and networking. But to understand our current dilemma, we should recognize at least three additional factors that helped foster the rapid spread of this composite paradigm through the global research community:

- **Both components were open source, public domain, and designed to support broad experimentation and rapid evolution**: The TCP/IP-Unix/Linux platform was introduced when the highly competitive (not to say ferocious) battles between different proprietary computing strategies (e.g., mainframe, minicomputer, PC), desktop operating systems (e.g., MS-DOS, Windows, OS2, Mac OS), and local area networking technologies (e.g., Novell, Apple, DECnet, SNA) were still ongoing. Avoiding high costs, loss of control of one’s own tools, barriers to collaboration, and other perils of “vendor lock-in” made the open source and public domain character of this new paradigm especially attractive. At the same time, as we discuss in Sec. 3.1 below, both halves of the dominant paradigm were designed in a way that facilitated freedom of innovation and speedy growth, making it especially well suited to the inclinations and the aptitudes of the science and engineering communities.

- **Each component embodies a different model of resource sharing**: Finding ways to share computational resources has long been a fundamental part of the cyberinfrastructure problematic; time sharing operating systems and digital data networking have long been essential parts of the solution. But the two parts of the dominant paradigm under discussion support resource sharing in different ways and with different consequences for their overall design [9]. In the context of large, shared systems, Unix/Linux was designed to allow the sharing of valuable processor, storage, and other system resources with authentication and access controls that created a secure environment supporting free sharing of most resources. Enforcement of storage quotas in Unix was a later adaption necessary in more highly shared/public data center environments and CPU metering and rationing has been implemented in specialized, high value supercomputing systems. By contrast, the TCP/IP was designed to facilitate communications among an enormous variety of devices used by a global community of indefinite size. With maximum deployment scalability as its goal, it shares available bandwidth in limited, lightweight allocations that are easy to access and that typically lack significant admission or accounting controls. The incredible power of this model of resource sharing, especially in terms of its network effects, is manifest.

- **Each component has a different approach to state management**: Perhaps the most significant asymmetry between the components of the dominant paradigm lies in the different ways that they handle process state: The Internet is based on a stateless (or virtually stateless) datagram delivery model, where the intermediate nodes of the network are stateless packet switches [22]. By contrast, the end systems that attach to the Internet, ranging from smart phones to supercomputers, are typically general purpose computing devices that regularly have to manage a great deal of computational or process state, and
Figure 3: Evolution of the network to deal with growth in data volumes and rapid fluctuations in their popularity. The need to be able to use storage and computation at intermediate nodes (e.g., for asynchronous point-to-multipoint transfer) stimulated the development of Content Delivery Networks (CDNs) and Clouds with proprietary networks and server replication, using standard IP only to reach clients at the network edge. [Credit: Beck et al. [12]]

a wide range of mechanisms have been implemented to serve that purpose; these end points manage all the state information required to use the network. The Internet community has traditionally held this design, which keeps the core of the network simple and passive by keeping services other than datagram delivery (e.g., a storage service for caching and prefetching) out of network layer of TCP/IP stack, has been essential to the remarkable scalability that the Internet has demonstrated. And so long as applications and services could be factored into two phases—using the datagram service to move data between end systems and then applying end system resources to achieve complex application or service goals—this symbiotic union of stateless and stateful systems was able to support an immense range of applications.

But problems with this bipartite paradigm, especially with respect to distributed state management in the wide area, have been both evident and growing for more than twenty-five years. In particular, lacking any general ability to do state management at its intermediate nodes (and thus, e.g., lacking native asynchronous point-to-multipoint capabilities), the Internet has long been plagued by bottlenecks or “hotspots for high volume and/or high popularity data traffic. Since data volumes have been growing at exponential rates over the same period, users and providers have been forced to search for new workaround strategies on a recurring basis. Indeed, the Internet community has seen an evolving series of such workarounds, from collateral storage services in the 90s (e.g., FTP mirror sites, web caches, and hierarchical web caches) to full blown server replication in Content Distribution Networks (CDN) and commercial Cloud infrastructure, beginning in this century, Figure 3. Todays CDNs and Clouds have more or less followed this path to its logical conclusion, using private or non-scalable mechanisms to implement internal communications among logically centralized, but physically distributed nodes or machine rooms, while using the Internet to implement selected parts of this scheme and to provide for end user access. Similarly, major HPC application communities have long since moved their high volume traffic to non-TCP-friendly data transfer methods using dedicated bandwidth on overprovisioned research networks.

Unfortunately, we have entered an era—the era of Big Data—when such workaround strategies seem to have reached their limits. The cause of this exhaustion, as we argue above, is the unprecedented explosion in data generation in edge environments. The burgeoning torrents of data that are flowing from highly diverse and widely distributed sources originate in environments which, for the most part, lack the capacity to process or manage the logistics of such immense flows. Whether because of sheer volume and flow rate, or because of application specific latency issues, the conventional strategy of backhauling all data across a fast link to a Cloud service provider or an HPC Data Center ( Figure 9 in Section 3 below)is no longer a viable option.
for many applications. Hence, the intense commercial and research interest in “fog” and “edge” computing infrastructures [10, 16, 49, 68, 72]. For perhaps obvious reasons, which we explicate in part in Section 3, we view the creation of future-defining distributed services platform that meets the fundamental requirements of the scientific community to be, at best, a hard problem, full of unknowns and fraught with economic and political obstacles. More immediately, this assessment has influenced the structure of this report, as we next describe in our document overview.

1.2 Pathways Overview: Prospects for Convergence at Three Different Levels

As noted at the outset of this report, the transition from the International Exascale Software Project (IESP) to the Big Data and Extreme-Scale Computing (BDEC) project forced a radical shift in perspective on the part of HPC community participants. In contrast to the “big machine” focus of traditional HPC, center stage in the era of Big Data has to be given to the many unsolved problems surrounding wide-area, multistage workflows—the diverse patterns of when, where, and how all that data is to be produced, transformed, shared, and analyzed. Consequently, the challenges involved in codesigning software infrastructure for science have to be reframed to fully take account of the diversity of workflow patterns that different communities want to create. All the imposing design and development issues of creating an exascale-capable software stack remain; but the supercomputers that need this stack must now be viewed as the nodes (perhaps the most important nodes) in the very large network of computing resources required to process and explore gigantic rivers of data.

As discussed above, the dominant CI paradigm that has for decades been the foundation of such workflows is eroding, if not collapsing, under the onslaught of this growing data deluge. Unfortunately, this fact requires the BDEC community to find a new way to express its results. IESP participants were able to successfully produce an influential technology roadmap [27] for creating a software stack to support science applications on extreme-scale platforms; but the IESP had the advantage of targeting a shared goal that was different in scale, but not different in kind from less extreme goals that had been achieved before. For BDEC, the shared goal is not so clear. Arguably, the main cyberinfrastructure challenge of the Big Data era is to adapt or replace the legacy paradigm with a new type of distributed services platform (DSP), one that combines computing, communication, and buffer/storage resources in a data processing network that is far more integrated than anything hitherto available. But since there is no widely agreed upon model for this platform, traditional technology road mapping techniques seem to be inapplicable.

Instead, we suggest that the development of a community-driven “shaping strategy” [43, 44] would be a far more appropriate goal to pursue. A shaping strategy is a plan for changing the infrastructure/ecosystem of a market, industry, or community by proposing a well-defined concept of a technical platform that can support diverse kinds of applications or enterprises, and combining it with an inspiring vision of the mutually beneficial future that could be created through its widespread adoption and use. By offering a range of possible incentives to all the stakeholders who would benefit from such convergence, shaping strategies seek to coordinate and direct the creativity and energy of participants who might build on this platform in a way that leverages network effects and produces positive externalities. Shaping strategies are thought to be especially appropriate when the absence or breakdown of an established infrastructure/ecosystem paradigm has disrupted or unsettled some large field of endeavor. With the advent of the era of Big Data, this is precisely the situation that the scientific community now confronts.

Against that background, the reflections of BDEC participants over the course of successive workshops have suggested that the prospects for integration of technological infrastructures and research ecosystems needs to be considered at three different levels, or from three different perspectives. The three major sections of this document focus in turn on one of these levels, as follows:

1. Opportunities for convergence of research applications and workflows (Section 2): We begin at the
level of applications and workflows (i.e., composite applications) for two reasons. First, operating on the general principle that the goal of any infrastructure is to serve its users, it seems appropriate to begin by examining the forms of inquiry, new and old, that a converged infrastructure for research is supposed to support. Second, pushing back against the popular idea that HDA represents a distinctly new paradigm of scientific methodology, we argue that HDA actually represents the computerization of two phases of the classic model of the scientific method which had heretofore been far less digitally empowered. Accordingly, we offer examples in which HPC and HDA applications are being composed in workflows that embody the entire inference cycle of scientific inquiry.

2. Issues in the creation of a converged infrastructure for large scale, logically decentralized facilities (Section 3): This section offers one account of some of the problems involved in creating a converged infrastructure for distributed edge environments, one which can be scalably deployed to meet the data processing, communication, and storage requirements of massive data workflows in the wide area. Developing such a “next generation Internet” for the era of Big Data in science and engineering is fraught with challenges in various dimensions. There is, however, a great deal of excitement and activity in this part of the infrastructure convergence space under the heading of “fog” and/or “edge” computing, but also very high levels of uncertainty with regard to many questions. Consequently, although we survey and discuss some of the prominent ideas and strategies, our review is by no means exhaustive.

3. Opportunities for convergence of infrastructures of large, logically centralized, resource rich facilities (Section 4): The third major section focuses on major facilities that execute large scale simulations and models, or that perform large scale data analytics. We refer to such systems as “logically centralized” because, whether or not they are actually physically distributed, the present themselves as being under the control of a single administrative domain, and users are required to interact with them in that form. Such facilities are already supporting some of the converged applications and workflows previously discussed and some convergence at this level can and is already occurring.

Drawing on discussions at the BDEC workshops\(^5\), we begin each of the major sections by suggesting some points of plausible consensus that are intended to provide “common context” for cyberinfrastructure planning, and especially for the development of a community-driven shaping strategy going forward. These points of convergent opinion include an integrated conception of the general process of scientific inquiry, the overarching issue of energy efficiency as critical for sustainability, the new importance of questions of “data logistics,” and prevalence of the “hourglass” model as a paradigm of good infrastructure/ecosystem design. We have assigned these assumed pieces of common context to the major sections that seemed most appropriate, but admittedly some are of a general nature and certainly apply in other sections as well.

Since the idea developing a community-driven shaping strategy for a new distributed services platform for science was arrived at late in the BDEC reporting process, we do not here describe even a strawman version of such a plan. None the less, we believe that the various observations, arguments and conclusions we record in what follows should feed directly into the dedicated community effort that will be required to develop such a plan. For example, the argument for focusing on the careful design of the “spanning layer” at the waist of the hourglass model (Section 3.1) dovetails perfectly with the need to define an attractive “shaping platform” that many stakeholder communities will build on and use; such a platform definition is one of the primary constituents of a successful shaping strategy. Likewise, we believe that analyzing and building on the application-workflow exemplars of the kind we describe and classify in Sections 2.2 and 2.3 is an essential step in developing the “shaping view” that successful strategies must have in order to incentivize participation and motivate adopters and users. Accordingly, as we note in Section 5, we offer

\(^5\)Please see Appendix A for a list and descriptions.
our final conclusions and recommendations with the intention of preparing the ground for a new community effort to develop the kind of shaping strategy for future cyberinfrastructure that the scientific community must have in order to thrive in the ongoing data revolution.

2 Emerging Convergence in Large Scale Scientific Applications

Despite the manifest challenges of a converged cyberinfrastructure for multidisciplinary research, the scientific and engineering opportunities are compelling. Many science communities are driven by a combination of computing tasks and managing large-scale data volumes resulting from data flows that range from continuous to sporadic. The associated computations may come from large-scale workflows that orchestrate simulations, or from different stages of large-scale analysis pipelines for data generated by simulations, experiments, or observations, including the transitions between these stages and provenance tracking. Communities that would benefit substantially from application and workflow convergence are abundant, spanning all of science and engineering. Examples include the following: (1) Multi-scale materials science; (2) Integrative environmental modeling and analysis; (3) Astronomy and cosmology; (4) Aerospace; (5) Autonomous vehicles; (6) Weather and climate prediction; (7) Smart cities; (8) Health and biomedicine; (9) Exploration geophysics and seismology. Several of these application communities are highlighted in our examples of convergence below.

It is important to note that when we talk about “applications” and “workflows” in this context, we are not talking merely about isolated software tools or application codes, but rather about complex (and changing) configurations of software, hardware, and data flows that support long running science and engineering campaigns as well as research practices. For this reason, we prefer to structure the discussion below around three computational archetypes that provide broader categories than specific traditional formulations (e.g., PDEs, PCAs, etc.) or approaches (e.g., implicit method, randomized SVD, etc.), and furnish a convenient grouping of collaborations by “culture” of users.

To provide the intellectual context for this analysis of application-workflow level convergence, we begin by describing a unified model of an inference cycle for the process of scientific inquiry, pushing back against the popular idea that “computational science” and “data science” represent disparate paradigms of the search for new knowledge (Section 2.1). After presenting the rationale for our division of application-workflow archetypes, we illustrate them with exemplars that “follow the data,” since it is the data that carry the costs (time, energy, FTEs needed to produce and manage the data). We address three modalities of data provenance: (1) data arriving from the edge (often in real time), never centralized; (2) federated multi-source archived data, and (3) combinations of data stored from observational archives with a dynamic simulation. These exemplars make it evident that the concept of workflows has become pivotal for understanding the convergence paradigm between data and simulation. Notably, however, we leave out of this account (but discuss later, Section 3) many issues surrounding the data logistics infrastructure that would and will be needed to support our exemplar workflows.

2.1 Common Context: A Shared Model of Scientific Inquiry for Infrastructure Planning

One notable objection to pursuing the goal of software infrastructure convergence for the scientific community draws on the idea that, along with traditional forms of experiment and theory, the emergence of digital information technology and the explosive growth in computing power have combined to produce two, distinctly new “paradigms” of how science can be done: modern computational science and data-intensive science. Commenting on the latter, Turing award winner Jim Gray, who apparently originated this way of narrating the transformation of science in the digital age, asserted that “The techniques and technologies for such data-intensive science are so different that it is worth distinguishing data-intensive science from computational science as a new, fourth paradigm for scientific exploration.” [47]. Sorting sciences into
Figure 4: The inference cycle for the process of scientific inquiry. The three distinct forms of inference (abduction, deduction, induction) facilitate an all-encompassing vision, enabling HPC and HDA to “converge” in a rational and structured way.

these different methodological boxes has become conventional wisdom in the HPC community, and this supposition, in turn, makes it plausible to argue that the HPC and HDA software ecosystems have separated because each is adapted to the peculiarities of a very different paradigm of the scientific research. If this were true, it would seem to put a significant obstacle in the path of software ecosystem convergence.

A recent white paper from the Computing Community Consortium addressed this question, presenting a generic account of the “scientific process” that accommodates a more unified point of view [48]. Following that suggestion, and leaving aside, for the moment, some important socio-economic aspects of the problem, Figure 4 presents a simplified version of the key logical elements of that model. It expresses the classic view that the scientific method is a complex inferential process that seeks to improve our predictive understanding of nature by building on a foundation of thorough and carefully controlled observation. The three distinct forms of inference it identifies, abduction (i.e., guessing at an explanation), deduction (i.e., determining necessary consequences of a set of propositions), and induction (i.e., making a sampling-based generalization) are the chief elements in the “logic of discovery” first articulated by American scientist and polymath Charles S. Peirce [13].

Likewise, in a more contemporary treatment of the same topic, Richard Feynman’s account of the logic

Adapted from illustration in Abduction and Induction: Essays on their relation and integration. [34]
of discovery for physical laws can be summarized as having essentially the same three steps or stages [33]:

1. We guess at a law that would explain what is currently inexplicable;
2. We derive the consequences of the law that we guessed;
3. We make further observations to see if the consequences predicted match the reality we find.\(^7\)

On this analysis, all three of these steps, taken in combination, are required to increase our predictive understanding of the world, i.e. to really make our knowledge grow.

Now if we accept this model as a plausible hypothesis, then we can draw at least two conclusions that are directly relevant to the problem of cyberinfrastructure convergence. First, by viewing the transformation of science in the era of digital computing through the lens of this model, we can see that there is an alternative way to account for these changes, one that does not require us to posit substantially new paradigms of scientific inquiry. Namely, rather than forking new methodological branches, one can explain the more rapid emergence of computational science, and the slower and later emergence of data-intensive science, by examining the factors that made it possible to apply vast amounts of computing power to the deductive stage of the inference cycle far earlier than the abductive and the inductive stages.

As conventionally defined, Computational Science covers primarily the deductive part of the inferential process: computer-based simulation and modeling shows what a given theory, expressed mathematically, predicts for a given set of input data. This could equally be viewed as “mapping complex models to data.” By the middle of the twentieth century, when the power of microprocessors began to follow their amazing exponential arc upward, many physical sciences already had well established mathematical models of their target phenomena, but had access to only enough computing power to solve them for relatively small problems and/or for cases where inherent uncertainties were not take into account. The impact of Moore’s law was, therefore, immediate and explosive.

By contrast, the gathering and analysis of observational data have always been the focus of the abductive and inductive stages of the process of scientific inquiry. Whether data are being explored to discover novel patterns or anomalies that might initiate new inquiry, or being carefully examined for some predicted phenomena that would test (i.e. further confirm or potentially falsify) some well formulated theory, data analysis strives to put the reasoning of scientists and engineers into relatively direct contact with the realities they are trying understand. When the data are digital, such analyses obviously require computational power. But in a mirror image to the HPC situation, so long as the data volumes remained tractable, concerns about the amount of computational power required to do the necessary data analysis could be sidelined: either a small cluster could be used to analyze data where it was collected (e.g., at the site of the instrument); or, when necessary, the raw data could be transferred via a high performance network to a supercomputing center for analysis.

Of course, since the turn of the century, these flows have become progressively more intractable, as remarkable improvements in sensor technology and other data gathering capabilities produce exponential growth in research data flows. This deluge was spotted on the horizon early in the first decade [46], with projects like the Large Hadron Collider serving as a harbinger of unprecedented increases in data rates across a wide variety of fields. Yet despite the burgeoning quantities of data that needed to be processed, the Big Data revolution was not really launched until the end of the decade, when the explosion of consumer/customer/usage being collected and utilized by online companies (e.g., Google, Amazon, Facebook, etc.) motivated the build out of massive, private, cloud computing infrastructures to store and process it all.

As we discuss in more detail below (Sections 4 and 3.2), this proliferation of distributed data sources means that scientific cyberinfrastructure design must focus as never before on issues of workflow and data logistics, covering the full path of data use from its collection to its use as a decision-making aid. Moreover this focus is required in no small part by the new efforts, in line with the cycle of inquiry illustrated in

\(^7\)This summary is a version of the Feynman’s account provided by Victor Baker in “The pragmatic roots of American Quaternary geology and geomorphology.” [7]
Figure 4, to synthesize elements of HPC and HDA in new application-workflow hybrids. In short, the concept of a scientific application, familiar from the heyday traditional computational science, is being gradually redefined. To set the stage for our application “exemplars,” we first briefly discuss the new perspective on application-workflows that is now emerging.

2.2 Classification of Application-workflow Archetypes

A good first step in understanding any new area typically consists in working out some rough classification of the different types of objects that make it up. It is no surprise, therefore, that every BDEC meeting has dedicated substantial amounts of time to the effort to categorize the various data-intensive, compute intensive, and hybridized applications, or application-workflows. Viewed from a relatively traditional standpoint, the classes that were frequently discussed included simulations, database and data management problems, scientific data analysis, commercial data analytics. The last three have many examples in the NIST collection of 51 Big Data use cases\(^8\) and simulations are illustrated by many HPC benchmarks (such as the NAS Parallel benchmarks) and the Berkeley dwarves. The ways in which such applications are driving new software infrastructure developments was a frequent point of interest. For example, it was noted that MapReduce was originally introduced to parallelize basic database operations as seen in Apache Hive but Andrew Ng from Stanford\(^9\) observed that many machine learning algorithms exhibited the “summation form” and could be parallelized with MapReduce. It was later noted that this could be optimized with so-called Iterative MapReduce; a model supported by Apache Spark and Flink today.

One BDEC white paper, by Fox et al.\(^{[36]}\), noted that the comparison of simulation and big data problems can be made more precise by distinguishing data and model for each use case and carefully comparing model-with-model and data-with-data and not confusing them. This paper introduced a common set of sixty four properties or facets, divided into four views, that could be used to characterize and compare use cases within all the application classes defined above. As examples of these facets, the first Problem Architecture view includes four very common facets describing the synchronization structure of a parallel job: Pleasingly Parallel, MapReduce, Iterative MapCollective and Map Point-to-Point. Another important Problem Architecture facet is Map Streaming, seen in recent approaches to processing real-time data. Other well known facets in this view are SPMD and Bulk Synchronous processing. There is an execution view including the facets such as model size and variety as well as data volume, velocity, variety and veracity. The third Data view includes storage and access models and association with Internet of Things, Geospatial Information Systems and need for provenance. The final Processing View includes algorithm characterization such as optimization, alignment, N-body method, spectral method etc. One can look at use-cases, assign facets and use this to understand commonalities and differences and how this is reflected in hardware and software support.

Complicating this algorithmic perspective on the classificatory problem is the fact that, from a strictly data/workflow point of view, data analysis is usually an iterative process. The model is often not known beforehand since principled statistical model selection is not solved in a general setting. Moreover, data must be interactively understood, and often “debugged” – that is, we need to find anomalies in the data, and to detect wrong assumptions on the data. In this context, schemes of distributed computing are evolving, but users often do not rely on distributed computing, hence the data analysis operations are not expressed in a language that renders distributed computing suitable. Typical code is a succession of operations written in an imperative way. Here, it is useful to think of the computing as a dataflow graph, since access to data (and related bandwidth) can often be a bottleneck.

Three schemes of dataflow are often encountered:

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8 http://dsc.soic.indiana.edu/publications/NISTUseCase.pdf
9 http://www.andrewng.org/portfolio/map-reduce-for-machine-learning-on-multicore/
A typical dataflow is illustrated in Figure 5, where several hundred gigabytes of data, coming from the Autism Brain Imaging Data Exchange, are treated and analyzed in order to extract the most predictive biomarkers. It should be noted that IO is critical in this pipeline and that data reduction dominates the computational costs. The results obtained in Abraham et al. [1] required 2 months of computation on a high-end cluster with a dedicated, local NAS housing the data. This can obviously not scale and the need for more efficient data communication and reduction, as well as convergence with a HPC-environment, are clearly needed here.

Although it is somewhat natural to try to classify applications either (most commonly) on the basis of the algorithms they share, or (more rarely) on the basis of the workflow patterns in which they are embedded, the fact that motivations abound for converging large-scale simulation and big data workflows that are executed largely independently today, suggests that we should try to classify application-workflows that represent
the combination or interaction of these two dimensions. The interaction matrix of Table 1 describes some benefits that are immediately available to each paradigm from the other, and includes the rise of machine learning. For this purpose, we distinguish among big data workflows those that are independent of the data and are throughput-oriented, from those that are learning-oriented and transform themselves by means of the data. Lumping together many varieties of batch-oriented scientific simulations, we therefore consider three types of workflows, each of which today has its own niche of applications, its own software stack, and its own user community.

<table>
<thead>
<tr>
<th></th>
<th>to large-scale simulation</th>
<th>to data analytics</th>
<th>to machine learning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation provides:</td>
<td>—</td>
<td>Physics-based “regularization”</td>
<td>Data for training, augmenting real-world data</td>
</tr>
<tr>
<td>Analytics provides:</td>
<td>Steering in high-dimensional parameter space; in situ processing</td>
<td>—</td>
<td>Feature vectors for training</td>
</tr>
<tr>
<td>Learning provides:</td>
<td>Smart data compression; replacement of models with learned functions</td>
<td>Imputation of missing data; detection and classification</td>
<td>—</td>
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Table 1: A 3 × 3 matrix showing beneficial interactions in the six off-diagonal locations between large-scale simulation, data analytics, and machine learning.

As indicated in the first column of the matrix, to take advantage of advances in analytics and learning, large-scale simulations should evolve to incorporate these technologies in-situ, rather than as forms of post-processing. This potentially reduces burdens of file transfer and the runtime IO that produces the files. In some applications (e.g., climate and weather modeling) at major computing centers, IO is well documented [57] to consume more resources than the computation, itself. In-situ data analytics allows the simulation to avoid writing data that is needed only to advance the simulation, but not for post examination. However, the benefits go far beyond this into the realm of steering. Smart steering may obviate significant computation, along with the IO that would accompany it, in unfruitful regions of physical parameter space, as guided by the in-situ analytics. In-situ machine learning offers additional benefits to large-scale simulation, beginning with smart data compression, which complements analytics in leading to reduced IO and reduced storage. Beyond assisting with the performance of the known implementation, machine learning has the potential to improve the simulation, itself. This is because many simulations incorporate empirical relationships, such as constitutive parameters or functions that are not derived from first principles, but tuned from dimensional analysis, intuition, observation, or other simulations. For such components, common in multiscale and multiphysics models, machine learning in-the-loop may already or ultimately be more effective than the tuning of expert scientists and engineers. Such learning would “probe” a simulation, necessitating an in-situ process.

Turning next to the first row of the interaction matrix, simulation potentially provides significant benefits in return to analytics and learning workflows, once the software and hardware environments are converged. Data science models have had limited penetration in systems representing complex physical phenomena. Theory-guided data science [51] is an emerging paradigm that aims to improve the effectiveness of data science models, by requiring consistency with known scientific principles (e.g., conservation laws). Theory-
guided data science is gaining attention in applications such as turbulence, materials, cosmology and climate modeling. It is analogous to “regularization” in optimization, wherein non-unique candidates are penalized by some physically plausible constraint (such as minimizing energy) to narrow the field. In analytics, among statistically equally plausible outcomes, the field could be narrowed to those that satisfy physical constraints, as checked by simulations. Simulation can also provide training data for machine learning, complementing data that is available from experimentation and observation. A traditional advantage of simulation over experiments is emphasized in this context: some interesting regions of parameter space, both physically realizable in principle, or representing an extreme limit that is not realizable (such as a flow with zero viscosity), can be opened up to a learning algorithm.

The other two nontrivial elements of the matrix of beneficial interactions of the paradigms are between the two workflows within big data. Analytics can provide, to machine learning, feature vectors for training. Machine learning, in turn, can provide to analytics the imputation of missing data and functions of detection and classification. For any of these “off-diagonal” fruits to be harvested efficiently, the corresponding workflows should be co-hosted. The scientific opportunities are potentially important enough to overcome the enormous inertia of the specialized communities that have gathered around each of these tremendously successful paradigms and spur convergence.

2.3 Exemplars of Application-workflow Convergence: Science at the Boundary of Observation and Simulation

Over the course of successive BDEC workshops, it quickly became apparent that application communities would be leading the drive towards convergence. Given the “converged” model of scientific inquiry described above (Sec. 2.1), this is more or less to be expected. Indeed, recent developments show that it is already happening. One contrast with much commercial cloud computing that these developments highlight is based on the fundamental difference between the data generated by human interaction with computers (such as social media and other commercial sites) and data collected from sensors and observations. The latter is governed by some underlying physical process even if it is a non-deterministic one, or one that has not been understood yet. The analysis performed on scientific data may, sometimes, resemble that performed on commercial data; that of drawing inferences without a hypothesis or conjecture. However, such analysis is limited to instances where there is little or no prior knowledge about the underlying physical processes. In those instances inferences help to formulate hypotheses and ultimately the theory. More often some theory exists, and the observations collect data that is used to prove or falsify a derived prediction that helps refine the theory. Examples of the different, rough and overlapping patterns with these research workflows fall into include the following:

- **Patterns of interplay between simulation and data analysis:** High energy physics (HEP) has several examples where interplay between simulations and data analysis plays a critical role in scientific insight. One example is large experiments at colliders that generate about 30 petabytes of data currently, which is expected to grow to 400 petabytes in a decade. Experiments need support from theory which is provided by the simulations. Confronting data generated from the simulations with the observational data helps tune both the model and the experiment design - see the inference cycle of Section 2.1. Another example of synergy between simulations and experimental data is in determining the placement of sensors in an experiment. This has been used in designing high-energy density physics laser experiments, for example, where simulations can predict where to place the measuring instruments to have the best chance of detecting features being formed. Without this interaction between simulation and placement of instruments in experiments, entire features can be missed, and have been known to have done so in the past. Use of simulations to determine the placement of instruments or sensors is now making its way into many areas, including for environmental and climate observations.
Patterns of alternating data generation and consumption: Another interesting class of workflows are ones that alternate between data generation and data consumption. These kind of workflows occur, for example, in experimental and observational validation and uncertainty quantification. Here the data volumes and patterns vary throughout the pipeline. The experimental data may require fine-grained “event” style analysis where data pipelines can be complex and need to be run many times. Demands on I/O can vary due to the nature of the simulations and the fine-grained nature of the outputs (many small files). An example of such complex workflows is in dark energy research where understanding Type Ia supernovae is critical. A typical workflow requires running a model simulation, post processing it, running it through another computational stage which results in generating the spectra and the intensity curves. On the other side similar artefacts are generated for comparison from the observational data through various stages of analysis. An important challenge faced in this kind of workflow is data movement. Large volumes of data are generated both from observations and computations, typically at different sites. It is not just the processing, but also the curation, migration and archiving of data that becomes the scientists’ concern. Good science requires provenance of data involved in scientific discovery, which makes the task of managing the data pipelining a highly resource intensive one for many scientists.

Patterns of multi-messenger scientific inquiry: Several discussions at the BDEC workshops highlighted the way in which the application of different observational modalities that can now be simultaneously applied to the same object promises to dramatically increase our predictive understanding of those objects. Generalizing the idea “multi-messenger astronomy,” [75] we refer to this application-workflow pattern as multi-messenger scientific inquiry.10 The ability to predict the effects that result from interactions between physical or biological systems, or to predict patient outcomes or treatment responses, hinges on the accurate multi-resolution characterization of the objects and systems involved. Happily, the dramatic reduction in costs required to obtain imaging and sensor data has made it increasingly feasible to capture the necessary data.

The general approach, which cuts across the many relevant application domains, is to carry out and synthesize the diverse, data streams that record different types of sensor observations of the same object, or set of objects; and in many such scenarios, analysis and integration of data streams from different types of sensors is coupled with simulations. The earth sciences offer a number of outstanding examples, as in the study of the earth’s magnetic field, where satellite data, ground instruments, paleo databases, and simulation are all combined. Aspects of this huge field are briefly surveyed below (Section 2.3.2 and 2.3.3). Likewise, biomedicine also contains a rich and growing collection of multi-messenger use cases, where, for example integration of information from Pathology, Radiology and molecular studies is becoming increasingly crucial in guiding cancer therapy(Section 2.3.4). Finally Light and neutron source beamline analyses constitute a third collection of multi-messenger use cases. Requirements have a great deal of commonality across, beamlines and scientific projects. Beamline experiments frequently generate data that when reconstructed, can be used to characterize properties of materials, tissue or chemical systems.

The examples of convergent application-workflows below bring out the kinds of factors that will have to be taken into account in developing platform infrastructure to support them. These considerations lead to a number of pertinent questions that will feed into the following two sections and motivate our discussions in the sequel.

10Just as multi-messenger astronomy is “the coordinated observation and interpretation of disparate “messenger” signals” from the same astronomical objects [75], multi-messenger scientific inquiry combines observations and interpretations of disparate streams of sensor or instrument data of the same objects in an integrated inferential process.
2.3.1 Plasma Fusion

Building the scientific foundations needed to accelerate the delivery of fusion power can best be accomplished by engaging the predictive capability of modern big-data-driven statistical methods featuring machine/deep learning (ML/DL). These techniques can be formulated and adapted to enable new avenues of data-driven discovery in key scientific applications areas such as the quest to deliver Fusion Energy.

An especially time-urgent and very challenging problem facing the development of a fusion energy reactor is the need to deal reliably with large-scale major disruptions in magnetically-confined tokamak systems such as the EUROfusion Joint European Torus (JET) today, and the burning plasma ITER device in the near future. The JET team has led the development of supervised Machine Learning Support Vector Machine (SVM) predictive methods which have achieved over 80% predictive capability for disruptions 30 milliseconds (ms) prior to such damaging events, far exceeding current HPC first principles approaches. However, ITER will require ~ 95% or better predictive accuracy with less than 5% false positives at least 30 ms before disruptions. This will accordingly demand the deployment of improved physics-based classifiers encompassing multi-dimensional features—a ML challenge for training that exceeds the current capabilities of SVM methods.

Very encouraging advances in the development and deployment of deep learning recurrent neural nets have recently been demonstrated by results obtained by the Princeton University/PPPL team which have already exceeded that of SVM methods i.e., better than 90% predictive accuracy with 5% false positives at least 30 ms before the occurrence of JET disruptions. Moreover, scalability studies of the associated Deep Learning Code—FRNN (Fusion Recurrent Neural Net) Code—first to 200 GPU’s at Princeton University’s “Tiger” Cluster and subsequently to 6000 GPUs on ORNLs Titan Supercomputer, provide great encouragement that sufficiently rapid training of higher physics fidelity classifiers is now feasible.

FRNN uses the well-known “Theano” and Googles Tensorflow back-ends to train deep neural networks (in particular, stacked LSTMs). With this approach, a replica of the model is kept on each worker, processing different mini-batches of the training dataset in parallel. The results on each worker are combined after each epoch using MPI, and model parameters are synchronized via parameter averaging. The learning rate is adjusted after each epoch to improve convergence.

This project has direct access to the huge EUROfusion/JET disruption data base (over a half-petabyte) to drive these studies. Since the JET signal data comes in sequences of variable length, the training of RNN’s for time intervals as long as 2000 time-steps is challenging but achievable in that FRNN uses a technique of patches and chunks that make it possible to capture physical patterns that are only visible for significantly long sequences (~ 1-2 seconds). Summarily, the FRNN project will explore the viability of an example modern Deep Learning code for deployment on international supercomputers featuring a very large number of modern Pascal P-100 GPUs such as “Piz Daint” at the CSCS (Switzerland), “Tsubame 3.0” at TiTech (Japan), and powerful future Volta GPU systems such as SUMMIT at the OLCF (USA).

With the establishment of rapid training capability for deep learning features, we will be able to develop higher physics fidelity classifiers to deliver further improvements in disruption predictions. In doing so, there will also be a natural complementarity with exascale HPC codes that can accelerate the pace to identifying supervised ML classifiers with associated features more accurately characterizing relevant pre-disruption burning plasma features.

The workflow that Plasma Fusion’s FRNN data analysis code requires is similar to that characteristic of typical distributed deep learning projects. First, the raw data is preprocessed and normalized. The pre-processing step involves cutting, re-sampling, and structuring the data—as well as determining and validating the disruptive properties of the shots considered. Various options for normalization are implemented. Secondly, with respect to distributed data-parallel training of the model, the associated parameters are checkpointed after each epoch on the disk, in HDF5 file format. Finally, regarding the cross validation and prediction step on unlabeled data, it is planned to also implement a “hyper-parameter tuning” approach using
a random search algorithm. The results are stored as HDF5 files, including the final neural network model parameters together with statistical summaries of the variables used during training to allow researchers to produce learning curves and performance summary plots.

2.3.2 Earth, Planetary and Universe Sciences

The Earth-Planetary-Universe (EPU) sciences are exemplary in their sharing of scientific culture with data-driven research practices that are based on observation (land, sea bottom, spatial), covering a wide spectrum of spatial and temporal scales. Research addresses fundamental problems associated with the understanding of the formation, the structures and the evolution of EPU systems (e.g. from Cosmic Microwave Background to cosmic structures and Earth and Planets’ interiors) in their environment (stellar and fluid envelopes), transient events (e.g. stellar explosion, earthquakes, volcanic eruptions) and their radiation (e.g. high-energy astro-particules, gravitational, electromagnetic, acoustic and seismic waves) together with added applications of societal and economical interest such as the prevention and risk mitigation of volcanic and seismic hazards, the exploration and the management of energetic resources, the evaluation and monitoring of environmental changes, spatial meteorology, etc. EPU communities are well organised and federated at the national and international levels around more and more complex space missions (e.g. EUCLID, LISA, INTEGRAL, SVOM, ATHENA, InSight, COPERNICUS etc.), large instruments (e.g. LSST, CTA, SKA) and observation systems (e.g. KM3NET, ASTROMEV, LIGO/VIRGO, EarthCube, EPOS-IP, etc.) often
run by international inter-governmental consortia and agencies. The communities place a great premium in internationally distributed and federated data resources for archiving and distributing data and have pioneered the prevailing philosophies of globally shared and open-data with internationally approved data, metadata and exchange standards including provenance and interoperability, together with a growing commitment to open science.

Building federated computing and data analysis platforms featuring persistent storage capability to capture and aggregate the large volumes and the diversity of data (events, time series, images) from the distributed archive resources associated with the observation systems, and from large numerical simulations (virtual instruments), and to accelerate the full path of data-use can best be accomplished by engaging a research-driven strategy aligned upon (see Figure 6):

- The design and the exploitation of more and more complex (multi-sensors) space missions, large instruments and federated observation systems that have complex on-the-fly data processing and analysis workflows for instrument calibration and data compression, together with large HPC simulations of the response of the experiments in their environment;

- Innovative big-data-driven methods accelerating the full path of data use, with data-stream workflows orchestrating data processing and physics-based or data-driven statistical analysis methods, in a Bayesian inference framework featuring machine/deep learning (ML/DL);

- Advanced physics-based stochastic simulations of multi-physics and multi-scale natural systems that map complex model space of high dimensions (e.g. cosmology, magneto-hydrodynamics, seismology) into data space, exploring prior density probability information together with data assimilation;

- Modern big-data-driven high-resolution and multi-scale imaging techniques featuring non-linear inversion methods in the framework of new Bayesian approximate and variational inference, together with machine learning, to efficiently sample posterior probability distribution in high dimension and quantify statistical incertitude measures and extreme events.

Recent advances in the development of high-end statistical data analysis have been demonstrated by new results in: the direct physics-based detection of gravitational waves signals from two ground interferometers (LIGO) opening a new astronomy for dense and massive astrophysics objects (e.g. black holes, neutronic stars); the physics-based extraction of coherent seismic signals from statistical correlation-based analysis of non-coherent background signals generated by environmental sources resulting from the coupling of the solid Earth with external fluid envelopes (atmosphere, ocean) recorded on dense seismic arrays opening new imaging methodologies in Earth sciences and exploration geophysics; the data-driven detection from dense seismic arrays of new unknown long-period seismic signals (tremors) associated with transient deformation processes in volcanic and tectonic contexts opening a completely new area of research for the understanding and monitoring of natural hazards. New discoveries in EPU sciences critically depend on innovative computing and data analysis platforms federating parallel computing and data resources with research-driven architectures and services that can integrate data-aware computing environments, data-aware architectures, collaborative design of software development with large, complex observation systems, and new virtualization techniques. In the EPU applications recent advances in Bayesian approximate and variational inference methods, together with machine learning, have the potential to dramatically impact both event detection, data analysis and data modelling methods. New statistical analysis methods featuring machine learning have also an increasing role in efficient data assimilation (see below) and in-situ data analysis of large-scale stochastic simulations of EPU systems. In parallel an increasing number of new scientific problems require today to combine and model multi-type data not only from experiments and simulation of the same type, but more and more across different domains.
Data assimilation combines observations with model outputs in an optimal fashion, to improve predictive capabilities. This provides a concrete illustration of the Inference Cycle of Section 2.1.

### 2.3.3 Data Assimilation in Climate

Data assimilation combines data coming from both observations and model outputs in an optimal way to provide a more complete and coherent description of the system and thus improve our predictive capabilities - see Figure 7. An obvious requirement is that a model of this system be available, whereby the increased and novel forms of data analysis helps drive the development of the system model. Climate and weather forecasting applications are among the most common and most important examples of this process, where observational data combines with simulation to do better than either separately, illustrating the saying that “two ugly parents can have a beautiful child.”

Data assimilation can be used with two different aims. Either reconstruct the actual state of a system, by combining the two types of information; in this case it could be said that observational data and model outputs complement each other, help correcting the largest errors from one or the other, and finally provide respective interpolation/extrapolation tools to reconstruct the best possible description of the actual system. Or data assimilation can be used for prediction in time; in this case the best reconstruction refers to the initial time of the forecasting model, and data assimilation ensures both that this initial state is as good as possible from a physical point of view, and that it is also coherent with the model dynamics, therefore avoiding too large transient effects in the simulation.

A technology complementary to simulation, namely emulation, is rapidly evolving in the domain of geospatial statistics. Emulation is emerging as a reliable and less expensive computational alternative to simulation in its predictive power; however, it lies wholly within the HDA-driven approach and is not covered in this brief discussion.

The relationship of assimilation to the computational model and the inputs and outputs of the combined system is shown in Figure 7. Two major approaches can be used: a variational approach based on optimization theory, and a statistical approach based on optimal (Kalman) filtering and ensemble averaging. Today, the tendency is to combine the two, into what are know as hybrid ensemble-variational approaches (see [4]) —
these approaches constitute a major challenge for convergence of HPC with HDA (high-end [statistical] data analysis).

The huge amounts of data required for weather prediction make forecasting a highly data- and compute-intensive exercise. For each forecast, data must be collected from multiple sources, including satellites, dropsondes, weather stations and buoys, current and historical observations, and simulations of the Earth’s physical patterns and processes. All of this information is then input into complex, nonlinear meteorological models that simulate weather patterns that are likely to occur, based on data assimilation, as shown in Figure 7.

When data assimilation is used in a forecasting context, the differences between the predicted values and the observed values are inputs to the assimilation engine. But the observational data are sparse compared to the number of degrees of freedom required to specify the state of the system; therefore, they are not used to directly reset individual state values. They go into an optimization process typically in the form of a Kalman Filter. Data assimilation is perhaps best understood in the context of inverse problems, the latter being well developed in theory and algorithms [4].

With the availability of increasing computing power, data assimilation can rely on an ensemble consisting of a large number of independent simulations. Given a thousand instances of a petascale simulation, one has an exascale computation, with the last factor of one thousand in scaling coming in a different dimension than traditional weak-scaling that employs a finer resolution of a given space-time domain. Data assimilation is therefore a prime example of the immediate utility of exascale capability, since the software and workflows already exist. Their combination is not trivial, but rides existing efforts to scale up individual simulations, with a higher payoff factor.

Recent work by Miyoshi et al. [61] addressed so-called “big data assimilation” for rapidly changing, severe weather forecasting. The aim is to provide early warnings to civilians and administrations of impending, high-magnitude weather events. By coupling a high resolution “Phased Array Weather Radar” system with the “K Computer” of the RIKEN center, they have been able to produce such early warnings for local, severe weather events. One hundred simulated states are fed into a (local transform) ensemble Kalman filter, and each state is simulated in 30 seconds (only) on 3,072 nodes of the 10PF K computer. This can be scaled up to the full capacity of 88,128 nodes (705,000 processors) of the K, yielding a full data assimilation cycle that remains within the 30 second time window and provides a constantly updated 30 minute forecast. It should be noted that data volumes are of the order of 1TB of observation data and 3PB of simulation-produced data. To achieve such spectacular execution times, this required extensive code optimization at all levels, from I/O to basic linear algebra routines.

### 2.3.4 Cancer Diagnosis and Treatment

The Cancer Moonshot\(^{11}\) aims to accomplish 10 years of cancer research in 5 years only. With complex, non-linear signaling networks, multiscale dynamics from the quantum to the macro level, and giant, complex datasets of patient responses, cancer is a major challenge for HPC-Big Data convergence. In light of the difficulty, and relative inefficiency of new drug development and screening\(^{12}\), the CANDLE (CANcer Distributed Learning Environment) project\(^{13}\) proposes to employ machine learning techniques to cancer biology, pre-clinical models, and cancer surveillance. The aim is to “...establish a new paradigm for cancer research for years to come by making effective use of the ever-growing volumes and diversity of cancer-related data to build predictive models, provide better understanding of the disease and, ultimately, provide guidance and support decisions on anticipated outcomes of treatment for individual patients.” The project’s specific

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\(^{11}\) https://www.cancer.gov/research/key-initiatives/moonshot-cancer-initiative

\(^{12}\) Between 2009 and 2013, the USFDA approved 20 new oncologic drugs, having $100,000 per year treatment costs, and an average PFS (progression-free survival) improvement of less than six months.

\(^{13}\) http://candle.cels.anl.gov
objective being to position deep learning at the intersection of RAS\textsuperscript{14} pathways, treatment strategies and drug response. Computational requirements associated with cancer diagnosis and treatment are extremely heterogeneous and the work carried out in the CANDLE project is a very interesting subset of a much broader set of computational challenges.

Predictive modelling of drug response is a function of tumors (gene expression levels) and drug descriptors. These can be analyzed by deep, convolutional, supervised learning algorithms. But how can one search a trillion drug combinations to predict the response of a given tumor to a given drug combination? One possible answer is by deep learning. Within scientific computing applications, hundreds of examples of this technique are emerging, including fusion energy (see above), precision medicine, materials design, fluid dynamics, genomics, structural engineering, intelligent sensing, etc. To apply deep learning to drug response modeling requires a hyperparameter search of dimension ten thousand that can only be done by effective parallelism at the level of one million to one hundred million cores. In order to achieve this, the following questions need to be addressed:

1. What are the key frameworks and workloads for Deep Learning?
2. What hardware and systems architectures are emerging for supporting deep learning?
3. Is Deep Learning a distinct class, worthy of its own software stack in the BDEC Universe?

We will briefly address each of these in turn, noting that they remain largely open questions that are certainly application dependent.

The number of available frameworks is increasing every day, with the concomitant risk of dispersion and lack of interoperability. The most well-known are Torch, Theano, Caffe, Tensorflow, CNTK. Numerous languages are supported and this can vary from framework to framework, but they are mostly interactive, scripting type languages such as Julia, Python, Lua and R. In addition, the presence of interactive workflows is an important aspect of many Deep Learning projects. We are currently witnessing an exponential growth in the number of Deep Learning based projects. All of this argues in favor of some type of standardization that could be motivated by convergence issues.

But to apply deep learning across a broad range of fields, a number of DL system architecture challenges must also be confronted. The first is Node Centric vs. Network Centric architectures with either integrated resources on a node or disaggregated resources on a network. Then the issue of name-space/address-space across instances/stacks can be approached by either one integrated space across stacks, or each stack maintaining names and addresses—but are the technology components converging? Finally, the issue of Training vs. Inferencing must be addressed: what balance should there be between online vs. offline training, and what are the possibilities of embedding the training within simulation environments?

We are witnessing the emergence of numerous hardware and systems architectures for supporting deep learning. Here we can point out CPUs (AVX, VNNI, KNM, KNH,...), GPUs (Nvidia P100, AMD Instinct, Baidu GPU,...), ASICs (Nervana, DianNao, Eyeriss, GraphCore, TPU, DLU,...), FPGAs (Arria 10, Stratix 10, Falcon Mesa,...), and Neuromorphic (True North, Zeroth, N1,...) technologies. But which are best for a given application?

So, is Deep Learning a distinct class worthy of its own software stack in the BDEC Universe? The CANDLE project has developed a stack of its own (see also the data-flow and plasma fusion discussions above) made up of workflow, scripting, engine and optimization layers. The workflow contains hyperparameter sweeps and data management with DIGITS, Swift, etc. The scripting consists of a network description and an API for execution e.g. Keras, Mocha. A Tensor/Graph execution engine is based on Theano, Tensorflow, etc. Finally an architecture-specific optimization layer is added, based on cuDNN, MKL-DNN, etc.

\textsuperscript{14}A family of proteins whose overactivity can ultimately lead to cancer.
To enable HPC convergence, parallelism options and I/O must be critically examined. Data Parallelism (distributed training by partitioning training data) must be managed at an appropriate level in the stack. Model parallelism (parallel training by partitioning network) could be managed independently. At what level should streaming training data loaders be implemented? And main IO?

As we have seen, numerous fundamental questions are raised here. These will require careful consideration for a successful convergence of deep learning approaches within an HPC context.

2.3.5 Numerical laboratories

![Diagram of numerical laboratories](image)

Large supercomputer simulations are rapidly becoming instruments in their own right. Scientists in many disciplines seek to compare the results of their experiments to numerical simulations based on first principles. This requires not only that we can run sophisticated simulations and models, but that the results of these simulations are available publicly, through an easy-to-use portal. We have to turn the simulations into open numerical laboratories in which anyone can perform their own experiments. Integrating and comparing experiments to simulations is a non-trivial data management challenge— see Figure 8. Not every data set from the simulations has the same lifecycle. Some results are just transient and need to be stored for a short period to analyze, while others will become community references, with a useful lifetime of a decade or more.

As we have learned over the years, once the data volume is too large, we have to move the analysis to the data rather than the traditional approach, which moved the data where our computers were. With these large data volumes one has to approach the data in a fully algorithmic fashion— manual exploration of small (or large) files is no longer feasible. Even though the largest simulations today are approaching hundreds of billions of particles or grid points, the total size of the output generated rarely exceeds 100TB and almost never reaches a PB. As the interconnect speeds are not going to increase by a factor of 30-100, it is likely
that this limitation remains in place. Even with Exascale machines, the publicly available outputs will likely remain in the few PB range. To date, the usual way of analyzing somebody else’s simulation is to download the data. With PB scale data sets, this is obviously not going to work. For a scalable analysis we need to come up with a data access abstraction or metaphor that is inherently scalable. For the user it should not matter whether the data in the laboratory is a terabyte or a petabyte. The casual user should be able to perform very light-weight analyses, without downloading much software or data. Accessing data through the flat files violates this principle: the user cannot do anything until a very large file has been physically transferred. This implies an access pattern drastically different from the sequential I/O of the checkpoint restart. We need to support random access patterns, where we have a database of the most interesting events. This approach is reminiscent of how physicists at the Large Hadron Collider are only storing one out of 10 million events, still yielding tens of PB every year.

Supporting such localized access patterns can enable new metaphors for interacting with large numerical simulations. For example, one can create a so-called immersive environment in which the users can insert immersive virtual sensors into the simulation, which can then feed a data stream back to the user. By placing the sensors in different geometric configurations, users can accommodate a wide variety of spatial and temporal access patterns. The sensors can feed back data on multiple channels, measuring different fields in the simulation. They can have a variety of operators, like computing the Hessian or Laplacian of a field, or applying various filters and clipping thresholds. Imagine how scientists could launch mini accelerometers into simulated tornadoes, emulating the movie Twister!

Scientists at Johns Hopkins have successfully implemented this metaphor for various turbulence data sets, and are now porting it to cosmology simulations. This simple interface can provide a very flexible, yet powerful way to do science with large data sets from anywhere in the world. The availability of such a 4D dataset at your fingertips and the ability to make casual queries from anywhere is beginning to change how we think about the data. Researchers can come back to the same place in space and time and be sure to encounter the same values.

The Twister metaphor mentioned above, has been implemented in the Turbulence DB [55], the first space-time database for turbulent flows containing the output of large simulations, publicly available to the research community. It supports a web service that handles requests over the web for velocities, pressure, various space derivatives of velocity and pressure, and interpolation functions. The data and its interface are used by the turbulence research community and have led to about 100 publications to date. The service delivered over 44 trillion (!) data points to the user community to date. In a recent paper on MHD, trajectories were computed by moving the particles backward in time, impossible to do in an in-situ computation, only enabled by interpolation over the database [31].

A similar transformation is happening in cosmology. The SDSS SkyServer framework was reused for the Millennium simulation database [53]. The database has been in use for over 10 years, has hundreds of regular users, and has been used in nearly seven hundred publications.

These large numerical data sets, analyzed by a much broader range of scientists than ever before, using all the tools of the computer age, are creating a new way to do science, one that we are just starting to grapple with. We cannot predict where it will exactly lead, but it is already clear that these technologies will bring about dramatic changes in the way we do science and make discoveries and how we will use our exascale simulations.

### 3 Challenges to Converged Infrastructure in Edge Environments

Based on our report on the cumulative work of the BDEC community so far, one might reasonably draw at least two provisional conclusions. First, at the level of scientific applications and interdisciplinary research, the convergence of techniques and methods of compute-intensive simulation and data-intensive analytics is
Figure 9: The general problem with multiple high volume generators at the edge: Edge environments (i.e., across network from the centralized facilities) are, or soon will be, experiencing unprecedented increases of data rates from diverse and rapidly proliferating sources. Everyone agrees that this data will have to be buffered/stored and processed in various ways and for various reasons; but there is currently no shared, open, interoperable infrastructure adequate to the task, and no agreed upon roadmap for developing it.

already underway. Several of the examples given in Sec. 2 show that a more complete and integrated vision of the general logic of scientific inquiry is already being implemented in multiphase workflows, and there is every reason to expect that many more dramatic and complex products of this process will be emerging in the near and medium term. Second, at the level of (logically) centralized infrastructure, i.e. on stand-alone HPC system and distributed Cloud facilities (Sec. 4), promising avenues for integrating the HPC software stack and the HDA software stack are being opened and explored from both sides. If the ultimate success of these two developments, taken together, were sufficient to reestablish the shared foundation of interoperability and software portability that has proved so catalytic for scientific collaboration and progress over the past two decades, then the BDEC community, in concert with the other ongoing infrastructure planning efforts from around the world, would be well positioned to draft a road-map to get there. Unfortunately, the proliferation of huge and heterogeneous flows of data generated outside such centralized facilities, i.e. across the WAN in “edge environments,” as well as the need to distribute large data sets from the center to the edge, represents a third factor that makes the way forward uncertain. (Figure 9)

The explosive growth and dispersion of digital data producers in edge environments is a highly multidimensional problem. Looking at just the properties of the data flows being generated, the published lists of the challenging characteristics they exhibit include their volume, velocity, value, variety, variability, and veracity [15, 19, 42, 45, 71]. The size dimension tends to be highlighted first, if only because the volumes are so striking. Big instruments, such as the Large Hadron Collider (LHC) and the Argonne Photon Source (APS) mentioned below (see Sec. 4.2) provide familiar illustrations, but other examples are plentiful. For instance, a review of the records of over two decades of storage usage for neuroimaging and genetics data shows that the influx is doubling every year, with suggestions reaching +20PB per year by 2019 [26]. In a different domain, Light Detection And Ranging (LIDAR) survey technology [74], which has hundreds
(if not thousands) of applications in mapping and monitoring for many fields of science, engineering, and technology, already routinely produces TB data sets, with cumulative volumes that are correspondingly immense [18]. Autonomous vehicles will generate and consume roughly 40TBs of LIDAR data for every 8 hours of driving, and LIDAR prices have come down three orders of magnitude in ten years. Finally, taking a more comprehensive perspective, a recent Cisco Global Cloud Index report [50] asserts that mobile data traffic has increased more than three orders of magnitude over the last decade and will continue to grow at more than 50 percent annually until 2020, when they project that it will surpass 500ZB in total [69, 72].

Another set of factors that render edge environments complex is the diversity of the data collecting devices and the modes in which they can be used. Lidar remote sensing can be used in several modes: static terrestrial (e.g., tripod), mobile (e.g., autonomous vehicles), and aerial (e.g., drones). Some, like the SKA (Square Kilometer Array) and environmental sensor nets, are highly distributed, so that the data they produce generally needs to be aggregated and appropriately coordinated or merged. Others, like the LHC, are centralized. Moreover the power constraints under which some devices can or must operate obviously affects the schedule on which they can collect and transmit data. All these factors will need to be taken into account in designing a distributed services platform that will need to be deployed in order to support them.

Perhaps the most general designation for the field into which this large welter of problems falls is “data logistics,” i.e., the management of the time sensitive positioning and encoding/layout of data relative to its intended users and the resources they can use [20]. Any user who wants to analyze data that is generated at one (or many) locations, but is worked on somewhere else, and possibly in many other places or in transit, confronts challenges of data logistics in this sense. High profile examples for the international scientific community include the LHC, the SKA and the climate modeling communities, (e.g. through the Earth System Grid Federation) illustrate how managing the movement and staging of data, from where it is collected to where it needs to be analyzed, can take up most of the time to solution15. Moreover, in many, if not most cases, some form of data reduction has to be applied locally before any further data movement can be even attempted (c.f., Sec. 4.2). But other more mundane examples are plentiful, and clearly the concept of data logistics can be applied much more broadly. At the root of the problem is the fact that data and the computing resources needed to process it have to be co-located in order for work to proceed. From the point of view of “time to solution,” the challenges of just moving massive data objects into and out of the memory of HPC systems can also be characterized as logistical in nature. Hence, one can think of data logistics as defining a continuum, with I/O issues inside the Internet data center (IDC) or supercomputing facility falling at one end16, and Big Data (BD) workflows that begin at remote and/or distributed data sources possibly scattered across edge environments, falling at the other.

Now, experience shows that coping with the logistics of multiform workflows in the wide area is a non-trivial problem, especially when the only service the underlying network supplies is the routing of datagrams between end points. As noted above in Sec. 1.1.2, the Internet’s lack of native support for point-to-multipoint content distribution, among other things, has forced the research community (and service providers generally) to deploy workarounds to problems of data logistics since the earliest days of the network. Figure 3 provides a snapshot summary of successive attempts to bypass this problem: first by FTP mirrors and web caching, which generally preserve classic Internet article; and then via CDNs and Cloud computing, which use standard IP to connect to clients at the edge of the network, but deploy proprietary networks in their core that incorporate storage and computing as services at the intermediate nodes. Historically, work on CDNs served as the origin of current efforts to develop computing infrastructure for edge environments, i.e. infrastructure to provide storage, computing and networking at various places along the path from the Cloud or data center to the edge [67].

15In the 6th Annual ESGF Conference report (see http://esgf.llnl.gov/media/pdf/2017-ESGF_F2F_Conference_Report.pdf), a major concern expressed was to minimize the time spent finding, using and storing data.

16This point reminds one of Ken’s Batcher’s well-known quip that “A supercomputer is a device for turning compute-bound problems into I/O-bound problems [73],” the consequential truth of which is destined to be reinforced by emerging exascale systems.
A variety of different approaches under a variety of different names have been proposed for edge computing infrastructure: the ETSI Mobile Edge Computing (MEC) [49], Fog Computing [16], Cloudbot [68], and Edge Caching [10], to name some prominent contenders [72]. Wherever possible, we use the expression distributed services platform (DSP) as a more generically descriptive, less tendentious phrase for infrastructure designed to support compute- and/or data-intensive work that must be carried out between the Cloud (or Data/HPC center) ingress/egress and the network edge. This is motivated partly by the fact that there appears to be little consensus at this point about what the right approach should be or about which of the contenders might come to dominate [37, 72]. In this regard, the current situation in edge computing infrastructure has plausibly been compared to the situation in networking “at the dawn of the Internet in the late 1970s to early 1980s” [67]. In any event, the unsettled state of the field means that our exploration below of some of the important issues to be addressed by, and some of the main strategies for using, such an infrastructure needs to focus on possible points of agreement upon which the views of different stakeholders might converge.

3.1 Common Context: Converging on a new hourglass

If we want a new distributed infrastructure to support science and engineering research in the era of Big Data, an infrastructure with the kind of openness, scalability, and flexible resource sharing that has characterized the legacy Internet paradigm, then a recent community white paper on “intelligent infrastructure” for Smart Cities makes the nature of the challenge clear:

What is lacking—and what is necessary to define in the future—is a common, open, underlying ‘platform’, analogous to (but much more complex than) the Internet or Web, allowing applications and services to be developed as modular, extensible, interoperable components. To achieve the level of interoperation and innovation in Smart Cities that we have seen in the Internet will require [public] investment in the basic research and development of an analogous open platform for intelligent infrastructure, tested and evaluated openly through the same inclusive, open, consensus-driven approach that created Internet. [63] [Emphasis in source]

As argued above, the dominant CI paradigm of the past three decades actually has two main components: the Internet protocol (IP) stack and the Unix operating system, whose kernel interface became the foundation for an immense ecosystem of largely interoperable open source tools and operating systems, such as Linux. If we are to go in search of a “future-defining” distributed services platform (DSP), it seems reasonable to start from a prominent architectural feature that they share; specifically, they both conform to the “hourglass” design model for layered software stacks [11]. The hourglass image (see Figure 10) visually represents the idea that an appropriately designed common interface can be implemented on a wide variety of technology platforms (yielding a wide “lower bell”), while at the same time supporting an equally wide variety of applications (yielding wide “upper bell”). One of the leading designers of the IP stack, David Clark, called this common interface, or “thin waist of the hourglass,” the “spanning layer” because it bridges, through virtualization, a heterogeneous set of resources that lie below it [23]. In the case of IP, these underlying resources consist of different types of local area networks; in the case of the Unix/Linux kernel interface, the set of possible technology substrates includes an enormous variety of software/hardware platforms, from massive compute clusters to handheld devices and wrist watches.

In terms of cyberinfrastructure design generally, and cyberinfrastructure for science and engineering in particular, this combination of properties is critical. From the point of view of application communities, the ability to implement a spanning layer easily on new hardware is fundamental because the underlying platform technologies are constantly evolving; unless a spanning layer can be ported or reimplemented on each successive generation, the applications it supports will be stranded on some island of technical obsolescence. Yet new types of applications and application requirements are also constantly emerging. So
Figure 10: The “hourglass model” of the system software stack. The goal is to achieve deployment scalability while maximizing the diversity of applications. [Credit: Beck [11]]

no matter how portable a spanning layer is, if it cannot address innovative application demands, it will be abandoned for a software stack that can. The challenge, of course, is to provide a service specification (i.e., an API) for the spanning layer that can satisfy both these requirements.

The waist of the hourglass is called “thin” or “narrow” because it needs to be minimal, restricted, or otherwise weak in order for it to be easy to implement on new software/hardware substrates. However, as shown in figure 10, and contrary to what is commonly believed, squeezing the waist of the hourglass in order to increase the number of possible implementations covered by the lower bell, will tend to have the reverse effect on the width of the upper bell, i.e. it will reduce the range of possible applications that can be supported [11]. Hence the design challenge for creating a specification for a scalable DSP spanning layer is to find one that optimally balances these two opposing goals. If we assume that what we are talking about is a software stack for workflows, which are inherently stateful processes, that would seem to imply that the spanning layer must include (orthogonal) primitives for communication, computation, and storage. So striking the right balance is likely to prove challenging indeed.

Unfortunately, in seeking a new DSP spanning layer to address the challenges of the big data era, the science cyberinfrastructure community finds itself in something of a dilemma. On one hand, at present there does seem to be at least one plausible and widely touted candidate for the new spanning layer—operating-system-level virtualization that supports software “containers” (Figure 14 and Section 4.3.2). Certainly, converging on a common interface for containerization would go a long way to achieving ecosystem convergence, and do so in way that requires something closer to evolutionary, as opposed to revolutionary changes to current modes of operation. Perhaps for that reason, and as participants in the BDEC workshops made clear, the potential of containerization are a very active area of research and experimentation across all the contexts that scientific cyberinfrastructure will have to address, including commercial clouds, HPC systems, and computing resources deployed in edge environments. Indeed, the updated version of the “Two Ecosystems” picture (Figure 1) has been recently updated to show that both HDA and HPC are pursuing containerization strategies. In Section 4.3.2 below, we explore both the possible benefits and liabilities sliding another layer of virtualization for software containers into the current system software stack.
3.2 Common Context: A Common Distributed Services Platform for Data Logistics

Given the complex nature and broad scope of the data logistics problem space, the generic label “distributed services platform” (DSP) captures at least three features that any infrastructure adequate to these challenges may reasonably be supposed to have:

- **Wide area capable:** The intermediate nodes of the DSP must support services that can be deployed in a decentralized fashion across the wide area (i.e., outside the machine room and the LAN);
- **Offer flexible compute, storage, and communication services:** These nodes must go beyond simple datagram forwarding to provide compute and storage/buffering services in the system’s core as well. The need for this capability follows directly from what is perhaps the primary application requirement for edge computing, namely, relatively low latency processing (e.g., aggregation, analysis, compression, distillation) of massive quantities of data flowing from edge devices and sensors [25].
- **Provide a scalable model of resource sharing:** Like the legacy CI paradigm that is becoming increasingly problematic (Sec. 1.1.2), the aspirational DSP that is supposed to eventually replace it will, for both technical and practical reasons, need to enable a variety of different application communities to share a core set of services and the resources they require.

Yet while several of the proposed alternatives for edge computing (e.g., Fog, cloudlet, MEC) might provide a DSP that meets what seem to be the major technical requirements for this problem space—highly responsive and resilient cloud services, scalability through local data processing, flexible control of privacy, computational offloading for client devices [67]—the overarching goal of the BDEC community requires a broader perspective. In particular, the guiding purpose of the BDEC community has always been to foster the co-design of a software infrastructure for science and engineering research that supports the broadest possible spectrum of fields or domains, and empowers international cooperation both within and among them. Consequently, since the scientific community, thus broadly conceived, embraces an enormous network of organizations and actors, extending not just around the world but also across the generations, the problem of designing a DSP that can be voluntarily adopted as foundational by this community raises unique software ecosystem considerations (Figure 11) that ought to frame our deliberations. Following both the suggestion of the CCC whitepaper quoted above (Section 3.1, [63]), and the spirit of the original IESP [27], below we briefly discuss three ecosystem design constraints that seem to be among the most important: commonality, openness, and interoperability.

- **A Common Distributed Services Platform:** The legacy DSP paradigm—the Internet—enabled the scientific community to bridge geographic, organizational, political and technological boundaries and it fostered a profusion of interdisciplinary collaborations across a vast range of fields; the motivation for seeking a “future-defining” DSP that provides a similarly common foundation for future scientific inquiry should, therefore, be evident. Of course, it should be equally evident that the problem of designing a common DSP that everyone in the community might voluntarily adopt, in the absence of coercive legal or economic power, is truly formidable.

The upper and lower bells of the “Hourglass” software architecture model (see Section 3.1 and Figure 10) are intended to image two critical conditions that any proposed universal solution would apparently have to satisfy. First, a wide lower bell for a given DSP means its spanning layer [23, 52, 60], i.e., the common interface at the narrow waist, can be implemented on a very large collection of heterogeneous hardware technologies, so that all the applications and services above the spanning layer can, through it, access and utilize the resources these technologies make available. The wider the lower bell, the stronger the assurance that hardware technology, both legacy and future, will support that DSP’s spanning layer. Second, a wide upper bell means that the small set of primitive services that the spanning layer makes available on the systems nodes can be composed, in combination with end system resources, to support a very large diversity of higher level services and applications. The
wider the upper bell, the stronger the assurance that all more specialized application communities, down to the level of individuals, can build on top of the shared infrastructure that the community provides. Now if a given DSP can thus be implemented with reasonable ease on an extremely broad spectrum of hardware technologies, and can thus be used to create an enormous diversity of services and applications to satisfy multifarious user demands, those facts will tend to minimize barriers to its universal adoption. However, it is important to remember that defining a spanning layer that includes shared compute and/or storage services, and that is weak enough to achieve the former but strong enough to achieve the latter, is still an unsolved problem [11, 12].

- **An Open Distributed Services Platform:** Even if a DSP spanning layer with requisite technical properties can be specified, lack of *openness* would also present a major barrier to the kind of ubiquitous acceptance the scientific community needs to achieve. Absent proprietary legal constraints, such a software specification is paradigmatic of a *public good*, i.e., of something that no one is excluded from using and which can be exploited in a completely non-rivalrous fashion. At a minimum, then, the specification should be freely accessible for people to use as their circumstances require. Moreover, the standardization process should be equally non-proprietary and open, carried out with due process, broad consensus, and transparency [32]. We know that in the case of the Internet protocol stack such openness was critical to its relatively rapid acceptance by the global scientific community. We also know that that acceptance, working outward from the universities, governmental laboratories, and all the institutional niches where research gets done, played an instrumental role in spreading the Internet to society generally. It is reasonable to expect that if the more general DSP that science now seeks is kept open, then similar, if not more powerful and more positive, spill-over effects for society are likely.
An Interoperable Distributed Services Platform: Although both openness and community deployment are essential objectives for a next generation DSP for data logistics, the linchpin of any plan for achieving those goals is interoperability, i.e. the capacity for different modules or devices using shared protocols to exchange information with and/or invoke services on one another, despite differences in their implementations. For one thing, interoperability fosters openness by lowering or eliminating switching costs, which helps users to avoid well known problems, such as “vendor lock-in,” while enabling well known advantages, such as “fork-lift upgrades.” More importantly, providing a foundation for widespread interoperability tends to catalyze community adoption and deployment through powerful direct and indirect network effects, in which increases in the number of adopters of platform-compatible systems drives up the platforms value for all its users [60]. The success of the Internet paradigm has been due in no small degree to these effects of interoperability, and so one should reasonably expect the same would be true of a new DSP paradigm that supported similar levels interoperability.

But if we believe that “…[a]s a practical matter, real interoperation is achieved by the definition and use of effective spanning layers” [23] (see also [52, 59]), we must also acknowledge that the goal of creating a more general, future-defining DSP, with a primary spanning layer that the entire community is willing to adopt, has already shown itself to be very elusive. In the United States alone, over the past twenty years at least four well supported efforts—Active Networking [70], Globus [35], PlanetLab [3], and GENI [58]—took up this challenge explicitly; and while all of them have been (and even continue to be) successful in many other respects, their proposed platforms, and the alternative spanning layers that they have tried to build on, have not yet achieved the kind of broad acceptance and organic growth that the aspirational DSP would require.

Although these interrelated design assumptions may not be exhaustive, we treat them as sufficient for our discussion in this report of the alternative strategies for dealing with the general problem of data logistics. There seem to be at least four, non-exclusive alternatives for interfacing HPC to this new paradigm in which no strong assumptions are made about where the data are: (1) data streaming, (2) in-transit processing, (3) processing at the edge of the distributed system, i.e. as close as possible to the data sources, and (4) logically centered cloud-like processing. This last option is not of the same nature as the first three — it could encompass them: the user could have a cloud-inspired vision of processing that is decoupled from physical resource distribution; under the hood, the actual processing can rely on options 1-3: in situ processing, in transit processing or streaming across multiple sites.

We briefly discuss each of these strategies below (in Section 3.3), but expect the BDEC and Big Data communities to substantially develop this discussion.

3.3 Strategies for processing and state management between the edge and the centralized computing facility

As the examples described or discussed in Section 2.3 should suggest, various combinations of computations and data movement are required to integrate often noisy information from often spatially distributed sensors to create a high quality multi-scale description of the physical or biological system under study. For instance, a variety of commonly employed methods cut across many multi-messenger uses cases, making this area both an important opportunity and a complex challenge for the design of shared software infrastructure. Most include the need to 1) carry out low level reconstruction, filtering and noise reduction processing to improve data quality, 2) detect and often segment pertinent objects, to extract imaging features and to classify objects and regions of images, 3) characterize temporal changes and 4) make use of simulation, machine learning or statistical methods to make predictions.
3.3.1 Strategy 1: Streaming

An emerging model of big data applications is that data is generated or collected at multiple places in the "system". The data may need to move from location to location in the system, and there may need to be processing that occurs at locations as the data moves through the system. Further, unlike classical HPC, where the data source and sink where the same single location, in the new model there may be multiple sources and sinks, and they may not be at the same location. An example is the SKA project. Scattered telescopes collect data. Because of the vast amounts of data collected, not all the data can be streamed to a single location for processing. Instead, there are advantages to doing some amount of processing direction at the instrument. Data is then streamed to intermediate sources, where once again, the ability to aggregate and perform local processing, allows for smarter [required] reduction of the data streams. While the SKA project will have a relatively static mapping of sources, sinks, and data streams to processing locations, other applications may have a more dynamic nature. Regardless, to support this emerging model, tools are being developed that let workflow designers abstractly describe the sources, sink, streams or data and the processing elements and then dynamically connect them as the situation requires.

To accommodate the needs of such applications, stream processing languages have been developed to allow programmers to specify the needs of their workflows and applications to feed into the tools and runtimes being developed. A common example from the cloud space is Apache Spark and Flink. These data centric libraries and runtimes allow the programmer to more easily describe the requirements laid out above of being able to specify where data is originating, ending, and how it needs to be processed as it moves from source to sink. Many of the languages and runtimes abstract the notion of a processing element, and network connections data source, sink, and the processing elements. This provides for a separation of concerns, allowing the programmers to focus on describing what connections need to exist and what processing needs to occur without specifying where it occurs and how the processing elements are connected. Some of the languages and runtimes allow the programmers to provide hints or specify where (on which nodes or computers) the processing should occur and what networking topology should be used to connect the processing elements.

The use of data streaming has three benefits: a) the low overheads, particularly for local coupling, means that it is efficient for scientists to compose low-cost steps, called “fine-grained workflow”, b) the direct handling of streams means that scientists can develop methods for live, continuously flowing observations, and c) the load placed on the increasingly limiting bottleneck of disk I/O is minimised.

One area for investigation is that as we examine the need to converge the tools for HPC, big data, and analytics, determining whether we can move to a common model in this space would be beneficial. Because there is not significant past work in HPC on stream processing, it provides a hopefully easier path toward convergence. However, there are challenges. Many existing cloud stream processing capabilities have not been designed with HPC in mind, and are only more recently starting to examine the high performance aspects of their runtimes, in particular that of low latency. This area represents a good area of focus for convergence.

3.3.2 Strategy 2: Content Delivery Networks (Processing In-transit)

Over the past decade and a half, the relentless increase in demand for rich multimedia content has driven commercial providers to build or buy services from sophisticated content distribution (or delivery) networks (CDNs) in order to ensure the kind of quality of service that their customers want and expect [64, 65]. Unfortunately, commercial CDNs are expensive and difficult to operate, and are practical only for implementing Web and media streaming sites that generate enough income to pay for their service. Consequently, a myriad of non-commercial research and education communities who need to distribute large amounts of data to numerous receivers are unable to make use of existing CDN services.
To see why, we need to briefly consider how CDN’s work. A CDN delivers data from a collection of servers distributed in the wide area, either at a large number of collocation sites such as network interchange points ISP points of presence (e.g. Akamai, Layer3) or at a smaller number of cloud data centers (e.g. Google, Amazon). While URLs are used to name content and services in a CDN, they are not interpreted in the same way as in the implementation of traditional Web services. Instead of using the DNS to translate the domain component to an undifferentiated set of servers, a CDN chooses the best server according to its own resolution algorithm. CDNs use a proprietary resolution protocol provides the network interface of an uncacheable DNS servier, which is how it integrates with existing Application Layer clients, such as Web browsers.

If a CDN’s resolution algorithm is implemented using only the abstractions provided by the Internet’s Network Layer, then the CDN can be viewed as an overlay network implemented at the Application Layer. However, it is difficult to get highly accurate and effective resolution using only the abstraction provided by the Internet’s Network Layer. So commercial CDNs instead reach down past the Network Layer to monitor the Link Layer network topology (which is not directly observable using the abstractions provided by the Network Layer). So from an architectural point of view, commercial CDNs should be characterized as an alternative Network Layer which is implemented using a combination of mechanisms from the Link, Network and Application Layers of the Internet.

The implication of this strategy for implementing CDNs is that the mechanisms used to implement it as an alternative Network Layer are proprietary, non-interoperable and not particularly scalable. Monitoring and even controlling the network at the Link Layer (by determining the topological location of replica servers) and maintaining replicas of complex Application Layer services are expensive and difficult engineering undertakings. This makes commercial CDNs expensive to run and creates barriers to interoperation, which in any case is not seen as congruent with CDN business strategies. These considerations explain why commercial CDN services are too expensive for large-scale use by the scientific community, in spite of the fact that the cost of the underlying servers and software are relatively modest. What is missing are 1) a scalable approach to CDN implementation (i.e., suitably designed forms of storage and processing at the nodes of the distribution tree) and 2) the aggregate organizational will of the scientific community.

In the HPC context, a framework for in-transit processing has been proposed by Bennett et al. [14], where data generated by simulations is transferred from the supercomputer to intermediate storage, for asynchronous processing, before archiving. This has allowed scientists dealing with the data deluge at extreme scale to perform analyses at increased temporal resolutions, mitigate I/O costs, and significantly improve the time to insight.

### 3.3.3 Strategy 3: Computing at the Edge (at the Source)

“Edge computing” can be differentiated from in-transit processing in two ways: 1) it may not need to support competing users, although it probably does need to support multiple applications on behalf of cooperating users, and 2) there may be fate sharing between the end user and the edge computation, meaning that fault tolerance is not required. In addition, the resource limitations of the node on which edge computing is implemented may be more stringent than the constraints on shared intermediate nodes.

Different edge scenarios may allow the constraints imposed on shared intermediate nodes (weak, simple, general, limited) to be loosened in different ways. In some cases, such as indefinite, localized storage, implementation at the edge is the only possibility.

In a network that only implements delivery of data between end-systems, all computation and storage must be implemented at the edges of the network. However, certain shared infrastructure can be thought of as defining overlay networks that do support these services implemented at the Application Layer (see Content Delivery Networks). The limitation of this approach is the inability to provision and operate shared resources on behalf of a larger community and the inability to locate such resources at arbitrary points within the network topology.
4 Pathways to Convergence for Large, Logically Centralized Facilities

The examples presented in Section 2 of application-workflow convergence, which integrate both HPC and HDA methods, promise to open new frontiers of scientific inquiry in almost all fields of science and engineering. Today, scientific discovery almost universally integrates both advanced computing and data analytics. This fusion strongly motivates also integrating the associated software with the hardware infrastructures and ecosystems. Moreover, there are equally strong political and economic motivations for such an approach, both within countries and across borders. Consequently, when the US National Strategic Computing Initiative (NSCI) [29, 30] expresses the goal of “[driving] the convergence of compute-intensive and data-intensive systems . . .,” and this goal is echoed in the strategic plans of EU, Japan, and China (as presented above in Section 1), we can see that the question of what “convergence” might mean has at least one clear answer in this context: At minimum, “convergence” means a scientific software ecosystem that overcomes the current state of Balkanization. However, this raises challenges and problem areas that include, but are not limited to, the following:

- **Differing, though converging, cultures and tools.** When the 1990s dot.com revolution began, the underlying hardware and software infrastructure used for e-commerce sites was strikingly similar to that used in HPC. Software developers could and did move readily across the two domains. Indeed, the web and the web browser originated at scientific computing facilities—CERN and NCSA, respectively. Today’s cloud services run atop hardware strikingly similar to that found in HPC systems—x86 systems with accelerators and high-performance interconnects. Although the programming models and tools and the underlying software differed markedly (see again Fig. 1) just a few years ago, there are now signs of convergence. Container (virtualization) technology is now available on HPC systems, and machine learning tools and techniques are increasingly being integrated into HPC workflows.

- **Shifting workforce skills.** Over the past twenty years, the IT industry has expanded dramatically, driven by e-commerce, social media, cloud services, and smartphones, with the Internet of Things, healthcare sensors, industrial automation and autonomous vehicles further expanding the domain of big data analytics and services. In response to seemingly insatiable workforce demands, most students are now trained in software tools and techniques that target these commercial opportunities rather than scientific computing and HPC. Few students outside scientific areas learn C, FORTRAN, or numerical methods, the traditional “tools of the trade” in computational sciences and engineering. This trend is an extension of one that began in the 1990s and is irreversible. Consequently, the HPC community must and is beginning to embrace new tools and approaches, while also encouraging students to learn both HPC and data analytics tools.

- **Adopting new infrastructure.** The HPC community neither can nor should attempt to replicate the vibrant big data and machine learning infrastructure and ecosystem. Simply put, the locus of investment and human resources in data analytics and machine learning now rests with the commercial sector, and it will drive ecosystem evolution. Lest this seem an insurmountable hurdle, it is worth remembering that the HPC community has long been dependent on and a contributor to the Linux and open source communities. Likewise, as core components of the HDA ecosystem become open source, they will continue to create benefits for the HPC community. In particular, the Apache software stack, R and other machine learning toolkits are galvanizing a generation of faculty and students who see a multitude of scientific and engineering applications for big data and machine learning technology. Similarly, science and engineering researchers are increasingly applying machine learning technology to their own domains.

- **Stream and batch model co-existence.** Leading edge scientific computing systems are, by definition, scarce resources. Thus, the HPC community has long relied on batch scheduling to maximize utilization
of limited hardware resources and to serve multiple scientific communities. By contrast, cloud services and most sensor data, whether from small, environmental monitors or large-scale observatories, are (soft) real-time streams, necessitating continuous processing with flexible workflow systems. Not surprisingly, these differences have profound implications for application programming models, software tools and system software, as streaming data analysis requires that at least some of the resources be dedicated for days, months, and sometimes years. As new generations of scientific instruments and environmental sensors produce ever larger streams of daily data, real-time data processing and statistical assimilation with computational models will drive fusion of batch and stream models and will provide a strong motivation (as well as an opportunity) for the emergence of a flexible common model meeting the needs of both HPC and HDA.

- **Computing at the edge.** Another consequence of real-time data streams is the need for computing and analysis at the edge (i.e., at the data sources). Whether for data reduction and conditioning or more rapid response than end-to-end network delays would permit for centralized analysis, workflows must increasingly span a continuum of device types, bandwidth differences, and computing capabilities. The shift of intelligence to the edge, coupled with central computing support, is a new model that combines elements of HPC and HDA.

- **Virtualization for sharing.** Traditional virtual machine (VM) environments based on hypervisors and replicated operating systems imposed large overheads and latencies, rendering them less suitable for tightly coupled scientific applications. However, new technology, e.g. Linux Containers such as Docker, have far less overhead for such workloads and are increasingly being deployed for scientific computing. This enables developers to shape their application’s computing environment and for the provider to simultaneously run many such environments. Containerization also brings scientific application portability, allowing workflows and software to be packaged, shared, and redeployed without complex and often arduous configuration. In turn, this enables users and communities to evaluate approaches and software easily and rapidly.

- **Resource allocation and efficiency.** The value of a large, centralized resource rests in part on its scale. By allocating a substantial portion of the total resource, one can achieve results not possible with smaller scale infrastructure. This is equally true for commercial cloud infrastructure and the largest HPC systems. On large HPC systems, this resource management is via work queueing (i.e., batch processing). Policies control resource allocation, e.g. to select only the most worthwhile applications, and to match the resource funders’ priorities. Permission for use depends on the quality of an application’s optimization for the platform. Implicit in such an approach is the need for efficiency, lest a precious resource be consumed unnecessarily. Efficiency may refer to application execution efficiency, system utilization rate, and energy efficiency (see also Section 4.1 below). The cloud and big data communities tend to emphasize user experience and scalability, far more than efficiency, though this is also changing rapidly as parallel computing techniques are being applied to machine learning. This is an additional convergence opportunity, as both the HPC and BDA communities learn from one another.

Now the raison d’être for the BDEC is to help plan and create, in a coordinated and international way, a new generation of software infrastructure for scientific research; but our discussion in this section of strategies for integrating the infrastructures and ecosystems of large HPC computing platforms and facilities, on the one hand, and commercial Cloud facilities, on the other, can address only some of them, and those only partially. In particular, in this section we largely abstract away from the large set of difficult issues surrounding the explosive growth of data in edge computing environments, which is discussed in Section 3.
4.1 Common Context: Energy as an overarching challenge for sustainability

One challenge probably deserves special attention: Making the scientific enterprise sustainable given current technology would seem to demand that the total energy consumption of a given investigation should be minimized, or at least kept within reasonable limits. Since information and computing technology (ICT) required about 4.7% of the world’s electrical energy in 2012\(^{17}\) and continues to grow [39], its role in this problem cannot be assumed to be negligible, especially if we include all aspects of the ICT supporting a scientific method. These are not limited to the energy used for simulations and statistical analyses. Data movement, from the observations, to quality assurance and integration organisations, to archival and curation sites, to each scientific step that accesses such data, to visualizations, to researchers’ workspaces and to result archives, can all represent a very significant use of energy.

We can identify four steps towards energy minimization: (1) reduce computational costs by using platforms well-matched to the stage within the scientific method; (2) reduce data-movement costs by co-location, compression and caching; (3) encourage re-use of calculations and data, by effective sharing, metadata and catalogues, a strategy that a provenance system supports well; and (4) reduce computing system entropy (workloads interference, system jitter, tail latency, and other noises) by on-demand isolation, noise-resistant priority, Cache QoS and novel uncertainty bounding techniques. The e-infrastructure itself has the task of taking care of energy minimization as it has access to the required information — burdening domain scientists is not desirable, since it would divert them from their scientific goals.

Moving information is fundamentally energy consuming, more so if it is moved fast. Moving it across boundaries, e.g. from site to site or from an HPC system to an analysis platform system within the same site, from node to node, from one storage medium to another, incurs greater costs. Avoiding unnecessary repetitions of transfers, e.g. by caching, reducing distances and boundary crossing by co-location, reducing speed requirements by pre-fetching, and reducing volume by compression, can all help reduce these costs.

\(^{17}\)Recent estimates place this as high as 10% .

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Figure 12: Trends of speed, energy efficiency, and power consumption of the world’s fastest computers.[56, 77]
Reducing data transport costs and delays also motivates co-location of simulation platforms with data-analysis platforms, and with archival storage sites holding reference data.

However, there are challenges due to the limits to what can be achieved as environmental and social science observing systems are inevitably a globally distributed endeavor. Furthermore, the many approaches, different timescales and different manifest effects, make for growing diversity of primary data collection and quality assurance. This is undertaken by a wide range of organisations in many localities, managing a wide variety of globally dispersed instruments. Data quality control has also to be done close to the acquisition expertise. It is crucial that as methods for caching data are developed they do not detract from the recognition of the value of data collectors, quality assurance teams and data curation organisations.

Hence, a political and accounting model is needed to make energy savings and to sustain the respect for the value of contributing institutions. For example, institutions responsible for emergency response information services and hazard estimation, as well as research, will need to recruit the relevant experts and demonstrably have resources that are needed in a major emergency. Major research universities, and national centers, need to have a sufficiently powerful computational resource, acting as a “totem”, so that they can continue to attract leading researchers, projects, contracts and funds. Therefore, there are pressures to maintain the visibility of independent resources and to sustain their diversity. An e-infrastructure spanning autonomous resources needs to minimize energy consumption to reduce environmental impact, but with due consideration for the organisational and social issues. Encouraging sharing and efficient use of simulation runs and their results, may have two benefits: a reduction in the environmental impact and an improvement in quality and pace of the science, as has been demonstrated in cosmology and climate modelling.

Publishing and sharing for an appropriate period the models and the results of simulation runs, could establish virtual numerical laboratories (see Section 2.3.5), e.g. as done in astronomy and climate sciences with for example IVOA and ESGF, where many researchers could explore interpretations and comparisons of simulation results with primary data. This results in amortizing the costs of the simulation runs, and data gathering, over more investigations and over time.

4.2 Common Context: Data Reduction as a fundamental pattern in HPC and Big Data convergence

Data reduction is a common issue for both centralized as well as edge computing infrastructures and facilities. In this section we take the “centralized” standpoint, though all messages concern equally the outer edge where, as is explained in Section 3, data logistics are a vital issue with the concommitant need for reduction in order not to saturate the upstream (towards the center) communication channels.

Scientific simulations and instruments are already generating more data than can be stored, transmitted and analyzed. One of the most challenging issues in performing scientific simulations, running large-scale parallel applications or performing large scale physics experiments today, is the vast amount of data to store in disks, to transmit over networks, or to process in post-analysis. The Hardware/Hybrid Accelerated Cosmology Code (HACC), for example, can generate 20 PB of data for a single 1-trillion-particle simulation; yet a system such as the Mira supercomputer at the Argonne Leadership Computing Facility has only 26 PB of file system storage, and a single user cannot request 75% of the total storage capacity for a simulation. Climate research also deals with a large volume of data during simulation and post-analysis. As indicated by [40], nearly 2.5 PB of data were produced by the Community Earth System Model for the Coupled Model Inter comparison Project (CMIP) 5, which further introduced 170 TB of post-processing data submitted to the Earth System Grid [76]. Estimates of the raw data requirements for the CMIP6 project exceed 10 PB [6].

Scientific experiments on large scale instruments also require significant data reduction. And updates of these instruments will produce orders of magnitudes more data. For example, the NIH Brain Initiative focuses on high-throughput x-ray tomography of whole mouse brains, using the upgrade of the Argonne Photon Source (APS-U). Researchers need to generate high-throughput mosaic tomography with a total reconstruction
volume of about 40 teravoxels (corresponding to 160 TB) per specimen, followed by automated transport, cataloging, analysis and comparison of a very large number of specimens in order to understand disease-correlated changes in brain structure. Another example is the integrated circuit (IC) imaging study under the IARPA RA VEN program, still at the APS-U. Every IC will involve about 8 petavoxels (corresponding to 32 PB) in the reconstructed image obtained via x-ray ptychography. Today's detector can acquire up to 500 frames per second, and each frame is about 1K square, at 16 bits - so 0.98 GB/second. With the APS-U, researchers expect to acquire data at a 12 KHz frame rate or 23 GB/second, for a total volume of data reaching 70 exabytes (EB)! In these two cases, the produced data will be transferred to a supercomputing facility (the Argonne Leadership Computing Facility-ALCF- in those cases) for data analysis. Even upgrading the connection between the APS and the ALCF will not allow to transfer the data quickly enough to keep up with the flow produced by the instrument. For example, a 20Gb/s connection would still require months to move the produced data from the source to its analysis location.

The communication, analysis and storage of data from these experiments will only be possible through aggressive data reduction, capable of shrinking datasets by one or more orders of magnitude. Aggressive data reduction techniques already exist but in a very ad hoc form. The LHC for example already reduces the data produced by the detectors and plans to reduce the data even more in Run 3 [2]. The raw data per event is about 1MB for Atlas and CMS, and 100Kb for LHCb. Atlas, CMS and LHCb currently produces events respectively at 100Mhz and 1Ghz for Run 2. Run 3 will produce events for these experiments respectively at 0.4Mhz, 0.5Khz and 40Mhz. These detectors will produce a gigantic amount of data at an extraordinary rate: 60TB/s for ATLAS and CMS, 2TB/s for LHCb. To take this unprecedented data flow, the Alice project has defined a new combined offline-online framework called O2 that supports data flows and processing. It performs online compression of events to reduce data rate to storage to 20 GB/s. For Run 3, the O2 framework design features 463 FPGA Detectors for readout and fast cluster finding, 100,000 CPU cores to compress 1.1 TB/s data streams, 5000 GPUs to speed up the reconstruction and 50PB of disk storage to allow more precise calibration.

Aggressive data reduction is already used in the consumer environment and the consumer big data domain is preceding the scientific domain on the systematic use of lossy data reduction. Most of the photos taken by smartphone or camera are stored in a lossy compressed version. This is also true for music files. Digital music is stored in lossy compressed format on most devices. The projection made by CISCO about future Internet traffic is striking: in 2025, 80% of Internet traffic will be video streaming; which means that more than 80% of the data transiting on the Internet will be lossy compressed. Microsoft has already deployed FPGAs into its data center to accelerate LZMA and JPEG compression as well as other frequent operations, such as encryption.

An important distinction between scientific and consumer big data domains is the specificity of the data reduction techniques. As mentioned previously, aggressive data reduction techniques in the scientific domain are currently ad hoc. Conversely, the consumer big data domain relies on generic compressors (e.g. JPEG for images, MP3 for audio and MPEG4 for video). This also reveals a certain advance of the consumer big data domain over the scientific domain. An important push toward the use of generic lossy compressors in scientific applications is the trend toward a generalization of its usage. The Exascale Computing Project in USA helped to identify and better quantify these needs. Many scientific applications at extreme scale already need aggressive data reduction. Spatial sampling and decimation in time are used to reduce data but these techniques also reduce significantly the quality of the data analytics performed on the sampled or decimated datasets. Advanced lossy compression techniques provide a solution to this problem by allowing the user to control the data reduction error. Another important distinction between scientific and consumer big data domains is the difference in quality assessment of the reduced data set. JPEG, MP3 and MPEG4 are not only generic they are universal: all users have the same perception of images and sound. This allowed to define compression quality criteria that correspond to a very large population of users. This is not the case in the scientific big data domain, where each combination of application and data set may lead users to define
different sets of quality criteria. One open question is the relevant set of quality criteria for scientific data sets. Users have already expressed the need to assess spectral alteration, correlation alteration, the statistical properties of the compression error, the alteration of first and second order derivatives, and more. As the domain of lossy data reduction for scientific data sets grows, the community will learn what metrics are relevant and needed.

Although compression is critical to enable the evolution of many scientific domains to the next stage, the technology of scientific data compression and the understanding on how to use it are still in their infancy. The first piece of evidence is the lack of results in this domain: over the 26 years of the prestigious IEEE Data Compression Conferences, only 12 papers identify an aspect of scientific data in their title (floating-point data, data from simulation, numerical data, scientific data). The second piece of evidence is the poor performance on some datasets.

Beyond the research on compression, scientists also need to understand how to use lossy compression. The classic features of compressors (integer data compression, floating-point data compression, fast compression and decompression, error bounds for lossy compressors) do not characterize compressors specifically with respect to their integration into a high performance computing and data analytics workflow. For example, in the IC imaging application of the APS-U, assuming a lossy compressor capable of a factor of 100 compression, can we perform the tomography and the following data analytics directly from the compressed data? Obviously, if the subsequent analysis steps can only work from decompressed data, large storage and significant decompression time will be needed. If the data needs to be decompressed, can we decompress it only partially to allow for pipelined decompression, reconstruction, and analytics? Note that partial decompression requires random access to the compressed dataset, a capability that is not systematically considered a priority today in aggressive data reduction techniques. The same set of questions applies to large scale simulations: if we can avoid data sampling and decimation and compress the raw dataset by a factor of 100, can the following data analytics steps be performed on the compressed data?

4.3 Architecture

4.3.1 Radically improved resource management for next generation workflows

As large HPC systems become major nodes in data intensive workflows that encompass not just classical HPC applications, but big data, analytics, machine learning, and more, it becomes important to provide both the hardware and software support to run those workflows as seamlessly as possible. It is certainly clear that the diverse application communities described in Section 2.3 would benefit from a combination of HPC, data-intensive, and high-throughput computing resources. Many of the requirements of such communities can be summarized as follows:

- Software stack – ability to run an arbitrarily complex software stack on demand.
- Resilience – ability to handle failures of job streams and ability to checkpoint/restart applications (ideally using application based methods) for dynamically allocating resources to urgent computing/post-processing workloads (massive amount of data coming from large scale instrument, clinical data from hospitals, . . .)
- Resource flexibility – ability to run complex workflows with changing computational ‘width’.
- Centralised Intelligence of the resource manager: by knowing the behaviour/request of each application, the policies of the center, the current status of the systems, the number of jobs running/to be executed - ability to smart schedule jobs on the system with the appropriate level of resource allocation (in terms of energy, memory and storage placement, . . .).
- Wide-area data awareness – ability to seamlessly move computing to the data (and vice versa where possible); access to remote databases and data consistency.
- Automated workloads – ability to run automated production workflows.
End-to-end simulation-based analyses – ability to run analysis workflows on simulations using a combination of in situ and offline/co-scheduling approaches.

Although the notion of being able to launch the multiple application-workflows from the exemplars presented in Section 2.3 in a converged manner is attractive, having to launch them on a single converged hardware platform is not. Fortunately, however, this is a place where the hourglass model can be beneficial. We want to be able to support workflows consisting of multiple and divergent applications, e.g., classical HPC, machine learning, visualization (the top large portion of the hourglass). We also envision, as described in the hardware trends section, an increasing proliferation of hardware, be it in processors, accelerators, FPGAs, etc., to target these divergent applications. This is positive as this hardware will be able to best meet (in terms of performance, power, and cost) the needs of the different applications. This is the bottom portion of the hourglass. However, in an ideal world, the application would just be built and execute on the correct hardware. Thus the middle, narrow portion, of the hourglass allows application writers to just be concerned with their code. Between the ideal world and what is implementable in early version, there is a continuum of system software options that allow the application programmer to focus less on how to run their workflow, and more on what interactions between different applications in their workflow need to occur. Thus the goal of this section is to describe from a system management perspective the different levels we can take to move us toward the ideal world, where the users need only to care about their application.

We define system management to be how a machine (or collection of machines) is controlled via system software to boot, execute workflows, and allow administrators or users to interact with and control the system. The “control system” comprises the set of components in the software stack that enable this functionality. From the OpenHPC software stack (see www.openhpc.community) depicted in Figure 13, we define the control system to be those components shown on the left side in blue. Many of these components need to be extended to provide a converged view and operation of the machine especially in the face of divergent hardware. As described above there is a continuum from a manually (by application effort) converged machine to a fully automated one.

We view the roadmap to successful convergence as moving along this continuum, freeing the user from the responsibility of managing the underlying machines themselves. This accomplishes two things. It makes the user wishing to leverage a converged system more productive. More importantly, it opens up such an
architecture to a much broader user base. Without system software efforts in moving us towards the converged hourglass model, it will be difficult to gain widespread use of the increasingly complex machines.

So that we can discuss clearly the different capabilities that needed to be added, we divide the continuum into the following discrete points:

c1) The user workflow (via scripting) knows about the different underlying machines and architectures and launches its individual application on the various machines, interacts with the various resource management and monitoring components, and collates the data coming from the different machines and applications. The user must manage the individual steps in the workflow and assure the data is correctly transferred and is where it needs to be.

c2) The user workflow knows about the different underlying machines and architectures and indicates where and how different applications in the workflow should run. The underlying control system manages the launching of the different application and staging of the data before and between the applications. It returns back to the user when the workflow is finished.

c3) The user specifies the workflow by describing each application. The compiler, runtimes (MPI, PGAS, OpenMP, ML, etc.), control system, etc., automatically construct the workflow, launch the individual applications, shepherd the data to the applications, collate the results, and present the collated results of the workflow back to the user. (Note: there is probably a reasonable point between c2 and c3, but given that c2 is a significant piece of and likely to be challenge enough in the short to middle term, we leave the various aspects of moving from c2 to c3 as good topics for advanced research without pre-supposing how they would be divided).

We now describe the system software including the control system work that needs to occur for each of the points. Even though c1 appears to place all the burden on the user, there is still control system work that needs to occur, even to get to a reasonable c1. In particular, today’s accelerators, FPGA, and non-standard-core computing elements are not well understood by the operating system, resource manager, or monitoring and control system. Work needs to occur to enhance these components to comprehend the new types of hardware that will be available. Much, but probably not all, of this work will be undertaken by the vendors producing the new hardware. However, there will be open source work, e.g., SLURM in the RM space, PAPI in the monitoring space, that either the vendors would need to fund or the community will need to contribute.

As indicated, c2 is the desired intermediate step and where we believe efforts should be directed to achieve widespread use of the converged system. Significant control system work must be undertaken to achieve c2. First, high-level architecture work needs to determine the best way of bring together machines. We use resource management as an example, but it applies for many of the other components such as provisioning, fabric management, etc. One piece of work that needs to occur is to determine whether there should be a single resource manager that spans each of the underlying machines or whether there should be an overarching (new) resource manager that knows how to communicate with the resource managers on each machine. Either path is a non-trivial effort. It is likely the latter can be more easily achieved because individual resource managers will be developed to handle each machine, either by the open community, the vendor producing a machine, or a combination. However, the downside of this overarching resource manager approach, is there will likely be inefficiencies and potentially missing functionality in each individual manager. The positive side of this approach is that the effort to build even a single resource manager and keep it current with the broadening architecture is very large, so keeping the sum total effort reduced is a plus. The overarching approach also has the advantage of being able to leverage more readily particular features put in by a particular resource manager for a given hardware platform. A hybrid approach is also possible. There are likely to be resources managers that work on many of the underlying hardware platforms, and some additional capability could be
added with modest cost to get them to recognize they are managing a machine in a group of machines, where another of those machines is managed by another copy of the same resource manager.

In addition to this, the control system components must be made aware of the different types of machines and be able to map between the user specific “where and how” to the underlying machine. In this model, the components also (given a sufficiently rich enough description) need to be able to ensure the data is available to a particular application of a workflow at the right time in the right place. This could be as simple as a single globally shared file system. However, given the impending memory hierarchy architecture, it is much more likely to mean that many of the components, e.g., provision, resource manager, etc., need to be connected to a data manager that knows in which NVM a particular data set resides in, and also has the capability to move the data around and pre-stage it for efficiency. In this model, the user still needs to have knowledge of the various applications in their workflow and where they would like those applications to run.

Thirdly, c3 represents an ideal state, where the user writes the applications in the workflow and describes how they are related. During compilation phase, information is extracted to determine the best underlying architecture to run on. The various runtimes move the computations dynamically between the different hardware types on a given machine, and the control system components move the computation between different machines at the appropriate times. Data is moved around between the NVM connected to each of the computing components. This removes the burden of determining the best type of hardware to run on, and of creating the workflow specifying where the individual applications need to run each application (or even subsets or phases of applications) on. While there is considerable and unknown research work that needs to be accomplished, some aspects of that type of work is already occurring. For example, OpenMP runtimes manage systems with standard cores and GPUs, or cores and accelerators, and try to move computation automatically based on monitoring information achieved from running the application. For c3, likely pieces will be researched in the medium term with the overall puzzle being filled in based on interest of the researchers and availability of funding.

Having described the steps for system software along the path toward providing a converged machine, including the different possible points along the path and the work needed to achieve them, it is important to note that OpenHPC is not the only implementation strategy. In particular, OpenStack (https://www.openstack.org/) provides a set of alternative implementations to many of the control system components depicted in Figure 13. For example: OpenHPC provides validated recipes using bare-metal provisioners like Warewulf and xCAT, while OpenStack uses Glance and Ironic for image management and provisioning. OpenStack has been focused on the Cloud, while OpenHPC has been focused on Classical HPC. As this report exemplifies, there is interest from both sides for bringing the stacks together. There are two approaches. It is possible to use an OpenStack environment to deploy OpenHPC runtimes and development tools across a set of compute resources. The nodes would run with the high performance of OpenHPC and provide HPC performance in a cloud. The other approach would be to run elements of OpenStack within an OpenHPC environment. The former approach was demonstrated as a Proof Of Concept during Supercomputing 2016. Other work in this vein has been to run an instance of OpenHPC in Azure. These examples demonstrate the value the community sees for some types of workflows to having a more unified approach.

### 4.3.2 Considering Containerization as the new “narrow waist”

A typical HPC application code is composed of source code (Fortran, C, C++, Python) explicitly developed and managed by the application development team and links to reusable, component libraries. Commonly used libraries such as MPI and BLAS are often obtained from pre-built object code that is installed and managed by a system administrator. However, other libraries, such as solver, I/O and data analysis packages are often downloaded from a website supported by the library development team and built from source code.

This model of building from source is accepted in the HPC community, but unfamiliar to much of the HDA community. Although software components developed by the HPC community may have much to offer
the HDA community in terms of scalable computational and data management capabilities, the build from source assumption is a non-starter.

One of the first places where this spanning layer analysis is likely to be used is in consideration of “container” technology (Figure 14). Containerization has emerged as a technology that, already used in HDA, has strong potential to serve as a software bridge to the HPC community. Containers avoid the runtime overhead of virtual machines (VMs) by integrating into the host kernel, making execution times within a container essentially the same as those from a native installation on a given system. This fact has spurred interest on the part of HPC system vendors to start supporting containers on leadership computing platforms. For this reason and others, and as shown in Figure 14, containers are already being considered as a potential spanning layer for cloud infrastructure. [38] Since containers have emerged as a viable delivery platform for HPC software, and are already used widely in HDA, they have become a most attractive target for convergence between HDA and HPC. Packaging reusable HPC software components in containers dramatically reduces the usage barrier for the HDA community (and the HPC community), providing a large collection of high performance capabilities never seen before by the HDA community. For the HPC community, containers also dramatically reduce the usage barrier, making previously challenging workflow setups almost trivial, and providing a portable software environment on many HPC systems. Also, once containers are adopted by the HPC community, HDA components become available to the HPC community. Thus, bidirectional benefits of containerization are very compelling.

The HPC community is just starting its exploration of the potential for containerization. Further HPC opportunities include isolation to reduce performance variability due to kernel interrupts, coexistence of distinct software stacks on the same hardware platform, launchtime detection of special compute devices such as GPUs, and more. Issues to be explored include the following:

- The use of containers promise greater portability and isolation. The former reduces or eliminates sensitivity to differences in the underlying platform, thereby increasing flexibility when multiple platform versions are in use; the latter provides better protection from performance variability by reducing interrupts in multi-kernel environments.
• The enhanced portability provided by containers suggest that they might be used to create a spanning layer that provides a bridge between the data center/cloud and edge systems. In that context two issues will need to be explored. First, loading the entire runtime environment of an indeterminate number of processes on an edge system and making available the CPU, memory, and other resources to enable them to run to completion is heavyweight. A thin edge node may not be able to support many, or even a single large container. The second is that the runtime environment in such a scenario is indivisible. A process invoked on one processor may be tied to that processor until it completes. A container which has allocated and is using resources within the host operating system may have to reside on that host until its entire cohort of processes has completed. If changing or unexpected events prevent the successful completion of the containers execution, it may or may not be possible to checkpoint and migrate the environment, depending on the characteristics of the host operating system.

• While the container ecosystems of the HDA community are already very valuable to the HPC community, notable security features, essential for any effective deployment in a multi-user environment, are currently missing. But HPC environments are always multi-job, multi-user environments. Furthermore, sensitive system and user data are typically present on the system at any given time. Common container environments such as Docker [cite] effectively permit root access from the container into the host environment, which is clearly unacceptable on an HPC platform. Augmented environments such as Shifter [cite] can encapsulate a standard container and improve the security and device detection capabilities needed for HPC.

4.4 Software

As the new era of Big Data and extreme-scale computing continues to develop, it seems clear that both centralized systems (viz., HPC centers and commercial cloud systems) and decentralized systems (viz., any of the alternative designs for edge/fog infrastructure) will share many common software challenges and opportunities. For example, continued exponential growth in data volumes will make data reduction of one form or another indispensable on all fronts. None the less, we locate much of the discussion of software issues and possibilities in this section on centralized infrastructure because, despite the recognized differences and uncertainties, architectural and hardware questions for HPC and Cloud computing environments are still far clearer than they are for edge/fog environments, where proposals, blueprints, and promises now prevail. Thus, many of the software issues that are discussed in this section will need to be revisited for Edge/Fog environments as their platform models acquire more definition and begin to stabilize.

4.4.1 Software Libraries for Common Intermediate Processing Tasks

One common theme in the workflow descriptions at the BDEC workshop was the amount of “intermediate” (or pre) processing that data requires before the more substantial analysis and visualization processes occur. For instance, we describe multi-messenger forms of inquiry in Section 2.3, which tend to exhibit a relatively common set of requirements:

• Identify and segment trillions of multi-scale objects from spatio-temporal datasets.
• Extract features from objects and spatio-temporal regions.
• Support queries against ensembles of features extracted from multiple datasets.
• Statistical analyses and machine learning to link features to physical and biological phenomena.
• Feature driven simulation – use extracted features as simulation initial, boundary conditions and to assimilate data into simulations.
• Develop and enrich in-situ/in-transit framework with machine/deep learning capabilities for on-the-fly automatic pertinent structures (turbulence, seismic noise, image, . . . .) detection/extraction for both static and dynamic analysis.
• And then as a reverse loop, perform smart computational steering of the application (as was also seen above in Sec. 2.3.5).

Many of the intermediate transformations in this list are normally described in generic terms: cleaning, subsetting, filtering, mapping, object segmentation, feature extraction, registration, etc. The question is whether or not some of these operations are generic enough so that a common set of software tools, appropriately layered and modularized, could be developed to serve the diverse purposes of a number of different communities at the same time. For example, image-driven workflows from fields such as medical imaging, microscopy, and remote (satellite) sensing, utilize all of the operations given above. Although the co-design effort that would probably be necessary to produce it would be challenging to organize, common software infrastructure that (suitably configured) could satisfy intermediate processing needs in a wide variety of fields would be a boon to data-driven research.

• A common and visible data model: One major obstacle to creating shared software infrastructure for intermediate processing is the absence of interoperable data object models, or, just as importantly, a way of making the object model being used visible. The effort to develop a common model achieved limited success when OODB’s were introduced in the 1990s, but that success was largely restricted to tightly coupled systems; they did not succeed for many more loosely coupled situations, which are typical today for many emerging BDEC domains and workflows. And Web based approaches (e.g., REST API, etc.) are likely to be viable for only a relatively small segment of these BD applications. Common object models have been established in some application domains (e.g., in multi-physics applications or climate modeling community), but creating a common software stack that supports interoperability far more generally has proved elusive. Moreover, for any such model to succeed, it will need to be flexible enough to provide data layout distribution options to support the kind of parallelism that applications and the I/O services that support them will require.

• Shared software infrastructure for intermediate processing: The translation of all scientific data into digital form has opened up a major opportunity space for research methods that integrate or synthesize data of multiple types and/or from multiple sources or sensor modalities. This is particularly true for application areas, now common, that utilize and combine multi-dimensional spatial-temporal datasets. Examples include Radio- and Microscopy Imaging combined with omic data; simulation data (e.g., for oil fields, carbon sequestration, groundwater pollution/remediation) combined with seismic and earth sensor data; and weather prediction based on the real time integration of data from simulations, satellites, ground sensors, and live video feeds. The Google self-driving car provides a more practical, consumer illustration of the use of real-time integrated analysis of correlative data from multiple sensor modalities and sources. The multi-dimensional data space that these applications define tends to be high resolution in each of their correlative dimensions, so that, when even a modest number of data steps is involved, extremely large volumes of data need to be accessed and processed in a coordinated way.

4.4.2 Math Libraries, Software Ecosystems for application development

Leveraging HPC Math Libraries in HDA The HPC community has a large and growing collection of high performance math libraries for scientific computing. Many of these libraries have been carefully designed and implemented to exploit scalable parallel systems, from multicore and GPU enabled laptops to the largest computing systems in the world. At the same time, these libraries are typically used by the HPC community in the form of user-compiled source code. Furthermore, the interfaces to these libraries are complex, with many options that require substantial experience in mathematical algorithms and parallel computing.

The advent of component based software ecosystems such as Docker, enables pre-compilation and pre-defined parametrization of HPC math libraries for dedicated problem solving in a component software
ecosystem. For example, the Trilinos eigensolver package Anasazi has many algorithmic and parameter options that can be adapted to provide capabilities for a variety of problems. Furthermore, Anasazi has a complex build environment that supports optimized compilation on a variety of platforms. While attractive to experts, the sheer range of choices can be a non-starter to someone who “just wants a solver for large sparse eigenvalue problems.”

Containers provide an opportunity to encapsulate the complexity of a solver like Anasazi by supporting pre-compilation of source and a simplified interface such that the resulting container can be considered a filter that takes a sparse matrix as input and produces eigenvalues and eigenvectors as output, executing on a laptop, parallel cluster or supercomputer, providing a portable workflow environment for the user. This capability will enable turnkey use of sophisticated solvers for both HPC and HDA users.

**New Efforts for Dense Linear Algebra Standards** The emergence of new markets related to the HDA community has created renewed and expanded interest in new standard functionality and interfaces for dense linear algebra. The so-called “batched BLAS” are a new standards effort looking at how to efficiently compute dense linear operations on a large collection of matrices at the same time. These kernels have always been of interest in finite element computations, part of the HPC community, but have never had the market potential to drive toward a standard. The emergence of “deep learning” algorithms in HDA provides new incentive, and the community is working toward a standard. Batched BLAS and other potential standards that can benefit both HPC and HDA, represent a synergistic opportunity that would not be otherwise easy to exploit.

**Challenges in the HPC Software Ecosystem** While in many ways the HPC Software Ecosystem is rich and stable, providing a ready-made environment for attaining good performance, there are some challenges that only time, exploration and “coopetition” can resolve. Of particular importance is standards for shared memory parallel programming. While MPI is the ubiquitous and acknowledged standard for inter-node (across node) parallel programming and execution, intra-node parallel programming and execution environments are not nearly as stable. Presently there are two dominant efforts, OpenMP and OpenACC, which are targeting two distinct approaches to node-level parallelism.

OpenMP and its predecessors have been available for more than three decades. This approach is designed with particular suitability to multi-core and many-core parallel processors, such as Intel multiprocessors and Intel PHI. OpenACC started as a forked effort from OpenMP, with the intent to focus more specifically on accelerator processors such as Nvidia GPUs. While there is resolve on the part of the HPC community to bring OpenMP and OpenACC back together, the obvious self-interest of specific vendors leads to competitive concerns that fundamental design choices could bias the community for or against a particular architecture. This coopetition is healthy and necessary in order to assure a truly portable standard that can support all important intra-node parallelism approaches. Even so, the present state of uncertainty makes the writing of portable intra-node parallel code particularly challenging at this time.

**4.4.3 Interoperability between programming models and data formats**

While traditionally HPC programming applications are based on MPI to support parallel and distributed execution, and OpenMP or other alternatives to exploit the parallelism inside the node, Big Data programming models are based on interfaces such as Hadoop/MapReduce or Spark. It is not only the programming model, but also the programming language which differs between the two communities, being Fortran and C/C++ the most common languages in the HPC community and Java/Scala or Python the most used in Big Data applications and offered by the previous mentioned interfaces.

This divergence between programming models and languages poses a convergence issue, not only with regard to interoperability of the applications but also to the interoperability between data formats from different programming languages. In this scenario, we need to consider how to build end-to-end workflows,
providing a coordination layer that enables the management of dynamic workflows composed of simulations, analytics and visualization, including inputs/outputs from streams. In such a scenario, simulations can be MPI applications written in Fortran or C/C++, and the analytics can be codes written in Java or Python, maybe parallelized with Spark, or with PyCOMPSs/COMPSs, for example. To enable the efficient exchange of data between the simulations and analytics parts of the workflows, other means beyond traditional POSIX files should be considered. Alternatives to implement this are being considered, with approaches such as dataClay or Hecuba, that provide persistent storage libraries and tools, but further research still remains to be done in order to better support data interoperability between different programming languages.

5 Conclusions and Recommendations

The goal of the BDEC workshops has been to develop an ICT planning document for science and engineering that articulates an analysis and vision of the conjoint evolution of data-intensive research and extreme scale computing. As we argued above, however, since there is no widely agreed upon model for the new kind of distributed services platform that data-intensive workflows of the Big Data era seems to require, traditional technology road mapping techniques seem to be inappropriate. Following the structure of the document, we have divided our findings and recommendations into three categories: global recommendations, recommendations for edge environments, recommendations for centralized facilities. However, our ultimate goal is to to prepare the ground for the kind of community-driven “shaping strategy” [43, 44] approach that we believe would be both more appropriate and more successful – see above in Sec. 1.2. Consequently, the conclusions as they appear below, may have to be refactored in order to serve the shaping strategy model.

Global recommendations The major recommendation is to address the basic problem of the two paradigm splits: the HPC/HDA software ecosystem split and the wide area data logistics split. For this to be achieved, there is a need for new standards that will govern the interoperability between data and compute. However, if we want a new distributed infrastructure to support science and engineering research in the era of Big Data, an infrastructure with the kind of openness, scalability, and flexible resource sharing that has characterized the legacy Internet paradigm, then we will have to define a new, common and open Distributed Services Platform (DSP), one that offers programmable access to shared processing, storage and communication resources, and that can serve as a universal foundation for the component interoperability that novel services and applications will require. As the data revolution continues, such well-designed DSP infrastructure will be necessary to support such compute- and/or data-intensive work that many application areas will have to carry out between the ingress/egress to the Cloud (or Data/HPC center) and the network edge. As the history of the Internet shows, the scientific community is, with appropriate public investment in basic research and development, uniquely positioned to create and develop the kind of DSP that the emerging era of extreme scale data and computing requires, building on the kind of open, consensus-driven approach that helped establish the Internet.

Recommendations for decentralized facilities for edge and peripheral ecosystems

1. Converging on a New Hourglass Architecture for a Common Distributed Service Platform (DSP). The hourglass represents the idea that an appropriately designed common interface can be implemented on an ever increasing variety of technology platforms (yielding a wide lower bell), while at the same time supporting an equally diverse and growing variety of applications (yielding a wide upper bell). The common interface, or thin waist of the hourglass, is called the spanning layer because it bridges, through virtualization, a heterogeneous set of resources that lie below it, but leaves the application and services above it free to evolve independently. This point clearly ties in with the global recommendation, above. Unfortunately, in seeking a new spanning layer to address the challenges of the big data era,
the science cyberinfrastructure community finds itself in something of a dilemma. On one hand, at present there does seem to be at least one plausible and widely touted candidate for the new spanning layer—operating-system-level virtualization that supports software containers. Certainly, converging on a common interface for containerization would go a long way to achieving ecosystem convergence, and do so in way that requires something closer to evolutionary, as opposed to revolutionary changes to current modes of operation. Containerization should thus be a very active area of research and experimentation across all the contexts that scientific cyberinfrastructure will have to address, including commercial clouds, HPC systems, and computing resources deployed in edge environments. At the same time, the fact that containers preserve legacy silos for storage, processing and communication at a low-level, and may therefore bring with them unexpected impediments to interoperable convergence, suggests that other ideas for a new spanning layer should also be aggressively pursued.

2. **Target Workflow Patterns for Improved Data Logistics** There seem to be at least four, non-exclusive alternatives for interfacing HPC to this new DSP paradigm in which no strong assumptions are made about where the data are: (1) data streaming, (2) in-transit processing, (3) processing at the edge of the distributed system, i.e. as close as possible to the data sources, and (4) logically centered cloud-like processing. These should be the basis for new research funding with an applications-oriented objective.

3. **Cloud stream processing capabilities** have not been designed with HPC in mind, and there is a need to examine the high performance aspects of their runtimes.

4. **Content Delivery/Distribution Networks.** Commercial CDNs are expensive to run and creates barriers to interoperation. To resolve this requires (1) a scalable approach to CDN implementation (i.e., suitably designed forms of storage and processing at the nodes of the distribution tree) and (2) the aggregate organizational will of the scientific community.

5. **Software Libraries for Common Intermediate Processing Tasks.** One common theme in the workflow descriptions is the amount of intermediate (or pre-) processing that data requires before the more substantial analysis and visualization processes can occur. Some of these operations are generic enough so that a common set of software tools, appropriately layered and modularized, could be developed to serve the diverse purposes of a number of different communities at the same time.

**Recommendations for centralized facilities**

1. **Energy as an overarching challenge for sustainability.** We can identify four steps towards energy minimization: (1) reduce computational costs by using platforms well-matched to the stage within the scientific method; (2) reduce data-movement costs by co-location, compression and caching; (3) encourage re-use of calculations and data, by effective sharing, metadata and catalogues, a strategy that a provenance system supports well; and (4) reduce computing system entropy (workloads interference, system jitter, tail latency, and other noises) by on-demand isolation, noise-resistant priority, Cache QoS and novel uncertainty bounding techniques. The e-infrastructure itself has the task of taking care of energy minimization as it has access to the required information - burdening domain scientists is not desirable, since it would divert them from their scientific goals.

2. **Data reduction as a fundamental pattern.** The communication, analysis and storage of data from large scientific experiments will only be possible through aggressive data reduction, capable of shrinking datasets by one or more orders of magnitude. This is equally valid for data from sensors (see below). Although compression is critical to enable the evolution of many scientific domains to the next stage, the technology of scientific data compression and the understanding on how to use it are still in their infancy. Beyond the research on compression, scientists also need to understand how to use lossy
compression. If the data needs to be decompressed, can we decompress it only partially to allow for pipelined decompression, reconstruction, and analytics? The same set of questions applies to large scale simulations: if we can avoid data sampling and decimation and compress the raw dataset by a factor of 100, can the following data analytics steps be performed on the compressed data?

3. **Radically improved resource management.** As HPC workflows start encompassing not just classical HPC applications, but big data, analytics, machine learning, and more, it becomes important to provide both the hardware and software support to run those workflows as seamlessly as possible. We define system management to be how a machine (or collection of machines) is controlled via system software to boot, execute workflows, and allow administrators or users to interact with and control the system. The roadmap to successful convergence requires freeing the user from the responsibility of managing the underlying machines themselves and enabling widespread use of these complex machines.

4. **Software issues.** As the new era of Big Data and extreme-scale computing continues to develop, it seems clear that both centralized systems (viz., HPC centers and commercial cloud systems) and decentralized systems (viz., any of the alternative designs for edge/fog infrastructure) will share many common software challenges and opportunities. Eminent among these are the following needs:

   (a) Leverage HPC math libraries for HDA.
   (b) More efforts for dense linear algebra standards.
   (c) New standards for shared memory parallel processing.
   (d) Interoperability between programming models and data formats.

5. **Machine learning** is emerging as a general tool to augment and extend mechanistic models in many fields. It’s becoming an important component of scientific workloads. From a computational architecture standpoint, deep neural network (DNN) based scientific applications have some unique requirements. They require high compute density to support matrix-matrix and matrix-vector operations, but they rarely require 64-bit or even 32 bits of precision, thus architects should continue to create new instructions and new design points to accelerate the training stage of the neural network. Most current DNNs rely on dense fully connected networks and convolutional networks and thus are reasonably matched to current HPC accelerators. However future DNNs may rely less on dense communication patterns. DNNs in general do not have good strong scaling behavior, so to fully exploit large-scale parallelism they rely on a combination of model, data and search parallelism. Deep learning problems also require large-quantities of training data to be made available or generated at each node, thus providing opportunities for NVRAM. Discovering optimal deep learning models often involves a large-scale search of hyperparameters. It’s not uncommon to search a space of tens of thousands of model configurations. Naive searches are outperformed by various intelligent searching strategies, including new approaches that use generative neural networks to manage the search space. HPC architectures that can support these large-scale intelligent search methods as well as efficient model training are needed.

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David Barkai, Jean-Yves Berthou, Taisuke Boku, Bertrand Braunschweig, Franck Cappello, Barbara
Chapman, Xuebin Chi, Alok Choudhary, Sudip Dosanjh, Thom Dunning, Sandro Fiore, Al Geist,
Bill Gropp, Robert Harrison, Mark Hereld, Michael Heroux, Adolfy Hoisie, Koh Hotta, Zhong Jin,
Yutaka Ishikawa, Fred Johnson, Sanjay Kale, Richard Kenway, David Keyes, Bill Kramer, Jesus
Labarta, Alain Lichnewsky, Thomas Lippert, Bob Lucas, Barney Maccabe, Satoshi Matsuoka, Paul
Messina, Peter Michielse, Bernd Mohr, Matthias S. Mueller, Wolfgang E. Nagel, Hiroshi Nakashima,
Michael E Papka, Dan Reed, Mitsuhsisa Sato, Ed Seidel, John Shalf, David Skinner, Marc Snir, Thomas
Sterling, Rick Stevens, Fred Streitz, Bob Sugar, Shinji Sumimoto, William Tang, John Taylor, Rajeev
Thakur, Anne Trefethen, Mateo Valero, Aad Van Der Steen, Jeffrey Vetter, Peg Williams, Robert
http://dx.doi.org/10.1177/1094342010391989.


[29] Executive Office of the U.S. President. National Strategic Computing Initiative Executive Order,
strategic-computing-initiative.


469, 2013.

No. 33, Global Commission on Internet Governance Paper Series.


[34] Peter A Flach and Antonis M Hadjiantonis. *Abduction and Induction: Essays on their relation and

[35] Ian Foster, Carl Kesselman, and Steven Tuecke. The anatomy of the grid: Enabling scalable virtual


A  Appendix: Summary Review of BDEC Workshops

A.1  BDEC Charleston, 2013

A.1.1  BDEC Charleston Attendees
Yutaka Akiyama (Tokyo Institute of Technology)
Jean-Michel Alimi (Laboratoire Univers et Théories)
Giovanni Aloisio (University of Salento & CMCC, Italy)
Pete Beckman (Argonne National Laboratory/U. of Chicago)
Jean-Yves Berthou (French National Research Agency [ANR])
Alok Choudhary (Northwestern University)
Tim Cornwell (Square Kilometre Array)
Bronis de Supinski (Lawrence Livermore National Laboratory)
Jack Dongarra (University of Tennessee)
Teresa Finchum (University of Tennessee)
Sandro Fiore (University of Salento & CMCC, Italy)
Geoffrey Fox (Indiana University)
Kelly Gaither (Texas Advanced Computing Center)
Al Geist (Oak Ridge National Laboratory)
William Gropp (University of Illinois)
Michael Heroux (Sandia National Laboratories)
Yutaka Ishikawa (University of Tokyo)
Daniel Katz (National Science Foundation)
William Kramer (University of Illinois)
Andrew Lumsdaine (Indiana University)
Satoshi Matsuoka (Tokyo Institute of Technology)
William Michener (University of New Mexico)
Takemasa Miyoshi (RIKEN Advanced Institute for Computational Science)
Bernd Mohr (Jülich Supercomputing Centre)
Reagan Moore (University of North Carolina at Chapel Hill)
Terry Moore (University of Tennessee)
Shinichi Morishita (University of Tokyo)
Wolfgang E. Nagel (TU Dresden, ZIH)
Lori O'Connor (Argonne National Laboratory)
Kenji Ono (RIKEN Advanced Institute for Computational Science)
Tracy Rafferty (University of Tennessee)
Philippe Ricoux (Total SA)
Joel Saltz (Emory University)
Vivek Sarkar (Rice University)
Arie Shoshtani (Lawrence Berkeley National Laboratory)
Rick Stevens (Argonne National Laboratory)
Toyotaro Suzumura (Tokyo Institute of Technology)
Martin Swany (Indiana University)
Alex Szalay (Johns Hopkins University)
William Tang (Princeton University)
Osamu Tatebe (University of Tsukuba)
Ranga Vatsavai (Oak Ridge National Laboratory)
Pier Luigi Vidale (University of Reading)
Jean-Pierre Vilotte (Institut de Physique du Globe de Paris)
Voevodin Vladimir (Research Computing Center – Moscow State University)
Ramin Yahyapour (GWDG)
A.1.2 BDEC Charleston Agenda

Monday, April 29

- 5:30 p.m. to 7:30 p.m. – Registration and Reception

Tuesday, April 30

- **8:00 a.m. to 9:00 a.m. – Breakfast**
- **8:30 a.m. to 9:00 a.m. – Registration**
- **Session 1 (Chair: Jack Dongarra, University of Tennessee)**
  - 9:00 a.m. to 9:10 a.m. – Welcome to Big Data and Extreme Computing: Goals and Overview
    - Pete Beckman, Argonne National Laboratory
    - Jean-Yves Berthou, French National Research Agency (ANR)
    - Jack Dongarra, University of Tennessee
    - Yutaka Ishikawa, University of Tokyo
    - Satoshi Matsuoka, Tokyo Institute of Technology
    - Philippe Ricoux, Total SA
  - 9:10 a.m. to 9:30 a.m. – Big Data’s Biggest Needs – Deep Analytics for Actionable Insights
    - Alok Choudhary, Northwestern University
  - 9:30 a.m. to 9:50 a.m. – Big Data and Big Crunch for the Square Kilometre Array
    - Tim Cornwell, Square Kilometre Array
  - 9:50 a.m. to 10:10 a.m. – Turning Large simulations into Numerical Laboratories
    - Alex Szalay, Johns Hopkins University

- **10:10 a.m. to 10:40 a.m. – Break**

- **Session 2 (Chair: Jean-Yves Berthou, French National Research Agency [ANR])**
  - 10:40 a.m. to 11:00 a.m. – Can we converge big data, big compute and big Interaction in future hardware and software?
    - Rick Stevens, Argonne National Laboratory
  - 11:00 a.m. to 11:20 a.m. – Big Data Parallel Processing of Personal Genomes
    - Shinichi Morishita, University of Tokyo
    - [http://www.exascale.org/bdec/sites/www.exascale.org.bdec/files/6_BDEC_Shi
chi Morishita_U_Tokyo.pdf](http://www.exascale.org/bdec/sites/www.exascale.org.bdec/files/6_BDEC_Shi
chi Morishita_U_Tokyo.pdf)
• 11:20 a.m. to 11:40 a.m. – Beyond Embarrassingly Parallel Big Data
  ▪ William Gropp, University of Illinois
• 11:40 a.m. to 12:00 p.m. – Weather and Climate Modelling: ready for exascale?
  ▪ Pier Luigi Vidale, University of Reading

• 12:00 p.m. to 1:00 p.m. – Lunch

• Session 3 (Chair: Pete Beckman, Argonne National Laboratory)
  • 1:00 p.m. to 2:30 p.m. – Panel 1
    ▪ Jean-Michel Alimi, Laboratoire Univers et Théories
    ▪ Reagan Moore, University of North Carolina at Chapel Hill
    ▪ Wolfgang E. Nagel, TU Dresden, ZIH
    ▪ Osamu Tatebe, University of Tsukuba
    ▪ Pier Luigi Vidale, University of Reading
    ▪ Toyotaro Suzumura, Tokyo Institute of Technology

• 2:30 p.m. to 3:00 p.m. – Break

• Session 4
  • 3:00 p.m. to 5:00 p.m. – Breakout Groups 1
    ▪ Track 1 – International Collaboration, Frameworks, Funding, and Co-design:
      Bronis de Supinski, Jean-Yves Berthou
    ▪ Track 2 – Architecture: Rick Stevens, Satoshi Matsuoka
    ▪ Track 3 – Software: Vivek Sarkar, William Kramer, Wolfgang Nagel
  • 5:00 p.m. to 5:30 p.m. – Breakout Report 2

• 5:30 p.m. to 6:30 p.m. – Cocktail Reception

• 6:30 p.m. – Dinner

Wednesday, May 1

• 8:00 a.m. to 9:00 a.m. – Breakfast

• Session 5 (Chair: Philippe Ricoux, Total SA)
  • 9:00 a.m. to 9:20 a.m. – Integrative Biomedical Informatics, Big Data and Extreme Scale Computing
    ▪ Joel Saltz, Emory University
• On the Role of Indexing for Big Data in Scientific Domains
  Arie Shoshani, Lawrence Berkeley National Laboratory

• Big Data and extreme-scale computing challenges in solid Earth Sciences
  Jean-Pierre Vilotte, Institut de Physique du Globe de Paris

• 10:00 a.m. to 10:30 a.m. – Break

• Session 6 (Chair: Yutaka Ishikawa, University of Tokyo)
  • 10:30 a.m. to 10:50 a.m. – Co-existence: Can Big Data and Big Computation Co-exist on the Same Systems?
    William Kramer, University of Illinois
  • 10:50 a.m. to 11:10 a.m. – Synergistic Challenges in Data-Intensive Science and Extreme Computing
    Vivek Sarkar, Rice University
  • 11:10 a.m. to 11:30 a.m. – Computational Challenges in Big Data Assimilation with Extreme-scale Simulations
    Takemasa Miyoshi, RIKEN Advanced Institute for Computational Science

• 11:30 a.m. to 12:30 p.m. – Lunch

• Session 7 (Chair: Satoshi Matsuoka, Tokyo Institute of Technology)
  • 12:30 p.m. to 2:00 p.m. – Panel 2
    Sandro Fiore, University of Salento & CMCC, Italy
    Kenji Ono, RIKEN Advanced Institute for Computational Science
    Geoffrey Fox, Indiana University
    Andrew Lumsdaine, Indiana University
    Shinichi Morishita, University of Tokyo
    Ranga Vatsavai, Oak Ridge National Laboratory

• 2:00 p.m. to 2:30 p.m. – Break
• Session 8
  o 2:30 p.m. to 4:30 p.m. – Breakout Groups 2
    ▪ Track 1 – Interoperability: Bronis de Supinski, Jean-Yves Berthou
    ▪ Track 2 – Workflows: Rick Stevens, Satoshi Matsuoka
    ▪ Track 3 – Taxonomy: Vivek Sarkar, Bill Kramer, Wolfgang Nagel
  o 4:30 p.m. to 5:00 p.m. – Breakout Report 2

• 5:00 p.m. – Dinner on your own

A.1.3 BDEC Charleston White Papers
# A.2 BDEC Fukuoka, 2014

## A.2.1 BDEC Fukuoka Attendees

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization/Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jim Ahrens</td>
<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>Yutaka Akiyama</td>
<td>Tokyo Institute of Technology</td>
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<tr>
<td>Jean-Claude Andre</td>
<td>Jca Consultance &amp; Analyse</td>
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<td>Mutsumi Aoyagi</td>
<td>Kyushu University</td>
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<td>Akira Asawa</td>
<td>Hitachi</td>
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<tr>
<td>Chaitan Baru</td>
<td>San Diego Supercomputer Center</td>
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<td>Pete Beckman</td>
<td>Argonne National Laboratory</td>
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<td>Jean-Yves Berthou</td>
<td>French National Research Agency</td>
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<td>Budhendra Bhaduri</td>
<td>Oak Ridge National Laboratory</td>
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<td>Thierry Bidot</td>
<td>NEOVIA</td>
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<tr>
<td>Francois Bodin</td>
<td>Institute for Research in Computer Science and Random Systems</td>
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<td>Taisuke Boku</td>
<td>University of Tsukuba</td>
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<td>Franck Cappello</td>
<td>Argonne National Laboratory / University of Illinois</td>
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<td>Alok Choudhary</td>
<td>Northwestern University</td>
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<td>Bronis de Supinski</td>
<td>Lawrence Livermore National Laboratory</td>
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<td>Ewa Deelman</td>
<td>University of Southern California Information Sciences Institute</td>
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<td>Jack Dongarra</td>
<td>University of Tennessee</td>
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<td>Sudip Dosanjh</td>
<td>Lawrence Berkeley National Laboratory</td>
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<td>Anshu Dubey</td>
<td>Lawrence Berkeley National Laboratory</td>
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<td>Toshio Endo</td>
<td>Tokyo Institute of Technology</td>
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<td>Teresa Finchum</td>
<td>University of Tennessee</td>
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<td>Sandro Fiore</td>
<td>Euro-Mediterranean Center on Climate Change / University of Salento</td>
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<td>Ian Foster</td>
<td>Argonne National Laboratory / University of Chicago</td>
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<td>Geoffrey Fox</td>
<td>Indiana University</td>
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<td>Katsuki Fujisawa</td>
<td>Chuo University / Japan Science and Technology Agency</td>
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<td>Keiichiro Fukazawa</td>
<td>Kyushu University</td>
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<td>Al Geist</td>
<td>Oak Ridge National Laboratory</td>
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<td>Sergi Girona</td>
<td>Partnership for Advanced Computing in Europe / Barcelona Supercomputing Center</td>
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<td>William Gropp</td>
<td>University of Illinois</td>
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<td>Toshihiro Hanawa</td>
<td>University of Tokyo</td>
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<tr>
<td>William Harrod</td>
<td>United States Department of Energy</td>
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<tr>
<td>Yuta Higuchi</td>
<td>Fujitsu / Laboratoire Univers et Théories</td>
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<tr>
<td>Kimihiko Hirao</td>
<td>RIKEN Advanced Institute for Computational Science</td>
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<td>Atsushi Hori</td>
<td>RIKEN Advanced Institute for Computational Science</td>
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<td>Soonwook Hwang</td>
<td>Korean Institute of Science and Technology Information</td>
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<td>Koji Inoue</td>
<td>Kyushu University</td>
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<td>Masaki Ishida</td>
<td>Data Direct Networks</td>
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<td>Yutaka Ishikawa</td>
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<td>Takeshi Iwashita</td>
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<td>David Kahaner</td>
<td>Asian Technology Information Program</td>
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<td>Takahiro Katagiri</td>
<td>University of Tokyo</td>
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<td>Yoshio Kawaguchi</td>
<td>MEXT</td>
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<td>Kate Keahey</td>
<td>Argonne National Laboratory</td>
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<td>Dries Kimpe</td>
<td>Argonne National Laboratory</td>
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<td>Itaru Kitayama</td>
<td>RIKEN Advanced Institute for Computational Science</td>
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<tr>
<td>Masaru Kitsuregawa</td>
<td>University of Tokyo</td>
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<tr>
<td>Shingo Komatsu</td>
<td>Cray Japan, Inc.</td>
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</tbody>
</table>
William Kramer (National Center for Supercomputing Applications / University of Illinois)
Tomohiro Kudoh (AIST)
Jesus Labarta (Barcelona Supercomputing Center)
Jean-Francois Lavignon (Bull)
Maryline Lengert (European Space Agency)
Yutong Lu (National University of Defense Technology)
Volker Markl (Technical University of Berlin)
Naoya Maruyama (RIKEN Advanced Institute for Computational Science)
Satoshi Matsuoka (Tokyo Institute of Technology)
Piyush Mehrotra (NASA Ames Research Center)
Bernd Mohr (Jülich Supercomputing Centre)
Terry Moore (University of Tennessee)
Wolfgang Nagel (TU Dresden ZIH)
Kengo Nakajima (University of Tokyo)
Hiroshi Nakamura (University of Tokyo)
Mamoru Nakano (Cray Japan, Inc.)
Hiroshi Nakashima (Kyoto University)
Takeshi Nanri (Kyushu University)
Sai Narasimhamurthy (Xyratex)
Itsuki Noda (National Institute of Advanced Industrial Science and Technology)
Kenji Ono (RIKEN Advanced Institute for Computational Science)
Irene Qualters (National Science Foundation)
Tracy Rafferty (University of Tennessee)
Philippe Ricoux (Total SA)
Joel Saltz (Stony Brook University)
Hitoshi Sato (Tokyo Institute of Technology)
Mitsuhisa Sato (RIKEN Advanced Institute for Computational Science / University of Tsukuba)
Marie-Christine Sawley (Intel)
Satoshi Sekiguchi (AIST)
Masaaki Shimizu (Hitachi)
Shinji Shimojo (Osaka University)
Chie Shiraiwa (NEC Corporation)
Shinji Sumimoto (Fujitsu)
Martin Swany (Indiana University)
Alex Szalay (Johns Hopkins University)
Yusong Tan (National University of Defense Technology)
Yoshio Tanaka (National Institute of Advanced Industrial Science and Technology)
William Tang (Princeton University / Princeton Plasma Physics Lab)
Osamu Tatebe (University of Tsukuba)
Rie Toh (NEC Corporation)
Hirofumi Tomita (RIKEN Advanced Institute for Computational Science)
Robert Friendl (Data Direct Networks)
Jean-Pierre Vilotte (Paris Institute of Earth Physics)
Vladimir Voevodin (Moscow State University Research Computing Center)
Marcus Wilms (DFG)
Min Xie (National University of Defense Technology)
Akinori Yonezawa (RIKEN Advanced Institute for Computational Science)
A.2.2 BDEC Fukuoka Agenda

Wednesday, February 26

- 6:00 p.m. – Registration and Reception

Thursday, February 27

- 9:00 a.m. – Registration

- Session 1
  - 9:15 a.m. to 9:30 a.m. – Welcome to Big Data and Extreme Computing: Goals and Overview
    - Pete Beckman, Argonne National Laboratory
    - Jean-Yves Berthou, French National Research Agency (ANR)
    - Jack Dongarra, University of Tennessee
    - Yutaka Ishikawa, University of Tokyo
    - Satoshi Matsuoka, Tokyo Institute of Technology
    - Philippe Ricoux, Total SA
  - 9:30 a.m. to 9:45 a.m. – Japan’s Policy toward Exascale Computing
    - Yoshio Kawaguchi, MEXT
  - 9:45 a.m. to 10:20 a.m. – Invited Talk from Japan
    - Masaru Kitsuregawa, University of Tokyo

- 10:20 a.m. to 10:30 a.m. – Break

- Session 2
  - 10:30 a.m. to 10:50 a.m. – Overview of Department of Energy Activities
    - William Harrod, United States Department of Energy
  - 10:50 a.m. to 11:10 a.m. – Overview of National Science Foundation Activities
    - Irene Qualters, National Science Foundation
  - 11:10 a.m. to 11:20 a.m. – EU and International Futures Call
    - Marcus Wilms, DFG
  - 11:20 a.m. to 11:25 a.m. – High Performance Computing in Horizon 2020
    - Jean-Yves Berthou, French National Research Agency
  - 11:25 a.m. to 11:35 a.m. – PRACE: Expression of Interest Big Data
    - Sergi Girona, Partnership for Advanced Computing in Europe
- 11:35 a.m. to 11:45 a.m. – Building a Globally Competitive HPC Technology Ecosystem in Europe
  - Jean-François Lavignon, Bull
- 11:45 a.m. to 11:55 a.m. – European Exascale Software Initiative (EESI2): Towards Exascale Roadmap Implementation
  - Philippe Ricoux, Total SA
- 11:55 a.m. to 12:25 p.m. – China Overview Talk
  - Yutong Lu, HPCL
- 12:25 p.m. to 1:05 p.m. – Japan Overview Talk
  - Hirofumi Tomita, RIKEN Advanced Institute for Computational Science
  - Yutaka Ishikawa, University of Tokyo
  - Mitsuhisa Sato, RIKEN Advanced Institute for Computational Science
- 1:05 p.m. to 1:45 p.m. – Lunch
- Session 3
  - 1:45 p.m. to 2:30 p.m. – BDEC 1 and a Strawman Architecture for a Data Facility
    - Pete Beckman, Argonne National Laboratory
  - 2:30 p.m. to 4:00 p.m. – Seven 6-minute Talks Based on White Papers and Panel Discussion
    - Chair: Bill Gropp
    - Scribes: Bill Kramer & Piyush Mehrotra
- 5:30 p.m. – Evening Reception

Friday, February 28
- Session 4
  - 9:00 a.m. to 10:45 a.m. – Eight 6-minute Talks Based on White Papers and Panel Discussion
    - Chair: Taisuke Boku
    - Scribes: Marie-Christine Sawley and Dries Kimpe
- 10:45 a.m. to 11:00 a.m. – Break
• **Session 5**
  
  o 11:00 a.m. to 12:30 p.m. – Three Breakout Sessions
    - Apps: Joel Saltz & Bronis de Supinski
    - Architecture: Satoshi Matsuoka & Pete Beckman
    - Data: Chaitan Baru & Jim Ahrens
  
  o 12:30 p.m. to 1:00 p.m. – Breakout Report
    - Pete Beckman, Argonne National Laboratory
    - Jim Ahrens, Los Alamos National Laboratory
    - Joel Saltz, Stony Brook University

• **1:00 p.m. to 1:30 p.m. – Lunch**

• **Session 6**
  
  o 1:30 p.m. to 3:30 p.m. – Three Breakout Sessions
    - Apps: Joel Saltz & Bronis de Supinski
    - Architecture: Satoshi Matsuoka & Pete Beckman
    - Data: Chaitan Baru & Jim Ahrens

• **3:30 p.m. to 4:00 p.m. – Break**

• **Session 7**
  
  o 4:00 p.m. to 5:00 p.m. – Breakout Report
    - Pete Beckman, Argonne National Laboratory
    - Chaitan Baru, San Diego Supercomputer Center
    - Bronis de Supinski, Lawrence Livermore National Laboratory
    - Joel Saltz, Stony Brook University
  
  o 5:00 p.m. to 5:30 p.m. – Future Planning
### A.2.3 BDEC Fukuoka White Papers

A.3  BDEC Barcelona, 2015

A.3.1  BDEC Barcelona Attendees
James Ahrens (Los Alamos National Laboratory)
Jean-Claude Andre (Jca Consultance & Analyse)
Gabriel Antoniu (INRIA)
Mark Asch (Ministry of Higher Education and Research)
Eduard Ayguade (Barcelona Supercomputing Center)
Rosa Badia (Barcelona Supercomputing Center)
Pete Beckman (Argonne National Laboratory)
Ramón Beivide (Barcelona Supercomputing Center)
Jean-Yves Berthou (French National Research Agency)
Thierry Bidot (European Exascale Software Initiative (EESI))
Mathis Bode (RWTH Aachen University)
Francois Bodin (Institute for Research in Computer Science and Random Systems)
Augusto Burgueño-Arjona (European Commission / DG Connect)
Franck Cappello (Argonne National Laboratory / University of Illinois)
Marc Casas (Barcelona Supercomputing Center)
Alok Choudhary (Northwestern University)
Toni Cortes (Barcelona Supercomputing Center)
Sam Crawford (University of Tennessee)
Fernando Cucchietti (Barcelona Supercomputing Center)
Bronis de Supinski (Lawrence Livermore National Laboratory)
Ewa Deelman (University of Southern California Information Sciences Institute)
Jack Dongarra (University of Tennessee)
Sudip Dosanjh (Lawrence Berkeley National Laboratory)
Anshu Dubey (Lawrence Berkeley National Laboratory)
Iain Duff (UK Science & Technology Facilities Council)
Toshio Endo (Tokyo Institute of Technology)
Giovanni Erbacci (CINECA)
Hugo Falter (ParTec Cluster Competence Center)
Geoffrey Fox (Indiana University)
Fabrizio Gagliardi (Barcelona Supercomputing Center)
Adriano Galano (Fujitsu)
Al Geist (Oak Ridge National Laboratory)
Françoise Genova (Strasbourg Astronomical Data Centre)
Sergi Girona (Partnership for Advanced Computing in Europe / Barcelona Supercomputing Center)
Ramon Goni (Barcelona Supercomputing Center)
Jean Gonnord (Atomic Energy and Alternative Energies Commission (CEA))
William Gropp (University of Illinois)
Michael Heroux (Sandia National Laboratories)
Herbert Huber (Leibniz Supercomputing Centre)
Yutaka Ishikawa (RIKEN Advanced Institute for Computational Science)
Takeshi Iwashita (Hokkaido University)
Kate Keahey (Argonne National Laboratory)
Alison Kennedy (EPCC)
David Keyes (King Abdullah University of Science and Technology (KAUST))
Jamie Kinney (Amazon)
Bastian Koller (High Performance Computing Center Stuttgart)
Masaaki Kondo (University of Tokyo)
William Kramer (National Center for Supercomputing Applications / University of Illinois)
Stefan Krieg (Jülich Supercomputing Centre)
Jesus Labarta (Barcelona Supercomputing Center)
Jean-Francois Lavignon (Bull)
Bryan Lawrence (National Centre for Atmospheric Science)
Jysoo Lee (Korean Institute of Science and Technology Information)
Yutong Lu (National University of Defense Technology)
Filippo Mantovani (Barcelona Supercomputing Center)
Naoya Maruyama (RIKEN Advanced Institute for Computational Science)
Satoshi Matsuoka (Tokyo Institute of Technology)
Piyush Mehrotra (NASA Ames Research Center)
Marek Michalewicz (Agency for Science, Technology, and Research (A*STAR))
Peter Michielse (SURFsara)
Takemasa Miyoshi (RIKEN Advanced Institute for Computational Science)
Bernd Mohr (Jülich Supercomputing Centre)
Terry Moore (University of Tennessee)
Carlos Morais-Pires (European Commission)
Miquel Moretó (Barcelona Supercomputing Center)
Malcolm Muggeridge (Seagate Technology, LLC)
Wolfgang Nagel (TU Dresden ZIH)
Hidemoto Nakada (National Institute of Advanced Industrial Science and Technology)
Kengo Nakajima (University of Tokyo)
Hiroshi Nakashima (Kyoto University)
Jean-Philippe Nomine (Atomic Energy and Alternative Energies Commission (CEA))
Modesto Orozco (Barcelona Supercomputing Center)
Mark Parsons (EPCC)
Stan Posey (NVIDIA)
Jeremy Purches (NVIDIA)
Irene Qualters (National Science Foundation)
Anna Queralt (Barcelona Supercomputing Center)
Tracy Rafferty (University of Tennessee)
Dan Reed (University of Iowa)
Stephane Requena (Grand équipement national de calcul intensif (GENCI))
Alejandro Ribés (Électricité de France)
Philippe Ricoux (Total SA)
Morris Riedel (Jülich Supercomputing Centre)
Catherine Riviere (Grand équipement national de calcul intensif (GENCI))
Joel Saltz (Stony Brook University)
Hitoshi Sato (Tokyo Institute of Technology)
Marie-Christine Sawley (Intel)
Estela Suárez (Forschungszentrum Jülich)
Francesc Subirada (Barcelona Supercomputing Center)
Martin Swany (Indiana University)
Alex Szalay (Johns Hopkins University)
William Tang (Princeton University / Princeton Plasma Physics Lab)
Jordi Torres (Barcelona Supercomputing Center)
Panagiotis Tsarchopoulos (European Commission)
Akira Ukawa (RIKEN Advanced Institute for Computational Science)
Osman Unsal (Barcelona Supercomputing Center)
Patrick Valduriez (INRIA)
Mateo Valero (Barcelona Supercomputing Center)
Wim Vanroose (University of Antwerp)
Pier Luigi Vidale (University of Reading)
Vladimir Voevodin (Moscow State University Research Computing Center)
Dengping Wei (National University of Defense Technology)
Marcus Wilms (DFG)
Robert Wisniewski (Intel)
Ramin Yahyapour (GWDG)
A.3.2 BDEC Barcelona Agenda  
Wednesday, January 28  

- 6:30 p.m.– Welcome Reception & Registration  

Thursday, January 29  

- Session 1 – Regional Vision and Strategy  
  
  o 9:20 a.m. to 9:40 a.m. – EU Overview  
    ▪ Augusto Burgueño-Arjona, European Commission  
  
  o 9:40 a.m. to 9:50 a.m. – EU HPC Roadmap and the EXDCI Initiative  
    ▪ Sergi Girona, Partnership for Advanced Computing in Europe  
    ▪ Francois Bodin, Institute for Research in Computer Science and Random Systems  
    ▪ [http://www.exascale.org/bdec/sites/www.exascale.org.bdec/files/3-EXDCI@BDEC.pdf](http://www.exascale.org/bdec/sites/www.exascale.org.bdec/files/3-EXDCI@BDEC.pdf)  
  
  o 9:50 a.m. to 10:05 a.m. – NSF Overview  
    ▪ Irene Qualters, National Science Foundation  
  
  o 10:05 a.m. to 10:20 a.m. – DOE Overview  
    ▪ William Harrod, United States Department of Energy  
  
  o 10:20 a.m. to 10:35 a.m. – Japan Overview  
    ▪ Satoshi Matsuoka, Tokyo Institute of Technology  
  
  o 10:35 a.m. to 10:50 a.m. – China Overview  
    ▪ Yutong Lu, National University of Defense Technology  
  
  o 10:50 a.m. to 10:55 a.m. – Korea Overview  
    ▪ Jysoo Lee, Korean Institute of Science and Technology Information  
  
  o 10:55 a.m. to 11:00 a.m. – Singapore Overview  
    ▪ Marek Michalewicz, Agency for Science, Technology, and Research (A*STAR)
- 11:00 a.m. to 11:30 a.m. – Break

- **Session 2 – White Papers on HPC Software and Infrastructure**
  - 11:30 a.m. to 11:40 a.m. – RoMoL: Riding on Moore’s Law
    - Mateo Valero, Barcelona Supercomputing Center
  - 11:40 a.m. to 11:50 a.m. – The Role of Scientific Workflows in Bridging Big Data and Extreme Scale Computing
    - Ewa Deelman, University of Southern California Information Sciences Institute
  - 11:50 a.m. to 12:00 p.m. – Execution Environments for Big Data: Challenges for User Centric Scenarios
    - Wolfgang E. Nagel, TU Dresden ZIH
  - 12:00 p.m. to 12:10 p.m. – A Case For Investing in Software Architectures and Framework Research
    - Anshu Dubey, Lawrence Berkeley National Laboratory
  - 12:10 p.m. to 12:20 p.m. – LRZ’s Position in European Supercomputing
    - Herbert Huber, Leibniz Supercomputing Centre
  - 12:20 p.m. to 12:30 p.m. – Power Management Framework for Extreme-Scale Computing
    - Masaaki Kondo, University of Tokyo
  - Q&A for Session 2

- **Session 3 – White Papers on HPC and Big Data Applications**
  - 12:30 p.m. to 12:40 p.m. – Two Remarks on Future Developments of Climate Simulation, with Strong Impact on Computing and Data Processing
    - Jean-Claude Andre, Jca Consultance & Analyse
  - 12:40 p.m. to 12:50 p.m. – Ogres: A Systematic Approach to Big Data Benchmarks
    - Geoffrey Fox, Indiana University
  - 12:50 p.m. to 1:00 p.m. – Data and Next Generation Scalable Applications
    - Michael Heroux, Sandia National Laboratories
• 1:00 p.m. to 1:10 p.m.– In-situ Analysis and Visualization of Ensemble Data Sets: the case of Fluid Dynamics Simulations in Energy Production
  ▪ Alejandro Ribés, Électricité de France
• 1:10 p.m. to 1:20 p.m.– Finding Regularity in Irregularities
  ▪ Hiroshi Nakashima, Kyoto University
• 1:20 p.m. to 1:30 p.m.– Data Analytics, Sensor Data, Simulation, and Cancer Research
  ▪ Joel Saltz, Stony Brook University
• Q&A for Session 3

• 1:30 to 2:30 p.m. – Lunch Break

• Breakout Sessions
  
  o 2:30 p.m. to 2:45 p.m.– Introduction to Breakout Sessions
  
  o 2:45 p.m. to 4:45 p.m.– Breakout Sessions
  ▪ Room 6: Applications and Science
  ▪ Room 8: Algorithms and Applied Math
  ▪ Room 7: Architecture and Operations
  ▪ Room 9: Software Stack

• 4:45 p.m. to 5:15 p.m. – Break

• Breakout Reports
  
  o 5:15 p.m. to 5:20 p.m.– Applications and Science
  
  o 5:20 p.m. to 5:25 p.m.– Algorithms and Applied Math
  
  o 5:25 p.m. to 5:30 p.m.– Architecture and Operations
  
  o 5:30 p.m. to 5:35 p.m.– Software Stack

• 8:00 p.m.– Evening Banquet

Friday, January 30

• Session 4 – Keynotes
  
  o 9:00 a.m. to 9:20 a.m. – Big Data Meets HPC
• Dan Reed, University of Iowa
  o 9:20 a.m. to 9:40 a.m. – Data-intensive HPC: Opportunities and Challenges
    ▪ Patrick Valduriez, INRIA
  o 9:40 a.m. to 10:00 a.m. – The Post-K Project and its Big Data Aspects
    ▪ Yutaka Ishikawa, RIKEN Advanced Institute for Computational Science

- Session 5 – White Papers on HPC Software and Infrastructure
  o 10:00 a.m. to 10:10 a.m. – DataClay: Towards Usable and Shareable Storage
    ▪ Toni Cortes, Barcelona Supercomputing Center
  o 10:10 a.m. to 10:20 a.m. – Supercomputers at Exascale: BigData and Extreme Computing of the Total Monitoring
    ▪ Vladimir Voevodin, Moscow State University Research Computing Center
  o 10:20 a.m. to 10:30 a.m. – Chameleon: A Large-Scale, Reconfigurable Experimental Environment for Cloud Research
    ▪ Kate Keahey, Argonne National Laboratory
  o 10:30 a.m. to 10:40 a.m. – Percipient Storage: A Storage Centric Approach to BDEC
    ▪ Malcolm Muggeridge, Seagate Technology, LLC
  o 10:40 a.m. to 10:50 a.m. – Accelerating Time to Insight in the Exascale Ecosystem Through the Optimization of Scientific Workflows
    ▪ James Ahrens, Los Alamos National Laboratory
  o 10:50 a.m. to 11:00 a.m. – Dataflow-centric Warehouse-scale Computing
    ▪ Hidemoto Nakada, National Institute of Advanced Industrial Science and Technology
  o Q&A for Session 5

• 11:00 a.m. to 11:30 a.m. – Break

• Session 6 – White Papers on Applied Mathematics/Algorithms
  o 11:30 a.m. to 11:40 a.m. – Writing Efficient Computational Workflows in Python
    ▪ Rosa M. Badia, Barcelona Supercomputing Center
- 11:40 a.m. to 11:50 a.m. – Numerical Libraries and Software Framework for Application Programs in the Post Peta Era
  - Takeshi Iwashita, Hokkaido University
- 11:50 a.m. to 12:00 p.m.– Using Data Analytics to Detect Corruptions in Numerical Simulations on Potentially Unreliable Environments
  - Franck Cappello, Argonne National Laboratory
- 12:00 p.m. to 12:10 p.m.– Bringing Compute to the Data
  - Bryan Lawrence, National Centre for Atmospheric Science
- 12:10 p.m. to 12:20 p.m.– Optimization of Serial and Parallel Communications Towards Scalable Algorithms on Supercomputers in Next Generation
  - Kengo Nakajima, University of Tokyo
- 12:20 p.m. to 12:30 p.m.– Scaling Resiliency and Analysis Via Machine Learning
  - Alok Choudhary, Northwestern University
- Q&A for Session 6

- **Breakout Sessions**
  - 12:30 to 4:00 p.m.– Breakout Sessions
    - Room 6: Applications and Science
    - Room 8: Algorithms and Applied Math
    - Room 7: Architecture and Operations
    - Room 9: Software Stack

- **1:30 p.m. to 2:30 p.m.– Lunch Break**

- **Breakout Reports**
  - 4:00 p.m. to 4:15 p.m.– Applications and Science
  - 4:15 p.m. to 4:30 p.m.– Algorithms and Applied Math
  - 4:30 p.m. to 4:45 p.m.– Architecture and Operations
  - 4:45 p.m. to 5:00 p.m.– Software Stack
• **Concluding Remarks**
  
  o BDEC Steering Committee
**A3.3 BDEC Barcelona White Papers**

A.4 BDEC Frankfurt, 2016

A.4.1 BDEC Frankfurt Attendees

James Ahrens (Los Alamos National Laboratory)
Jean-Michel Alimi (Observatoire de Paris)
Giovanni Aloisio (Euro-Mediterranean Center on Climate Change / University of Salento)
Jean-Claude Andre (Jca Consultance & Analyse)
Gabriel Antoniu (INRIA)
Mark Asch (University of Picardy Jules Verne)
Edouard Audit (Atomic Energy and Alternative Energies Commission [CEA])
Rosa Badia Sala (Barcelona Supercomputing Center)
Peter Beckman (Argonne National Laboratory)
Costas Bekas (IBM Research)
Francesco Benincasa (Barcelona Supercomputing Center)
Thierry Bidot (Néovia Innovation)
Mathis Bode (RWTH Aachen University)
Francois Bodin (University of Rennes 1)
Taisuke Boku (University of Tsukuba)
Christophe Calvin (Atomic Energy and Alternative Energies Commission [CEA])
Franck Cappello (Argonne National Laboratory)
Marc Casas (Barcelona Supercomputing Center)
Barbara Chapman (Stony Brook University)
Susumu Date (Osaka University)
Bronis de Supinski (Lawrence Livermore National Laboratory)
Ewa Deelman (University of Southern California Information Sciences Institute)
Jack Dongarra (University of Tennessee)
Sudip Dosanjh (Lawrence Berkeley National Laboratory)
Anshu Dubey (Argonne National Laboratory)
Giovanni Erbacci (CINECA)
Hugo Falter (ParTec Cluster Competence Center)
Sandro Fiore (Euro-Mediterranean Center on Climate Change / University of Salento)
Geoffrey Fox (Indiana University)
Fabrizio Gagliardi (Barcelona Supercomputing Center)
Adriano Galano (Fujitsu)
Sergio Girona (Barcelona Supercomputing Center)
Jean Gonnot (Atomic Energy and Alternative Energies Commission [CEA])
Jim Harrell (Cray)
William Harrod (United States Department of Energy)
Michael Heroux (Sandia National Laboratories)
Vasant Honavar (Pennsylvania State University)
Hans-Christian Hoppe (Intel)
Yutaka Ishikawa (RIKEN Advanced Institute for Computational Science)
Takeshi Iwashita (Hokkaido University)
Kate Keahey (Argonne National Laboratory)
Alison Kennedy (Partnership for Advanced Computing in Europe)
Jamie Kinney (Amazon)
Masaaki Kondo (University of Tokyo)
Tomohiro Kudoh (National Institute of Advanced Industrial Science and Technology)
Jesus Labarta (Barcelona Supercomputing Center)
Jean-Francois Lavignon (Bull / Atos)
Jysoo Lee Korean (Institute of Science and Technology Information)
Corentin Lefevre (Néovia Innovation)
Barney Macabe (Oak Ridge National Laboratory)
Michael Malms (IBM Research)
Satoshi Matsuoka (Tokyo Institute of Technology)
Piyush Mehrotra (NASA Ames Research Center)
Marek Michalewicz (Agency for Science, Technology, and Research [A*STAR])
Bernd Mohr (Jülich Supercomputing Centre)
Terry Moore (University of Tennessee)
Malcolm Muggeridge (Seagate Technology, LLC)
Kengo Nakajima (University of Tokyo)
Hiroshi Nakashima (Kyoto University)
Jean-Philippe Nomine (Atomic Energy and Alternative Energies Commission [CEA])
Marcin Ostasz (Barcelona Supercomputing Center)
Tracy Rafferty (University of Tennessee)
Rajiv Ramnath (National Science Foundation)
Dan Reed (University of Iowa)
Joel Saltz (Stony Brook University)
Mitsuhisa Sato (RIKEN Advanced Institute for Computational Science / University of Tsukuba)
Thomas Schulthess (ETH Zurich / Swiss National Supercomputing Centre)
Satoshi Sekiguchi (National Institute of Advanced Industrial Science and Technology)
Xuanhua Shi Huazhong University Of Science And Technology)
Rick Stevens (Argonne National Laboratory)
Martin Swany (Indiana University)
Alex Szalay (Johns Hopkins University)
Osamu Tatebe (University of Tsukuba)
Rajeev Thakur (Argonne National Laboratory)
Panagiotis Tsarchopoulos (European Commission)
Junichi Tsujii (AIST)
Akira Ukawa (RIKEN Advanced Institute for Computational Science)
Jean-Pierre Vilotte (Paris Institute of Earth Physics)
Robert Wisniewski (Intel)
Kathy Yelick (Lawrence Berkeley National Laboratory)
Rio Yokota (Tokyo Institute of Technology)
Igor Zacharov (Eurotech)
A.4.2 BDEC Frankfurt Agenda
Wednesday, June 15

- 6:00 p.m. to 8:00 p.m. – Reception and Registration

Thursday, June 16

- Introduction and Keynotes
  - 9:00 a.m. to 9:15 a.m. – Welcome, Overview and Goals of the Meeting
    - Sergio Girona, Barcelona Supercomputing Center
    - Mark Asch, University of Picardy Jules Verne
  - 9:15 a.m. to 9:45 a.m. – Keynote #1
    - Vasant Honavar, Pennsylvania State University
  - 9:45 a.m. to 10:15 a.m. – Numerical Laboratories on Exascale
    - Alex Szalay, Johns Hopkins University
  - 10:15 a.m. to 10:45 a.m. – AI Platform and Challenges: Perspectives from AI Research Center (AIRC)
    - Junichi Tsujii, AIST

- 10:45 a.m. to 11:15 a.m. – Coffee Break

- BDEC Pathways to Convergence – Flashes
  - 11:15 a.m. to 1:00 p.m. – White Paper Presentations (Session 1)
    - Using an LWK in a Multi-Kernel Environment to Improve Containers
      - Balazs Gerofi, Yutaka Ishikawa, Rolf Riesen, Robert Wisniewski
      - Presented by Robert Wisniewski
    - OpenHPC: a Collaborative Environment for Development of a Cohesive Comprehensive HPC Software Stack Suitable for Cloud Integration
      - Robert Wisniewski
    - Pathways to Convergence
      - Osamu Tatebe
    - Integrative Multi-Scale Imaging, Simulation and Precision Cancer Therapy
      - Joel Saltz
    - Toward the Converge of In-Situ Data Analysis and Deep-Learning Methods for Efficient Pre/Post Processing of Pertinent Structure Among Massive Amount of Scientific Data
• Sandro Fiore, Giovanni Aloisio, Philippe Ricoux, S. Brun, Jean-Michel Alimi, Mathis Bode, R. Apostolov, Stephane Requena
• Presented by Jean-Michel Alimi

Names Matter: Eliminate the False Dichotomy Between Big Data and HPC
• Dan Reed

Framework for Development of Data-Movement Centric Applications
• Kengo Nakajima

Merging Big Data and HPC for Large-scale Analysis/Analytics at the NASA Advanced Supercomputing (NAS) Division
• Piyush Mehrotra

• 1:00 p.m. to 2:00 p.m. – Lunch Break

• Pathways to Convergence
  o 2:00 p.m. to 4:00 p.m. – White Paper Presentations (Session 2)
    ▪ Why convergence? A contrarian view and a path to convergence enabling specialization
      • Barney Maccabe
    ▪ Current Status and Future Prospects of Optical Communications Technology and Possible Impact on Future BDEC Systems
      • Tomohiro Kudoh, Kiyo Ishii, Shu Namiki
      • Presented by Tomohiro Kudoh
      • Takeshi Iwashita
    ▪ Big Data, Simulations and HPC Convergence
      • Geoffrey Fox, Judy Qiu, Shantenu Jha, Supun Kamburugamuve, Saliya Ekanayake
      • Presented by: Geoffrey Fox
    ▪ Big Data Analytics and High Performance Computing Convergence Through Workflows and Virtualization
      • Ewa Deelman
- Scalable Compression as a Fundamental Pattern for HPC–Big Data Convergence
  - Franck Cappello, Sheng Di
  - Presented by: Franck Cappello

- On-Demand Data Analytics and Storage for Extreme-Scale Simulations and Experiments
  - Presented by Franck Cappello

- Big Data for Climate and Air Quality
  - Pierre-Antoine Bretonnière, Francesco Benincasa, Francisco Doblas-Reyes, Kim Serradell
  - Presented by Francesco Benincasa

- Enablement of Multi-Scale Simulation, Analytics and Visualization Workflows
  - Marc Casas, Miquel Moretó, Rosa Badia Sala, Raul Sirvent, Eduard Ayguade, Jesus Labarta, Mateo Valero
  - Presented by Rosa Badia

- Toward Large Scale Distributed Experiments for Climate Change Data Analytics in the Earth System Grid Federation (ESGF) Eco-System
  - Sandro Fiore, Dean Williams, Valentine Anantharaj, Sylvie Joussamme, Davide Salomoni, Stephane Requena, Giovanni Aloisio
  - Presented by Sandro Fiore

- SAGE: Percipient Storage for Exascale Data Centric Computing
  - Malcolm Muggeridge, Sai Narasimhamurthy
  - Presented by Malcolm Muggeridge

- Data Intensive and High Performance Computing: The View from High Energy Physics
  - Anshu Dubey, Salman Habib
- CEA: Connecting Co-design Capabilities with the Operation of Large HPC and Data Processing Facilities
  - Edouard Audit, Christophe Calvin, Jean Gonnord, Jacques-Charles Lafoucrière, Jean-Philippe Nomine
  - Presented by Edouard Audit

- 4:00 p.m. to 4:30 p.m. Coffee Break

- Breakout Groups
  - 4:30 p.m. to 4:50 p.m. – Pathways to Convergence: Where do we go from here?
    - Jack Dongarra, University of Tennessee
    - Peter Beckman, Argonne National Laboratory
    - Terry Moore, University of Tennessee
  - 4:50 p.m. to 6:30 p.m. – Breakouts on Pathways

- 8:00 p.m. – Dinner

Friday, June 17

- Roadmaps and Overviews
  - 9:00 a.m. to 9:30 a.m. – Convergence: What it Means to Me
    - Rick Stevens, Argonne National Laboratory
  - 9:30 a.m. to 9:50 a.m. – EU Overview
    - Jean Gonnord, Atomic Energy and Alternative Energies Commission (CEA)
  - 9:50 a.m. to 10:10 a.m. – USA-NSF Overview
    - Rajiv Ramnath, National Science Foundation
  - 10:10 a.m. to 10:30 a.m. – Japan Overview
    - Yutaka Ishikawa, RIKEN Advanced Institute for Computational Science
    - Satoshi Matsuoka, Tokyo Institute of Technology
  - 10:30 a.m. to 11:00 a.m. – China Big Data and HPC Initiatives Overview
    - Xuanhua Shi, Huazhong University Of Science And Technology
  - 11:00 a.m. to 11:30 a.m. – Data and Data-intensive computing challenges in Earth and Universe Sciences
    - Jean-Pierre Vilotte, Paris Institute of Earth Physics
- 11:30 a.m. to 12:15 p.m. – Breakout Review and Reporting

- 12:15 p.m. to 1:30 p.m. – Lunch Break

- Keynotes 2
  - 1:30 p.m. to 2:00 p.m. – Keynote #5
    - Gabriel Antoniu, INRIA

- Breakout Groups 2
  - 2:00 p.m. to 4:00 p.m. – Breakouts on Pathways and Reporting

- 4:00 p.m. to 4:30 p.m. – Coffee Break

- Breakout Reports and Closing
  - 4:30 p.m. to 5:30 p.m. – Breakout Reports
  - 5:30 p.m. to 5:45 p.m. – Conclusion and Next Steps
A.4.3 BDEC Frankfurt White Papers


A.5  BDEC Wuxi, 2017

A.5.1  BDEC Wuxi Attendees
Jean-Claude Andre (Jca Consultance & Analyse)
Mark Asch (University of Picardy Jules Verne)
Rosa Badia Sala (Barcelona Supercomputing Center)
Pete Beckman (Argonne National Laboratory)
Thierry Bidot (Néovia Innovation)
Francois Bodin (University of Rennes 1)
Franck Cappello (Argonne National Laboratory)
Alok Choudhary (Northwestern University)
Ewa Deelman (University of Southern California Information Sciences Institute)
Jack Dongarra (University of Tennessee)
Anshu Dubey (Argonne National Laboratory)
Tarek El-Ghazawi (The George Washington University)
Hugo Falter (ParTec Cluster Competence Center)
Geoffrey Fox (Indiana University)
Haohuan Fu (National Supercomputing Center in Wuxi)
Balazs Gerofi (RIKEN Advanced Institute for Computational Science)
Judit Gimenez Lucas (Barcelona Supercomputing Center)
Sergio Girona (Barcelona Supercomputing Center)
William Gropp (National Center for Supercomputing Applications)
Yutaka Ishikawa (RIKEN Advanced Institute for Computational Science)
Kate Keahey (Argonne National Laboratory)
Katarzyna Keahey (Argonne National Laboratory)
David Keyes (King Abdullah University of Science and Technology / Columbia University)
William Kramer (National Center for Supercomputing Applications / University of Illinois)
Jean-Francois Lavignon (Bull / Atos)
Miron Livny (University of Wisconsin-Madison)
Satoshi Matsuoka (Tokyo Institute of Technology)
Takemasa Miyoshi (RIKEN Advanced Institute for Computational Science)
Terry Moore (University of Tennessee)
Jean-Pierre Panziera (Bull / Atos)
Depei Qian (Jiaotong University)
Tracy Rafferty (University of Tennessee)
Robert Ross (Argonne National Laboratory)
Hitoshi Sato (National Institute of Advanced Industrial Science and Technology)
Thomas Schulthess (ETH Zurich / Swiss National Supercomputing Centre)
Rick Stevens (Argonne National Laboratory)
Martin Swany (Indiana University)
Sandor Szalay (Johns Hopkins University)
William Tang (Princeton University / Princeton Plasma Physics Lab)
Gael Varoquaux (INRIA)
Jean-Pierre Vilotte (Paris Institute of Earth Physics)
Robert Wisniewski (Intel)
Zhiwei Xu (Institute of Computing Technology, Chinese Academy of Sciences)
Watson Yin (Baidu)
Ya-qin Zhang (Baidu)
A.5.2 BDEC Wuxi Agenda

Wednesday, March 8

- 7:00 p.m. – Reception at the Grand Kingtown Hotel Wuxi

Thursday, March 9

- Welcome & Keynotes
  - 8:20 a.m. to 8:30 a.m. – Intro & Welcome
    - Jack Dongarra, University of Tennessee
    - Pete Beckman, Argonne National Laboratory
  - 8:30 a.m. to 8:50 a.m. – Keynote
    - Watson Yin, Baidu
  - 8:50 a.m. to 9:15 a.m. – Keynote
    - Zhiwei Xu, Institute of Computing Technology, Chinese Academy of Sciences
  - 9:15 a.m. to 9:45 a.m. – Keynote
    - Rick Stevens, Argonne National Laboratory

- Overviews
  - 9:45 a.m. to 10:00 a.m. – China Overview
    - Haohuan Fu, National Supercomputing Center in Wuxi
  - 10:00 a.m. to 10:15 a.m. – United States Overview
    - Robert Ross, Argonne National Laboratory
  - 10:15 a.m. to 10:30 a.m. – European Union Overview
    - Jean-Pierre Panzier, Bull
    - Sergio Girona, Barcelona Supercomputing Center
  - 10:30 a.m. to 10:45 a.m. – Japan Overview
    - Satoshi Matsuoka, Tokyo Institute of Technology
  - 10:45 a.m. to 11:00 a.m. – Overview of Pathways Document and Intro to Breakouts

- 11:00 a.m. to 11:15 a.m. – Break
• 11:15 a.m. to 12:30 p.m. – First Breakout Session
  o HPC/Cloud/Datacenter
    ▪ Facilitator/Scribes: Satoshi Matsuoka, Kate Keahey, Thomas Schulthess
  o Data Workflows and Edge Computing
    ▪ Facilitator/Scribes: Ewa Deelman, Gabriel Antoniu, Geoffrey Fox
  o Applications/Algorithms
    ▪ Facilitator/Scribes: David Keyes, Jean-Pierre Vilotte, Anshu Dubey

• 12:30 p.m. to 1:30 p.m. – Lunch Break

• Afternoon Sessions
  o 1:30 p.m. to 2:00 p.m. – Keynote
    ▪ Takemasa Miyoshi, RIKEN Advanced Institute for Computational Science
  o 2:00 p.m. to 2:15 p.m. – NSF and Extreme Scale
    ▪ William Gropp, National Center for Supercomputing Applications

• 2:15 p.m. to 3:45 p.m. – Second Breakout Session
  o HPC/Cloud/Datacenter
    ▪ Facilitator/Scribes: Satoshi Matsuoka, Kate Keahey, Thomas Schulthess
  o Data Workflows and Edge Computing
    ▪ Facilitator/Scribes: Ewa Deelman, Gabriel Antoniu, Geoffrey Fox
  o Applications/Algorithms
    ▪ Facilitator/Scribes: David Keyes, Jean-Pierre Vilotte, Anshu Dubey

• Breakout Reports
  o 3:45 p.m. to 4:15 p.m. – Breakout Reports and Synthesis of Document Status

• 4:15 p.m. – Tour of Supercomputer Center

• 5:00 p.m. – Banquet

Friday, March 10

• Keynotes
  o 8:30 a.m. to 9:00 a.m. – Keynote
    ▪ Thomas Schulthess, ETH Zurich
  o 9:00 a.m. to 9:30 a.m. – Keynote
    ▪ Gael Varoquaux, INRIA
• **9:30 a.m. to 11:30 a.m. – Third Breakout Session**
  o HPC/Cloud/Datacenter
    ▪ Facilitator/Scribes: Satoshi Matsuoka, Kate Keahey, Thomas Schulthess
  o Data Workflows and Edge Computing
    ▪ Facilitator/Scribes: Ewa Deelman, Gabriel Antoniu, Geoffrey Fox
  o Applications/Algorithms
    ▪ Facilitator/Scribes: David Keyes, Jean-Pierre Vilotte, Anshu Dubey

• **11:30 a.m. to 12:30 p.m. – Lunch**

• **12:30 p.m. to 2:30 p.m. – Fourth Breakout Session**
  o HPC/Cloud/Datacenter
    ▪ Facilitator/Scribes: Satoshi Matsuoka, Kate Keahey, Thomas Schulthess
  o Data Workflows and Edge Computing
    ▪ Facilitator/Scribes: Ewa Deelman, Gabriel Antoniu, Geoffrey Fox
  o Applications/Algorithms
    ▪ Facilitator/Scribes: David Keyes, Jean-Pierre Vilotte, Anshu Dubey

• **Breakout Reports**
  o 2:30 p.m. to 3:30 p.m. – Reports from Breakouts, Document Synthesis and Next Steps