Grid Technologies & Applications: Architecture & Achievements

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Abstract. The years 2000 and 2001 have seen significant advances in Grid computing. While in early 2000, Grid computing was a novel concept that most scientists were being exposed to for the first time, we now see considerable consensus on Grid architecture, a solid and widely adopted technology base, major funding initiatives, a wide variety of projects developing applications and technologies, and major deployment projects aimed at creating robust Grid infrastructures. I provide a summary of major developments and trends, focusing on the Globus open source Grid software project and the GriPhyN data grid project.

1. Introduction

The term "Grid" was coined to denote a proposed distributed "cyberinfrastructure" for advanced science and engineering (Foster 1999). The term is now understood to refer to technologies and infrastructure that enable *coordinated resource sharing and problem solving in dynamic, multi-institutional virtual organizations*. This sharing relates primarily to direct access to computers, software, data, and other resources, as is required by a range of collaborative problem-solving and resource-brokering strategies emerging in industry, science, and engineering. This sharing is, necessarily, highly controlled, with resource providers and consumers defining clearly and carefully just what is shared, who is allowed to share, and the conditions under which sharing occurs. A set of individuals and/or institutions defined by such sharing rules form a *virtual organization* (VO).

Grid concepts are particularly relevant to high energy physics (HEP) and astronomy due to the collaborative nature of HEP experiments and astronomical observations and the increasing complexity of data analysis tasks, and hence a need for next-generation experiments and instruments to exploit large distributed collections of shared resources. We thus see considerable interest in the creation of so-called *Data Grids*, i.e., Grid infrastructures, tools, and applica-

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tions designed to enable distributed access to, and analysis of, large amounts of science data.

The broad significance of Grid concepts, in advanced scientific collaborations and in business, means that data-intensive science is just one of a number of communities (albeit a particularly ambitious and important one) that are developing and/or driving Grid technologies. The resulting interrelationships make it important to understand the state of the art and likely future directions in this field. In this paper, I attempt to provide such an understanding.
In order to focus my presentation, I approach this overview from the perspective of two major projects in which I am involved. These two projects address complementary aspects of the Grid problem, with Globus conducting research and development on foundation Grid issues such as security, policy, data management, and resource management, and GriPhyN tackling issues relating specifically to Data Grids, addressing in particular data grid architectural concepts and issues relating to virtual data. Both projects also produce significant software systems, the Globus Toolkit and GriPhyN Virtual Data Toolkit, respectively. Hence, a summary of Globus and GriPhyN activities and their partnerships provide a broad-brush, if not complete, view of Grid computing.

In the following, I review Grid architecture concepts; describe the current state of, and future plans for, the Globus Toolkit; review major Grid projects that are using Globus; and finally describe GriPhyN goals and initial achievements. Other sources provide a survey of Grid concepts and technologies (Foster 1999) and a detailed picture of Grid architecture (Foster 2001b).

2. Grid Architecture

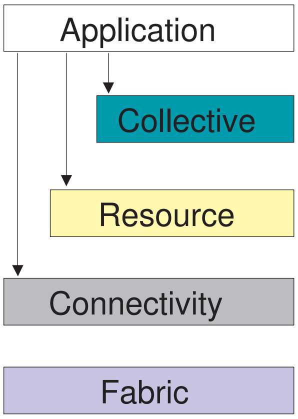

Figure 1. Grid architecture schematic.

Grid technologies comprise protocols, services, and tools that address the challenges that arise when we seek to build scalable VOs. These technologies include security solutions that support management of credentials and policies when computations span multiple institutions; resource management protocols and services that support secure remote access to computing and data resources and the co-allocation of multiple resources; information query protocols and services that provide configuration and status information about resources, organizations, and services; and data management services that locate and transport datasets between storage systems and applications.

Figure 1 illustrates a categorization that we have found useful when explaining the roles played by various Grid technologies. In the *Fabric*, we have the resources that we wish to share: computers, storage systems, data, catalogs, etc. The *Connectivity* layer provides communication and authentication services needed to communicate with these resources. *Resource* protocols (and, as in each layer, associated APIs) negotiate access to individual resources. *Collective* protocols, APIs, and services are concerned with coordinating the use of multiple resources, and finally application toolkits and applications themselves are defined in terms of services of these various kinds. Other papers present views on necessary components of a Grid architecture (Foster 2001b) and the additional services required within a Data Grid architecture (Foster 2001a).

3. The Globus Toolkit

The Globus Toolkit (Foster 1999, Foster 2001b) is a community-based, open-architecture, open-source set of services and software libraries that support Grids and Grid applications. The Toolkit includes software for security, information infrastructure, resource management, data management, communication, fault detection, and portability. It is packaged as a set of components that can be used either independently or together to develop useful Grid applications and programming tools. Globus Toolkit components include the Grid Security Infrastructure (GSI), which provides a single-sign-on, run-anywhere authentication service, with support for delegation of credentials to subcomputations, local control over authorization, and mapping from global to local user identities; the Grid Resource Access and Management (GRAM) protocol and service, which provides remote resource allocation and process creation, monitoring, and management services; the Meta Directory Service (MDS) (Czajkowski 2001), an extensible Grid information service that provides a uniform framework for discovering and accessing system configuration and status information such as compute server configuration, network status, or the locations of replicated datasets. Data Grid-specific technologies include a replica catalog, GridFTP, a high-speed data movement protocol (Allcock 2001), and reliable replica management tools. For each of these components, the Toolkit both defines protocols and APIs and provides open source reference implementations in C and, in most cases, Java. A variety of higher-level services can be, and have been, implemented in terms of these basic components.

3.1. Recent Developments

2001 has seen significant enhancements to the Globus Toolkit in terms of functionality, robustness, flexibility, and performance. I summarize some major developments here. Some are already part of the main Globus release; the rest are slated for release in 2001.

- A major *packaging* thrust, with NCSA, is transforming the (conceptually) modular but (in practice) monolithic Globus software into a modular collection of distinct packages, hence enabling the creation of source and/or binary distributions for different purposes and architectures.
- Significant enhancements to the *Globus information service*, MDS, produced MDS-2.1 (Czajkowski 2001), which in addition to a highly scalable distributed design features integrated GSI security and more efficient information source interface and indexing mechanisms.
- Work at NCSA produced the "MyProxy" *online credential repository*, an important contribution to improved usability of public key infrastructure authentication mechanisms (Welch 2001).
- A collaborative effort with the Condor (Livny 1999) group at U.Wisconsin significantly enhanced the *GRAM protocol* and implementation to improve reliability and ability to recover from failures.
- The Condor group also produced *Condor-G* (Frey 2001), a job management system for Grid computations that combines Condor job management with Globus security and remote job submission.
- Further work on *commodity Grid toolkits* ("CoG Kits") (von Laszewski 2001) at ANL, LBNL, and Rutgers produced improved Java interfaces to Grid services and early versions of Python and CORBA interfaces.
- Alpha releases of our *GridFTP* protocol implementation saw extensive use. GridFTP extends FTP with additional features aimed at high-performance transport (e.g., parallel data sources), flexibility (e.g., partial file transfers), and robustness (e.g., extended restart capabilities).
- A new *replica catalog* service supports registration and discovery of physical copies of logical files and collections. A new *GDMP* (Stockinger 2001) data replication software version uses Globus services.

We also evolved the Globus development process, introducing an external review process for specifications and an alpha-testing program for new software. These changes are part of an ongoing process aimed at creating an effective, scalable open source platform for Grid software.

3.2. Current Developments

An aggressive R&D program at ANL, UChicago, ISI, and other partner institutions is continuing to enhance the capabilities of the Globus Toolkit. Here I mention a few developments underway.

- A *Community Authorization Service* (CAS) will support authorization decisions within large VOs, in which it is desirable to be able to delegate policy decisions concerning who can do what from individual resources and users to community representatives.
- Other work in *security* aims at enhancing significantly the ease of use of security technologies, by for example further enhancements to the online credential repository concept.
- Continued refinements to the *MDS-2 architecture and implementation* will allow its use as an integrating framework for Grid monitoring.
- A next-generation *GRAM-2 protocol* will provide significant enhancements to the robustness and capabilities of GRAM, extending its range of application to other resource types.

- We continue to investigate application of Globus technologies within commodity computing, and expect to propose enhancements to the *Web Services framework* to support Grid applications.

4. The GriPhyN Project

GriPhyN is a large collaboration of information technology (IT) researchers and experimental physicists who aim to provide the IT advances required to enable Petabyte-scale data intensive science in the 21^{st} century (Avery 2001a). Driving the project are unprecedented requirements for geographically dispersed extraction of complex scientific information from large collections of measured data. To meet these requirements, which arise initially from four partner physics experiments (ATLAS, CMS, LIGO and SDSS) but will also be fundamental to science and commerce in the 21^{st} century, the GriPhyN team is pursuing IT advances centered on the creation of *Petascale Virtual Data Grids* (PVDG) that meet the data-intensive computational needs of a diverse community of thousands of scientists spread across the globe.

GriPhyN has adopted the concept of virtual data as a unifying theme for its investigations of Data Grid concepts and technologies. This term is used to refer to two related concepts: transparency with respect to location as a means of improving access performance, with respect to speed and/or reliability, and transparency with respect to materialization, as a means of facilitating the definition, sharing, and use of data derivation mechanisms. In order to realize these concepts, GriPhyN conducts research into virtual data cataloging, execution planning, execution management, and performance analysis issues (see Figure 2). The results of this research, and other relevant technologies, are developed and integrated to form a Virtual Data Toolkit (VDT). Successive VDT releases are applied and evaluated in the context of the four partner experiments.

GriPhyN has been underway just over half a year and after an initial rampup/definition phase has established strong research, development, and application projects. Accomplishments to date include:

- The definition of a Data Grid Reference Architecture, defining requirements and proposing interfaces and implementations for the core components required in a Data Grid system.
- The development, in collaboration with experiments, of requirements documents for virtual data services in each of the partner experiments. E.g., see (Allen 2001, Holtman 2001).
- Successful demonstration of distributed analysis of CMS simulation data using systems at Caltech, U.Wisconsin, and NCSA, with Condor-G used as a computation management system.

Version 1 of the GriPhyN Virtual Data Toolkit, slated for late 2001, will provide packaged, documented, integrated, tested, and supported versions of a core set of Data Grid software, including GridFTP data transfer, replica catalog, Condor-G computation management, and Globus Toolkit security, information, and resource management services. Subsequent versions will provide expanded functionality (e.g., community authorization, scheduling, automated replica selection, request planning), scalability (e.g., number of data, number of resources), and performance.

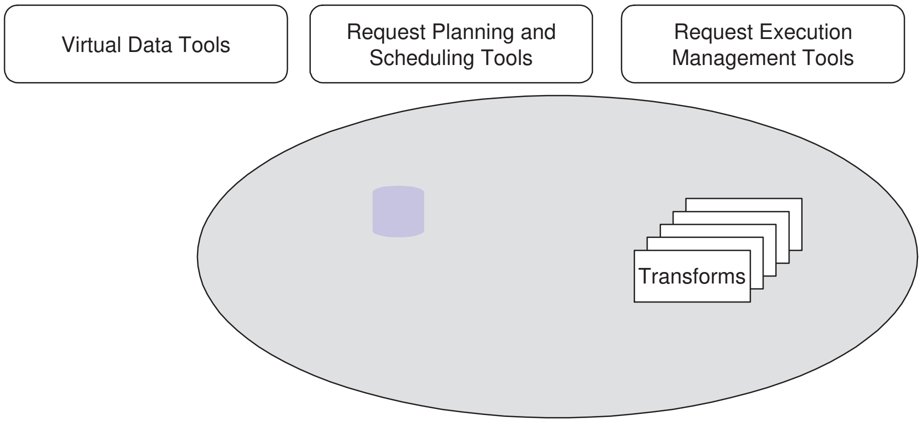

Figure 2. GriPhyN data grid architecture.

5. Grid Deployments and Applications

The last year has seen major Grid projects mature and others emerge as a result of new funding initiatives within the U.S. and E.U. Momentum is also building within Asia-Pacific. The table provides a *far-from-complete* list of projects, selected to emphasize the breadth and depth of the endeavor. Some projects address the creation of Grid technology, some the application of Grid technology, and yet others the deployment of this technology to create "production" Grids. Some are still in the proposal review stage, most are underway. Some URLs were not yet operational at the time of writing. All have adopted Globus software as a significant technology component.

6. Project Coordination and iVDGL

Coordination among various Data Grid projects is vital if we are to avoid replicated effort, profit from hard-won experiences, and achieve interoperable international Grid infrastructures. Coordination is being pursued on several fronts. An international coordination committee involving the various HEP Data Grid projects (EU DataGrid, GriPhyN, PPDG) and representatives of associated physics experiments meets regularly to discuss approaches and opportunities for joint work. The Global Grid Forum (www.gridforum.org) supports information exchange and standards setting. The Globus community also works to encourage communication and common approaches.

Another new initiative will create and operate an International Virtual Data Grid Laboratory (iVDGL) (Avery 2001b) comprising computing and storage resources in the U.S., Europe, Japan, and Brazil—and ultimately other regions—linked by high-speed networks, and operated as a single system for interdisciplinary experimentation in Grid-enabled data-intensive scientific computing. The creation of this laboratory is intended to both drive the development, and transition to every day production use, of Petabyte-scale virtual data applications, and help encourage the adoption of the protocol and policy standards needed for interoperability and large-scale operation.

Initiatives such as iVDGL are possible in part because of advances in national and international networking. National initiatives such as IWIRE, TeraGrid, and Geant will soon provide 10 Gb/s or more. Internationally, STAR-TAP (www.startap.net) in Chicago plays a valuable role as an international interconnection point for research networks. Now, StarLight (www.startap.net/starlight) is providing an interconnection point for optical networks, with already two groups (SURFnet from the Netherlands, and DATATAG from CERN) planning to connect to the U.S. at 2.5 Gb/s.

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Name	URL + Funding Agency	Focus
Access Grid	accessgrid.org DOE, NSF	Create & deploy group collaboration systems using commodity display technologies
Blue Grid	IBM	Grid testbed linking IBM laboratories
DISCOM	www.cs.sandia.gov/ discom; DOE Defense Programs	Create an operational Grid providing access to resources at three U.S. DOE weapons laboratories
DOE Science Grid	sciencegrid.org DOE Office of Science	Create an operational Grid providing access to resources and applications at U.S. DOE science laboratories and partner universities
Earth System Grid (ESG)	earthsystemgrid.org; DOE Office of Science	Delivery and analysis of large climate model datasets for the climate research community.
European Union (EU) DataGrid	eu-datagrid.org European Union	Create & apply an operational grid for applications in high energy physics, environmental science, bioinformatics.
EuroGrid & Grid Interoperability (GRIP)	eurogrid.org European Union	Create & apply technologies for remote access to supercomputer resources and simulation codes; in GRIP, integrate with Globus technologies
Fusion Collaboratory	fusiongrid.org DOE Office of Science	Create a national computational collaboratory for fusion research.
Globus	globus.org DARPA, DOE, NSF, NASA	Research on Grid technologies; development and support of Globus Toolkit; application and deployment.
GridLab	gridlab.org European Union	Grid technologies and applications
GridPP	gridpp.ac.uk U.K. eScience Program	Create and apply an operational grid within the U.K. for particle physics research

Grid Research Integration Development & Support (GRIDS) Center	grids-center.org NSF	Integration, deployment, support of the NSF Middleware Infrastructure for research & education
Grid Application Development Software	hipersoft.rice.edu/grads NSF	Basic research into program development technologies for Grid applications
Grid Physics Network	griphyn.org NSF	Technology R&D for data analysis in physics experiments: ATLAS, CMS, LIGO, SDSS
Information Power Grid	ipg.nasa.gov NASA	Create and apply a production Grid for aerosciences and other NASA missions
International Virtual Data Grid Laboratory (iVDGL)	ivdgl.org NSF	Create international Data Grid to enable large-scale experimentation on Grid technologies & applications
National Virtual Observatory (NVO)	voforum.org NSF	Create and apply production Grids for data analysis in astronomy
Network for Earthquake Eng. Simulation Grid	neesgrid.org NSF	Create and apply a production Grid for earthquake engineering
Particle Physics Data Grid (PPDG)	ppdg.net DOE Office of Science	Create and apply production Grids for data analysis in high energy and nuclear physics experiments
Southern California Earthquake Center 2	scec.org NSF	Full geophysics modeling using Grids and knowledge-based systems
TeraGrid	teragrid.org NSF	U.S. science infrastructure linking four major resource sites at 40 Gb/s
UK Grid Support Center	grid-support.ac.uk U.K. eScience Program	Support center for Grid projects within the U.K.
Unicore	German Government	Technologies for remote access to supercomputers

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