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***Abstract*—We consider the problem of efficiently managing massive data in a large-scale distributed environment. We consider data strings of size in the order of Terabytes, shared and accessed by concurrent clients. On each individual access, a segment of a string, of the order of Megabytes, is read or modified. Our goal is to provide the clients with efficient fine-grain access the data string as concurrently as possible, without locking the string itself. This issue is crucial in the context of applications in the field of astronomy, databases, data mining and multimedia. We illustrate these requiremens with the case of an application for searching supernovae. Our solution relies on distributed, RAM-based data storage, while leveraging a DHT-based, parallel metadata management scheme. The proposed architecture and algorithms have been validated through a software prototype and evaluated in a cluster environment.**

I. Introduction

Large scale data management is becoming increasingly important for a wide range of applications, both scientific and industrial: modeling, astronomy, biology, gouvernamental and industrial statistics, etc. All these applications generate huge amounts of data that need to be stored, processed and eventually archived globally. In order to better illustrate these needs, this paper focuses on a real life astronomy problem: finding supernovae (stellar explosions).

In a typical scenario, a telescope is used to take pictures of the same part of space at regular intervals, usually every month. Corresponding digital images are then compared in an attempt to find variable objects, which might be candidates for supernovae. To confirm that such objects are supernovae, considerable computational effort is necessary in order to distinguish the supernovae themselves from the other variable objects that may be present in the image: this requires to analyze the light curve and spectrum of each potential candidate.

To speed up the process of finding supernovae, multiple parts of space should be analyzed concurrently: as there is no dependency between different regions of space, the analysis itself is an embarrassingly parallel problem. The difficulty lies in the massive amount of data that needs to be managed and made available to the machines providing the computational power.

Huge data size. Hundreds of GB of images from various parts of the sky may correspond to a single point in time. Since the analysis requires multiple consecutive images of the same part of the sky, the order of TB is quickly reached.

Global view. Managing independent images manually is cumbersome. Applications finding supernovae (and not only) are much easier to design if a global view of the sky is available: finding the right image at a given time simply translates into accessing the right part of the sky view for that time. Let us consider a very simple abstraction of this problem, in which the view of the sky is a very long string of bytes (blob), obtained by concatenating the images in binary form. Assuming all images have a fixed size, a specific part of the sky is accessible by providing the corresponding offset in the string. A simple transformation from two-dimensional to unidimensional coordinates is sufficient.

Efficient fine grain access. While many images make up the global view of the sky, each of them needs to be accessed individually. As each image is much smaller than the size of the string representing the sky, fine-grain access to substrings is crucial.

Versioning. As new images are taken by the telescope, the view of the sky needs to be updated, while the previous views of the sky still need to be accessible. It is desirable to refer to views of the sky at particular moments in time, therefore versioning is necessary.

Read-read concurrency. Comparison of images for different parts of the sky is a massively parallel problem. That is, concurrent reads of different images in a view or concurrent reads of the same image in different views should be efficiently processed in parallel.

Read-write concurrency. The telescope may gather and store new pictures (i.e. new versions of some part of the sky) while the analysis proceeds on the previous versions. Consequently, in our model, it is important to allow new versions of our global string to be generated and written while the earlier versions are read and analyzed: read-write concurrency is highly desirable for efficiency.

Write-write concurrency. As multiple telescopes may be available for gathering pictures from different parts of the sky, it is also desirable for the storage system to efficiently support concurrent writes: concurrent substring updates should generate the new corresponding strings in parallel.

Our case study clearly illustrates typical requirements for the more general problem of massive data analysis: storage of massive data, efficient fine grain access to small data sets, snapshoting support. These requirements need to be addressed in a space efficient way (by sharing common parts of snapshots) and in a performance efficient way (by supporting read/read, read/write and write/write concurrency). Such requirements are also exhibited by many other types of applications: databases ([1], [2], [3]), large-scale, continuous data mining ([4]), multimedia ([5]), etc.

To address these requirements, one may rely on scalable distributed file systems, which provide a familiar, file-oriented API allowing to transparently access physically distributed data through globally unique logical file paths. A very large distributed storage space is thus made available to existing applications that usually use file storage, with no need for modifications. This approach has been taken by a few projects like GFS [6], GFarm [7], GridNFS [8], LegionFS [9], etc. Note however that most such approaches are not highly optimized to efficiently support highly-parallel, fine-grain accesses to the same file, especially when some concurrent accesses modify the file. A similar, RAM-based approach is provided by the concept of *grid data-sharing service* [10], illustrated by the JuxMem [11] platform. However, in JuxMem data blocks are not not fragmented, so the largest data block that the service is able to store is limited by the size of the RAM of a *single* node.

In this work, we explore the possibility of simultaneously addressing massive data storage, with efficient fine-grain access optimized for high read-read, read-write and write-write concurrency. As opposed to grid file systems, our service mainly relies on RAM storage. This favors access efficiency, while data persistence can still be provided following the scheme described in [12]. Our paper is organized as follows. Section II restates the specification of the problem in a more formal way. Section III provides an overview of our algorithmic design and precisely describes how data access operations are handled. Concurrency issues are discussed in Section IV. Section V provides a few implementation details and reports on a preliminary experimental evaluation on a multi-site grid testbed. On-going and future work is discussed in Section VI.

II. Specifications

We focus on managing massive binary strings (in the order of TB) in a highly concurrent environment. We introduce two further denominations used throughout this paper: A *page* is any substring whose size is fixed (*pagesize*) and whose offset is a multiple of *pagesize*. A *segment* is any concatenation of consecutive pages. By convention, both the *size* of the strings we manipulate and *pagesize* are powers of 2. We define two primitives to access strings:

$$\text{vw} = \text{WRITE(id, buffer, offset, size)}$$

A WRITE results in *patching* the string identified by *id* with the contents of the local *buffer* of length *size* at the specified *offset*. This generates a new incremental snapshot of the string, identified by its version number: the returned value *vw*. Version numbers are successive integers starting with 0, which is the initial version. (By convention, version 0 is the all-zero string.) The generated snapshot is the view resulting from the successive application of all previous patches (including the current one). At this point, the string version *rw* is said to be *published*. We obviously want that each WRITE will eventually publish its version (*liveness*).

$$\text{vr} = \text{READ(id, v, buffer, offset, size)}$$

A READ results in filling *buffer* with the segment identified by *(offset, size)* of string *id*. This segment is extracted from version *v* if *v* has already been published. The returned value *vr* is then the number of the latest *published* version of the string and $vr \geq v$ holds. If *v* has not yet been published, then the read fails.

Observe that the above conditions guarantee that all non-failing READ operations on the same version *v* and same *offset* and *size* will yield the same substring. This substring is the segment *(offset, size)* which is obtained by successively applying the first *v* patches to the initial string. This ensures that all READ operations “see” the WRITE operations in the same order. Everything happens as if the patches had been applied in the same successive order. This is a variant of *global serializability*.

For completeness, we provide an additional primitive allowing to allocate storage space (ALLOC), which generates a globally unique *id*.

III. Design

Our system is striping-based: the set of *pages* which make up the global binary string is distributed among multiple nodes. *Metadata* defines the association between an access request defined by *(v, offset, size)* and the corresponding set of pages storing the actual data. A WRITE operation generates a new list of *fresh* pages stored on potentially new physical nodes. This way, no page is deleted from the system at that time: the previous version of the pages remain available through READ requests until some garbage collection is ordered by the client. Each page is labeled with the corresponding version number.

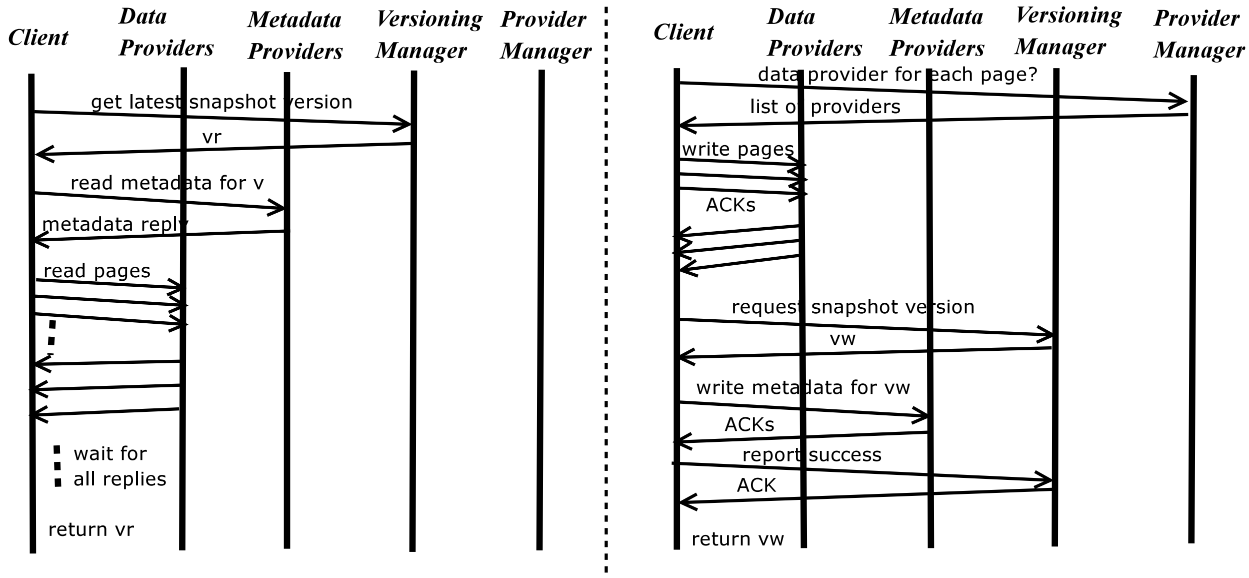


Fig. 1. Interactions between the actors: reads(left) and writes(right)

A. General architecture overview

Five kinds of actors make up the system:

Clients issue READ and WRITE requests. There may be multiple concurrent clients. Their number may dynamically vary in time without notifying the system.

Data providers physically store in their local memory the pages created by the WRITE operations. New data providers may dynamically join the system.

A provider manager keeps a information about the available data providers. On entering the system, each data provider register with the provider manager. On each WRITE request, the provider manager decides which providers should be used to store the newly generated pages, based on some strategy that favors global load balancing.

The metadata provider physically stores the metadata allowing generated when new pages are created by WRITE requests. This entity is queries by clients issuing READ requests, in order to find the pages corresponding to the requested range and version. Note that this can be a distributed entity, based on an off-the-shelf distributed hash table (DHT), which allows efficient concurrent access to metadata.

The version manager is the key actor of the system. It stores the number of the latest published version of a given data string. It is also responsible for serializing WRITE requests to each string, and for supplying READ requests with the latest published string version.

Our service consists of distributed communicating processes. Their interaction is described below. In a typical setting, each process runs on a separate physical node. A node may fulfill a specific role by running a single process, but it may also play multiple roles.

B. How reads and writes work

The interactions between the entities of our architecture are briefly illustrated on Figure 1, both for READ (left) and WRITE requests (right). For a READ request, the client contacts the version manager to get the latest version available for the corresponding string. If the specified version is available the client contacts the metadata provider to retrieve the metadata describing the pages of the requested segment at the requested version. This operation results in sending and processing parallel requests to the metadata providers (as metadata are distributed and stored on a DHT). Once the client gathers all the metadata, it contacts (in parallel again) the data providers that store the corresponding pages and downloads them into the local buffer.

On issuing a WRITE request, a client first contacts the provider manager to get a list of providers, one for each page of the segment to be written. The client then contacts (in parallel) the corresponding providers and requests them to store the respective pages. Each provider executes the request and sends an acknowledgment to the client. When the client has received all acknowledgments, the client contacts the version manager and requests a new version number. This version number is then used by the client to generate the corresponding new metadata. Then the client sends these metadata to the metadata provider (in parallel again) and waits for an acknowledgment. Finally, the client contacts the version manager and reports success.

Note that both for READ and WRITE requests, the only serialization occurs when interacting with the version manager. These interactions are reduced to simply requiring a version number: all the other steps are fully parallel.

C. Metadata management

Metadata store information about the pages which make up a given data string, for each version available in the system. Our goal is to support fast metadata query for the READ requests, fast metadata update for the WRITE requests, and to minimize the overall metadata storage space in the system.

We organize metadata as a distributed *segment tree* [13], one associated to each version of a given string *id*. It is a full binary tree, with each node of associated to a segment in the string identified by *offset* and *size*. Such a node is said to *cover* the segment. The left child of the node covers the first half of the segment and the right child the other half, with leaves covering a single page. The node stores additional information: the global string *id* and its version number *v* (Figure 2(a)). To find the pages making up a segment, one must traverse down the segment tree, starting from the root. A node is visited only if its covered interval intersects the segment. All leaves reached this way correspond to the pages that are part of that segment. For example, in Figure 2(a), the set of nodes explored for segment $[1, 2]$ is $(0, 4), (0, 2), (2, 2), (1, 1), (2, 1)$. Out of these, $(1, 1)$ and $(2, 1)$ are the leaves and refer to the pages of segment $[1, 2]$.

A WRITE request producing version *v* of a given string needs to build a new metadata tree. This tree is the smallest (possibly incomplete) binary tree of the same height as the initial tree such that its leaves are exactly the leaves covering the pages of the patched segment. The leaves of this new tree exactly refer to these pages that are part of the segment. This incomplete metadata tree needs to be "weaved" into the previous complete metadata tree such that its incomplete nodes (having a single left or a single right child and referred to as *border nodes*) will become complete by referring to the missing corresponding child in the metadata tree corresponding to the previous version. Figure 2(b) illustrates this feature through a simple scenario, in which the the initial version (white) is 1. The WRITE request on segment $[1, 1]$ is assigned version 2 (grey). Its tree, is woven into the white tree: the missing left child of B_2 is set to D_1 and the missing right child of A_2 is set to C_1. Similarly, a consequent WRITE request on segment $[2, 1]$ is assigned version 3 (black). Interweaving with the previous tree (gray) translates into setting the right child of C_3 to G_1 and the left child of A_3 to B_2. Once they are built, the metadata tree nodes are uniformly dispersed among the metadata providers (through the underlying DHT).

IV. Managing concurrency

A. Enabling parallel reads

Dealing with concurrent reads is straightforward. As explained in Section III, each client starts by requesting the latest version available from the version manager. This step (whose cost is negligible with respect to the following steps) is the only interaction with a centralized entity. Then each traverses the tree down to the leaves to fetch the corresponding pages. Both tree traversal page fetching can be performed by clients with full parallelism, with no synchronization necessary with respect to other clients. This is favored by the fine-grain dispersal of both data and metadata across the distributed nodes.

B. Enabling parallel reads with respect to concurrent writes

As explained above, reads are performed in total isolation by each client once the latest version is received from the version manager. The only possible conflict with a concurrent write request may occur at the level of the version manager, when a writer increments the latest published version number. Consequently, the relative cost due to such a potential conflict is negligible with respect to the total access cost, we may consider that accesses are fully parallel.

C. Enabling parallel writes

As explained in Section III, WRITE operations involve two phases: writing the data (i.e., the pages), then writing the metadata (i.e., creating the metadata tree nodes). For any concurrent WRITE operations to segments of the same string, pages may be written in parallel with no synchronization. This holds even when the WRITE operations concern non-disjoint segments of the string, as each written segment involves a new set of pages to be stored on potentially new data providers. Remember that data is never actually modified: the old version of the data still remains available on some providers.

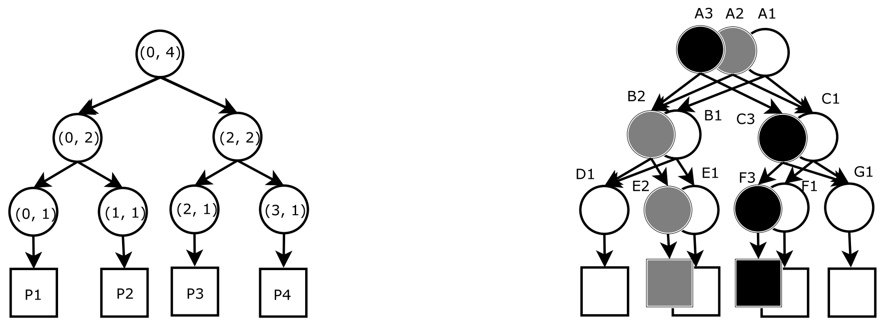
Building and writing new metadata tree nodes might seem to require serialization. Writing a newer version implies weaving the metadata subtree into the full metadata tree of the previous version, as explained in Section III. Even when the previous version is being written concurrently, we can actually predict the missing children for the border nodes at a slight computation overhead on the side of the versioning manager, no matter how many concurrent writes compete for metadata weaving. Due to space constraints, we do not develop the details of this mechanism here. Getting a precomputed set of border nodes from the version manager enables the writer to generate the metadata in complete isolation with respect to the other writers. After metadata is written, the client reports success to the version manager.

V. Experimental evaluation

A. Implementation details

Our implementation is based on the Boost C++ collection of libraries [14]. We chose Boost for its standardization throughout the C++ community, and for the wide range of functionalities it provides, among which serialization, threading and asynchronous I/O are of particular interest to us. For metadata storage and retrieval, we use BambooDHT [15], a stable, scalable DHT implementation on top of which we build the abstraction of our metadata providers.

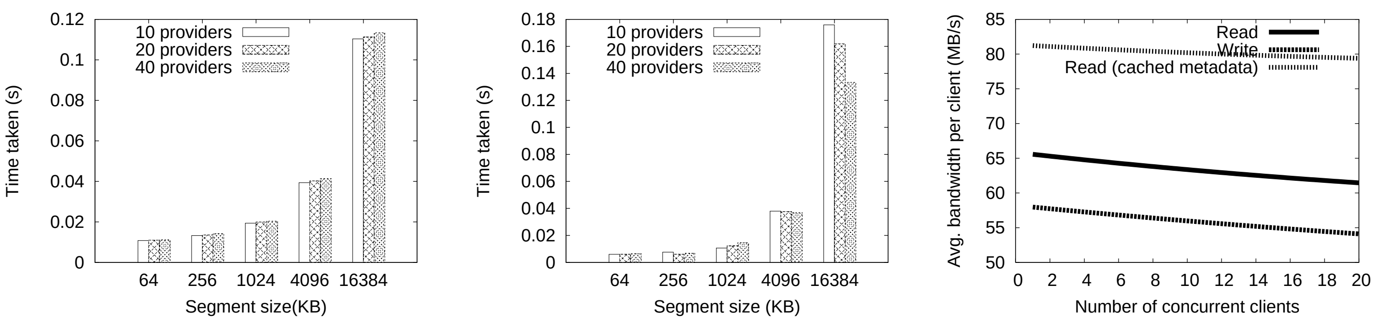
Processes in our system communicate through RPCs. We allow a single client to perform a large number of concurrent RPCs to enhance parallelism and turn fine grain dispersion of data and metadata in our advantage. However there is a tradeoff between striping and streaming. Dispersing data too fine grained might not pay off because of RPC call overhead.



(a) A segment tree: each node covers *(offset, size)*, leaves refer to the pages

(b) Constructing new metadata: colored nodes are generated and linked to the previous version

Fig. 2. Metadata representation of a 4-page block



(a) Metadata overhead, single client: reads

(b) Metadata overhead, single client: writes

(c) Throughput of concurrent client access

Fig. 3. Metadata overhead for a single client and throughput for concurrent clients when nodes are in the same cluster (latency = 0.1 ms)

For this reason we use lightweight custom RPC framework, which delays RPC calls to a single machine and streams all of them in a singe real RPC call.

B. Experimental platform

Evaluations have been performed using the Grid'5000 [16] testbed, a reconfigurable, controllable and monitorable experimental Grid platform gathering 9 sites geographically distributed in France. We used 50 nodes from a cluster located on the Grid'5000 site in Rennes. Nodes are outfitted with x86_64 CPUs and 4 GB of RAM, and run Ubuntu (Linux 2.6). Intracluster bandwidth is 1 Gbit/s (measured: 117.5MB/s for TCP sockets with MTU = 1500 B), latency is 0.1 ms.

C. Metadata overhead

As a major goal of our system is to allow applications to store huge data (of the order of 1 TB), we first evaluate how our metadata scheme impacts the performance of data accesses. We first consider a single client which allocates 1 TB of memory, then accesses a segment varying from 16 KB to 16 MB. Note that the system allocates on write, which means that only the segments that are written are physicaly allocated. The data and metadata are distributed among a varying number of data providers and metadata providers. We successively use 10, 20 and 40 distinct physical nodes, each hosting one data provider and one metadata provider. The provider manager and the version manager are deployed on separate, dedicated nodes.

We measure the time it takes for metadata to be completely read (respectively written) for a READ (respectively WRITE), for a 1 TB string, using 64 KB pages (Figure 3).

We observe that increasing the number of providers has a small impact on the cost perceived by the client issuing a READ request. For a fixed number of tree nodes distributed on a variable number of metadata providers, the retrieval cost perceived by the client is almost the same. In fact, using a larger number of metadata providers slightly increases the overall cost, as the client needs to manage more connections. The main limiting factor is actually the performance of the client's processing power. However, there is a benefit in using a large number of metadata providers: this improves the reactivity of the metadata providers when they are under heavy load, in conditions of high access concurrency, because of the better load balancing.

In the case of WRITE requests, our observation is different: using a larger number of metadata providers improves the cost of writing the overall metadata. This is explained by our optimized RPC mechanism, which aggregates requests for storage sent to the same remote process. This is more visible when writing larger segments.

D. Throughput of concurrent clients

Our second experiment aims at evaluating the efficiency of our lock-free scheme in a highly-concurrent environment. We measure the average bandwidth per client for READ (respectively WRITE) requests when increasing the number of simultaneous readers (respectively writers). We use 20 distinct nodes to deploy 20 reader clients and another 20 physical nodes, each of which hosts one data provider and one metadata provider. The version manager and the provider manager run on another two dedicated physical nodes. The same configuration is used with writers instead of readers.

The experiments run as follows. First, a data string of 1 TB is allocated, using tiny, 64-KB pages (in order to generate a access various disjoint segments within a 1 GB interval of the data string in a 100-iteration loop. Clients start simultaneously, then run without any synchronization. As illustrated on Figure 3, in all settings, we can notice that the per client bandwidth hardly decreases when the number of concurrent clients significantly increases. Besides, note that this read bandwidth corresponds to a worst-case experiment, in which client-level caching has been totally disabled! Read bandwidth is much higher in real life situations, where client-side caching of metadata tree nodes results in optimizing out a large amount of RPC calls. In our experiments, the cache can accommodate 2^{20} tree nodes.

VI. Conclusion

We address the problem of efficiently managing massive data in a distributed environment. As a case study, we consider a problem in the field of astronomy, consisting in searching for supernovae in a huge set of images representing the sky at various moments in time. Our problem illustrates typical requirements for massive data analysis: storage of massive data, efficient fine grain access to small data sets, snapshoting support, with efficient read/read, read/write and write/write access concurrency. We consider binary strings of size in the order of Terabytes, which are intensively accessed by a set of concurrent clients. For each such access, only a tiny segment of such a string, of the order of Megabytes, is read or modified.

Our contribution is to propose an algorithm and system design which let the clients access the strings as concurrently as possible, without locking the string itself. Efficient fine-grain access to arbitrarily tiny parts of the data is provided thanks to a distributed, memory-based storage of individual pages, while leveraging a DHT-based, inherently parallel metadata management scheme.

Preliminary experiments have been run on a cluster from the Grid'5000 testbed. It turns out that our approach scales well, both in terms of storage providers and in terms of concurrency degree: the per-client bandwidth remains high when the number of concurrent clients increases.

Our prototype is however a work in progress and needs further refinement. First, fault tolerance, which becomes critical in large-scale grid environments, is only partially addressed through the use of the off-the-shelf DHT which implements the metadata provider. We plan to also include fault-tolerance mechanisms for the entities that currently represent single points of failure (version manager, provider manager). Second, we also intend to address the issue of garbage collection. Finally, we intend to realize large-scale experimens with real applications in the fields of databases and data mining.

References

[1] K. Douglas and S. Douglas, *PostgreSQL*. Thousand Oaks, CA, USA: New Riders Publishing, 2003.

[2] A. Thomasian, “Concurrency control: methods, performance, and analysis,” *ACM Comput. Surv.*, vol. 30, no. 1, pp. 70–119, 1998.

[3] M. Nicola and M. Jarke, “Performance modeling of distributed and replicated databases,” *IEEE Trans. on Knowl. and Data Eng.*, vol. 12, no. 4, pp. 645–672, 2000.

[4] R. Jin and G. Yang, “Shared memory parallelization of data mining algorithms: Techniques, programming interface, and performance,” *IEEE Trans. on Knowl. and Data Eng.*, vol. 17, no. 1, pp. 71–89, 2005, member-Gagan Agrawal.

[5] M. A. Casey and F. Kurth, “Large data methods for multimedia,” in *MULTIMEDIA ’07: Proceedings of the 15th international conference on Multimedia*. New York, NY, USA: ACM, 2007, pp. 6–7.

[6] S. Ghemawat, H. Gobioff, and S.-T. Leung, “The google file system,” *SIGOPS Oper. Syst. Rev.*, vol. 37, no. 5, pp. 29–43, 2003.

[7] O. Tatebe, Y. Morita, S. Matsuoka, N. Soda, and S. Sekiguchi, “Grid datafarm architecture for petascale data intensive computing,” in *CC-GRID’02*. Washington, DC, USA: IEEE Computer Society, 2002, p. 102.

[8] P. Honeyman, W. A. Adamson, and S. McKee, “GridNFS: global storage for global collaborations,” in *Proceedings of the IEEE International Symposium Global Data Interoperability - Challenges and Technologies*. Sardinia, Italy: IEEE Computer Society, Jun. 2005, pp. 111–115.

[9] B. S. White, M. Walker, M. Humphrey, and A. S. Grimshaw, “LegionFS: a secure and scalable file system supporting cross-domain high-performance applications,” in *Proceedings of the 2001 ACM/IEEE Conference on Supercomputing (SC ’01)*. New York, NY, USA: ACM Press, 2001, pp. 59–59.

[10] G. Antoniu, M. Bertier, E. Caron, F. Desprez, L. Bougé, M. Jan, S. Monnet, and P. Sens, *Future Generation Grids*, ser. CoreGRID series. Springer Verlag, 2006, ch. GDS: An Architecture Proposal for a grid Data-Sharing Service, pp. 133–152.

[11] G. Antoniu, L. Bougé, and M. Jan, “JuxMem: An adaptive supportive platform for data sharing on the grid,” *Scalable Computing: Practice and Experience*, vol. 6, no. 3, pp. 45–55, Nov. 2005.

[12] G. Antoniu, L. Cudennec, M. Ghareeb, and O. Tatebe, “Building hierarchical grid storage using the gfarmglobal file system and the juxmemgrid data-sharing service,” in *Euro-Par*, 2008, pp. 456–465.

[13] C. Zheng, G. Shen, S. Li, and S. Shenker, “Distributed segment tree: Support of range query and cover query over dht,” in *5th Intl. Workshop on Peer-to-Peer Systems (IPTPS-2006)*, Santa Barbara, USA, Feb. 2006, electronic proceedings.

[14] “The Boost C++ libraries,” http://www.boost.org/.

[15] S. Rhea, B. Godfrey, B. Karp, J. Kubiatowicz, S. Ratnasamy, S. Shenker, I. Stoica, and H. Yu, “Opendht: a public dht service and its uses,” in *SIGCOMM ’05: Proceedings of the 2005 conference on Applications, technologies, architectures, and protocols for computer communications*. New York, NY, USA: ACM, 2005, pp. 73–84.

[16] F. Cappello, E. Caron, M. Dayde, F. Desprez, E. Jeannot, Y. Jegou, S. Lanteri, J. Leduc, N. Melab, G. Mornet, R. Namyst, P. Primet, and O. Richard, "Grid'5000: A Large Scale, Reconfigurable, Controlable and Monitorable Grid Platform," in *Proceedings of the 6th IEEE/ACM International Workshop on Grid Computing (Grid '05)*, Seattle, Washington, USA, Nov. 2005, pp. 99–106.