

## Swift: Fast, Reliable, Loosely Coupled Parallel Computation

Yong Zhao<sup>1</sup>, Mihael Hategan<sup>2</sup>, Ben Clifford<sup>2</sup>, Ian Foster<sup>1,2,3</sup>,

Gregor von Laszewski<sup>2,3</sup>, Ioan Raicu<sup>1</sup>, Tiberiu Stef-Praun<sup>2</sup>, Mike Wilde<sup>2,3</sup>

<sup>1</sup>Department of Computer Science, University of Chicago, Chicago, IL 60637, USA

<sup>2</sup>Computation Institute, University of Chicago & Argonne National Laboratory

<sup>3</sup>Mathematics and Computer Science Division, Argonne National Laboratory, Argonne, IL 60439, USA

{yongzh,iraicu}@cs.uchicago.edu, benc@hawaga.org.uk, {foster,gregor,hategan,tiberius,wilde}@mcs.anl.gov

### Abstract

A common pattern in scientific computing involves the execution of many tasks that are coupled only in the sense that the output of one may be passed as input to one or more others—for example, as a file, or via a Web Services invocation. While such “loosely coupled” computations can involve large amounts of computation and communication, the concerns of the programmer tend to be different than in traditional high performance computing, being focused on management issues relating to the large numbers of datasets and tasks (and often, the complexities inherent in “messy” data organizations) rather than the optimization of interprocessor communication. To address these concerns, we have developed Swift, a system that combines a novel scripting language called SwiftScript with a powerful runtime system based on CoG Karajan and Falkon to allow for the concise specification, and reliable and efficient execution, of large loosely coupled computations. Swift adopts and adapts ideas first explored in the GriPhyN virtual data system, improving on that system in many regards. We describe the SwiftScript language and its use of XDTM to describe the logical structure of complex file system structures. We also present the Swift system and its use of CoG Karajan, Falkon, and Globus services to dispatch and manage the execution of many tasks in different execution environments. We summarize application experiences and detail performance experiments that quantify the cost of Swift operations.

### 1. Introduction

Consider the following painful but all-too-familiar scenario: *A neuroscientist needs to analyze ten thousand functional magnetic resonance imaging (fMRI) files. The analysis program is a complex Perl script. Files are stored in a collection of UNIX directories, with metadata coded in directory and file names. Local computing facilities are inadequate. Thus, the scientist must manually extract files, copy them to a remote cluster, start a home-grown script to dispatch tasks, and check exit codes and output files to see which tasks succeeded and failed. And when the computation is finally completed, the problem remains of documenting what was done.*

Such difficulties have motivated our design of Swift, a parallel programming system that integrates the following elements to meet the needs of scientists tackling such problems.

- A scripting language, **SwiftScript**, allows users to express operations on datasets in terms of their logical organization; the XML Dataset Typing and Mapping (**XDTM**) [10] notation is used to define a mapping between that logical organization and the underlying physical structure.
- An execution engine, CoG **Karajan** [9], a lightweight provisioning and job submission system, **Falkon** [13], and a compiler and associated runtime libraries, execute tasks specified via SwiftScript programs, on local or remote computers.
- A provenance-recording component, **Kickstart** [18], captures execution details for diagnosis and eventual recording in a provenance database.

These elements together make it possible for a few lines of SwiftScript to specify computations involving extremely large numbers (tens or hundreds of thousands) of files and tasks, and for those computations to be executed efficiently and reliably on many distributed computers. The impact on end users such as our unfortunate neuroscientist can be enormous. Code sizes can be reduced by an order of magnitude or more [19]. In another example, a 160-member climate model ensemble took 2.5 months when performed manually; a 250-member ensemble was finished within 4 days—admittedly on a faster computer—when automated with a precursor to Swift [11]. Other users are found in the physical, biological, and social sciences, and in the humanities, computer science, and education.

Swift grew out of work on the GriPhyN Virtual Data System (VDS) [7], which provided a simple virtual data language, planners (including Pegasus [6]) for program optimization and scheduling, the DAGMan task management system for task management [4], kickstart, and a virtual data catalog [20]. Swift improves on VDS in several regards, in particular its use of XDTM to define logical views of datasets; SwiftScript and CoG Karajan support for iteration operations, which together allow for more concise specifications of computations over larger datasets; and Falkon for efficient task dispatch.

The rest of the paper is organized as follows. We introduce SwiftScript and the Swift system design in Sections 2 and 3. We present system evaluation results and applications in Sections 4 and 5. We discuss related work in the specification and execution of loosely coupled problems in Section 6, and summarize in Section 7.

## 2. Notation: SwiftScript and XDTM

The need to process large numbers of tasks reliably and efficiently arises in many scientific and engineering disciplines, for example when performing large-scale data analysis or when executing large numbers of computations to study sensitivity to parameter values (in parameter studies) and/or initial conditions (in ensemble simulations). Users working on such problems frequently struggle with bookkeeping tasks due to large numbers of tasks, datasets, and computational resources.

Users need a concise and readable notation to simplify the description, maintenance, and debugging of problem specifications. Such a notation should also facilitate high-performance execution by revealing opportunities for concurrent execution. Conventional scripting languages such as UNIX Shell or Perl, frequently used to implement the sorts of application that we target here, are not concise, readable, easily parallelizable or analyzable, and are not amenable to the automation of provenance tracking. We overcome these problems with XDTM and SwiftScript.

## XDTM

Even logically simple applications can become complicated when they must deal with “messy” data stored in odd formats and storage organizations. For example, compare the logical and physical layouts in Figure 1. The *logical* organization is a clean hierarchy of studies, groups, subjects (patients), runs (series of volumes), and volumes (brain scans), while the *physical* layout is a complex mix of directory structures and files [8]. (The uninformed reader will be hard pressed to determine that ‘/knottastic’ is a *Study*, which contains *Group* ‘AA’, which in turn contains *Subject* ‘04nov06aa,’ etc.) The result, in the absence of Swift, was complex and hard-to-maintain application orchestration code.

We address this problem by using XDTM, which allows logical datasets to be defined in a manner that is independent of the datasets’ concrete physical representations. XDTM employs a two-level description of datasets, defining separately via a type system based on XML Schema the abstract structure of datasets, and the mapping of that abstract data structure to physical representations.

A dataset’s *logical structure* is specified via a subset of XML Schema, which defines primitive scalar data types such as Boolean, Integer, String, Float, and Date, and also allows for the definition of complex types via the composition of simple and complex types. The use of XML Schema as a type system has the benefit of supporting powerful standardized query languages such as XPath in our selection methods.

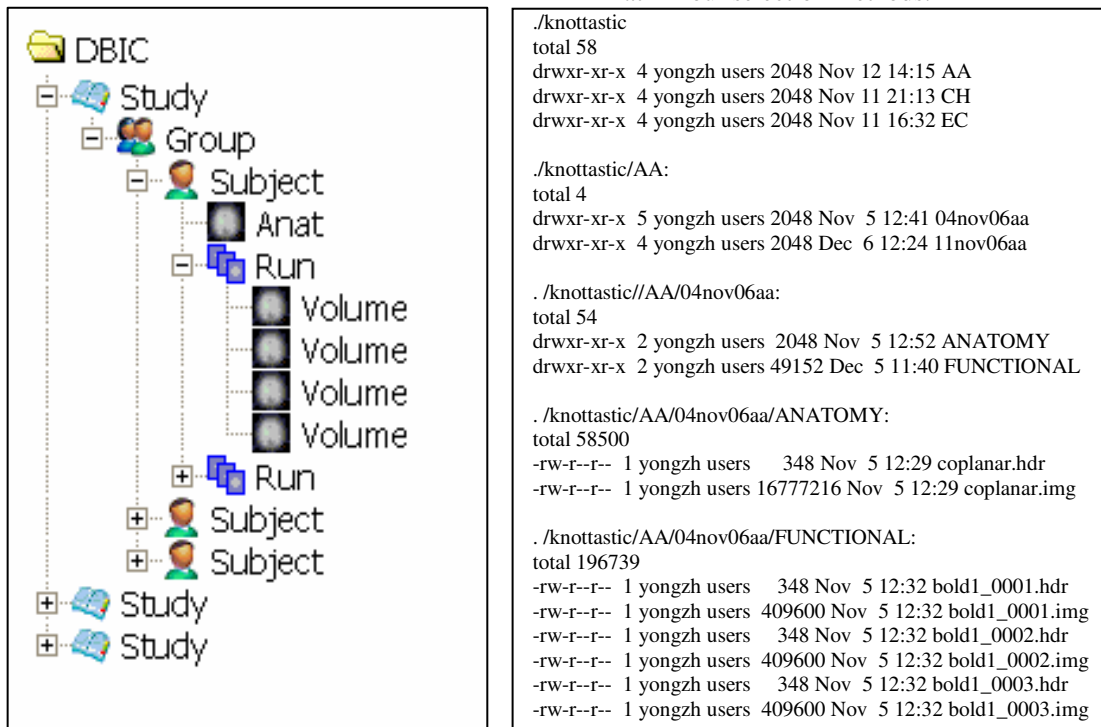


Figure 1: fMRI logical data structure (left) vs. physical file system layout (right)

```

type Study {
  Group g[ ];
}

type Group {
  Subject s[ ];
}

type Subject {
  Volume anat;
  Run run[ ];
}

(Run resliced) reslice_wf ( Run r ) {
  Run yR = reorientRun( r, "y", "n" );
  Run roR = reorientRun( yR, "x", "n" );
  Volume std = roR.v[1];
  AirVector roAirVec =
    alignlinearRun(std, roR, 12, 1000, 1000, "81 3 3");
  resliced = resliceRun( roR, roAirVec, "-o", "-k");
}

type Run {
  Volume v[ ];
}

type Volume {
  Image img;
  Header hdr;
}

type AirVector {
  Air a[ ];
}

```

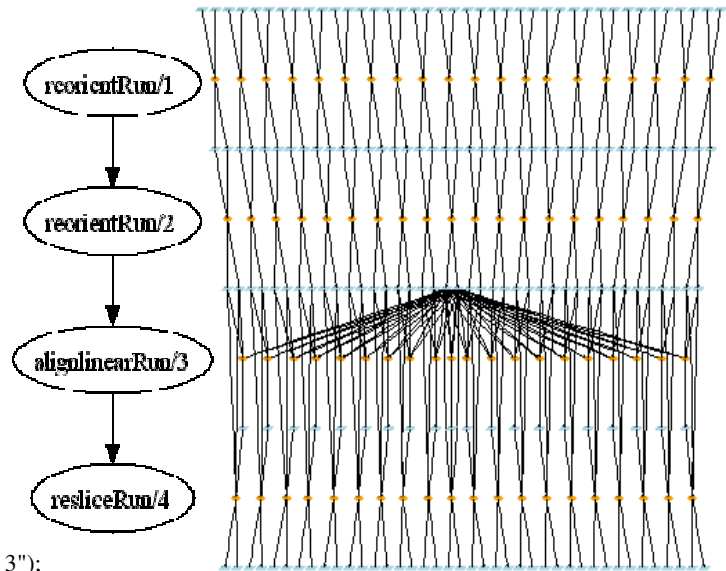


Figure 2 A Swift program (fragment) and the resulting task graph

A dataset's *physical representation* is then defined by a mapping descriptor, which describes how each element in the dataset's logical schema is stored in/fetched from physical structures such as directories, files, and database tables. In order to permit reuse for different datasets, mapping descriptors typically refer to external parameters for such things as dataset location(s).

We use a virtual integration approach to implement the mapping mechanism. Each data source is regarded as a virtual XML source, with its structure described in an XML Schema. A mapper is responsible for accessing the data source and converting its data to/from an XML document or stream that conforms to the XML schema. The case is somewhat different from a traditional data integration approach, since we need to deal with writing/updating to data sources as well as querying them.

We define a standard mapping interface so that different data providers can implement the interface to support access to various data representations. We provide default mapping implementations for string mapping, file system mapping, and CSV (comma separated-value) files.

## SwiftScript

The SwiftScript scripting language builds on XDTM to allow for the definition of typed data structures and procedures that operate on such data structures. SwiftScript procedures define logical data types and operations on those logical types; the SwiftScript implementation uses mappers to access the corresponding physical data. In addition to providing the usual advantages of strong typing (type checking, self-

documenting code, etc.), this approach allows SwiftScript programs to express opportunities for parallel execution easily, for example by applying transformations to each component of a hierarchically defined logical structure.

As an example, the logical structure of the fMRI dataset shown in Figure 1 can be represented by the SwiftScript type declarations in the upper left of Figure 2. Here, *Study* is declared as containing an array of *Group*, which in turn contains an array of *Subject*, etc. Similarly, an fMRI *Run* is a series of brain scans called volumes, with a *Volume* containing a 3D image of a volumetric slice of a brain image, represented by an *Image* (voxels) and a *Header* (scanner metadata).

Figure 3 includes two example procedures. We examine *reorientRun* first. This is what we call a compound procedure, meaning it calls one or more other SwiftScript procedures. Note the typed input arguments (to the right of the procedure name) and output argument (to the left). The procedure takes in a run *ir* and applies the procedure *reorient* (which rotates a brain image along a certain axis) to each volume in the run to produce a reoriented run *or*. Because the multiple calls to *reorient* operate on independent data elements, they can proceed in parallel.

The procedure *reorient* in Figure 3 is *atomic*, corresponding to an invocation of an executable program or a Web Service. This procedure has typed input parameters *iv*, *direction* and *overwrite* and one output *ov*. The body of this particular procedure specifies that it invokes a program (conveniently, also called *reorient*) that will be dynamically mapped to a binary executable. (This executable will execute at an execution site chosen by the Swift runtime system.) The body also specifies how input parameters map to command line arguments. The notation

@filename is a built-in mapping function that maps a logical data structure to a physical file name.

```
(Volume ov) reorient (Volume iv, string direction,
                    string overwrite) {
    app {
        reorient @filename(iv.hdr)
                @filename(ov.hdr)
                direction
                overwrite;
    }
}

(Run or) reorientRun (Run ir, string direction,
                    string overwrite) {
    foreach Volume iv, i in ir.v {
        or.v[i] = reorient (iv, direction, overwrite);
    }
}
```

Figure 3 fMRI procedure declarations

A compound procedure can also comprise a series of procedure calls, using variables or datasets to establish data dependencies. Such procedures can themselves be called by other procedures, thus defining a potentially large and complex execution graph.

The procedure *reslice\_wf* (Figure 2, lower left) applies *reorientRun* to a run first in the *x* axis and then in the *y* axis, and then aligns each image in the resulting run with the first image. The program *alignlinear* determines how to spatially adjust an image to match a reference image, and produces an *air* parameter file. The actual alignment is done by the program *reslice*. Note that variable *yR*, being the output of the first step and the input of the second step, defines the data dependencies between the two steps. More complex procedures can be composed in similar fashion, combining with iterations and other control constructs.

The *reslice\_wf* example defines a simple four-step pipeline computation. The pipeline is illustrated in the center of Figure 2, while on the right we show the expanded graph for a 20-volume run. Each volume comprises an image file and a header file, so there are a total of 40 input files and 40 output files. We can also apply the same procedure to a run containing hundreds or thousands of volumes.

SwiftScript allows concise definitions of logical data structures and logical procedures that operate on them, and complex computations to be composed from simple and compound procedures. Its support for nested iterations can allow a compact SwiftScript program (for example, a nested set of iterations that applies the program *reorient* to each volume in a whole *Study*) to express hundreds of thousands of parallel tasks. We have shown that SwiftScript programs can be at least an order of magnitude smaller in lines of code than other

approaches such as Shell scripts and directed acyclic graph specifications [19].

### 3. Implementation

The Swift runtime system (see Figure 4) is a scalable environment for efficient specification, scheduling, monitoring and tracking of SwiftScript programs. We describe its components one by one.

**Program specification:** computations are defined in SwiftScript programs, they are compiled by a SwiftScript compiler into abstract computation plans, which can be scheduled for execution by the execution engine.

**Scheduling:** Swift uses CoG Karajan as its underlying execution engine. Karajan provides a set of convenience libraries for file operation, data transfer, job submission, and Grid services access. Such operations can be organized using language constructs such as sequential and parallel execution, sequential and parallel iterations, conditional execution and functional abstraction etc. We extend Karajan with specific libraries to support the XDTM type system and logical dataset manipulation, adapters to access legacy VDS components (for instance, site catalog), mappers for accessing heterogeneous physical data storage, and also with fault tolerance mechanisms. Karajan uses light-weight threading techniques to instantiate and dispatch tasks, and thus can execute large scale task graphs (see Section 4).

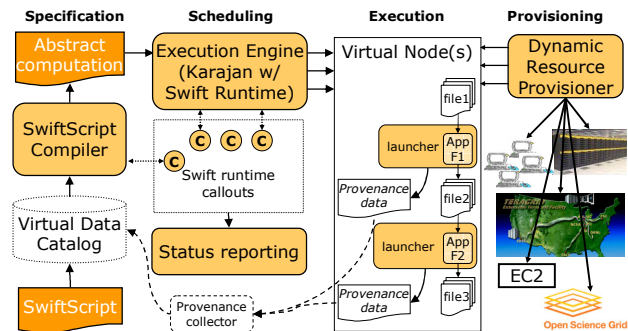


Figure 4 Swift system diagram

**Execution:** Intermediate abstract execution plans represented in customized Karajan scripts are interpreted and dispatched by Karajan onto execution sites. We call these plans abstract because execution can be carried out in a location independent fashion: tasks are dispatched to virtual nodes, which can be bound to different kinds of computing facilities varying from personal desktops and clusters to multi-site Grid environments. Swift determines at runtime the actual execution processes such as site selection, data stage-ins and stage-outs, and error checking. A set of callouts allow customized functions to determine where to dispatch tasks, how to group tasks to increase granularity, and/or when and how to perform data staging operations etc. Swift also supports advanced

Grid scheduling and optimization, such as load balance, fault tolerance, computation restart, etc.

**Provenance tracking:** Individual tasks are invoked by a launcher program (for instance, kickstart) which monitors and records the execution process and gathers provenance information. In the future, we will record this information in a virtual data catalog (VDC), as first introduced and implemented in the virtual data system.

**Provisioning:** Tasks determined to be executable by Karajan can be submitted directly, via a GRAM job submission, to a (local or remote) scheduler for execution; in this way, resource provisioning and task submission are handled together. The Swift architecture also allows for those two functions to be separated. Specifically, a dynamic resource provisioner (right hand side of figure) can interact with local or remote computing systems to get computing resources, and then deploy task execution services onto those resources. The execution services then interact with a task queue service to obtain tasks to execute.

## 4. Evaluation

We report on experiments that evaluate the performance of various elements of the Swift system.

We consider first the size of the computations that can be executed correctly. Figure 5 shows the maximum number of tasks (measured by the number of nodes in a task graph) that Swift can process and dispatch with certain amount of available memory. The system can support about 4000 nodes with 32MB of memory and 160,000 nodes with 1GB memory.

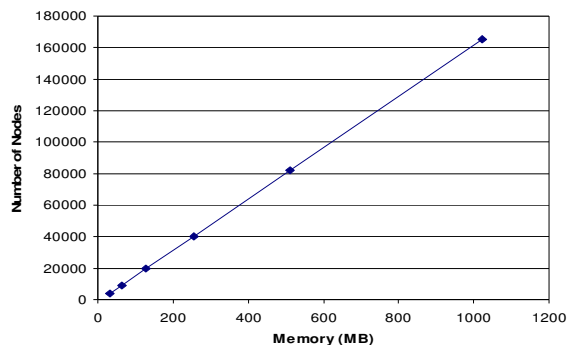


Figure 5 Swift system scalability

Swift addresses reliability issues at several levels. At the software development level, its type checking capabilities allow it to identify potential problems in a program prior to execution. Its support for virtual nodes makes it easy to first test a program using local host submission mechanism with a small set of datasets, and then move to larger problems and execution sites.

During execution, the underlying Karajan engine supports flexible exception handling mechanism.

Transitory problems are recovered by retrying the faulty tasks (for instance, retry a transfer if a GridFTP server is busy), and host level faults (where a resource exhibits problems with unknown duration) are dealt with by rescheduling a task on a different site.

Swift also keeps a restart log, allowing it to resume the state of a computation in case of premature termination (for instance, caused by a machine reboot). We have tested restartability by repeatedly interrupting program execution, and verified that our programs continue from where they were interrupted. We also note some (good) side effects to this mechanism: (1) new inputs can be added after a computation has been run for some time, and once we restart the computation, the system is able to figure out that these new inputs are present and not processed, and thus schedule their executions. (2) We can make modifications to a program and restart it, as long as the modifications do not affect data flows that have already happened. This effect is useful for debugging and testing purposes. The Swift restart log is similar to a Condor rescue DAG, except that Condor tags jobs that are finished, where we log datasets that are successfully produced.

Swift engages the following mechanisms to improve efficiency:

**Pipelining:** which refers to the ability to optimize execution by executing dependent iterations incrementally. Swift is built on data-driven mechanism, so once an item in a collection is processed, any processes that are dependent on that data item can proceed right away without waiting for the whole collection to finish.

**Clustering:** many scientific computations are composed of large number of short running jobs, for instance, the reorient program in the sample fMRI computation usually finishes in a few seconds. The initialization and scheduling of large number of such jobs can pose significant overhead. To address this we (optionally) bundle groups of (mostly independent) jobs and submit them as a single job.

**Pluggable execution providers:** Swift can schedule the execution of a program on different compute resources based on an abstract provider interface in CoG Karajan. Karajan provides support for local host execution, cluster scheduler submission, GRAM job submission, etc. We have also integrated Swift with the Falcon (Fast and Lightweight Task Execution) service [13] by implementing the provider interface for the Falcon service. Falcon is a Web Services-based system whose main goal is to support the efficient execution of large numbers of small tasks in batch scheduled environments that are typically found in most production Grids. We measure the speedups of running synthetic jobs over the Falcon provider and we show the results in Figure 6.

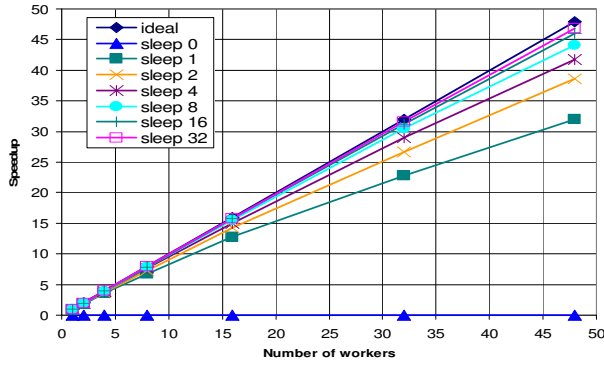


Figure 6 Swift speedup with Falcon provider

In the experiment, Swift executed computations comprising 960 test jobs (which simply sleep), from a submit host located at the University of Chicago, which we refer to as UC\_SUB, to a Falcon service running on the TeraGrid ANL cluster. We varied the sleep durations and also configured Falcon to allocate different number of nodes to execute the tasks. The ideal speedup is equal to the number of nodes used. We observe that the service can keep a large number of workers busy even for short jobs (one second duration) and process them efficiently, and for relatively longer running jobs, we get linear speedups that are close to the ideal speedup. For instance, with a cluster of 48 nodes, the Swift system can achieve close to 47 times speedup for jobs with a duration of 32 seconds.

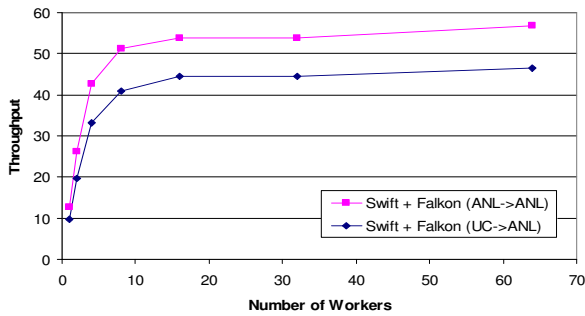


Figure 7 Swift throughput with Falcon provider

Figure 7 shows Swift throughput with the Falcon provider. In the experiment, the Falcon service ran on the TeraGrid ANL site and we submitted both from a separate node within that cluster (ANL->ANL), and from UC\_SUB (UC->ANL). We measured the throughput, defined as the number of sleep(0) jobs completed per second. Swift was able to achieve up to 56 jobs/second in the LAN setting and 46 jobs/second in the remote setting. The scheduling of each sleep job actually involved many extra steps such as site selection, execution directory set up, exit code checking, and clean up. But comparing with a standard setting where we use GT2 GRAM and PBS cluster scheduler where we can only get up to 2 jobs per

second, the throughput of this combination is improved by a factor of 23.

We also measured the turn-around time for the fMRI workflow defined in Figure 1, with various input sizes (number of volumes) and different scheduling strategies. We submitted from UC\_SUB to the TeraGrid ANL cluster, and we repeat the experiment a few times. We show the results in Figure 8, in which error bars indicate the standard deviation of measurements.

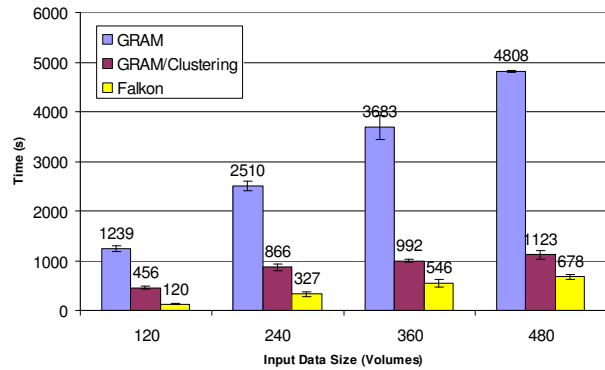


Figure 8 Execution time for the fMRI workflow

Since for each volume, all the four stages in the workflow ran very fast on a cluster node (a few seconds each), it is quite inefficient to schedule each job over GRAM and PBS, since the overhead of GRAM job submission and PBS resource allocation is large compared with the short execution time. The GRAM (over PBS) submission had low throughput although it could have potentially used all the available nodes on the site. With the clustering mechanism the execution time was reduced by up to 4 times (jobs were bundled into roughly 8 group), as the overhead was amortized by the bundled jobs. The Falcon execution service (with 8 worker nodes) however further cuts down the execution time by 40-70%, as each job was dispatched efficiently to the workers.

## 5. Swift Applications

Swift has been applied to a variety of science applications in disciplines such as physical sciences, biological sciences, social sciences, humanities, computer science, and science education. We summarize some applications and their scales in Table 1.

Table 1: Example Swift applications

Application	#Jobs/Run	#Levels
fMRI AIRSN Image Processing	100s	12
fMRI Aphasia Study	500	4
NVO/NASA Photorealistic Montage	1000s	16

QuarkNet/I2U2* Physics Science Education	10s	3-6
Radiology Classifier Training	1000s	5
SIDGrid EEG Wavelet Processing, Gaze Analysis	100s	20

The applications involve computations with various complexities, shown with the number of jobs in a typical analysis run, and the number of levels (or stages) in such analyses.

## 6. Related Work

MapReduce [5] is another programming tool for large parallel computations. However, MapReduce is limited to processing key-value based data, and the runtime environment requires Google File System. Swift targets various scientific applications that process heterogeneous data formats, and can schedule computations in a location-independent way.

Pegasus [6] and DAGMan [4] can also schedule large scale computations in Grid environments. DAGMan provides a workflow engine that manages Condor jobs organized as directed acyclic graphs (DAGs) in which each edge corresponds to an explicit task precedence. It has no knowledge of data flow, and in distributed environments works best with a higher-level, data-cognizant layer. DAGMan also lacks dynamic features such as iteration or conditional execution. Pegasus is primarily a set of DAG transformers that can translate a workflow graph into a location-specific DAGMan input file; prune tasks for files that exist; select sites for jobs; and cluster jobs based on various criteria. A weakness is that planners must operate on an entire workflow statically, and execution sites can not be changed after Pegasus processes a workflow, which can be long before a job runs, a strategy that may not work well in dynamic environments.

BPEL [3] has primarily been applied in service composition and orchestration. It lacks the specification for iteration which would result in large size of workflow specification, although the problem is being addressed in its latest 2.0 specification. In addition, the complex XML specification is cumbersome to write compared with our compact scripting language.

Taverna [12], Triana [17], Kepler [1] have also been applied in science problems. However, they do not abstract dataset types or provide location transparency. Data movement and Grid job submission all need to be explicitly specified and organized. Their support for multi-site Grid execution is also of limited scale.

As discussed earlier, Swift integrates CoG Karajan [9]. Karajan provides the libraries and primitives for job scheduling, data transfer, and Grid job submission; Swift adds support for high-level abstract specification of large

parallel computations, data abstraction, and workflow restart, and also (via Falkon) fast, reliable execution over multiple Grid sites.

## 7. Summary and Future Work

Swift is a parallel programming system that addresses important end-to-end issues in large-scale loosely coupled parallel computation. Swift imposes elegant order on a messy complex world of distributed and failure-prone applications. It provides the XDTM model for clean separation of logical data structures and physical storage formats, a scripting language SwiftScript for concise specification and convenient composition of large complex workflows, and a scalable runtime system that manage and dispatch hundreds of thousands parallel computations, onto a variety of parallel and distributed computation facilities.

As we have described here, the Swift system provides a wide range of capabilities to support the formulation, execution and management of large compute- and data-intensive computations:

**Scalability in Grid environments:** Swift has demonstrated large-scale execution of extremely large computations on both parallel computers and distributed systems.

**Scripting:** Scientists often seem to prefer scripting languages to more cumbersome alternatives. SwiftScript meets this need with a simple, familiar, and expressive notation.

**Dataset typing and iteration:** Swift allows the declaration of logical data structures and typed procedures to iterate over such datasets. A nested approach of such iterations can easily scale up to thousands or even millions of data objects.

**Dataset mapping:** This feature is critical for automating task execution with location independence. Systems need to know how to access dataset components and how to pack datasets and transport them to an execution site. Swift's dataset layout description model allows users to work at a clean abstract level.

**Application service interoperability:** Swift can integrate both service-oriented and command-oriented applications based on the XDTM model. While Service Oriented Architecture is gaining adoption, most scientists use non service-oriented applications. Swift provides a bridge between these two models of application deployment.

**Provenance and annotation:** Swift integrates provenance and annotation with computation through a language that makes data flow explicit and trackable, and a catalog (soon to be integrated) that records data derivation activities.

The combination of such distinctive features enables the automation of scientific data and workflow

managements, and improves usability and productivity in scientific applications and data analyses.

We continue to work to improve Swift's usability, functionality, and scalability. In particular, we are working on more intuitive application interface in SwiftScript, and we are integrating the data provenance structures created in VDS to represent programs, metadata, and runtime provenance [19] to support a wide range of provenance queries [20], we are also in the process of benchmarking system components with large scale application runs.

## Acknowledgements

This work was carried out on computing facilities at the Computation Institute at the University of Chicago, and at the Teragrid UC/ANL site. This work was supported by the National Science Foundation GriPhyN Project, grant ITR-800864 and iVDGL, grant PHY-122557; I2U2 – Interactions in Understanding the Universe, grant PHY-0636265; the Mathematical, Information, and Computational Sciences Division subprogram of the Office of Advanced Scientific Computing Research, U.S. Department of Energy under contract DE-AC02-06CH11357; and the National Institutes of Health, grants NS37470, NS44393 and DC008638-01. The authors thank Veronika Nefedova, Rob Jacob, Steven Small, Uri Hasson, Dan Katz, Maryellen Giger, Andrew Jamieson and the SIDGrid project (Bennett Bertenthal and Sarah Kenney, NSF award BCS 05-37849) for their collaboration on the application of Swift to the scientific investigations described here.

## 8. References

- [1] Altintas, I., Berkley, C., Jaeger, E., Jones, M., Ludäscher, B. and Mock, S., Kepler: An Extensible System for Design and Execution of Scientific Workflows. in *16th Intl. Conference on Scientific and Statistical Database Management*, (2004).
- [2] Annis, J., Zhao, Y., Voeckler, J., Wilde, M., Kent, S. and Foster, I., Applying Chimera Virtual Data Concepts to Cluster Finding in the Sloan Sky Survey. in *SC2002*, (Baltimore, MD, 2002).
- [3] Business Process Execution Language for Web Services, Version 1.0, <http://www-106.ibm.com/developerworks/webservices/library/ws-bpel/>, 2002.
- [4] The Condor DAGMan (Directed Acyclic Graph Manager), <http://www.cs.wisc.edu/condor/dagman>, 2007.
- [5] Dean, J. and Ghemawat, S., *MapReduce: Simplified data processing on large clusters*. In OSDI, 2004.
- [6] Deelman, E., Singh, G., Su, M.-H., Blythe, J., Gil, Y., Kesselman, C., Mehta, G., Vahi, K., Berriman, G.B., Good, J., Laity, A., Jacob, J.C. and Katz, D.S. Pegasus: A Framework for Mapping Complex Scientific Workflows onto Distributed Systems. *Scientific Programming*, 13 (3). 219-237.
- [7] Foster, I., Voeckler, J., Wilde, M. and Zhao, Y., Chimera: A Virtual Data System for Representing, Querying, and Automating Data Derivation. in *14th Intl. Conf. on Scientific and Statistical Database Management*, (Edinburgh, Scotland, 2002).
- [8] Horn, J.V., Dobson, J., Woodward, J., Wilde, M., Zhao, Y., Voeckler, J. and Foster, I. Grid-Based Computing and the Future of Neuroscience Computation. in *Methods in Mind*, MIT Press, 2006.
- [9] Laszewski, G.v., Hategan, M. and Kodeboyina, D. Java CoG Kit Workflow. in Taylor, I.J., Deelman, E., Gannon, D.B. and Shields, M. eds. *Workflows for eScience*, 2007, 340-356.
- [10] Moreau, L., Zhao, Y., Foster, I., Voeckler, J. and Wilde, M., XDTM: XML Data Type and Mapping for Specifying Datasets. in *European Grid Conference*, (2005).
- [11] Nefedova, V., Jacob, R., Foster, I., Liu, Y., Liu, Z., Deelman, E., Mehta, G. and Vahi, K., Automating Climate Science: Large Ensemble Simulations on the TeraGrid with the GriPhyN Virtual Data System. in *2nd IEEE International Conference on eScience and Grid Computing*, (2006).
- [12] Oinn, T., Addis, M., Ferris, J., Marvin, D., Senger, M., Greenwood, M., Carver, T., Glover, K., Pocock, M.R., Wipat, A. and Li, P. Taverna: A Tool for the Composition and Enactment of Bioinformatics Workflows *Bioinformatics Journal*, 20 (17). 3045-3054.
- [13] Raicu, I., Dumitrescu, C. and Foster, I., "Dynamic Resource Provisioning in Grid Environments", submitted for review to TeraGrid Conference 2007.
- [14] Sulakhe, D., Rodriguez, A., Wilde, M., Foster, I. and Maltsev, N., Using Multiple Grid Resources for Bioinformatics Applications in GADU. in *IEEE/ACM International Symposium on Cluster Computing and Grid*, (2006).
- [15] Swift, <http://www.ci.uchicago.edu/swift>, 2007
- [16] The TeraGrid, <http://www.teragrid.org>, 2007.
- [17] Taylor, I., Shields, M., Wang, I. and Harrison, A. Visual Grid Workflow in Triana. *Journal of Grid Computing*, 3 (3-4). 153-169.
- [18] Vöckler, J.-S., Mehta, G., Zhao, Y., Deelman, E. and Wilde, M., Kickstarting Remote Applications. in *2nd International Workshop on Grid Computing Environments* (2006).
- [19] Zhao, Y., Dobson, J., Foster, I., Moreau, L. and Wilde, M. A Notation and System for Expressing and Executing Cleanly Typed Workflows on



To appear: *2007 IEEE International Workshop on Scientific Workflows*, Salt Lake City, Utah, U.S.A.

Messy Scientific Data. *SIGMOD Record* 34 (3).  
37-43.

[20] Zhao, Y., Wilde, M., Foster, I., Applying the  
Virtual Data Provenance Model, Proceedings of the

International Provenance and Annotation  
Workshop 2006 (IPAW2006), Lecture Notes in  
Computer Science, Springer, 2006.