

Turbine: A distributed-memory dataflow engine for extreme-scale many-task applications

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ABSTRACT

Efficiently utilizing the rapidly increasing concurrency of multi-petaflop computing systems is a significant programming challenge. One approach is to structure applications with an upper-layer of many loosely-coupled coarse-grained tasks, each comprising a tightly coupled parallel function or program. “Many-task” programming models such as functional parallel dataflow may be used at the upper layer to generate massive numbers of tasks, each of which generates significant tightly-coupled parallelism at the lower level via multithreading, message passing, and/or partitioned global address spaces. At large scales, however, the management of task distribution, data dependencies, and inter-task data movement is a significant performance challenge. In this work, we describe *Turbine*, a new highly scalable and distributed many-task dataflow engine. *Turbine* executes a generalized many-task intermediate representation with automated self-distribution, and is scalable to multi-petaflop infrastructures. We present here the architecture of *Turbine* and its performance on highly concurrent systems.

Categories and Subject Descriptors

D.3.3e [Programming Languages]: Concurrent programming structures

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SWEET 2012 May 20-25, Scottsdale, AZ

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General Terms

Languages

Keywords

MPI, ADLB, Swift, Turbine, exascale, concurrency, dataflow

1. INTRODUCTION

Developing programming solutions to help applications utilize the high concurrency of multi-petaflop computing systems is a challenge. Languages such as Dryad, Swift, and Skywriting provide a promising direction. Their implicitly parallel dataflow semantics allow the high-level logic of large-scale applications to be expressed in a manageable way while exposing massive parallelism through many-task programming. However, current implementations of these languages limit the evaluation of the dataflow program to a single-node computer, with resultant tasks distributed to other nodes for execution.

We propose here a model for *distributed-memory* evaluation of dataflow programs that spreads the overhead of program evaluation and task generation throughout an extreme-scale computing system. This execution model enables function and expression evaluation to take place on any node of the system. It breaks parallel loops and concurrent function invocations into fragments for distributed execution. The primary novel features of our workflow engine, use of distributed-memory and message passing, enable the scalability and task generation rates needed to efficiently utilize future systems.

We describe the design and implementation of *Turbine*, a distributed evaluation model for implicitly parallel dataflow programs, motivating it with requirements projected from scientific applications. This paper demonstrates that Tur-

bine can execute Swift programs on large-scale, high performance computing (HPC) systems such as the Blue Gene/P. Our preliminary implementation shows promising scalability curves processing synthetic and useful application patterns.

1.1 Context

Exaflop computers capable of 10^{18} floating-point operations/s are expected to provide concurrency at the scale of $O(10^9)$ on $O(10^6)$ nodes [3]; each node will contain extremely high levels of available task and data concurrency [26]. Such extreme-scale systems will enable and demand new problem-solving methods that do not follow today’s dominant single program, multiple data (SPMD) paradigm but instead will involve hierarchical programming models [28]. Such a model could be based on composing a logical application from a time-varying number of interacting tasks. Methodologies such as rational design, uncertainty quantification, parameter estimation, and inverse modeling all have this many-task property. All will frequently have aggregate computing needs that require exascale computers [27].

Running many-task applications efficiently, reliably, and easily on large parallel computers is challenging. The many-task model may be split into two important processes: *task generation*, which evaluates a user program, often a dataflow script, and *task distribution*, which distributes the resulting tasks to workers. The user work is performed by *leaf functions*, which may be implemented in native code or as external applications. Leaf functions themselves may be multi-core or even multinode tasks. This computing model draws on recent trends that emphasize the identification of coarse-grained parallelism as a first distinct step in application development [19, 31, 33]. Additionally, applications built as workflows of many tasks are highly adaptable to complex, fault-prone environments [9].

1.2 Current approaches

Currently, many-task applications are programmed in two ways. In the first, the logic associated with the different tasks is integrated into a single program, and the tasks communicate through MPI messaging (where they exist in different memory spaces) or function calls (as in the parallel version of the Common Component Architecture, CCA [4], where components exist in the same memory space.) This approach uses familiar technologies but can be inefficient unless much effort is spent incorporating load-balancing algorithms into the application. Moreover, the approach can involve considerable programming effort if multiple component codes have to be tightly integrated.

Load balancing libraries based on MPI, such as the Asynchronous Dynamic Load Balancing Library (ADLB) [18], or on Global Arrays, such as Shared Collections of Task Objects (Scioto) [10], have recently emerged as promising solutions to aid in this approach. They provide a master/worker system with a put/get API for task descriptions, thus allowing workers to add work dynamically to the system. However, they lack a comprehensive programming model, data model, and other features required for high productivity programming.

In the second approach, a script or workflow is written that invokes the tasks, in sequence or in parallel, with each task reading and writing files from a shared file system. Examples include Dryad [15], Skywriting [20], and Swift [34]. This approach is convenient for the user, particularly when

```

1 Model m[];
2 Analysis a[];
3 Validity v[];
4 Plot p[];
5 int n;
6 foreach i in [0:n] {
7   // run model with random seed
8   m[i] = runModel(i);
9   a[i] = analyze(m[i]);
10  v[i] = validate(m[i]);
11  p[i] = plot(a[i], v[i]);
12 }

```

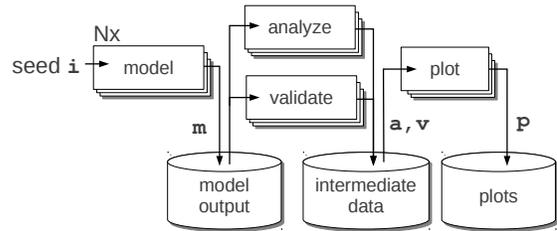


Figure 1: Swift example and corresponding dataflow diagram.

each task is a distinct executable program. Performance can be poor, however, since existing many-task scripting languages are implemented with *centralized evaluators* that cannot sustain the high overall task rate necessary to efficiently utilize $O(10^6)$ cores.

1.3 Turbine: a scalable dataflow engine

Consider the example application in Swift shown in Figure 1. This parallel `foreach` loop runs N independent instances of the model. In a dataflow language like Swift, this loop generates N concurrent loop iterations, each of which generates four user tasks with data dependencies. In previous implementations, the *evaluation* of the loop itself takes place on a single compute node (typically a cluster “login node”). Such nodes, even with many cores (today ranging from 8 to 24) are able to *generate* only about 500 tasks/s. Recently developed distribution systems such as Falcon [24] can *distribute* 3,000 tasks/s if the tasks are generated and enumerated in advance.

Despite the fact that the Swift language exposes abundant task parallelism, *the evaluation of the language has till now been constrained to take place on a single compute node.* Hence, task generation rates can be a significant scalability bottleneck. Consider a user task that occupies a whole node for 10 seconds. For an application to run 10^9 such tasks across 10^6 nodes, 1000 tasks must run per node, and 10^5 tasks must be initiated per second to keep that many cores fully utilized. *This is many orders of magnitude greater than the rates achievable with single-node dataflow language evaluation.*

We describe here an model capable of generating and distributing tasks at this scale. Our implementation, the distributed *Turbine* engine, allocates a small fraction of the system as control processes that cooperate to rapidly evaluate the user script. Its innovation is based on expressing the semantics of parallel dataflow in a language-independent representation with semantics similar to the Swift parallel scripting language, and implementing a distributed evalu-

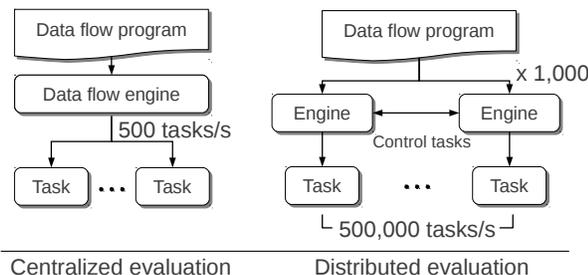


Figure 2: Left: prior centralized evaluator; Right: distributed evaluation with Turbine.

ation engine for that representation that decentralizes the overhead of task generation. Turbine execution employs distributed dependency processing, task distribution via a previously developed load balancer, and a distributed in-memory data store that makes script variables accessible from any node of a distributed-memory system. The system combines the performance benefits of explicitly parallel asynchronous load balancing with the programming productivity benefits of implicitly parallel dataflow scripting.

The remainder of this paper is organized as follows. In §2, we motivate this work by providing two representative examples of scripted applications. In §3, we describe the programming and task distribution models on which our work is based. In §4, we describe our design for parallel evaluation of Turbine programs. In §5, we present the implementation of the Turbine engine framework. In §6, we report performance results from the use of the implementation in various modes. In §7, we discuss other related work and in §8, we offer concluding remarks.

2. MOTIVATION: APPLICATIONS

Using parallel scripted to represent applications for many-task computations is convenient for both the user and the underlying evaluation engine. Traditionally, scripts have been imperative programs, with some exceptions such as `make` [12]. This section presents many-task applications that may be conveniently represented by the parallel scripting paradigm and motivates our work by demonstrating the need for a highly scalable many-task programming model.

2.1 Highly parallel land use modeling

The focus of the Decision Support System for Agrotechnology Transfer (DSSAT) application is to analyze the effects of climate change on agricultural production. Projections of crop yields at regional scales are carried out by running simulation ensemble studies on available datasets of land cover, soil, weather, management, and climate. The computational framework starts with the DSSAT crop systems model and evaluates this model in parallel by using Swift. Benchmarks have been performed on prototype simulation *campaigns*, measuring yield and climate impact for a single crop (maize) across the conterminous USA (120k cells) with daily weather data and climate model output spanning 120 years (1981-2100) and 16 different configurations of fertilizer, irrigation, and cultivar choice. Figure 3 shows a listing of the DSSAT application in Swift. It represents the prototype simulation carried out for four different

```

1  app (file output) RunDSSAT (file input[]) {
2  RunDSSAT @output @input ;
3  }
4
5  string campaigns[] = ["srb","ncep","cpc","cpc_srb"];
6  string glst[] = readData("gridList.txt");
7
8  foreach c in campaigns {
9  foreach g, i in gridList {
10     file out <strcat(cmp, "/", glst[i], ".tar">;
11     file in[] <strcat(c, "/", glst[i], "/*.*)>;
12     out = RunDSSAT(in);
13  }
14 }

```

Figure 3: Swift code for DSSAT application.

```

1  foreach i in innovation_values { // O(20)
2  foreach r in repeats { // 15
3  iterate cycle in annealing_cycles { // O(100)
4  iterate p in params { // 3
5  foreach n in reruns { // 1000
6  evolve(...); // 0.1 to 50 seconds
7  }}}

```

Figure 4: Swift code for SciColSim application.

campaigns, each running 120,000 jobs. Future DSSAT runs are expected to run at a global scale, cover more crops, and consume more computation time by 3-4 orders of magnitude.

2.2 Scientific collaboration graph analysis

The SciColSim project assesses and predicts scientific progress through a stochastic analysis of scientific collaboration networks. The software mines scientific publications for author lists and other indicators of collaboration. The strategy is to devise parameters whose values model real-world human interactions. These parameters are governed by an “evolve” function that performs a simulated annealing. A “loss” factor is computed on each iteration of annealing denoting the amount of effort expended.

Swift-like psuedo-code for this application is shown in Figure 4. Note that Swift’s `foreach` statement indicates a parallel loop, whereas the `iterate` statement indicates a sequential loop. The computation involves a repetition of annealing cycles over a range of innovation values recomputed for increased precision. The number of jobs as a result of these computations is on the order of 10 million for a single production run, with complex dependencies due to the interaction of the loop types.

2.3 Other applications

In addition to the mentioned applications, ensemble studies involving different methodologies such as uncertainty quantification, parameter estimation, massive graph pruning and inverse modeling all require the ability to generate and dispatch tasks in the order of millions to the distributed resources. *Power grid distribution design* is an example of a problem that involves solving a single-integer nonconvex optimization problem. The initial solution reveals how to subdivide the domain (*branching*); then, a new, tighter approximation is constructed on the subdomain and solved. A problem with partial differential equation constraints could require the solution of 1,000 subdomains, each using 1,000 processors, allowing the use of 1 million processors simulta-

Table 1: Quantitative description of applications and required performance on 10^6 cores.

| Application | Stage | Measured | | Required | |
|-------------------------|-------------------|------------|---------------|----------|---------------------|
| | | Tasks | Task Duration | Tasks | Task Rate |
| Power-grid Distribution | economic-dispatch | 10,000 | 15 s | 10^9 | $6.6 \times 10^4/s$ |
| DSSAT | runDSSAT | 500,000 | 12 s | 10^9 | $8.3 \times 10^4/s$ |
| SciColSim | evolve | 10,800,000 | 10 s | 10^9 | $10^5/s$ |
| SWAT | swat | 2,200 | 3-6 h | 10^5 | 55/s |
| modftdock | dock | 1,200,000 | 1,000 s | 10^9 | $10^3/s$ |
| | modmerge | 12,000 | 5 s | 10^7 | $2 \times 10^5/s$ |
| | score | 12,000 | 6,000 s | 10^7 | 166/s |

neously. *Regional watershed analysis and hydrology* are investigated by the Soil and Water Assessment Tool (SWAT), which analyzes hundreds of thousands of data files via Matlab scripts on hundreds of cores. This application will utilize tens of thousands of cores and more data in the future. SWAT is a motivator for our work because of the large number of data files. *Biomolecular analysis* via ModFTDock results in a large quantity of available tasks [14], and represents a complex, multi-stage workflow.

Summary. Table 1 shows a summary of required task rates for a full utilization of 10^6 cores at a stable state. Excluding the ramp up and ramp down stage, a steady flow of tasks per second is determined by a division of number of cores by task duration. Turbine was designed based on the computational properties these applications display, and we intend that performance and resource utilization will increase when these applications are run on the new system.

3. PROGRAMMING AND TASK DISTRIBUTION MODELS: SWIFT AND ADLB

The work described here builds on the Swift parallel scripting programming model, which has been used to express a wide range of many-task applications, and the Asynchronous Distributed Load Balancing library (ADLB), which provides the underlying task distribution framework for Turbine.

Swift [34] is a parallel scripting language for scientific computing. The features of this typed and concurrent language that support distributed scientific batch computing, include data structures (arrays, structures), string processing, use of external programs, and external data access to filesystem structures. The current Swift implementation compiles programs into the Karajan workflow language, which is interpreted by a runtime system based on the Java CoG Kit [30]. While Swift can generate and schedule thousands of tasks and manage their execution on a wide range of distributed resources, each Swift script is evaluated on one node, resulting in a performance bottleneck. Removing such bottlenecks is the primary motivation for the work described here.

ADLB [18] is an MPI-based library for managing a large distributed work pool. ADLB applications use a simple put/get interface to deposit “work packages” into a distributed work pool and retrieve them. Work package types, priorities, and “targets” allow this interface to implement sophisticated variations on the classical master/worker parallel programming model. ADLB is efficient (can deposit up to 25,000 work packets per second per node on an Ethernet-connected Linux cluster) and scalable (has run on 131,000 cores on an IBM BG/P for nuclear physics applications [18]). ADLB is used as the load-balancing component of Turbine, where its

work packages are the indecomposable tasks generated by the system. The implementation of its API is invisible to the application (Turbine, in this case) and the work packages it manages are opaque to ADLB. An experimental addition to ADLB has been developed to support the Turbine data store, implementing a publish/subscribe interface.

4. SCALABLE DISTRIBUTED DATAFLOW PROCESSING

We describe here the evaluation model that Turbine uses to execute programs with implicitly concurrent dataflow semantics. Turbine’s function is to interpret an intermediate representation of a dataflow program on a distributed-memory computing resource. Turbine specifies semantics similar to those of the Swift parallel scripting language; however, it is general enough to serve as a model for performing the parallel evaluation of many similar languages.

The main aspects of the Turbine model are as follows.

Implicit, pervasive parallelism. Most statements are relations between single assignment variables. Dynamic data dependency management enables expressions to be evaluated and statements executed when their data dependencies are met.

Typed variables and objects. Variables and objects are constructed with a simple type model comprising the typical primitive scalar types, a container type for implementing arrays and structures, and a file type for external files and external in-memory variables.

Constructs to support external execution. Most application-level work is performed by external user application components (programs or functions); Turbine is primarily a means to carry out the composition of the application components.

4.1 The Swift programming model

To underscore the motivation for this work, we briefly summarize the Swift program evaluation model [34]. A Swift program starts in a global scope in which variables may be defined. Attempting to assign to a scalar variable more than once is an error detectable at compile time. All statements in the scope are allowed to make progress concurrently, in dataflow order. Statements that must wait on input variables are recorded and entered into a data structure that will be notified when the inputs are stored. Upon notification, the statement is started. When variables are returned by functions, they are closed. Input and output variables passed to functions exist in the original caller’s scope and are passed and accessed by reference. Since input variables cannot be modified in the called function, they behave as if

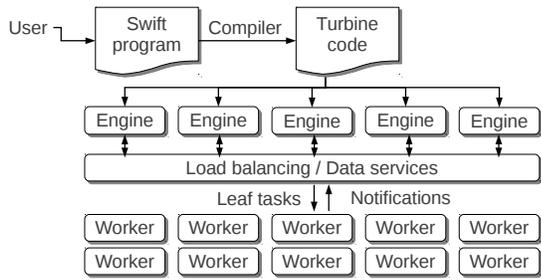


Figure 5: Turbine component architecture.

passed by value.

A key feature of Swift is the distinction between composite functions and leaf functions (denoted with the `app` keyword). Composite invocations cause the creation of new scopes (stack frames) in which new local variables are dynamically created and new statements may be issued. Leaf functions are used to launch external execution. Originally, this was used primarily to launch remote execution using techniques related to grid computing.

The original Swift system can support large scripts that run on thousands of cores. However, the evaluation of the script itself is constrained to run on a single node. This limitation is in large part due to the fact that Swift’s data dependency model is a shared in-memory data structure in a single node; no mechanism exists for cross-address-space communication and synchronization of the state of future objects. The execution model of Turbine eliminates the limitations of this centralized evaluation model.

4.2 Overview of Turbine features

The high-level architecture of Turbine is shown in Figure 5. The center of the system is the network of ADLB *servers*, which provide load balancing and data services. *Engines* evaluate the user Turbine code and its data dependencies, generating and submitting tasks to other engines and to *workers* which execute external code such as user programs and functions. Tasks may store data, resulting in notifications to listening engines, allowing them to satisfy data dependencies and release more tasks.

Turbine operations include data manipulation, the definition of data-dependent execution expressed as data-dependent *statements*, and higher-level constructs such as loops and function calls. Programs consist of *composite functions*, which are essentially a context in which to define a body of statements. *Leaf functions* are provided by the system as built-ins or may be defined by the user execute to external (leaf) tasks; this is the primary method of performing user work. Generally, composite functions are executed by engines and leaf functions are executed by workers. Each statement calls a composite or leaf function on input and output variables. Thus, statements serve as links from task outputs to inputs, forming an implicit, distributed task graph as the script executes.

Variables are typed in-memory representations of user data. Variable values may be scalars, such as integers or strings or containers representing language-level features, such as arrays or structures (records). All variables are single-assignment futures: they are open when defined and closed after a value

has been assigned. Containers are also futures, as are each of their members. Containers can be open or closed; while they are open, their members can be assigned values. A container is closed by Turbine when all program branches eligible to modify the container complete. In practice, this action is controlled in the translation from the source (Swift) program by scope analysis and the detection of the last write, the end of the scope in which it is defined, as any returned containers must be closed output variables. *Scopes* (i.e., stack frames) provide a context for variable name references. Scopes are composed into a linked call stack. Execution continues until all statements complete.

Script variables are stored in a globally accessible data store provided by the servers. Turbine operations are available to store and retrieve data to local memory as in a typical load-store architecture.

Data dependencies for statements are stored locally on the engine that issued the statement. Engines register notifications with the global data store to make progress on data-dependent statements when data is stored, regardless of which process stored the data.

Thus, the main contribution of Turbine that facilitates distributed evaluation is a *distributed variable store based on futures*. This store, accessible from any computing node within a Turbine program, enables values produced by a function executing on one node to be passed to and consumed by a function executing on another; the store manages the requisite event subscriptions and notifications. Examples of the use of the distributed future store follow in the next section.

4.3 Turbine use cases

In this section, we enumerate critical high-level dataflow language features as expressed by Swift examples and demonstrate that our highly distributed evaluation model satisfies the required feature set.

Basic dataflow. Turbine statements that require variables to be set before they can execute (primarily the primitives that call an external user application function or program) are expressed as the target operations of statements that specify the action, the input dependencies required for the action to execute, and what output data objects are then set by the action.

Consider the fragment derived from the example in Figure 1:

```

1 | Model m; // ... etc.
2 | m = runModel();
3 | a = analyze(m);
4 | v = validate(m);
5 | p = plot(a, v);

```

Example 1(a): Swift

This fragment assumes variables `a`, `v`, and `p` are to be returned to a calling procedure. The input and output data dependencies are captured in the following four Turbine statements:

```

1 | allocate m # ... etc.
2 | call_app runModel [ m ] [ ]
3 | call_app analyze [ a ] [ m ]
4 | call_app validate [ v ] [ m ]
5 | call_app plot [ p ] [ a v ]

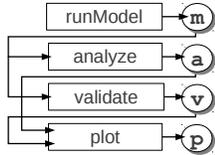
```

Example 1(b): Turbine

These statements correspond to data dependencies stored in the process that evaluated them. Data definitions correspond to addresses in the global data store. The `runModel`

task may result in a task issued to the worker processes; when `m` is set by the worker as a result of the first action, the engines responsible for dependent actions are notified, and progress is made.

Each Turbine engine maintains a list of data-dependent statements that have been previously read. Additionally, variable addresses are cached. Thus, a sequence of statements as given in Example 1(b) results in an internal data structure that links variable addresses to statement actions. As shown in the figure below, the `runModel` task has no dependencies. Statements `analyze` and `validate` refer to data `m`, which the engine links to the execution of these statements.



Expression evaluation. In practice, scripting languages provide much more than the coordination of external execution. Because Swift and other higher-level workflow languages offer convenient arithmetic and string operations, processing expressions is a critical feature. The following Swift fragment shows the declaration of two integers, their addition, and the printed result via the built-in `trace`.

```
1 | int i = 3, j = 4, k;
2 | k = i + j;
3 | trace(k);
```

Example 2(a): Swift

At the Turbine level, this results in the declaration of three script variables and two statements. At run time, all five lines are read by the Turbine engine. Variable `k` is open. Statement `plus_integer`, a built-in, is ready because its inputs, two literals, are closed. The engine executes this function, which closes `k`. The engine notifies itself that `k` is closed, which makes statement `trace` ready; it is then executed.

```
1 | allocate i integer 3
2 | allocate j integer 4
3 | allocate k integer
4 | call_builtin plus_integer [ i j ] [ k ]
5 | call_builtin trace [ k ] [ ]
```

Example 2(b): Turbine

Conditional execution. Turbine offers a complete set of features to enable high-level programming constructs. Conditional execution is available in Swift in a conventional way. The following example shows that the output of a user function may be checked for a condition, resulting in a context block for additional statements:

```
1 | c = extractStatistic(a);
2 | if (c) {
3 |   trace("Warning: c is non-zero");
4 | }
```

Example 3(a): Swift

At the Turbine level, the conditional statement is dependent on a single input, the result of the conditional expression. When it executes, it essentially executes as a built-in that conditionally jumps into a separate context block. This

block is trivially generated by the compiler from the body of the conditional construct. Code executing in the body block references variables as though it were in the original context by retrieving from the data store.

```
1 | ... # open code
2 | call_app extractStatistic [ a ] [ c ]
3 | statement [ c ] if-1 [ c ]
4 | }
5 |
6 | proc if-1 { c } {
7 |   set v:c [ get_integer c ]
8 |   if (v:c) {
9 |     allocate s string "Warning: c is non-zero"
10 |    call_builtin trace [ ] [ s ]
11 |   }
12 | }
```

Example 3(b): Turbine

Our compiler is capable of translating `switch` and `else if` expressions using this basic technique.

Since the variables are accessible in the global data store, and the condition could be blocked for a long time (e.g., if `extractStatistic` is expensive), the condition body block could be started on another engine. However, since the dependencies here are essentially linear, shipping the execution would yield no scalability benefit and would just generate additional traffic to the load-balancing layer. Consequently, our model does not distribute conditional execution.

Composite functions. As discussed previously, there are two main types of user functions: composite functions and leaf functions. Leaf functions are opaque to the dataflow engine and are considered in §5. Composite functions provide a context in which to declare data and issue statements. Since statements are eligible to be executed concurrently, composite function call stacks enable concurrency.

Example 4(a) shows part of the recursive implementation of the n th Fibonacci number in Swift syntax. The two recursive calls to `fib` may be executed concurrently. Thus, Turbine packs these statements as work units tagged for execution on peer engines as made available by the load balancer.

```
1 | (int f) fib(int n) {
2 |   if (n > 2)
3 |     f = fib(n-1) + fib(n-2);
4 |   ...
5 | }
```

Example 4(a): Swift

The translated Turbine code below demonstrates that after the arithmetic operations are laid out, `call_composite` is used to issue the two recursive calls on *different* engines as selected by the load balancer. When such a work unit is received by another engine, it unpacks the statement and its attached data addresses (e.g., `f` and `n`), jumps into the appropriate block, and evaluates the statements encountered there.

```
1 | proc fib { n f } {
2 |   allocate t0 integer 1
3 |   allocate t1 integer
4 |   allocate t2 integer
5 |   call_builtin minus_integer [ t1 ] [ n t0 ]
6 |   # fib(n-1)
7 |   call_composite fib [ t2 ] [ t1 ]
8 |   ...
9 |   # fib(n-2)
10 |  call_composite fib ...
11 |  call_builtin plus_integer [ f ] [ t2 ... ]
12 |  ...
13 | }
```

Example 4(b): Turbine

Data structures. Swift contains multiple features for structured data, including C-like arrays and structs. Swift arrays may be treated as associative arrays; the subscripts may be strings, and so forth. Structured data members are linked into the containing data item, which acts as a table. These structures are fully recursive. Structured data variables may be treated as futures, enabling statements that are dependent on the whole variable. Swift arrays and structs are allocated automatically as necessary by the compiler and are closed automatically by the runtime system when no more modifications to the data structure are possible. Swift limits the possible modifications to a structured data item to the scope in which it was declared; in other scopes, the data is read-only.

As shown, `eye2` builds a 2×2 array. The data structure `a` is allocated by the compiler since it is the function output.

```

1 | (int a[ ][ ]) eye2() {
2 |   a[0][0] = 1;
3 |   a[0][1] = 0;
4 |   a[1][0] = 0;
5 |   a[1][1] = 1;
6 | }

```

Example 5(a): Swift

In the Turbine implementation, a reusable *containers* abstraction is used to represent linked data structures. A container variable, stored in a globally accessible location, allows a user to insert and look up container subscripts to store and obtain data addresses for the linked items.

In the example below, multiple containers are allocated by the `data` `container` statement, including the top-level container `a`, the container `t2=a[0]`, etc. The `container_insert` command inserts `t1` at `a[0]`, and so on.

```

1 | proc eye2 { a } {
2 |   allocate_container a
3 |   allocate_container t1
4 |   allocate_container t2
5 |   allocate i0 integer 0
6 |   allocate i1 integer 1
7 |   container_insert_imm a 0 t1
8 |   container_insert_imm t1 0 i0
9 |   container_insert_imm t1 1 i1
10 |   ...
11 | }

```

Example 5(b): Turbine

When `eye2` returns, `a` is closed, and no further changes may be made. Thus, a user statement could be issued that is dependent on the whole array.

Iterations. The primary iteration method in Swift is the `foreach` statement, which iterates over an array. At each iteration, the index and value are available to the executing block. In the example below, the user transforms each `a[i]` to `b[i]` via `f`:

```

1 | int b[ ];
2 | foreach i, v in a {
3 |   b[i] = f(a[i]);
4 | }

```

Example 6(a): Swift

Each execution is available to be run concurrently, that is, when each `a[i]` is closed. Thus, we reuse our block statement distribution technique on a compiler-generated block:

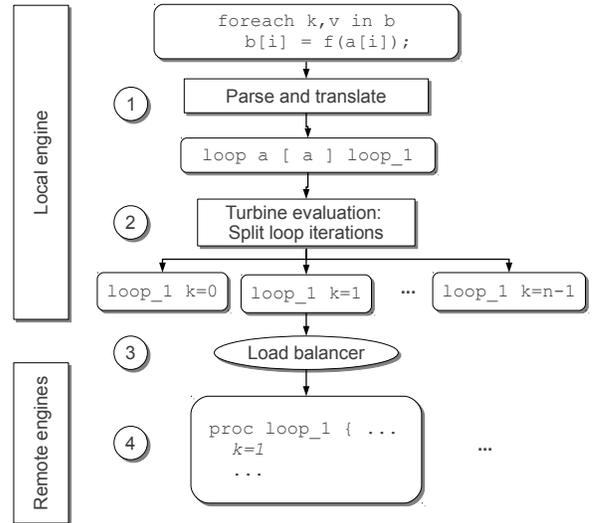


Figure 6: Distributed iteration in Turbine.

```

1 | ... # open code
2 | allocate_container b
3 | loop a [ a ] loop_1
4 | }
5 |
6 | # inputs: loop counter, loop variable and additional
7 | proc loop_1 { i v a } {
8 |   # t1 is a local value
9 |   set t1 [ container_lookup_imm [ a i ] ]
10 |  allocate t2 integer
11 |  call_composite f [ t2 ] [ t1 ]
12 |  container_insert_imm b i t2
13 | }

```

Example 6(b): Turbine

The built-in `statement` `loop` retrieves the set of available indices in `a`; for each index, a work unit for block `loop_1` is sent to the load balancer for execution on a separate engine. Thus, data dependencies created by statements in each iteration are balanced among those engines.

An example of this process is shown in Figure 6. First, the user script is translated into the Turbine format ①. Following Example 6(b), a `loop` statement is evaluated, resulting in the interpretation of a distributed loop operation, producing additional new work units containing script fragments ②. These fragments are distributed by using the load balancer system ③ and are evaluated by engines elsewhere, resulting in the evaluation of application programs or functions, which are blocks of Turbine statements ④. These blocks execute, producing data-dependent expressions for their respective local engines.

5. TURBINE ENGINE IMPLEMENTATION

In this section, we describe our prototype implementation of Turbine, which implements the model described in the previous section.

5.1 Program structure

To represent the functionality described in §4, the Turbine implementation consists of the following components:

- A compiler to translate the high-level language (e.g. Swift) into its Turbine representation

- The load balancing and data access services
- The data dependency engine logic
- Built-ins and features to perform external execution and data operations

The source program (e.g., in Swift) is translated into its Turbine representation by a provided compiler, described elsewhere [2].

In our prototyping work, we leverage Tcl [32] as the implementation language and express available operations as Tcl extensions. We provide a Tcl interface to ADLB to operate as the load balancer. The load balancer was extended with data operations; thus, in addition to task operations, data storage, retrieval, and notification operations are available. ADLB programs are standard MPI programs that can be launched by `mpirun` (see §3). Generated Turbine programs are essentially ADLB programs in which some workers act as data dependency processing engines. Core Turbine features were implemented as a C-based Tcl extension as well. Tcl features are used simply to represent the user script and not to carry out performance-critical logic.

The engines cooperate to evaluate the user script using the techniques in §4 to produce execution units for distribution by the distribution system. The engines use the ADLB API to create new tasks and to distribute the computational work involved in evaluating parallel loops and composite function calls — the two main concurrent language constructs.

ADLB performs highly scalable task distribution but does incur some client overhead and latency to ingest tasks. As more ADLB client processes are employed to feed ADLB servers, this overhead becomes more distributed, and the overall task ingestion and execution capacity increases. Each client is attached to one server, and traffic on one server does not congest other server processes. ADLB can scale task ingestion fairly linearly with the number of servers on systems with hundreds of thousands of cores. Thus a primary design goal of the Turbine system is to distribute the work of script evaluation to maximize the ADLB task ingestion rate and hence the utilization of extreme-scale computing systems.

5.2 Distributed data storage in Turbine

The fundamental system mechanics required to perform the operations required by the previous section were developed in Turbine, a novel *distributed future store*. The Turbine implementation comprises a globally addressable data store, an evaluation engine, a subscription mechanism, and an external application function evaluator. Turbine script variable data is stored on servers and processed by engines and workers. These variables may be `string`, `integer`, `float`, `file`, or `container` data.

Variable addresses in Turbine are represented as 64-bit integers. Addresses are mapped to responsible server ranks through a simple hashing scheme. Unique addresses may be obtained from servers. Given an address, a variable may be allocated and initialized at that location. An initialized variable may be the target of a notification request by any process. A variable may be set once with a value, after which the value may be obtained by any process.

Progress is made when futures are set and engines receive notification that new input data is available. Turbine uses a simple subscription mechanism whereby engines notify servers that they must be notified when a data item is

ready. As a result, the engine either 1) finds that the data item is already closed or 2) is guaranteed to be notified when it is. When a data item is closed, the closing process receives a list of engines that must be notified regarding the closure of that item, which allows dependent statements to progress.

A variable of type `file` is associated with a string file name; however, unlike a `string`, it may be read before the file is closed. Thus, output file locations may be used in Turbine statements as *output* data, but the file name string may be obtained to enable the creation of a shell command line.

```

1 | allocate a file "input.txt"
2 | allocate b file "output.txt"
3 | call_app create_file [ a ] [ ]
4 | call_app copy_file [ b ] [ a ]

```

At the end of this code fragment, `output.txt` is closed, allowing it to be used as the input to other Turbine tasks. Note that this file-type variable does not represent the contents of the file; it is simply the future variable corresponding to the existence of the file with the given name. The user leaf task (here, `copy_file`) is responsible for carrying out I/O.

Container variables are similar to other Turbine script variables, but the value of a container variable is a mapping from keys to Turbine variable addresses. Operations are available to insert, lookup, and list values in containers.

6. PERFORMANCE RESULTS

Our performance results focus on three main aspects of Turbine performance: task distribution using ADLB, data operations using the new ADLB data services, and evaluation of the distributed Turbine loop construct. These demonstrate the ability of Turbine to meet the performance goals required by our applications.

In each case, we present results from systems of Turbine control processes and neglect worker processes because the focus of this paper is our distributed-memory dataflow evaluation functionality and not task distribution. We report elsewhere [2] that the full implementation, including worker processes, is capable of achieving 90% utilization on 64K cores of the Blue Gene/P for 10-second tasks in a case compiled from a realistic Swift program.

All presented results were obtained on the SiCortex 5872 at Argonne. Each MPI process was assigned to a single core of a six-core SiCortex node, which runs at 633 MHz and contains 4 GB RAM. The SiCortex contains a proprietary interconnect with ~1 microsecond latency.

6.1 Raw task distribution

To evaluate the ability of the Turbine architecture to meet its performance requirements, we first report the performance of ADLB. Following that model, each ADLB server occupies one control process. Thus, we desire to measure the task throughput rate of a single ADLB server. We configured ADLB with one server and a given number of workers. A single worker reads an input file containing a list of tasks for distribution over ADLB to other workers. This emulates a Turbine use case with a single engine that can produce tasks as fast as lines can be read from an input file. Two cases are measured: one in which workers execute `sleep` for a zero-duration run (labeled “/bin/sleep”) and one in which they do nothing (labeled “no-op”).

The results are shown in Figure 7. In the no-op case, for increasing numbers of client processes, performance im-

proved until the number of clients was 384. At that point, the ADLB server was processing 21,099 tasks/s, far exceeding the desired rate of 1,000 tasks/s per control process. The no-op performance is then limited by the single-node performance and does not increase as the number of clients is increased to 512. When the user task actually performs a potentially useful operation such as calling an external application (`/bin/sleep`), the single-node ADLB server performance is not reached by 512 client processes.

We note that in practice a Turbine application may post multiple “system” tasks through ADLB in addition to the “user” tasks required for the user application. Thus, the available extra processing on the ADLB server is appropriate. Overall, this test indicates that ADLB can support the system at the desired scale.

6.2 Data operations

Next, we measure another key underlying service used by the Turbine architecture: the ADLB-based data store. This new component is intended to scale with the number of tasks running in the system; each task will need to read and write multiple small variables in the data store to enable the user script to make progress.

We configured a Turbine system with a given number of servers and clients and with one engine that is idle. ADLB store operations are performed on each client, each working on independent data. Each client interacts with different servers on each operation. Each client creates 200,000 small data items in a two-step process compatible with the dataflow model; they are first allocated and initialized, then set with a value and closed.

Figure 8 shows that for increasing numbers of servers and clients, the insertion rate increases monotonically. In the largest case, 1,024 servers were targeted by 1,023 workers with 1 idle engine, achieving an insertion rate of 19,883,495 items/s. Since data operations are independent, congestion occurs only when a server is targeted by multiple simultaneous operations, creating a temporary hot spot. Continuing with the performance target of 1,000 tasks/s per server, this allows each task to perform almost 20 data operations without posing a performance problem.

The data item identifiers were selected randomly, thus the target servers were selected randomly. Using the existing Turbine and ADLB APIs, an advanced application could be more selective about data locations, eliminating the impact of hot spots. This case does not measure the performance

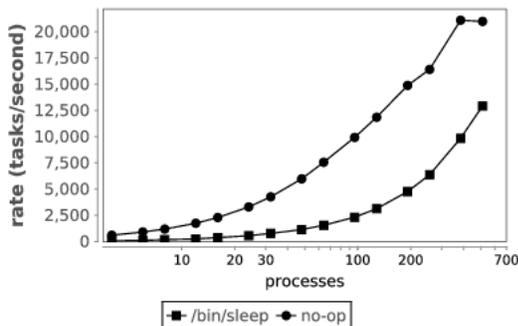


Figure 7: Task rate result for ADLB on SiCortex.

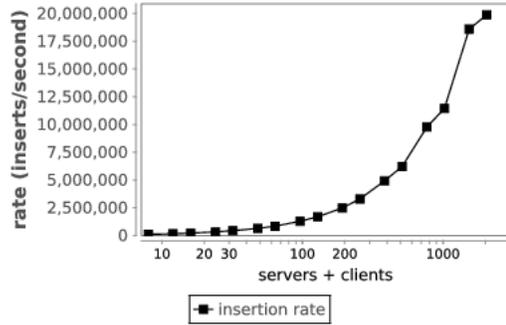


Figure 8: Data access rate result for ADLB on SiCortex.

of data retrieval operations, covered implicitly in §6.4.

6.3 Distributed data structure creation

Thus far we have measured only the performance of underlying services. Here, we investigate the scalability of the distributed engine processes. The engines are capable of splitting certain large operations to distribute script processing work. An important use case is the construction of a distributed container, which is a key part of dataflow scripts operating on structured data. The underlying operations here are used to implement Swift’s range operator, which is analogous to the colon syntax in Matlab; for example, `[0:10]` produces the list of integers from 0 to 10. This can be performed in Turbine by cooperating engines, resulting in a distributed data structure useful for further processing.

We measured the performance of the creation of distributed containers on multiple engines. For each case plotted, a Turbine system was configured to use the given number of engines and servers. A Turbine distributed range operation was issued, creating a large container of containers. This triggered the creation of script variables storing all integers from 0 to $N \times 100,000$, where N is the number of Turbine engine processes. The operation was split so that all engines were able to create and fill small containers that were then linked into the top-level container. Workers were not involved in this operation.

Figure 9 shows that the number of cooperating control processes, increasing to the maximal 2,048, half of which act as ADLB servers and half of which act as Turbine engines, does not reach a performance peak. Each operation creates an integer script variable for later use. At the maximum measured system size, the system created 1,262,639 usable script variables per second, in addition to performing data structure processing overhead, totaling 204,800,000 integer script variables in addition to container structures.

6.4 Distributed iteration

Once the application script has created a distributed data structure, it is necessary to iterate over the structure and use its contents as input for further processing. For example, once the distributed container is created in the previous test, it can be used as the target of a `foreach` iteration by multiple cooperating engines.

To measure the performance of the evaluation of distributed loops on multiple engines, for each case plotted, we configured a Turbine system to use the given number of engines

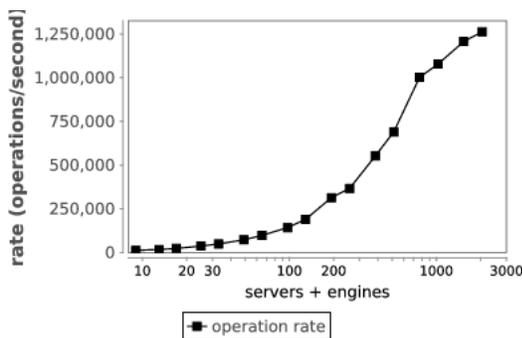


Figure 9: Range creation rate result for Turbine on SiCortex.

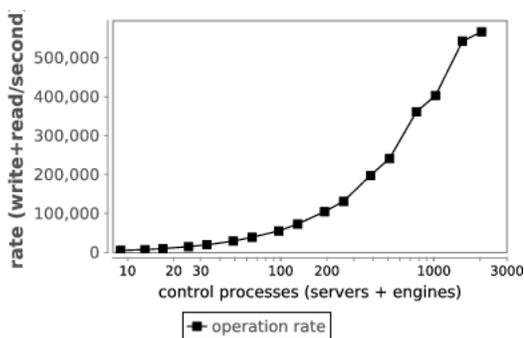


Figure 10: Range creation, iteration rate result for Turbine on SiCortex.

and servers. In each case, a Turbine distributed range operation is issued, which creates a large container of containers. The operation is split so that all engines are able to create and fill small containers that are then linked into the top-level container. Then, the engines execute no-op tasks that read each entry in the container once. The measurement was made over the whole run, capturing range creation and iteration. Thus, each “operation” measured by the test is a complex process that represents the lifetime of a user script variable in a Turbine distributed data structure.

As in the previous test, each engine creates 100,000 variables and links them into the distributed container, over which a distributed iteration loop is carried out. Figure 10 shows that performance increases monotonically up to the largest measured system, containing 1,024 servers and 1,024 engines, in addition to 1 idle worker. At this scale, Turbine processes 566,685 operations per second.

There are multiple ways that performance could be improved. First, this test was performed on the individually slow SiCortex processors. Additionally, we plan multiple optimizations to improve this performance. As noted in the previous test, variables are created in a multiple-step manner corresponding to a straight-forward use of our dataflow model. Since we are creating “literal” integers, these steps could be replaced with composite operations that allocate, initialize, and set values in one step. Multiple literals could be simultaneously set if batch operations were added to the API. The loop-splitting algorithm itself is targeted for optimization and better load balancing. As a last resort, an application could use proportionally more processes as control processes and fewer workers.

7. RELATED WORK

Our work is related to a broad range of previous work, including programming models and languages, task distribution systems, and distributed data systems. These parallel task distribution frameworks and languages provide mechanisms to define, dispatch and execute tasks over a distributed computing infrastructure or provide distributed access to data, but they have important differences from our work in scope or focus.

7.1 Many-task programming models

Recent years have seen a proliferation of programming models and languages for distributed computing.

One family comprises the “big data” languages and programming models strongly influenced by MapReduce [7], which are aimed at processing extremely large batches of data, typically in the form of records. Task throughput is not an important determinant of performance, unlike in our work, because very large numbers of records are processed by each task. The other major family closest to our work is Partitioned Global Address Space (PGAS) languages, which are designed for HPC applications and provide some related features but differ greatly in their design and focus.

Skywriting [20] is a coordination language that can distribute computations expressed as iterative and recursive functions. It is dynamically typed, and it offers limited data mapping mechanisms through a static file referencing; our language model offers a wider range of static types with a rich variable-data association through its dynamic mapping mechanism. The underlying execution engine, called CIEL [21], is based on a master/worker computation paradigm where workers can spawn new tasks and report back to the master. A limited form of distributed execution is supported, where the control script can be evaluated in parallel on different cluster nodes. The CIEL implementation is not designed specifically for high task rates: task management is centralized, and communication uses HTTP over TCP/IP rather than a higher-performance alternative.

Interpreted languages building on MapReduce to provide higher-level programming models include Sawzall [23], Pig Latin [22] and Hive [29]. These languages share our goal of providing a programming tool for the specification and execution of large parallel computations on large quantities of data and facilitating the utilization of large distributed resources. However, the MapReduce programming model just supports key-value pairs as input or output datasets and offers two types of computation functions, map and reduce, with more complex dataflow patterns requiring multiple MapReduce stages. In contrast, we implement a full programming language with a type system, complex data structures, and arbitrary computational procedures. Some systems such as Spark [36] and Twister [11] are incremental extensions to the MapReduce model to support iterative computations, but this approach does not give the same flexibility or expressiveness as a new language.

Dryad [15] is an infrastructure for running data-parallel programs on a parallel or distributed system, with functionality roughly a superset of MapReduce. In addition to the

MapReduce communication pattern, many other dataflow patterns can be specified. Communication between Dryad operators can use TCP pipes and shared-memory FIFOs to be the communication as well as files. Dryad dataflow graphs are explicitly developed by the programmer; whereas our dataflow model is implicit. Furthermore, Dryad’s dataflow graphs cannot easily express data-driven control flow, a key feature of Swift. Higher-level languages have been built on Dryad: a scripting language called Nebula, which does not seem to be in current use, and DryadLINQ [35], which generates Dryad computations from the LINQ extensions to C#.

7.2 Approaches to task distribution

Scioto [10] is a lightweight framework for providing task management on distributed-memory machines under one-sided and global-view parallel programming models. Scioto has strong similarities to ADLB: both are libraries providing dynamic load balancing for HPC applications.

Falcon [24] performs dynamic task distribution and load balancing. Task distribution is distributed but uses a hierarchical tree structure, with tasks inserted into the system from the top of the tree, in contrast to the flatter decentralized structure of ADLB.

DAGuE [6] is a framework for scheduling and management of tasks on distributed and many-core computing environments. The programming model is minimalist, based around explicit specification task of DAGs, which does not bear much resemblance to a traditional programming languages, and does not support data structures such as arrays.

Cilk-NOW [5] is a distributed-memory version of a functional subset of the Cilk task-parallel programming model. It provides fault tolerance and load balancing on networks of commodity machines but does not provide globally visible data structures.

7.3 Approaches to distributed data

Linda [1] introduced the idea of a distributed tuple space, a key concept in ADLB and Turbine. This idea was further developed for distributed computing in Comet [17] which has a goal similar to that of our work but focuses on distributed computing and is not concerned with scalability on HPC systems. Turbine’s data store is different in functionality because it is designed primarily to support the implementation of a higher-level language. It does not support lookup based on templates or approximate key, only lookup of values by exact key.

Recently, considerable research has been devoted to distributed *key-value stores*, which are not fundamentally different from tuple spaces but tend to emphasize simple data-storage rather than data-driven coordination and support simpler query methods such as exact key lookups or range queries. Memcached [13] is a simple RAM-based key-value store that provides high performance with no durability and minimal consistency guarantees; it provides a single, completely flat hash table with opaque keys and values. Redis [25] provides similar functionality to memcached, as well as a range of data structures including hashtables and lists and the ability to subscribe to data items. Other, more sophisticated key-value stores that are highly scalable, use disk storage, and provide consistency and durability guarantees include Dynamo [8] and Cassandra [16]. While these key-value systems provide a range of options for data storage, they do not take advantage of high-performance message

passing available on many clusters and do not provide all of the coordination primitives that were required in Turbine to implement a dataflow language like Swift.

8. CONCLUSION

We have described three main contributions of the Turbine engine and its programming model.

First, we have identified many-task, dataflow programs as a highly useful model for many real-world applications, many of which are currently running in Swift. We provided projections of exascale parameters for these systems, resulting in requirements for a next-generation task generator.

Second, we identified the need for a distributed-memory system for the evaluation of the task-generating script. We identified the *distributed future store* as a key component and produced a high performance implementation. This involved the development of a dependency processing engine, a scalable data store, and supporting libraries to provide highly scalable data structure and loop processing.

Third, we reported the performance results from running the core system features on the SiCortex. The results show that the system can achieve the required performance for extreme cases.

While the Turbine execution model is based on the semantics of Swift, it is actually much more general. We believe that it is additionally capable of executing the dataflow semantics of languages such as Dryad, CIEL, and PyDFlow, and could thus serve as a prototype for a common execution model for these and similar languages.

Acknowledgments

This work was supported in part by the U.S. Department of Energy under the ASCR X-Stack program (contract DE-SC0005380) and contract DE-AC02-06CH11357. Computing resources were provided by the Mathematics and Computer Science Division and Argonne Leadership Computing Facility at Argonne National Laboratory.

The authors thank Matei Ripeanu and Gail Pieper for many helpful comments, and our application collaborators: Joshua Elliott (DSSAT), Andrey Rzhetsky (SciColSim), Victor Zavala (Power Grid), Yonas K. Demissie and Eugene Yan (SWAT), and Marc Parisien (ModFTDock).

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