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Flexible and Scalable Data Fusion using Proactive, Schemaless Information Services

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Abstract

Exascale data environments are fast approaching, driven by diverse structured and unstructured data such as system and application telemetry streams, open-source information capture, and on-demand simulation output. Storage costs having plummeted, the question is now one of converting vast stores of data to actionable information. Complicating this problem are the low degrees of awareness across domain boundaries about what potentially useful data may exist, and write-once-read-never issues (data generation/collection rates outpacing data analysis and integration rates). Increasingly, technologists and researchers need to correlate previously unrelated data sources and artifacts to produce fused data views for domain-specific purposes. New tools and approaches for creating such views from vast amounts of data are vitally important to maintaining research and operational momentum. We propose to research and develop tools and services to assist in the creation, refinement, discovery and reuse of fused data views over large, diverse collections of heterogeneously structured data. We innovate in the following ways. First, we enable and encourage end-users to introduce customized index methods selected for local benefit rather than for global interaction (flexible multi-indexing). We envision rich combinations of such views on application data: views that span backing stores with different semantics, that introduce analytic methods of indexing, and that define multiple views on individual data items. We specifically decline to build a big fused database of everything providing a centralized index over all data, or to export a rigid schema to all comers as in federated query approaches. Second, we proactively advertise these

application-specific views so that they may be programmatically reused and extended (data proactivity). Through this mechanism, both changes in state (new data in existing view collected) and changes in structure (new or derived view exists) are made known. Lastly, we embrace found data heterogeneity by coupling multi-indexing to backing stores with appropriate semantics (as opposed to a single store or schema).

Acknowledgments

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Introduction and Background

This report discusses the background, design, and implementation of a software service, Drift, designed to support *data fusion*. We use the term to mean the ability to treat distinct, possibly heterogeneous, pieces of data as a single entity, for the purposes of identification, manipulation, and analysis. We address a universe of structured and semi-structured data, from scientific experimental and simulation results and inputs about which almost all possible metadata is known to word-processor and spreadsheet documents whose provenance is unclear.

Indeed, this disparity in metadata availability in large part motivates this project. An abstract data type (ADT) is a idiom directly supported by object-oriented programming languages, in which developers are encouraged to map the intellectual process of data-driven design from the top (i.e. the "real world") down, as opposed to trying to think in detail about varied collections of primitive data types. Drift represents an exploration of applying this principle at a higher level. Fast networks, cheap near-line storage, and the emergence of "big data" problems have led engineers and scientists to develop data-centric design and problem-solving processes. These processes incorporate many different kinds of data produced by different methods, with varying degrees of attached metadata, and with lifetimes exceeding typical project durations or even employee tenures.

Drift explores the possibility of forming abstractions around data that has no previous explicit interrelationships. We see much of the potential usefulness of a service such as Drift in assisting users to make explicit relationships between data that were previously part of shared understanding, cultural assumptions, or hand-me-down knowledge among developers, or artificially separated by administrative or other boundaries. Making these relationships explicit and available has the potential to reduce misconceptions about how data in organizations is used.

Although making it easier to define such abstractions, to fuse data, is a key goal of Drift, it is also an enabling step for data analysis. Assigning names to fused data objects is one way to reference them, but applying analytic techniques to that naming process promises interesting benefits. In particular, using components of the fused data itself to drive indexing schemes that support automated learning and categorization can provide important leverage for queries and data mining-style operations. In this Drift is designed to support making fused data objects into "first-class" entities for the purposes of data mining and analysis, to be operated on using analytic methods in the same way as primitive data types are in current usage.

Background and approach

The database research community was among the first to address problems of data fusion, exploring approaches such as revised relational algebras and SQL optimization[4]. Large-scale availability of distributed system middleware later drove investigations into federated database and query services[11, 19] in 3-tier enterprise application architectures, and this flavor of data fusion has persisted through an evolution to service-oriented architectures[16].

Drift is intended to improve the availability and utility of federated query-style data services for researchers in large-data environments comprising multiple heterogeneous sources by making it easier for them to construct views on distributed data that are meaningful to them. Drift embodies a proposition that significant expressive power can be obtained by connecting application-specific views to fused and discrete data sources (flexible multi-indexing), and that tools and software systems that directly support this will prove useful. Drift's design further assumes that, given such tools and systems, facilities that provide push-based notification of changes in those views and that can be integrated directly into applications and data (data proactivity) will also prove useful.

Our method of defining and advertising views on distributed data is more flexible than traditional federated query approaches in that it encourages a bottom-up approach where multiple, perhaps inconsistent views on the same data are possible. Rather than finding ways to limit the proliferation of these views, Drift makes them reusable and extensible. Drift also aims to reintroduce distributed query capabilities for data other than semantically organized text, as much recent research has emphasized federated text search[1]. In contrast to existing data mining/analysis tools such as Splunk[2], Drift provides programmatic solutions compatible with extremely high-throughput streaming data environments where indexing, analysis and shaping of metadata and data must be performed *in situ*, and where advanced analytic indexing capabilities can be introduced directly by scientists and researchers.

By implementing flexible multi-indexing, Drift enables users to define their own customized views for the metadata they are concerned with, and directly embed these structures into a metadata service. While defining indexing structures is a fairly straightforward (and obviously useful) operation for commonly used hierarchical naming structures such as tries, we believe that more novel results will come from the use of analytic data structures for indexing.

For example, as high-dimensional, big-data scenarios become commonplace, and in a dynamic metadata environment such as that we envision, kd-trees[3] whose dimensional components can be customized by end-users have the potential to provide extremely granular data selection while still maintaining efficient indexing. Another example is the use of a kd-tree to implement a nearest-neighbor search, which can for example complement the automatic classification tasks in the Cyber domain. Of particular interest are scenarios where metadata objects (potentially comprising multiple objects spanning multiple backing data stores) can be indexed by more than one user-defined index structure (for example, consider a feature set generated by computational simulation, indexed both hierarchically by a trie and by an N- dimensional hyperplane through the feature set).

Users wishing to construct a new fused data product through the use of multiple indexes may wish to know if related data products are already available so that those products might be reused or extended. Drift provides a publish/subscribe-like model where entities interested in changes in the data represented in a service, or changes in the structure of the service itself (addition of new indexes, for example), can be proactively notified rather than having to interrogate the service. This style of state management provides an asynchronous, eventually-consistent global picture of the available views defined by all users, which is both necessary to enable discovery and encourage reuse, and more flexible and scalable than federated query approaches enforcing stricter consistency semantics. We also expect proactivity to provide direct benefits to users, allowing coupling between computational or sensor-based results. Consider for example the advertisement of a fused data product that must await a cooperating computation to be completed, or the establishment of a condition driven by asynchronous external phenomena (such as a malicious network attack detected by a stateful firewall). Proactive interfaces can also complement the trigger- or change-based mechanisms already available in the backing stores Drift uses.

Drift uses flexible and scalable schemaless data stores to store and make available heterogeneously-structured and unstructured data. These tools have been studied in detail at Sandia and elsewhere, and Drift does not innovate in their design or construction. There are several flavors of these stores, each representing a particular choice of trade-offs: key-value (Amazon Dynamo[14] and descendants), column-oriented (e.g. Google BigTable[8], Apache Cassandra), document-oriented (e.g. Couch, Mongo), and graph/RDF/adjacency (e.g. Neo4j, Allegro). Drift uses this diversity of data representation to more effectively cope with the variety of data and metadata we expect to encounter.

More interestingly, Drift extends traditional federated-query-style data management by providing the ability to construct logical views over physical data residing in multiple such stores, leveraging the unique benefits of each. For example, the best method for representing relationships between documents might be a graph database, but it could prove useful to associate that relationship with sets of experimental results residing in a column-store. Lastly, being able to incorporate tools like HBase (thereby coupling map-reduce computations) enables a further degree of richness in data view definition.

Use Cases

Issues raised in the following use cases motivate our work:

1. Long-running engineering efforts accumulate vast stores of different but equally important data over time as artifacts of design, testing, and production. Design documents include reports, schematics, spreadsheets, emails, and other notes; these are typically produced by and manipulated with commercial office productivity software such as Microsoft Office. Testing data adds to this large amounts of numerical results, test descriptions, and parameter sets. Production data adds another type of data store to the problem, as database management software is frequently used to maintain inventory information. When problems are detected during testing or production use, answering the questions that lead to root causes requires a holistic look back at a large and interrelated data space: What testing regime was used for the widget in question? was its design valid? how many of these widgets are in production? Combining different heterogeneous data in the right ways can quickly illuminate these issues.

2. Certain corporate data must be mined for features which are relevant to ongoing operations. For instance, streaming telemetry collection from internal cloud deployments can pose issues deriving from all four of the "V's" of big data: volume, velocity, variety, and veracity. This telemetry can include system health and performance monitoring as well as application data streams. Fusing these data streams to support enterprise decision-making is an impor-

tant capability (consider, for example, an internal cloud-based “honeypot” used to isolate, diagnose, and respond to cybersecurity attacks in near-real-time).

The Drift Service

Drift is a client/server implementation, based on publish/subscribe middleware, of the data fusion service design described in the previous section. The following components of Drift are of interest and will be discussed in more detail in this chapter.

- A persistent daemon `driftd` that runs as an independent process on a POSIX-flavored system;
- A client library, `libdrift`, of C++ objects that are used to interact with `driftd`;
- An instance of the Neo4J graph database, used by `driftd` for relationship management;
- An (optional) instance of the MongoDB schemaless data store, used by `driftd` for arbitrary data storage;
- An (optional) instance of the Mule Enterprise Service Bus, whose integration with Drift is described in Chapter .

`driftd`

`driftd` is a persistent, independent process which receives messages from clients and sends response messages to those clients. `driftd` also periodically sends advertisement messages with certain information about the current state of the service as well as update messages when information items managed by the service undergo state changes. These advertisement and proactive messages go out to any interested (*subscribed*) party.

`driftd` encapsulates several capabilities and/or subsystems of note which will be described in this chapter. All communication is accomplished in a *publish/subscribe messaging* style and is enabled by a third-party messaging subsystem. This subsystem also provides the infrastructure for defining message types and is responsible for data marshaling between client and server. *Flexible analytic indexing* provides novel ways for clients to refer to data items. The *raison d’être* of Drift is its implementation of *data fusion*, which is accomplished via a composite data structure termed the *parts list*. Finally, we discuss the *proactivity* features of Drift and how they make interacting with the service more natural.

Publish/subscribe messaging

Drift is based in part on ideas realized in a research artifact known as the *Proactive Directory Service*[7]. This service was used as a key infrastructure component for several years, but over time several shortcomings were identified. In particular, PDS required clients to establish a session-based conversation with a server using a set of remote procedure calls (RPCs). Clients that were only interested in updates about data items or otherwise had limited or bursty interactions with the server were forced to maintain this session for the duration of their interaction. Part of the design rationale for PDS was to provide a more lightweight, scalable means of information awareness among cooperating processes. Even though this situation only affected a certain subset of applications using PDS, this was enough to justify revisiting the design.

Interactions with `driftd` are explicitly message-based, as opposed to RPC-based, and there is no notion of a persistent session with a particular instance of `driftd`. A publish/subscribe (pub/sub) model is implemented, and while `driftd` is a central point of published messages, there is in principle nothing preventing multiple `driftd` services from operating cooperatively in a peer-to-peer arrangement. The implementation described here assumes a single `driftd` instance.

There are many implementations of pub/sub middleware available as open-source software, each with relative advantages and disadvantages. We now describe the EVpath middleware that was chosen for the implementation of Drift.

EVpath middleware

EVpath[9] is an event transport middleware layer that can be used to form arbitrary dataflow graphs among cooperating processes. EVpath is built around the concept of *stones* (as in "stepping stones") which can be linked together to form a path. Stones in EVpath are lightweight entities that roughly correspond to processing points in dataflow diagrams. Stones of different types perform data filtering, data transformation, mux and demux of data as well as transmission of data between processes over network links.

Figure shows an example dataflow network that one might use EVpath to implement. Connected stones distribute data from the source through the network to the sinks. It's unreasonable to assume that all sinks are interested in the same data, and in fact each sink might want to customize the event stream in its own particular way (with sink i customizing its stream with a function F_i). An efficient implementation of event delivery would place these *filter* functions as close to the source as possible to avoid transmitting unwanted data that would only be discarded on arrival at its destination (Figure).

Drift uses EVpath to establish just such dataflow graphs between `driftd` and its clients. Furthermore, Drift allows clients using `libdrift` to customize their event streams (this is described more fully in Section .

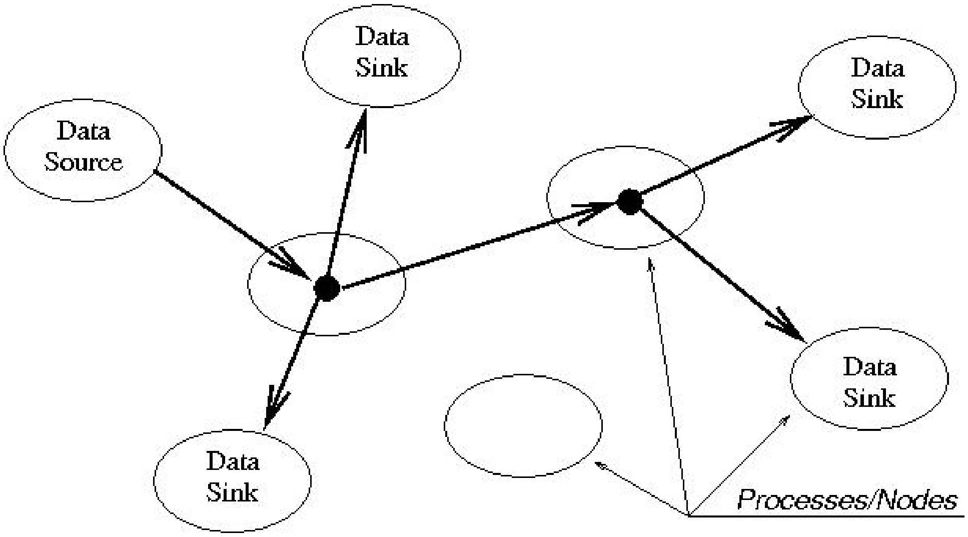

Figure 1. An example dataflow network that can be implemented using EVpath.

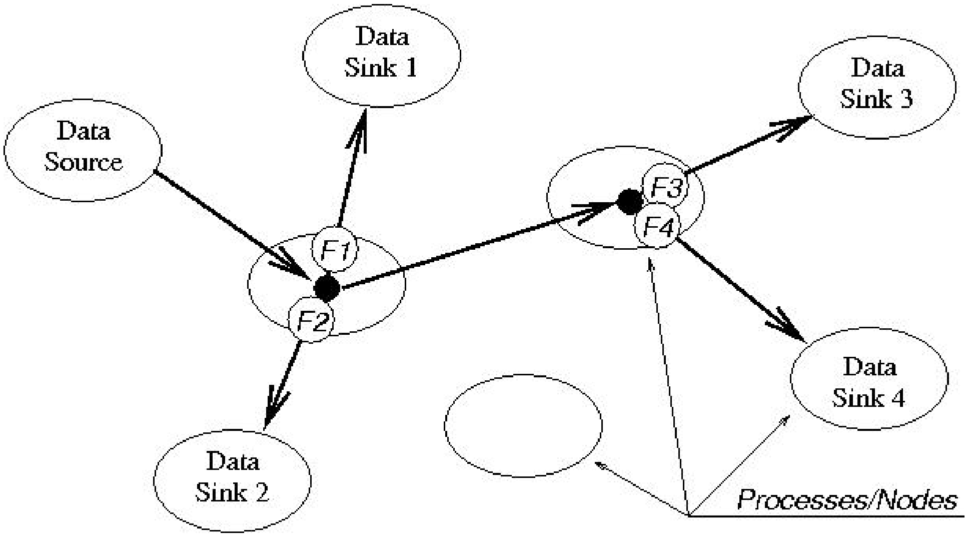

Figure 2. A customized dataflow network that can be implemented with EVpath.

```
typedef struct _simple_part_xfer {
    unsigned long flags;
    struct _simple_part part;
    char* index_name;
    char* index_spec;
  } simple_part_xfer, *simple_part_xfer_ptr;


FMField drift::simple_part_xfer_fields[] =
    {
      {"flags", "integer", sizeof(unsigned long), FMOffset(drift::simple_part_xfer_ptr, flags)},
      {"part", "simple_part", sizeof(drift::simple_part), FMOffset(drift::simple_part_xfer_ptr,
          part)},
      {"index_name", "string", sizeof(char*), FMOffset(drift::simple_part_xfer_ptr, index_name)},
      {"index_spec", "string", sizeof(char*), FMOffset(drift::simple_part_xfer_ptr, index_spec)},
      FMfields_terminator
    };
```

Constructing messages

Part of EVpath's management of the dataflow graph is the marshaling and unmarshaling of data as it is passed to and from the network. EVpath relies on a companion library, FFS [10], to accomplish the message definition and description required for this data management. Drift, in turn, uses FFS facilities to define the different messages that are exchanged between `driftd` and its clients.

Figure shows how a sample Drift message is defined using FFS for use with EVpath. The message structures are defined in conventional C-language style for use in the code of clients and `driftd`, but extra information has to be supplied in order for those structures to be marshaled to and from the network. An exhaustive description of all the message definition options possible in FFS is beyond the scope of this document, but examining this structure in slightly more detail is instructive:

Each field of the C structure is represented in a metadata structure used by FFS. Each field is tagged with the following:

- A type specifier (e.g. "integer" for `flags`). This specifier indicates what kind of marshaling is required for the field, which can enable certain optimizations. This corresponds loosely to C-style typing but size and signed-ness is not reflected here.
- The size of the field in bytes.
- The offset of the field from the beginning of the structure.

New messages are added to the set that `driftd` understands by defining them in this fashion. While recompilation is necessary to incorporate new messages defined using this method, there are also some limited EVpath facilities for defining message types dynamically and using introspection-based marshaling.

Processing messages in **driftd**

All defined messages are registered by driftd with EVpath and given an associated handler function. These handler functions are called asynchronously when messages arrive. Each handler has access to the main Drift service object in driftd, and uses this object reference to invoke methods on the service object. The body of driftd is simply an event loop, waiting on messages to arrive and their handler functions to use the service object. Appropriate thread exclusion measures are used by driftd to ensure the integrity of its internal data.

Data Fusion, Relationship Management, and the Parts List

Drift's data fusion functionality revolves around the Part concept. Fundamentally, a Part encapsulates the following:

- A datum, along with any metadata necessary to store or retrieve that datum;
- A UUID that can be associated with index entries in any index maintained by a driftd instance;
- A list of "child" Parts

In this section we describe how Parts are used by driftd to store and retrieve data, the different types of data storage used by driftd, and how relationships between fused Parts are maintained.

How **Parts** operate

The Part concept is realized in a class, drift::part. This class encapsulates the information described above. Each time driftd receives a request to associate a datum with an index entry, it generates an UUID (using the boost::uuid library). These UUIDs are formed in part using the network address of the service and so are designed to be globally unique across multiple driftd instances. The UUID is then added as the stored value, using the given indexing information in the request, to the specified index structure. It is important to note that Parts know nothing about the various index structures maintained by driftd —they cannot retrieve the index key of any entries they may be associated with.

Drift allows more than one index to maintain an entry associated with a particular UUID. This allows very flexible treatment of data items. For instance, enumerating a complete set of data items using a name-based index is straightforward, and it might be useful to simultaneously be able to perform nearest-neighbor searches on members of that set (based on information maintained in another index structure).

Data storage

Once a UUID is associated with a `drift::part`instance, the metadata for the indicated datum is handled. `driftd` distinguishes between two types of storage for data, *immediate* and *external*. This reflects a need to compromise between efficiency and flexibility. Many uses of Drift will involve simple or primitive data items —character strings and real or integral numbers. Rather than generate metadata and store these primitive items in MongoDB, `driftd` denotes the `Part` holding that data as *immediate* and loads/stores the data along with the `Part` metadata. In practice, this means that immediate data items are kept in the memory of the `driftd` process, and accessing them does not typically require a request to an external database. While there are caching issues associated with this type of behavior, addressing them is not a priority for Drift.

An *external* data item has associated with it sufficient metadata to store and retrieve it from some backing store external to the `driftd` process. `driftd` makes use of its companion MongoDB database for some external items, and for these the metadata consists of the database, collection, and column name sets required to uniquely identify data within a MongoDB service. Other external data can include items in relational databases, for which the metadata contains database connection information as well as a SQL query that will retrieve the data. Another external type is files on a filesystem, for which the metadata is a Universal Resource Locator (URL) that can be used to retrieve the file from a remote location.

`drift::part`has methods for loading and storing data from the storage specified by the metadata. There is currently a size threshold beyond which a `Part`'s data will not be held by `driftd` in memory, and any requests for it will be satisfied by forwarding the current metadata to the requestor.

Relationship management

A `Part` also contains the foundations for data fusion. This is implemented in each `drift::part`by an associative set of *child* `Part` references and UUIDs. Constructing a fused data part is then done internally to `driftd` by adding a set of child `Parts` to this set. The fused `Part`, being an instance of `drift::part`, is given a UUID and can be indexed just like any other. From the user point of view, since `Parts` are not typically referred to by UUID (although there is a message type that will send the UUID on `driftd`'s advertisement channel), a set of index entries representing different `Parts` is supplied as part of a "fuse" request along with a proposed index entry to refer to the fused `Part`.

`Part` metadata on the backing store indicates whether the `Part` is a fused part or not. If so, the set of child `Part` UUIDs is retrieved and each `Part`'s data is loaded in turn as though it were a simple `Part`. While nothing in principle prevents this recursive design from extending to arbitrary levels of `Part` composition, the current `driftd` implementation prohibits `Parts` that are part of a composite from holding child `Parts` themselves.

In order to persist information about Part relationships, Drift uses the Neo4j [1] graph database. This information could have been stored using MongoDB or a low-overhead relational database like SQLlite. The choice of using Neo4j as opposed to SQLlite came down to a design tradeoff. SQLlite functions as an in-memory query-able data store with persistence ability, while Neo4j requires a connection to an external process. It was decided that the more natural representation of a network of interrelated Parts would be obtained by using Neo4j, which would not require the multiple joins of a relational database solution or the relatively complicated query expressions needed to store and retrieve that representation in a column-store like Mongo. Additionally, this choice gives driftd greater control over its own memory usage, allowing it to trade greater request latency for a smaller footprint; for an asynchronously-oriented service this seems a reasonable choice.

A composite Part with 5 child Parts in its part-list is persisted in Neo4j as a Part node with outgoing arcs to 5 other Part nodes. The Neo4j API allows information about all such related nodes to be retrieved with a single call to the server, which is convenient for driftd's purposes. Neo4j allows the association of data with relationship entities (conceptually, associating data with arcs in the relationship graph). Part UUIDS, metadata, and immediate Part values are stored in these property lists. For Parts that are not immediate-data, or those whose immediate data values exceed the size threshold, the metadata for retrieving that data from MongoDB is stored instead (in MongoDB these data are stored as a column-set indexed by UUID).

driftd communicates with the Neo4j server using a REST-style interface over HTTP. There is no C/C++ language level interface for Neo4j, and even in other development languages the language-level libraries are implemented on top of Neo4j's REST interface. We use the open-source Casablanca REST SDK [2] to facilitate communication through the REST APIs of Neo4j and other services [3]. Load and store operations of Parts are implemented by calling through the Casablanca library to Neo4j.

Flexible Analytic Indexing

Flexible analytic indexing is central to the design of Drift. *Flexible* refers to the ability of driftd to accommodate user-defined data structures into its architecture without requiring major code changes. Two of the three existing indexes used by driftd are *analytic* ones, allowing arbitrary data to be tracked using selected features either from the data itself or selected by the user. This section describes the three index structures used by driftd and discusses possible future enhancements to the indexing arrangement.

[1] Available at http://www.neo4j.org/.

[2] Available at http://casablanca.codeplex.com/.

[3] Incidentally, it is our use of Casablanca which drives the requirement of a C++ compiler implementing the C++-11 standard in order to build driftd.

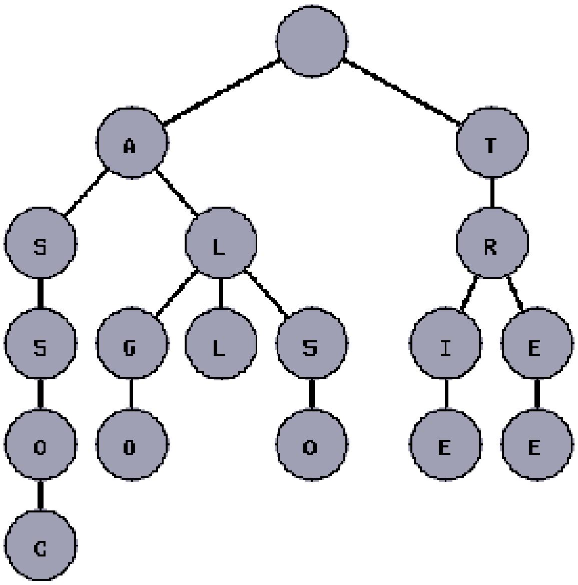

Figure 3. An example of a prefix tree.

Prefix trie

A hierarchical name space is a basic means of organizing information. File systems, the Windows registry, and several directory service protocols have all provided such name spaces; they are well-understood and highly flexible. The base data structure for these name spaces tends to be associative data structures with character strings for keys; very frequently some form of hash table is chosen.

Another associative structure that can be used for this, and the one that Drift uses, is a *prefix trie* or *trie*[6]. Tries have lookup-cost and storage advantages over hash tables, especially when the entire trie can fit in memory. A `driftd` instance contains a `Trie` class object that is used to implement a POSIX-style hierarchical mapping of '/'-delimited strings to UUIDs. This is intended to be the default index structure for Drift, and should prove to be sufficient for many application needs.

R-tree and kd-tree

A large part of the utility of Drift comes from its ability to use analytic methods to map to `Parts`. Indexes that deal with multidimensional data, in particular, are useful for "big data" applications. Two such indexes are the *kd-tree*[3] and *R-tree*[13, 18].

A kd-tree is useful for splitting a k-dimensional search space into hyperplanes, in the same way a binary tree partitions its key space into two halves at each node. A kd-tree is a generalization

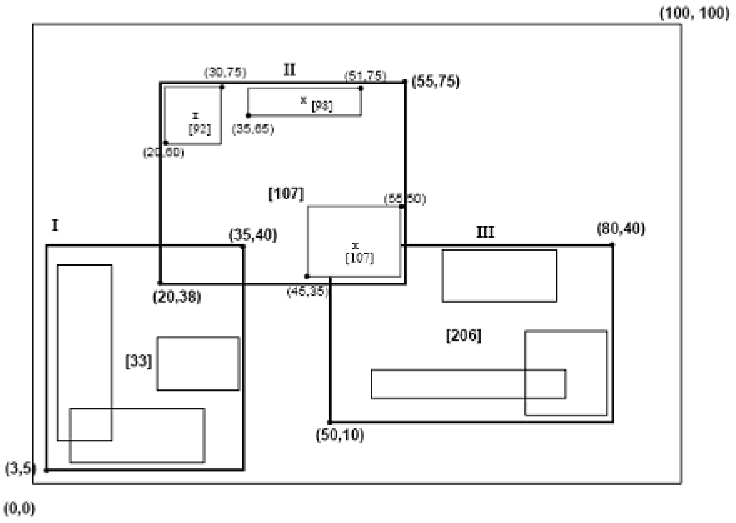

Figure 4. Visualization of data layout in an R-tree.

of a binary tree for data with k dimensions. The kd-tree is useful for efficient range-based and nearest-neighbor searches of multidimensional data.

R-trees are used primarily for spatial indexing of multi-dimensional data. Where a kd-tree would, by construction, split each dimension in the key space into halves at each node of the tree, an R-tree organizes its key space hierarchically, in that each node in the tree forms a "bounding polygon" that "contains" the keys in the subtree beneath it. R-trees are generally used to index geographical data and polygons for graphical systems, and Drift's usage of them is analogous. To illustrate, consider using an R-tree to index machines in a data center using a vector of performance data from each machine as the key space. An R-tree would then allow the identification of a set of machines contained in a range for each component of that vector (identifying the minimum bounding polygon where each point in the polygon is represented by a component of the vector). This is a slightly different but related query and result than would be handled by a kd-tree. For instance, a nearest-neighbor query of a kd-tree would return only the nearest N neighbors, even if there were $2N$ neighbors in the given range; the R-tree would return all the neighbors in the ranges specified in the query.

The current `driftd` implementation uses an R-tree implementation provided by the Boost suite of C++ libraries[5]. The kd-tree implementation is an open-source library[15].

Discussion

We recognize that the index structures included with Drift are unlikely to address all possible indexing needs. This is a key design aspect of Drift realized in the `Part` concept. Any associative container that can map some input to a `Part` will be sufficient for Drift, as long as a set of message definitions and handlers are added to allow `libdrift` clients to use it.

Drift was originally designed to accommodate index addition at runtime. This design goal was eventually deferred in order to achieve a sort of “minimum viable implementation” which could be used as a basis for iteration and improvement. However, future possible extensions to Drift may revisit this issue.

Currently, adding an additional index to Drift requires modification of the project source and rebuilding. More flexible options were considered as part of the design, each with tradeoffs between ease of programming, deployment, and performance. The first is the use of a C++ shared object containing the new index structures and message definitions. Installing a new index is triggered by a message from a client with a reference to the shared object, which is loaded using the`dlopen()` system call. This obviously requires shared objects for all possible desired indexes to be deployed along with `driftd`.

The second solution relies on a C++-to-Python passthrough, where new index structures can be moved between address spaces running Python interpeters using that languages built-in code mobility facilities. Access to the `Part` UUIDs maintained by `libdrift` is accomplished through a specialized set of messages. This approach, with at least one interposed layer of software, imposes additional performance penalties, although in Drift’s intended usage regimes it’s unclear that this would be a practical issue.

Other more radical rearchitectures of Drift to solve this issue are possible, and were considered during the design stage. One in particular would implement the entire indexing layer in Python, communicating with a separate UUID/`Part` management service.

Another interesting question for possible future evolution of Drift is which indexes might be useful to incorporate as first-class citizens, as it were, by bundling them in the source code. Possibly of greatest interest here is the use of remote processing to point to a `Part`. In this way, significantly more complex analysis on multi-dimensional data might be possible, at the cost of extra network traffic. Such architectures are common in enterprise systems, where output from multiple application logic tiers is combined in order to produce a logically-organized response to an end-user request.

Proactivity

Rationale

We use the term *proactivity* in the same manner as was used in prior research[7], to denote the use of an active interface between entities where updated information is transmitted to interested observers without their having to continually poll for it. Such an interface presents advantages in system scalabilty, information freshness, and allows applications to be written in a more modular, decentralized style. We note that proactivity is a well-established design technique, with instances found at architectural (“write-through” caches), operating system (device interrupt handling), and software engineering (Java EE Beans, Microsoft DCOM).

Drift applies proactive interfaces to several of its internal information structures. These updates take the form of EVpath messages, which are defined using the same FFS facilities as are used to define Drift system messages. There is a well-known contact point (TCP/IP host/port or other unique network connection identifier) serviced by `driftd` known as the *advertisement channel*. If a Drift client is interested in general `driftd` updates, or knows that it will subscribe to data updates, that client subscribes to the advertisement channel before performing any other Drift operations, and is prepared to handle (i.e. has handler functions defined for) update events for the data in question. Subscribing to the advertisement channel before performing other operations ensures that no update messages about specific data are missed by the client.

Drift clients indicate when they request or store data in `driftd` if they wish to receive updates for that data. When `driftd` sees this indication, it adds that data to the list of updates it pushes on the advertisement channel. By default, separate update events for all proactive data are pushed to the single advertisement channel. However, if a client wishes to split updates for a particular item off into a separate channel, it can indicate so to `driftd`, which then replaces the data update payload in the advertisement channel event with contact information for the new channel. Once the client sees this in the advertisement channel, it can retrieve that contact information and subscribe to the new channel. This technique is most useful if the data in question is frequently updated or if summarization of that data is useful. In the next section, we illustrate how this is accomplished in Drift using EVpath facilities.

Preserving client control of updates

The primary advantage to clients of pull-based interfaces is control. Pull-based interfaces allow clients to manage when/if messages are sent and to anticipate replies (since the fact that a reply is impending and the type of information the reply carries are both known). Proactivity allows clients to trade control for performance, as message traffic is only generated when updates occur. As long as updates occur infrequently, this lack of control is not significant. However, a client that registers interest in an object that begins changing with unanticipated frequency soon finds itself swamped with update messages. These update messages may not even be needed when they arrive, or may only be needed depending on other application-specific factors; proactivity in this case does more harm than good.

At first glance, providing a filter at the client to discard unwanted or unneeded updates might seem enough. Although this does allow the application to ignore updates, the update messages are still sent across the network, increasing the load on the server, the network, and the client. Providing a single interface at the server to control proactive traffic is also insufficient, as different clients interested in changes may have different criteria for discarding update messages.

A better approach allows client-specific *customization* of the update channel. To customize a channel, a client provides a specification (in the form of a function) of what events it will be interested in. The server then uses these specifications, on a per-client basis, to determine whether

```
{
  int i, j; double sum = 0.0;
  for (i = 0; i < MAXI; i = i + 1) {
    for (j = 0; j < MAXJ; j = j + 1) {
      sum = sum + input.array[i][j];
    }
  }
  output.avg_array = sum / (MAXI * MAXJ);
  if (sum > THRESHOLD) return 1; /* submit */
  else return 0; /* filter out */
}
```

Figure 5. An EVpath filter function. Such a filter would be executed in a context of the form `int F( input, output )`.

or not to send the update event.

EVpath enables customization of update channels through a mechanism called *filter stones*. Drift handles the interface with EVpath, and Drift clients simply need to supply a filter function. The filter is installed at `driftd` and runs each time an update event is generated. The filter function can inspect the message payload, transform part of it, or simply discard the message before it is sent from `driftd` according criteria in the function.

Filters are sent by the client as functions written in a subset of C[4], supplied as a character string in a request message to `driftd`. The filter function is then dynamically translated using an in-memory compiler to machine code for the target architecture and called directly as a C function when update messages are generated. Figure 5 shows a typical filter function. In this example, the update message (available to the function as a structure called `input`) contains an array of doubles, and the client is only interested in receiving the update message if the average of this array's values is above a certain threshold. The filter function computes the average and compares against the threshold value, discarding the message if the constraint is not met.

In this way, clients can maintain control over which updates they see for particular data, while preserving their ability to stay aware of all changes in other data.

Drift proactive elements

The following conditions in `driftd` will result in the generation of an update message on the advertisement channel:

- Change to an existing index (addition or removal of an index entry)
- Installation or removal of an index

[4] The filter language has been restricted in certain ways related to pointer manipulation and memory management for code safety considerations.

- Modification of a Part
- Updates generated by backing stores
- New Part defined
- New Part fusion defined
- New update channel created

Clients are free to ignore these updates as they wish, or delegate them to individual update channels for customization.

libdrift

libdrift is a C-language-based shared object library designed to be linked into applications that wish to use Drift. It contains facilities for declaring message structures, submitting request messages to driftd, and subscribing to advertisement and control channels.

In this section we present several interaction diagrams that show how a user executable would use libdrift to contact and make requests of driftd, covering a set of common use cases.

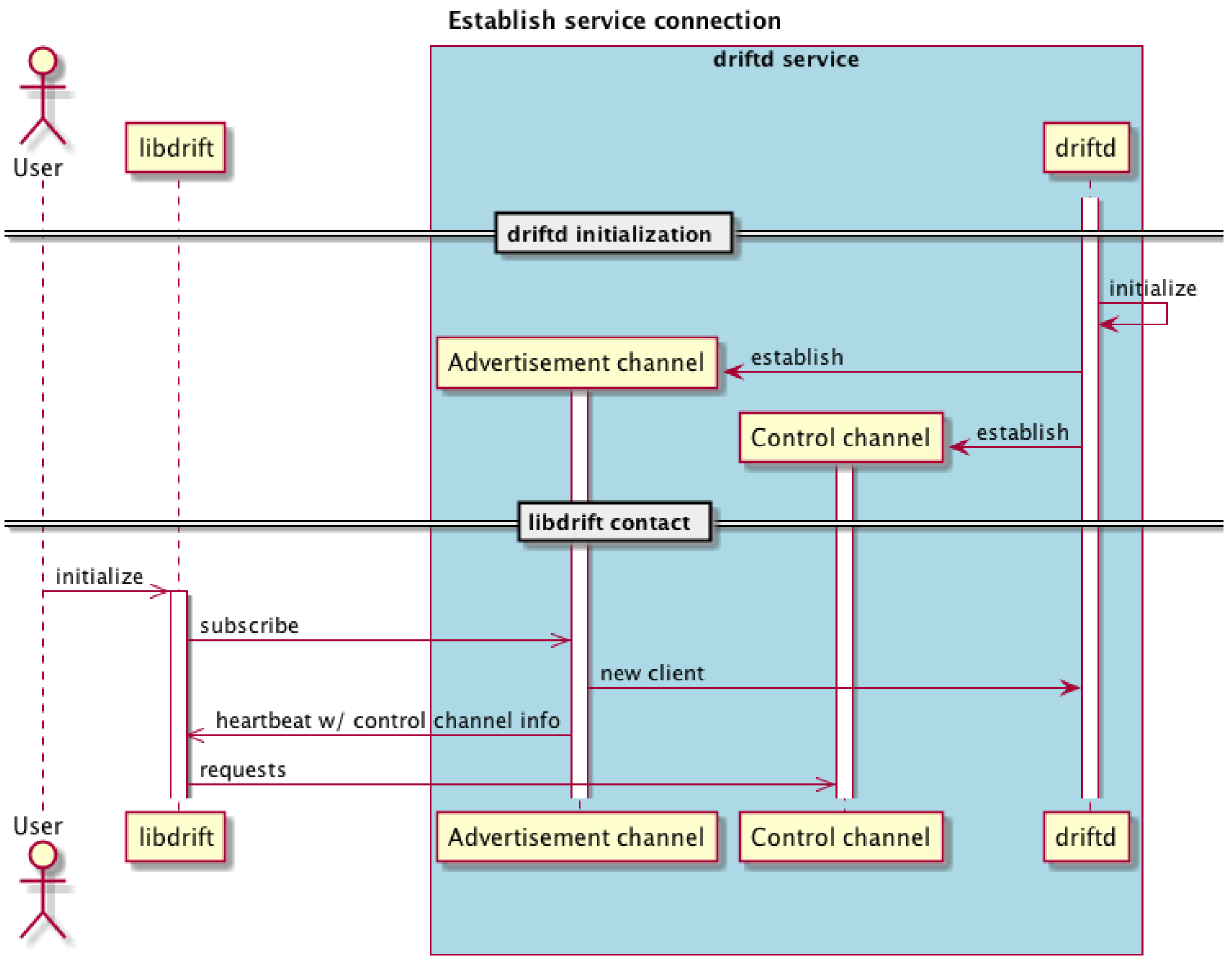

Figure 6. Using `libdrift` to connect to `driftd` and perform initial setup.

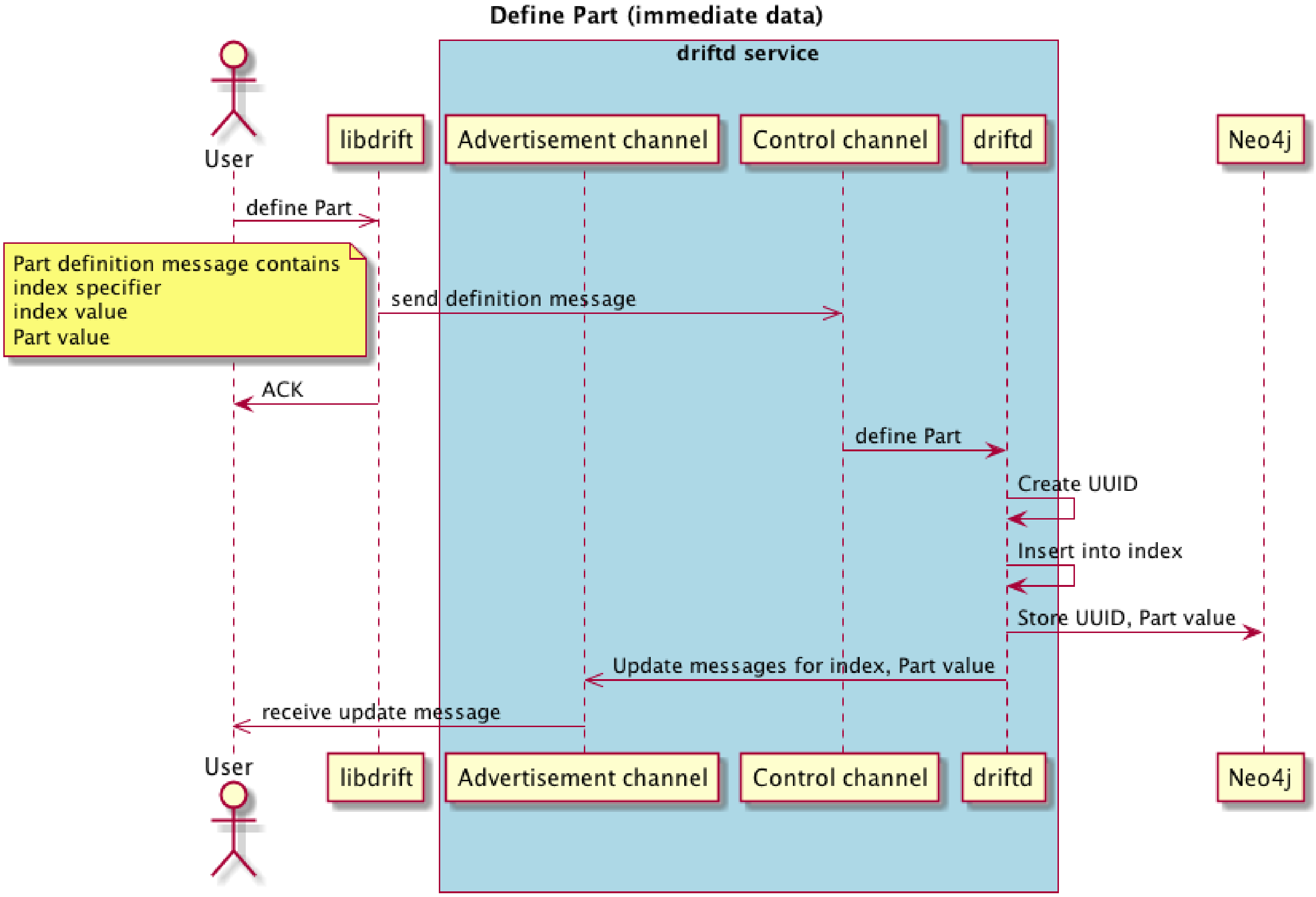

Figure 7. Using `libdrift` to define a `Part` that contains immediate data.

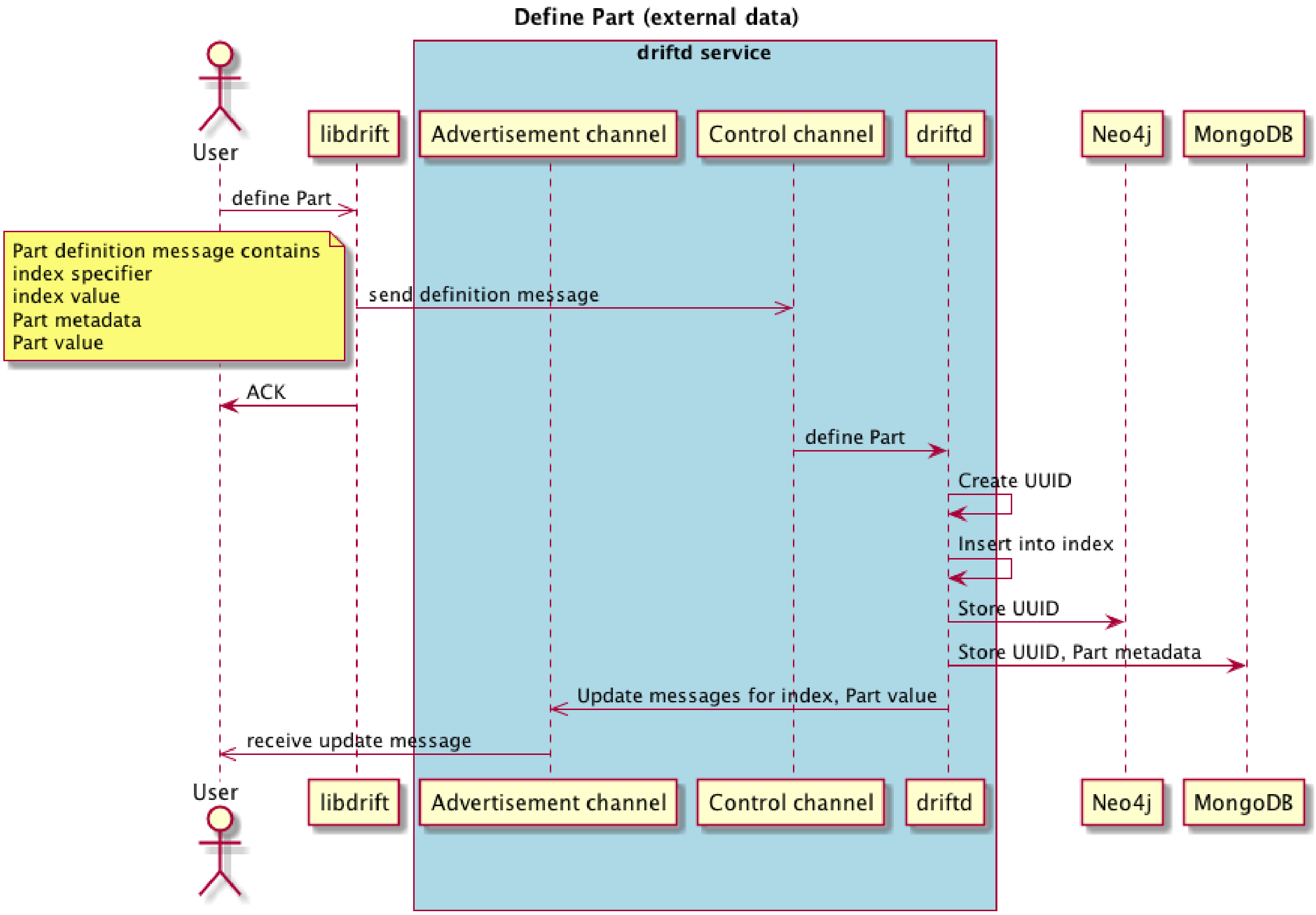

Figure 8. Using `libdrift` to define a `Part` that contains external data.

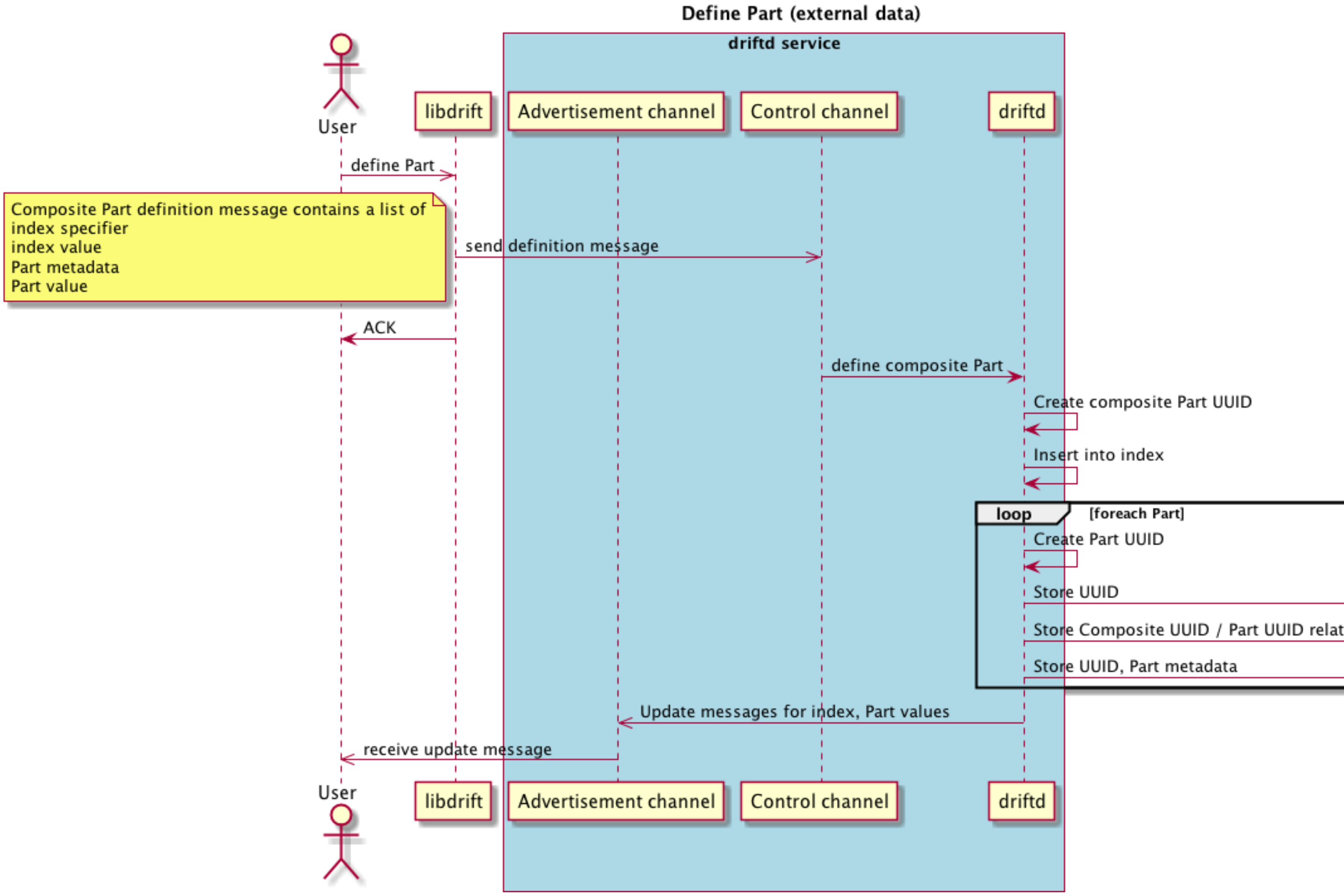

Figure 9. Using `libdrift` to define a composite (fused) `Part`.

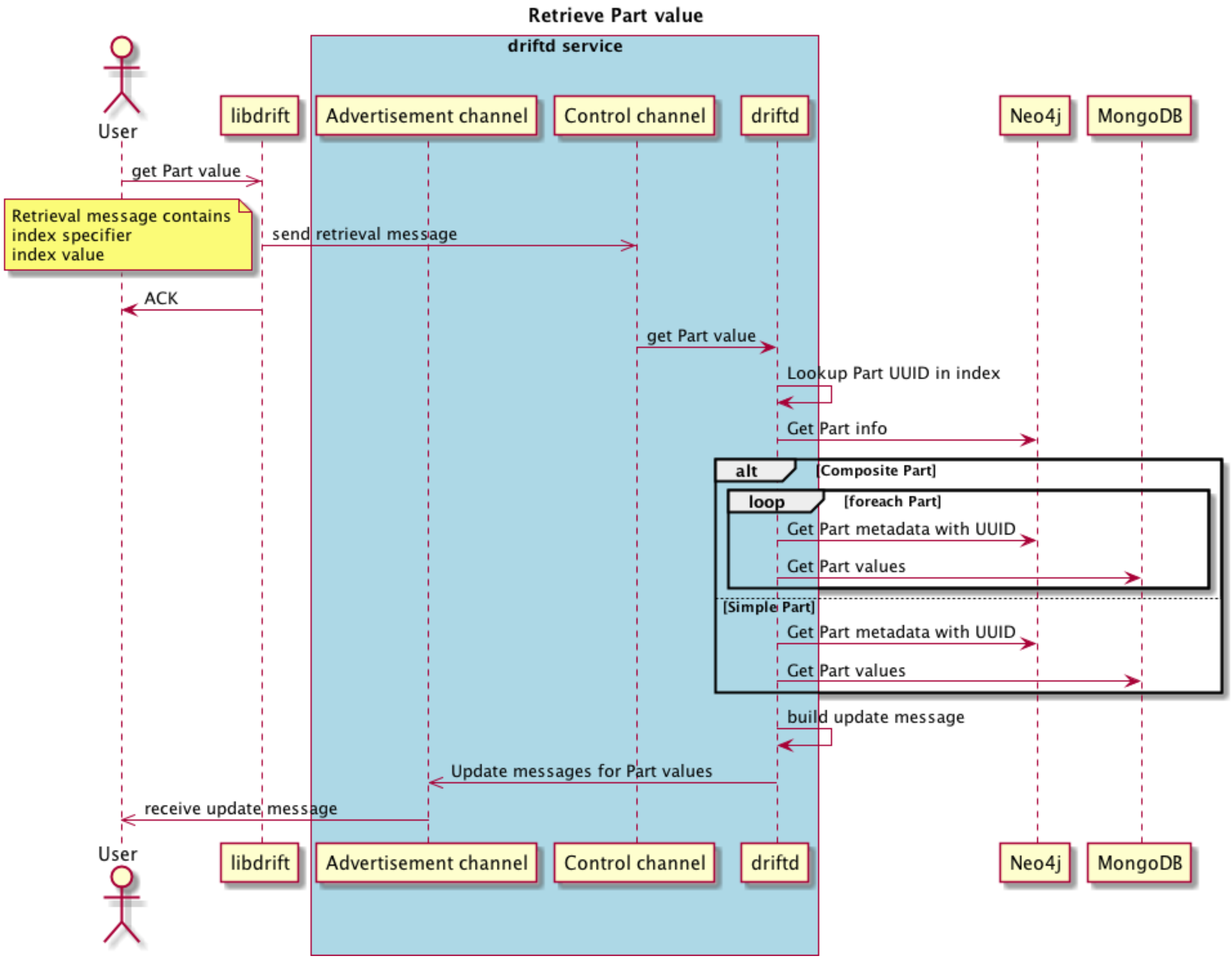

Figure 10. Using `libdrift` to retrieve the value of a `Part`.

Extending Drift for enterprise use

The effects of “big data” problems on information technology organizations have been well-documented. Whether managing huge online presences, performing large-scale scientific experimentation and simulation, or ingesting dense streaming data, these organizations face the challenge of converting vast stores of data to actionable information. Some of the specific problems faced in the application domain, however, also manifest themselves in the management of enterprise data stores and sources. For instance, computational scientists and enterprise application developers both encounter “siloed data”, where domain boundaries restrict awareness about what potentially useful data may exist. “Write-once-read-never” issues, where data generation/collection rates outpace analysis and integration processes, occur in both realms, as simulations generate petabytes of data per day and as documents relating to design and testing processes accumulate over time, eventually succumbing to bit-rot.

We anticipate the integration of enterprise data stores and sources, once considered the exclusive province of “the IT shop”, with data analysis capabilities developed for use in application domains. An example of this is the mining of employee safety incident data to reveal previously unknown trends and correlations. A service-based integration can also provide benefits in the opposite direction. For organizations which develop and maintain their own toolsets to support their work processes (such as software libraries for high-performance computing tasks), making raw and analyzed data outputs available in regular, extensible, and composable ways can improve productivity, accelerate the solution of new problems and reduce reinvention of the wheel.

Drift includes specialized low-overhead publish/subscribe interfaces which are necessary for its HPC role, but are not suitable for enterprise integration. We are using an Enterprise Service Bus to provide a service-oriented, discoverable, and general interface to Drift.

Enterprise Data Fusion Services

Drift was originally targeted at HPC and cloud environments, with specialized, low-overhead publish/subscribe interfaces suited to their requirements. While those kinds of considerations are appropriate and necessary in a research software environment, they make integration into larger software architectures very challenging. Service-oriented architectures and software-as-a-service models adopted in the pursuit of enterprise application integration have provided traction on these problems for business applications. The growing importance of metadata, Big Data problems, and coupled computations on heterogeneous platforms is driving the development of research software whose SOA-style encapsulation promises benefits outside their application domains—if the integration challenges can be overcome.

We have explored the feasibility of such integration, using the data fusion and flexible indexing capabilities of Drift as a test case. Our goal is to create an enterprise service with well-defined endpoints, discovery and introspection capabilities. We also want to make possible the construction of more complex service-based offerings which make use of Drift service endpoints.

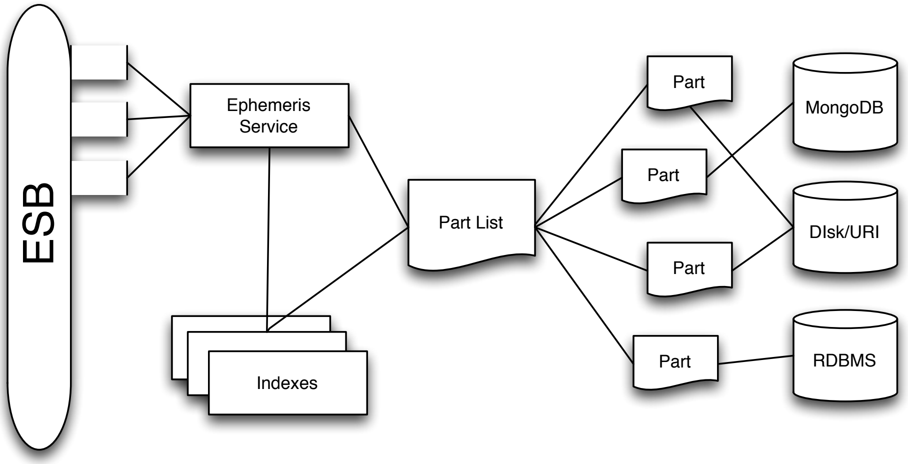

Figure 11. Depiction of system-level relationship between Drift, the ESB, and other ESB services.

Given this goal, we have pursued an Enterprise Service Bus (ESB) approach using the open-source Mule ESB [17], extending Drift as a component called Ephemeris[20] (Figure 11). Also, we have built *Connectors* (integration units defined in the Mule development framework) which will make Drift services available on a deployed Mule ESB. The Connectors mediate service requests to a separately running instance using a REST API. The Drift instance will at the same time be servicing application clients using its high-performance publish/subscribe interfaces. In this manner, any service deployed on the ESB will be able to interact with the data fusion facilities provided by Drift, using fused data defined by applications which have no coupling with the ESB. This integration will also provide benefits in the opposite direction: business processes attached to the ESB will be able to define data fusions which will then be available for Drift application clients.

We have developed a Mule ESB Connector for Neo4j, so that fused data definitions and relationships can be discovered and examined without interacting with the main service. We believe this will be a powerful new capability for integrating application data with enterprise data, making possible more holistic views of an organization's data environment. To explore the integration possibilities afforded by Mule's ESB, we have also developed Connectors for certain internal Sandia services, as well as third-party tools used internally at Sandia. A test case for this is the Splunk connector (listing provided as Appendix . Using this Connector and the ones provided for Sandia services such as SAPLE and Drift, a Mule workflow can be constructed which retrieves information on up-to-date operational information from a Splunk service, queries SAPLE for relevant employee contact information, and stores the result data in a Drift instance. Once stored in Drift, the data becomes "fuse-able" just as any other data, providing end users with great flexibility in constructing data types for their own use that reflect operational data.

Conclusion

Our exploration of data fusion issues with Drift has been illuminating in several respects.

- While the Drift software itself has enjoyed limited penetration in the Sandia software development community, the ideas behind it still resonate with developers and designers working with diverse data. Sandia's Cyber community appears satisfied with the Splunk toolset. However, Splunk's licensing costs are burdensome enough that other domain researchers are starting developments projects, based on open-source software, with capability sets similar to both Splunk and Drift. While the Drift implementation may not be ideal infrastructure for all such efforts, there is clearly value in establishing this type of software/services layer for use across the Laboratories.

- A corollary to the previous point is that Laboratory funding for data analytics software should be carefully rationalized. At the beginning of this project, the intended feature set for Drift subsumed the capabilities of the Splunk installed base. 12 months later, that situation was dramatically reversed, owing entirely to a growing community of Sandians focused on Splunk extension and integration development. Unfortunate timing/coscheduling has been the cause of much unrealized potential in software development in large organizations, and part of the research agenda is, and properly, to support simultaneous investigation into broad areas (such as software to support data science) in order to gain multiple perspectives on large and stubborn issues. Notwithstanding this, and build-vs-buy considerations aside, we believe decisions by the Laboratories to invest large amounts of funding (for licensing and development effort) into products like Splunk, creating lock-in engagements with software that is itself built from open-source components, should be considered carefully.

- An ongoing priority for the Laboratories, properly within the purview of the Data Science Research Challenge, is to establish procedures for gaining research access to operational data. In multiple instances during this project, goals of the project were significantly impeded by the decision of a single individual who happened to be the owner of a particular set of operational data. No indictment of any kind of those individuals is intended here; they are responsible for important components of Sandia's operational infrastructure and have acted in good faith with respect to their mission(s). However, processes for gaining access to operational data for research purposes should be formalized so that they are well-understood and can be applied in an objective manner.

We will be licensing the Drift code as open-source by the end of FY14. A test suite (including a document corpus drawn from [12]) is also planned for inclusion. Our intention is to explore future collaborations with university partners that have common interest in the research areas explored by Drift. We hope to obtain future funding to continue developing these ideas from the LDRD program, DOE, or external agencies such as the National Science Foundation.

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Appendix

Sample Mule ESB Cloud Connector

```
/**
 * Sandia Splunk Cloud Connector
 *
 * @author Patrick Widener <patrick.widener@sandia.gov>
 */
@Connector(name="splunk", schemaVersion="0.1", friendlyName="Splunk")
public abstract class SplunkConnector
{
    public static final String BASE_URI = "https://s950881.sandia.gov:8089/";


    private HttpClient httpClient;

    public SplunkConnector()
    {
        httpClient = new SystemDefaultHttpClient();
        this.setSessionKey(null);
    }

    /**
     * Set property
     *
     * @param httpClient
     */
    public void setHttpClient(HttpClient httpClient) { this.httpClient = httpClient; }
    public HttpClient getHttpClient() { return this.httpClient; }


    /**
     * Configurable
     */
    @Configurable
    private String splunkUser;

    /**
     * Set property
     *
     * @param splunkUser
     */
    public void setSplunkUser(String splunkUser) { this.splunkUser = splunkUser; }
    /**
     * Get property
     */
    public String getSplunkUser() { return this.splunkUser; }

    /**
     * Configurable
     */
    @Configurable
    private String splunkPasswd;

    /**
     * Set property
     *
     * @param splunkPasswd
     */
    public void setSplunkPasswd(String splunkPasswd) { this.splunkPasswd = splunkPasswd; }
    /**
     * Get property
     */
    public String getSplunkPasswd() { return this.splunkPasswd; }
```

```
private URIBuilder getUriBuilderBase(String hname) {
    return new URIBuilder().setScheme("https").setHost(hname).setPort(8089);
}

/**
 * Connect
 *
 * @param username A username
 * @param password A password
 * @throws ConnectionException
 */
@Connect
public void connect(@ConnectionKey String username, String password)
    throws org.mule.api.ConnectionException {
    /*
     * CODE FOR ESTABLISHING A CONNECTION GOES IN HERE
     */

    try {

        ResponseHandler<String> handler =
            new ResponseHandler<String>() {
            public String handleResponse(HttpResponse response) throws
                ClientProtocolException, IOException {
                HttpEntity e = response.getEntity();
                if (e != null) {
                    return EntityUtils.toString(e);
                } else {
                    return null;
                }
            }
        };

        // Try to copy with Splunk server's self-signed certificate
        SSLContext sslctx = SSLContext.getInstance("TLS");
        sslctx.init(null, null, null);
        SSLSocketFactory sf = new SSLSocketFactory(sslctx,
            SSLSocketFactory.ALLOW_ALL_HOSTNAME_VERIFIER);
        Scheme sch = new Scheme("https", 443, sf);
        getHttpClient().getConnectionManager().getSchemeRegistry().register(sch);

        URIBuilder b = getUriBuilderBase("s950881.sandia.gov");
        b.setPath("/servicesNS/admin/search/auth/login");
        HttpPost httpPost = new HttpPost(b.build());
        List<NameValuePair> postdata = new ArrayList<NameValuePair>();
        postdata.add(new BasicNameValuePair("username", getSplunkUser()));
        postdata.add(new BasicNameValuePair("password", getSplunkPasswd()));
        postdata.add(new BasicNameValuePair("output_mode", "json"));
        UrlEncodedFormEntity ure = new UrlEncodedFormEntity(postdata);
        httpPost.setEntity(ure);

        String jsonResponse = getHttpClient().execute(httpPost, handler);
        ObjectMapper jsonMapper = new ObjectMapper();
        Map<String,String> result = jsonMapper.readValue(jsonResponse, Map.class);
        this.setSessionKey("Splunk␣" + result.get("sessionKey"));
        System.out.println(this.getSessionKey());
    }
    catch (java.lang.Exception X) {
        System.out.println(X.toString());
        //      throw new ConnectionException(ConnectionExceptionCode.INCORRECT_CREDENTIALS,
            null, "Bye!");
    }


}
```

```
/**
 * Disconnect
 */
@Disconnect
public void disconnect() {
    /*
     * CODE FOR CLOSING A CONNECTION GOES IN HERE
     */
}

/**
 * Are we connected
 */
@ValidateConnection
public boolean isConnected() {
    if (this.getSessionKey() != null) {
        return true;
    }
    return false;
}

/**
 * Are we connected
 */
@ConnectionIdentifier
public String connectionId() {
    return getSessionKey();
}

/**
 * Custom processor
 *
 * {@sample.xml ../../../doc/Splunk-connector.xml.sample splunk:my-processor}
 *
 * @param content Content to be processed
 * @return Some string
 */
@Processor
public String myProcessor(String content)
{
    /*
     * MESSAGE PROCESSOR CODE GOES HERE
     */
    System.out.println("in␣myProcessor,␣string␣is␣" + content);
    return content;
}


/**
 * Configurable REST header parameter
 */
@RestHeaderParam("Authorization")
private String sessionKey;

/**
 * Set property
 *
 * @param sessionKey the session key
 */
public void setSessionKey(String sessionKey) { this.sessionKey = sessionKey; }

/**
 * Get property
 */
public String getSessionKey() { return this.sessionKey; }


/**
```

```
 * Custom processor
 *
 * {@sample.xml ../../../doc/Splunk-connector.xml.sample splunk:get-results}
 *
 * @param searchId Content to be processed
 * @return Some string
 * @throws java.io.IOException just because
 */
@Processor
@RestCall(uri =
    "https://s950881.sandia.gov:8089/servicesNS/admin/search/search/jobs/?output_mode=json",
    method = HttpMethod.GET)
//        exceptions="{@RestFailOn(expression = "#[header:http.status != 200]")}")
public abstract String getResults(@RestUriParam("searchId") String searchId) throws
    java.io.IOException;

/**
 * GET search/fields
 *
 * Retrieves information about the named field.
 *
 * {@sample.xml ../../../doc/Splunk-connector.xml.sample splunk:get-search-fields}
 *
 * @param fieldName Field to retrieve information for
 * @param outputMode 'json' or 'xml' output format
 * @return XML fragment with field information
 *
 * @throws java.io.IOException For some reason
 */
@Processor
@RestCall(uri = BASE_URI +
    "/servicesNS/admin/search/search/fields/{fieldName}/?output_mode={outputMode}", method =
    HttpMethod.GET)
public abstract String getSearchFields(@RestUriParam("fieldName") String fieldName,
                                       @Optional @Default("xml")
                                           @RestQueryParam("output_mode") String outputMode)
                                           throws IOException;

/**
 * GET search/fields/{field_name}/tags
 *
 * Retrieves tags for the named field.
 *
 * {@sample.xml ../../../doc/Splunk-connector.xml.sample splunk:get-search-fields-tags}
 *
 * @param fieldName Field to retrieve tags
 * @param outputMode 'json' or 'xml' output format
 * @return XML/JSON fragment with field tag information
 *
 * @throws java.io.IOException For some reason
 */
@Processor
@RestCall(uri = BASE_URI +
    "/servicesNS/admin/search/search/fields/{fieldName}/tags/?output_mode={outputMode}",
    method = HttpMethod.GET)
public abstract String getSearchFieldsTags(@RestUriParam("fieldName") String fieldName,
                                       @Optional @Default("xml")
                                           @RestQueryParam("output_mode") String outputMode)
                                           throws IOException;


/**
 * POST search/fields/{field_name}/tags
 *
 * Updates tags for the named field.
 *
 *
 * {@sample.xml ../../../doc/Splunk-connector.xml.sample splunk:post-search-fields-tags}
```

```
     *
     * @param fieldName Field to update tags for
     * @param outputMode 'json' or 'xml' output format
     * @param value Tag name to update for this field
     * @param add Tag to attach to the field_name:value combo
     * @param delete Tag to remove from the field_name:value combo
     * @return XML/JSON fragment with field tag information
     *
     * @throws java.io.IOException For some reason
     */
    @Processor
    @RestCall(uri = BASE_URI +
        "/servicesNS/admin/search/search/fields/{fieldName}/tags/?output_mode={outputMode}",
        method = HttpMethod.POST)
    public abstract String postSearchFieldsTags(@RestUriParam("fieldName") String fieldName,
                                                @RestQueryParam("value") String value,
                                                @Optional @RestQueryParam("add") String add,
                                                @Optional @RestQueryParam("delete") String
                                                    delete,
                                                @Optional @Default("xml")
                                                    @RestQueryParam("output_mode") String
                                                    outputMode)
        throws IOException;


    /**
     * GET search/tags/{tag_name}
     *
     * Returns a list of field:value pairs associated with tag_name
     *
     * {@sample.xml ../../../doc/Splunk-connector.xml.sample splunk:get-search-tags}
     *
     * @param tagName Name of tag of interest
     * @param outputMode 'json' or 'xml' output format
     * @return XML/JSON fragment with field_name:value pairs
     *
     * @throws java.io.IOException For some reason
     */
    @Processor
    @RestCall(uri = BASE_URI +
        "/servicesNS/admin/search/search/tags/{tagName}/?output_mode={outputMode}", method =
        HttpMethod.GET)
    public abstract String getSearchTags(@RestUriParam("tagName") String tagName,
                                         @Optional @Default("xml")
                                             @RestQueryParam("output_mode") String outputMode)
        throws IOException;


    /**
     * GET directory
     *
     * Enumerate objects in Splunk.
     *
     * {@sample.xml ../../../doc/Splunk-connector.xml.sample splunk:directory}
     *
     * @param tagName Name of tag of interest
     * @param outputMode 'json' or 'xml' output format
     * @return XML/JSON fragment with field_name:value pairs
     *
     * @throws java.io.IOException For some reason
     */
    @Processor
    @RestCall(uri = BASE_URI + "/servicesNS/admin/search/directory", method = HttpMethod.GET)
    public abstract String directory()
        throws IOException;

}
```

DISTRIBUTION:

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