

# Tintenfisch: Namespace Schemas and Generators for Scalable File System Metadata Access

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## 1 Introduction

The file system metadata service is the scalability bottleneck for many of today’s workloads [22, 2, 3, 4, 26]. Common approaches for attacking this “metadata scaling wall” include: caching inodes on clients and servers [9, 25, 14, 10, 28], caching parent inodes for path traversal [19, 21, 7, 27, 21], and dynamic caching policies that exploit workload locality [29, 32, 17]. These caches reduce the number of remote procedure calls (RPCs) but the effectiveness is dependent on the overhead of maintaining cache coherence and the administrator’s ability to select the best cache size for the given workloads. Recent work reduces the number of RPCs to 1 without using a cache at all, by letting clients “decouple” the subtrees from the global namespace so that they can do metadata operations locally [31, 23]. Unfortunately, *even with* this technique, we show that file system metadata workloads for can still be a bottleneck because large scale applications have (1) namespaces with many requests and (2) namespaces that are very large.

We propose Tintenfisch, a file system that allows users to succinctly express the structure and patterns of the metadata they intend to create. Using this semantic knowledge, Tintenfisch can optimize performance by reducing the number of metadata operations needed to complete a job and the metadata storage footprint. Figure 1 provides an architectural overview: clients first decouple the file system subtree they want to operate on<sup>1</sup> then clients and metadata servers lazily generate subtrees as needed using a “namespace generator”. The namespace generator is stored in the root inode of the decoupled subtree and can be used later to efficiently merge new metadata (that was not explicitly stated up front) into the global namespace. The fundamental insight is that the client and server both understand the final structure of the file system metadata so there is no need to communicate. As a consequence, less work is done on

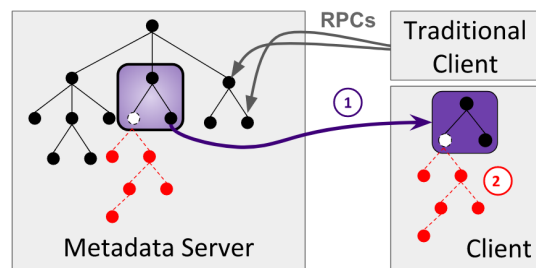


Figure 1: In (1), clients decouple file system subtrees and interact with their copies locally for high performance. In (2), clients and metadata servers generate subtrees using “namespace generators”, thus reducing RPC load.

the metadata servers and clients help process some of the metadata load. The idea uses concepts from decoupled namespaces [30, 31] and patterned IO [13] to build a scalable global namespace. Our contributions are as follows:

- we motivate our work (Section §2) by examining namespace descriptions and overheads for examples from different domains (high performance computing, high energy physics, and large simulations)
- we define namespace schemas (Section §3.1) for categorizing file system hierarchies and namespace generators (Section §3.2) to compact metadata, thus reducing RPC amplification and facilitating lazy metadata generation when needed
- a programmable storage approach that pushes user-defined functionality into the storage system, facilitating application-specific storage stacks using a ‘dirty-slate’ approach

## 2 Motivating Examples

We look at the namespaces of 3 applications. Each is from different domains and this list is not meant to be

<sup>1</sup>This is not a contribution as it was presented in [23].

exhaustive. Similar organizations exist for many domains, even something as distant as the mail application on a Mac. To highlight the scalability challenges for file system metadata management, we focus on large scale systems in high performance computing, high energy physics, and large scale simulations.

## 2.1 High Performance Computing: PLFS

Checkpointing performs small writes to a single shared file but because file systems are optimized for large writes, performance is poor. It is easier for applications to write checkpoints to a single file with unaligned writes of varying length (N-1) but general-purpose distributed file systems are designed for writes to different files (N-N). The general problem is that the application understands the workload but cannot communicate a solution to the storage system. The common solution is for the file system to expose configurations that describe alignment requirements but this forces application developers to specify “magic numbers” for parameters like write size [6] or stripe size [5], which are hard to find and may not even exist. Another solution is to add middleware (*i.e.* software that sits between the application and the storage system) to translate the data into a format the storage system performs well at.

PLFS [6] solved the checkpoint-restart problem by mapping logical files to physical files on the underlying file system. The solution targets N-1 strided checkpoints, where many processes write small IOs to offsets in the same logical file. The key insight of PLFS is that general purpose file systems perform well for applications that use N-N checkpoints and that the N-1 strided checkpoint style can be transformed with a thin interposition layer. To map offsets in the logical file to physical files each process maintains an index of {logical offset, physical offset, length, physical block id}. Each process sequentially writes to its own, unshared data file in the hierarchical file system and records an offset and length in an index file. Reads aggregate per-process index files into a global index file, which it uses as lookup table for logical file.

### 2.1.1 Namespace Description

When PLFS maps a single logical file to many physical files, it deterministically creates the namespace in the backend file system. For metadata writes, the number of directories is dependent on the number of client nodes and the number of files is a function of the number of client processes. A directory called a container is created per node and processes write data and index files to the container assigned to their host. So for a write workload (*i.e.* a checkpoint) the underlying file system creates a

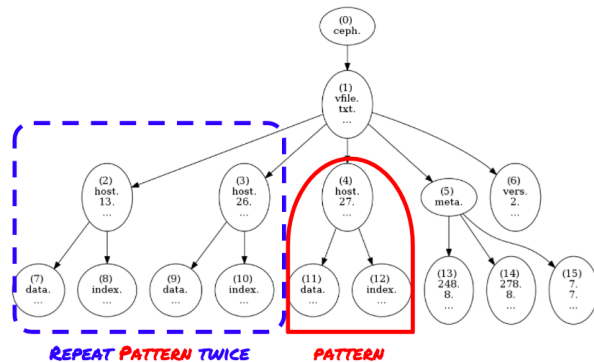


Figure 2: The PLFS file system namespace is structured and predictable; the pattern (solid line) is repeated for each hosts. In this case, there are three hosts so the pattern is repeated two more times.

deep and wide directory hierarchy.

The namespace structure for 3 processes writing to variable offsets in a single PLFS file is shown in Figure 2. The host\* directory and data\*/index files (denoted by the solid red line) are created for every node in the system. The pattern is repeated twice (denoted by the dashed blue line) in the Figure, representing 2 additional hosts.

### 2.1.2 Namespace Size

For writing a checkpoint, the number of file system metadata operations for  $n$  client processes is at least  $2n$ . Figure 3 shows the number of metadata requests serviced by the file system (y-axis) over time (x-axis) with inode caching turned off for three client processes. Each time the number of requests increases, clients are writing to a new PLFS file and the number of lookup()s is  $2 \times$  the number of creates. For a million processes checkpointing a portion of a 3D simulation for 1000 timestamps, the size of the namespace will be 2 billion files.

For reading a checkpoint, clients must coalesce index files to reconstruct the logical PLFS file. So for every physical file, the metadata server services a lookup() and open() request. Current efforts improve read scalability by reducing the space overhead of index files [13] and transferring index files after each write [12] but these approaches do not reduce the file system metadata load and reading the index files still requires multiple RPCs.

**Takeaway:** the PLFS namespace scales with the number of client processes. Decoupling the namespace helps parallelize metadata operations across clients when writing checkpoints but the size of the namespace is a problem when restarting checkpoints; index files need to be

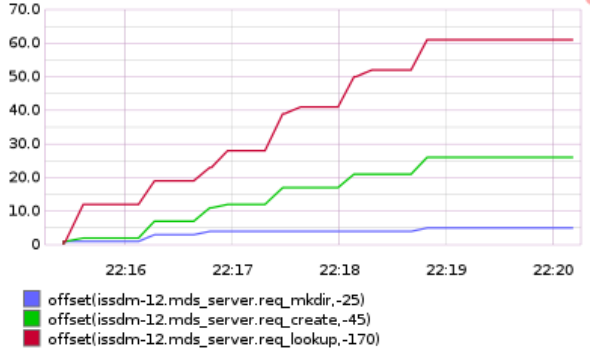


Figure 3: TODO: Change this GRAPH!. The requests scale linearly with the number of clients. lookup() requests dominate because clients share the root and must do path traversal.

coalesced and performance will be bottlenecked by the speed of transferring metadata updates across the network.

## 2.2 High Energy Physics: ROOT

The High Energy Physics (HEP) community uses a framework called ROOT to manipulate, manage, and visualize data about proton-proton collisions collected at the large hadron collider (LHC). The data is used to re-simulate phenomena of interest for analysis and there are different types of reconstructions each with various granularities. The data is organized as nested, object oriented event data and the length of the runs (and thus the number of events) are of arbitrary length and type (e.g., particle objects, records of low-level detector hit properties, etc.). Reconstruction takes detector conditions (e.g., alignment, position of the beam, etc.) as input. Data is streamed from the LHC into large immutable datasets, stored publicly in data centers around the world. Physicists analyze the dataset by downloading interesting events stored in ROOT files.

### 2.2.1 System Architecture

A ROOT file is a list of objects and data is accessed by consulting metadata in the header and seeking to a location in the bytestream, as shown in Figure 4a. Scattered in the ROOT file is both data and ROOT file specific metadata called Logical Record Headers (LRH). For this discussion, the following objects are of interest: a “Tree” is a table of a collection of events, listed sequentially and stored in a flat namespace; a “Branch” is a data container representing columns of a Tree; and “Baskets” are byte ranges partitioned by events and indexed by LRHs. Other objects, such as “Keys”, “Directories”,

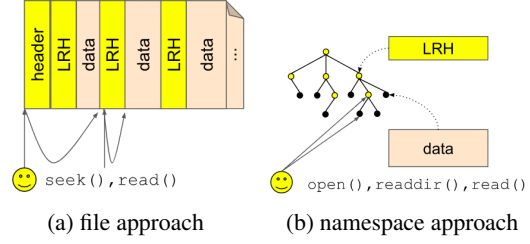


Figure 4: (a) shows how the file approach for handling HEP data stores everything in a single ROOT file, where the client reads the header and seeks to metadata (LRH) and data. For ROOT files stored in distributed file systems reads will have amplification because the system’s striping strategies are not aligned to Baskets. (b) shows how the namespace approach stores Baskets as files in the file system namespace so clients read only the data they need.

and “Leaves”, contain HEP-specific metadata. Clients request Branches and data is transferred as Baskets; so Branches are the logical view of the data for users and Baskets are the compression, parallelization, and transfer unit. In summary, ROOT files are self-describing files containing data located with metadata and serialized/deserialized with the ROOT framework. Much of the development was done at CERN in parallel with other HPC ventures. As a result, the strategies are similar to techniques used in HDF5, Parquet, and Avro.

The advantages of the ROOT framework is the ability to (1) read only parts of the data and (2) easily ingest remote data over the network. Unfortunately, the HEP community is running into scalability problems. The current effort is to integrate the ROOT framework with Ceph. But naive approaches such as storing ROOT files as objects in an object store or files in a file system have read amplification (*i.e.* read more than is necessary). Users would pull the entire GB-sized blob to their laptop instead of reading metadata and Branches a-la-cart. An alternative strategy that attempts to reduce read amplification is the “namespace approach” [20].

### 2.2.2 Namespace Description

The namespace approach views a ROOT file as a namespace of data. At the top of the namespace are Keys, each containing pointers to groups of Branches. For example, “MetaData” has data about the run and “Events” has all the proton-proton activity. Physicists ask for Branches, where each Branch can be made up of multiple sub-Branches (*i.e.* Events/Branch0/Branch1), similar to pathname components in a file system file name. To accommodate this model, the namespace approach partitions the ROOT file onto a file system namespace. As shown

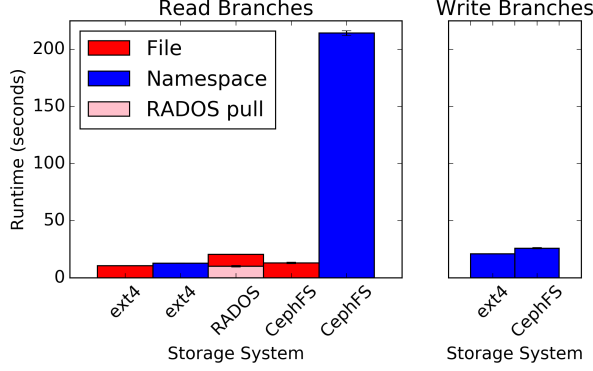


Figure 5: The “File” bars show the runtime of storing HEP data as a single ROOT file and the “Namespace” bars show the runtime of storing a file per Basket. The baseline is the runtime of “ext4” on a single node, “RADOS” is reading HEP data as a Ceph object, and “CephFS” is reading HEP data as files in a CephFS mount. “CephFS” is far slower because of the file system metadata load.

in Figure 4b, file system directories hold Branch metadata and files contain Baskets. Clients only pull baskets they care about, which prevents read amplification. Unfortunately, storing this metadata in a file system would overwhelm most file systems in two ways: (1) too many inodes and (2) per-file overhead. To quantify (1), consider the Analysis Object Dataset which has a petabyte of data sets made up of a million ROOT files. If these ROOT files are split by Branches, there would be a billion files. To quantify (2), we benchmark a simple ROOT workload over CephFS.

### 2.2.3 Namespace Size

We benchmark the write and read overhead of storing HEP data with the file approach stored as one object in an object store, with the file approach stored as one file in a file system, and with the namespace approach stored as many files in a file system. The file approaches are deployed without any changes to the ROOT framework. For the namespace approach, HEP-specific metadata is mapped onto the file system namespace. In CephFS, Baskets are stored in Ceph objects and the Branch hierarchy is managed by the metadata server. Clients contact the metadata server with a Branch request, receive back the Branch hierarchy necessary to name the Ceph object containing the Basket as well as the deserialization metadata necessary to read the object. The workload is a list of Branch accesses from a trace of the NPTupleMaker high energy physics application. Each Branch access is:

Branch0/Branch1,3,1740718587,5847,97,136  
where the tuple is the full Branch name, Basket num-

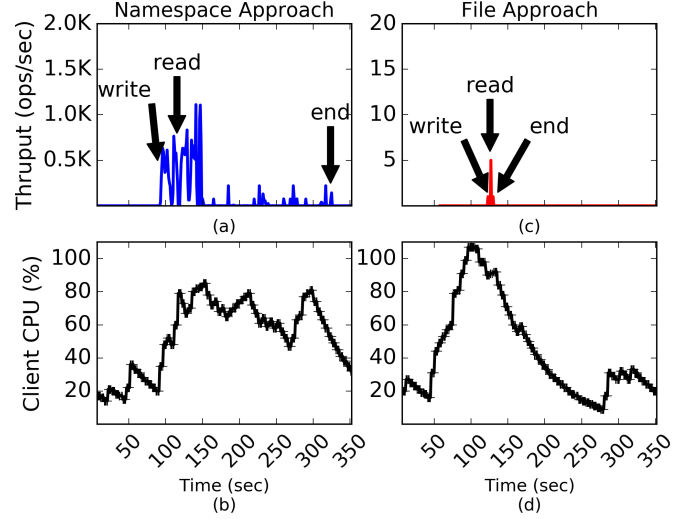


Figure 6: Reading and writing high-energy physics (HEP) data as many files allows physicists to read just the data they care about. But using this namespace approach sends many RPCs to the metadata server (a), resulting in worse performance and lower CPU utilization at the client (b). Alternatively, using the traditional file approach has IO amplification because all data moves over the network but less RPCs (c), better performance, and higher client CPU utilization (d).

ber, offset into the ROOT file, size of the Basket, start entry of the Basket, and end entry of the Basket. For the file approach, we use the offset into the ROOT file and the size of the Basket. In setup 1, the ROOT file is pulled locally and the Branches are read from the file. In setup 2, the offset and size of the read are sent to the CephFS metadata server. For setup 3, the full Branch name and Basket number are used to traverse the file system namespace.

The read and write performance for the different approaches are shown in Figure 5, where the x-axis is different storage backends, the y-axis is runtime, and the error bars are the standard deviations for six runs. Compared to the single node baseline (ext4), the namespace approach on CephFS is  $16.8\times$  slower.

**Takeaway:** the ROOT namespace would store up to a billion files. Decoupling the namespace helps parallelize metadata operations across clients when writing Baskets into the ROOT namespaces but the size of the namespace is a problem when reading branches; only a fraction of the Baskets need to be read and performance will be bottlenecked by the performance of reading subtrees that are not relevant to the workload.

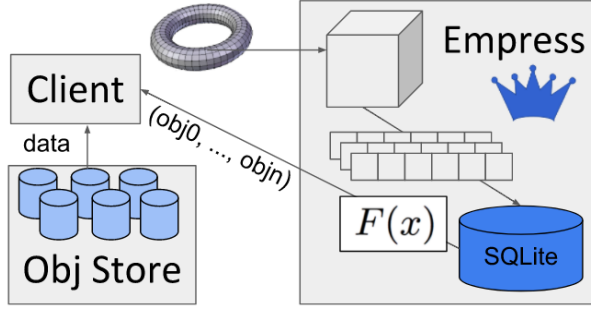


Figure 7: The SIRIUS project uses Empress to store metadata for bounding boxes in a 3D torus. Bounding box coordinates and a list of object names are stored in SQLite. The object names are calculated using an objecter function, labeled  $F(x)$  above. For reads, clients query Empress for the object list before reading from the object store.

## 2.3 Large Scale Simulations: SIRIUS

SIRIUS [15] is the Exascale storage system being designed for the Storage System and I/O (SSIO) initiative. The core tenant of the SIRIUS project is application hints that allow the storage to reconfigure itself for higher performance. Techniques include tiering, management policies, data layout, quality of service, and load balancing.

### 2.3.1 System Architecture

SIRIUS includes a metadata service called Empress [16], which is a query-able SQLite instance that stores metadata for bounding boxes (*i.e.* a 3-dimensional coordinate space). Figure 7 shows how metadata is stored in and retrieved from Empress; the entire simulation space, represented as a 3D torus, is partitioned into bounding boxes, whose coordinates are stored in SQLite for each variable (*e.g.*, temperature, pressure, etc.). The objecter function,  $F(x)$ , translates the bounding box coordinates into a list of object names, which are used to write/read data to/from the scalable object store. SIRIUS aims to satisfy queries structured like the “Six Patterns in HPC” [18].

### 2.3.2 Namespace Description

The seven columns in the database are six coordinates, which are integers representing the contents at a location in the global space, and a string representing the object name. The global space is partitioned into non-overlapping, regular shaped cells. Each row in the database is duplicated for each variable in the simulation because variables may have a different partitioning of the global space; for example temperature is computed for every cell while pressure is computed for ever  $n$  cells. Figure 7 only has three variables, represented by the rows

of boxes but most simulations will have a minimum of 10 variables.

### 2.3.3 Namespace Size

Empress lists all objects names for a bounding box and clients filter for data of interest. This is a problem because of the size of the object name list. Listing large numbers of items in file systems is notoriously slow and studies on 1s have shown the operation to be especially heavy-weight [8, 11]. As currently designed, Empress would store too many object names while the target query types only request subsets of the resulting list.

*# of object names:* a back-of-the-envelope calculation for the number of object names in the system is:

$$= \frac{(\# \text{ processes}) \times (\text{data/process}) \times (\text{timesteps}) \times (\text{variables})}{(\text{object size})}$$

where reasonable values would be one million processes, each writing 8GB of data for 100 timesteps and 10 variables. This represents a simulation space of  $10K \times 10K \times 10K$  cells containing 8 byte floats. Using an 8MB stripe size (the optimal object size in RADOS), the object name list size is:

$$= \frac{(1 * 10^6) \times (8 * 10^9) \times (100) \times (10)}{(8 * 10^6)} = 1 * 10^{12} \text{ objects}$$

*Queries use a subset of object names.* When running queries characterized by the “Six Patterns in HPC”, Empress must exhaustively list objects and filter the coordinates of interest. In addition to the time it would take to search 1 trillion objects in SQLite, another problem is the actual storage footprint of storing this many items.

**Takeaway:** the SIRIUS storage system would store up to a billion names. Decoupling the namespace helps parallelize metadata operations across clients when writing out objects but the size of the namespace is problem a problem when reading bounding box metadata; filtering for relevant coordinates would be bottlenecked by the performance of building the namespace and scanning lists.

## 3 Methodology: Tintenfisch

For three domain-specific applications and use-cases, we have identified scalability challenges because of the size of the namespace. Tintenfisch compacts metadata by defining namespace schemas and proposing namespace generators. Namespace schemas and generators help clients and servers establish an understanding of the final file system metadata shape and size (*i.e.* a “generation” contract) that eliminates metadata overheads.



For  $n$  processes on  $m$  servers:

```
# of dirs =  $m \times \text{mkdir}()$ 
# of file =  $2 \times n \times m$ 
# of file per dir =  $n/m$ 
```

(a) Function generator for PLFS

```
local box require 'box2d'
for i=_x,_x+x do -- iterate over the
  for j=_y,_y+y do -- given bounding
    for k=_z,_z+z do -- box coordinates
      if temperature>30 then
        -- partition object list one way, e.g.,
        b0, b1 = box.nsplrit(2)
      else
        -- partition a different way, e.g.,
        b0, b1, b2, b3 = box.nsplrit(4)
      end
    end
  end
end end end
return obj_list
```

(b) Code generator for SIRIUS

pointer\_generator: (o0, o2, o9)

code\_generator:

```
void recurseBranch(TObjArray *o) {
  TIter i(o);
  for(TBranch *b=i.Next(); i.Next()!=0; b=i.Next()) {
    processBranch(b);
    recurseBranch(b->GetListOfBranches());
  }
}
```

(c) Pointer and Code generators for HEP

Figure 8: Namespace generators subtrees for 3 motivating examples.

### 3.1 Namespace Schemas

Namespace schemas describe the structure of the namespace. A “balanced” namespace means that subtree patterns (*i.e.* files per directory) are repeated and a “bounded” namespace means that the range of file/directory names can be defined *a-priori*<sup>2</sup>. In the previous section, we observe three types of namespace schemas (1) unbalanced and unbounded, (2) balanced and bounded, and (3) unbalanced and bounded.

General file system workloads, like user home directories, have an unbalanced and unbounded namespace schema because users can create any combination of files per directory and the range of file/directory names is unknown *a-priori*. Traditional shared file systems are designed to handle these types of workloads. PLFS is an example of a balanced and bounded namespace because the distribution of files per directory is fixed (and re-

peated) and any subtree can be generated just using the client hostname and number of processes. The ROOT and SIRIUS use cases are examples of the unbalanced and bounded namespace schema. The file per directory shape is not repeated (it is determined by application-specific metadata, LRH metadata for ROOT and variable names like temperature or pressure for SIRIUS) but the range of file/directory names can be determined before the job starts.

### 3.2 Namespace Generators

A namespace generator is a compact representation of a namespace that allows clients and servers to generate file system metadata. Namespace generators can be used for a namespace schema that is balanced or bounded (not mutually exclusive) This approach reduces the size of the namespace (helps PLFS and ROOT use cases) facilitates lazy file system metadata generation when the metadata is needed (helps ROOT and SIRIUS use cases). Tintenfisch relies on the user to design effective namespace generators that leverage domain-specific knowledge to get the highest performance. This programmable storage approach [24] helps application developers tailor the storage system to the use case without having to design a new storage system from scratch.

Tintenfisch is built on Cudele [23] so a centralized, globally consistent metadata service (either a single metadata server or a cluster of active-active metadata servers) provides clients with the root inode of the subtree of interest and clients can do metadata IO locally with the consistency/durability semantics they require. In Tintenfisch, the namespace generators are stored in the directory inode of the root of the subtree that the client cares about. We use the “file type” interface from the Malacology [24] project to facilitate this domain-specific functionality. Next we discuss three example namespace generators: formula, code, and pointers.

#### 3.2.1 Formula Schema

For this generator, a formula that generates the file system namespace is stored in the inode. This formula takes domain-specific information as input and produces a list of files and directories. For example, because PLFS clients deterministically create files and directories based on the number of clients, Tintenfisch can use a formula generator like the one in Figure 8a. The function takes as input the number of processes and hosts in the cluster and outputs the number of directories, the number of files, and the number of files per directory. For the example, the namespace drawn in Figure 2 can be generated with the formula in Figure 8a using an input of 3 hosts each with 1 process. The output is 3 directories and 6

<sup>2</sup>By *a-priori* we mean before the job has run but after metadata has been read.

files, with 2 files per directory. With this namespace generator, clients can open just the container inode and then compute and access its contents without `lookup()` and `open()` RPCs to a centralized metadata service.

### 3.2.2 Code Schema

Sometimes the namespace generator logic is too complex to store as a single function or requires external libraries to interpret metadata. For example, the SIRIUS use case constructs the namespace using domain-specific partitioning logic written in Lua (for sandboxing purposes). Tintenfisch provides a code generator that gives users the flexibility to write programs that generate the namespace.

A code generator for the SIRIUS project is shown in Figure 8b. A namespace is constructed by iterating through the bounding box coordinates and checking if a threshold temperature is eclipsed. If it is, then extra names are generated using the `box2d` Lua package. Although the partitioning function itself is not realistic, it shows how code generators can accommodate domain-specific data layout policies that are complex and/or require external libraries.

### 3.2.3 Pointer Schema

Sometimes there is no formal specification for the namespace. For example, the ROOT framework uses self-describing files so headers and metadata need to be read for each ROOT file. In these scenarios, a code generator is insufficient for generating the file system namespace because all necessary metadata is in objects scattered in the object store. Pointer generators reference data in scalable storage and avoids storing large amounts of metadata in inodes, which is a frowned upon in distributed file systems like CephFS [1].

For example, a code generator containing library code for the ROOT framework *and* a pointer generator for referencing the input to the code can be used to describe a ROOT file system namespace. The pointer generator would point to objects in the object store that contain the necessary metadata for constructing the file system namespace. This is shown in Figure 8c; clients requesting Branches would follow the pointer generator to the objects containing metadata and would read them to locate Baskets using the code generator. An added benefit to this solution is that Tintenfisch can lazily construct parts of the namespace as needed, which avoids the problem of running out of inodes discussed in Section 2.2.2.

## A Fresh, Unorthodox, Unexpected, Controversial, and Counterintuitive Idea

Global file systems can be scalable if programmed correctly. For example, the following notions are out-dated:

- robust so they are fast... but we show that today's apps are so large that we need to specialized storage systems
- general because they have been around for so long... but we show that most apps don't need fs metadata
- subject to data IO performance... but we show that metadata is slow

## References

- [1] Ceph Documentation. [http://docs.ceph.com/docs/jewel/dev/mds\\_internals/data-structures/](http://docs.ceph.com/docs/jewel/dev/mds_internals/data-structures/), December 2017.
- [2] ABAD, C. L., LUU, H., LU, Y., AND CAMPBELL, R. Metadata Workloads for Testing Big Storage Systems. Tech. rep., Citeseer, 2012.
- [3] ABAD, C. L., LUU, H., ROBERTS, N., LEE, K., LU, Y., AND CAMPBELL, R. H. Metadata Traces and Workload Models for Evaluating Big Storage Systems. In *Proceedings of the International Conference on Utility and Cloud Computing, UCC '12*.
- [4] ALAM, S. R., EL-HARAKE, H. N., HOWARD, K., STRINGFELLOW, N., AND VERZELLONI, F. Parallel I/O and the Metadata Wall. In *Proceedings of the Workshop on Parallel Data Storage, PDSW '11*.
- [5] BEHZAD, B., LUU, H. V. T., HUCHETTE, J., BYNA, S., AYDT, R., KOZIOL, Q., SNIR, M., ET AL. Taming Parallel I/O Complexity with Auto-Tuning. In *Proceedings of the International Conference on High Performance Computing, Networking, Storage and Analysis, SC '13*.
- [6] BENT, J., GIBSON, G., GRIDER, G., MCCLELLAND, B., NOWOCZYNSKI, P., NUNEZ, J., POLTE, M., AND WINGATE, M. PLFS: A Checkpoint Filesystem for Parallel Applications. In *Proceedings of the Conference on High Performance Computing Networking, Storage and Analysis, SC '09*.
- [7] BRANDT, S. A., MILLER, E. L., LONG, D. D. E., AND XUE, L. Efficient Metadata Management in Large Distributed Storage Systems. In *Proceedings of the 20th IEEE/11th NASA Goddard Conference on Mass Storage Systems and Technologies (2003)*, MSST '03.
- [8] CARNS, P., LANG, S., ROSS, R., VILAYANNUR, M., KUNKEL, J., AND LUDWIG, T. Small-file Access in Parallel File Systems. In *Proceedings of the Symposium on Parallel and Distributed Processing, IPDPS '09*.
- [9] DEPARDON, B., LE MAHEC, G., AND SÉGUIN, C. Analysis of six distributed file systems. Tech. rep., French Institute for Research in Computer Science and Automation, 2013.
- [10] DEVULAPALLI, A., AND WYCKOFF, P. File creation strategies in a distributed metadata file system. In *Parallel and Distributed Processing Symposium, 2007. IPDPS 2007. IEEE International (2007)*, IEEE, pp. 1–10.
- [11] ESHEL, M., HASKIN, R., HILDEBRAND, D., NAIK, M., SCHMUCK, F., AND TEWARI, R. Panache: A Parallel File System Cache for Global File Access. In *Proceedings of the Conference on File and Storage Technologies, FAST '10*.

- [12] GRIDER, G. If the plfs index is still too large too efficiently read/distribute pull out the hammerplfs collectives, reduces plfs index to nearly nothing enabling strategy for optimizing reads and active analysis.
- [13] HE, J. Io acceleration with pattern detection.
- [14] HILDEBRAND, D., AND HONEYMAN, P. Exporting Storage Systems in a Scalable Manner with pNFS. In *Proceedings of the 22nd IEEE / 13th NASA Goddard Conference on Mass Storage Systems and Technologies* (2005), MSST '05.
- [15] KLASKY, S. A., ABBASI, H., AINSWORTH, M., CHOI, J., CURRY, M., KURC, T., LIU, Q., LOFSTEAD, J., MALTZAHN, C., PARASHAR, M., PODHORSZKI, N., SUCHYTA, E., WANG, F., WOLF, M., CHANG, C. S., CHURCHILL, M., AND ETHIER, S. Exascale Storage Systems the SIRIUS Way. *Journal of Physics: Conference Series*.
- [16] LAWSON, M., ULMER, C., MUKHERJEE, S., TEMPLET, G., LOFSTEAD, J. F., LEVY, S., WIDENER, P. M., AND KORDENBROCK, T. Empress: Extensible Metadata Provider for Extreme-Scale Scientific Simulations. In *Proceedings of the Joint International Workshop on Parallel Data Storage & Data Intensive Scalable Computing Systems*, PDSW '17.
- [17] LI, W., XUE, W., SHU, J., AND ZHENG, W. Dynamic Hashing: Adaptive Metadata Management for Petabyte-scale Scale Systems. In *Proceedings of the 23rd IEEE/14th NASA Goddard Conference on Mass Storage Systems and Technologies* (2006), MSST '06.
- [18] LOFSTEAD, J., POLTE, M., GIBSON, G., KLASKY, S., SCHWAN, K., OLDFIELD, R., WOLF, M., AND LIU, Q. Six Degrees of Scientific Data: Reading Patterns for Extreme Scale Science IO. In *Proceedings of High Performance and Distributed Computing*, HPDC '11.
- [19] PATIL, S. V., AND GIBSON, G. A. Scale and Concurrency of GIGA+: File System Directories with Millions of Files. In *Proceedings of the 9th USENIX Conference on File and Storage Technologies* (2011), FAST '11.
- [20] PIVARSKI, J. How to make a petabyte ROOT file: proposal for managing data with columnar granularity.
- [21] REN, K., ZHENG, Q., PATIL, S., AND GIBSON, G. IndexFS: Scaling File System Metadata Performance with Stateless Caching and Bulk Insertion. In *Proceedings of the Conference on High Performance Computing, Networking, Storage and Analysis* (2014), SC '14.
- [22] ROSELLI, D., LORCH, J. R., AND ANDERSON, T. E. A Comparison of File System Workloads. In *Proceedings of the USENIX Annual Technical Conference*, ATC '00.
- [23] SEVILLA, M. A., JIMENEZ, I., WATKINS, N., FINKELSTEIN, S., LEFEVRE, J., ALVARO, P., AND MALTZAHN, C. Cud-ele: An API and Framework for Programmable Consistency and Durability in a Global Namespace. In *Proceedings of the 32nd IEEE International Parallel and Distributed Processing Symposium* (2018), IPDPS '18.
- [24] SEVILLA, M. A., WATKINS, N., JIMENEZ, I., ALVARO, P., FINKELSTEIN, S., LEFEVRE, J., AND MALTZAHN, C. Malacology: A Programmable Storage System. In *Proceedings of the European Conference on Computer Systems* (2017), EuroSys '17.
- [25] SINNAMOHIDEEN, S., SAMBASIVAN, R. R., HENDRICKS, J., LIU, L., AND GANGER, G. R. A Transparently-Scalable Metadata Service for the Ursa Minor Storage System. In *USENIX ATC '10* (Boston, MA, June 23-25 2010), ATC '10.
- [26] WEIL, S. A., BRANDT, S. A., MILLER, E. L., LONG, D. D. E., AND MALTZAHN, C. Ceph: A Scalable, High-Performance Distributed File System. In *Proceedings of the Symposium on Operating Systems Design and Implementation*, OSDI '06.
- [27] WEIL, S. A., POLLACK, K. T., BRANDT, S. A., AND MILLER, E. L. Dynamic Metadata Management for Petabyte-Scale File Systems. In *Proceedings of the Conference on High Performance Computing Networking, Storage and Analysis*, SC '04.
- [28] WELCH, B., UNANGST, M., ABBASI, Z., GIBSON, G., MUELLER, B., SMALL, J., ZELENKA, J., AND ZHU, B. Scalable Performance of the Panasas Parallel File System. In *Proceedings of the 6th USENIX Conference on File and Storage Technologies* (2008), FAST'08.
- [29] XING, J., XIONG, J., SUN, N., AND MA, J. Adaptive and Scalable Metadata Management to Support a Trillion Files. In *Proceedings of the Conference on High Performance Computing Networking, Storage and Analysis* (2009), SC '09.
- [30] ZHENG, Q., REN, K., AND GIBSON, G. BatchFS: Scaling the File System Control Plane with Client-funded Metadata Servers. In *Proceedings of the Workshop on Parallel Data Storage*, PDSW '14.
- [31] ZHENG, Q., REN, K., GIBSON, G., SETTLEMYER, B. W., AND GRIDER, G. DeltaFS: Exascale File Systems Scale Better Without Dedicated Servers. In *Proceedings of the Workshop on Parallel Data Storage* (2015), PDSW '15.
- [32] ZHU, Y., JIANG, H., WANG, J., AND XIAN, F. HBA: Distributed Metadata Management for Large Cluster-Based Storage Systems. *IEEE Transactions on Parallel Distributed Systems* 19, 6 (June 2008).