Efficient, Modular Metadata Management with Loris

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File systems as lightweight data stores

- File systems have remained data agnostic for several decades
  - Files are still unstructured sequence of bytes
  - Simple hierarchy-based organization of files
- Generality has enabled widespread adoption as:
  - Document stores in personal computing
  - Dedicated data and metadata stores in enterprise computing
  - Local node stores for cluster/parallel file systems in HPC
  - Local node stores for distributed file systems in DISC

Domain-specific metadata management: a growing trend

- The "Generalized FS – domain-specific metadata" gap
  - User-level metadata management systems bridge the gap
- Desktop and multimedia search applications (Personal computing)
  - Maintain application-specific indices
  - Provide attribute or tag-based query interface
- Enterprise search appliances (Enterprise computing)
  - Periodic, incremental crawling of metadata
  - Admin-friendly interface to assist in policy enforcement

Domain-specific metadata management (2)

- User-level provenance management subsystems (HPC)
  - Low impact, complete, automated provenance gathering
  - Provenance-friendly storage and query runtime subsystems
- Custom-built databases for housing metadata (DISC)
  - Databases optimized for metadata storage and retrieval
  - Avoid using inefficient local file systems as metadata stores

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Domain-specific metadata management:
a least common denominator functionality across application areas

Issues with existing metadata management solutions

- Stale query results
  - Outside mainline metadata modification path
  - Indices not maintained in real time
- Performance impact of file system crawling
  - Unoptimized metadata placement in local file systems
  - Resource-intensive index scans and updates
- Storage inefficiency
  - Unwarranted metadata duplication

File systems and metadata management

- If local file systems provide metadata management:
  - No polling/gathering will be required
  - No metadata duplication
  - Custom layout schemes for storing indexed metadata
- However, traditional file systems lack modularity
  - Integration of metadata management on a case-by-case basis
  - Impossible to plug in domain-specific naming systems

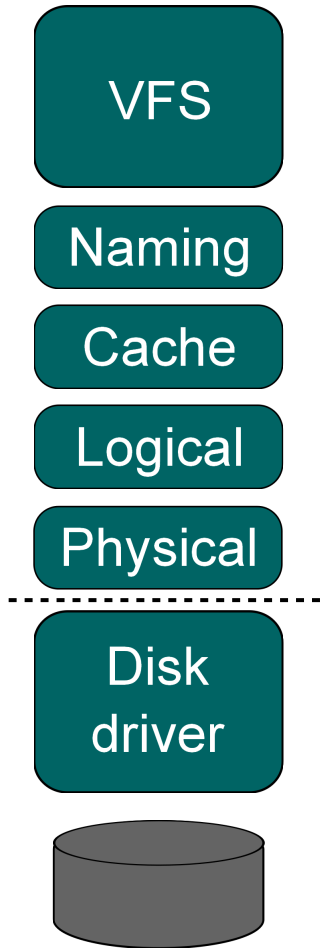
Context: the Loris Storage Stack

- Traditional stack also suffers from several other issues
  - Silent data corruption, RAID write hole
  - Lack of support for graceful degradation
  - Complicated device administration
  - Lack of support for integration of heterogeneous devices
- In prior work, we presented Loris
  - A modular redesign of the traditional storage stack

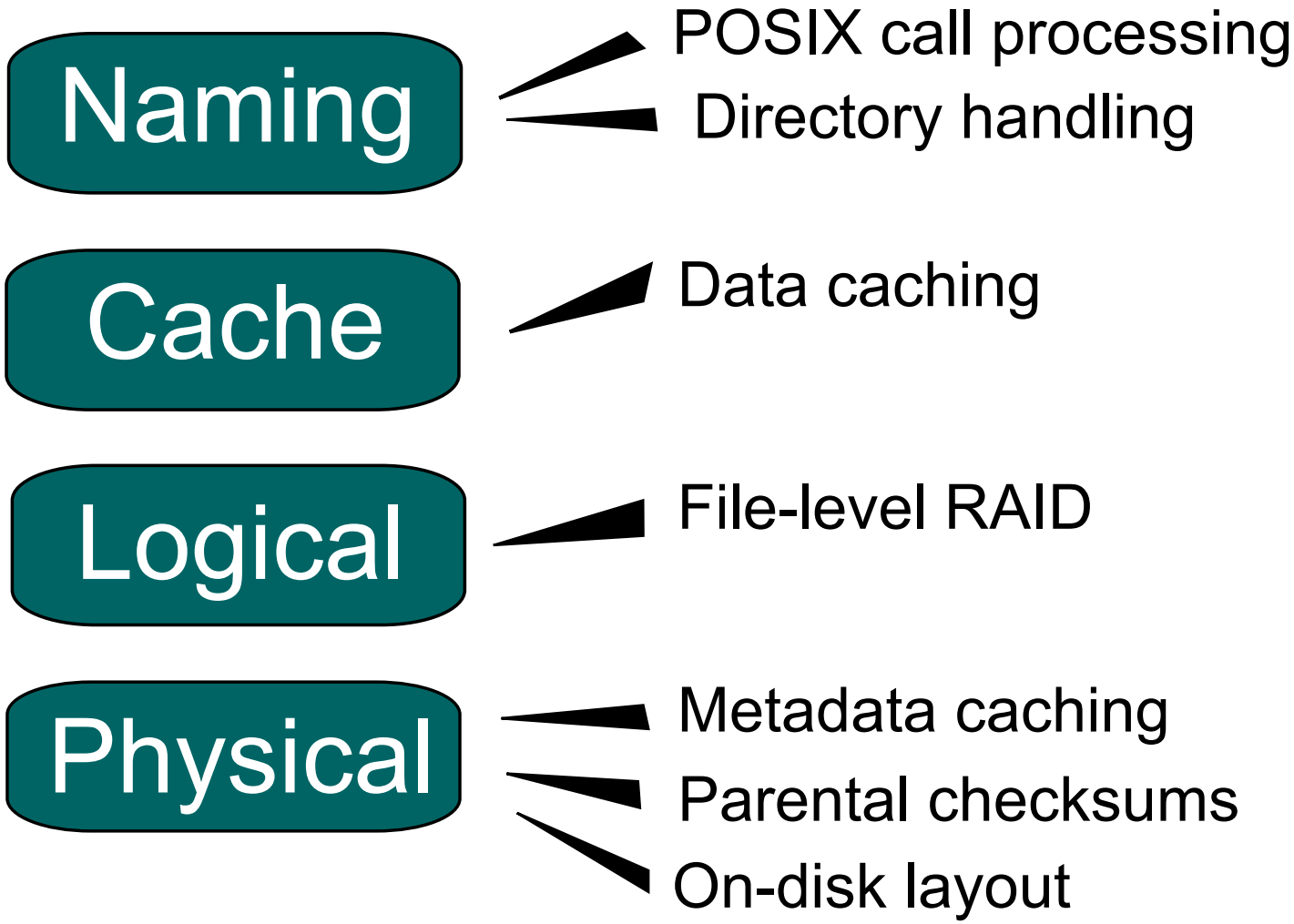
The Loris Storage Stack: layers and interfaces

- File-based interface between layers
  - Each file has a unique file identifier
  - Each file has a set of attributes
- File-oriented requests:

create	**truncate**
delete	**getattr**
read	**setattr**
write	**sync**



Loris: division of labor

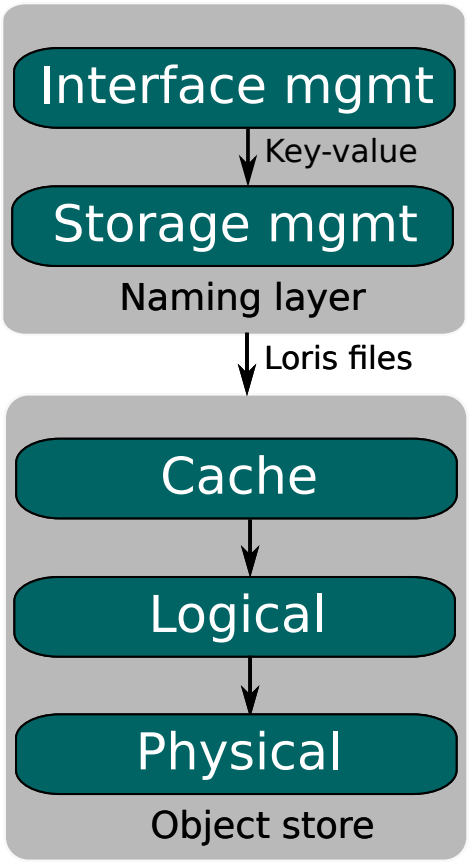


Loris as a customizable metadata management framework

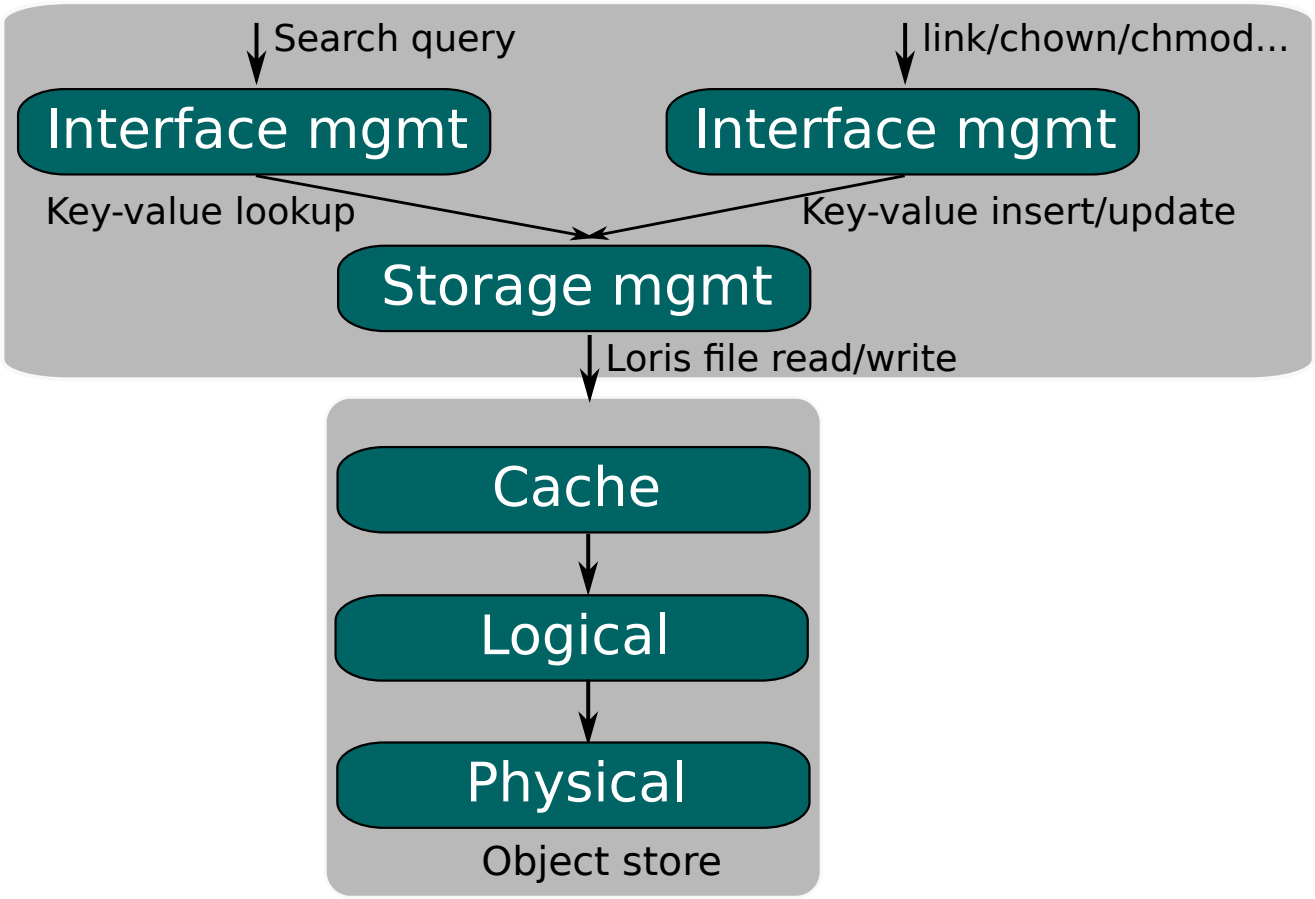
- Loris' naming layer views the lower layers as an object store
  - User-level metadata solutions view FS as object store
  - Metadata management is a straightforward extension
- Modular integration of metadata management
  - Can change naming modules without affecting other layers
- Each naming implementation in essence builds a database
  - Database files stored as Loris files
  - Domain-specific file formats used for packing metadata
  - Domain-specific query interfaces used for searching metadata

Our Loris-based metadata management solution

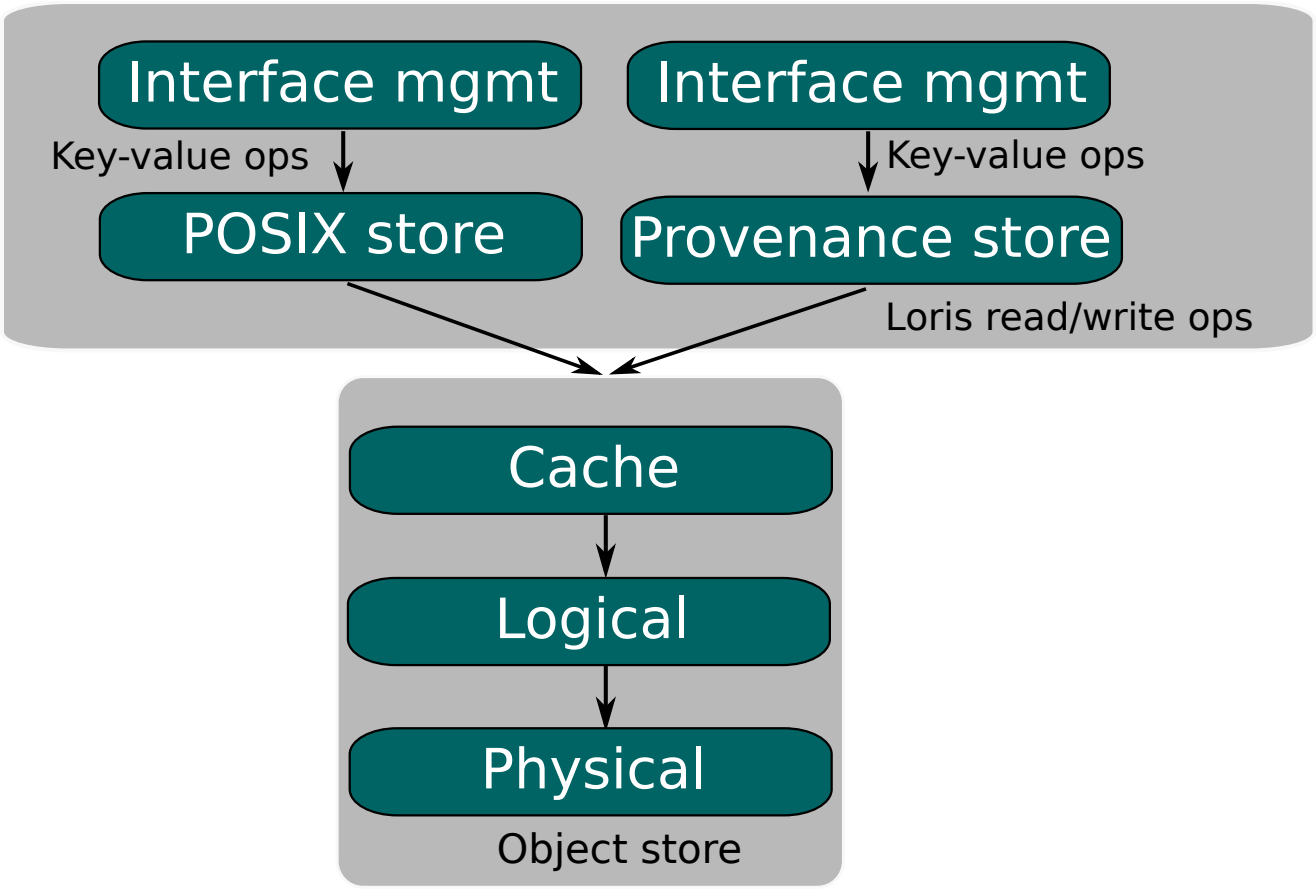
- Plug-in-based naming layer
  - Decomposed into two sublayers
- Storage management sublayer
  - Key-value store for metadata
  - Stores key-value pairs in domain-specific file formats
- Interface management sublayer
  - Mapping domain abstractions to key-value pairs (ex: Directories)
  - Domain-specific interfaces (ex: POSIX)



Abstraction boundaries and mapping (1)



Abstraction boundaries and mapping (2)



Our storage management sublayer

- Key-value pairs stored in write-optimized Log-Structured Merge trees
  - Multicomponent trees with in-memory and on-disk parts
  - In-memory components provide buffering
  - Immutable on-disk components created by batch flushing
- LSM trees have several advantages over other indexing trees
  - Random metadata updates converted into sequential writes
  - Key format can be used to control locality
  - Short-lived metadata dies in memory
- Our LSM data structures
  - AVL tree as the in-memory component
  - Densely-packed B+-trees as on-disk components

Our interface management sublayer : POSIX emulation

- All POSIX metadata maintained in a single LSM tree
  - Unified key structure for storing directories and attributes
  - < parentID, name, record type > is used as the key
  - Special mechanism for handling hard links

Key	**Value**
<0, /, f> <0, /, r>	atime=2011-01-01 . . . id=1 links=4 mode=drwxr-xr-x . . .
<1, etc, f> <1, etc, r>	atime=2011-01-02 . . . id=5 links=2 mode=drwxr-xr-x . . .
<1, tmp, f> <1, tmp, r>	atime=2011-01-03 . . . id=3 links=2 mode=drwxr-xr-x . . .
<3, prog.c, f> <3, prog.c, r>	atime=2011-01-01 . . . size=2000 id=10 links=1 mode=-rw-r–r– . . .
<3, t.txt, f> <3, t.txt, r>	atime=2011-01-03 . . . size=100 id=13 links=1 mode=-rw——- . . .
<5, rc, f> <5, rc, r>	atime=2011-01-02 . . . size=1024 id=20 links=1 mode=-rwx—— . . .

Table: Mapping for /, /etc, /tmp, /tmp/prog.c, /tmp/t.txt and /etc/rc

Our interface management sublayer : real-time Indexing

- LSM-tree-based indexing of attributes
  - Policy-based inclusion/exclusion of attributes
  - Index updates in LSM trees incur little overhead
  - Separate merge parameters for index and metadata trees
  - All attributes indexed in a single tree
  - Uses <attribute ID, value, fileid> as the key

Key	**Value**
<atime, 2011-01-02, 20>	
<atime, 2011-01-03, 13>	
⋮	⋮
<size, 100, 13>	
<size, 1024, 20>	
⋮	⋮

Our interface management sublayer: attribute-based search

- Using typed virtual directories as query interface
  - Read-only directories created on the fly
  - Different plugins can be used to generate entries
  - Example: version virtual directory
- Attribute-based search virtual directory plugin
  - Query term is a combination of attributes/conditions
  - Conjunctive queries map onto hierarchies
  - Examples: cd [uid $=$ 100]/[size $>$ 1048576]
- Query evaluated using the auxiliary attribute index

Evaluation

- 31% speedup with Postmark
- 3-52% speedup with application benchmark
  - Copies src, build, find and grep, rm etcetera.
- Indexed search is 25x faster than the find utility
  - Find all files modified in the last N days (200,000 files)
  - Find all files with size $>$ 1 GB (200,000 files)
- Real-time indexing incurs moderate (10-15%) overhead
  - With both Postmark and application-level benchmarks while indexing seven frequently updated attributes

Conclusion

- Ad hoc, domain-specific metadata management solutions suffer from serious limitations
- Lack of modularity in traditional file systems complicates integration of metadata management
- Loris provides a modular, flexible framework for implementing such solutions
- Our naming layer design provides
  - High-performance metadata storage using LSM trees
  - Customizable, real-time indexing of attributes
  - Search-friendly, attribute-based interface in addition to the traditional POSIX interface