Decentralized Deduplication in SAN Cluster File Systems

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Abstract

File systems hosting virtual machines typically contain many duplicated blocks of data resulting in wasted storage space and increased storage array cache footprint. *Deduplication* addresses these problems by storing a single instance of each unique data block and sharing it between all original sources of that data. While deduplication is well-understood for file systems with a centralized component, we investigate it in a decentralized cluster file system, specifically in the context of virtual machine storage.

We propose DEDE, a block-level deduplication system for live cluster file systems that does not require any central coordination, tolerates host failures, and takes advantage of the block layout policies of an existing cluster file system. In DEDE, hosts keep summaries of their own writes to the cluster file system in shared on-disk structures. Each host periodically and independently processes the summaries of its locked files, merges them with a shared index of blocks, and reclaims any duplicate blocks, manipulating the file system structure using general file system interfaces without knowledge of the file system implementation. We present the design, implementation, and evaluation of our techniques in the context of VMware ESX Server. Our results show an 80% reduction in space with minor performance overhead for realistic workloads.

1 Introduction

Deployments of consolidated storage using Storage Area Network (SAN) hardware are increasing, motivated by universal access to data from anywhere, ease of backup, flexibility in provisioning, and centralized administration. SAN arrays already form the backbone of modern data centers by providing consolidated data access for multiple hosts simultaneously. This trend is further fueled by the proliferation of virtualization technologies, which rely on shared storage to support features such as live migration of workloads across hosts.

SANs provide multiple hosts with direct SCSI access to shared storage volumes. Of course, regular file systems assume exclusive access to the disk and would quickly corrupt a shared disk. To tackle this, numerous shared disk cluster file systems have been developed, including VMware VMFS [20], RedHat GFS [15], and IBM GPFS [18], which use distributed locking to coordinate concurrent access to the shared file system between multiple hosts.

Cluster file systems play an important role in virtualized data centers, where multiple physical hosts each run potentially hundreds of virtual machines (VMs) whose virtual disks are stored as regular files in the shared file system. SANs provide hosts access to shared storage for VM disks with near native SCSI performance while also enabling advanced features like live migration, load balancing, and failover of VMs across hosts.

These shared file systems represent an excellent opportunity for detecting and coalescing duplicate data. Since they store data from multiple hosts, not only do they contain more data, but data redundancy is also more likely. Shared storage for VMs is a particularly ripe application for deduplication because common system and application files are repeated across VM disk images and hosts can automatically and transparently share data between and within VMs. This is particularly true of virtual desktop infrastructures (VDI) [23], in which desktop machines are virtualized, consolidated into data centers, and accessed via thin clients. Our experiments show that a real enterprise VDI deployment can expend as much as 80% of its overall storage footprint on duplicate data from VM disk images. Given the desire to lower costs, such waste provides motivation to reduce the storage needs of virtual machines both in general and for VDI in particular.

Existing deduplication techniques [1, 3–5, 8, 14, 16, 17, 25] rely on centralized file systems, require cross-host communication for critical file system operations, perform deduplication in-band, or use content-addressable storage (CAS). All of these approaches have limitations in our domain. Centralized techniques would be difficult to extend to a setting with no centralized component other than the disk itself. Existing decentralized techniques require cross-host communication for most operations, often including reads. Performing deduplication in-band with writes to a live file system can impose severe limits to achieved system bandwidth and IO latency. Finally, content-addressable storage, where data is addressed by its content hash, also suffers from performance issues related to expensive metadata lookups as well as loss of spatial locality [10].

Our work addresses deduplication in the decentralized setting of VMware's VMFS cluster file system. Unlike existing solutions, DEDE coordinates a cluster of hosts to cooperatively perform block-level deduplication of the live, shared file system. It takes advantage of the SAN as the only centralized point in the system and does not require cross-host communication for regular file system operations, retaining the direct-access advantage of SAN file systems. As a result, the only failure that can stop deduplication is a failure of the SAN itself, without which there is no file system to deduplicate. Because DEDE is an online system for primary storage, all deduplication is best-effort and performed as a background process, out-of-band from writes, in order to minimize impact on system performance. Finally, unlike other systems, DEDE builds block-level deduplication atop an existing file system and takes advantage of regular file system abstractions, layout policy, and block addressing. As a result, deduplication introduces no additional metadata IO when reading blocks and permits in-place writes to blocks that have no duplicates.

This paper presents the design of DEDE. We have implemented a functional prototype of DEDE for VMware ESX Server [22] atop VMware VMFS. Using a variety of synthetic and realistic workloads, including data from an active corporate VDI installation, we demonstrate that DEDE can reduce VM storage requirements by upwards of 80% at a modest performance overhead.

Section 2 provides an overview of the architecture of our system and our goals. Section 3 details the system's design and implementation. We provide a quantitative evaluation of our system in Section 4, followed by a discussion of related work in Section 5. Finally, we conclude in Section 6.

2 System Overview

DEDE operates in a cluster setting such as the one shown in Figure 1, in which multiple hosts are directly connected to a single, shared SCSI volume and use a file system designed to permit symmetric and cooperative access to the data stored on the shared disk. DEDE itself runs on each host as a layer on top of the file system, taking advantage of file system block layout policies and native support for copy-on-write (COW) blocks. In this section, we provide a brief overview of our approach to deduplication and the file system support it depends on.

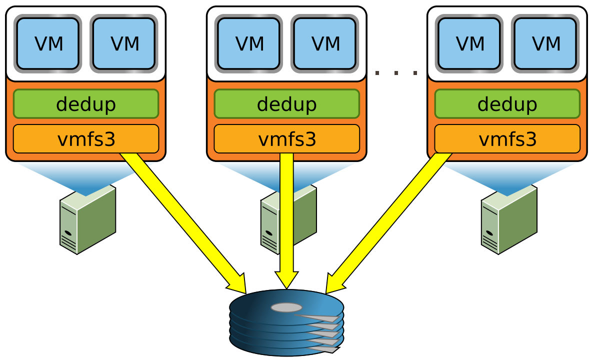


Figure 1: Cluster configuration in which multiple hosts concurrently access the same storage volume. Each host runs the VMFS file system driver (`vmfs3`), the deduplication driver (`dedup`), and other processes such as VMs.

DEDE uses content hashes to identify potential duplicates, the same basic premise shared by all deduplication systems. An index stored on the shared file system and designed for concurrent access permits efficient duplicate detection by tracking all known blocks in the file system by their content hashes.

In order to minimize impact on critical file system operations such as reading and writing to files, DEDE updates this index *out of band*, buffering updates and applying them in large, periodic batches. As part of this process, DEDE detects and eliminates duplicates introduced since the last index update. This task can be done as an infrequent, low priority background task or even scheduled during times of low activity. Unlike approaches to deduplication such as content-addressable storage that integrate content indexes directly into the file system storage management, DEDE's index serves solely to identify duplicate blocks and plays no role in general file system operations.

DEDE divides this index update process between hosts. Each host monitors its own changes to files in the cluster file system and stores summaries of recent modifications in on-disk *write logs*. These logs include content hashes, which are computed as blocks are written out to disk. To update the shared index, each host periodically consumes the write logs of files it has (or can gain) exclusive access to and updates the index to reflect these recorded modifications. In the process, it discovers and reclaims any block whose content is identical to the content of some previously indexed block. Partitioning the index update process allows hosts to divide the burden of deduplication, while sharing the index allows hosts to detect duplicates even if they are introduced by separate hosts.

Out-of-band index updates mean DEDE must be resilient to stale index entries that do not reflect the latest content of recently updated blocks. Indeed, this is essentially unavoidable in a decentralized setting even given communication delays alone. While this means DEDE generally must verify block contents when updating the index, this resilience has an important implication: DEDE's correctness does not depend on its ability to monitor every write to the file system. This has important performance benefits. First, updates to write logs do not have to be crash-consistent with updates to file contents, which both simplifies fault tolerance and allows hosts to buffer updates to write logs to minimize additional IO. Second, this allows users to trade off the CPU and memory overhead of write monitoring for peak file system performance on a per-file basis. For example, a user could simply disable deduplication for VMs that are performance-critical or unlikely to contain much duplicate data. Finally, this allows the write monitor to shed work if the system is overloaded.

Because DEDE operates on a live file system, it specifically optimizes for *unique* blocks (blocks with no known duplicates). Unlike *shared* blocks, these blocks remain mutable after deduplication. The mutability of unique blocks combined with DEDE's resilience to stale index information means these blocks can be updated in place without the need to allocate space for a copy or to synchronously update the index. As a result, deduplication has no impact on the performance of writing to unique blocks, a highly desirable property because these are precisely the blocks that do not benefit from deduplication.

Similar to some other deduplication work related to virtual disks [10, 13], DEDE uses fixed-size blocks. Unlike stream-oriented workloads such as backup, where variable-sized chunks typically achieve better deduplication [25], our input data is expected to be block-structured because guest file systems (*e.g.*, ext3, NTFS) typically divide the disk into fixed-size 4 KB or 8 KB blocks themselves. Consistent with this expectation, earlier work [12] and our own test results (see Section 4.1), we use a block size of 4 KB.

2.1 Required File System Abstractions

Most approaches to deduplication unify duplicate elimination and storage management, supplanting the file system entirely. DEDE, in contrast, runs as a layer on top of VMFS, an existing file system. This layer finds potentially identical blocks and identifies them to the file system, which is then responsible for merging these blocks into shared, copy-on-write blocks.

DEDE requires the file system to be block oriented and to support file-level locking. The file system block size must also align with the deduplication block size, a requirement VMFS's default 1 MB block size, unfortunately, does not satisfy. Our only non-trivial change to VMFS was to add support for typical file system block sizes (*i.e.*, 4 KB), as detailed later in Section 2.2.

Finally, DEDE requires block-level copy-on-write support, a well understood, but nevertheless uncommon feature supported by VMFS. Specifically, it requires an unusual *compare-and-share* operation, which replaces two blocks with one copy-on-write block after verifying that the blocks are, in fact, identical (using either bit-wise comparison or a content hash witness). Despite the specificity of this operation, it fits naturally into the structure of block-level copy-on-write and was easy to add to the VMFS interface. DEDE manipulates file system blocks solely through this interface and has no knowledge of the underlying file system representation.

There are two noteworthy capabilities that DEDE does *not* require of the file system. First, hosts running DEDE never modify the metadata of files they do not have exclusive locks on, as doing so would require cross-host synchronization and would complicate per-host metadata caching. As a result, a host that discovers a duplicate block between two files cannot simply modify both files to point to the same block if one of the files is locked by another host. Instead, when DEDE detects a duplicate between files locked by different hosts, it uses a third file containing a *merge request* as an intermediary. One host creates a merge request containing a COW reference to the deduplicated block, then passes ownership of the merge request file's lock to the other host, which in turn replaces the block in its file with a reference to the block carried by the merge request.

Second, DEDE does *not* require the file system to expose a representation of block addresses. Much like any regular application, it only ever refers to blocks indirectly, by their offset in some locked file, which only the file system can resolve into block addresses. This restricts the design of our index, since it cannot simply refer to indexed blocks directly. However, this is an important limitation, since requiring the file system to expose block addresses outside the file system's own data structures would interfere with its ability to free and migrate blocks and could result in dangling pointers. Worse, any operations introduced to manipulate blocks directly would conflict with file-level locking and host metadata caching.

In lieu of referring to blocks by block addresses, DEDE introduces a *virtual arena* file. This is a regular file in the file system, but it consists solely of COW references to shared blocks that are present in at least one other file. This file acts as an alternate view of all shared blocks in the system: DEDE identifies shared blocks simply by their offsets in the virtual arena file, which the file system can internally resolve to block addresses using regular address resolution.

Because DEDE builds on the underlying file system, it inherits the file system's block placement policy and heuristics. If the underlying file system keeps file blocks sequential, blocks will generally remain sequential after deduplication. Shared blocks are likely to be sequential with respect to other blocks in at least one file, and common sequences of shared blocks are likely to remain sequential with respect to each other. Furthermore, the placement and thus sequentiality of unique blocks is completely unaffected by the deduplication process; as a result, not only is IO performance to individual unique blocks unaffected after deduplication because they do not require copying, but sequential IO performance across spans of unique blocks is also unaffected.

2.2 VMFS

Many of the design decisions in DEDE were influenced by the design of its substrate file system, VMFS. VMFS is a coordinator-less cluster file system [20] designed to allow hosts to cooperatively maintain a file system stored on a shared disk. In this section, we provide a quick overview of how VMFS addresses and manages concurrent access to its resources in order to provide better context for the design of DEDE.

VMFS organizes the shared disk into four different resource pools: inodes, pointer blocks, file blocks, and sub-blocks. Inodes and pointer blocks play much the same role as in traditional UNIX file systems, storing per-file metadata and pointers to the blocks containing actual file content. File blocks and sub-blocks both store file content, but are different sizes, as discussed below. The divisions between these pools are currently fixed at format time and can only be expanded by adding more storage, though this is not a fundamental limitation. In each pool, resources are grouped into *clusters*. The header for each cluster maintains metadata about all of its contained resources; most importantly, this includes a reference count for each individual resource and tracks which resources are free and which are allocated.

In order to support concurrent access by multiple hosts, VMFS uses a distributed lock manager to protect file data and resource metadata. Unlike most cluster file systems, which assume the availability of an IP network for synchronization, VMFS synchronizes all file system access entirely through the shared disk itself using on-disk locks. VMFS ensures atomic access to on-disk lock structures themselves using SCSI-2-based LUN reservations to guard read-modify-write critical sections. In addition to taking advantage of the reliability of storage area networks, using the same means to access both file system

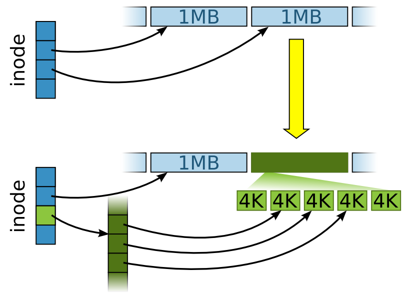


Figure 2: Mixed block sizes allow any 1 MB file block to be divided into 256 separate 4 KB sub-blocks.

state and synchronization state prevents "split brain" problems typical of IP-based lock managers in which multiple hosts can access the file system state but cannot communicate locking decisions with each other.

VMFS protects file data from concurrent access by associating a coarse-grain lock with each file that covers all of a file's metadata (its inode and pointer blocks) as well as all of the file blocks and sub-blocks comprising the file's content. Files in VMFS tend to be locked for long durations (*e.g.*, a VM's disk files are locked as long as the VM is powered on), so DEDE respects file system locking by partitioning the deduplication process according to which hosts hold which file locks.

VMFS protects resource metadata using per-cluster locks. Thus, allocation and deallocation of resources must lock all clusters containing any of the resources involved. The number of resources packed per cluster reflects a trade-off between locking overhead and cross-host cluster lock contention. Higher cluster density allows hosts to manipulate more resources with fewer locks, but at the cost of increased lock contention. Since DEDE stresses the sub-block resource pool more than typical VMFS usage, we increase the sub-block cluster density from 16 to 128 resources per cluster, but otherwise use the default VMFS densities.

VMFS maintains two separate resource types for storing file content: file blocks and sub-blocks. File sizes in VMFS typically fit a bimodal distribution. Virtual machine disks and swap files are usually several gigabytes, while configuration and log files tend to be a few kilobytes. Because of this, VMFS uses 1 MB file blocks to reduce metadata overhead and external fragmentation for large files, while for small files, VMFS uses smaller sub-blocks in order to minimize internal fragmentation. DEDE must be able to address individual 4 KB blocks in order to COW share them, so we configure VMFS with 4 KB sub-blocks. Furthermore, rather than simply eschewing the efficiency of 1 MB blocks and storing all file content in 4 KB blocks, we extend VMFS to support *mixed block sizes*, depicted in Figure 2 so that DEDE can address individual 4 KB blocks of a file when it needs to share a duplicate block, but when possible still store unique regions of files in efficient 1 MB blocks. This change introduces an optional additional pointer block level and allows any file block-sized region to be broken into 256 separate 4 KB blocks, which, in turn, add up to the original file block. This can be done dynamically to any 1 MB block based on deduplication decisions, and leaves address resolution for other data intact and efficient.

Beyond these unusual block sizes, VMFS supports a number of other uncommon features. Most important to DeDe is support for block-level copy-on-write (COW). Each file or sub-block resource can be referenced from multiple pointer blocks, allowing the same data to be shared between multiple places in multiple files. Each reference to a shared resource is marked with a COW bit, indicating that any attempts to write to the resource must make a private copy in a freshly allocated resource and write to that copy instead. Notably, this COW bit is associated with each *pointer* to the resource, not with the resource itself. Otherwise, every write operation would need to take a cluster lock to check the COW bit of the destination block, even if the block was not COW. However, as a result, sharing a block between two files requires file locks on *both* files, even though only one of the references will change. Thus, DeDe must use merge requests for all cross-host merging operations.

VMFS forms the underlying substrate of DeDe and handles critical correctness requirements such as specialization of COW blocks and verification of potential duplicates, allowing DeDe to focus on best-effort duplicate detection. Virtual arenas and merge requests allow DeDe to achieve complex, decentralized manipulations of the file system structure without knowledge of the file system implementation using only a few general-purpose interfaces.

3 Design and Implementation

In this section, we provide details of the design and implementation of DeDe's best-effort write monitoring subsystem and the out-of-band indexing and duplicate elimination process.

3.1 Write Monitoring

Each host runs a *write monitor*, as shown in Figure 3, which consists of a lightweight kernel module (`dedup`) that monitors all writes by that host to files in the file system and a userspace daemon (`dedupd`) that records this information to logs stored in the shared file system. The write monitor is the only part of the system that lies in the critical IO path of the file system, so the write monitor itself must incur as little additional disk IO and CPU overhead as possible.

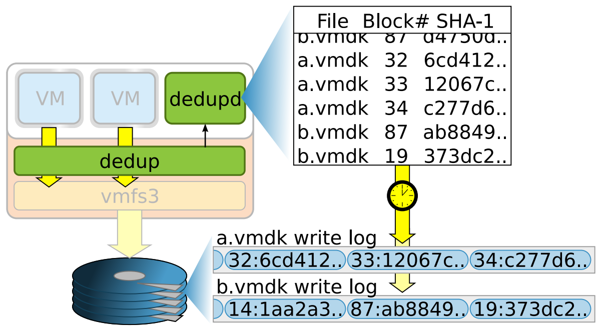


Figure 3: For write monitoring, only a lightweight kernel module lies in the IO critical path to opportunistically calculate hashes of blocks while they are still in memory. A userspace daemon flushes write logs to disk periodically. Duplicate detection and elimination are done out-of-band.

The kernel module provides the userspace daemon with a modification stream indicating, for each write done by the host: the file modified, the offset of the write, and the SHA-1 hashes of all modified blocks. While the in-band CPU overhead of the monitor could have been virtually eliminated by computing these hashes lazily (*e.g.*, at indexing time), this would have required reading the modified blocks back from disk, resulting in a large amount of additional random IO. We opted instead to eliminate the extra IO by computing these hashes while the blocks were in memory, though the trade-off between run-time CPU overhead and deduplication-time IO overhead could be set dynamically by user-defined policy.

The userspace daemon divides the modification stream by file, aggregates repeated writes to the same block, and buffers this information in memory, periodically flushing it to individual write log files associated with each regular file. These write logs are stored on the shared file system itself, so even if a host fails or transfers ownership of a file's lock, any other host in the system is capable of reading logs produced by that host and merging information about modified blocks into the index.

The daemon can safely buffer the modification stream in memory because the index update process is designed to deal with stale information. Without this, write logs would have to be consistent with on-disk file state, and each logical write to the file system would result in at least two writes to the disk. Instead, buffering allows our system to absorb writes to over 150 MB of file blocks into a single infrequent 1 MB sequential write to a log file. This is the only additional IO introduced by the write monitor.

Similarly, we rely on the best-effort property of write monitoring to minimize IO in the case of partial block writes. If a write to the file system does not cover an entire block, the monitor simply ignores that write, rather than reading the remainder of the block from disk simply to compute its hash. In practice, this is rarely a problem when writes originate from a virtual machine because guest operating systems typically write whole guest file system blocks, which are generally at least 4 KB.[1]

Write monitoring can be enabled or disabled on a per-file basis. Thus, if the performance of some VM is too critical to incur the overhead of write monitoring or if the system administrator has a priori knowledge that a VM's duplication ratio is small, such VMs can be opted out of deduplication.

3.2 The Index

The shared on-disk index tracks all known blocks in the file system by their content hashes. As discussed in Section 2, each host updates this index independently, incorporating information about recent block modifications from the write logs in large batches on a schedule set by user-defined policy (*e.g.*, only during off-peak hours). A match between a content hash in the index and that of a recently modified block indicates a potential duplicate that must be verified and replaced with a copy-on-write reference to the shared block.

The index acts as an efficient map from hashes to block locations. Because DEDE treats unique blocks (those with only a single reference) differently from shared blocks (those with multiple references), each index entry can likewise be in one of two states, denoted Unique(H,f,o) and Shared(H,a). An index entry identifies a unique block with hash H by the inumber f of its containing file and its offset o within that file. Because index updates are out-of-band and unique blocks are mutable, these entries are only *hints* about a block's hash. Thus, because a mutable block's contents may have changed since it was last indexed, its contents must be verified prior to deduplicating it with another block. Shared blocks, on the other hand, are marked COW and thus their content is guaranteed to be stable. The index identifies each block by its offset a in the index's *virtual arena*, discussed in the next section.

3.2.1 Virtual Arena

When duplicate content is found, DEDE reclaims all but one of the duplicates and shares that block copy-on-write between files. Because hosts can make per-file, mutable copies of shared blocks at any time without updating the index, we cannot simply identify shared blocks by their locations in deduplicated files, like we could for unique blocks. The index needs a way to refer to these shared blocks that is stable despite potentially shifting references from deduplicated files. As discussed earlier, DEDE cannot simply store raw block addresses in the index because exposing these from the file system presents numerous problems. Instead, we introduce a *virtual arena* file as an additional layer of indirection that provides stable identifiers for shared blocks without violating file system abstractions.

While the virtual arena is a regular file, unlike typical files, it doesn't have any data blocks allocated specifically for it (hence, it is virtual). Rather, it serves as an alternate view of all shared blocks in the file system. In this way, it is very different from the arenas used in other deduplication systems such as Venti [16], which store actual data blocks addressed by content addresses.

In order to make a block shared, a host introduces an additional COW reference to that block from the virtual arena file, using the same interface that allows blocks to be shared between any two files. Apart from uncollected garbage blocks, the virtual arena consumes only the space of its inode and any necessary pointer blocks. Furthermore, this approach takes advantage of the file system's block placement policies: adding a block to the virtual arena does *not* move it on disk, so it is likely to remain sequential with the original file.

The index can then refer to any shared block by its *offset* in the virtual arena file, which the file system can internally resolve to a block address, just as it would for any other file. The virtual arena file's inode and pointer block structure exactly form the necessary map from the abstract, stable block identifiers required by the index to the block addresses required by the file system.

3.2.2 On-disk Representation

DEDE stores the index on disk as a simple packed list of entries, sorted by hash. Because index updates are always done in large batches and hashes exhibit no spatial locality, the update process simply scans the entire index file linearly and produces a new index file. Despite the simplicity of this approach, it outperforms more common index structures optimized for individual random accesses (*e.g.*, hash tables and B-trees) even if the update batch size is relatively small. Generally, given an average index entry size of b bytes, a sequential IO rate of s bytes per second, and a average seek time of k seconds, as long as the ratio of the batch size to the index size exceeds $2b/sk$, sequentially rewriting the entire index is optimal. Given an entry size of 23 bytes and assuming a respectable SAN capable of 150 MB/s and 8 ms seeks, the batch size only needs to exceed 0.004% of the index size. Furthermore, hosts defer index updates until the batch size exceeds

[1]Unfortunately, owing to an ancient design flaw in IBM PC partition tables, guest writes are not necessarily *aligned* with DEDE blocks. Section 4.1 has a more detailed analysis of this.

some fixed fraction of the index size (at least 0.004%), so not only are index updates efficient, but the amortized cost remains constant regardless of index size.

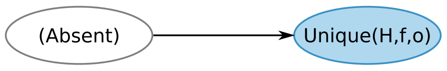
In order to allow access to the index to scale with the number of hosts sharing the file system, while still relying on file locking to prevent conflicting index access, hosts *shard* the index into multiple files, each representing some subdivision of the hash space. Once the time a host takes to update a shard exceeds some threshold, the next host to update that shard will split the hash range covered by the shard in half and write out the two resulting subshards in separate files. This technique mirrors that of extensible hashing [6], but instead of bounding the size of hash buckets, we bound the time required to update them. Combined with file locking, this dynamically adjusts the concurrency of the index to match demand.

3.3 Indexing and Duplicate Elimination

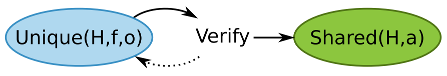
As the index update process incorporates information about recently modified blocks recorded in the write logs, in addition to detecting hash matches that indicate potential duplicates, it also performs the actual COW sharing operations to eliminate these duplicates. The duplicate elimination process must be interleaved with the index update process because the results of block content verification can affect the resulting index.

In order to update the index, a host sorts the recent write records by hash and traverses this sorted list of write records in tandem with the sorted entries in the index. A matching hash between the two indicates a potential duplicate, which is handled differently depending on the state of the matching index entry. Figure 4 gives an overview of all possible transitions a matching index entry can undergo, given it current state.

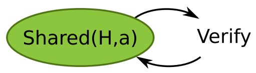
When DEDE detects a potential duplicate, it depends on the file system's compare-and-share operation, described in Section 2.1, to atomically verify that the block's content has not changed and replace it with a COW reference to another block. Based on user-specified policy, this verification can either be done by reading the contents of the potential duplicate block and ensuring that it matches the expected hash (*i.e.*, compare-by-hash), or by reading the contents of *both* blocks and performing a bit-wise comparison (*i.e.*, compare-by-value). If the latter policy is in effect, hash collisions reduce DEDE's effectiveness, but do not affect its correctness. Alternatively, if a host can prove that a block has not changed—for example, if it has held the lock on the file containing the block for the entire duration since the write record was generated and no write records have been dropped—then it can skip content verification. While this is a fairly specific condition, it is often met in DEDE's target setting because locks on VM disks are usually very long duration.



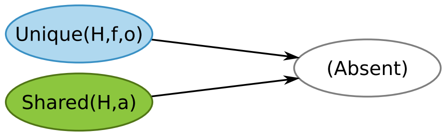
(a) When the hash H of the block at offset o in file f is not in the index, a new unique entry is added.



(b) When a second occurrence of hash H is found and the block's contents pass verification, we place it in the virtual arena and upgrade the index entry to shared.



(c) When a duplicate of a shared block is found, we verify its contents and replace the block with a reference to the existing shared block.



(d) Unique entries are garbage collected when the indexing process finds a write record to that block with a different hash. Shared entries are garbage collected when only the reference from the virtual arena remains.

Figure 4: All possible updates to an index entry.

3.3.1 Single Host Indexing

We begin with an explanation of the index update process assuming only a single host with exclusive access to the file system. In a single host design, the host can modify the metadata of any file. We lift this assumption in the next section, where we extend the process to support multiple hosts.

Any write record without a corresponding hash in the index indicates a new, unique block. Even though this write record may be stale, because index entries for unique blocks are only hints, it is safe to simply add the new unique block to the index without verifying the block's content, performing an *absent-to-unique* transition as shown in Figure 4(a). This single sequential, buffered write to the index is the only IO incurred when processing a new unique block.

When a write record's hash corresponds to an index entry for a unique block, then the host attempts to share both blocks (freeing one of them in the process) and upgrade the index entry to refer to the shared block. This *unique-to-shared* transition is shown in Figure 4(b). However, because the write record and index entry may both be stale, the host must verify the contents of both blocks before actually sharing them. Assuming this verification succeeds, the file system replaces both blocks with a shared block and the host inserts this block into the virtual arena and upgrades the index entry to refer to the new, shared block.

Finally, if a write record's hash matches an index entry for a shared block, then the host attempts to eliminate this newly detected potential duplicate, performing a *shared-to-shared* transition as shown in Figure 4(c). Because the write record may be stale, it first verifies that the content of the potential duplicate has not changed. If this succeeds, then this block is freed and the reference to the block is replaced with a reference to the shared block found via the virtual arena.

3.3.2 Multi-Host Indexing

Extending the index update process to multiple hosts, we can no longer assume that a host will have unfettered access to every file. In particular, hosts can only verify blocks and modify block pointers in files they hold exclusive locks on. As a result, indexing *must* be distributed across hosts. At the same time, we must minimize communication between hosts, given the cost of communicating via the shared disk. Thus, sharing of blocks is done without any blocking communication between hosts, even if the blocks involved are in use by different hosts.

In the multi-host setting, the write logs are divided amongst the hosts according to which files each host has (or can gain) exclusive access to. While this is necessary because hosts can only process write records from files they hold exclusive locks on, it also serves to divide the deduplication workload between the hosts.

Absent-to-unique transitions and shared-to-shared transitions are the same in the multi-host setting as in the single host setting. Adding a new, unique block to the index requires neither block verification, nor modifying block pointers. Shared-to-shared transitions only verify and rewrite blocks in the file referenced by the current write log, which the host processing the write log must have an exclusive lock on.

Unique-to-shared transitions, however, are complicated by the possibility that the file containing the unique block referenced by the index may be locked by some host other than the host processing the write record. While the host processing the index may not have access to the indexed block, it does have access to the block referred to by the write log. The host verifies this block's contents and promotes it to a shared block by adding it to the virtual arena and upgrading the index entry accordingly. However, in order to reclaim the originally indexed block, the host must communicate this deduplication opportunity to the host holding the exclusive lock on the file containing the originally indexed block using the associated merge request file. The host updating the index posts a merge request for the file containing the originally indexed block. This request contains not only the offset of the unique block, but also another COW reference to the shared block. Hosts periodically check for merge requests to the files they have exclusive locks on, verifying any requests they find and merging blocks that pass verification. Including a COW reference to the shared block in the merge requires allows hosts to process requests without accessing the arena.

3.3.3 Garbage Collection

As the host scans the index for hash matches, it also garbage collects unused shared blocks and stale index entries, as shown in Figure 4(d). For each shared block in the index, it checks the file system's reference count for that block. If the block is no longer in use, it will have only a single reference (from the virtual arena), indicating that it can be removed from the virtual arena and freed. In effect, this implements a simple form of weak references without modifying file system semantics. Furthermore, this approach allows the arena to double as a victim cache before garbage collection has a chance to remove unused blocks.

Unique blocks do not need to be freed, but they can leave behind stale index entries. Hosts garbage collect these by removing any index entries that refer to any block in any of the write records being processed by the host. In the presence of dropped write records, this may not remove all stale index entries, but it will ensure that there is at most one index entry per unique block. In this case, any later write or potential duplicate discovery involving a block with a stale index entry will remove or replace the stale entry. The garbage collection process also check for file truncations and deletions and removes any appropriate index entries.

4 Evaluation

In this section, we present results from the evaluation of our deduplication techniques using various microbenchmarks and realistic workloads. We begin in Section 4.1 with experiments and analysis that shows the space savings achievable with deduplication as well as the space overheads introduced by it, using data from a real enterprise VDI deployment. We also draw a comparison against linked clones, an alternative way of achieving space savings.

We have implemented a functional prototype of DEDE atop VMware VMFS. Although we haven't spent any significant time optimizing it, it is worthwhile examining its basic performance characteristics. In Section 4.2, we present the run-time performance impact of write monitoring and other changes to the file system introduced by deduplication, as well as the run-time performance gained from improved cache locality. Finally, we look at the performance of the deduplication process itself in Section 4.3.

4.1 Analysis of Virtual Disks in the Wild

To evaluate the usefulness of deduplication in our target workload segment of VDI, we analyzed the virtual disks from a production corporate VDI cluster serving desktop VMs for approximately 400 users on top of a farm of 32 VMware ESX hosts. Out of these, we selected 113 VMs at random to analyze for duplicate blocks, totaling 1.3 TB of data (excluding blocks consisting entirely of NULL bytes). Each user VM belonged exclusively to a single corporate user from a non-technical department like marketing, accounting, etc. The VMs have been in use for six to twelve months and all originated from a small set of standardized Windows XP images. From our experience, this is typical for most enterprise IT organizations, which limit the variation of operating systems to control management and support costs.

Figure 5 shows the reduction in storage space for this VDI farm using deduplication block sizes between 4 KB and 1 MB. As expected, VDI VMs have a high degree of similarity, resulting in an $\sim$80% reduction in storage footprint for the 4 KB block size, which falls off logarithmically to $\sim$35% for 1 MB blocks. Deduplication at the 4 KB block size reduces the original 1.3 TB of data to 235 GB. Given the significant advantage of small block sizes, we chose to use a default 4 KB block size for DEDE. However, a reasonable argument can be made for the smaller metadata storage and caching overhead afforded by an 8 KB block size. We are exploring this as well as dynamic block size selection as future work.

Figure 6 shows a CDF of the same data, detailing the duplication counts of individual blocks in terms of the number of references to each block in the file system *after* deduplication. For example, at the 4 KB block size, 94% of deduplicated blocks are referenced 10 or fewer times by the file system (equivalently, 6% of deduplicated blocks are referenced more than 10 times). Thus, in the original data, most blocks were duplicated a small number of times, but there was a very long tail where some blocks were duplicated many times. At the very peak of the 4 KB distribution, some blocks were duplicated over 100,000 times. Each of these blocks individually represented over 400 MB of space wasted storing duplicate data. Overall, this data serves to show the potential for space savings from deduplication in VDI environments.

4.1.1 Space Overheads

While DEDE reduces the amount of space required by file data, it requires additional space for both the index and the additional metadata introduced by mixed block sizes.

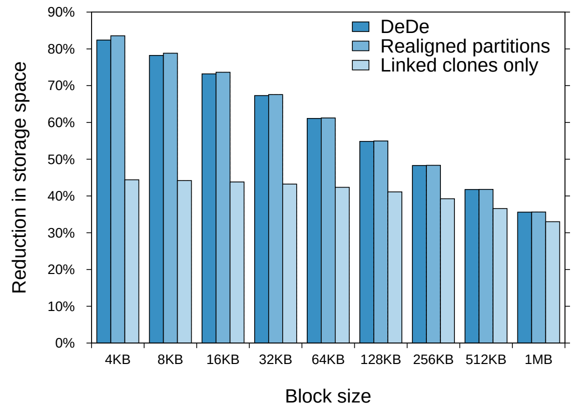


Figure 5: Duplication available at various block sizes and for different variations on the approach. Data is from a production VDI deployment of 113 Windows XP VMs.

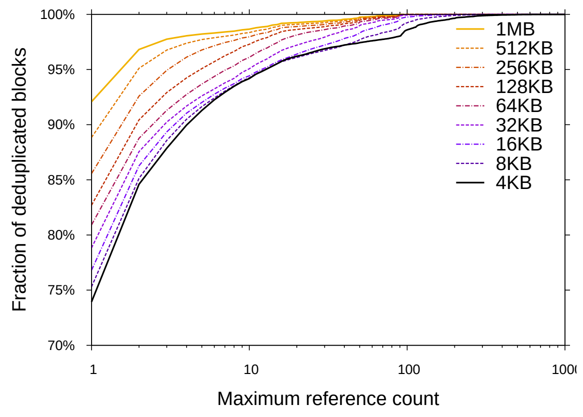


Figure 6: CDF of block duplication counts. A few blocks occur over 100,000 times. Data is from the same deployment as shown in Figure 5.

For our VDI data set, at a 4 KB block size, this additional data totaled 2.7 GB, a mere 1.1% overhead beyond the deduplicated file data.

The index represented 1.5 GB of this overhead, 194 MB of which was file system metadata (pointer blocks) for the virtual arena. In general, the size of the index scales linearly with the size of the deduplicated data because each deduplicated block has one index entry. However, its relative overhead does vary with the ratio of unique to shared blocks because shared blocks require 4 bytes to locate plus virtual arena metadata, while unique blocks require 12 bytes beyond the $\sim$18 bytes required on average for each entry's header and hash. However, even in the worst case, the index represents only 0.73% overhead.

Prior to deduplication, file metadata (inodes and pointer blocks) represented a mere 0.0004% overhead, owing to the efficiency of tracking VMFS's 1 MB file blocks. After deduplication, each 1 MB block that was divided into sub-blocks requires a new pointer block at 1 KB apiece. As a result, metadata overhead increased to 0.49% after deduplication, or 1.1 GB of data in total. While this is a dramatic increase, metadata is still a small fraction of the overall space.

4.1.2 Partition Alignment Issues

Our approach of dividing disks into fixed size blocks is sensitive to the alignment of data on those disks. Unfortunately, for historical reasons, the first partition of partition tables created by utilities like `fdisk` on commodity PC systems has a start address 512 bytes short of a 4 KB boundary, which can in turn cause all logical file system blocks to straddle 4 KB disk block boundaries. This has well-known negative performance effects [21], particularly for storage array caches, which are forced to fetch two blocks for each requested file system block. We were initially concerned that this partition misalignment could negatively impact deduplication opportunities, so we "fixed" the alignment of our VDI data by shifting all of the virtual disks by 512 bytes. Figure 5 compares the results of deduplication with and without this realignment and shows that, in practice, partition alignment actually had very *little* impact on achieved deduplication. While this may still prove to be a problem for well-aged guest file systems, if necessary, it can be solved in a virtualized environment by padding the virtual disk image file to re-align the guest file system blocks with the host file system blocks.

4.1.3 Deduplication Versus Linked Clones

Linked clones are a simpler space saving alternative to deduplication where individual user VMs are initially constructed as block-level COW snapshots of a golden base VM. This uses the same COW mechanism as DEDE, but all sharing happens during VM creation and the user VM images strictly diverge from the base disk and from each other over time.

In order to compare the efficacy of linked clones versus full deduplication, we simulated the structured sharing of linked clones on our VDI data set. This comparison was necessarily imperfect because we had access to neither the base disks nor ancestry information for the VDI VMs, but it did yield a *lower bound* on the total space required by linked clones. The analysis used our regular deduplication algorithm but restricted it to deduplicating blocks only when they were at the same offset in two files, a reasonable approximation to user disks that are a minimal delta from the base disk (*e.g.*, no security patches or software updates have been installed in the user disks).

Figure 5 compares the savings achieved by linked clones against those achieved by DEDE, again at various COW block sizes. Linked clones max out at a 44% reduction in space, reducing the 1.3 TB of original data to 740 GB, a storage requirement over three times larger than full deduplication achieved.

%-Sequential	Baseline			DEDE		
	T (MB/s)	L (ms)	CPU	T (MB/s)	L (ms)	CPU
100%	233	8.6	33%	233	8.6	220%
0%	84	24	16%	84	24	92%

Table 1: Overhead of in-band write monitoring on a pure IO workload. Results are in terms of throughput (T) and latency (L) for Iometer issuing 32 outstanding 64 KB IOs to a 5 GB virtual disk. The CPU column denotes the utilized processor time relative to a single core.

4.2 Run-time Effects of Deduplication

DEDE operates primarily out of band and engenders no slowdowns for accessing blocks that haven't benefited from deduplication. It can also improve file system performance in certain workloads by reducing the working set size of the storage array cache. For access to deduplicated blocks, however, in-band write monitoring and the effects of COW blocks and mixed block sizes can impact the regular performance of the file system. Unless otherwise noted, all of our measurements of the run-time effects of deduplication were performed using Iometer [9] in a virtual machine stored on a 400 GB 5-disk RAID-5 volume of an EMC CLARiiON CX3-40 storage array.

4.2.1 Overhead of In-Band Write Monitoring

Since DEDE's design is resilient to dropped write log entries, if the system becomes overloaded, we can shed or defer the work of in-band hash computation based on user-specified policy. Still, if write monitoring is enabled, the hash computation performed by DEDE on every write IO can represent a non-trivial overhead.

To understand the worst-case effect of this, we ran a write-intensive workload with minimal computation on a 5 GB virtual disk. Table 1 shows that these worst case effects can be significant. For example, for a 100% sequential, 100% write workload, the CPU overhead was $6.6\times$ that of normal at the same throughput level. However, because VMware ESX Server offloads the execution of the IO issuing path code, including the hash computation, onto idle processor cores, the actual IO throughput of this workload was unaffected.

We don't expect the effect of the additional computation to be a severe limitation in realistic workloads, which, unlike our microbenchmark, perform computation in addition to IO. To illustrate this, we ran the in-band SHA-1 computation on a realistic enterprise workload.

	Baseline	Error	SHA-1	Error
Operations/Min	29989	1.4%	29719	0.8%
Response Time (ms)	60 ms	0.8%	61ms	1.4%

Table 2: Overhead of in-band write monitoring on a SQL Server database VM running an online e-commerce application. The mean transaction rate (operations/min) and response times for 10 runs are within noise for this workload. The reported "error" is standard deviation as a percentage of mean.

We experimented with a Windows Server 2003 VM running a Microsoft SQL Server 2005 Enterprise Edition database configured with 4 virtual CPUs, 6.4 GB of RAM, a 10 GB system disk, a 250 GB database disk, and a 50 GB log disk. The database virtual disks were hosted on an 800 GB RAID-0 volume with 6 disks; log virtual disks were placed on a 100 GB RAID-0 volume with 10 disks. We used the Dell DVD store (DS2) database test suite [2], which implements a complete online e-commerce application, to stress the SQL database and measure its transactional throughput and latency. The DVD Store workload issues random 8 KB IOs with a write/read ratio of 0.25, and a highly variable number of outstanding write IOs peaking around 28 [7]. Table 2 reports a summary of overall application performance with and without the in-band SHA-1 computation for writes. For this workload, we didn't observe any application-visible performance loss, though extra CPU cycles on other processor cores were being utilized for the hash computations.

4.2.2 Overhead of COW Specialization

Writing to a COW block in VMFS is an expensive operation, though the current implementation is not well optimized for the COW sub-blocks used extensively by DEDE. In our prototype, it takes ~10 ms to specialize a COW block. As such, any workload phase shift where a large set of previously deduplicated data is being specialized will result in significant performance loss. However, in general, we expect blocks that are identical between VMs are also less likely to be written to and, unlike most approaches to deduplication, we do not suffer this penalty for writes to unique blocks. Optimizations to delay sharing until candidate blocks have been "stable" for some length of time may help further mitigate this overhead, as suggested in [8].

4.2.3 Overhead of Mixed Block Sizes

VMFS's 1 MB file blocks permit very low overhead translation from virtual disk IO to operations on the physical disk. While the support we added to VMFS for mixed block sizes is specifically designed to retain this efficiency whenever 1 MB blocks can be used, it unavoidably introduces overhead for 4 KB blocks when traversing the additional pointer block level and from increased external fragmentation.

% Sequential	IO Type	Throughput (MB/s)		Overhead
		BS=1 MB	BS=4 KB	
100%	Writes	238	150	37%
0%	Writes	66	60	9%
100%	Reads	245	135	45%
0%	Reads	37	32	14%

Table 3: Overhead of mixed block fragmentation. Throughput achieved for 64 KB sequential and random workloads with 16 outstanding IOs. The comparison is between two virtual disks backed by block sizes (BS) of 1 MB and 4 KB, respectively. In the 4 KB case, the virtual disk file consists of 163 disjoint fragments, which implies a sequential run of 31 MB on average.

To measure the effects of this, we compared IO to two 5 GB virtual disks, one backed entirely by 1 MB blocks and one backed entirely by 4 KB blocks. These configurations represent the two extremes of deduplication: all unique blocks and all shared blocks, respectively. The first disk required one pointer block level and was broken into 3 separate extents on the physical disk, while the second disk required two pointer block levels and spanned 163 separate extents.

The results of reading from these virtual disks are summarized in Table 3. Unfortunately, sub-blocks introduced a non-trivial overhead for sequential IO. This is partly because VMFS's sub-block placement and IO handling is not yet well-optimized since sub-blocks have not previously been used in the VM IO critical path, whereas VMFS's file block IO has been heavily optimized. One possible way to mitigate this overhead is by simply preventing the deduplication process from subdividing file blocks unless they contain some minimum number of 4 KB candidates for sharing. This would impact the space savings of deduplication, but would prevent DEDE from subdividing entire file blocks for the sake of just one or two sharable blocks. Improvements in both sub-block IO performance and block subdivision are considered future work.

4.2.4 Disk Array Caching Benefits

For some workloads, deduplication can actually *improve* run-time performance by decreasing the storage array cache footprint of the workload. To demonstrate this, we picked a common, critical, time-limited VDI workload: booting many VMs concurrently. VDI boot storms can happen as part of a nightly cycle of shutting down VMs and their hosts to conserve power, from patching guest

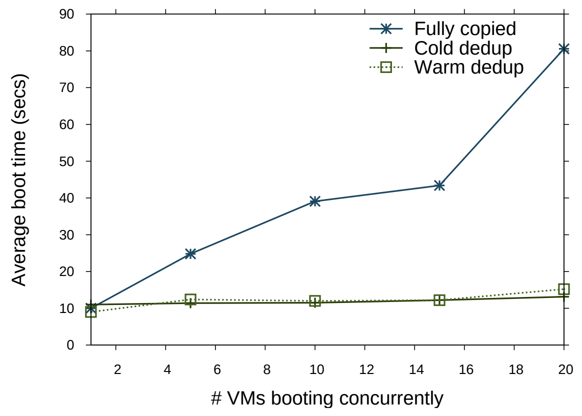


Figure 7: Windows XP VM boot up time comparison between fully copied VMs and deduplicated VMs. Deduplicated VMs are booted twice in order to measure the impact of writing to deduplicated blocks.

operating systems *en masse*, from cluster fail-over, or for a myriad of other reasons.

To test the cache effects of deduplication, we compared the average time required to boot from one to twenty VMs simultaneously between two configurations: one where the VMs were each full copies of the golden VM (much like the VDI configuration from Section 4.1) and another where VMs were deduplicated copies. The results plotted in Figure 7 show a dramatic improvement of deduplication versus full copies, owing to the dramatic decrease in cache footprint.

To further validate the overhead of COW specialization for a realistic workload, we also booted each set VMs a second time after deduplication. The first time the disk images were "cold" and consisted entirely of COW blocks. The second time, any blocks that had been modified the first time were already specialized and could be written to directly. The graph shows virtually no difference between these two cases, indicating that COW specialization overhead is not an issue for this workload. This is not unexpected, as there are fairly few write operations during VM boot.

4.3 Deduplication Rate

While our prototype's implementation of indexing has not yet been optimized, we measured the overall rate at which it could process modified blocks, as well as the performance of the three main operations performed by it: scanning the index, subdividing 1 MB blocks into 4 KB blocks, and COW sharing duplicates.

The index scanning process operates at nearly the disk's sequential access rate, as discussed in Section 3.2.2. At $\sim$23 bytes per index entry, our prototype can process entries for 6.6 GB of blocks *per second*. However, unlike block subdivision and COW sharing, which require time proportional to the number of newly shared blocks, the index scan requires time proportional to the total number of blocks in the file system, so it is critical that this be fast. Once new duplicates have been discovered by the index scan, 1 MB file blocks containing any of these duplicates can be subdivided into 4 KB blocks at 37.5 MB/sec. Finally, these newly discovered duplicates can be eliminated via COW sharing at 2.6 MB/sec.

The COW sharing step limits our prototype to processing $\sim$9 GB of new *shared* blocks per hour. Unique blocks (*i.e.*, recently modified blocks whose hashes do not match anything in the index) can be processed at the full index scan rate. Furthermore, provisioning from templates, a source of large amounts of duplicate data, can be performed directly as a COW copy (at roughly 1 GB/sec), so our deduplication rate applies only to duplicates that arise outside of provisioning operations. Still, we feel that our COW sharing rate can be significantly improved with more profiling and optimization effort. However, even at its current rate, the prototype can eliminate duplicates at a reasonable rate for a VDI workload given only a few off-peak hours per day to perform out of band deduplication.

5 Related Work

Much work has been done towards investigating deduplication for file systems with a centralized component. Venti [16] pioneered the application of content-addressable storage (CAS) to file systems. Venti is a block storage system in which blocks are identified by a collision-resistant cryptographic hash of their contents. Blocks are stored in an append-only log on disk and an on-disk index structure maps from content hashes to block locations. Because of Venti's append-only structure, it is well suited to archival, but not to live file systems. Venti also depends heavily on a central server to maintain the block index.

Various other systems, notably Data Domain's archival system [25] and Foundation [17], have extended and enhanced the Venti approach, but still follow the same basic principles. While deduplication for archival is generally well understood, deduplication in live file systems presents very different challenges. Because backup systems are concerned with keeping data for arbitrarily long periods of time, backup deduplication can rely on relatively simple append-only data stores. Data structures for live deduplication, however, must be amenable to dynamic allocation and garbage collection. Furthermore, live file systems, unlike backup systems, are latency sensitive for both reading and writing. Thus, live file system deduplication must have minimal impact on these critical paths. Backup data also tends to be well-structured and presented to the backup system in sequential streams, whereas live file systems must cope with random write patterns.

Many CAS-based storage systems, including [5,16,19], address data exclusively by its content hash. Write operations return a content hash which is used for subsequent read operations. Applying this approach to VM disk storage implies multi-stage block address resolution, which can negatively affect performance [10]. Furthermore, since data is stored in hash space, spatial locality of VM disk data is lost, which can result in significant loss of performance for some workloads. DEDE avoids both of these issues by relying on regular file system layout policy and addressing all blocks by ⟨filename, offset⟩ tuples, rather than content addresses. DEDE uses content hashes only for identifying duplicates.

Both NetApp's ASIS [14] and Microsoft's Single Instance Store [1] use out of band deduplication to detect duplicates in live file systems in the background, similar to DEDE. SIS builds atop NTFS and applies content-addressable storage to whole files, using NTFS filters to implement file-level COW-like semantics.

While SIS depends on a centralized file system and a single host to perform scanning and indexing, Farsite builds atop SIS to perform deduplication in a distributed file system [3]. Farsite assigns responsibility for each file to a host based on a hash of the file's content. Each host stores the files it is responsible for in its local file system, relying on SIS to locally deduplicate them. However, this approach incurs significant network overheads because most file system operations, including reads, require cross-host communication and file modifications require at least updating the distributed content hash index.

Hong's Duplicate Data Elimination (DDE) system [8] avoids much of the cross-host communication overhead of Farsite by building from IBM's Storage Tank SAN file system [11]. DDE hosts have direct access to the shared disk and can thus read directly from the file system. However, metadata operations, including updates to deduplicated shared blocks, must be reported to a centralized metadata server, which is solely responsible for detecting and coalescing duplicates. DEDE is closest in spirit to DDE. However, because DEDE uses a completely decentralized scheme with no metadata server, it doesn't suffer from single points of failure or contention. Furthermore, DEDE prevents cross-host concurrency issues by partitioning work and relying on coarse-grain file locks, whereas DDE's approach of deduplicating from a central host in the midst of a multi-host file system introduces complex concurrency issues.

Numerous studies have addressed the effectiveness of content-addressable storage for various workloads. In particular, work that has focused on VM deployments [12,17] has concluded that CAS was very effective at reducing storage space and network bandwidth compared to traditional data reduction techniques (such as compression).

Other work has addressed deduplication outside of file systems. Our work derives inspiration from Waldspurger [24] who proposed deduplication of memory contents, now implemented in the VMware ESX Server hypervisor [22]. In this system, identical memory pages from multiple virtual machine are backed by the same page and marked copy-on-write. The use of sharing hints from that work is analogous to our merge requests.

6 Conclusion

In this paper, we studied deduplication in the context of decentralized cluster file systems. We have proposed a novel software system, DEDE, which provides block-level deduplication of a live, shared file system without any central coordination. Furthermore, DEDE builds atop an existing file system without violating the file system's abstractions, allowing it to take advantage of block layout policies and in-place updates to unique data.

We believe our techniques are applicable beyond virtual machine storage and, for future work, plan to examine DEDE in the context of other settings. We also plan to explore alternate indexing schemes that allow for greater control of deduplication policy. For example, high-frequency deduplication could prevent temporary file system bloat during operations that produce large amounts of duplicate data (*e.g.*, security updates and software installations), and deferral of merge operations could help reduce file system fragmentation. Additionally, we plan to further explore the trade-offs mentioned in this paper, such as block size versus metadata overhead, in-band versus out-of-band hashing, and sequential versus random index updates.

DEDE represents just one of the many applications of deduplication to virtual machine environments. These applications—file system deduplication, memory compression, network bandwidth optimization, etc.—are becoming well understood in isolation and we believe there is substantial promise in integrating and unifying them.

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