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Application Crash Consistency and Performance with CCFS

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Abstract. Recent research has shown that applications often incorrectly implement crash consistency. We present ccfs, a file system that improves the correctness of application-level crash consistency protocols while maintaining high performance. A key idea in ccfs is the abstraction of a *stream*. Within a stream, updates are committed in program order, thus helping correctness; across streams, there are no ordering restrictions, thus enabling scheduling flexibility and high performance. We empirically demonstrate that applications running atop ccfs achieve high levels of crash consistency. Further, we show that ccfs performance under standard file-system benchmarks is excellent, in the worst case on par with the highest performing modes of Linux ext4, and in some cases notably better. Overall, we demonstrate that both application correctness and high performance can be realized in a modern file system.

1 Introduction

"*Filesystem people should aim to make 'badly written' code 'just work'*" – Linus Torvalds [52]

The constraint of ordering is a common technique applied throughout all levels of computer systems to ease the construction of correct programs. For example, locks and condition variables limit how multi-threaded programs run, making concurrent programming simpler [2]; memory consistency models with stricter constraints (e.g., sequential consistency) generally make reasoning about program behavior easier [47]; `fsync` calls in data management applications ensure preceding I/O operations complete before later operations [5, 35].

Unfortunately, constraining ordering imposes a fundamental cost: poor performance. Adding synchronization primitives to concurrent programs adds overhead and reduces performance [19, 21]; stronger multiprocessor memory models are known to yield lower throughput [16]; forcing writes to a disk or SSD can radically reduce I/O performance [5, 6]. While in rare cases we can achieve both correctness and performance [39], in most cases we must make an unsavory choice to sacrifice one.

Within modern storage systems, this same tension arises. A file system, for example, could commit all updates in order, adding constraints to ease the construction of applications (and their crash-recovery protocols) atop them [3, 35]. Many file system developers have determined that such ordering is performance prohibitive; as a result, most modern file systems reduce internal ordering constraints. For example, many file systems (including ext4, xfs, btrfs, and the 4.4BSD fast file system) re-order application writes [1], and some file systems commit directory operations out of order (e.g., btrfs [35]). Lower levels of the storage stack also re-order aggressively, to reduce seeks and obtain grouping benefits [22,23,41,43].

However, research has shown that user-level applications are often incorrect because of re-ordering [35, 56]. Many applications use a specialized write protocol to maintain crash consistency of their persistent data structures. The protocols, by design or accident, frequently require all writes to commit in their issued order [36].

The main hypothesis in this paper is that a carefully designed and implemented file system can achieve *both* ordering and high performance. We explore this hypothesis in the context of the Crash-Consistent File System (ccfs), a new file system that enables crash-consistent applications while delivering excellent performance.

The key new abstraction provided by ccfs, which enables the goals of high performance and correctness to be simultaneously met, is the *stream*. Each application's file-system updates are logically grouped into a stream; updates within a stream, including file data writes, are guaranteed to commit to disk in order. Streams thus enable an application to ensure that commits are ordered (making recovery simple); separating updates between streams prevents *false write dependencies* and enables the file system to re-order sufficiently for performance.

Underneath this abstraction, ccfs contains numerous mechanisms for high performance. Critically, while ordering updates would seem to overly restrict file-system implementations, we show that the journaling machinery found in many modern systems can be adopted to yield high performance while maintaining order. More specifically, ccfs uses a novel hybrid-granularity journaling approach that separately preserves the order of each stream; hybrid-granularity further enables other needed optimizations, including delta journaling and pointer-less metadata structures. Ccfs takes enough care to retain optimizations in modern file systems (like ext4) that appear at first to be incompatible with strict ordering, with new techniques such as order-preserving delayed allocation.

We show that the ordering maintained by ccfs im-

```
creat(jrnl);
write(jrnl, "<offset>,<chksum>,
        <size>,<data>");
fsync(jrnl);
fsync(./);
write(dbfile, offset, data);
fsync(dbfile);
unlink(jrnl);
```

Journal file can end up with garbage, in ext2, ext3-wb, ext4-wb

`write(jrnl)` and `write(dbfile)` can re-order in all considered configurations

`creat(jrnl)` can be re-ordered after `write(dbfile)`, according to warnings in Linux manpage . Occurs on ext2.

`write(dbfile)` can re-order after `unlink(jrnl)` in all considered configurations except ext3's default mode

Figure 1: **Journaling Update Protocol.** *Pseudo-code for a simple version of write-ahead journaling; each statement is a system call. The normal text correspond directly to the protocol's logic, while the bold parts are additional measures needed for portability. Italicized comments show which measures are needed under the default modes of ext2, ext3, ext4, xfs, and btrfs, and the writeback mode of ext3/4 (ext3-wb, ext4-wb).*

proves correctness by testing five widely-used applications, including Git and LevelDB (both of which are inconsistent on many modern file systems [35]). We also show that most applications and standard benchmarks perform excellently with only a single stream. Thus, ccfs makes it straightforward to achieve crash consistency efficiently in practice without much developer overhead.

The paper is structured as follows. We provide motivation and background (§2), present ccfs (§3) and evaluate it (§4). We discuss related work (§5) and conclude (§6).

2 Motivation and Background

In this section, we first explain the extent to which current data-intensive applications are vulnerable during a crash. We then describe why a file system that preserves the order of application updates will automatically improve the state of application-level crash consistency. Finally, we discuss the performance overheads of preserving order, and how the overheads can be addressed.

2.1 State of Crash Consistency

To maintain the consistency of their user-level data structures in the event of a crash, many applications [20, 24, 32] modify the data they store in the file system via a carefully implemented *update protocol*. The update protocol is a sequence of system calls (such as file writes and renames) that updates underlying files and directories in a recoverable way. As an example, consider a simple DBMS that stores its user data in a single database file. To maintain transactional atomicity across a system crash, the DBMS can use an update protocol called *journaling* (or *write-ahead logging*): before updating the database file, the DBMS simply records the updates in a separate journal file. The pseudocode for the update protocol is shown in Figure 1. If a crash happens, the DBMS executes a *recovery protocol* when restarted: if the database file was only partially updated, the full update from the journal is replayed.

Correctly implementing crash-consistency protocols has proven to be difficult for a variety of reasons. First, the correctness inherently depends on the exact semantics of the system calls in the update protocol with respect to a system crash. Because file systems buffer writes in memory and send them to disk later, from the perspective of an application the effects of system calls can get re-ordered before they are persisted on disk. For example, in a naive version of the journaling update protocol, the unlink of the journal file can be re-ordered before the update of the database file. In Figure 1, an explicit `fsync` system call is used to force the update to disk, before issuing the `unlink`. Also, the semantics of system calls can differ between file systems; for example, the aforementioned re-ordering occurs in the default configurations of ext2, ext4, xfs, and btrfs, but not in ext3.

Second, the recovery protocol must correctly consider and recover from the multitude of states that are possible when a crash happens during the update protocol. Application developers strive for update protocols to be efficient, since the protocols are invoked during each modification to the data store; more efficient update protocols often result in more possible states to be reasoned about during recovery. For example, the journal protocol in Figure 1 is often extended to batch multiple transactions onto the journal before the actual update to the database file, so as to avoid performance-intensive `fsync` calls.

Finally, crash-consistency protocols are hard to test, much like concurrency mechanisms, because the states that might occur on a crash are non-deterministic. Since efficient protocol implementations are inherently tied to the format used by the application's data structures and concurrency mechanisms, it is impractical to re-use a single, verified implementation across applications.

Unsurprisingly, past research [35, 56, 57] has found many vulnerabilities in the implementations of crash consistency protocols in widely used applications written by experienced developers, such as Google's LevelDB and Linus Torvalds's Git. However, in this paper, we argue that it is practical to construct a file system that automatically improves application crash consistency. We base our arguments on the following hypotheses:

The Ordering Hypothesis: Existing update and recovery protocols (mostly) work correctly on an ordered and weakly-atomic file system (the exact definition of these terms is explained subsequently).

The Efficiency Hypothesis: An ordered and weakly-atomic file system can be as efficient as a file system that does not provide these properties, with the proper design, implementation, and realistic application workloads.

2.2 Weak Atomicity and Order

We hypothesize that most vulnerabilities that exist in application-level update protocols are caused because the related application code depends on two specific file-system guarantees. File systems that provide these guar-

	Time (s)	Seeks	Median seek distance (sectors)
Re-ordered	25.82	23762	120
FIFO	192.56	38201	2002112

Table 1: **Seeks and Order.** *The table shows the number of disk seeks incurred and the total time taken when 25600 writes are issued to random positions within a 2GB file in a HDD. Two different settings are investigated: the writes can be re-ordered or the order of writes is maintained using the FIFO strategy. The number of seeks incurred in each setting and the LBA seek distance shown are determined from a block-level I/O trace.*

antees, therefore, automatically mask application vulnerabilities. The first guarantee, and the major focus of our work, is that the effect of system calls should be persisted on disk in the order they were issued by applications; a system crash should not produce a state where the system calls appear re-ordered. The second (minor) guarantee is that, when an application issues certain types of system calls, the effect of the system call should be atomic across a system crash. The second guarantee, which we term *weak atomicity*, is specifically required for system calls that perform directory operations (including the creation, deletion, and renaming of files and hard links). Weak atomicity also includes stipulations about writes to files, but only at sector granularity (i.e., there is generally no need to guarantee that arbitrarily large writes are atomic). If a system call appends data to the end of a file, both increasing the file size and the writing of data to the newly appended portion of the file should be atomic together.

The fundamental reason that order simplifies the creation of update protocols is that it drastically reduces the number of possible states that can arise in the event of a crash, i.e., the number of states that the recovery protocol has to handle. For example, consider an update protocol that simply overwrites n sectors in a file; if the file system maintains order and weak atomicity, only n crash states are possible, whereas 2^n states are possible if the file system can re-order. Maintaining order makes it easier to reason about the correctness of recovery for both humans and automated tools [35].

The effectiveness of maintaining weak atomicity and order can be understood by considering the application-level crash-consistency vulnerabilities discovered recently [35]. Among 60 vulnerabilities in the study, the authors state that 16 are masked by maintaining weak atomicity alone. They also state that 27 vulnerabilities are masked by guaranteeing order. Of the remaining vulnerabilities, 12 are attributed to durability; however, the authors observe that 8 of these 12 will be masked if the file system guarantees order. Thus, in all, 50 of the 60 vulnerabilities are addressed by maintaining order and weak atomicity; the remaining 10 have minor consequences and are readily masked or fixed [36].

2.3 Order: Bad for Performance

Most real-world deployed file systems (such as btrfs) already maintain the weak atomicity required to mask application-level crash-consistency vulnerabilities. However, all commonly deployed file-system configurations (including ext4 in metadata-journaling mode, btrfs, and xfs) re-order updates, and the re-ordering only seems to increase with each new version of a file system (e.g., ext4 re-orders more than ext3 [35]; newer versions of ext4 re-order even more [53], as do newer systems like btrfs [35]). While maintaining update order is important for application crash consistency, it has traditionally been considered bad for performance, as we now discuss.

At low levels in the storage stack, re-ordering is a fundamental technique that improves performance. To make this case concrete, we created a workload that issues writes to random locations over a disk. Forcing these writes to commit in issue order takes roughly eight times longer than a seek-optimized order (Table 1). Re-ordering is important for hard drives [43] and SSDs [23]; approaches that constrict write ordering are insufficient.

Higher up the stack, ordering can induce negative (and sometimes surprising) performance degradations. Consider the following code sequence:

`write(`f_1`); write(`f_2`); fsync(`f_2`); truncate(`f_1`);`

In this code, without mandated order, the forced writes to f_2 can move ahead of the writes to f_1; by doing so, the truncate obviates the need for any writes to f_1 at all. Similarly, if the user overwrites f_1 instead of truncating it, only the newer data needs to be written to disk.

We call this effect *write avoidance*: not all user-level writes need to be sent to the disk, but can instead be either forgotten due to future truncates or coalesced due to future overwrites. Re-ordering allows write avoidance across `fsync` calls. Global write ordering, in contrast, implies that if writes to f_2 are being forced to disk, so must writes to f_1. Instead of skipping the writes to f_1, the file system must now both write out its contents (and related metadata), and then, just moments later, free said blocks. If the write to f_1 is large, this cost can be high.

We call this situation, where `fsync` calls or cache eviction reduce write avoidance in an ordered file system, a *write dependence*. Write dependence is not limited to writes by a single application; any application that forces writes to disk could cause large amounts of other (potentially unneeded) I/O to occur. When write dependence does not improve crash consistency, as when it occurs between independent applications, we term it a *false dependence*, an expected high-cost of global order.

Apart from removing the chance for write avoidance, write dependence also worsens application performance in surprising ways. For example, the `fsync(`f_2`)` becomes a high-latency operation, as it must wait for all previous writes to commit, not just the writes to f_2. The overheads associated with write dependence can be further exacerbated by various optimizations found in modern file systems. For example, the ext4 file system uses a technique known as *delayed allocation*, wherein it batches together multiple file writes and then subsequently allocates blocks to files. This important optimization is defeated by forced write ordering.

2.4 Order with Good Performance

We believe it is possible to address the overheads associated with maintaining order in practice. To reduce disk-level scheduling overheads, a variety of techniques have been developed that preserve the *appearance* of ordered updates in the event of a crash while forcing few constraints on disk scheduling.

For example, in ext4 data journaling, all file-system updates (metadata and data) are first written to a journal. Once committed there, the writes can be propagated (checkpointed) to their in-place final locations. Note that there are no ordering constraints placed upon the checkpoint writes; they can be re-ordered as necessary by lower layers in the storage stack to realize the benefits of low-level I/O scheduling. Further, by grouping all writes into a single, large transaction, writes are effectively committed in program order: if a write to f_1 occurs before a write to f_2, they will either be committed together (in the same transaction), or the write to f_2 will commit later; never will f_2 commit before f_1. We discuss ext4 journaling in more detail in the next section.

Unfortunately, total write ordering, as provided with data journaling, exacts a high performance cost: each data item must be written twice, thus halving disk bandwidth for some workloads. For this reason, most journaling file systems only journal metadata, maintaining file-system crash consistency but losing ordering among application writes. What would be ideal is the performance of metadata-only journaling combined with the ordering guarantees provided by full data journaling.

However, even if an efficient journaling mechanism is used, it does not avoid overheads due to false dependence. To address this problem, we believe a new abstraction is needed, which enables the file system to separate update orderings across different applications. Within an application, we believe that false dependence is rare and does not typically arise.

Thus, we are left with two open questions. Can a metadata-only journaling approach be adopted that maintains order but with high performance? Second, can a new abstraction eliminate false dependence? We answer these questions in the affirmative with the design of ccfs.

3 Crash-Consistent File System

In this section, we describe ccfs, a file system that embraces application-level crash consistency. Ccfs has two goals: preserving the program order of updates and weak atomicity, and performance similar to widely-used re-ordering file systems. So as to satisfy these goals, we derive ccfs from the ext4 file system. Ext4 is widely used, includes many optimizations that allow it to perform efficiently in real deployments, and includes a journaling mechanism for internal file-system consistency. In ccfs, we extend ext4's journaling to preserve the required order and atomicity in an efficient manner without affecting the optimizations already present in ext4.

The key idea in ccfs is to separate each application into a *stream*, and maintain order only within each stream; writes from different streams are re-ordered for performance. This idea has two challenges: metadata structures and the journaling mechanism need to be separated between streams, and order needs to be maintained within each stream efficiently. Ccfs should solve both without affecting existing file-system optimizations. In this section, we first explain ext4's journaling mechanism (§3.1), then the streams abstraction (§3.2), how streams are separated (§3.3) and how order is maintained within a stream (§3.4), and our implementation (§3.5). We finally discuss how applications can practically start using the streams abstraction (§3.6).

3.1 Journaling in Ext4

To maintain internal file-system metadata consistency, ext4 requires the atomicity of sets of metadata updates (e.g., all metadata updates involved in creating a file) and an order between these sets of updates. Ext4 uses an optimized journaling technique for this purpose. Specifically, the journaling occurs at block granularity, batches multiple sets of atomic metadata updates (*delayed logging* [11]), uses a circular journal, and delays forced checkpointing until necessary. The block-granularity and circular aspects prove to be a challenge for adoption in ccfs, while delayed logging and checkpointing are important optimizations that ccfs needs to retain. We now briefly explain these techniques of ext4 journaling.

Assume the user performs a metadata operation (such as creating a file), causing ext4 to modify metadata structures in the file-system blocks b_1, b_2, b_3. Ext4 associates b_1, b_2, b_3 with an in-memory data structure called the *running transaction*, T_i. Instead of immediately persisting T_i when the metadata operation completes, ext4 waits for the user to perform more operations; when this happens, the resulting set of block modifications are also associated with T_i (i.e., *delayed logging*). Periodically, ext4 *commits* the running transaction, i.e., writes the updated contents of all the associated blocks of T_i and some bookkeeping information to an on-disk journal. When T_i starts committing, a new running transaction (T_{i+1}) is created to deal with future metadata operations. Thus, ext4 always has one running transaction, and at most one committing transaction. Once T_i finishes committing, its blocks can be written to their actual locations on disk in any order; this is usually done by Linux's page-flushing daemon in an optimized manner.

If a crash happens, after rebooting, ext4 scans each transaction written in the journal file sequentially. If a transaction is fully written, the blocks recorded in that transaction are propagated to their actual locations on disk; if not, ext4 stops scanning the journal. Thus, the atomicity of all block updates within each transaction are maintained. Maintaining atomicity implicitly also maintains order within a transaction, while the sequential scan of the journal maintains order across transactions.

The on-disk journal file is circular: after the file reaches a maximum size, committed transactions in the tail of the journal are freed (i.e., *checkpointed*) and that space is reused for recording future transactions. Ext4 ensures that before a transaction's space is reused, the blocks contained in it are first propagated to their actual locations (if the page-flushing mechanism had not yet propagated them). Ext4 employs techniques that coalesce such writebacks. For example, consider that a block recorded in T_i is modified again in T_j; instead of writing back the version of the block recorded in T_i and T_j separately, ext4 simply ensures that T_j is committed before T_i's space is reused. Since the more recent version (in T_j) of the block will be recovered on a crash without violating atomicity, the earlier version of the block will not matter. Similar optimizations also handle situations where committed blocks are later unreferenced, such as when a directory gets truncated.

For circular journaling to work correctly, ext4 requires a few invariants. One invariant is of specific interest in ccfs: the number of blocks that can be associated with a transaction is limited by a threshold. To enforce the limit, before modifying each atomic set of metadata structures, ext4 first verifies that the current running transaction (say, T_i) has sufficient capacity left; if not, ext4 starts committing T_i and uses T_{i+1} for the modifications.

3.2 Streams

Ccfs introduces a new abstraction called the *stream*; each application usually corresponds to a single stream. Writes from different streams are re-ordered for performance, while order is preserved within streams for crash consistency. We define the stream abstraction such that it can be easily used in common workflows; as an example, consider a text file $f1$ that is modified by a text editor while a binary file $f2$ is downloaded from the network, and they are both later added to a VCS repository. Initially, the text editor and the downloader must be able to operate on their own streams (say, A and B, respectively), associating $f1$ with A and $f2$ with B. Note that there can be no constraints on the location of $f1$ and $f2$: the user might place them on the same directory. Moreover, the VCS should then be able to operate on another stream C, using C for modifying both $f1$ and $f2$. In such a scenario, the stream abstraction should guarantee the order required for crash consistency, while allowing enough re-ordering for the best performance possible.

Hence, in ccfs, streams are transient and are not uniquely associated with specific files or directories: a file that is modified in one stream might be later modified in another stream. However, because of such flexibility, while each stream can be committed independently without being affected by other streams, it is convenient if the stream abstraction takes special care when two streams perform operations that affect logically related data. For example, consider a directory that is created by stream A, and a file that is created within the directory by stream B; allowing the file creation to be re-ordered after the directory creation (and recovering the file in a *lost+found* directory on a crash) might not make logical sense from an application's perspective. Hence, when multiple streams perform logically related operations, the file system takes sufficient care so that the temporal order between those operations is maintained on a crash.

We loosely define the term *related* such that related operations do not commonly occur in separate streams within a short period of time; if they do, the file system might perform inefficiently. For example, separate directory entries in a directory are not considered related (since it is usual for two applications to create files in the same directory), but the creation of a file is considered related to the creation of its parent. Section 3.5 further describes which operations are considered logically related and how their temporal order is maintained.

Our stream interface allows all processes and threads belonging to an application to easily share a single stream, but also allows a single thread to switch between different streams if necessary. Specifically, we provide a `setstream(s)` call that creates (if not already existing) and associates the current thread with the stream s. All future updates in that thread will be assigned to stream s; when forking (a process or thread), a child will adopt the stream of its parent. The API is further explained in Section 3.5 and its usage is discussed in Section 3.6.

3.3 Separating Multiple Streams

In ccfs, the basic idea used to separately preserve the order of each stream is simple: ccfs extends the journaling technique to maintain multiple in-memory running transactions, one corresponding to each stream. Whenever a synchronization system call (such as `fsync`) is issued, only the corresponding stream's running transaction is committed. All modifications in a particular stream are associated with that stream's running transaction, thus maintaining order within the stream (optimizations regarding this are discussed in the next section).

Using multiple running transactions poses a challenge: committing one transaction without committing others

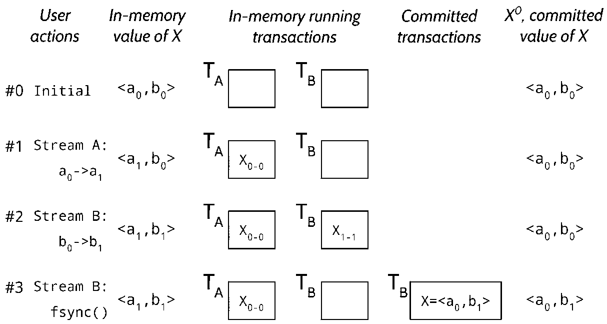


Figure 2: **Hybrid-granularity Journaling.** *Timeline showing hybrid-granularity journaling in ccfs. Block X initially contains the value $\langle a_0, b_0 \rangle$, T_A and T_B are the running transactions of streams A and B; when B commits, X is recorded at the block level on disk .*

(i.e., re-ordering between streams) inherently re-orders the metadata modified across streams. However, internal file-system consistency relies on maintaining a global order between metadata operations; indeed, this is the original purpose of ext4's journaling mechanism. It is hence important that metadata modifications in different streams be logically independent and be separately associated with their running transactions. We now describe the various techniques that ccfs uses to address this challenge while retaining the existing optimizations in ext4.

3.3.1 Hybrid-granularity Journaling

The journaling mechanism described previously (§3.1) works at block-granularity: entire blocks are associated with running transactions, and committing a transaction records the modified contents of entire blocks. Ccfs uses *hybrid-granularity journaling*, where byte-ranges (instead of entire blocks) are associated with the running transaction, but transactional commits and checkpointing still happen at block-granularity.

Ccfs requires byte-granularity journaling because separate metadata structures modified by different streams might exist in the same file-system block. For example, a single block can contain the inode structure for two files used by different applications; in block-granularity journaling, it is not possible to associate the inodes with the separate running transactions of two different streams.

Block-granularity journaling allows many optimizations that are not easily retained in byte-granularity. A major optimization affected in ext4 is data coalescing during checkpoints: even if multiple versions of a block are committed, only the final version is sent to its in-place location. Since the Linux buffer cache and storage devices manage data at block granularity, such coalescing becomes complicated with a byte-granularity journal.

To understand hybrid-granularity journaling, consider the example illustrated in Figure 2. In this example, block X initially contains the bytes $\langle a_0 b_0 \rangle$. Before allowing any writes, ccfs makes an in-memory copy (say, X^0) of the initial version of the block. Let the first byte of X be modified by stream A into a_1; ccfs will associate the byte range X_{0-0} with the running transaction T_A of stream A (X_{i-j} denotes the ith to jth bytes of block X), thus following byte-granularity. Let stream B then modify the second byte into b_1, associating X_{1-1} with T_B; the final in-memory state of X will be $\langle a_1 b_1 \rangle$. Now, assume the user calls `fsync` in stream B, causing T_B to commit (T_A is still running). Ccfs converts T_B into block-granularity for the commit, by super-imposing the contents of T_B (i.e., X_{1-1} with the content b_1) on the initial versions of their blocks (i.e, X^0 with content $\langle a_0 b_0 \rangle$), and committing the result (i.e., $\langle a_0 b_1 \rangle$). When T_B starts committing, it updates X^0 with the value of X that it is committing. If the user then calls `fsync` in A, X_{0-0} is super-imposed on X^0 ($\langle a_0 b_1 \rangle$), committing $\langle a_1 b_1 \rangle$.

Thus, hybrid-granularity journaling performs in-memory logging at byte-granularity, allowing streams to be separated; the delayed-logging optimization of ext4 is unaffected. Commits and checkpoints are block-granular, thus preserving delayed checkpointing.

3.3.2 Delta Journaling

In addition to simply associating byte ranges with running transactions, ccfs allows associating the exact changes performed on a specific byte range (i.e., the *deltas*). This technique, which we call *delta journaling*, is required when metadata structures are actually shared between different streams (as opposed to independent structures sharing the same block). For example, consider a metadata tracking the total free space in the file system: all streams need to update this metadata.

Delta journaling in ccfs works as follows. Assume that the byte range X_{1-2} is a shared metadata field storing an integer, and that stream A adds i to the field and stream B subtracts j from the field. Ccfs associates the delta $\langle X_{1-2}: +i \rangle$ to the running transaction T_A and the delta $\langle X_{1-2}: -j \rangle$ to the running T_B. When a transaction commits, the deltas in the committing transaction are imposed on the initial values of their corresponding byte ranges, and then the results are used for performing the commit. In our example, if X_{1-2} initially had the value k, and stream B committed, the value $(k - j)$ will be recorded for the byte range during the commit; note that hybrid-granularity journaling is still employed, i.e.., the commit will happen at block-granularity.

In ext4, shared metadata structures requiring delta journaling are the *free inode count* and the *free block count*, which concern the global state across the file system. Delta journaling is also needed for the *nlink* and the modification time fields of directory inodes, since multiple streams can modify the same directory.

3.3.3 Pointer-less Data Structures

Metadata in file systems often use data structures such as linked lists and trees that contain internal pointers, and these cause metadata operations in one stream to update pointers in structures already associated with another stream. For example, deleting an entry in a linked list will require updating the *next* pointer of the previous entry, which might be associated with another stream. Ccfs eliminates the need to update pointers across streams by adopting alternative data structures for such metadata.

Ext4 has two metadata structures that are of concern: directories and the *orphan list*. Directories in ext4 have a structure similar to linked lists, where each entry contains the relative byte-offset for the next entry. Usually, the relative offset recorded in a directory entry is simply the size of the entry. However, to delete a directory entry d_i, ext4 adds the size of d_i to the offset in the previous entry (d_{i-1}), thus making the previous entry point to the next entry (d_{i+1}) in the list. To make directories pointer-less, ccfs replaces the offset in each entry with a *deleted* bit: deleting an entry sets the bit. The insert and scan procedures are modified appropriately; for example, the insert procedure recognizes previously deleted entries in the directory and uses them for new entries if possible.

The orphan list in ext4 is a standard linked list containing recently freed inodes and is used for garbage collecting free blocks. The order of entries in the list does not matter for its purposes in ext4. We convert the orphan list into a pointer-less structure by substituting it with an orphan directory, thus reusing the same data structure.

3.3.4 Order-less Space Reuse

Ccfs carefully manages the allocation of space in the file system such that re-ordering deallocations between streams does not affect file-system consistency. For example, assume stream A deletes a file and frees its inode, and stream B tries to create a file. The allocation routines in ext4 might allocate to B the inode that was just freed by A. However, if B commits before A, and then a crash occurs, the recovered state of the file system will contain two unrelated files assigned the same inode.

Ext4 already handles the situation for block allocation (for reasons of security) by reusing blocks only after the transaction that frees those blocks has fully committed. In ccfs, we extend this solution to both inode and directory-entry reuse. Thus, in our example, B will reuse A's freed inode only if A has already been committed.

3.4 Maintaining Order Within Streams

We saw in the previous section how to separate dependencies across independent streams; we now focus on ordering the updates within the same stream. Ext4 uses metadata-only journaling: ext4 can re-order file appends and overwrites. Data journaling, i.e., journaling all updates, preserves application order for both metadata and file data, but significantly reduces performance because it often writes data twice. A hybrid approach, selective data journaling (SDJ) [5], preserves order of both data and metadata by journaling only overwritten file data; it only journals the block pointers for file appends. Since modern workloads are mostly composed of appends, SDJ is significantly more efficient than journaling all updates.

System calls	No delayed allocation	Order-violating delayed alloc	Order-preserving delayed alloc
`write(f1, 1);`	`alloc(f1, 1);`		
`write(f2, 1);`	`alloc(f2, 1);`		
`write(f1, 1);`	`alloc(f1, 1);`		
`write(f2, 1);`	`alloc(f2, 1);`		
`fsync(f2);`		`alloc(f2, 2);`	`atomic{alloc(f1, 2) alloc(f2, 2)};`

Figure 3: **Order-preserving Delayed Allocation.** *Timeline of allocations performed, corresponding to a system-call sequence.*

We adopt the hybrid SDJ approach in ccfs. However, the approach still incurs noticeable overhead compared to ext4's default journaling under practical workloads because it disables a significant optimization, *delayed allocation*. In our experiments, the createfiles benchmark results in 8795 ops/s on ext4 with delayed allocation on a HDD, and 7730 ops/s without (12% overhead).

Without delayed allocation, whenever an application appends to files, data blocks are allocated and block pointers are assigned to the files immediately, as shown in the second column of Figure 3. With delayed allocation (third column), the file system does not immediately allocate blocks; instead, allocations for multiple appends are delayed and done together. For order to be maintained within a stream, block pointers need to be assigned immediately (for example, with SDJ, only the order of allocations is preserved across system crashes): naive delayed allocation inherently violates order.

Ccfs uses a technique that we call *order-preserving delayed allocation* to maintain program order while allowing delayed allocations. Whenever a transaction T_i is about to commit, all allocations (in the current stream) that have been delayed so far are performed and added to T_i before the commit; further allocations from future appends by the application are assigned to T_{i+1}. Thus, allocations are delayed until the next transaction commit, but not across commits. Since order is maintained within T_i via the atomicity of all operations in T_i, the exact sequence in which updates are added to T_i does not matter, and thus the program order of allocations is preserved.

However, the running transaction's size threshold poses a challenge: at commit time, what if we cannot add all batched allocations to T_i? Ccfs solves this challenge by reserving the space required for allocations when the application issues the appends. Order-preserving delayed allocation thus helps ccfs achieve ext4's performance while maintaining order. For the createfiles benchmark, the technique achieves 8717 ops/s in ccfs, and thus performs similar to the default configuration of ext4 (8795 ops/s).

3.5 Implementation

Ccfs changes 4,500 lines of source code (ext4 total: 50,000 lines). We now describe our implementation.

Stream API. The `setstream()` call takes a *flags* parameter along with the stream. One flag is currently supported: `IGNORE_FSYNC` (ignore any `fsync` calls in this stream). We provide a `getstream()` call that is used, for example, to find if the current process is operating on the *init* stream (explained in §3.6) or a more specific stream. A `streamsync()` call flushes all updates in the current stream.

Related Operations Across Streams. The current version of ccfs considers the following operations as logically related: modifying the same regular file, explicitly modifying the same inode attributes (such as the owner attribute), updating (creating, deleting, or modifying) directory entries of the same name within a directory, and creating a directory and any directory entries within that directory. To understand how ccfs maintains temporal ordering between related operations from different streams, consider that stream A first performs operation O_A at time t_1 and stream B then performs a related operation O_B at t_2. If stream A gets committed between t_1 and t_2 (either due to an `fsync` or a periodic background flush), the required temporal order is already maintained, since O_A is already on disk before O_B is performed. If not, ccfs temporarily merges the streams together and treats them as one, until the merged streams get committed to disk; the streams are then separated and allowed to proceed independently.

Maintaining Order Within Streams. An implementation challenge for order-preserving delayed allocation is that the allocations need to be performed when a transaction is about to commit, but before the actual committing starts. We satisfy these requirements without much complexity by performing the allocations in the `T_LOCKED` state of the transaction, a transient state in the beginning of every commit when all file-system updates are blocked. A more efficient implementation can carefully perform these allocations before the `T_LOCKED` state.

To correctly maintain the order of file updates, SDJ requires careful handling when data is both appended and overwritten on the same block. For example, consider an append when T_i was running and an overwrite when T_i is committing (when T_{i+1} is running); to maintain order, two versions of the block must be created in memory: the old version (that does not contain the overwrite) must be used as part of T_i's commit, and the new version must be journaled in T_{i+1}. Ccfs handles these cases correctly.

3.6 Discussion

We now discuss how we expect applications to use streams. Overall, the abstraction is flexible: while we expect most applications to use a single stream, if needed, applications can also use separate streams for individual tasks, or multiple applications can share a single stream. In the current version of ccfs, the *init* process is assigned an *init* stream; hence, all applications inherit this stream by default. We expect most applications whose write performance are user visible to issue a single `setstream()` call in the beginning of the application (but to not make any other code changes). Thus, applications by default will have improved crash consistency, and applications issuing `setstream()` will have both improved consistency and high performance. If so desired, applications can also significantly improve their performance (while maintaining consistency) by first setting the `IGNORE_FSYNC` flag and removing any `O_SYNC` flags, and issuing `streamsync()` calls only when durability is actually desired.

Application	ext4	ccfs
LevelDB	1	0
SQLite-Roll	0	0
Git	2	0
Mercurial	5	2
ZooKeeper	1	0

(a) Vulnerabilities found

Application		ext4	ccfs
LevelDB	Images	158 / 465	427 / 427
	Time (s)	24.31 / 30	30 / 30
Git	Images	84 / 112	96 / 96
	Time (s)	9.95 / 40	40 / 40

(b) Consistent post-reboot disk states produced by BoB

Table 2: **Consistency Testing.** *The first table shows the results of model-based testing using Alice, and the second shows experimental testing with BoB. Each vulnerability reported in the first table is a location in the application source code that has to be fixed. The* Images *rows of the second table show the number of disk images reproduced by the BoB tool that the application correctly recovers from; the* Time *rows show the time window during which the application can recover correctly from a crash (x / y: x time window, y total workload runtime). For Git, we consider the default configuration instead of a safer configuration with bad performance (§4.4).*

4 Evaluation

In our evaluation, we answer the following questions:

- Does ccfs improve application crash consistency?
- Does ccfs effectively use streams to eliminate the overhead of write dependencies?
- How does ccfs perform in standard file system benchmarks run in a single stream?
- What is the performance effect of maintaining order on real applications?

We performed a set of experiments to answer these questions. For the experiments, we use an Intel Core 2 Quad Processor Q9300 with 4 GB of memory running Linux 3.13, with either an SSD (Samsung 840 EVO 500 GB) or a HDD (Toshiba MK1665GSX 160 GB).

4.1 Reliability

We first examine whether the in-order semantics provided by ccfs improves application crash consistency compared to the widely-used ext4 file system (which reorders writes). We follow a model-based testing strategy to check application consistency on both file systems using the Alice tool [35]. The tool records the system-call trace for a given application workload, and then uses a file-system model to reproduce the possible set of file-system states if a system crash occurs. We configured Alice with the models of ext4 (model provided with the tool) and ccfs (system calls are weakly atomic and in-order). We tested five applications previously reported [35] to exhibit crash inconsistencies on ext4: LevelDB, SQLite, Git, Mercurial, and ZooKeeper. We use workloads similar to the previous study, but newer versions of the applications; we do not check durability in Git and Mercurial since they never call `fsync`.

The results of our testing are shown in Table 2(a). Ext4 results in multiple inconsistencies: LevelDB fails to maintain the order in which key-value pairs are inserted, Git and Mercurial can result in repository corruption, and ZooKeeper may become unavailable. With ccfs, the only inconsistencies were with Mercurial. These inconsistencies are exposed on a process crash with any file system, and therefore also occur during system crashes in ccfs; they result only in *dirstate corruption*, which can be manually recovered from and is considered to be of minor consequence [27]. Thus, our model-based testing reveals that applications are significantly more crash consistent on ccfs than ext4.

We used the BoB tool [35] to test whether our implementation of ccfs maintains weak atomicity and ordering, i.e., whether the implementation reflects the model used in the previous testing. BoB records the block-level trace for an application workload running on a file system, and reproduces a subset of disk images possible if a crash occurs. BoB generates disk images by persisting blocks in and out of order; each image corresponds to a time window during the runtime where a crash will result in the image. These windows are used to measure how much time the application remains consistent.

We used Git and LevelDB to test our implementation and compare it with ext4; both have crash vulnerabilities exposed easily on a re-ordering file system. Table 2(b) shows our results. With ext4, both applications can easily result in inconsistency. LevelDB on ext4 is consistent only on 158 of the 465 images reproduced; a system crash can result in being unable to open the datastore after reboot, or violate the order in which users inserted key-value pairs. Git will not recover properly on ext4 if a crash happens during 30.05 seconds of the 40 second runtime of the workload. With ccfs, we were unable to reproduce any disk state in which LevelDB or Git are inconsistent. We conclude that our implementation provides the desired properties for application consistency.

Thus, our results show that ccfs noticeably improves the state of application crash consistency. We next evaluate whether this is achieved with good performance.

4.2 Multi-stream Benefits

Maintaining order causes write dependence during `fsync` calls and imposes additional overheads, since each `fsync` call must flush all previous dirty data. In the simplest case, this results in additional `fsync` latency; it can also prevent writes from being coalesced across `fsync` calls when data is overwritten, and prevent writes from being entirely avoided when the previously written data is deleted. We now evaluate if using separate streams in ccfs prevents these overheads.

Micro-Benchmark	File system	`fsync` latency (s)	`fsync` written (MB)	Total written (MB)
Append	ext4	0.08	0.03	100.19
	ccfs-1	1.28	100.04	100.18
	ccfs-2	0.08	0.03	100.20
Truncate	ext4	0.07	0.03	0.18
	ccfs-1	1.28	100.04	100.21
	ccfs-2	0.05	0.03	0.20
Overwrite	ext4	0.08	0.03	100.19
	ccfs-1	1.27	100.04	300.72
	ccfs-2	0.07	0.03	100.20

Table 3: **Single-`fsync` Experiments.** *`fsync` latencies in the first column correspond to the data written by the `fsync` shown in the second column on HDD, while the total data shown in the third column affects the available device bandwidth and hence performance in more realistic workloads.*

We devised three microbenchmarks to study the performance effects of preserving order. The *append* microbenchmark appends a large amount of data to file A, then writes 1 byte to file B and calls `fsync` on B; this stresses the `fsync` call's latency. The *truncate* benchmark truncates file A after calling `fsync` while *overwrite* overwrites A after the `fsync`; these benchmarks stress whether or not writes are avoided or coalesced.

We use two versions of each benchmark. In the simpler version, we write 100 MB of data in file A and measure the latency of the `fsync` call and the total data sent to the device. In another version, a foreground thread repeatedly writes B and calls `fsync` every five seconds; a background thread continuously writes to A at 20 MB/s, and may truncate A or overwrite A every 100 MB, depending on the benchmark. The purpose of the multi-`fsync` version is to understand the distribution of `fsync` latencies observed in such a workload.

We ran the benchmarks on three file-system configurations: ext4, which re-orders writes and does not incur additional overheads, ccfs using a single stream (ccfs-1), and ccfs with modifications of A and B in separate streams (ccfs-2). Table 3 and Figure 4 show our results.

For the append benchmark, in ext4, the `fsync` completes quickly in 0.08 seconds since it flushes only B's data to the device. In ccfs-1, the `fsync` sends 100 MB and takes 1.28 seconds, but ccfs-2 behaves like ext4 since A and B are modified in different streams. Repeated `fsync` follows the same trend: most `fsync` calls are fast in ext4 and ccfs-2 but often take more than a second in ccfs-1. A few `fsync` calls in ext4 and ccfs-2 are slow due to interference from background activity by the page-flushing daemon and the periodic journal commit.

With truncates, ext4 and ccfs-2 never send file A's data to disk, but ccfs-1 sends the 100 MB during `fsync`, re-

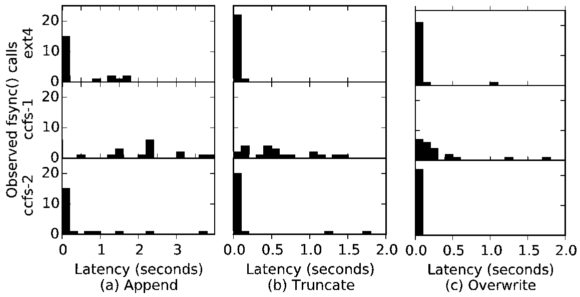


Figure 4: **Repeated `fsync` Experiments** *Histogram of user-observed foreground latencies in our multi-`fsync` experiments. Each experiment is run for two minutes on a HDD.*

sulting in higher latency and more disk writes. Most repeated `fsync` calls in ext4 and ccfs-2 are fast, as expected; they are slow in ccfs-1, but still quicker than the append benchmark because the background thread would have just truncated A before some of the `fsync`.

With overwrites, in both ext4 and ccfs-2, only the final version of A's data reaches the disk: in ccfs-2, SDJ considers the second modification of A an append because the first version of A is not yet on disk (this still maintains order). In ccfs-1, the first version is written during the `fsync`, and then the second version (overwrite) is both written to the journal and propagated to its actual location, resulting in 300 MB of total disk writes. Repeated `fsync` calls are slow in ccfs-1 but quicker than previous benchmarks because of fewer disk seeks: with this version of the benchmark, since A is constantly overwritten, data is only sent to the journal in ccfs-1 and is never propagated to its actual location.

These results show that ccfs is effective at avoiding write dependence overheads when multiple streams are used (in comparison to a file system providing global order). The results also show that, within a stream, write dependence can cause noticeable overhead. For certain applications, therefore, it is possible that dividing the application into multiple streams is necessary for performance. The subsequent sections show that the majority of the applications do not require such division.

4.3 Single-stream Overheads

The previous experiments show how ccfs avoids the performance overheads across streams; we now focus on performance within a stream. The performance effects of maintaining order within a stream are affected by false dependencies between updates within the stream, and hence depend significantly on the pattern of writes. We perform our evaluation using the Filebench [12, 51] suite that reflects real-world workload patterns and microbenchmarks, and compare performance between ext4 (false dependencies are not exposed) and ccfs (false dependencies are exposed because of ordering within streams). Another source of overhead within streams is the disk-level mechanism used to maintain order, i.e., the SDJ technique used in ccfs. Hence, we compare performance between ext4 (no order), ccfs (order-preserving delayed allocation and SDJ), and ext4 in the data=journal mode (*ext4-dj*, full data journaling). We compare performance both with a HDD (disk-level overheads dominated by seeks) and an SSD (seeks less pronounced).

The overall results are shown in Figure 5; performance is most impacted by overwrites and `fsync` calls. We now explain the results obtained on each benchmark.

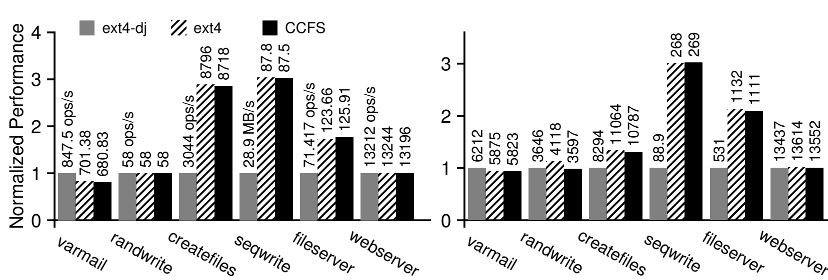
The *varmail* benchmark emulates a multithreaded mail server, performing file creates, appends, deletes, reads, and `fsync` calls in a single directory. Since each append is immediately followed by an `fsync`, there is no additional write dependence due to ordering. Performance is dominated by seek latency induced by the frequent `fsync` calls, resulting in similar performance across ext4 and ccfs. Ext4-dj issues more writes but incurs less seeks (since data is written to the journal rather than the in-place location during each `fsync`), and performs 20% better in the HDD and 5% better in the SSD.

Randwrite overwrites random locations in an existing file and calls `fsync` every 100 writes. Since the `fsync` calls always flush the entire file, there is no additional write dependence due to ordering. However, the overwrites cause both ccfs (SDJ) and ext4-dj (full journaling) to write twice as much data as ext4. In the HDD, all file systems perform similarly since seeks dominate performance; in the SSD, additional writes cause a 12% performance decrease for ccfs and ext4-dj.

Createfiles and *seqwrite* keep appending to files, while *fileserver* issues appends and deletes to multiple files; they do not perform any overwrites or issue any `fsync` calls. Since only appends are involved, ccfs writes the same amount of data as ext4. Under the HDD, similar performance is observed in ccfs and in ext4. Under SSDs, createfiles is 4% slower atop ccfs because of delayed allocation in the `T_LOCKED` state, which takes a noticeable amount of time (an average of 132 ms during each commit); this is an implementation artifact, and can be optimized. For all these benchmarks, ext4-dj writes data twice, and hence is significantly slower. *Webserver* involves mostly reads and a few appends; performance is dominated by reads, all file systems perform similarly.

Figure 5(c) compares the CPU usage of ccfs and ext4. For most workloads, our current implementation of ccfs has moderately higher CPU usage; the significant usage for *fileserver* and *seqwrite* is because the workloads are dominated by block allocations and de-allocations, which is especially CPU intensive for our implementation. This can be improved by adopting more optimized structures and lookup tables (§3.5). Thus, while it does not noticeably impact performance in our experiments, reducing CPU usage is an important future goal for ccfs.

Overall, our results show that maintaining order does



(a) HDD Performance (b) SSD Performance

	Writes (KB/op)			CPU ($\mu s/op$)	
	ext4-dj	**ext4**	**ccfs**	**ext4**	**ccfs**
varmail	3.42	2.91	2.98	59.9	67.2
randwrite	8.1	4.1	8.1	16.8	24.4
createfiles	12.22	5.53	5.49	89.1	94.4
seqwrite	2.0	1.0	1.0	0.9	2.4
fileserver	1093	321	327	1040	2937
webserver	0.49	0.24	0.15	74.4	75.5

(c) HDD Writes and CPU usage

Figure 5: **Imposing Order at Disk-Level: Performance, Data Written, and CPU usage.** *(a) and (b) show throughput under standard benchmarks for ccfs, ext4, and ext4 under the data=journal mode (ext4-dj), all normalized to ext4-dj. (c) shows the total writes and CPU usage with a HDD. Varmail emulates a multithreaded mail server, performing file creates, appends, deletes, reads, and `fsync` in a single directory. Randwrite does 200K random writes over a 10 GB file with an `fsync` every 100 writes. Webserver emulates a multithreaded web server performing open-read-close on multiple files and a log file append. Createfiles uses 64 threads to create 1M files. Seqwrite writes 32 GB to a new file (1 KB is considered an op in (c)). Fileserver emulates a file server, using 50 threads to perform creates, deletes, appends, and reads, on 80K files. The fileserver, varmail, and webserver workloads were run for 300 seconds. The numbers reported are the average over 10 runs.*

not incur any inherent performance overhead for standard workloads when the workload is run in one stream. False dependencies are rare and have little impact for common workloads, and the technique used to maintain order within streams in ccfs is efficient.

4.4 Case Studies

Our evaluation in the previous section shows the performance effects of maintaining order for standard benchmarks. We now consider three real-world applications: Git, LevelDB, and SQLite with rollback journaling; we focus on the effort required to maintain crash consistency with good performance for these applications in ccfs and the default mode (*data=ordered*) of ext4. For ext4, we ensure that the applications remain consistent by either modifying the application to introduce additional `fsync` calls or using safe application configuration options. All three applications are naturally consistent on ccfs when run on a single stream.

Single Application Performance. We first ran each application in its own stream in the absence of other applications, to examine if running the application in one stream is sufficient for good performance (as opposed to dividing a single application into multiple streams). Specifically, we try to understand if the applications have false dependencies. We also consider their performance when `fsync` calls are omitted without affecting consistency (including user-visible durability) on ccfs.

The results are shown in Table 4. For Git, we use a workload that adds and commits the Linux source code to an empty repository. While Git is naturally consistent atop ccfs, it requires a special option (*fsyncobjectfiles*) on ext4; this option causes Git to issue many `fsync` calls. Irrespective of this option, Git always issues 242 MB of appends and no overwrites. In ccfs, the 242 MB is sent directly to the device and the workload completes in 28.9 seconds. In ext4, the `fsync` calls needed for correctness prevent updates to metadata blocks from being coalesced; for example, a block bitmap that is repeatedly updated by the workload needs to be written to the journal on every `fsync`. Moreover, each `fsync` call forces a separate journal transaction, writing a separate descriptor block and commit block to the disk and causing two disk cache flushes. Thus, in ext4, the workload results in 1.4 GB of journal commits and takes 2294 seconds to complete (80× slower).

For SQLite, we insert 2000 rows of 120 bytes each into an empty table. SQLite issues `fsync` calls frequently, and there are no false dependencies in ccfs. However, SQLite issues file overwrites (31.83 MB during this workload), which causes data to be sent to the journal in ccfs. Sending the overwritten data to the journal improves the performance of ccfs in comparison to ext4 (1.28×). Because SQLite frequently issues an `fsync` after overwriting a small amount (4 KB) of data, ext4 incurs a seek during each `fsync` call, which ccfs avoids by writing the data to the journal. SQLite can also be heavily optimized when running atop ccfs by omitting unnecessary `fsync` calls; with our workload, this results in a 685× improvement.

For LevelDB, we use the fillrandom benchmark from the db_bench tool to insert 250K key-value pairs of 1000 bytes each to an empty database. Atop ext4, we needed to add additional `fsync` calls to improve the crash consistency of LevelDB. LevelDB on ccfs and the fixed version on ext4 have similar write avoidance, as can be seen from Table 4. Since LevelDB also does few file overwrites, it performs similarly on ccfs and ext4. With ccfs, existing `fsync` calls in LevelDB can be omitted since ccfs already guarantees ordering, increasing performance 5×.

Thus, the experiments suggest that false-dependency overheads are minimal within an application. In two of the applications, the ordering provided by ccfs can be used to omit `fsync` calls to improve performance.

Multiple Application Performance. We next test whether ccfs is effective in separating streams: Figure 6 shows the performance when running Git and SQLite

		Throu-ghput		User-level Metrics			Disk-level Metrics		
				fsync()	*Append (MB)*	*Overw-rite(kB)*	*Flushes*	Data (MB) *Journal*	*Total*
Git	ext4	17	*files/s*	38599	242	0	77198	1423	1887
	ccfs	1351		0	242	0	10	18	243
	ccfs+	1351		0	242	0	10	18	243
SQLite	ext4	5.23	*ops/s*	6000	31.56	31.83	12000	70	170
	ccfs	6.71		6000	31.56	31.83	12000	117	176
	ccfs+	4598		0	0.32	0	0	0	0
LevelDB	ext4	5.25	*MB/s*	598	1087	0.01	1196	16.3	1131
	ccfs	5.1		523	1087	0	1046	16.2	1062
	ccfs+	25.5		0	199	0	2	0.074	157

Table 4: **Case Study: Single Application Performance.** *The table shows the performance and observed metrics of Git, LevelDB, and SQLite-rollback run separately under different file-system configurations on HDD. Ccfs+ denotes running ccfs with unnecessary* `fsync` *calls omitted; in both ccfs configurations, the application runs in a single stream. The user-level metrics characterize each workload; "appends" and "overwrites" show how much appended and overwritten data needs to be flushed by* `fsync` *calls (and also how much remain buffered when the workload ends). Overhead imposed by maintaining order will be observed by* `fsync` *calls in the ccfs configuration needing to flush more data. The disk-level metrics relate the characteristics to actual data written to the device.*

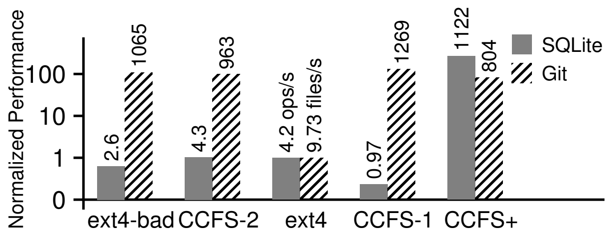


Figure 6: **Case Study: Multiple Application Performance.** *Performance of Git and SQLite-rollback run simultaneously under different configurations on HDD, normalized to performance under* `ext4` *configuration.* `Ext4-bad` *configuration runs the applications on ext4 with consistency sacrificed in Git.* `CCFS-2` *uses separate streams for each application on ccfs.* `Ext4` *uses ext4 with consistent Git.* `CCFS-1` *runs both applications in the same stream on ccfs.* `CCFS+` *runs applications in separate streams without unnecessary* `fsync`*. Workload: Git adds and commits a repository 25 times the size of Linux; SQLite repeatedly inserts 120-byte rows until Git completes.*

simultaneously. The situation in current real-world deployments is exemplified by the *ext4-bad* configuration in Figure 6: both applications are run on ext4, but Git runs without the *fsyncobjectfiles* option (i.e., consistency is sacrificed). The *ccfs-2* configuration is the intended use case for ccfs: Git and SQLite are in separate streams on ccfs, achieving consistency while performing similar to *ext4-bad*. (SQLite performs better under *ccfs-2* because ccfs sends some data to the journal and reduces seeks, as explained previously.) Thus, ccfs achieves real-world performance while improving correctness.

The *ccfs-1* configuration demonstrates the overhead of global order by running Git and SQLite in the same stream on ccfs; this is *not* the intended use case of ccfs. This configuration heavily impacts SQLite's performance because of (false) dependencies introduced from Git's writes. Running applications in separate streams can thus be necessary for acceptable performance.

The *ext4* configuration re-iterates previous findings: it maintains correctness using Git's *fsyncobjectfiles* on ext4, but Git is unacceptably slow due to `fsync` calls. The *ccfs+* configuration represents a secondary use case for ccfs: it runs the applications in separate streams on ccfs with unneeded `fsync` calls omitted, resulting in better SQLite performance (Git is moderately slower since SQLite uses more disk bandwidth).

Thus, running each application in its stream achieves correctness with good performance, while global order achieves correctness but reduces performance.

Developer Overhead. Achieving correctness atop ccfs (while maintaining performance) required negligible developer overhead: we added one `setstream()` call to the beginning of each application, without examining the applications any further. To omit unnecessary `fsync` calls in ccfs and improve performance (i.e., for the ccfs+ configuration), we used the `IGNORE_FSYNC` flag on the `setstream()` calls, and added `streamsync()` calls to places in the code where the user is guaranteed durability (one location in LevelDB and two in SQLite).

Correctness with ext4 required two additional `fsync` calls on LevelDB and the *fsyncobjectfiles* option on Git. The changes in ext4 both reduced performance and were complicated; we carefully used results from the Alice study to determine the additional `fsync` calls necessary for correctness. Note that, while we happened to find that Git's *fsyncobjectfiles* makes it correct on ext4, other changes are needed for other file systems (e.g., btrfs).

Thus, developer effort required to achieve correctness atop ccfs while maintaining performance is negligible; additional effort can improve performance significantly.

5 Related Work

We briefly describe how ccfs differs from previous work:
Atomicity interfaces. Transactional file-system interfaces have a long history [44] and allow applications to delegate most crash-consistency requirements to the file system. Recent work in this space includes file systems providing ACID semantics such as Amino [55], Valor [48], and Windows TxF [28], atomicity-only file systems as proposed by Vermat et al. [54], Park et al. [33], and CFS [29], and OS-level transaction support as advocated by TxOS [37]. Such interfaces allow adding crash consistency easily to applications which do not already implement them, and help heavily optimized applications that trade portability for performance [26].

For applications with existing consistency implementations, proponents of atomicity interfaces and transactional file systems advocate replacing the existing implementation with the interface provided by the file system. This is not trivial to achieve (though perhaps much easier than writing a new consistency implementation). For instance, consider the SQLite database, and assume that we replace its consistency implementation using a straightforward *begin_atomic()–end_atomic()* interface provided by the file system. This does not work for two reasons. First, it does not offer SQLite's ROLLBACK command [50] (i.e., abort transaction) and the SAVEPOINT command (which allows an aborted transaction to continue from a previous point in the transaction). Second, unless the file system provides isolation (which recent research argues against [29]), it requires re-implementing isolation and concurrency control, since SQLite's isolation mechanism is inherently tied to its consistency mechanism [49]. With applications such as LevelDB, where the consistency mechanism is tightly coupled to query-efficient on-disk data structures [24, 32], adopting alternative consistency mechanisms will also cause unnecessary performance changes.

To summarize, adopting atomicity interfaces to overcome vulnerabilities is nonoptimal in applications with existing consistency implementations. One challenge is simply the changes required: CFS [29], with arguably the most user-friendly atomic interface, requires changing 38 lines in SQLite and 240 lines in MariaDB. Another challenge is portability: until the interfaces are widely available, the developer must maintain both the existing consistency protocol and a protocol using the atomic interface; this has deterred such interfaces in Linux [9]. Finally, the complexity of data structures and concurrency mechanisms in modern applications (e.g., LSM trees) are not directly compatible with a generic transactional interface; Windows TxF, a transactional interface to NTFS, is being considered for deprecation due to this [28]. In constrast, streams focus on masking vulnerabilities in existing application-level consistency implementations. Ccfs advocates a single change to the beginning of applications, and running them without more modification on both stream-enabled and stream-absent file systems.

Ordering interfaces. Fine-grained ordering interfaces [4, 5, 13] supplement the existing `fsync` call, making it less costly for applications to easily achieve crash consistency. They allow better performance, but require developers to specify the exact ordering required, and as such are not optimal for fixing existing protocol implementations. Ext4's data-journaled mode and LinLogFS [10] provide a globally ordered interface, but incur unacceptable disk-level ordering and false-dependence overhead. Xsyncfs [31] provides global order and improves performance by buffering user-visible outputs; this approach is complementary to our approach of reducing false dependencies. Other proposed ordering interfaces [8, 34] focus only on NVMs.

Implementation. Ccfs builds upon seminal work in database systems [17, 30] and file-system crash consistency [7, 11, 14, 15, 18, 40, 42, 45], but is unique in assembling different techniques needed for efficient implement of the stream API. Specifically, ccfs uses journaling [7, 18] for order within a stream, but applies techniques similar to soft updates [14, 15, 45] for separating streams. Such design is necessary: using soft updates directly for a long chain of dependent writes ordered one after the other (as ccfs promises within a stream) will result in excessive disk seeks. Block-level guarantees of atomicity and isolation, such as Isotope [46] and TxFlash [38], can simplify ccfs' separation of streams; however, techniques in Section 3 are still necessary. IceFS [25] extends ext3 to support multiple virtual journals, but requires data journaling within each journal to support ordered data writes, and hence cannot be directly used to improve application consistency without reducing performance. IceFS also does not use techniques similar to soft updates to separate the virtual journals, associating only a static and coarse-grained partition of the file-system namespace to each journal (compared to the dynamic and fine-grained stream abstraction).

In principle, one should be able to easily construct a stream-ordered file system atop a fine-grained ordering interface. However, the direct implementation of ordering in Featherstitch [13] uses the soft-updates approach, which is incompatible as described. OptFS' interface [5] is insufficient for implementing streams. Ccfs uses the SDJ technique from OptFS but optimizes it; the original relies on specialized hardware (durability notifications) and decreased guarantees (no durability) for efficiency.

6 Conclusion

In this paper, we present the stream abstraction as a practical solution for application-level crash consistency. We describe the stream API and the ccfs file system, an efficient implementation of the API. We use real applications to validate consistency atop the file system and compare performance with ext4, finding that ccfs maintains (and sometimes signficantly improves) performance while improving correctness. Our results suggest that developer effort for using the streams API is negligible and practical.

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