Accelerating Filesystem Checking and Repair with pFSCK

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Abstract

File system checking and recovery (C/R) tools play a pivotal role in increasing the reliability of storage software, identifying and correcting file system inconsistencies. However, with increasing disk capacity and data content, file system C/R tools notoriously suffer from long runtimes. We posit that current file system checkers fail to exploit CPU parallelism and high throughput offered by modern storage devices.

To overcome these challenges, we propose pFSCK, a tool that redesigns C/R to enable fine-grained parallelism at the granularity of inodes without impacting the correctness of C/R’s functionality. To accelerate C/R, pFSCK first employs data parallelism by identifying functional operations in each stage of the checker and isolating dependent operation and their shared data structures. However, fully isolating shared structures is infeasible, consequently requiring serialization that limits scalability. To reduce the impact of synchronization bottlenecks and exploit CPU parallelism, pFSCK designs pipeline parallelism allowing multiple stages of C/R to run simultaneously without impacting correctness. To realize efficient pipeline parallelism for different file system data configurations, pFSCK provides techniques for ordering updates to global data structures, efficient per-thread I/O cache management, and dynamic thread placement across different passes of a C/R. Finally, pFSCK designs a resource-aware scheduler aimed towards reducing the impact of C/R on other applications sharing CPUs and the file system. Evaluation of pFSCK shows more than 2.6x gains of e2fsck and more than 1.8x over XFS’s checker that provides coarse-grained parallelism.

1 Introduction

Modern ultra-fast storage devices such as SSDs, NVMe, and byte-addressable NVM storage technologies offer higher bandwidth capabilities and lower latency compared to hard disks providing better opportunities for exploiting CPU parallelism. While I/O access performance has increased, storage hardware errors have continued to grow coupled with newer and exploratory high-performance designs impacting file system reliability [9, 19, 39]. For decades, file system checking and repair tools (referred to as C/R henceforth) has played a pivotal role in increasing reliability of software storage stacks, identifying and correcting file system inconsistencies [35]. In fact, in the event of a system crash or storage failure in data centers, file system checkers are typically used as the first remedial solution to system recovery [19].

File system C/R tools work by identifying and fixing the structural inconsistencies of file system metadata, such as inconsistencies in inodes, data and inode bitmaps, links, and directory entries. Well-known and widely used tools such as e2fsck (file system checker for Ext4) divides C/R across multiple stages (commonly referred to as passes) with each pass responsible for checking a file system structure (e.g., directories, files, links). However, C/Rs are known to be notoriously slow, showing a linear increase in C/R time with an increase in file and directory count and the disk utilization [21, 32–35]. Although modern flash and NVM technologies provide lower latency and bandwidth, current C/R tools fail to utilize such hardware capabilities or multicore CPU parallelism fully. While modern C/Rs have attempted to increase parallelism, their coarse-grained approaches, such as parallelizing C/R across logical volumes or logical groups, are insufficient to accelerate C/R on file systems with data imbalance across logical groups [18, 21, 33, 36].

To overcome such limitations, we propose pFSCK, a parallel C/R that exploits CPU parallelism and modern storage’s high bandwidth to accelerate file system checking and repair time without compromising correctness. Accelerating file system C/R could significantly reduce system downtime and improve storage availability [9, 18, 19, 33]. In this pursuit, pFSCK introduces fine-grained parallelism, i.e., parallelism at the granularity of inodes and directory blocks, resulting in a significantly faster execution compared to traditional C/Rs. pFSCK first employs data parallelism by breaking up the work done at each pass, redesigning data structures for scalability, and allowing multiple threads to process. Although data parallelism accelerates checking, updates to global data structures (e.g., bitmap) within each pass are designed to match the file system’s layout (e.g., block bitmap in an Ext4 file system) and must be synchronized and serialized to ensure checking correctness. As a result, with increasing threads, the cost of synchronization and serialization can quickly outweigh the performance gains. Hence, pFSCK introduces pipeline parallelism to parallelize C/R along with the logical flow (i.e., across multiple passes).

Supporting data and pipeline parallelism within pFSCK requires addressing several challenges. First, updates to data structures shared must be ordered for C/R correctness. For example, a directory cannot be certified to be error-free by the directory checking pass unless all its files are verified as consistent by the inode checking pass. To address these ordering constraints, taking inspiration from out-of-order executions in hardware processors, we isolate the global data structures and perform all necessary operations in parallel but certify correctness only when the results are merged. Second, static partitioning of CPU threads across different passes is suboptimal because each pass checks different metadata (e.g., file,
directly attach to the memory controller and provide byte-addressable persistence. These technologies scale 4x larger than DRAM capacity, with variable read (100-200ns) and write (400-800ns) latencies, and bandwidth capabilities ranging from 8 GB/s to 20 GB/s.

On the software side, a huge body of prior research is in progress to redesign and optimize file systems for modern storage hardware, which includes file systems for SSD, NVMe, and NVMs [26, 29, 30, 37, 41] and storage stack in general [13, 27]. Besides, the open-source community is investing a substantial effort to optimize traditional file systems such as Ext4 and XFS for modern storage hardware, given the wide-usage and reliability of these file systems. For example, file systems such as Ext4-DAX continue to retain traditional file system structure and optimize performance by removing components such as page cache, schedulers, and logging. Reducing data corruption for both these approaches can be challenging and requires a few years of production use [8, 24].

2.2 File System Checking and Repair

Since the dawn of file systems, file system consistency has always been an issue. Though modern file systems deploy mechanisms such as journaling, copy-on-write, log-structured writes, and soft updates to handle inconsistencies, they cannot fix errors that may have been present due to corruptions manifested in the past by events such as a failing disk, bit flips, overheating, or correlated crashes [10–12, 25, 42]. A widely-used approach to handle disk and file system corruptions and errors is to check and fix inconsistencies using file system C/R tools, such as e2fsck and xfs_repair, that scan file system metadata for corruptions and fix them. Most C/R tools are designed specifically for the layout of a file system. C/Rs such as e2fsck and xfs_repair have multiple passes that check inode consistency, directory consistency, connectivity of all directories, directory entries, and lastly, the reference counts of inodes and blocks. The repair process involves fixing errors such as updating the block bitmap that does not indicate a block referenced by a file as being used. For more complex errors (e.g., a block referenced by several inodes), administrators are given an option to accept or decline repairs.

2.3 Related Work

With increasing disk capacities and file system size, C/Rs notoriously tend to run longer; specifically, the increase in system downtime may dominate the repair cost by orders of magnitude [1, 6, 7, 22, 31]. We next discuss the state-of-the-art C/R optimizations for offline (unmounted file systems) and online C/Rs and their limitations.

Offline C/Rs. To reduce C/R time, open-source C/Rs, such as the Ext4’s e2fsck and XFS file system’s xfs_repair, parallelize checking across disks (e2fsck) or logical groups (xfs_repair). C/R techniques like Ffscck [35] and Chunkfs [23], speed up by modifying the file system to provide a better balance across...
logical disk bandwidth by partitioning the file system into smaller, isolated groups that can be repaired individually and in parallel, whereas Ffsck [35] rearranges metadata blocks within the file system to reduce seek cost and optimize file system traversal. SQCK [17] enhances C/R by utilizing declarative queries for consistency checking across file system structures. Overall, while prior C/R designs have attempted to improve file C/R performance, they suffer from several weaknesses. First, Chunkfs (and XFS) require a coarse grain separation of file system blocks to accelerate file system checking. To take the case of an imbalanced file system with several large files spread across different logical groups of a disk. Interestingly, we show in Section § 6 the xfs_repair’s parallelism is limited to simple inode scans, omitting any parallelism for checking directory metadata. Other techniques such as SQCK and Ffsck require intrusive changes to the way we manipulate file system metadata or need completely rebuilding C/R, which could reduce or prevent widespread adoption.

Online C/Rs. To reduce system C/R downtime, proprietary online C/Rs such as WAFL file system’s Iron [28] (a NetApp-based C/R tool for WAFL file system) and ReFS [16] fix corruptions as they are encountered allowing file system operations to continue. WAFL-Iron performs incremental live C/R. Because storage blocks are made available as C/R is in progress, WAFL-Iron enforces invariants such as (1) checking all blocks before any software use, (2) checking ancestor blocks (directory) before any data or metadata block (inode block) is checked. These invariants avoid repeated checking of an inode for every data block, and also reduce memory usage. To scale C/R to petabytes, WAFL-Iron expects the presence of block-level checksums, RAID, and most importantly, good storage practices by customers. Open-source C/Rs such as e2fsck allows for online checking by utilizing LVM-based snapshotting and running C/R on the snapshot while the file system is still in use [2]. We evaluate e2fsck’s LVM-based online C/R in Section § 6. Recon protects file system metadata from buggy operations by verifying metadata consistency at runtime [14]. Doing so allows Recon to detect metadata corruption before committing it to disk, preventing error propagation. Recon does not perform a global scan and hence cannot identify or fix errors originating from hardware failures.

C/R Correctness. To ensure the correctness and crash-consistency of C/Rs itself and recover more reliably in light of system faults, Rfsck-lib [15] provides C/Rs with robust undo logging, pFSCK’s fine-grained parallelism goals are orthogonal to Rfsck-lib, however, incorporating Rfsck-lib can improve the reliability of pFSCK in case of failures.

Summary. To summarize, unlike prior systems, pFSCK is aimed towards fine-grained parallelism, the ability to utilize storage bandwidth efficiently across multiple passes of C/R, adapting to system resources, and the capability to reduce the impact on other applications.

Figure 1: Runtime of C/R for an 800GB file system with varying counts of files or directories

3 Motivation and Analysis

In the pursuit of accelerating C/Rs, we first decipher the performance bottlenecks of the widely-used Ext4 file system’s e2fsck C/R tool. We first provide an overview of e2fsck and then examine e2fsck’s runtime for different file system configurations. For brevity, we study xfs_repair in Section § 6.

3.1 E2fsck Overview

E2fsck uses five sequential passes for C/R: the first pass (referred to as Pass-1) checks the consistency of inode metadata; Pass-2 checks directory consistency; Pass-3 checks directory connectivity; Pass-4 checks reference counts; finally, Pass-5 checks data and metadata bitmap consistency.

3.2 Analysis Setup

To analyze and decipher the breakdown of e2fsck’s runtime, we run e2fsck on file systems with varying configurations. We conduct our analysis on a 64-core Dual Intel® Xeon Gold 5218, 2.30GHz, 64GB of DDR memory, and 1TB NVMe Flash Storage running Ubuntu 18.04.1. We fill the file system using fs_mark, an open-source, file system benchmark tool [40]. For our analysis, we mainly focus on file systems without corruptions. To get a finer understanding of how e2fsck scales with file system configurations, we study the sensitivity of C/R’s runtime for multiple file system variables such as file count and directory count.

File-intensive file systems. First, to understand how file count affects runtime, we generate multiple file intensive file system configurations with a 95:1 files to directories ratio. Operating on file-intensive file systems, Pass-1, which checks the consistency of inodes structures, dominates e2fsck runtime, followed Pass-2, which checks directory block consistency. Figure 2 shows the function-wise breakdown in Pass-1 that checks the consistency of file inodes as well as track directory blocks encountered to be examined in the next pass. We notice a function dcigettext (a seemingly
innocuous) language translator used for error handling gets incorrectly used for every inode check and poses a substantial slowdown on the C/R performance. Other Pass-1 steps such as check blocks that checks the blocks referenced by an inode, next inode that reads the next inode blocks from disk, mark bitmap that updates global bitmaps to track the metadata encountered, and icount store that stores inode references also increase in runtime. Although the number of directories is small, the Pass-2 (directory checking pass) runtime increases because the number of directory blocks that store directory entries increase. Pass-3 checks connectivity and ensures the reachability of directories from the root. For a small directory count, the runtime is a small compared to the runtime of Pass-1 and Pass-2. We also find that increasing file size while keeping the number of files constant does not increase e2fsck runtime significantly (not shown for brevity).

### 3.3 I/O utilization

To understand the computational vs. I/O bottlenecks, in Figure 3, we show the compute vs. I/O wait time ratio for e2fsck. As shown, the compute time dominates the I/O wait time. In all our experimental runs, we observe that e2fsck’s peak and average I/O bandwidth usage is 260 MB/s and 100 MB/s, respectively, on an NVMe device with 2 GB/s and 512 MB/s sequential and random read bandwidth. In general, file system C/R tools (e.g., e2fsck and XFS_repair) not only suffer from I/O access time but also computational cost.

**Summary.** To summarize, our analysis shows high runtime overheads of e2fsck across file system configurations; this is mainly due to the serial, single-threaded nature of e2fsck, designed in the era of spinning hard drives. The linear complexity of its runtime is unsuitable as file system capacities trend upward, potentially taking hours, or even days, to check datacenter-scale file systems. Besides, C/R’s repair when there are file system inconsistencies could further increase C/R runtime.

### 4 Goals and Design Insights

**pFSCK** aims to overcome the limitations of traditional file system C/Rs by exploiting fine-grained multi-core parallelism, higher disk bandwidth, efficient use of CPUs using a pFSCK scheduler, and ways to reduce the impact on other co-running applications. We next outline the goals and provide pFSCK’s design overview.

#### 4.1 pFSCK Goals

- **Decrease file system C/R runtime.** The main goal is to make file system C/R faster. We want to increase the speed at which file system metadata can be scanned and inconsistencies identified, without compromising repairing capabilities.

- **Adapt to different file system configurations.** The C/R performance should improve regardless of file system size, utilization, or configurations, such as a file-intensive or directory-intensive file system.

- **Support offline and online C/R.** C/Rs can be used when a disk is not mounted, and the file system is offline or when a system is online, and the file system is actively used. Hence, pFSCK aims to support both offline and online C/R.

- **Adapt to system utilization.** C/R should have the ability to adapt to varying system resource utilization over time to reduce the potential performance impact on any currently-running applications. pFSCK aims to adapt to varying system-wide CPU use.
4.2 pFSCK Design Insights

We next describe the key design insights to realize the above goals.

Insight 1: Maximize potential bandwidth through multiple cores and data parallelism. To overcome the bottlenecks of current serial C/Rs and C/Rs that parallelize at a coarse granularity such as across logical volumes or logical groups, pFSCK exploits fine-grained inode and directory block parallelism. Towards this goal, pFSCK first introduces data parallelism to C/R for better utilization of CPU parallelism enabled by modern storage bandwidth capabilities. At a high-level, in each pass, basic file system structures such as inodes, directory blocks, dirents, and links are divided and checked across a pool of worker threads. While seemingly simple, achieving data parallelism requires data structure isolation across threads to reduce synchronization bottlenecks.

Insight 2: Enable pipeline parallelism by reducing inter-pass dependencies. Though data parallelism improves performance, updates to several inter-pass global data structures used for building a consistent view of the file system and identifying inconsistencies (ex. bitmaps), must be serialized. Consequently, this limits data parallelism’s performance capability with higher CPU counts and also degrades performance at higher thread counts due to contention on the shared structures. Pipeline parallelism breaks the rigid wall across passes allowing multiple passes to be executed simultaneously along with the logical flow of an application, thereby increasing CPU parallelism and reducing the performance impact of serialization. To realize pipeline parallelism requires managing per-pass thread pools, isolating inter-pass shared structures using divide and merge approaches, delineating checking and certification of inodes, and reducing I/O wait times.

Insight 3: Adapt to file system configurations with dynamic thread scheduling. Enabling data and pipeline parallelism requires assigning threads across different passes of pFSCK. Static partitioning of CPU threads across different passes are suboptimal due to lack of information about metadata types (files, directories, links) and work across passes; for example, checking directory blocks in Pass-2 (directory checking pass) require more processing time than checking inodes in Pass-1 (file checking pass) as discussed in Section §3. To overcome the challenge of accelerating C/R for different file system configurations, we design a dynamic thread scheduler that assigns threads to process different types of file system objects as they are discovered and migrates threads across different passes of the pipeline.

Insight 4: Reduce system impact through resource utilization awareness. File system C/Rs could potentially run with other applications sharing CPUs while performing checking on separate disks. Given pFSCK’s goal to exploit available CPUs, this could potentially impact other co-running applications. Similarly, C/R could run on disks that are also actively used by other applications to store data. To reduce the overall system impact on co-running applications as well as pFSCK, we equip pFSCK’s scheduler with resource awareness to dynamically identify the number of cores to use at any single point in time to minimize potential impact on other co-running applications without significantly impacting pFSCK’s performance.

5 Design and Implementation

To realize the goals of pFSCK, we discuss the design and implementation of pFSCK’s data parallelism, pipeline parallelism, dynamic thread scheduler, and resource-aware scheduling. pFSCK extends e2fsck to realize these design changes.

5.1 Data Parallelism

pFSCK’s data parallelism divides work in each pass among a group of worker threads on the granularity of inodes and enables concurrent C/R. While seemingly simple, efficient data parallelism during C/R demands an efficient threading model for fine-grained inode parallelism, functional separation of C/R within each pass, and per-thread contexts for isolating data structures and reducing synchronization cost.

Fine-grained Inode-level Parallelism. For fine-grained inode-level parallelism, pFSCK uses the superblock information to identify the total number of inodes in the file system and evenly divides the inodes across a given set of C/R workers. To reduce the cost of worker threads management, pFSCK uses a thread-pool framework [38] that provides the ability to assign tasks to multiple worker threads. The worker threads are then reused across different passes of a C/R. pFSCK also co-locates threads of a pass to the same CPU and memory socket to avoid the lock variable bouncing across processor caches on different sockets. We will also discuss the need for dynamically identifying work done across threads and scheduling in Section §5.3.

Functional Parallelism for Reducing Synchronization Overheads. Only dividing inodes for checking across worker threads is insufficient. To benefit from fine-grained parallelism, it is critical to reduce synchronization across worker threads in each pass without compromising correctness.

We first break each C/R pass into four main functional steps and reduce synchronization across these steps. The steps include: (1) file system metadata C/R, (2) global file system metadata update, (3) C/R-level accounting, and finally, (4) intermediate result sharing; these four steps comprise 95% of the work. The metadata check performs logical checks that verify their integrity across each pass (for example, blocks of an inode). Next, updating global file system metadata includes updating file system-level bitmaps that keep track of blocks and inodes currently used and referenced. The bitmaps are also used to detect any inconsistencies between inodes such as duplicate block references where more than one inode claim the same block. Third, C/R-level accounting involves updating counters that track statistics such as file types. Finally, intermediate result sharing across passes involves creating
and updating data structures such as a red-black tree with inode information and a hash-tree based directory list.

While synchronization between file system metadata check (step 1) and global metadata update steps (step 2) are essential, synchronization between first two steps and step 3 (C/R counter/statistics update) can be avoided by allowing threads to maintain per-threads stats. The results of step 1 and 2 can be aggregated before the next pass, reducing the synchronization cost significantly.

**Thread Contexts for Isolation.** In current C/Rs such as e2fsck, upon which pFSCK is built, we identify significant data structure sharing across functions (steps 1 to 4) inside each pass and across passes. To reduce sharing and provide isolation, we introduce per-thread contexts (in contrast to a global context in e2fsck). The thread contexts are similar to OS thread contexts and contain information such as buffers used for processing file system objects, intermediate data structures, structures to track progress, locks held for shared data structures, and CPUs used. At the end of each pass, the information within each thread context, such as per-thread buffers and generated intermediate data structures, are aggregated before the subsequent pass.

### 5.2 Pipeline Parallelism

While data parallelism achieves concurrency for processing file system objects within a pass, fully isolating per-pass shared data structures and global data structures is not feasible without substantial changes to either the file system layout or the C/R. As a result, data parallelism does not fully benefit from increasing CPU count and in fact, as our results show, can degrade substantially in performance at higher core counts due to increasing synchronization overheads.

To reduce time on synchronization and increase the CPU effectiveness, pipeline parallelism breaks the limitation that C/R passes must be sequentially executed, thereby allowing a subsequent C/R pass (Pass_{i+1}) to start even before the completion of an earlier pass (Pass_i) in a pipelined fashion (i.e., checking directories in directory checking pass (Pass-2) even before the inode checking pass (Pass-1) has completed).

#### 5.2.1 Per-Pass Thread Pools and Work Queues.

First, to facilitate each pass operating in parallel, we use *per-pass thread pools*. As shown in Figure 4, the inode and directory checking passes each maintain a separate thread pool that is used to hold threads that carry out logic within the pass. In addition to the per-pass thread pools, each pass maintains a dedicated work queue filled with file system objects needing to be checked. As each pass operates, any intermediate work generated is placed in the next pass’s work queue. For example, within the inode checking pass (Pass-1) as directory inodes are identified, their directory blocks are queued to the directory checking pass’s work queue so they can be checked.

#### 5.2.2 Overcoming Dependent Checks with Delayed Certification.

Allowing multiple passes to run in parallel using pipeline parallelism requires reordering logical checks for correctness. Take an example of the inode checking pass (Pass-1) and the directory checking pass (Pass-2): in pFSCK (and e2fsck), the inode checking pass reads inodes from disk and checks all inodes including directories and adds directory block information in a shared directory block list (dbhlist) so the directory checking pass can check the directory entries. While the inode and directory checking passes can proceed in parallel, the directories can be marked as consistent only after the inode checking pass verifies the consistency of the inodes representing the files and subdirectories inside a directory.

**Providing Ordering Guarantee.** To address the challenge of ordering guarantee, pFSCK delays certain checks until the prior pipeline pass is complete. For example, the inode checking pass within the pipeline is responsible for creating in-memory directory structures that are used in the directory checking pass to check directories. The directory checking pass stores a list of subdirectories and checks whether the subdirectory’s parent entry point (represented by double dot ..) map back to the directory. However, because the inode checking and directory checking passes run in parallel, not all the inodes of the directory entries would have been checked when the parent directories are checked in the directory checking pass. To handle such scenarios, pFSCK delays certification by adding the uncompleted checks, just like the one described, in a separate work queue and completing them only after all inodes have been checked (e.g. after the inode checking pass completes) as shown in Figure 4.

#### 5.2.3 Reducing I/O Wait Time in Pipeline Parallelism.

Effective use of multiple CPUs for an I/O-intensive C/R requires efficient I/O prefetching and caching even for fast modern storage devices such as NVMe. Though current C/Rs such as e2fsck cache and prefetch file system blocks, they are inflexible and lack thread awareness. For example, e2fsck by default prefetches a few blocks at a time when reading in inodes and fetches only 1 block when fetching directory blocks. It is possible to change the amount of readahead done however we observe that statically or naively increasing the prefetch depth negatively impacts performance because threads access
the file system blocks at different offsets, frequently invalidating previously read cache entries, consequently increasing the overheads of I/O.

To overcome such limitations and accelerate I/O, we implement a per-thread caching and readahead-based prefetching mechanism that prevents the eviction of cache entries when multiple threads operate in parallel. As our results show in Section § 6, combining pipeline parallelism with data parallelism and employing dynamic workload-based threading (discussed next) improves pFSCK’s performance across different file system configurations.

5.3 Dynamic Thread Scheduling in pFSCK

The runtime of C/Rs can vary significantly depending on the configuration of the file system. For example, C/R on a file system with a larger ratio of smaller files could result in a substantially longer runtime compared to a file system with few, but large files due to more metadata needing to be checked. Similarly, heterogeneity in terms of inode types (files, directories, links) can impact runtime, and the exact configuration remains unknown until the inodes are iterated over in the inode checking pass (Pass-1). Additionally, each pass within C/R have differing degrees of accesses to shared structures. Therefore, a static assignment of threads across each pass could be ineffective. Hence, to adapt to file system configurations, pFSCK implements a C/R-aware scheduler, pFSCK-sched, supported by extending the thread pools to allow for migration of threads between the passes. In addition, pFSCK-sched maintains an idle thread pool to hold any threads not scheduled to run for any of the passes.

Thread Assignment and Migration of Worker Threads. In pFSCK, we enable dynamic assignment of threads across each pass by implementing a scheduler that actively monitors progress and migrates threads across the passes. The scheduler periodically scans through the work queues of each pass to identify the work distribution ratio across the pipelined passes and uses this ratio to assign threads across them.

Figure 5 shows an example of pFSCK-sched across the first two passes. Initially, all the CPU threads are assigned to the first pass (inode checker) given that pFSCK only knows total inodes from the file system superblock and not the types of inodes. When the inode checker’s worker thread identifies a group of directory inodes, it places the directory inodes and their corresponding directory blocks to the work queue of directory checking pass. If no threads are present in the thread pool used for the directory checking pass, threads from the inode checking pass (first pass) are migrated to the directory checking pass. To calculate the number of threads to be reassigned, a dedicated scheduler thread finds the total work to be done across all passes using the following model.

Let $W_{total}$ be the amount of work needing to be done. Let $q_i$ be the length of the work queue for pass $i$. Let $n_i$ be the number of discrete elements needing to be processed for each entry in the work queue. Let $w_i$ be some weight that normalizes the work to be done for each element in pass $i$. Let $C$ be the core budget and $t_i$ be the number of threads to assign for pass $i$.

\[
W_{total} = \sum_{i=0}^{N} q_i n_i w_i \tag{1}
\]

\[
t_i = C \cdot q_i n_i w_i \cdot \frac{1}{W_{total}} \tag{2}
\]

As shown in Equation (1), the total work needing to be done is a summation of outstanding work across all the passes. The outstanding work in each pass is a product of the work queue length ($q_i$), the number of objects encapsulated within each queue entry ($n_i$), and a normalizing weight ($w_i$). As shown in Equation (2), with the total amount of work needing to be done, the scheduler can determine the ideal number of threads to assign to a pass ($t_i$) based on the total core budget ($C$) and the relative amount of work calculated for each pass. Note that the normalizing weights are essential for accounting the differences in the time to process different file types (directories vs. regular files). In our experimentation, we find it beneficial to use higher weights for prioritizing work in the directory checking queue as directories can take significantly longer to check compared to regular files due to directory checksum calculations.

5.4 System Resource-Aware Scheduler

File system C/Rs could potentially coexist or even share CPUs with other applications using the same or another file system (or disk). In the pursuit of exploiting parallelism, pFSCK’s approaches must avoid or minimize the performance impact on other applications. To address this goal, we introduce pFSCK-rsched, which enables resource-awareness for pFSCK’s scheduler.

5.4.1 Efficient CPU Sharing

First, we discuss the case when pFSCK-rsched runs alongside other applications but using different file systems, where pFSCK-rsched performs C/R on a separate, unmounted disk. Initially, pFSCK-rsched schedules the main pFSCK process using the SCHED_IDLE priority to minimize any contention on CPUs with regular processes. The SCHED_IDLE priority mostly schedules a process on any idle CPUs [5]. As the
scheduler periodically runs, pFSCK-rsched first determines a core budget that represents the maximum number of threads pFSCK-rsched should be running at any point in time. It does this by identifying the number of CPU threads currently running, the number of idle cores available, and the number of cores pFSCK-rsched is currently running on. For idle cores not being utilized by any application (including pFSCK), pFSCK-rsched increases the core budget by the number of idle cores available. On the contrary, if pFSCK-rsched identifies that the total number of pFSCK threads are more than the idle cores, pFSCK-rsched reduces the core budget to avoid multiplexing pFSCK’s threads on the cores it runs on. The core budget remains unchanged if the available idle cores and pFSCK threads remain the same. After determining the core budget, the scheduler identifies the work ratio across passes to determine the ideal number of threads that should be assigned to each pass. The scheduler then redistributes the threads across the thread pools. In the case of the threads needing to be added due to an increase in the core budget, threads are taken from the idle thread pool and assigned to the thread pool to fulfill the ideal thread count. If threads need to be removed due to a decrease in the core budget, threads are signaled and reassigned to the idle thread pool. Our results in Section § 6 show the performance benefits and implication of pFSCK-rsched when co-running and sharing CPUs with another application (RocksDB).

### 5.4.2 Efficient CPU and File System Sharing

Given the renewed focus on supporting online-checking, open-source C/Rs such as e2fsck support C/R on a online file system (and disk) that is mounted and actively used by applications. E2fsck supports online-checking by utilizing Linux’s Logical Volume Manager’s (LVM) snapshot feature which preserves a file system’s state by capturing the changes to the file system [20]. E2fsck can then perform C/R on snapshot. The C/R time is dominated by an application’s activity in changing the file system objects. Consequently, this results in a longer C/R time for an actively modified file system.

Despite this, pFSCK still shows general improvement over e2fsck. First, pFSCK’s generic fine-grained parallelism supports and accelerates online C/R even when applications are sharing the same file system (and disks). Second, pFSCK’s resource awareness reduces the impact on co-running application. As our results show, even when running online C/Rs with I/O-intensive applications (RocksDB [3]), pFSCK provides considerable performance gains compared to running online C/R with vanilla e2fsck.

### 5.5 Verifying Correctness and Optimizations

**Correctness.** To ensure correctness with fine-grained C/R parallelism, pFSCK employs a series of steps. First, although the checks are done in parallel, an inode is not marked complete unless prior passes in the pipeline complete. For example, recall that a directory within the directory checking pass (Pass-2) cannot be marked as complete until all the inodes for all of its directory entries are checked. Second, threads are synchronized when performing complex fixes upon detecting errors. When a worker thread detects any inconsistencies, all threads across the different passes are notified and stalled using a barrier. The thread that detected the inconsistency attempts to fix the errors with (e.g., incorrect inode, blocks claimed by multiple inodes) or without user input (e.g., inconsistent bitmap), after which parallel execution is resumed. In addition, we plan to explore C/R crash-consistency for pFSCK in the future using prior approaches [15].

**Optimizations.** As additional optimizations to both e2fsck and pFSCK, we restrict the overheads of language localization discussed earlier to inode and directory block checking, use Intel hardware-accelerated CRC instead of the default CRC, as well as improve the cache-readahead mechanism. While the language localization optimization has been reported and upstreamed to e2fsck codes mainline, the other optimizations are under review. We evaluate the benefits of these optimizations in Section § 6 (referred to as e2fsck-opt in graphs).

### 6 Evaluation

Our evaluation of pFSCK aims to answer the following important questions:

- Does data parallelism improve runtime performance by increasing CPU parallelism?
- Can does pipeline parallelism address the limitations of data parallelism by running multiple passes of C/R simultaneously?
- How effective is pFSCK’s dynamic thread placement mechanism for different file system configurations?
- Can pFSCK’s resource-aware scheduler effectively minimize the performance impact on other applications when sharing CPUs?
- How does pFSCK perform for online file system checking?
6.1 Experimental Setup

We use a 64-core Dual Intel® Xeon Gold 5218, 2.30GHz, 64GB of DDR memory, and 1TB NVMe Flash Storage running Ubuntu 18.04.1. We run pFSCK on various file system configurations with varying thread counts. As seen in Table 1, we compare against vanilla e2fsck, e2fsck-opt (an optimized version of e2fsck that removes localization overheads and utilizes Intel CPU-accelerated CRC calculations), and finally, xfs_repair. Table 2 shows the incremental pFSCK’s design optimizations.

6.2 Data Parallelism

In order to evaluate the potential performance improvement with data parallelism, we run pFSCK with just data parallelism (bars shown as pFSCK[datapara]) that parallelizes each pass of a C/R by partitioning work. We compare two file system configurations: a file-intensive (99% files) and directory-intensive (50% directories) configuration. The x-axis shows the reduction in runtime with pFSCK and the stacked bars shows the runtime breakdown for each pass.

First, with a file-intensive configuration, as shown in Figure 6, the inode checking pass (Pass-1) shows a higher runtime compared to other passes. Secondly, our optimized e2fsck (e2fsck-opt) outperforms the vanilla e2fsck by optimizing the CRC mechanism, avoiding language localization overheads for every inode, and improving the readahead mechanism. Interestingly, both e2fsck and pFSCK outperform xfs_repair for all cases. Although xfs_repair is able to check inodes in parallel on the granularity of allocation groups, it is unable to check directory entries and link counts in parallel which unfortunately dominates the checking time for large file systems.

Finally, enabling data parallelism within pFSCK reduces the runtime of the first pass by 2.1x with 4 threads. Data parallelism also reduces the runtime of the directory checking pass (Pass-2) by 1.8x resulting in an overall C/R speedup of 1.9x. Beyond 4-threads, data parallelism does not scale due to higher serialization and lock contention overheads. Specifically, we find the functions that update shared structures such as the used/free block bitmap as the most prominent source of bottlenecks that hinders scaling.

Next, for the directory-intensive file system, as shown in Figure 7, pFSCK parallelizes inode checking (in Pass-1) and directory checking (in Pass-2). The runtime of Pass-1 and Pass-2 reduces by 1.8x and 1.3x respectively, resulting in an overall C/R speedup of 1.4x compared to the vanilla e2fsck. Similar to the file-intensive configuration, we see a performance gain of 1.8x compared to xfs_repair, for which the directory metadata check is not parallelized. Finally, pFSCK’s data parallelism does not scale beyond 4-cores.

6.3 Pipeline Parallelism and Dynamic Thread Placement

We next evaluate the benefits of combining data and pipeline parallelism and the need for a dynamic thread placement. In order to evaluate the performance improvement of pipeline parallelization, we compare pFSCK’s data parallelism (pFSCK[datapara]), with data and pipeline parallelism (pFSCK[ datapara+pipeline]) against file-intensive and directory-intensive file system configurations. When using pipeline parallelism, the threads of each pass adds work to be processed in the next pass. Because of this, logical boundaries between the passes within e2fsck diminishes, hence, we only report the full runtime of C/R. Because e2fsck and pFSCK outperform xfs_repair in all cases, we do not show xfs_repair’s results.

Figure 8a and Figure 8b show the results for a file-intensive and directory-intensive file system configuration. The x-axis shows the increase in the number of threads used for the C/R. In the figures, we compare four cases: (1) pFSCK[datapara], which only uses data parallelism running one pass at a time, (2) pFSCK[ datapara+pipeline-split-equal], which combines pipeline and data parallelism and statically uses an equal number of threads for each of the simultaneously executing passes (ex. 2 threads are assigned to Pass-1 and 2 threads to Pass-2 in a 4-thread configuration), (3) pFSCK[ datapara+pipeline-split-optimal], which represents a best manually selected thread configuration, and (4) pFSCK-sched, which dynamically assigns threads to each pass based
on the amount of work to be done and current progress.

First, for the file-intensive configuration, pFSCK\[datapara+pipeline-split-equal\] is not beneficial for low thread counts (2 and 4 threads) compared to the data parallelism-only approach, because threads are statically and equally assigned to Pass-1 and Pass-2 irrespective of the file system configuration. Increasing the thread count improves performance, because, for a file-intensive configuration, most work is done in the inode checking pass (Pass-1). As a result, threads statically assigned for subsequent passes are under-utilized. Increasing the thread count (along the x-axis) improves pFSCK’s performance marginally compared to using only the data parallelism. In contrast, pFSCK\[datapara+pipeline-split-optimal\], the manually selected thread configuration case improves performance by up to 1.3x compared to data parallelism by employing three-fourths of the threads to the inode checker. More importantly, the manually selected configuration avoids high synchronization and contention overheads of the data parallelism beyond four threads. Finally, pFSCK’s scheduler (pFSCK-sched) automatically migrates threads based on relative amount the outstanding work to be completed across each pass. As a result, pFSCK-sched can automatically provide optimal performance, improving performance by 1.1x compared to pFSCK\[datapara+pipeline-split-optimal\], resulting in an overall speedup of 2.6x compared to vanilla e2fsck.

Next, for the directory-intensive file system, unlike the data parallelism only approach, pipeline parallelism, which enables simultaneous inode and directory checking (without compromising correctness), provides some performance improvement as well. pFSCK\[datapara+pipeline-split-optimal\] reduces runtime by 1.1x with up to 8 threads compared to just using data parallelism. When employing pFSCK’s scheduler (pFSCK-sched), it automatically mitigates thread contention within the directory block checking by limiting the number of threads assigned to each pass. Consequently, the performance improves by 1.05x over pFSCK\[datapara+pipeline-split-equal\], resulting in an overall speedup of up to 1.6x over the vanilla e2fsck. Compared to the speedup with a file-intensive file system, since pFSCK employs delayed certification of directories, beyond 8 threads, processing dependent directories (directory with subdirectory) must join, synchronize, and merge their work for correctness, limiting scalability.

Interestingly, although not shown, we see that e2fsck uses the most memory for directory-intensive file systems. In order to check an 800GB directory-intensive file system, e2fsck uses as much as 3GB of memory as a significant amount of in-memory data structures are needed to track all the directory information needed to verify the relationships between the directories and the files and subdirectories that exist within them. Despite this, we find pFSCK’s memory usage is comparable, only using as much as 3.5GB resulting in only a 1.17x increase in memory usage.

Lastly, in **Figure 8c** shows pFSCK performance on a file-intensive file system backed by SSD. We see that pFSCK is able to show the similar speedups of up to 2.1x over vanilla e2fsck despite SSDs having lower bandwidth capabilities compared to NVMe. In summary, pFSCK’s pipeline parallelism reduces the serialization bottlenecks of data parallelism, and the dynamic thread placement reduces work imbalance, all leading to significant performance gains.

### 6.4 System Resource-Aware Scheduler

We next evaluate the effectiveness of pFSCK’s resource-aware scheduler (pFSCK-rsched) in reducing the impact on other applications compared to e2fsck. To illustrate the effectiveness, we pick a popular persistent key-value store, RocksDB [3], and use it to run a multithreaded system workload along with each system. We evaluate them in both an offline setting, where the checker and RocksDB operate on separate file systems, and an online setting, where the checker and RocksDB operate on the same file system. For each setting, we consider the following cases: (1) e2fsck-no-cpu-sharing, where e2fsck is runs with RocksDB without sharing the same CPU cores, (2) e2fsck-cpu-sharing, where e2fsck runs with RocksDB while sharing the same CPU cores, (3) pFSCK-rsched-no-cpu-sharing, where pFSCK-rsched runs with RocksDB without sharing the same CPU cores, and (4) pFSCK-rsched-cpu-sharing, where pFSCK-rsched runs with RocksDB while sharing the same CPU cores. We run RocksDB with 12 threads. In the case of CPU sharing we force e2fsck to share cores with RockDB by restricting the
affinity of all the threads to 12 cores resulting in the overlapping of one core. In the case of CPU sharing with pFSCK-rsched, we run pFSCK-rsched with 12 threads and restrict the affinity of all threads to 16 cores, resulting in the overlapping of 8 cores. For brevity, we show only the results for checking a file-intensive file system.

6.4.1 Offline C/R with CPU Sharing.

First, when overlapping e2fsck and RocksDB, performance significantly degrades by 1.4x and 1.6x respectively. Interestingly this is not only due to context switching between e2fsck and RocksDB but also due to overheads in utilizing LVM snapshots. As discussed before, LVM preserves file system state for a snapshot by capturing all updates to a file system and making a copy of the original data when modified for the entire duration the LVM snapshot is active. In the case of e2fsck sharing CPUs with RocksDB, since CPU sharing and context switching naturally decreases the performance of e2fsck, this means the snapshot is active for a longer period of time, compounding the degradation of performance for both e2fsck and RocksDB.

Despite the compounding performance degradation due to LVM snapshot overheads, the performance degradation when co-running pFSCK-rsched with RocksDB is minimal due to the following reasons: (1) pFSCK-rsched’s parallelization reduces C/R runtime compared to e2fsck, minimizing the amount of time the snapshot is active and reducing performance degradation for C/R and RocksDB. (2) In the case of overlapping cores, similar to an offline setting, pFSCK-rsched mitigates significant performance impact by scaling the number of threads it uses, reducing performance degradation of both pFSCK-rsched and RocksDB by only 1.2x. Compared to an offline setting, this increase in degradation from 1.07x for pFSCK-sched and 1.05x for RocksDB to 1.2x for both pFSCK-sched and RocksDB is due to compounding overheads of using LVM snapshots.

Summary. To summarize, pFSCK-rsched’s resource awareness is able to effectively adapt its number of threads to maximize the utilization of available cores (and performance) in both an offline and online setting while effectively minimizing the amount of impact on RocksDB.

7 Conclusion

With a goal of accelerating file system checking and repair tools, in this paper, we propose pFSCK, a parallel C/R tool that exploits CPU parallelism and the high bandwidth capabilities of modern storage to accelerate file system checking and repair time without compromising correctness. pFSCK explores fine-grained parallelism by assigning threads with inodes, blocks, or directories and efficiently performing C/R using data parallelism within each pass and pipeline parallelism across multiple passes. In addition, pFSCK also enables efficient thread management techniques to adapt to varying file system configurations as well as minimize performance impact on other applications. Evaluation of pFSCK shows more than 2.6x gains over e2fsck and 1.8x over xfs_repair that provides coarse-grained parallelism.
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