Position: On Failure Diagnosis of the Storage Stack

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Abstract

Diagnosing storage system failures is challenging even for professionals. One example is the “When Solid State Drives Are Not That Solid” incident occurred at Algolia data center, where Samsung SSDs were mistakenly blamed for failures caused by a Linux kernel bug. With the system complexity keeps increasing, such obscure failures will likely occur more often.

As one step to address the challenge, we present our on-going efforts called X-Ray. Different from traditional methods that focus on either the software or the hardware, X-Ray leverages virtualization to collects events across layers, and correlates them to generate a correlation tree. Moreover, by applying simple rules, X-Ray can highlight critical nodes automatically. Preliminary results based on 5 failure cases shows that X-Ray can effectively narrow down the search space for failures.

1 Motivation

The storage stack is witnessing a sea-change driven by the advances in non-volatile memory (NVM) technologies [58, 53, 60, 65, 46, 87, 77, 51, 84]. For example, flash-based solid state drives (SSDs) and persistent memories (PMs) are replacing hard disk drives (HDDs) as the durable device [93, 2, 73, 31, 12, 4]; NVMe [28] and CXL [7] are redefining the host-device interface; blk-mq [49] alleviates the single queue and lock contention bottleneck at the block I/O layer; the SCSI subsystem and the Ext4 file system, which have been tuned for HDDs for decades, are also being adapted for NVM (e.g., scsi-mq [32] [55] [91] and DAX [9]); in addition, various NVM-oriented new designs/optimizations have been proposed (e.g., F2FS [67], NOVA [94], Kevlar [59]), some of which require cohesive modifications throughout the storage stack (e.g., the TRIM support [34]).

The new systems generally offer higher performance. However, as a disruptive technology, the NVM-based components have to co-exist with the traditional storage ecosystem, which is notoriously complex and difficult to get right despite decades of efforts [95, 79, 71, 86]. Compared with the performance gain, the implication on system reliability is much less studied or understood.

As another example, Zheng et al. studied the behavior of SSDs under power fault [100]. The testing framework bypassed the file system, but relied on the block I/O layer to apply workloads and check the behavior of devices. In other words, the SSDs were essentially evaluated together with the block I/O layer. Their initial experiments were performed on Linux kernel v2.6.32, and eight out of fifteen SSDs exhibited a symptom called “serialization errors” [100]. However, in their follow-up work where similar experiments were conducted on a newer kernel (v3.16.0) [101], the authors observed that the failure symptoms on some SSDs changed significantly (see Table 1 adapted from [101]). It was eventually confirmed that the different symptoms was caused by a sync-related Linux kernel bug [101].

One commonality of the two cases above is that peo-
ple try to infer the behavior of storage devices indirectly through the operating system (OS) kernel, and they tend to believe that the kernel is correct. This is natural in practice because users typically have to access storage devices with the help of the kernel, and they usually do not have the luxury of inspecting the device behavior directly. Also, NVM devices are relatively young compared with the long history of the OS kernel, so they might seem less trustable. We call such common practice as a top-down approach.

Nevertheless, both cases show that the OS kernel may play a role in causing system failures, while the device may be innocent. More strangely, in both cases, different devices seem to have different sensitivity to the kernel bug, and some devices may even “tolerate” the kernel bug. For example, no failure was observed on Intel SSDs in the Algolia case [31], and the SSD-3 in Table 1 never exhibited any serialization errors in Zheng et al.’s experiments [100]. Since switching devices is one simple and common strategy to identify device issues when diagnosing system failures, the different sensitivity of devices to the software bugs can easily drive the investigation to the wrong direction, wasting human efforts and resulting in wrong conclusions, as manifested in the two cases above.

In fact, similar confusing and debatable failures are not uncommon today [29, 33, 27, 16]. With the trend of storage devices becoming more capable and more special features are being exposed to the host-side software [78, 41, 80], the interaction between hardware and software is expected to be more complex. Consequently, analyzing storage system failures solely based on the existing top-down approach will likely become more problematic. In other words, new methodologies for diagnosing failures of the storage stack are much needed.

The rest of the paper is organized as follows: First, we discuss the limitations of existing efforts (§2). Next, we introduce our idea (§3) and the preliminary results (§4); Finally, we describe other related work (§5) and conclude with the discussion topics section (§6).

2 Why Existing Efforts Are Not Enough

In this section, we discuss two groups of existing efforts that may alleviate the challenge of diagnosing storage stack failures to some extent. We defer the discussion of other related work (e.g., diagnosing performance issues and distributed systems) to §5.

2.1 Testing the Storage Software Stack

Great efforts have been made to test the storage software in the stack [95, 74, 76, 99], with the goal of exposing bugs that could lead to failures. For example, EXPLODE [95] and B³ [76] apply fault injections to detect crash-consistency bugs in file systems. However, testing tools are generally not suitable for diagnosing system failures because they typically require a well-controlled environment (e.g., a highly customized kernel [95, 76]), which may be substantially different from the storage stack that need to be diagnosed.

2.2 Practical Diagnosing Tools

To some extent, failure diagnosis is the reverse process of fault injection testing. Due to the importance, many practical tools have been built, including the following:

**Debuggers** [14, 52, 18] are the de facto way to diagnose system failures. They usually support fine-grained manual inspection (e.g., set breakpoints, check memory bytes). However, significant human efforts are needed to harness the power and diagnose the storage stack. The manual effort required will keep increasing as the software becomes more complex. Also, these tools typically cannot collect the device information directly.

**Software Tracers** [26, 3, 10, 57] can collect various events from a target system to help understand the behavior. However, similar to debuggers, they focus on host-side events only, and usually do not have automation support for failure inspection.

**Bus Analyzers** [15, 23] are hardware equipments that can capture the communication data between a host system and a device, which are particularly useful for analyzing the device behavior. However, since they only report bus-level information, they cannot help much on understanding system-level behaviors.

Note that both debuggers and software tracers represent the traditional top-down diagnosis approach. On the other hand, bus analyzers have been used to diagnose some of the most obscure failures that involved host-device interactions [8, 80], but they are not as convenient as the software tools.

3 X-Ray: A Cross-Layer Approach

Our goal is to help practitioners to narrow down the root causes of storage system failures quickly. To this end, we are exploring a framework called X-Ray, which is expected to have the following key features:

- **Full stack:** many critical operations (e.g., sync, TRIM) require cohesive support at both device and host sides; inspecting only one side (and assuming the other side is correct) is fundamentally limited;

- **Isolation:** the device information should be collected without relying on the host-side software (which may be problematic itself);

- **Usability:** no special hardware or software modification is needed; manual inspection should be reduced as much as possible.

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Figure 1: The X-Ray Approach. The target software stack is hosted in a virtual machine; DevAgent, HostAgent, and X-Explorer are the three main components; the basic mode visualizes a correlation tree for inspection; the advanced mode highlights critical nodes based on rules.

3.1 Overview

Figure 1 shows an overview of the X-Ray framework, which includes three major components: DevAgent, HostAgent, and X-Explorer.

First, we notice that the virtualization technology is mature enough to support unmodified OS today [25, 19, 20]. Moreover, recent research efforts have enabled emulating sophisticated storage devices in a virtual machine (VM), including SATA SSDs (e.g., VSSIM [96]) and NVMe SSDs (e.g., FEMU [68]). Therefore, we can leverage virtualization to support cross-layer analysis with high fidelity and no hardware dependence.

Specifically, we host the target storage software stack in a QEMU VM [47]. At the virtual device layer, the DevAgent (§3.2) monitors the commands (e.g., SCSI, NVMe) transferred from the kernel under the bug-triggering workload. Optionally, the associated data (i.e., bits transferred by commands) can be recorded too.

Meanwhile, to understand the high-level semantics of the system activities, the HostAgent (§3.3) monitors the function invocations throughout the software stack (e.g., system calls, kernel internal functions), and records them with timestamps at the host side. Optionally, key variables may be recorded too with additional overhead.

The X-Explorer (§3.4) helps to diagnose the system behavior in two modes: (1) the basic mode visualizes a correlation tree of cross-layer events for inspection; (2) the advanced mode highlights critical events based on rules, which can be either specified by the user or derived from a normal system execution.

3.2 DevAgent

The device-level information is helpful because storage failures are often related to the persistent states, and changing persistent states (in)correctly requires (in)correct device command sequences. The DevAgent records the information in a command log directly without any dependency on the host-side kernel (which might be buggy itself), similar to the bus analyzer [15].

SCSI Device. The Linux kernel communicates with a SCSI device by sending Command Descriptor Blocks (CDBs) over the bus. QEMU maintains a struct SCSICommand for each SCSI command, which contains a 16-byte buffer (SCSICommand->buf) holding the CDB. Every SCSI command type is identified by the opcode at the beginning of the CDB, and the size of CDB is determined by the opcode. For example, the CDB for the WRITE_10 command is represented by the first 10 bytes of the buffer. For simplicity, we always transfer 16 bytes from the buffer to the command log and use the opcode to identify valid bytes. QEMU classifies SCSI commands into either Direct Memory Access (DMA) commands (e.g., READ_10) or Admin commands (e.g., VERIFY_10), and both are handled in the same way in DevAgent since they share the same structure.

NVMe Device. QEMU maintains a struct NvmeCmd for each NVMe command, and emulates the io_uring [22, 17] interface to transfer NVMe commands to a NVMe device. The interface defines two types of command queues: submission and completion. The submission queues are further classified into either I/O submission queue or Admin submission queue, which are processed via nvme_process_sq_io and nvme_process_sq_admin in QEMU respectively. The DevAgent intercepts both queues and records both I/O commands and Admin commands, similar to SCSI.

3.3 HostAgent

The HostAgent aims to track host-side events to help understand the high level semantics of system activities. As mentioned in §2, many tracers have been developed with different tradeoffs [21]. The current prototype of HostAgent is based on ftrace [13], which has native support on Linux based on kprobes [3]. We select ftrace [13] because its convenient support on tracing caller-callee relationship. When CONFIG_FUNCTION_GRAPH_TRACER is defined, the ftrace_graph_call routine will store the pointer to the parent to a ring buffer at function return via the link register, which is ideal for X-Ray. On
the other hand, ftrace only records function execution time instead of the epoch time needed for synchronization with DevAgent events. To workaround the limitation, we modify the front end of ftrace to record the epoch time at system calls, and calculates the epoch time of kernel functions based on their execution time since the corresponding system calls. Another issue we observe is that ftrace may miss executed kernel functions. We are working on improving the completeness.

3.4 X-Explorer

The events collected by DevAgent and HostAgent are valuable for diagnosis. However, the quantity is usually too large for manual inspection. Inspired by the visualization layer of other diagnosis tools [48, 88, 39, 81], the X-Explorer visualizes the relationships among the events and highlights the critical ones.

3.4.1 TreeBuilder

The TreeBuilder generates a correlation tree to represent the relationships among events in the storage stack. The tree contains three types of nodes based on the events from HostAgent and DevAgent: (1) SYSCALL nodes represent the system calls invoked in the bug-triggering workload; (2) KERNEL nodes represent the internal kernel functions involved; (3) CMD nodes represent the commands observed at the device.

There are two types of edges in the tree: (1) the edges among SYSCALL and KERNEL nodes represent function invocation relations (i.e., parent and child); (2) the edges between CMD nodes and other nodes represent close relations in terms of time. In other words, the device-level events are correlated to the host-side events based on timestamps. While the idea is straightforward, we observe an out-of-order issue caused by virtualization: the HostAgent timestamp is collected within the VM, while the DevAgent timestamp is collected outside the VM; the device commands may appear to occur before the corresponding system calls based on the raw timestamps. To workaround the issue, we set up an NTP server [24] at the DevAgent side and perform NTP synchronization at the HostAgent Side. We find that such NTP based synchronization may mitigate the timestamp gap to a great extent, as will be shown in §4. Another potential solution is to modify the dynamic binary translation (DBT) layer of QEMU to minimize the latency.

3.4.2 TreePruner

The correlation tree is typically large due to the complexity of the storage stack. Inspired by the rule-based diagnosis tools [48], the TreePruner traverses the tree and highlights the critical paths and nodes (i.e., the paths and nodes of interest) automatically based on a set of rules stored in the RuleDB, which can be either specified by the user or derived from a normal system execution.

User-specified rules. Users may specify expected relations among system events as rules. For example, the sync-family system calls (e.g., sync, fsync) should generate SYNC_CACHE (SCSI) or FLUSH (NVMe) commands to the device, which is crucial for crash consistency; similarly, blkdev_fsync should be triggered when calling fsync on a raw block device. In addition, users may also specify simple rules to reduce the tree (e.g., all ancestor nodes of WRITE commands).

Our current prototype hard-coded a few rules as tree traversal operations based on the failure cases we studied [4]. We are exploring more flexible interfaces (e.g., SQL-like [61] or formula-based [50]) to enable expressing more sophisticated rules.

Normal system execution. Failures are often tricky to reproduce due to different environments (e.g., different kernel versions) [6]. In other words, failures may not always manifest even under the same bug-triggering workloads. Based on this observation, and inspired by delta debugging [97, 75], we may leverage a normal system as a reference when available.

When a normal system is available, we host the corresponding software stack in the X-Ray VM and build the correlation tree under the same bug-triggering workload. For clarity, we name the tree from the normal system execution as the reference tree, which essentially captures the implicit rules among events in the normal execution. By comparing the trees, divergences that cause different symptoms can be identified quickly.

Figure 2: A partial correlation tree. The tree includes one syscall (green), 704 kernel functions (white nodes), and 3 device commands (blue); the critical path (red) is selected by a simple rule: all ancestors of the command nodes.

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Figure 3: Comparison. (a) the critical path from Figure 2; (b) the critical path from a reference tree.

4 Preliminary Results

We have built a preliminary prototype of X-Ray and applied it to diagnose 5 failure cases based on real bugs from the literature [101, 70, 76, 63]. We discuss one case in details and summarize the results at the end.

Case Study. Figure 2 shows a partial correlation tree for diagnosing a failure where synchronous writes appear to be committed out of order on a raw block device. The tree starts with a syscall node (green), which triggers 704 kernel functions (white nodes) and three device commands (blue nodes). The red lines shows the critical path and nodes selected by one simple rule: "ancestors of device commands" (Rule#3). The tree itself is part of the original tree (not shown) selected via another simple rule: "syscalls with WRITE commands" (Rule#1).

Figure 3 (a) shows a zoomed in version of the critical path and nodes from Figure 2. We can easily see that the fsync syscall only generates three WRITE (0x2a) commands without explicitly sending SYNC_CACHE (0x35) command to the device, which is incorrect based on POSIX. Further investigation confirms that the root cause lies in the blkdev_fsync node on the critical path.

When a normal system is available, X-Ray may help more. Figure 3 (b) shows the critical path on a reference tree. Apparently, the SYNC_CACHE (0x35) command appears, and a new function blkdev_issue_flush is involved. By comparison, it is clear that the difference stems from the blkdev_fsync node.

| ID  | Original | Rule#1   | Rule#2   | Rule#3 |
|-----|----------|----------|----------|--------|
| 1   | 11,353   | 704      | 571      | 30     |
|     | (100%)   | (6.20%)  | (5.03%)  | (0.26%)|
| 2   | 34,083   | 697      | 328      | 22     |
|     | (100%)   | (2.05%)  | (0.96%)  | (0.06%)|
| 3   | 24,355   | 1,254    | 1,210    | 15     |
|     | (100%)   | (5.15%)  | (4.97%)  | (0.06%)|
| 4   | 273,653  | 10,230   | 9,953    | 40     |
|     | (100%)   | (3.74%)  | (3.64%)  | (0.01%)|
| 5   | 284,618  | 5,621    | 5,549    | 50     |
|     | (100%)   | (1.97%)  | (1.95%)  | (0.04%)|

Table 2: Result Summary.

Summary. Table 2 summarizes the result. Besides Rule#1 and Rule#3, we define another Rule#2: “functions between the syscall and commands”. Table 2 shows the node count of the original tree and the node counts after applying each rule. The bold cell means the root cause can be covered by the nodes selected via the corresponding rule. Overall, the simple rules can effectively narrow down the search space for root cause (0.06% - 4.97% of the original trees). We are studying other failure patterns and developing more intelligent rules.

5 Related Work

Analyzing Storage Devices. Many researchers have studied the behaviors of storage devices in depth, including both HDDs [43, 44, 56, 64, 82] and SSDs [38, 54, 58, 60, 66, 69, 83, 89, 72]. For example, Maneas et al. [72] study the reliability of 1.4 million SSDs deployed in NetApp RAID systems. Generally, these studies provide valuable insights for reasoning complex system failures involving device, which is complementary to X-Ray.

Diagnosing Distributed Systems. Great efforts have been made on tracing and analyzing distributed systems [40, 45, 88, 62, 81, 42]. For example, Aguilera et al. [40] trace network messages and infer causal relationships and latencies to diagnose performance issues. Similar to X-Ray, these methods need to align traces. However, their algorithms typically make use of unique features of network events (e.g., RPC Send/Receive pairs, IDs in message headers), which are not available for X-Ray. On the other hand, some statistic based methods [62] are potentially applicable when enough traces are collected.

Software Engineering. Many software engineering techniques have been proposed for diagnosing user-level programs (e.g., program slicing [37, 92, 98], delta debugging [97, 75], checkpoint/re-execution [85, 90]). In general, applying them directly to the storage stack remains challenging due to the complexity. On the other hand, some high-level ideas are likely applicable. For example, Sambasiva et al. [81] apply delta debugging to compare request flows to diagnose performance problems in Ursa Minor [35], similar to the reference tree part of X-Ray.
6 Discussion Topics Section

**Emulating Storage Devices.** As mentioned in §3, sophisticated SATA/NVMe SSDs have been emulated in QEMU VM [96, 68]. Among others, such efforts are important for realizing the VM-based full-stack tracing and diagnosis. However, we do have observed some limitations of existing emulated devices, which may affect the failure reproducing (and thus diagnosis) in VM. For example, advanced features like the TRIM operation are not fully supported on VSSIM or FEMU yet, but the Algolia failure case [31] requires a TRIM-capable device to manifest. As a result, we are not able to reproduce the Algolia failure in VM. Therefore, emulating storage devices precisely would be helpful for the X-Ray approach and/or failure analysis in general, in addition to the other well-known benefits [96, 68]. We would like to discuss how to improve the emulation accuracy under practical constraints (e.g., confidentiality).

**Deriving Rules.** The automation of X-Ray depends on the rules. The current prototype hard-coded a number of simple rules based on our preliminary study and domain knowledge, which is limited. We would like to explore other implicit rules in the storage stack with other domain experts. Also, we plan to collect correlation trees from normal system executions and apply machine learning algorithms to derive the potential rules. We would like to discuss the feasibility.

**Other Usages of X-Ray.** We envision that some other analysis could be enabled by X-Ray. For example, with precise latency and casual relationships among events, we may identify the paths that are critical for I/O performance, similar to the request flow analysis in distributed systems [31]. Another possibility is to measure the write amplification at different layers across the stack. We would like to discuss the opportunities.

**Other Challenges of Failure Diagnosis.** There are other challenges that are not covered by X-Ray. For example, X-Ray assumes that there is a bug-triggering workload that can reliably lead to the failure. In practice, deriving bug-triggering workloads from user workloads (which may be huge or inconvenient to share) is often tricky [11]. We would like to discuss such challenges.

**Sharing Failure Logs.** The cross-layer approach would be most effective for diagnosing obscure failures that involve both the OS kernel and the device [31] [101]. Based on our communications with storage practitioners, such failures are not uncommon. However, the details of such failures are usually unavailable to the public, which limits the use cases that could shape the design of reliability tools like X-Ray. The availability of detailed failure logs at scale is critical for moving similar research efforts forward. We would like to discuss how to improve log sharing given constraints (e.g., privacy).

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