Enlightening Flash Storage to Stream Writes by Objects

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ABSTRACT
For a write request, today’s flash storage cannot distinguish the logical object it comes from. In such object-oblivious flash devices, concurrent writes from different objects are simply packed in their arrival order to flash memory blocks; hence objects with different lifetimes are multiplexed onto the same flash blocks. This multiplexing incurs write amplification, worsening the performance.

Tackling the multiplexing problem, we propose a novel interface for flash storage. FlashAlloc. It is used to pass the logical address ranges of logical objects to the flash storage and thus enlighten the storage to stream writes by objects. The object-aware flash storage can de-multiplex writes from different objects with distinct deathtimes into per-object dedicated flash blocks. Given that popular data stores separate writes using objects (e.g., SSTables in RocksDB), we can achieve, unlike the existing solutions, transparent write streaming just by calling FlashAlloc upon object creation. Our experimental results using an open-source SSD prototype demonstrate that FlashAlloc can reduce write amplification factor (WAF) in RocksDB, F2FS, and MySQL by 1.5, 2.5, and 0.3, respectively and thus improve throughput by 2x, 1.8x, and 1.2x, respectively. In particular, FlashAlloc will mitigate the interference among multi-tenants. When RocksDB and MySQL were run together on the same SSD, FlashAlloc decreased WAF from 4.2 to 2.5 and doubled their throughputs.

1 INTRODUCTION
Most software systems, including LSM (Log-Structured-Merge) tree-based KV (Key-Value) stores, relational DBMSs, and file systems manage data using logical objects: to name a few, SSTables in RocksDB, DWB (double write buffer) in MySQL, and segments in F2FS. And, upon each object creation, its logical space is secured in advance before writes are made to the object. For instance, RocksDB calls fallocate() right after creating an SSTable file so as to secure the logical address space for the file. The logical address range allocated from the call belongs to the file object. For this reason, from an LBA address, the host-side data stores can identify its belonging object. In addition, when an object is deleted, all its data will be invalidated together at once; thus the data set belonging to an object is said to have the same deathtime. Meanwhile, different objects are, though created and populated simultaneously, usually destructed at different points in time; they have different deathtimes. In summary, host software stacks manage data by objects; each object is the unit of logical space allocation and, in many cases, all its pages will have the same deathtime.

Though host software stacks can distinguish objects by their logical address ranges, the host-side semantic about objects’ logical address ranges cannot cross the storage interface wall simply because no interface exists to pass it to the storage. As a result, today’s flash storage has no knowledge about the belongs-to relationship between LBA address and object. Therefore, when concurrent writes from different objects interleave, the conventional object-oblivious flash storage cannot distinguish each write’s object so that it has no choice but to simply append new data in their arrival order into flash blocks. As a consequence, writes from different objects collocate in the same flash blocks. That is, each flash block will be multiplexed by data from multiple objects with different deathtimes, as illustrated in Figure 1. We call this situation as multiplexing.

The multiplexing is the main culprit of physical write amplification in flash storage, worsening the performance and lifespan of flash storage. Since logical objects have different deathtimes each other in most cases (e.g., four SSTables in Figure 1 will be deleted at different points of time), pages in a multiplexed flash block will be incrementally invalidated at different points of time. When the block is chosen as a victim for garbage collection, the remaining valid pages have to be relocated to another block, amplifying physical writes inside flash storage. In particular, contrary to the common belief, the multiplexing will make even RocksDB and F2FS taking sequential write patterns suffer from severe device-level write amplification [7, 36, 39]. According to our experiments using commercial SSDs, write amplification factor (WAF in short) becomes even greater than eight (Figure 2(b)). In this sense, the so called flash-friendly sequential writes are not less harmful than random ones in the conventional flash storage [26]. In addition, the multiplexing can exacerbate the performance interference in multi-tenant environment [1]. When multiple applications, each with its set of objects, are run together on a flash device, more objects with more deviating deathtimes will be multiplexed onto the same flash blocks, worsening write amplification. To sum up, since no interface exists to offload the host semantic about objects’ logical address range to the storage, the valuable semantic is discarded and the object-oblivious flash device can not stream writes by objects, incurring multiplexing and write amplification.

Addressing the multiplexing problem, we propose a novel interface, FlashAllocate (FlashAlloc in short), which is used to pass the
host semantic about object’s logical address range to the flash storage and thus to enlighten the storage to be object-aware in handling writes. To be concrete, after creating an object, a data store calls FlashAlloc with the object’s local address range as a parameter to inform the flash device that the address range belongs to the same object. Then, upon receiving FlashAlloc, the flash device creates a corresponding FlashAlloc (FA in short) instance, which keeps the given range information and thus is now aware of the address range of the object. At the same time, the flash device will secure physical flash block(s) where to place writes from the object and dedicate those blocks to the FA instance. Hereafter, the logical address range of an FlashAlloc call has its corresponding physical space. For each write request, flash storage probes its matching FA instance, if it exists, using the starting LBA address of the request and then stream the write to the dedicated blocks for the FA instance.

Once logical objects are FlashAlloc-ed, their writes will be, as illustrated in the right bottom of Figure 1, de-multiplexed into per-object dedicated flash blocks. In this regard, we say that flash storage, enlightened by FlashAlloc, can stream writes by objects. The write streaming by objects is a natural way to achieve grouping data by deathtime [14] because logical objects have different deathtimes while all pages of an object become dead together at once upon the object destruction. Thus, the ultimate benefit of streaming writes by objects is to avoid GC-induced write amplification. For instance, as each SSTable file is deleted in Figure 1, all its pages are invalidated, and thus, its dedicated block can be erased in its entirety, not causing any page relocation. In summary, FlashAlloc provides an alternative in controlling the physical placement of writes inside flash devices: it enables to de-multiplex logical objects into the different flash block(s) just resorting to the already-existing host-side object semantic and thus without introducing other intermediate concepts such as stream-id or zone-id [3, 17].

Whilst effectively de-multiplexing objects with sequential write-once pattern, FlashAlloc is not a panacea for the write amplification problem. In particular, FlashAlloc is not intended to be used for objects with random overwrites (e.g., relational database’s tablespace under OLTP workload). For non-FlashAlloc-ed objects, their data will be stored in non-FA instance and managed by the conventional FTL. In this way, flash storage supporting FlashAlloc can support two types of objects, objects with sequential writes and objects with random overwrite, concurrently. In this respect, FlashAlloc is in stark contrast with the Zoned Name Space (ZNS) interface, which forces applications to follow the strict sequential write rule [3].

The main contributions of this paper are summarized below.

- We make an observation that data stores with flash-friendly write amplification, contrary to the common belief, experience severe write amplification on conventional SSDs and investigate the write multiplexing as the main culprit for the problem. We also show that the write multiplexing makes multi-tenants interfere with each other.
- We motivate that existing flash devices are object-oblivious simply because the host semantic about the object’s logical address range cannot cross the storage interface wall.
- Based on this motivation, we propose a new interface, FlashAlloc, which allows to offload the host semantic about object’s logical address range to the storage and thus to enlighten flash device to be able to stream writes by objects, reducing device-level write amplification. We also suggest an extended design of page-mapping FTL to support FlashAlloc.
- The abstraction used in FlashAlloc is so simple and intuitive that existing software stacks can realize the write streaming by objects with minimal change in its codebase.
- We have prototyped FlashAlloc using the Cosmos open-source SSD. Our experimental results show that FlashAlloc can reduce WAFs in RocksDB, F2FS, and MySQL by 1.5, 2.5, and 0.3, respectively, and accordingly improve throughput by 2x, 1.8x, and 1.2x, respectively. In particular, when RocksDB and MySQL are run together, FlashAlloc can reduce WAF from 4.2 to 2.5, and doubled their throughputs.

FlashAlloc is similar to the trim command [34]: both aim at reducing write amplification by hinting flash device about host semantics (i.e., logical address range allocated upon object creation and staled upon object deletion, respectively). Interestingly, when used together, they are synergistic to reduce write amplification further. Meanwhile, the FlashAlloc interface might not be such novel considering there already exists a write streaming interface, MS-SSD [17]. Unlike MS-SSD resorting to the stream-id concept, we can stream writes simply by calling FlashAlloc after object creation. Thus, developers are free from the burdens of determining the proper number of streams, grouping objects into limited streams, and assigning stream-id to every write call. Also, FlashAlloc will not incur the stream-id conflict among multi-tenants. In this sense, FlashAlloc is a simpler and more advanced abstraction than MS-SSD, enabling transparent write streaming.

2 BACKGROUND AND MOTIVATION

This section reviews several key concepts about flash storage, presents a few motivating examples about write amplification in flash-friendly data stores, and makes a problem statement on why flash storage is object-oblivious.

2.1 Flash Memory SSD

Here we review how the existing flash storage works and explain two key concepts of page deathtime and stream write by time.

FTL An FTL (Flash Translation Layer) is responsible for several key functionalities such as address mapping, GC and wear level management [23]. Because overwrites are not allowed in flash memory, a new page writes should be handled in an out of place manner (i.e., log-structured) - the old version of the page will be marked as invalid and new version will be stored in a new clean flash page. Thus, FTL has to manage the ever-changing address mapping between each page’s logical address at the file system layer and its physical address in flash memory chips. Since the address mapping scheme is critical to the performance and lifespan of flash storages, most flash storage prefers the page-mapping FTL scheme among numerous address mapping schemes, mainly for performance reason at the cost of memory resource for managing the logical-to-physical mapping at the page granularity [13, 18, 23].

Garbage Collection When clean space for new writes runs out, FTL has to reclaim new clean space by the garbage collection (GC in short) procedure. Upon GC, a victim block \(V\) is chosen, then its valid pages are relocated to a clean block \(B\) (i.e., valid pages
are read out from V and written back to B), and then V is erased and returned to the free block pool. After GC, new writes from the host will be appended to the remaining space in B. Relocating valid pages during GC amplifies physical writes inside flash storage. Informally, write amplification factor (WAF) represents the ratio of physical writes to flash memory over logical writes from the host.

**Page Deathtime** When a page copy in flash block is overwritten by new write or discarded by the trim command, the old copy is said to be dead. And the point of time it becomes invalidated is called as its deathtime [14]. The distribution of deathtimes of pages in flash blocks is critical to determining the write amplification. For instance, let us assume that a flash block fb1 stores only data pages from the same SSTable in RocksDB. All the pages in fb1 will be dead when the SSTable is deleted after compaction. Then, the GC procedure can secure a new clean block without relocating any page but simply by erasing fb1, incurring no write amplification. In contrast, when a flash block stores pages with quite distant deathtimes and later is chosen as a victim for GC, many valid pages should be relocated to another block. Therefore, grouping pages by deathtimes is paramount to reducing write amplification.

**Stream-Writes-by-Time** Consider how today’s flash storage handles writes when concurrent write requests from different objects interleave. For each write request with logical address (i.e., start_iba), the existing flash storage cannot distinguish the object the data belongs to. Therefore, the conventional object-oblivious flash storage will simply append writes from different objects in their arrival order at the clean flash memory space [4]; we call this write policy as stream-writes-by-time.

### 2.2 Motivation

It has long been believed that sequential writes are flash-friendly: less harmful than random writes in terms of write amplification [26]. With this expectation in mind, sequential writes have been opted for by many data stores such as LSM (log-structured merge) tree-based KV (key-value) stores [8, 12, 17, 27] and F2FS (Flash-Friendly File System) [20] which is a variant of log-structured file system [32].

Contrary to the belief, however, log-structured sequential writes at such flash-friendly software stacks are not effective in reducing write amplification. In reality, our experimental results below will clearly reveal that such sequential writes are as harmful as random ones (e.g., OLTP workloads on RDBMS) in terms of WAF in flash storage. Similar observations have been made consistently across different software stacks [7, 14, 36, 39], albeit they did not explain the reasons.

In this section, we demonstrate that two data stores, RocksDB and F2FS with the so-called flash-friendly write patterns, suffer from severe write amplification. We also motivate a write multiplexing problem in MySQL. In addition, we point out that two tenants of RocksDB and MySQL interfere each other and thus exacerbate the write amplification further. While running each workload on top of a commercial SSD of 256GB, we measured its throughput and also the running WAF at the device-level using smartmontools [35] and present the results in Figure 2. The figure clearly shows that WAFs increase over time across all cases, and application throughput inversely proportional degrade. In particular, it is noteworthy that WAF values in RocksDB and F2FS with sequential writes are no less than that in MySQL with random writes. Below, for each workload, in turn, we describe the experimental setting and explain its IO architecture and dominant write patterns. In particular, we elaborate on why they experience severe device-level WAF despite their flash-friendly write patterns.

#### RocksDB (Figure 2(a))
RocksDB is a popular KV store used in many large-scale data services as well as databases [8, 9]. Since it uses Log-Structured-Merge (LSM) tree [27] as the primary data structure, the dominant write pattern from RocksDB is sequential in the unit of SSTable (Single Sorted Tables). Upon memtable flush or compaction, RocksDB creates new SSTable file(s), allocates a logical space of (by default) 64MB to each file via the allocate() call, writes data, and then flushes the file. SSTables will be later deleted after compaction; all pages of an SSTable will be invalidated together upon the file deletion. Note that SSTable files which are created and populated simultaneously will be compacted and deleted at different points of time. Using the sequential batch write for each SSTable, RocksDB expects pages from the same SSTable and thus with the same deathtime to collocate in the same flash blocks and thus to barely cause write amplification.

To verify the WAF problem in RocksDB, we ran four RocksDB instances with db_bench’s f11r random workload on Ext4 file system until the commercial SSD was full. Each RocksDB instance has four concurrent user threads and uses four concurrent compaction threads to utilize storage better and thus mitigate the compaction overhead [9]. In addition, the discard option was enabled while mounting Ext4. While running the workload, we measured the average OPS (Operations Per Second) of four benchmarks and also running WAFs of the SSD in every five minutes, and plot the result in Figure 2(a). To our surprise, the WAF has continued to soar over time, ending around five. Note that the WAF value of five is even greater than that observed in OLTP workloads with random writes [18]. This unexpected result about flash-unfriendly RocksDB has been reported consistently by other researchers [7, 36, 39]. All other LSM tree-based KV stores will we believe experience the same WAF problem [12, 17].

Consider why RocksDB suffers from high WAF. Though each SSTable file is sequentially written, four compaction threads will flush their SSTables concurrently. In addition, each flush of 64MB SSTable file tends to split into smaller write requests due to file system fragmentation and kernel IO scheduling [5, 37]. Thus, write requests from multiple SSTables will interleave at the flash storage, and they are handled according to the stream-writes-by-time policy. Further, the striped architecture will divide each write request into smaller write chunks (e.g., 4KB) and distribute them over multiple channels [16, 19, 30]. As a result, pages from multiple SSTables being flushed concurrently tend to be stored together in the same flash blocks. Recalling that SSTables have distinct deathtimes, the multiplexing will incur write amplification.

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1. We refer to technical note from vendor [25] which describes how to measure the write amplification factor for client SSDs using the Self-Monitoring, Analysis, and Reporting Technology (SMART) attributes.
F2FS (Figure 2(b)) F2FS aims at reducing write amplification by taking log-structured writes [20]. In F2FS, a segment is a basic unit of management and, the whole storage volume is divided into fixed-size segments (by default 2MB). To turn random writes into sequential ones, F2FS basically builds on append-only logging to segments. That is, it appends new page write to one of six active segments depending on the page’s hotness. Hence, the write pattern in F2FS can be characterized as multi-head logging [20]: writes are concurrently made against six segments while write to each segment is append-only logging. When an active segment is filled up, the segment becomes inactive and a new segment becomes active. The old inactive segment will be later chosen as a victim for garbage collection and be cleansed [32]. Upon a segment cleansing, all logically valid pages will be relocated to a new segment and the old segment is returned as free segment. Note that all pages in a segment have the same dealtime because they are discarded altogether when the segment is cleansed.

To validate how WAF in F2FS varies, we measured OPS and device-level WAF while running the same four RocksDB instances used for Figure 2(a) on F2FS, and present the result in Figure 2(b). The device-level WAF became quite high (i.e., greater than 8) around the mid-phase of the experiment. Considering that the log-structured file system itself incurs logical write amplification [32, 39], it is not surprising to see that the average ops of four RocksDB instances was lower than that on Ext4 (i.e., Figure 2(a)). Other recent studies have also reported the device-level WAF issue when running F2FS on top of flash storage [36, 39]. Interestingly, the authors of F2FS acknowledged that its multi-head logging could mix pages from multiple active segments into the same flash block [20]. Thus, considering that segments are cleansed at different points of time, pages with different dealtimes are multiplexed in the same flash blocks. This is the reason F2FS experiences such high WAF.

MySQL (Figure 2(c)) In order to guarantee the write atomicity in the presence of crashes, MySQL takes the redundant journaling approach using the special object, called double write buffer (DWB in short): before flushing dirty pages to their original locations, InnoDB engine first appends them sequentially to DWB. On system booting, contiguous logical address space of 2 MB is allocated to DWB. Though tiny in capacity, DWB will account for half of the writes in InnoDB to the storage. When full, the DWB space will be reused from the beginning. Therefore, the write pattern to DWB can be characterized as sequentially appended and cyclically reused.

In addition, the pages written to DWB in the previous cycle will be quickly overwritten in the next cycle. Namely, the DWB object has short lifetime and its pages written during the same cycle will have almost the same dealtime.

Another characteristics in InnoDB engine’s write pattern is that sequential writes to DWB and random writes to original database locations will interleaver at the storage. Thus, in the case of flash storage, according to the stream-writes-by-time policy, both types of data with different dealtimes will collocate in the same flash blocks, thus adversely affecting WAF. To confirm this, we measured TPS and running WAF while running the TPC-C benchmark [21] with 32 client threads and initial database of 150GB (i.e., 1,500 warehouses) on Ext4 file system until the SSD is full, and present the result in Figure 2(c). As shown in the figure, the WAF has steadily worsened over time and accordingly the transaction throughput (TPS) has dropped continuously. The multiplexing of DWB pages and normal data pages on the same flash blocks is believed to contribute to the WAF in part, though not all. According to our experience [6, 29], we can lower write amplification moderately by separating normal and DWB writes into different flash blocks.

Multi-tenant Databases (Figure 2(d)) With the ever-growing capacity of SSDs, it is not uncommon for multiple databases to share a single large SSD, which is particularly true for the cloud environment [22]. In multi-tenant workloads, as different tenants concurrently issue writes for their own objects, pages from more objects with further distant dealtimes are likely to be multiplexed onto the same flash blocks. Thus, the write amplification would be worse than that when each tenant was run alone, which is undesirable in guaranteeing performance isolation among tenants [1].

To verify how the device-level WAF behaves under multi-tenant databases, we ran db_bench and TPC-C together on the commercial SSD. While running both benchmarks with initial database of 80GB until the SSD became full, we measured their throughputs and device-level WAF, and presented the result in Figure 2(d). By comparing WAF and throughput in the figure with those in Figure 2(a) and 2(c), we confirm that the WAF over time in multi-tenant case are much higher (i.e., almost double) than that when each tenant was run alone. Also, note that as the WAF spikes at the initial phase during the multi-tenant experiment, both OPS and TPS drop more rapidly than the throughput in either single tenant. To sum up, the write multiplexing among multi-tenants will exacerbate the write amplification and thus worsen their performance interference.

![Figure 2: Four Realistic Workloads on a Commercial SSD: WAF and Throughput](image-url)
In this subsection, we have demonstrated that, despite flash-friendly write patterns, database engines and file systems still suffer from high write amplification which is comparable to or even greater than that in OLTP workloads. Though only three data stores are used to illustrate the multiplexing problem, the problem is we believe ubiquitous: to name a few, SQLite’s RBJ or WAL journal, Ext4’s journal area, and temporary files generated in Spark/Map-reduce applications or during join processing in relational databases.

2.3 Object Characteristics in Data Stores

Understanding workloads is essential to storage system design. However, little work has been conducted on characterizing objects in popular data stores from the perspective of the write multiplexing in flash storage. In this section, we make three observations about object characteristics in flash-friendly data stores: logical space allocation, write pattern, and deathtime. The design of FlashAlloc capitalizes on these characteristics.

Eager Logical Space Allocation

The host data stores manage data using logical objects such as RocksDB’s SSTables, F2FS’s segments and InnoDB’s DWB. Each store will invoke the write system calls against such logical objects and those objects account for a dominant portion of total I/O in the store. To each logical object, data stores will allocate its logical address space at the file system layer in advance before writing data to the object. For instance, RocksDB calls the `fallocate()` call prior to writing any data to a newly created SSTable. Hence, the logical address range per each SSTable is statically determined before writes are made to the object. In this regard, we say that host-side stores know the relationship between objects and their logical address ranges and also stream writes by objects.

Write Pattern

The logical write pattern to each object can be characterized as sequential (in either batch or append). During flushing memtable in RocksDB, a write system call is made against L0 SSTable with memtable data as parameter, which we call batch sequential write. And, SSTables generated during the compaction in RocksDB will also be populated by batch sequential write. Meanwhile, the write pattern to individual segments in F2FS and DWB in InnoDB will be appended sequential write. It should be noted, however, that every data store usually armed with multiple write threads will issue writes from multiple objects concurrently to the storage. For example, RocksDB has by default four background compaction threads and F2FS employs multi-head logging for six active segments. Therefore, even though the write pattern to individual logical objects is sequential, writes from different objects will interleave each other to the underlying storage.

Deathtime

All pages of each individual object become dead together upon the object’s deletion. For instance, when an SSTable is deleted upon compaction in RocksDB, all its pages will be invalidated. Likewise, upon a segment cleaning in F2FS, all its log pages will be discarded. Meanwhile, different objects will, though created at the same time, have different deathtimes. For example, two SSTables concurrently generated at different levels by two compaction threads are likely to compacted at quite distant points of time. The similar argument can be made with segments in F2FS, which were active together but cleansed at different times.

2.4 Problem Statement

Multiplexing

The characteristics of object deathtime discussed above can bring to flash storage the chance of realizing stream-write-by-deathtime and avoiding write amplification. That is, given that pages from the same object tend to have the same deathtimes and objects differ in their deathtimes, once flash storage can stream pages from different objects into per-object dedicated flash blocks, its effect is to stream writes by deathtimes. However, despite the eager logical space allocation by objects and log-structured sequential write to individual object in flash-friendly data stores, concurrent writes from different objects in single or multiple tenants will interleave to the flash storage. Thus, according to the stream-writes-by-time policy, the existing flash storage will pair those writes in their arrival order into flash blocks. An undesirable consequence is that pages from different objects are packed onto the same flash blocks.

We call this phenomenon as multiplexing. As flash blocks are multiplexed with pages with different deathtimes, write amplification is inevitable. For example, consider the case where four SSTable files are multiplexed (left-bottom in Figure 1). When the SSTable1 file is deleted, each of the four flash blocks still keeps three valid pages. Thus, if a block becomes victim, three pages have to be relocated. In contrast, when four files are de-multiplexed into different files (right-bottom in Figure 1), a flash block with all pages invalidated is available. Thus, a clean block can be obtained without relocating any page.

Missing interface

Consider why existing flash devices should be object-oblivious in handling writes and thus incur the multiplexing problem. The main reason is that, from the logical address in a write request, flash storage can not distinguish the logical object the address belongs to. This is in turn because the conventional block interfaces do not provide any mechanism to pass the relationship between objects and their logical address ranges to the storage. That is, while the host software stacks are aware of the relationship, the valuable semantic cannot cross the storage interface wall but is simply discarded. In this sense, we say that a crucial semantic interface is missing which can make flash storage object-aware. Note that the absence of such useful interface is due to the legacy that the existing storage interfaces have been developed assuming harddisk. In the case of harddisk where overwrites are allowed, logical space allocation via the `fallocate()` call at the file system layer implicitly indicates physical space allocation at the storage. Thus, writes from the host will go to their corresponding physical location simply according to their `start`_lbas: harddisk is object-aware in handling writes without any hint from the host. For this reason, no storage interface was in need, which can pass the host semantic about object’s address range to the storage. This unwritten contract fails on SSDs where overwrites are not allowed.

3 DESIGN OF FLASHALLOC

In this section we propose new interface for flash storage, called FlashAlloc, and presents its design principles, semantics, and architecture. In addition, we explain its use cases and benefits.
3.1 Key Idea and Design Principles
As discussed in Section 2, grouping data by deathtime is effective in reducing write amplification [14]. Considering that pages of individual object have the same deathtime while different objects have different deathtimes, grouping data by objects will have the effect of grouping data by deathtime. However, as pointed out in Section 2.4, the existing flash devices can not group writes by objects simply because they are unaware of the relationship between objects and their logical address ranges. This is, in turn, because no interface exists to allow host to convey the semantic to the flash storage.

Recognizing the missing interface, we introduce a new interface, FlashAlloc, to hint flash devices about the host-side semantic that all pages in a logical address range belong to the same logical object. With the help of the simple hint, flash devices should be able to place writes into distinct flash blocks by objects. The design objectives of FlashAlloc are threefold. First, it takes advantage of the existing concept at the host layer, per-object logical address range. This is in stark contrast with other approaches (e.g., multi-stream SSD and ZNS [3, 17]) which introduce new concepts (e.g., stream-id and zone-id) and thus force applications to adapt to their interfaces. Second, host-side data stores should be able to leverage FlashAlloc with minimal change. In particular, required changes, if any, must be limited to the use of abstraction provided by FlashAlloc. Third, FlashAlloc aims at passing the host semantic to the storage without being limited to any specific application domain. So the abstractions of FlashAlloc must introduce minimal changes to the standards such as NVMe and the changes must not disrupt existing applications. This approach is novel in that it turns the common knowledge at host (i.e., a logical address range constitutes an object) into a strong point for flash storage (i.e., to be able to stream writes by objects).

3.2 Interface
As a way to pass the information that a logical address range constitutes an object from the host to the flash storage, we propose new FlashAlloc(logical_addr_range) interface, as detailed below.

FlashAlloc ((LBA, LENGTH)* \( ^1 \)) FlashAlloc informs flash storage that the logical address range parameter denoted by the range, \( \{ \text{LBA}, \ \text{LENGTH} \}^* \), belongs to one object. As indicated by *, an address range can consist of one or multiple logical chunks. Recall that an object may consist of multiple chunks because of the file system fragmentation [37]. Each chunk is presented by a pair of LBA and LENGTH which represent its starting address and length, respectively, and chunks should not be either continuous or overlapping.

Since the storage command is not always available to applications (e.g., database engines) that access objects through a file system, we exploited the iocctl infrastructure so that the FlashAlloc command can pass through the file system to the storage device, instead of invoking the new command directly from applications.

More importantly, calling a FlashAlloc command, the host expresses its intention that it will perform operations on the given logical address range, \( \text{LS} \), as an integral unit for writes: once a portion of the dataset is written, all the dataset is going to be written once, and later they will be invalidated together nearly at the same time. This is a useful hint for write optimization in flash storage. Upon receiving a FlashAlloc command, flash storage will dedicate the corresponding physical flash block(s) (\( \text{PS} \)). Then, flash storage will store all writes from \( \text{LS} \) in the arrival order into \( \text{PS} \). In this way, flash storage will guarantee the physical clustering of all pages from the same logical object. In particular, note that even when the writes from an FlashAlloc-ed object are spatially fragmented (e.g., due to file system aging [37]) or temporarily split (e.g., due to log-appending in F2FS), they are guaranteed to be eventually clustered into the same flash block(s). Thus, when properly FlashAlloc-ed, concurrent write streams from different logical objects will be de-multiplexed into each own dedicated flash block. Recalling the object deathtime characteristics that objects tend to be dead at different times while pages in each object are invalidated at the same time, the physical clustering by logical objects will have the effect of stream-write-by-deathtime, thus minimizing write amplification. The beauty of FlashAlloc lies in that it can achieve the transparent write streaming without the hassle of assigning stream-id or zone-id to each write request [3, 17].

Use Cases As illustrated in Figure 3, popular database engines and file systems have write-intensive objects (e.g., SSTable, DWB, segment) whose IO patterns fit well with the purpose of FlashAlloc: each object is written sequentially just once and later becomes dead in its entirety at the same or similar time. In addition, objects with such “write-once and dead-at-once” pattern are ubiquitous in most data stores: numerous LSM-based KV stores, WAL log files in relational databases, two journaling modes (RB and WAL) in SQLite, and file system journaling. In addition, FlashAlloc will naturally stream writes from different tenants so that it is, as demonstrated in Section 5, quite beneficial in reducing write amplification and performance interference in multi-tenant database environments [1]. Meanwhile, FlashAlloc is not a panacea for write amplification problem in flash storage. In particular, FlashAlloc would be inappropriate for objects with random overwrites (e.g., OLTP tablespace). Thus, data from such objects can be better handled, as discussed below, using conventional FTL techniques.

3.3 Architecture
Figure 3 illustrates the architecture of FlashAlloc. Using the figure, we explain the concept of FlashAlloc instance and its physical space management. Also, we explain how write and read operations work and describe how the logic of trim and garbage collection is extended to support FlashAlloc. Though the page-mapping FTL is assumed throughout this paper, FlashAlloc can be seamlessly supported by other FTL schemes such as block and hybrid mappings [23].

FlashAlloc Instance Upon receiving a FlashAlloc command with a logical address range, flash storage will create its corresponding FlashAlloc instance (in short, FA instance). In addition, flash storage will secure the corresponding physical space (i.e., one or more clean flash memory blocks whose total size amounts to the given logical address range’s size), and dedicate the space to the instance\(^1\). The physical space to an FA instance is allocated in the

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\(^1\)For the simplicity of discussion, we assume synchronous physical space allocation throughout this paper. Note, however, that the FlashAlloc interface does not mandate synchronous allocation. Instead, as long as the physical space is secured prior to the first write to the instance, either asynchronous or even on-demand physical space allocation
Enlightening Flash Storage to Stream Writes by Objects

Figure 3: FlashAlloc Architecture

unit of flash memory block (e.g., usually 2MB in flash memory chips) so as to isolate writes from the instance into the dedicated blocks. Though we assume flash memory block as the unit of physical space allocation for the simplicity of discussion, we do not exclude the case where two or more FA instances can share one physical flash block, when their logical address sizes are less than the size of a flash memory block. We would like to stress that, even when a flash memory block is shared by two or more FA instances, it is always beneficial to cluster pages from one logical object into the same physical flash block and thus to prevent them from scattering over different flash blocks. The dedicated blocks for FA instances are called as FlashAlloc-ed. Once multiple blocks are allocated to an instance, data for the instance will be striped across channels for better bandwidth [19]. As illustrated in Figure 3, an FA instance consists of three metadata: logical address range, physical flash blocks, and physical location for next write. Next write for an FA instance will be appended to the page pointed by next_write_ptr.

Active FA Instances Once created, every FA instance and its metadata will remain active and also be managed persistently until its destruction. An FA instance and its metadata will be destructed once its physical space is filled up. As depicted in Figure 3, multiple FA instances could be active at a point of time. Note that the logical address ranges of all instances should be disjoint from each other. Meanwhile, the number of active FA instances will remain rather small in practice, though unlimited in principle. For instance, considering that an SSTable file in RocksDB is, once created, quickly filled by memtable flushing or compaction, its FA instance will be destructed shortly after created. Thus, when running a RocksDB, the number of active FA instances will not be greater than that of concurrent compaction threads (i.e., four by default). Similar argument can be made for F2FS segments.

Non-FlashAlloc-ed Objects While good for objects with sequential or log-appending write patterns, FlashAlloc is not intended for objects with random write pattern. For the latter type of objects, FlashAlloc is not recommended to be called. Thus, flash devices supporting FlashAlloc are desirable to be able to support such non-FlashAlloc-ed objects as well; writes from non-FlashAlloc-ed objects can be handled same as in the conventional SSD and stored in normal blocks. For this reason, in our FlashAlloc architecture, there are two types of blocks, FlashAlloc-ed and normal, as illustrated in the bottom of Figure 3. In this regard, our approach is in contrast with the ZNS interface which strictly assumes all writes to be sequential and thus cannot support workloads with random writes.

Write For a write request with two parameters, LBA_start and length, indicating the starting LBA and length of the data respectively, flash storage first probes its matching FA instance using the LBA_start, as depicted in Figure 3. If a matching instance is found, the write data will be appended to a FlashAlloc-ed block pointed by the instance’s next_write_ptr, and the corresponding entry in L2P table and next_write_ptr value will be accordingly adjusted. Otherwise, the request comes from non-FlashAlloc-ed objects. In this case, as in the conventional SSDs, the writes will be stored in normal block. In this way, our approach supports two write policies: stream-write-by-object for FlashAlloc-ed objects and stream-write-by-time for normal writes.
**Read**  While FlashAlloc aims at reducing WAF by controlling the placement of writes into different blocks by objects, its read operation will proceed exactly same as in the conventional page-mapping FTLs: after looking up the physical page number (i.e., block-id + page-offset) from the mapping table with the given LBA address, FTL reads out the page from the corresponding flash block.

**Trim**  The trim command was introduced to notify the flash storage that a set of logical pages is no longer valid. Upon receiving a trim command, flash storage will invalidate the relevant pages, preventing them from being unnecessarily relocated. In our FlashAlloc architecture, the trim command will be handled same as in the conventional flash storage with one exception. Considering that pages in an FlashAlloc-ed object have the same deathtime and are also clustered in the same physical flash block(s), the trim command against the object can complete by erasing the block(s) instead of invalidating individual pages. In this sense, FlashAlloc enables to achieve nearly zero-overhead trim. In fact, the trim command is, though effective in lowering write amplification, known to induce non-trivial run-time overhead (e.g., trim spikes [9]).

**Garbage Collection (GC)**  When no space is available for new writes, FTL has to conduct the GC operation: copying valid pages from a victim block to a clean block, fb and then returning fb. Unfortunately, the conventional GC algorithm returning a partially clean block fb is inappropriate for FA instances. Recalling that FlashAlloc intends to disallow pages from different objects to mix in the same flash block(s), each FA instance needs total-clean block(s). Thus, FTL has to handle two cases of GC differently. The first case is when FlashAlloc is called, and the second one is when free space is unavailable for normal write. Recall that when a FlashAlloc-ed object is trimmed, all its blocks will be returned as free and thus the free block pool is likely to have some free blocks. In the case when GC is triggered for normal write, FTL will first check the free block pool for a free block and, if found, use it. Otherwise, it will carry out the conventional GC: it chooses a victim block with the least valid pages and merges the victim. In the second case, when a FlashAlloc call is made, FTL checks whether clean blocks are available in the free block pool and, when unavailable, has to merge multiple blocks to secure total-clean block(s) [18].

In addition, while selecting victim blocks for each of two GC cases, block types have to be taken into account so that pages from normal blocks are not mixed with those from FlashAlloc-ed blocks. In the case of GC for normal writes, only normal blocks can be victims. Otherwise, once an FlashAlloc-ed block is chosen as victim, non-FlashAlloc-ed normal writes should co-locate with the relocated pages from the old FlashAlloc-ed victim block. In the case of GC for FlashAlloc, as discussed above, multiple blocks have to be merged to secure total-clean block(s) for FlashAlloc. In this case, those multiple blocks should have the same type. In this sense, we call our algorithm as GC-By-Block-Types. Interestingly, the GC-By-Block-Types algorithm will adaptively allocate the space of FlashAlloc-ed and normal blocks: depending on victim block type, one region grows while the other shrinks. For instance, if a new FlashAlloc block is in need and no free block is available, multiple normal blocks have to be merged so as to secure a total-clean block, enlarging FlashAlloc-ed region. In this way, the space allocation to both regions will adapt to the changing workloads, requiring no static allocation or tuning.

### 3.4 Advantages

To the best of our knowledge, FlashAlloc is the first work which allows host applications to hint the storage that a logical address range belongs to the same object. The advantages of FlashAlloc are threefold. First, enlightened by FlashAlloc, flash storage can now cluster data from the same object and thus with the same deathtime into the same physical flash blocks, thus minimizing write amplification. In particular, data from objects which are even 

logically fragmented will be physically de-fragmented into the same flash block(s). In this regard, FlashAlloc could be a clean solution to the logical and physical fragmentation problem in flash storage [33, 36]. Second, since the abstraction used in FlashAlloc complies to the popular abstractions (e.g., `fallocate` call and segment in F2FS), the existing software stacks can achieve write streaming with minimal code changes, as detailed in Section 4.

Third, since the FlashAlloc semantic is simple and does not require involving intermediate layers such as the kernel block layer, it is easy to incorporate the command into the existing storage interface standards such as SATA, SAS and NVMe (e.g., using the vendor specific command).

### 4 IMPLEMENTATION

This section presents the implementation details of the FlashAlloc architecture. The dominant portion of the FlashAlloc implementation is made into the FTL firmware of the Cosmos development board by cross-compiling the source code written in C. The FlashAlloc command was prototyped via vendor unique command. A user-level library that implements a protocol for the new commands via the ioct1 system call supports applications and SSDs. This approach not only allows to quickly prototype the concept in a development environment but also to make the prototype portable to most file systems. In addition, this section describes the changes we made in file systems and database engines to enable them to run on the FlashAlloc interface. Note that the changes are, as summarized in Table 1, marginal and moreover local to a few modules.

#### 4.1 Changes made in F2FS

While initializing a file system volume, F2FS divides the whole volume into fixed-size segments. The segment is a basic unit of management in F2FS: it allocates storage pages in the unit of segments and also performs “cleaning” in the unit of segment. F2FS maintains multiple active segments (by default, six segments). To stream writes by active segments inside flash storage, F2FS is modified to obtain, whenever a segment becomes active, its logical address range using the super block data structure (i.e., `f2fs sb_info`) and segment number information and then to call FlashAlloc with the range as parameter. For this, only 26 lines were added to the segment-allocation module. Like in Ext4, the FlashAlloc-ed block
We have prototyped FlashAlloc on the OpenSSD Cosmos board [19] by extending its firmware. The Cosmos board is an SSD development platform that is made publicly available by the OpenSSD Project to promote research and education. The board employs the HYU Tiger 4 controller based on Dual-Core ARM Cortex-A9 on top of Xilinx Zynq-7000 board, and 16GB MLC Nand flash memory. Thus it has the same performance characteristics as a commercial SSD equipped with the Barefoot controller. The Cosmos board adopts a page mapping scheme for flash memory management, as in most contemporary SSD products. The board is connected to a host system through the NVMe interface. Main technical issues encountered while embodying FlashAlloc on the board are summarized below. Note that the existing FTL can support FlashAlloc with moderate changes in its codebase, as shown in Table 1.

| Applications       | Lines Added | Lines Removed |
|--------------------|-------------|---------------|
| RocksDB (v6.10)    | 72          | -             |
| MySQL/InnoDB (v5.7)| 74          | 16            |
| F2FS (v3.4.20)     | 26          | -             |
| FTL (cosmos+) (v3.0.0)| 1683      | 193           |

for a segment will be erased in their entireties when the trim command is automatically called for the segment upon its cleansing.

4.2 Changes made in Applications

RocksDB. As explained in Section 2, RocksDB manages key-value documents using SSTables. In particular, after creating each SSTable file, RocksDB secures its logical address space (whose size is by default 64MB) in advance by calling fallocate() for the file. Once allocating the logical space for the given fallocate() call, RocksDB engine calls FlashAlloc. For this reason, every SSTable’s data will be streamed to its dedicated flash block(s). Flash blocks dedicated to each SSTable remain full of valid pages until the SSTable is later compacted and deleted. When an SSTable is deleted, all its pages will be trimmed and thus invalidated altogether at once and accordingly all flash blocks dedicated for the SSTable can be simply erased, thus causing no write amplification. Hence, as shown in Section 5, RocksDB can achieve near ideal WAF (i.e., 1) transparently with minimal changes in its codebase.

MySQL/InnoDB. In order to isolate DWB pages from normal ones into different flash blocks and thus to reduce write amplification [6], we modified the InnoDB engine to call FlashAlloc with the logical address range of DWB as parameter before writing to the journal area for the first time. To obtain the address range was used the F5_IOC_FIEMAP ioctl call. Also, whenever DWB is cyclically reused, the trim call is made for the journal area so as to invalidate all the old pages and thus to make the old FlashAlloc-ed block to be erased in its entirety. As shown in Table 1, the changes made in InnoDB engine were minimal - less than 100 lines of code change were made at two modules of double-write-buffer and file.

4.3 Changes made in FTL

We have prototyped FlashAlloc on the OpenSSD Cosmos board [19] by extending its firmware. The Cosmos board is an SSD development platform that is made publicly available by the OpenSSD Project to promote research and education. The board employs the HYU Tiger 4 controller based on Dual-Core ARM Cortex-A9 on top of Xilinx Zynq-7000 board, and 16GB MLC Nand flash memory. Thus it has the same performance characteristics as a commercial SSD equipped with the Barefoot controller. The Cosmos board adopts a page mapping scheme for flash memory management, as in most contemporary SSD products. The board is connected to a host system through the NVMe interface. Main technical issues encountered while embodying FlashAlloc on the board are summarized below. Note that the existing FTL can support FlashAlloc with moderate changes in its codebase, as shown in Table 1.

FA Instances For each FlashAlloc command, a corresponding FA instance is created in Cosmos board’s DRAM, which contains its logical address range, the list of flash blocks dedicated to the instance, and the current write pointer. The memory requirement per instance is, while slightly varying depending on address range and the number of flash blocks, just several tens bytes. Thus, considering that the number of active FA instances is in practice limited (e.g., less than 100), small amount of DRAM (i.e., several tens KB) will suffice to maintain active FA instances.

GC and Block Type The existing GC firmware in the Cosmos board was extended to support the GC-By-Block-Type policy. Also, since FTL need distinguish two types of blocks, normal and FlashAlloc-ed, one bit flag, FA-BLK, was added to the block_header struct in the Cosmos firmware. A block’s FA-BLK flag will be set on dedicating the block to an FA instance and later reset when the block is erased and returned as free.

Probing the matching FA instance For a write request, FTL should be able to quickly probe the matching FA instance using the given LBA address. If the probing fails (i.e., no matching instance exists), the request is not for active FA instance thus will be written to non-FA instance. To determine whether the given write is for active FA instance or not, a flag bit was added to every entry in page-mapping table. The flag bit of every relevant logical page is set when an FlashAlloc command is invoked and later reset when the page is overwritten or discarded. The next issue is, when the flag is turned on, how to probe the matching instance. While there should be alternative implementations such as hardware-acceleration and pipelining, rather a simple approach was taken for fast prototyping. That is, while scanning each of all active FA instances, we check whether its logical address range contains the start_LBA in the given write request. Once a matching instance is found, the write will be appended at the physical space pointed by the next_write_ptr of the instance.

5 PERFORMANCE EVALUATION

In this section, we present performance evaluation carried out to analyze the impact of FlashAlloc on key-value store, log-structured file system, relational database, and multi-tenancy.

5.1 Experimental Setup

All experiments were conducted on a Linux platform with 5.4.20 Kernel running on an Intel Core i7-6700 CPU 3.40GHz processor with two sockets of four cores and 50GB DRAM. The host machine has two storage devices, 16GB Cosmos OpenSSD and 256GB Samsung 850 Pro SSD. The Cosmos OpenSSD employs a controller based on Dual Core ARM Cortex-A9 on top of Xilinx Zynq-7000 board with 256KB SRAM, 1GB DDR3DRAM, and 16GB MLC Nand flash memory [28]. The Cosmos OpenSSD was used as the main storage device for the experimental data and connected to host using PCIe interface. The over-provisioning area in the board was set to 10% (i.e., 1.6GB) for all experiments. The Samsung 850 Pro SSD was used as the log device when MySQL/InnoDB was run.

5.2 Workloads

To demonstrate the benefit of FlashAlloc, we used a synthetic workload and two realistic workloads, db_bench and TPC-C. The fio
tool was used to generate a synthetic workload. And, to evaluate the effect of FlashAlloc on key-value stores, we ran the db_bench benchmark using RocksDB on ext4 file system. The same db_bench workload was run also using F2FS [20] to test the impact of FlashAlloc on log-structured file system. In addition, the TPC-C benchmark was used to measure the effect of separating DWB in MySQL/InnoDB into dedicated flash blocks. Finally, to highlight the benefit of FlashAlloc in multi-tenancy, we ran db_bench using RocksDB and TPC-C using MySQL concurrently on Ext4 file system. In all experiments, the default I/O option (0, DIRECT) was enabled to minimize the interference from file system’s page caching and the TRIM option was turned on for both file system. To compare the performance impact of FlashAlloc, we ran those workloads using the vanilla databases and file systems on the Cosmos board running the original FTL and also ran them using the modified versions with the board supporting FlashAlloc. The three workloads used in the experiments are summarized below.

FIO The Flexible I/O (FIO) benchmark is commonly used to test the performance of file and storage systems [11]. It spawns a number of thread or processes doing a particular type of I/O operations as specified by the user parameters.

db_bench RocksDB provides db_bench as the default benchmark program, consisting of several configurable workloads [10]. The fillrandom workload was used to evaluate the impact of FlashAlloc, which writes key-value pairs in random key order. Each key-value entry was sized to have a key of 16 bytes and a value of 100 bytes. The workload was run against empty database till the Cosmos board became full.

TPC-C The tpcc-mysql tool [31] was used for TPC-C benchmarking [21]. The benchmark was run using 32 clients against initial database of 80 warehouses until no space was left in the storage device.

5.3 Performance Analysis

Let us briefly review the overall performance benefit of FlashAlloc using Figure 4. While running four experiments using vanilla and FlashAlloc-ed configurations, we measured the throughput of each benchmark program and the running WAF at the Cosmos device every minute till no space is left in the Cosmos device, and present the results in Figure 4. In the figure, the X-axis represents the time and the left and right Y-axis does the running WAF and the throughput of each benchmark, respectively. As shown in Figure 4, FlashAlloc-ed version outperforms the vanilla one considerably in terms of throughput as well as WAF consistently across all four experiments. The running WAF gaps between two versions are ever-growing over time in all experiments. That is, as the Cosmos board is filled with data, the effect of de-multiplexing different objects into different blocks in FlashAlloc becomes outstanding. In particular, the running WAF in FlashAlloc-ed version remain close to 1 even at the ends of RocksDB and F2FS experiments.

Synthetic FIO Workload Before explaining the effect of FlashAlloc on realistic workloads in Figure 4, let us show the benefit of FlashAlloc using a synthetic write workload. For this, using the fio tool, we created eight 2GB files on Linux and Cosmos board and ran eight threads, each of which performs random overwrites in the unit of 2MB against its dedicated 2GB file. The same experiments were conducted in two modes, vanilla and FlashAlloc-ed. In the FlashAlloc-ed mode, before invoking each 2MB overwrite, FlashAlloc was called a prior so as to secure a dedicated flash block to store new data. While running each experiment during one hour, we measured the device WAF and the write bandwidth and plotted the result in Figure 5. FlashAlloc has reduced the device WAF from 3.1 to 1 and has doubled the write bandwidth (i.e., approximately from 75MB to 150MB). In addition, to further highlight the effect of FlashAlloc when the multiplexing degree is increased, we carried out another experiment by increasing the number of concurrent write threads to 32 in fio tool and thus decreasing the per-thread file size to 512MB, and present the result in Figure 5. Note that, under more concurrent write threads, a flash block in the Cosmos board will be multiplexed by more files with more deviating life-times. As clearly shown in the figure, FlashAlloc has reduced the device WAF from 4 to 1 and thus has tripled the write bandwidth (i.e., roughly from 60MB to 180MB). The considerable gain in WAF and write bandwidth was direct reflection of reductions in the garbage collection overhead.

RocksDB on EXT4 To analyze the effect of FlashAlloc on RocksDB engine, we ran 4 RocksDB instances concurrently on top of two configurations of ext4 file system and the Cosmos board, vanilla and FlashAlloc-ed. Each RocksDB instance was run with the fillrandom workload in the db_bench benchmark. In order to minimize the interference from flushing the WAL log, the log file was stored in a separate storage device. While running both experiments, we measured device-level WAF and average OPS of four RocksDB instances over time and present the result in Figure 4(a). In the case of vanilla mode, as SSTables at different levels are simultaneously created and populated by multiple compaction threads in RocksDB, they are multiplexed into the same flash blocks. Recall that SSTables at different levels will be compacted and thus deleted at different points of time. For this reason, in the vanilla version, device-level WAF increased steadily while RocksDB’s OPS decreased inverse-proportionally, which is consistent with the result in Figure 2(a). In contrast, in the case of FlashAlloc-ed mode, WAF at the Cosmos board, as expected, remained nearly one even till the end of the experiment and accordingly the average RocksDB’s OPS improved by 1.5x, compared to the vanilla version. This clearly illustrates that FlashAlloc can drastically reduce write amplification in RocksDB by de-multiplexing SSTables into different flash blocks.

Nonetheless, write amplification was not completely removed in FlashAlloc-ed mode. The running WAF was 1.1 at the end of the experiment. The residual physical write amplification is attributable to metadata files. RocksDB maintains several metadata files (e.g., MANIFEST and CURRENT) to keep track of database state changes whose write patterns are not log-structured instead random writes. Though the sizes of those files are relatively small, they contribute non-marginal fraction of total writes from RocksDB. Those random writes go to the non-FA instance which is managed by the conventional Greed FTL and hence incur write amplifications.

Note that the OPS gain by FlashAlloc over vanilla is relatively smaller than the WAF gain. Recalling that OPS is determined by logical write amplification at the RocksDB level as well as device-level
write amplification at the device level, the physical WAF reduction is offset by the same logical write amplification in both modes.

**RocksDBs on F2FS** To evaluate the effect of FlashAlloc on log-structured file systems, we ran four RocksDB instances each with the same f111-random workload used in subsection 5.3 on top of two configurations of F2FS and Cosmos boards, vanilla and FlashAlloc-ed. While concurrent log writes from active segments are multiplexed into the same flash block in the vanilla configuration, writes from each segment is perfectly isolated into its dedicated flash block in the FlashAlloc-ed version. Thus, the FlashAlloc-ed version can nearly remove write amplification due to the write multiplexing in the vanilla version; the WAF at the final phase was reduced from 3.5 to 1.1, as shown in Figure 4(b). The residual WAF of 0.1 in FlashAlloc-ed version is we guess contributed by random writes for hot metadata in F2FS [20]. Accordingly, FlashAlloc-ed version outperforms the vanilla version about by three folds in terms of the db_bench’s TPS at the end of experiment.

The result from F2FS experiment indicates that FlashAlloc can be a fundamental solution to the log-on-log problem [36, 39] by allowing to perfectly align logical segments in higher F2FS with physical blocks in lower flash storage. Namely, FlashAlloc enables F2FS and RocksDB to achieve an ideal WAF of 1 and thus realize the full potential of their flash-friendly log-structured write patterns.

**DWB in MySQL/InnoDB** To evaluate the effect of separating the DBW object with cyclic and sequential writes from the main database with random writes, we measured the throughput and the device-level WAF while running the TPC-C benchmark using the vanilla and FlashAlloc-ed MySQL/InnoDB engines, and present the result in Figure 4(c). Recall that half of writes goes to the FA instance for DBW in the case of FlashAlloc-ed version while the other half (that is, random writes against original database) does to the non-FA instance. Hence, the write amplification induced by the random writes in non-FA instance is inevitable even in the FlashAlloc-ed mode. Though, as shown in Figure 4(c), FlashAlloc can reduce the additional write amplifications by one third (i.e., 1.2 to 0.8) and thus improve the throughput by 50%. We believe that the benefit of FlashAlloc on DBW will hold also on other ubiquitous journal objects including WAL files in RocksDB, SQLite and relational databases and jbd2 in Ext4 file system.

**Multi-Tenancy** As discussed in Section 2, when run together on the same SSD, multi-tenants can interfere each other in terms of write amplification since objects from different tenants with more distant lifetimes are multiplexed in the same flash blocks. To demonstrate the benefit of FlashAlloc in mitigating the WAF interference in multi-tenancy, we ran two databases concurrently on Ext4 file system and the Cosmos board, one RocksDB instance (used in Figure 4(a)) and one MySQL instance (used in Figure 4(c)), in vanilla and FlashAlloc-ed modes, respectively, and present the results in Figure 4(d). In the case of vanilla version, the WAF in multi-tenancy is much worse than that in either single tenant (i.e., Figure 4(a) and Figure 4(c), which is consistent with the result in Figure 2(d) obtained from commercial SSDs. In the case of FlashAlloc-ed version, the WAF in multi-tenancy remains lower than that in either single tenant. As a result, both benchmarks’ throughputs in FlashAlloc-ed mode are considerably higher than in vanilla mode. The result in Figure 4(d) indicates that FlashAlloc is not only beneficial to the calling tenant itself but also altruistic to neighbor tenants and is thus effective in isolating the performance between tenants [1].

6 RELATED WORK

In that FlashAlloc aims at reducing physical WAF by passing the host semantic to flash devices, three interfaces are closely related to it: Trim [34], Multi-stream SSD [17] and Zoned Name Space [3].

**Trim** Even when a file is deleted, the old storage interface (e.g., SATA) provides no mechanism to pass the host semantic about the file deletion and thus flash devices regard pages from the deleted file as still valid and unnecessarily relocate them during GC, causing write amplification. To address this, the trim command was proposed to inform flash devices that page(s) specified by a logical address range are no longer valid (i.e., dead) at the host [34]; the trim-hinted device will not relocate those pages upon GC [2]. FlashAlloc and trim are common in that both explicitly provide flash storages with host-side semantic so as to lower write amplification: FlashAlloc is used to pass the semantic about the logical address
space constituting an object and the FlashAlloc-hinted device will de-multiplex different objects into different blocks. In addition, they are synergetic to each other: when a file is FlashAlloc-ed, the trim command can complete simply by erasing all the FlashAlloc-ed blocks (that is, nearly zero-overhead trim), instead of invalidating all pages individually [15]. Meanwhile, they differ in their invoke time: FlashAlloc is called at object creation while trim is at object deletion. Lastly, let us remark that FlashAlloc and trim are not in need for harddisks: since overwrite are allowed, logical space management implies physical one as well.

**Multi-Stream SSD** A novel interface for flash storages, Multi-Stream SSD (MS-SSD), was proposed and standardized [17, 38], which allows applications to place pages with different lifetimes to different streams (i.e., flash blocks). More specifically, when invoking a write system call, applications can assign a proper stream identifier (i.e., stream-id) for the data being written, and, on receiving the write command with a stream-id, MS-SSD will place the data into the corresponding physical stream. This interface performs effectively when correctly hinted by applications [17].

While both commonly aim at streaming writes to reduce write amplification, MS-SSD and FlashAlloc are in stark contrast in their abstractions for write streaming. The MS-SSD interface has introduced the additional concept of stream-id and mandates applications to statically bind stream-id to each write call. The static binding of stream-id, combined with the limited number of physical streams available in commercial MS-SSDs (e.g., 8), will raise several practical issues. First of all, it is a non-transparent abstraction in that every write call has to come with static stream-id. Next, it would be a non-trivial task for developers to estimate the number of physical streams for their applications and to correctly group numerous objects with different lifetimes into the limited streams. Third, the static stream-id assignment is non-adaptive. As the lifetimes of objects can change over time, programmers need scrutinize those statistics and periodically re-assign stream-ids to objects. Lastly, the effect of write streaming would be useless due to the stream-id conflict in the multi-tenant environment [22]. Different applications which were independently developed might have assigned the same stream-id to their objects. Therefore, different tenants’ objects with quite distant lifetimes might share the same physical stream.

In contrast, FlashAlloc supports the per-object write streaming abstraction, which provides several benefits over MS-SSD. First, it enables transparent write streaming: since it simply requires the logical address range of each object upon object creation, application can achieve write streaming with no or minimal change. Second, since it provides fine-grained per-object streaming, the application developers are free from burdens of managing stream-ids to objects and further need not care about the stream-id conflict in multi-tenant environment. In summary, FlashAlloc is we believe more advanced streaming mechanism than MS-SSD.

**Zoned Name Space** To overcome the write amplification problem in the conventional SSDs with block interface while obviating the need for in-device GC, DRAM resource for page mapping FTL, and the over-provisioned physical space, the system community has recently proposed a new interface for flash storage, ZNS (Zoned Name Space) [3], which exposes zones (a set of logical blocks) to the host as the unit of data management.

Though novel and worth investigating, however, the interface imposes strict write-ordering rules: all writes to zones should be to be sequential and also in their LBA order. In other words, ZNS disallows out-of-LBA-order random writes to each zone. Such strict rules will bring two drawbacks. First, all the software stacks from applications, database engines to file system should be modified to meet the sequential write ordering. A storage interface which mandates the whole software stacks to adapt to it is unlikely to succeed. Second, while exempting from the block interface tax, ZNS instead introduces yet-more-expensive tax of log-structured writes (e.g., compaction in RocksDB and segment cleaning in F2FS). Such operations are known to induce application-level logical WAF of more than 10 [7, 39]. In addition, log-structured write inevitably needs over-provisioned logical space. In contrast, FlashAlloc does not ask the existing software stacks to adapt to it; they can achieve transparent write streaming. Also, flash storage supporting FlashAlloc can support random writes as well simultaneously.

**7 CONCLUSION**

Existing flash devices are object-oblivious in handling writes and thus allow to colocate data from different objects in the same flash block, causing high write amplification. To remedy such write multiplexing problem, we proposed a novel interface, FlashAlloc, which is used to enlighten flash devices to de-multiplex writes from different logical objects into different flash blocks (i.e., object-aware in handling writes), thus minimizing write amplification.

To verify the effect of FlashAlloc, we have prototyped FlashAlloc on a real SSD board by extending its conventional FTL firmware and also modified a set of representative software stacks so as to use the FlashAlloc interface. Experimental results have confirmed that FlashAlloc can enable RocksDB and F2FS to eliminate write amplification, realizing their full potential of flash-friendliness. Also, we have demonstrated that FlashAlloc is effective in mitigating the performance interference between multi-tenant applications.

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