



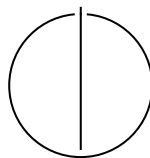
SCHOOL OF COMPUTATION,
INFORMATION AND TECHNOLOGY —
INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Master's Thesis in Informatics

Reducing Write-Amplification in B-trees

Marlene Bargou





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**Reduzierung der Schreib-Verstärkung in
B-Bäumen**

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Submission Date:	03.11.2025



I confirm that this master's thesis is my own work and I have documented all sources and material used.

Munich, 03.11.2025

Marlene Bargou

Acknowledgments

I thank my supervisor, Prof. Thomas Neumann, and Altan Birler for their inspiration, continuous support, and guidance throughout this thesis.

Abstract

B-trees are the most used data structure in modern database systems, due to their efficient access patterns and excellent lookup performance on large volumes of data. However, B-trees perform suboptimally under random writes, a pervasive pattern for secondary indexes. Such workloads introduce write amplification in B-trees, a phenomenon where the amount of data written to storage is significantly larger than that of logically changed data. As a result, B-trees suffer increased latency, reduced throughput, and premature device wear with write-intensive workloads.

An alternative is Log-Structured-Merge-Trees (LSM-trees), which trade off low read performance for high write performance. However, this trade makes LSM-trees unsuitable for generic database systems that require more balanced performance characteristics. Other attempts to reduce write amplification in B-trees either reduce concurrency, impact read performance, or rely on hardware-specific features, limiting their effectiveness and applicability.

This thesis introduces a lightweight buffering layer that minimizes the frequency and volume of write operations to external storage by reducing write amplification. We hereby enable high performance under random writes, while sustaining all the benefits of traditional B-trees.

We implement the proposed structure, evaluate its performance under different workloads, and compare it against state-of-the-art methods. Compared to traditional B-trees, our method achieves up to 70% fewer page writes while maintaining comparable read performance.

These results suggest that write-aware B-tree optimizations can extend the lifespan of storage devices and significantly improve the efficiency of write-intensive applications; contributing to the broader effort of designing storage-efficient data structures suited for modern hardware.

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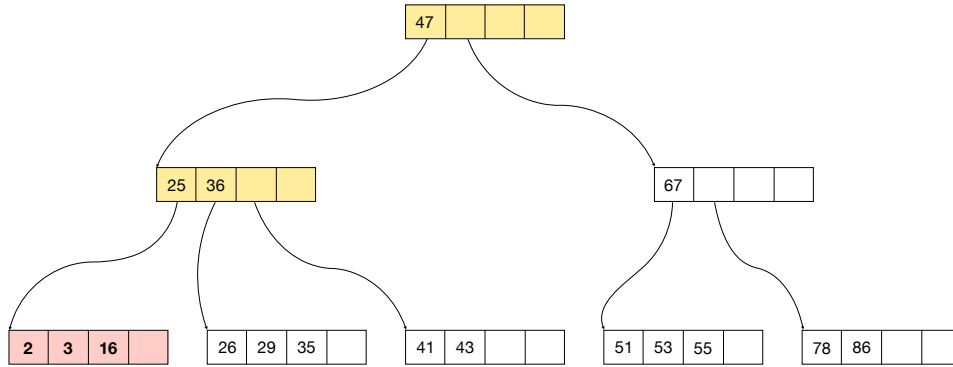
1 Introduction

Efficiently managing large data sets is a core requirement for database systems. Therefore, minimizing Input/Output (I/O) operations remains the fundamental premise for designing modern, high-performance Database Management Systems (DBMS). Primarily, this is done by caching frequently accessed pages in Dynamic Random Access Memory (DRAM) using a buffer manager [16]. The system stores data in pages, which the buffer manager can cache and uniformly serve to all components in the system. This modular design separates concerns between the buffer manager and its users, such as indexes and data structures. However, this also means that the buffer manager is agnostic of user access patterns. While the buffer manager minimizes the number of I/O operations, to the best of its knowledge, every system component must design its access patterns to be as efficient as possible.

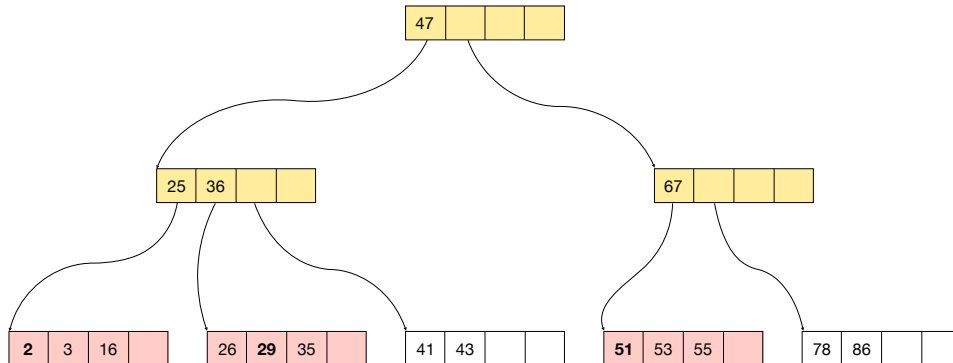
A prominent example of such a component is the B-tree [2]. B-trees are the dominant data structure for indexing large datasets in disk-based DBMS due to their excellent lookup performance, support for range queries, and simplicity. However, random writes, a prevalent pattern for secondary indexes, lead to inefficient access patterns that a buffer manager cannot hide for out-of-memory workloads.

B-trees organize their nodes as pages. Due to their sorted order, accessing random keys leads to random accesses of different pages, which the buffer manager must load into the buffer. At eviction time, each modified page requires a complete rewrite to storage, even if only a small portion of the page has changed. Figure 1.1 illustrates this effect by comparing a B-tree’s sequential and random update patterns. We consider three updates to the tree. In the sequential update, the B-tree reads only three pages and writes to one of them. In the random update, the B-tree reads six pages and writes to three of them. Merely changing the access pattern from sequential to random leads to a threefold increase in the amount of data written to storage. Assuming that each page is 4 KB, the sequential update requires one storage write of 4 KB. The random update requires three storage writes of 12 KB in total. Random writes introduce *write amplification*, a phenomenon where the amount of data written to storage is significantly larger than the amount of data that logically changed.

Write amplification inflates I/O operations, wastes bandwidth, and ultimately increases latency in bandwidth-bound scenarios. For example, in cloud environments, where storage can be remote, an unnecessary network round-trip directly translates to increased



(a) Sequential Access Pattern: Updating keys {2, 3, 16}.



(b) Random Access Pattern: Updating keys {29, 51, 2}.

Figure 1.1: Comparison of access patterns in a B-tree. Written pages are highlighted in red. Read pages are highlighted in yellow.

latency and reduced throughput in the system.

Additionally, the Solid State Drive (SSD) has its own internal write amplification due to its flash translation layer performing garbage collection [12]. This leads to a multiplication of unnecessary physical writes, wearing out the device faster.

In summary, to design a truly efficient, high-performance system, we must minimize I/O operations in all components of the storage stack. This thesis focuses on closing the efficiency gap in B-trees by reducing write amplification.

1.1 Problem Statement

While B-trees are the backbone of indexing in modern storage engines, their in-place updates introduce significant write amplification, leading to performance degradation and reduced device lifespan.

LSM-trees address write costs by always writing sequentially, but they introduce high read amplification and complex tuning requirements, making them unsuitable for general-purpose database systems.

B_e-trees buffer and batch updates starting from the root and propagating them down the tree to reduce write amplification. Firstly, this introduces two searches per node, one for the next pivot and one for a buffered update for the looked-up key. Secondly, the reduced space for pivots in each node reduces the fanout of the tree, leading to taller trees and more I/O operations per lookup. Most importantly, though, it significantly limits concurrency in the data structure, as the hottest nodes are locked for more extended periods of time to write the update messages, reducing throughput in the tree.

We identify a research gap for a B-tree variant that effectively reduces write amplification while preserving the excellent query efficiency and concurrency traits of traditional B-trees.

1.2 Objectives

The primary objective of this thesis is to design, implement, and evaluate a B-tree variant that reduces write amplification while maintaining the high read performance and concurrency of traditional B-trees. We focus on the following research questions:

1. How can we effectively reduce write amplification in B-trees?
2. How can we preserve read performance and concurrency in the presence of write optimizations?

3. How does the proposed approach compare to existing methods regarding write amplification, query performance, and throughput?

While we reflect on significant hardware trends in this thesis, such as the increasing prevalence of SSD, we do not target optimizations for specific hardware features. Instead, we aim to design a solution that is broadly applicable across different storage media and hardware configurations.

We also do not aim to outperform LSM-trees in write-intensive workloads, as they are fundamentally optimized for such scenarios, trading off lookup performance.

While the page-oriented design is one reason for I/O amplification in B-trees in general, we do not aim to redesign the data structure from the ground up. Instead, we focus on a lightweight extension to the traditional B-tree that can be integrated into existing systems with minimal changes.

1.3 Contributions

This thesis introduces 3B-tree, a B-tree variant incorporating a lightweight buffering layer to minimize write amplification. The buffering layer batches small write operations, reducing the frequency and volume of writes to external storage. When the buffer manager evicts a B-tree node from memory, we determine whether it has changed significantly enough to warrant a full write to storage. If not, we buffer the changes. Essentially, we minimize I/O operations to those strictly necessary.

The novelty of our approach lies in its non-intrusive design: We only perform additional operations when the buffer manager exchanges B-tree nodes between memory and external storage. In contrast to other approaches (see Chapter 3), we neither alter the B-tree structure its fundamental operations, nor impact concurrency in the tree. We keep read amplification low by only introducing additional lookups during page reads. Our approach is easy to integrate into existing systems and preserves the desirable properties of traditional B-trees.

We hereby contribute to the broader effort of minimizing the overhead of beyond memory systems and designing efficient, high-performance database systems for modern hardware.

2 Background

This chapter provides the necessary background for understanding the problem of write amplification in B-trees and the proposed method by outlining the characteristics of external storage, the architecture of database systems, and the behavior of B-trees in out-of-memory environments. Furthermore, it introduces the concepts of write, read, and space amplification, which allow for a differentiated analysis of index structures for their efficiency and performance characteristics.

2.1 External Storage Characteristics

For some time, in-memory database systems like Hyper [13] have gained popularity due to the decreasing cost of DRAM. However, that trend has reversed recently, as DRAM prices have stagnated [12] and SSD price-performance-ratios have improved significantly [15]. Therefore, modern database systems are designed to operate efficiently on external storage and since index structures are the performance-critical component, out-of-memory indexing has become a key consideration again. B-trees have been the dominant index structure for out-of-memory indexing, since their high fanout minimizes the number of I/O operations.

Historically, hard disks were the dominant storage medium. Hard disks have a significant imbalance in latency between random and sequential I/O due to their mechanical nature. While SSD have a smaller difference between random and sequential I/O, they still exhibit asymmetric performance, especially in writes [12]. Therefore, to amortize the cost of random I/O, database systems and their index structures are designed to access data in pages of multiple kilobytes instead of individual tuples. This assumes that subsequent accesses exhibit some locality, which is often the case in practice. While we will be referencing disk-based systems throughout this thesis, we speak of systems operating on external storage, which can be either disk-based or flash-based.

2.2 Database System Architecture Overview

In the scope of this thesis we focus on a classic architecture of a single-node, disk-based database system. Note that this architecture is not a constraint of our method, which

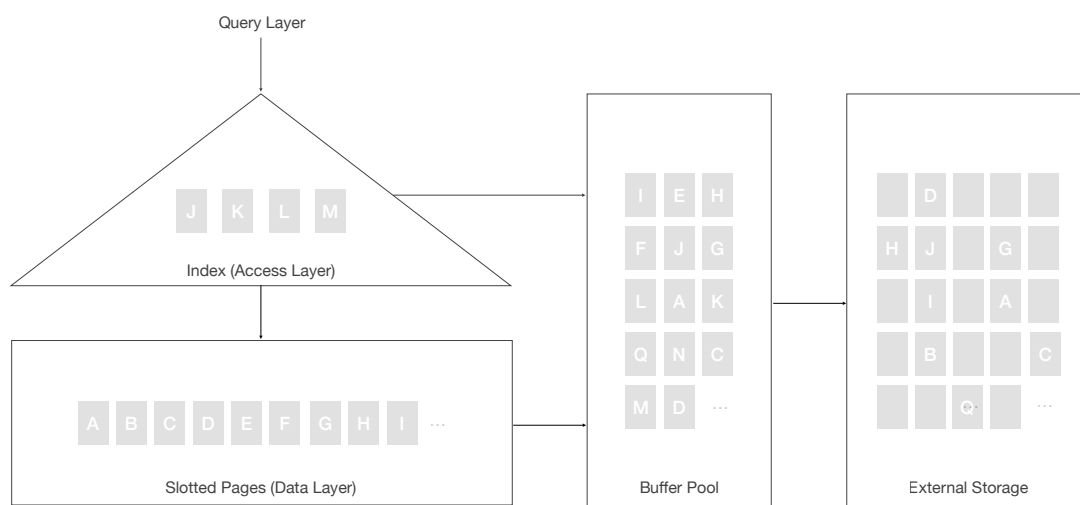


Figure 2.1: The storage and access layer of a database system. The index provides access to the tuples stored in the slotted pages. Each component requests data from the buffer manager, which handles caching and loading pages from external storage. Adapted from "Database Systems on Modern CPU Architectures" [19].

can be applied to any database system using B-trees as an index structure. However, for clarity, we describe our method in the context of this architecture.

The access and storage layer of a database system typically consist of a buffer manager, one or more index structures and the slotted pages that store tuples identified by Tuple ID (TID)s, as illustrated in Figure 2.1. Since we operate in a beyond memory setting, the buffer manager is responsible for caching pages in DRAM and loading them from external storage when needed. Therefore, all components accessing physical data interact with the buffer manager to load and store their pages. When a query is executed, the index is accessed by a given key (e.g. the primary key) to find the TID of the relevant tuple. The index is typically stored in pages, which are loaded into the buffer pool by the buffer manager. Using the TID, the corresponding tuple can be retrieved from the slotted pages. The TID encodes the Page ID (PID) and the slot number within the page. When a tuple is updated, the corresponding page is loaded into the buffer pool, modified, and marked as dirty. Should the buffer pool be full, the buffer manager evicts pages based on its replacement policy. Clean, unchanged pages can be discarded, while dirty, modified pages must be written back to external storage.

2.3 Index Structures

Index structures are data structures that enable efficient access to data stored in a database. Typically, they map a key to a constant, unique TID. Ideally, the TID never changes, as this would require all indexes pointing to that tuple to be updated. Keys can be arbitrary types and therefore of fixed or variable size, such as integers or strings. We will consider both within this thesis. When the key of a tuple changes, the index must be updated to reflect the new key.

Some key-value stores directly map keys to tuples within their index structure, omitting the indirection via TID and slotted pages. However, in a general purpose DBMS, we typically want to support multiple indexes on the same data. If we stored tuples directly in the index, we would need to update all indexes when a tuple changes. Therefore the access and storage layer are decoupled via TIDs. For the context of this thesis, however, it does not matter whether the index maps keys to TIDs or directly to tuples.

Indexes can be classified into primary and secondary indexes. A primary index is built on the primary key of a table, which uniquely identifies each tuple. A secondary index is built on a non-primary key, which can be non-unique.

Consider the following example use-case: a user database with a primary key on the user ID and a secondary index on the email address. When inserting several new users, we update the indices. The primary index is updated with an auto-incrementing user ID, thus, the primary key follows a sequential access pattern. However, the email

addresses of new users are likely to be random and not follow any specific order. Therefore, if the secondary index is sorted on the keys, as they are in a B-tree, the index exhibits a random access pattern. Such access patterns have implications on the performance of index structures, as we will discuss in the following sections.

2.4 B-trees

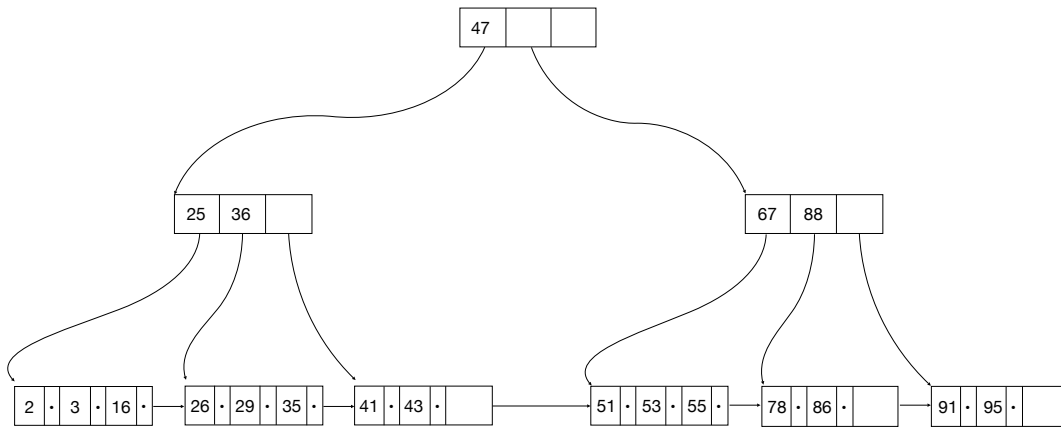


Figure 2.2: A B+-tree. Child pointers are represented as arrows. Values (the TID) are represented as bullet points •.

B-trees [2] are a self-balancing tree data structure that maintains sorted data and allows for insertion, deletion, and search operations in logarithmic time, $\mathcal{O}(\log n)$, where n is the number of entries in the tree. A B-tree is organized in fixed-size pages, called nodes. These pages are transferred and cached transparently by the buffer manager between external storage and DRAM. Each node can split off a sibling once it is full. If a node is full and a new key needs to be inserted, the node splits into two nodes, and the middle key is promoted to the parent node. Additionally, nodes can merge with a sibling if they become less than half full. For simplicity, we omit merging of nodes in this thesis.

The tree only increases in height when the root node splits. Each node contains between 2 and $2k$ entries, except for the root node, which can contain between 1 and $2k$ entries.

Each entry is a triple of a key, a pointer to a child node, and optionally a value (the TID). The entries in each node are sorted by key. On leaf nodes (nodes without children), the pointer to a child node is undefined. An inner node (a node that is not a leaf) with k keys has $k+1$ children. Each entry in an inner node separates the key space of its children. The additional child pointer is necessary to separate the key space above the largest key in the node. For example, consider an inner node with keys $\{10, 20, 30\}$. The first child contains all keys less than 10, the second child contains all keys between 10 and 20, and the third child contains all keys between 20 and 30. The fourth child contains all keys greater than 30.

When searching for a key in the tree, we start at the root node. On each node, we perform a binary search to find the appropriate pivot key and follow the corresponding child pointer. We stop when we reach a node with the desired key.

B+-trees

When addressing B-trees in this thesis, we actually refer to B+-trees, a variant of B-trees where all values are stored in the leaf nodes and internal nodes only store keys and child pointers to guide the search. The separator keys in internal nodes may or may not occur in the data. An example B+-tree is illustrated in Figure 2.2. The lookup procedure is the same as in a B-tree, however we always traverse the full tree from root to leaf to find a key. Not only does this simplify the B-tree logic, it also increases the fanout of inner nodes, leading to a lower tree height and therefore fewer I/O operations for lookups since less pages are involved in reaching the leaf level. Also, it allows for efficient range queries by scanning the leaf nodes in order. Due to its excellent lookup performance, support for range queries, and simplicity, B+-trees are the dominant data structure for external storage [19].

Disk-Access-Model

To analyze the performance of B-trees in a beyond memory setting, we use the Disk-Access-Model (DAM) [1] [14]. The model has two levels of memory: an internal memory of size M and external storage of infinite size. The storage device is organized in fixed-size pages, which are the units of data transfer between memory and storage and determine the size of nodes in a B-tree. For simplicity of this analysis of the DAM for B-trees, we assume that records are constant sized (An assumption that simplifies this explanation but does not hold in practice. Therefore we will **not** assume this in our method and implementation.) and that nodes are always completely filled. When a database has N records, and the storage device has pages of size P , the B-tree has a height of $\log_P(N/P)$, where inner nodes contain $O(P)$ children and leaf nodes contain

$O(P)$ records.

Each lookup/insertion/deletion requires a traversal from the root to a leaf node, leading to $O(\log_p(N/P))$ I/O operations. Since the majority of nodes in the tree are leaf nodes, we can assume that most inner nodes can be cached by the buffer manager. In that case, we would require only a single I/O per B-tree operation.

In practice, B-trees are often used to index variable-sized keys and values. Therefore, we will consider variable-sized records in our method and implementation. However, the DAM provides an approximation.

Node Size & Fanout

The node size (i.e. the page size) is a crucial parameter in the design of a B-tree, as it affects the height of the tree. Larger nodes lead to more entries per node, increasing the fanout for inner nodes and decreasing the height of the tree. When we can address more children per node, we need fewer levels in the tree to address the same number of keys. Since every lookup/insert/delete operation requires a traversal from the root to a leaf node, fewer levels lead to fewer pages involved in the lookup. Thus, larger nodes lead to fewer I/O operations per lookup. Additionally, since we need fewer distinct pages, we induce less page management overhead in the buffer manager.

Large nodes are particularly beneficial for analytical, read-heavy workloads, which often perform large scans and are interested in large parts of the data. However, workloads that perform many updates and point queries, are sometimes only interested in a small portion of the page. As a result, larger nodes lead to more I/O amplification, as we read and write significantly more data than necessary to perform the operation. If subsequent operations follow a sequential access pattern, the I/O amplification is not a problem, as we will be operating on pages already cached by the buffer manager. Ideally, no or very few additional I/O operations are necessary. With random access patterns, however, this I/O amplification due to large page sizes becomes a problem. Node sizes are a tuning parameter that is not the primary focus of this thesis. Instead, we focus on reducing I/O amplification in B-trees at any node size.

2.5 Write Amplification

Write amplification is the ratio of the amount of data written to storage versus the amount of logical data written by the user. For example, if the database updates an entry of 64 B, but needs to write a full page of 4 KB to storage, the write amplification is $4096 \text{ B} / 64 \text{ B} = 64$. Write amplification WA is formally defined as:

$$WA = \frac{\text{BytesWrittenPhysically}}{\text{BytesWrittenLogically}}$$

There are multiple layers of write amplification in a database system, which we need to differentiate from each other.

Application Layer. At the application layer, we consider an external end user interacting with the database system, e.g. through SQL. When an end user inserts a tuple through a query, the database system must insert the tuple in the table itself, in the Write-Ahead Log (WAL) and all indexes that serve to access the tuple later. Consequently, we write significantly more bytes than the user requested logically. Additionally, updating a B-tree index might cause structural changes such as node splits or merges that create new nodes, delete new nodes and update the parent nodes. Thus, a database system inherently comes with write amplification merely to perform its purpose: manage data. This is not the focus of this thesis; we consider all updates to tables, data structures and the WAL as necessary and focus on reducing write amplification within the index layer specifically.

Index Layer. At the index layer, we consider the B-tree as the user of pages. When a B-tree entry is updated, the bytes written logically include not only the updated key but also any additional metadata required to maintain the tree structure. This can include information about node splits, merges, and the promotion of keys to parent nodes. The writes are amplified by the B-tree's page structure that requires rewriting the entire page even if only a small portion has changed. As mentioned in Section 2.4, the node size directly impacts the write amplification at this level. This is the write amplification we focus on in this thesis, by minimizing the number of pages written to storage for a given set of updates (see Chapter 4).

Physical Layer. At the physical layer, we consider the database system as the user (the host) of the physical storage device. When the database system writes a page to storage, the bytes written logically are the size of the page. However, due to the characteristics of the storage device, the actual bytes written physically can be larger. SSD typically operate in larger units called blocks, which consist of multiple pages. When a page is updated, the entire block containing that page must be rewritten, leading to write amplification. Additionally, when garbage collection is performed, valid pages within a block must be copied to a new block before the old block can be erased and reused. Recent research observed write amplification factors up to 10x on modern SSD [11]. Consequently, a page write of 4 KB can lead to physical writes of up to 40 KB on the device, using up valuable bandwidth and wearing out the device faster. While we do not focus on hardware-level write amplification in this thesis, it shows the importance of reducing write amplification at the host level. Unnecessary writes by the database system are multiplied by SSD.

2.6 Read Amplification

Read amplification is the number of I/O operations required to answer a query [14]. As described above, a B-tree lookup requires a traversal from the root to a leaf node, which is $\mathcal{O}(\log_p(N/P))$ I/O operations in the DAM, assuming that our cache is cold. In practice, the buffer manager caches pages in DRAM, which can significantly reduce the number of I/O operations. To answer range queries, we can scan the leaf nodes in order, which is efficient in B+-trees. Therefore, we only traverse the tree once to find the start of the range and then scan the leaf nodes sequentially. Read amplification is a common tradeoff when reducing write amplification, as we will see in alternative data structures (see Chapter 3). We will analyze the introduced read amplification of our method compared to the traditional B-tree in our evaluation (see Chapter 6).

2.7 Space Amplification

Space amplification is the ratio of the amount of space used by the data structure versus the amount of logical data stored [14]. Most nodes in a B-tree are leaf nodes, which store the actual data. However, inner nodes only store keys and child pointers to guide the search, inflating the space usage. Additionally, B-tree nodes are not always completely filled. Therefore, B-trees exhibit some space amplification. Space amplification is not the focus of the thesis, however we will analyze space utilization of our method compared to the traditional B-tree in our evaluation (see Chapter 6).

3 Related Work

In this chapter, we review related work on write-optimized data structures, focusing on B-tree variants and alternatives and compression techniques to reduce write amplification. For each data structure, we discuss its design, how it addresses write amplification, and its trade-offs in terms of read performance, concurrency and applicability. We outline the gap in existing work that we aim to address in this thesis. In Section 3.1, we discuss LSM-trees, a popular write-optimized data structure alternative to B-trees. In Section 3.2, we review B^e-trees, a write-optimized B-tree variant. In Section 3.3, we discuss the Bw-tree, another B-tree variant optimized for modern hardware. In Section 3.4, we review Graefe’s Write-Optimized B-trees, an approach to improve write performance in B-trees by batching page writes. In Section 3.5, we discuss FineLine, a storage manager that decouples in-memory data structures from their disk representation. Finally, in Section 3.6, we review a hardware-based approach to reduce write amplification in B-trees using transparent compression.

3.1 Log-Structured-Merge-Trees

LSM-trees [20] are a popular alternative index data structure to B-trees for write-heavy workloads. They are increasingly used in key-value stores such as RocksDB at Meta [24] or BigTable at Google [6].

Basic Structure. LSM-trees consist of two main components: an in-memory component and a disk-based component. The in-memory component is typically implemented as a balanced tree such as a red-black tree, called a MemTable. The MemTable accepts and applies updates in memory. Once it is full, it is flushed to disk as a sorted, immutable run in a file called SSTable. Over time, multiple runs accumulate on disk. Since those runs may have overlapping key ranges, lookups need to check both memory and multiple disk files to find a key.

To limit the number of runs on disk and improve lookup performance, LSM-trees organize runs into multiple levels, where each level is larger and more data is sorted than in the previous one. When a level reaches its size limit, it triggers a compaction process to sort-merge runs into the next level, retaining only the latest version of each key. As a result, higher levels contain more recent data with several, smaller files with

overlapping key ranges while lower levels contain few, large files with non-overlapping key ranges. Since runs are immutable, each compaction generates new files for the merged runs. Outdated files are deleted by a garbage collector [22].

High Write Performance. B-trees maintain a fully sorted view of the data and update this view in-place. In contrast, LSM-trees update out-of-place in a sequential, log-structured manner by buffering updates in memory and flushing them to external storage in large, sorted batches, enabling high write throughput. The excellent write performance of an LSM-trees makes this data structure suitable for write-heavy workloads, such as time-series data or logging systems.

Write Amplification. LSM-trees exhibit write amplification because data is written multiple times as it moves through the tree's storage hierarchy [14]. Each write is first stored in memory, then flushed to disk as an SSTable, and repeatedly rewritten during compactions that merge overlapping files across levels. These repeated rewrites cause the total bytes written to disk to exceed the amount of user data written, resulting in write amplification.

Low Read Performance. Essentially, LSM-trees trade high write performance at the cost of low read performance. This is useful for specific scenarios where writes dominate reads. However, it makes LSM-trees unsuitable for general-purpose DBMS as they incur significantly higher lookup costs compared to a B-tree as shown in [8].

When performing point lookups, the LSM-trees checks the MemTable first and then each level on disk from top to bottom until it is found or not. In use-cases, where we only lookup hot keys that are likely to be in memory, LSM-trees can perform well. However, such temporal locality is an assumption that we cannot make in a general-purpose system that needs to balance performance for all use-cases. When looking up cold keys that are not in memory, LSM-trees need to check multiple files on disk, leading to high read amplification.

To improve lookup performance, each SSTable has an in-memory Bloom filter to check if a key is present in the file before performing a search [6]. However, Bloom filters come with other problems. For one, it can yield false positives. Secondly, the larger the data set they are addressing, the larger the Bloom filter needs to be, inflating the memory footprint of LSM-trees.

Most importantly though, Bloom filters cannot handle range queries. For range queries, all SSTables across levels must be checked. While there is an effort to improve range query performance in LSM-trees [26], they are not designed for efficient range queries, as range data is scattered across the tree [22].

Summary. Overall, both LSM-trees and B-trees are efficient data structures, but built for

different scenarios. This update/query trade-off has been well studied in literature [4]. In this thesis we focus on general-purpose database systems, which require balanced performance characteristics across-the-board. For such a system, B-trees are the superior data structure. We therefore investigate how to improve B-trees to close the gap in write performance to LSM-trees while retaining their superior read performance.

3.2 B^ϵ -trees

Basic Structure. B^ϵ -trees [3] are a write-optimized variant of B-trees. Each internal node has a buffer to temporarily encode incoming updates as messages. When a buffer is full, messages are flushed to the appropriate child node. When messages reach a leaf node, they are applied to the respective leaf. Deletes are handled as tombstone messages that mark a key as deleted. Only when the message reaches the leaf, the key-value pair is removed from the leaf. Each message encodes a timestamp to ensure that the updates are applied in the right order.

The ϵ , which is a value between 0 and 1, refers to the tunable parameter that controls the size of the buffers in relation to the node size. Given a page size B , it determines how much of its space is used for storing pivots (B^ϵ) versus buffering updates ($B - B^\epsilon$). Choosing a larger ϵ increases the space for keys and pointers, improving read performance similar to a B-tree, while a smaller ϵ increases the buffer size, enhancing write performance similar to a buffered repository tree [5].

Mitigation of Write Amplification. This design allows B^ϵ -trees to batch updates, reducing the number of I/O operations and improving write performance while maintaining comparable read performance to B-trees. A benefit of using a top-down approach to propagate updates is that it primarily writes to higher levels of the tree which are more frequently accessed and thus more likely to be cached in memory. Alongside with a good eviction strategy, this can effectively reduce number of write operations to external storage. Another effect of this design is that it allows for large node sizes. For one, we need larger node sizes to accommodate the buffers and maintain a high fanout. But more importantly, batching updates mitigates write amplification. At the time of reaching a leaf node to apply updates, many updates have accumulated and can be applied at once. A leaf node will not be rewritten for individual updates. Therefore, the larger node sizes are less problematic in B^ϵ -trees, since they do not incur as much write amplification as in B-trees.

Read Overhead. Messages are usually binary search trees like a red-black tree to allow efficient searching within the buffer. When searching for a key, the tree is traversed from the root to the leaf, checking each buffer along the path for messages that belong

to the key. This ensures that the most recent updates are considered during the search. However, this also means that two searches are required per node: one for the pointer to the child node and one for messages in the buffer. This introduces some overhead for read operations compared to B-trees.

On the other hand, B^e -trees can achieve faster scans, because larger node sizes are more attractive in this design, better utilizing the bandwidth of external storage.

Concurrency Limitation. Since updates are propagated top-down, we introduce contention on higher levels of the tree. However, higher levels of the tree are more frequently accessed to locate entries. When they are written to, this blocks a large amount of nodes below. This is especially problematic for the root node, which needs to be accessed by every operation in the tree, limiting concurrency in the system significantly.

Summary. While B^e -trees have been shown to effectively mitigate write amplification in a single-threaded scenario, they significantly limit concurrency in the data structure. A characteristic that makes B^e -trees unsuitable for high-performance database systems. In this thesis, we aim to reduce write amplification in B-trees while retaining high concurrency.

3.3 Bw-trees

Basic Structure. The Bw-tree [18] is a B-tree variant optimized for modern hardware. It introduces a latch-free design, leveraging atomic compare-and-swap operations to ensure consistency without traditional locking mechanisms. They employ out-of-place updates, where deltas are prepended to nodes as linked lists instead of modifying them in place. This avoids cache invalidation, enabling higher concurrency in the tree. To update the delta chain, they use atomic Compare-And-Swap (CAS) operations to allow latch-free updates. The delta chain of a node is eventually consolidated, by creating a new node that applies the deltas to the base node. Outdated base nodes are reclaimed by a garbage collector. Additionally, they employ a log-structured store that migrates nodes to contiguous storage locations. While they specifically target flash-based storage, the design principles apply to other storage media as well.

Mitigation of Write Amplification. When a page with a delta-chain is flushed to external storage, only the new deltas need to be written, not the entire page. This effectively reduces write amplification, as they only write the changes instead of the whole page. The deltas of several pages can be consolidated in memory, allowing to

batch writes to external storage. Only when creating new pages during consolidation, they need to write the entire page. In that case, the node has experienced sufficient modifications that justify writing the entire page.

Read Overhead. The delta chain needs to be traversed for every single node on the read path to a leaf, introducing overhead for every lookup. While the goal is to keep cache lines valid, applying deltas out-of-place and traversing a linked list of deltas per node, pollutes the caches of every core. When loading a page from external storage, the entire delta chain needs to be read and applied to reconstruct the current state of the node. This requires multiple random read operations on storage.

High Coupling. This design introduces invasive changes to the B-tree's implementation, requiring a change in lookup and update logic as well as a consolidation mechanism and garbage collection. Most importantly, it heavily couples the cache management layer with the indexing layer. For example, the indirection via the mapping table from PIDs to physical addresses becomes a requirement to implement the CAS logic to update the delta chain. The data structure needs to be aware of the storage layer and their implementation details to implement this logic. This makes changes to the caching layer difficult. For example, pointer swizzling [10] would be infeasible with this design. Everytime a delta is prepended to a node, the swizzled pointers would become invalid. Updating each pointer to the new root of the delta chain would require updating all outdated pointers in the tree. However, pointer swizzling is a common technique for disk-based database systems [16] to compete with in-memory database systems. Therefore, we want to keep each layer transparent to the other, allowing independent optimizations.

Summary. Overall, the Bw-tree presents a novel approach to reduce write amplification in B-trees and we take notes for our own design. However, Wang et al. showed in their paper "Building a Bw-tree Takes More Than Just Buzz Words" [25] that the Bw-tree's performance is actually not competitive with traditional B-trees using optimistic lock coupling [17]. In our approach, we aim to introduce a small overhead when loading a page from external storage, not for every read operation in memory. Additionally, we want to keep the changes to the B-tree minimal, introducing a lightweight layer between the data structure and the storage manager that buffers and batches updates.

3.4 Write-Optimized B-trees

Graefe proposes "Write-Optimized B-trees" [9] to address the write efficiency gap between log-structured file systems and the B-tree. Log-structured data structures write

large, sequential chunks of data to disk, making optimal use of the available bandwidth. B-trees, on the other hand, perform many small, random writes by writing individual pages. To improve write efficiency in B-trees, Graefe proposes to batch multiple dirty nodes and write them to disk in a single, large write operation.

The buffer manager can invoke such page migrations for the chosen dirty pages. By introducing logical fence keys, the pages can be written to arbitrary locations, without requiring an update to the sibling pointers. Since page migrations are optional, the B-tree can still decide to update pages in place if that is more efficient.

This work provides an approach to get the log-structured style of writing in a B-tree, without changing the data structure itself. It supports the effort of improving write performance in B-trees, while retaining their high read performance and concurrency. While this approach improves write performance by batching multiple pages, in this thesis we address the write amplification caused by individual page and in-place updates. We avoid writing individual pages as a whole, by deferring updates and buffering them in batches instead.

3.5 Decoupling Storage from In-Memory Data Structures

Sauer et al. [23] propose FineLine, a storage manager that decouples in-memory data structures from persistence concerns in a database system. In-memory data structures are never propagated to disk. Instead, FineLine merely uses the log for persistence. When an in-memory data structure (for example a B-tree) causes a cache miss, FineLine reconstructs its state by replaying the log of operations from disk. When a transaction commits, its log of changes to the data structures is flushed to disk in a sequential manner, allowing for high write performance. To improve read performance for reconstruction, FineLine employs a compaction mechanism that merges partitions of the log, similar to LSM-trees.

Since all flushes to disk are sequential, write amplification is small. Some write amplification is introduced by the compaction process. Also, traditional systems need to write both, the data structure pages and the WAL to disk. In FineLine, the log is the only component that requires persistence. This reduces random writes in the system further.

FineLine also allows for a graceful recovery mechanism, as the log can be replayed when the in-memory state is lost (e.g., after a crash) in a similar way that a cache miss is handled.

One drawback of this approach is the high read amplification when reconstructing data structures from the log. Every time a node is reconstructed, the log needs to be scanned for all entries that affect the node. Due to compaction, this search can be

efficient. However, assume a high update rate on a certain data structure node. Many partitions of the log may contain updates for this node, requiring multiple reads from disk to reconstruct the node.

3.6 Transparent Compression

Qiao et al. [21] propose a hardware-based approach to reduce write amplification in B-trees. They use transparent compression, a hardware feature of some modern storage devices that offer lossless data compression transparent to the host. The storage device compresses data before writing it to the physical medium. When a page is empty, no data is written at all. When a page is partially filled, only the actual data is written, not the empty space. This can be used to reduce write amplification in B-trees, as it allows for sparse data structures which do not actually waste space on the storage device.

In their approach, Qiao et al. apply out-of-place updates like previous approaches. Each node's page is followed by a modification log that records changes to the node. In contrast to previous approaches of out-of-place updates, they do not need to collect updates to a node across storage but instead, they can perform a single read operation to load the node and its modification log. When loading the node from storage, they apply the modifications in the log to reconstruct the current state of the node. When a node is modified, they append the modification to the log instead of rewriting the entire page. When a node is flushed to storage, they obtain the delta, and decide whether they invoke the page modification logging which is appended to the page or whether they write the entire page in-place.

This approach reduces write amplification in B-trees, as they avoid rewriting entire pages for small updates. However, for small deltas they still need to perform an I/O operation to write the modification log to storage. The purpose of reducing write amplification is not only to reduce the amount of data written, but primarily to reduce the frequency of writing data by batching updates. We want to avoid writing at all for small updates.

A benefit of this approach is that it does not require invasive changes to the B-tree structure itself. In memory, the B-tree remains the same and only the storage manager needs to be aware of the modification log. This only requires overhead at the point of loading and unloading a page to and from external storage. A similar approach is taken in this thesis. However, this approach relies on hardware-based compression which is not widely available. We aim to provide a software-based solution that can be used on any storage device.

4 Method

4.1 Design Goals

Chapter 3 reviewed existing approaches to reduce write amplification and their trade-offs. We disclose the gaps in existing work that we aim to address in this thesis and identify the following design goals for our approach to reduce write amplification in B-trees.

Reducing Write Amplification

Write Amplification in B-trees is primarily caused by the page-oriented design that requires rewriting entire pages to storage even if only a small portion changed. This page-oriented design is crucial to utilize bandwidth of modern storage devices and to minimize buffer management overhead. Merely reducing write amplification by reducing the amount of data written to storage is not the goal. Instead, high write amplification suggests that we perform unnecessary writes to storage, which we would like to avoid. We aim to minimize the number of I/O operations induced by the B-tree to perform a set of updates. The overall goal is to create a B-tree variant that is more write-efficient regardless of the access pattern.

Comparable Read Performance

B-trees are widely used in general-purpose database systems due to their excellent read performance for point lookups and range scans. As we showed in Chapter 3, many write-optimized data structures sacrifice read performance. For example, LSM-trees incur high read amplification to achieve high write-efficiency. Bw-trees introduces a delta chain to each node that needs to be traversed on every node read. Bc-trees introduce an extra binary search for every node on the search path. While every write-optimized data structure has to trade-off read performance for write-efficiency to some degree, we aim to keep the read performance of B-trees as close as possible to the original B-tree.

Preserving Concurrency

B-trees are designed for high concurrency, allowing multiple threads to perform operations simultaneously. Many write-optimized data structures compromise concurrency to achieve high write-efficiency. For example, the Be-tree introduces longer locking periods of the most frequently accessed nodes, reducing throughput in the tree. In contrast, we aim to keep our optimizations outside of the data structure itself, without introducing further locking in the B-tree. Our method remains independent of the concurrency control mechanism used in the B-tree.

Maintaining Simplicity

B-trees are widely used in practice due to their simplicity. Some write-optimized data structures, like the B- ϵ -tree, introduce significant complexity to the data structure itself. In contrast, we aim to keep our optimizations lightweight, allowing for easy integration into existing systems. The changes we introduce to the B-tree itself should be minimal. We aim to keep a low coupling between the data structure and the storage manager, allowing for optimizations in both layers independently. Neither do we require special hardware features, making our approach broadly applicable across different storage media and hardware configurations.

4.2 High-Level Description of the Data Structure

We avoid writing a page to storage if changes are small. To achieve this, we introduce a Delta Tree that acts as a hesitation layer, as illustrated in Figure 4.1. When evicting a dirty page, we can buffer the changes of the B-tree pages instead of writing them to storage immediately. We can just discard the page, saving us the write to storage. When loading a page from storage, we apply all buffered changes to it before returning it to the B-tree. Only when enough changes accumulate, we write the full page to storage.

Reducing Write Amplification. Write amplification in a B-tree happens at the point of eviction, when a page is written to storage. The buffer manager is only aware that a page is dirty. It does not know which parts of the page changed. Therefore, we keep track of the modifications made to each page in the B-tree. Our component interacts with the buffer manager to intercept the eviction of dirty pages. When evicting a dirty page, we can buffer the changes in the Delta Tree instead of writing them to storage immediately. This way, we can defer small random writes and accumulate them in the Delta Tree until we have enough changes to justify a full rewrite to storage. We aim for a batching effect in two ways:

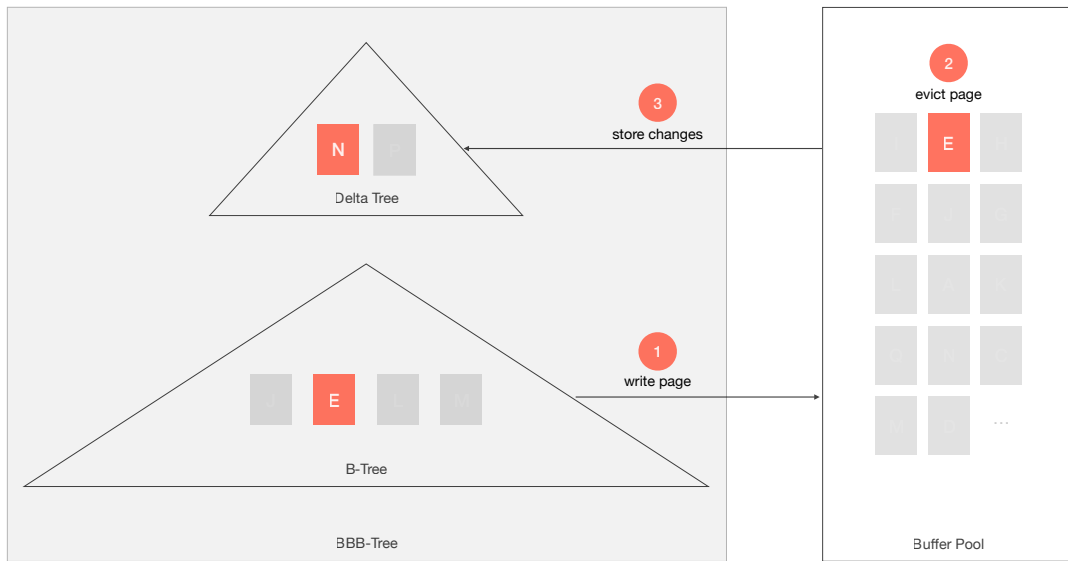


Figure 4.1: High-level architecture of the data structure. We add a Delta Tree to a B-tree. When evicting a dirty page from the B-tree, we can buffer the changes of the B-tree pages instead of writing them to storage. When loading a page from storage, we apply all buffered changes to it before returning it to the B-tree.

1. **Batching Changes of Single Pages:** We buffer multiple small changes to the same page until we have accumulated enough changes to justify a full rewrite. We then write all changes to the page in one batch.
2. **Batching Changes Across Pages:** A single Delta Tree page can buffer changes for multiple B-tree pages. Therefore, we can batch changes across multiple pages into a single write operation. This way, we can turn many small random writes into few large writes.

Both effects help to reduce write amplification in the B-tree.

We also perform writes to the Delta Tree itself. Firstly, when storing changes of B-tree pages. Secondly, when enough changes accumulate in the B-Tree pages, we write them back to storage. In that case, we need to remove the corresponding changes from the Delta Tree. At the point of applying changes from the Delta Tree to a B-tree page, we can keep the changes in the Delta Tree for future evictions. This way, we perform less updates to the Delta Tree and can keep the state of the B-tree page clean. Should there be no further changes to that page, the next eviction can simply discard the page without any writes. These observations suggest that the Delta Tree should be small and fit into memory as much as possible (see Chapter 6). As a result, we can expect fewer evictions of Delta Tree pages compared to B-tree pages.

Comparable Read Performance. To nodes in memory, this method is transparent. When searching pages in memory, we do not incur overhead.

The only time we incur overhead is when loading a page from storage or unloading it to storage. We argue that this overhead is acceptable, as we are already loading a page from storage. The overhead of applying the buffered changes is small compared to the I/O operation.

However, the buffering layer itself is a disk-based data structure, which might require I/O operations to look up buffered changes. We will be evaluating the read overhead in Chapter 6.

Preserving Concurrency. The Delta Tree is separate from the B-tree. Therefore, we do not compromise concurrency of the B-tree itself, since we do not introduce further locking in the B-tree itself. The Delta Tree can be implemented as a B-tree variant itself, allowing for high concurrency.

Maintaining Simplicity. The modifications we introduce to the B-tree itself are minimal. Within the B-tree, we only need to track the modifications made to the nodes. Essentially, we mark entries as dirty.

The Delta Tree is a separate component that interacts with the buffer manager. We do not dictate how the buffer manager is implemented or how it manages pages. As a

result, we maintain a low coupling between the data structure and the storage manager, allowing for optimizations in both layers independently. For example, pointer swizzling is an optimization that could be applied with our method.

The Delta Tree itself is a B-tree variant, which we already have present in our system. Therefore, we can reuse existing code and concepts, reducing implementation complexity. Neither do we assume any special hardware features, making our approach broadly applicable across different storage media.

4.3 Data Structure Modifications

Buffer Manager

The buffer manager is the component that decides when a page is evicted from memory and when a page is loaded into memory. At the same time, the buffer manager should not be aware of any semantics of its pages. More specifically, it does not know if it is evicting or loading pages of a B-tree or any other data structure. However, we require specific logic to be executed when evicting or loading pages of a B-tree. We need a way to inject this logic into the buffer manager without leaking B-tree specific logic into the buffer manager itself. Therefore, users can register function pointers that are invoked at eviction time and loading time. That way, the buffer manager remains agnostic of the semantics of its pages.

B-tree

We modify the traditional B-tree in three ways to support our approach.

1. **Tracking Write Amplification:** We need to be aware of the degree of write amplification per node. Whenever we modify a node, for example through an insertion or a node split, we keep track of the amount of bytes that were changed. Then, in relation to the page size, we can determine the write amplification of the node. Based on that parameter, we can decide if a write operation to external storage is justified, or if we want to defer it.
2. **Tracking Deltas:** We need to determine the changes that occurred on a node since the last time it has been loaded from external storage. To that end, each entry on a node has an additional "state" field that indicates if the entry was inserted, updated, or deleted since the last time the node was loaded from external storage. That way, we can buffer the "delta" image of a node at eviction-time and apply it again at loading time to ensure that we can reconstruct the logical state of a

node when it is accessed again at a later point in time. We do not incur any space overhead for the state field as elaborated in Section 5.1.

3. **Injecting Callbacks:** As described above, we need to execute specific logic at eviction time and loading time of a B-tree page. However, the B-tree has no control over the point in time a page is evicted or loaded. Therefore, we inject callbacks into the buffer frames that are later invoked by the buffer manager. Whenever we request a B-tree page from the buffer manager, we register function pointers for the Delta Tree. At eviction- and loading-time, these function pointers are called by the buffer manager to execute the necessary logic.

Alternatively, we could have immediately inserted changes into the Delta Tree whenever a change occurred on a B-tree node. This way, we would not need to track changes on the B-tree nodes themselves. However, this would introduce significant overhead on every write operation to the B-tree. Imagine a sequential workload that updates the same B-tree node multiple times while it is in memory. Every write would require an update to the Delta Tree as well. However, when evicting the page, we would write the full page to storage anyway, as many changes occurred. We would degrade performance unnecessarily. Therefore, we only interact with the Delta Tree at eviction- and loading-time of a B-tree page instead. Only if we decide to buffer changes, we insert them into the Delta Tree. This way, we keep the performance impact for B-tree operations minimal. We evaluate the tracking overhead of our approach in Chapter 6.

Delta Tree

The Delta Tree is the component that buffers changes of B-tree nodes. The Delta Tree itself is a B-tree with PIDs as keys and lists of changes as values. The buffer manager calls back the Delta Tree everytime a dirty B-tree page is evicted from memory or loaded into memory.

1. **Eviction Time:** The Delta Tree can decide if a B-tree page should be written to storage or not based on the write amplification of the page. Should it decide to not write the page to storage, it buffers its changes. It does so, by scanning the node for entries that were marked as dirty and inserting them into its own B-tree. The buffer manager is informed that the page does not need to be written to storage anymore and can simply be discarded.

Should it decide to continue writing the page to storage, it simply returns and the buffer manager writes the page to storage as usual. In this case, we clean the state of the B-tree page and remove any buffered changes from the Delta Tree, as it is now in sync with storage.

2. **Loading Time:** When loading a B-tree page from storage, the Delta Tree looks up if there are any buffered changes for that page. If so, it applies the changes to the page before returning it to the B-tree. Together with the state of the page on storage, we can reconstruct the state of the page in memory.

When changes were applied, we keep them in the Delta Tree, as they might be useful for future evictions. This way, we perform less updates to the Delta Tree and can keep the state of the B-tree page clean. Should there be no further changes to that page, the next eviction can simply discard the page without any writes.

The Delta Tree itself contains pages that are managed by the buffer manager. Its pages can be evicted to storage as well. Therefore, we want to keep the Delta Tree small to batch changes more effectively.

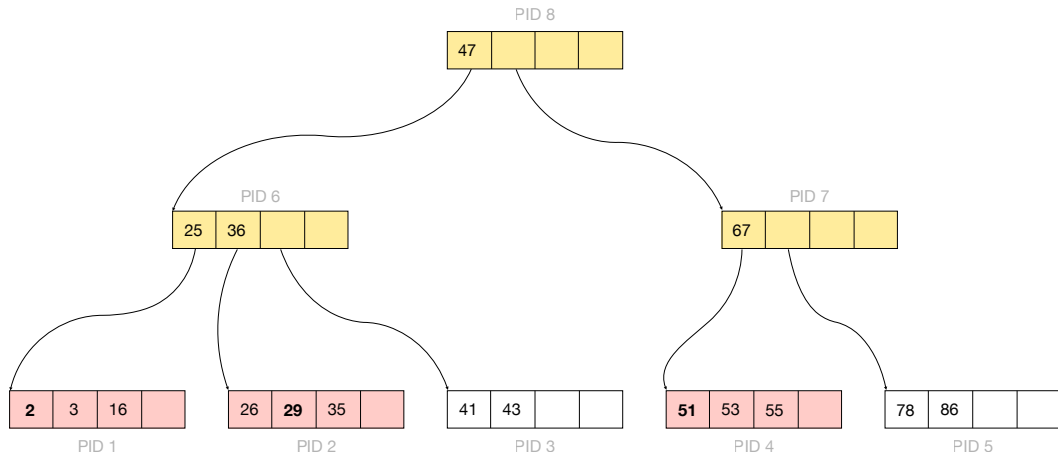
4.4 Implications on Write Amplification

We can illustrate the effect of our approach on write amplification with a simple example. Figure 4.2 shows a B-tree with updates across three nodes with PIDs 1, 2, 4. In a traditional B-tree, we would need to write all three pages to storage. Assuming a page size of 4 KB and each update being 64 B, the write amplification is $(4096B/64B) * 3 = 192$.

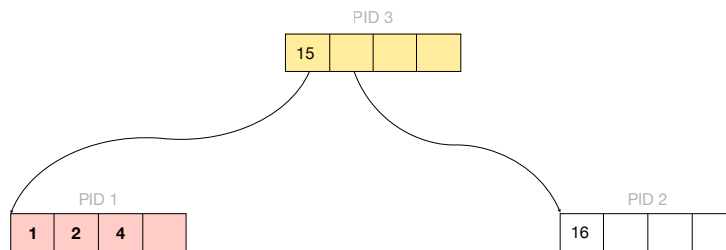
With our approach, we can buffer the changes of the three pages in the Delta Tree. In this example, the Delta Tree only needs to write one page to storage, containing the three updates. Assuming a page size of 4 KB again and approximating the delta entries to be 64 B each, the write amplification is now $4096B / (3 * 64B) = 21.33$. In this simple example, we have reduced the write amplification by a factor of >9 .

This demonstrates the goal of our approach: batching small writes on many distinct pages into larger writes on fewer pages. This way, we can reduce the number of pages written to storage for a given set of updates, thereby reducing write amplification.

Another effect is that we can avoid writing B-Tree pages that are frequently evicted with small updates. With a single Delta Tree page, we can address the changes of multiple B-tree pages. Therefore, the Delta Tree can be much smaller than the B-tree itself and fit into memory more easily. While the Delta Tree might evict pages occasionally, the B-tree pages are less likely to be evicted frequently. As a result, we can accumulate changes of B-tree pages over a longer period of time, reducing the frequency of writes to storage.



(a) A B-tree with updates to nodes with PID 1, 2, 4.



(b) The corresponding Delta Tree. Buffered the changes of B-tree nodes by their PIDs 1, 2, 4.

Figure 4.2: Example of a B-tree and its corresponding Delta Tree. The B-tree has three updated nodes marked in red. In this example, we require only one page write for the Delta Tree instead of three writes for the B-tree.

5 Implementation

5.1 System Architecture

We have implemented our system according to Figure 2.1 in C++. In the following, we inspect the particular implementation of each component.

Buffer Manager

Our buffer manager serves our system with pages, transparently swapping them between memory and external storage. Upon construction, it receives a `page_size` that determines the fixed-sized number of bytes of every page in the system, as well as a `page_count` that determines the maximum number of pages that can be buffered in memory. Each component requests a page with `fix_page` returning a buffer frame. After operating on the page, the page is released again by calling `unfix_page` on the given frame. The user can pass a boolean flag to indicate whether the page was modified or not.

When fixing a page we can pass a pointer to a `PageLogic` object. `PageLogic` is an abstract class that can be defined by the user to inject user-specific logic into the buffer manager. This object will be called by the buffer manager when a page is loaded from external storage to memory or evicted from memory. This allows us to insert user-specific logic, such as invoking the Delta Tree upon eviction, without coupling the two components.

If a page is not already present in the buffer pool, it is loaded from a file from storage. If a `PageLogic` object is injected into the page's corresponding frame, we call it to perform user-specific logic on the loaded page. When the user unfixes the page again, we keep the page in the buffer pool until it is chosen for eviction.

When the buffer pool is full, our buffer manager selects a page for eviction. The eviction strategy is not under inspection in this thesis, therefore we choose a page at random. Should the page be marked dirty or new, we call the `PageLogic` object. Should it return true, we continue writing the page to storage. Should it return false, we do not continue with the write and simply discard the page.

Slotted Pages

We store tuples within slotted pages, accessed through the buffer manager. As shown in Figure 5.1, a slotted page consists of a header, a slot array and a data segment. The header contains metadata about the page, such as the number of slots and the pointer to the data segment. Each slot points to the corresponding tuple data stored in the data segment. Through this indirection we can accommodate for variable-length tuples [19]. Introducing this indirection impacts the cache locality as we need to follow an additional pointer for every comparison. There are some optimizations, such as storing parts of the key in the slot itself to speed up comparisons [10]. Since our approach is orthogonal to these optimizations, we do not implement them in our prototype.

Each tuple in the system is identified through its unique TID. Each TID consists of 8 B, whereas the upper 6 B contain the PID and the lower 2 B contain the slot's ID.

When looking up a tuple in the system, we retrieve the corresponding TID from the index given the key. Through the TID we can request the corresponding page through the PID from the buffer manager. When loaded into memory, we can access the slot through the slot ID and retrieve the actual tuple data.

When inserting a new tuple, we first need to find an appropriate page to store it in. If the buffer pool is full, we need to evict a page before we can load a new one. Once we have a page, we can allocate a slot for the new tuple in the page's slot array and store the tuple data in the data segment. We then create a new TID for the tuple and insert it into the index.

B-tree

As shown in Figure 5.2, each node in our B-tree is implemented similar to a slotted page to accommodate variable-sized keys and values. While we depict a leaf node in the figure, inner nodes are implemented similarly. Leaf nodes store keys and values, whereas inner nodes store keys and PIDs to child nodes.

We template our B-tree implementation on the key and value type. A third boolean template parameter indicates whether we require tracking information for this B-tree instantiation as described in the next section. This allows us to use the same B-tree implementation for both the standard B-tree and the B-tree with tracking required for the 3B-tree.

3B-tree

We call our method the 3B-tree. It wraps a B-tree with tracking information and a corresponding Delta Tree to store the changes made to the B-tree nodes. Both components are described in the following.

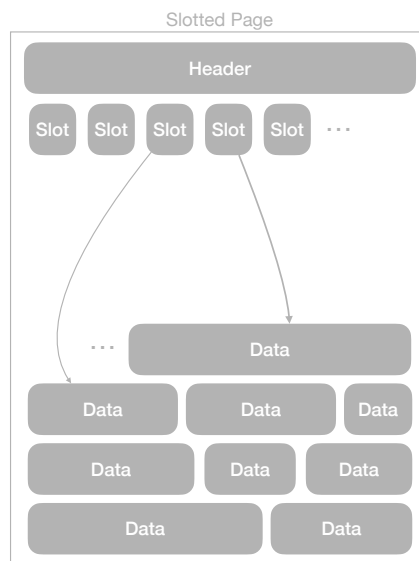


Figure 5.1: The data layout of a slotted page. The header contains metadata about the page, such as the number of slots and the pointer to the data segment. Each slot points to the actual tuple data stored in the data segment. Tuples can be of variable length and are accessed through their TID. Adapted from "Database Systems on Modern CPU Architectures" [19].

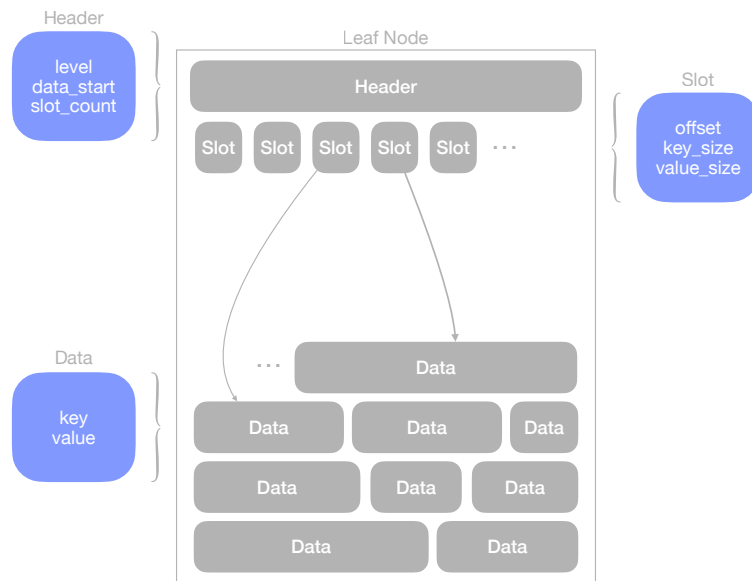


Figure 5.2: The data layout of a leaf node in the B-tree supporting variable-sized keys and values. The header contains metadata about the node, such as the level in the tree, the offset to the data segment and the number of slots. The slots point to the actual entries stored in the data segment. The data segment contains the keys and values. Inner nodes store keys and pointers to child nodes. Adapted from "Database Systems on Modern CPU Architectures" [19].

B-tree with Tracking

The B-tree with tracking is a standard B-tree as described above, but with the addition of tracking changes made to its nodes. It is templated on the key type `KeyT` and the value type `ValueT`, which is always a TID in our case. As described above, we template the B-tree on a third boolean template parameter. When set to true, we extend the page header and slots with additional fields to track changes made to the node, as shown in Figure 5.3.

Header. The header is extended by a `uint16_t bytes_changed` field to track the degree of write amplification on the page. Everytime a change is made to the page, we increase this counter by the number of bytes changed. When the page is evicted, we can use this information to decide whether to write out the page or not. However, this is only an approximation of the actual write amplification, as some changes might be overwritten by subsequent changes. For example, a node split, where we remove half the entries, followed by several insertions can lead to more bytes changed than the actual node size.

Slots. Each slot is extended by a state field to track whether the corresponding entry was Unchanged, Inserted, Updated or Deleted since the last time the page was written to storage. More specifically, it does not track the change of the entry itself, but rather the change of the entry from the perspective of the node. For example, if an entry is split off during a node split, the slot is deleted from the perspective of the node. The entry still exists in the tree, but it is now part of a different node. To the new sibling node, where we move over the split off entry, the slot is marked as Inserted. To reconstruct the state of a node when loading it from storage again, we need to know whether an entry was newly inserted or whether it existed on disk already and was only updated in memory. Assume a deletion of an entry that was inserted since the last write to storage. In that case, we can simply discard the slot and do not need to store any delta for it. If the entry existed on disk already, we need to track the deletion as a delta to ensure that we do not let the entry reappear when loading the node from storage again. Therefore, we need to differentiate between newly inserted entries and existing entries that were updated. The state machine of the operation state field is shown in Figure 5.4 and elaborated in Section 5.2.

Since we only have four states, we can store the state in two bits only. Therefore, we can hide the space overhead of the state field by using the upper two bits of the 32 bit offset field in the slot, assuming that we do not need more than 30 bits to address all offsets on the page. This is crucial to keep the fanout of the tree as high as possible. Otherwise we would introduce more pages than the baseline B-tree, negatively impacting performance.

Buffer Manager Integration. Our Delta Tree uses this information to determine which changes to store. When a B-tree with tracking enabled, fixes a page through the buffer manager, it injects a PageLogic object into the page's frame. The buffer manager calls this object later when evicting the node to interact with the Delta Tree to extract deltas and to apply deltas when loading the node from storage again.

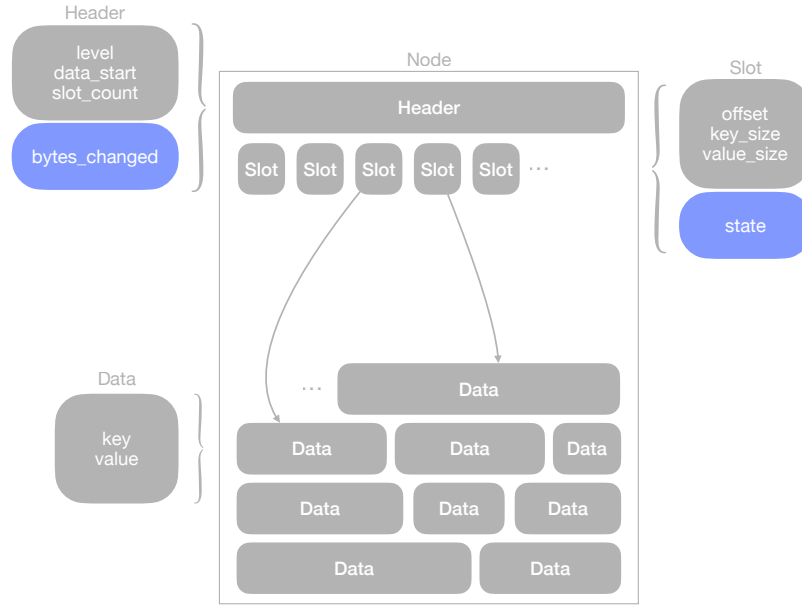


Figure 5.3: A B-tree with tracking enabled. The header is extended by a `bytes_changed` field to track the degree of write amplification on the page. Each slot is extended by a `state` field to track whether the corresponding entry is Unchanged, Inserted, Updated or Deleted.

Delta Tree

The Delta Tree is responsible for storing and applying the changes made to the B-tree nodes. It is also a B-tree but templated on a PID as KeyT and a variable-sized Delta array as ValueT.

The Delta array stores the changes made to the corresponding page in the B-tree. A Delta array can contain either `InnerNodeDeltas` or `LeafDeltas`. `InnerNodeDeltas` represent changes to inner nodes, therefore they store keys and PID changes. `LeafDeltas` represent changes to leaf nodes, therefore they store keys and TID changes.

Each Delta array stores the `slot_count` of the corresponding page in the B-tree at the

time of eviction. For `InnerNodeDeltas` we additionally store the upper child PID. We do not need to store the level of the node, as a page never changes its level. Therefore, we can retrieve this information from the B-tree when extracting or applying deltas. After extracting and storing the Deltas of a B-tree node in the Delta Tree, we can discard the node's page from the buffer manager without writing it to storage. When the node is loaded from storage again, we can apply the stored Deltas to reconstruct the state of the node at the time of eviction. In Section 5.2 we elaborate how we can reconstruct the state of a node from the information stored in the Delta Tree together with the disk-state of the node.

Database

Our database class ties all components together. It owns the buffer manager, the index and the slotted pages. It exposes a simple key-value interface to the user, allowing to insert, update, delete and lookup tuples by keys. The class is templated on the key type `KeyT` and the index type `IndexT`. For simplicity, we only support a single table and a single `uint64_t` value in our implementation. Through the `IndexT` template parameter, the user can choose between a standard B-tree or a 3B-tree as index structure.

Whenever a user requests an operation, the database class translates it into the corresponding operations on the index and the slotted pages.

5.2 Algorithms

In this section we describe the algorithms for the main operations of our 3B-tree. While most operations are similar to a standard B-tree [19], we describe how we extend them to support tracking changes and ensure that we do not lose any changes made to a node. We then describe how we use the tracking information in the B-tree nodes to extract deltas when evicting a node from memory and how we can reconstruct the state of a node when loading it from storage again.

We do not implement concurrency or node merges in our implementation and therefore do not describe them here. However, all algorithms were implemented with concurrency in mind and therefore can be extended to support it.

Lookup

A lookup operation is straightforward in a 3B-tree, we merely perform a standard B-tree lookup. We first access the root node and traverse the tree down to the leaf level, following the appropriate child pointers based on the key being looked up. We always perform binary search within a node to find the appropriate slot. Once we reach the

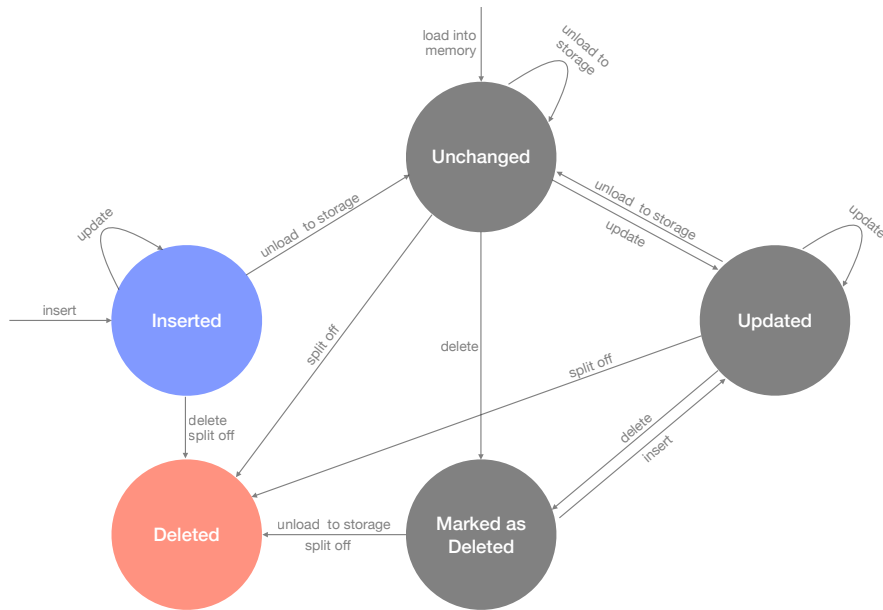


Figure 5.4: The state machine of a slot's state. The state always resembles the delta of a slot in comparison to its image on disk. Therefore, every slot starts in the Unchanged state when being loaded from memory. A slot's lifetime starts with an insertion (highlighted in blue). Its lifetime ends when the slot is deleted (highlighted in red). When a slot already exists on disk, we only mark it as Deleted to account for removing it when loading the node from storage again. When a page is written to storage, all Inserted and Updated slots are reset to Unchanged state.

leaf level, we perform a final binary search to find the key. If the key is found, we return the corresponding value, the TID. Since we return an `std::optional<ValueT>`, we can also indicate that the key was not found by returning an empty optional `nullopt`.

Tracking. Since we do not modify any nodes during a lookup, we do not need to update any tracking information.

Insert

To perform an insertion, we first traverse the tree down to the appropriate leaf node as described in the lookup operation.

Possibly, the leaf node does not have enough space to accommodate the new entry. In this case, we need to split the node first (see Split 5.2). Once we have an appropriate leaf node with enough space, we insert the new entry into the node.

Since we want to perform binary search within the node, we keep the slots sorted by key. Therefore, we search for the `lower_bound` of the new key to find the appropriate position in the slot array to insert the new slot. We then shift all slots after the insertion position by one to make space for the new slot. We then insert the new slot and the corresponding key and value into the data segment.

The property that slots are always sorted by key is important for the following algorithms.

Tracking. When inserting a new entry into a node, we need to update the tracking information accordingly. Firstly, we increase the `bytes_changed` field in the header by the size of the new entry and the size of the new slot. Secondly, we set the state field of the new slot to `Inserted`.

A new slot always starts in the `Inserted` state, as it does not exist on disk (see Figure 5.4). Any subsequent updates to this slot do not change this state, as to the disk image it is still a new slot. During delta extraction, we simply store the latest key and value of this new slot. If the new entry is deleted again before the page is evicted, we can simply discard the slot and do not need to store any delta for it. To the disk image, it is as if the entry was never inserted.

Update

To perform an update on an entry, we first traverse the tree down to the appropriate leaf node as described in the lookup operation. Once we reach the leaf level, we perform binary search to find the slot with the given key. If the key is found, we update the corresponding entry in the data segment. Our prototype only supports updates to

values of the same size as the old value. During node splits, for example, we must update the child pointers of the entries in the parent node (see Split 5.2). Alternatively, all updates can be implemented as a delete followed by an insert.

Tracking. When updating an existing entry in a node, we increase the `bytes_changed` field in the header by the size of the entry only if the entry was previously `Unchanged`. If the entry was previously marked as `Inserted` or `Deleted`, we do not increase the `bytes_changed` field, as we have already accounted for it.

We then set the state field of the slot to `Updated` if it was previously `Unchanged`. If the slot was previously marked as `Inserted`, we do not change its state, as to the disk image it is still a new slot.

Delete

To perform a delete operation, we would first traverse the tree down to the appropriate leaf node as described in the lookup operation. We then perform binary search to find the slot with the given key. If the key is found, we remove the slot from the array and the corresponding entry from the data segment. We do not reclaim the space in the data segment eagerly on every deletion. Instead, we compactify lazily. For example, during a node split we remove half of the slots and their data, justifying a compactification.

Tracking. While we do not implement deletion tracking in our current implementation, we describe how we would implement it here for completeness. When deleting an existing entry in a node, we increase the `bytes_changed` field in the header by the size of the entry and the size of the slot only if the entry was previously `Unchanged`. When it was previously `Inserted`, we decrease the `bytes_changed` field, since the insert never happened from the perspective of the disk image of the node. For the same reason, we only actually delete the slot and entry if it was also `Inserted` since its last write to storage. In any other case, we cannot immediately delete the slot. This is, because we must indicate the deletion to the Delta Tree. The entry exists on disk and without an entry to track the deletion, we would not be able to create a delta for it. When loading the node again from storage, the deleted entry would reappear. Therefore, we set the state field of the slot to `Deleted` instead. Only when the page is written to disk, we actually delete all slots marked as `Deleted` from the node. Should an insertion for the same key follow, we can simply reuse the slot marked as `Deleted`, changing its state to `Updated`. To the disk image, it is as if the entry was never deleted in between.

Split

When a leaf node does not have enough space to accommodate a new entry, we need to split the node first. To address the possibility of concurrent splits in the future, we use a restart mechanism. Our method is independent of the split strategy and can therefore be easily adapted to different strategies to optimize for concurrency for example.

We first traverse the tree down to the appropriate leaf node as described in the lookup operation. However this time, we keep track of the path taken down the tree and keep the pages fixed in memory. Once we reach the leaf level, we check whether the node has enough space to accommodate the new entry in the current iteration. Firstly, this is necessary in a concurrent setting, as another thread might have split the node in the meantime. Secondly, this is necessary, because splitting a leaf node once might not be enough to accommodate the new entry when supporting variable-sized entries. For example, we could have a new entry that is as large as the entire node. In that case, we would need to split the node multiple times until we reach an empty node.

If the leaf has enough space, we return. Otherwise, we split the node. We allocate a new sibling node and move half of the entries from the current node to the sibling. Then, the new PID of the sibling and the new fence key are propagated up the tree. The new fence key is the largest key in the left node after the split. We can move upwards now, since we locked the path exclusively when traversing down the tree. If the parent node does not have enough space to accommodate the new fence key and child pointer, we need to split the parent node as well. We repeat this process until we reach a node that has enough space in an upwards motion. Should we reach the root node and it does not have enough space, we create a new root node, increasing the tree's height by one. Once a node has enough space, we can insert the new entry and move back down the tree to insert the respective entries on each level. Again, we might need to split nodes on the way down again, since we support variable-sized keys. Therefore, we can repeatedly move down and up the tree until we reach the leaf level again. When reaching the leaf level, we repeat the process until the leaf has enough space to accommodate the new entry.

Finally, we insert the new entry into the leaf node.

Some implementations use "safe" inner pages that always have enough space to accommodate a new entry [19]. This simplifies the split operation, as we never have cascading splits that need to propagate up the tree. However, this is limited to fixed-sized keys. With variable-sized keys, we cannot know how much space we need to reserve in the inner nodes to accommodate a new fence key.

When creating a new node, we always write it out to storage on eviction. This is because new nodes carry enough information to justify the write. Also, it greatly simplifies tracking, since we can express all deltas as slot changes.

After splitting a node, we compactify the node to reclaim space from deleted slots and to defragment the data segment.

Tracking. Arguably, when splitting a node, about half of the node's entries are modified. We carry enough change on a node to justify a write-out of the page. We could therefore simply set the `bytes_changed` field in the header to the size of the node and stop tracking changes for that page. However, we leave it to the evaluation (see Chapter 6) to determine a reasonable threshold for the degree of change required to justify a write-out. Therefore, to investigate this, we implemented tracking for node splits.

When splitting a node, we delete half of the slots from the perspective of the current node. For each deleted slot, we increase the `bytes_changed` field in the header by the size of the entry and the size of the slot only if the entry was previously `Unchanged`. If the entry was previously `Inserted` or `Updated`, those `bytes_changed` were already accounted for.

As we discussed in the delete operation (see Subsection 5.2), we usually cannot actually delete the slots from the node, as we need to track the deletion as a delta to ensure that we do not make entries reappear when loading the node from storage again. However, we cannot mark the slots as `Deleted`, since that would keep the data in the node and therefore not free up any space, negating the purpose of a node split. For node splits we use a different approach. Due to the fact that slots are always sorted by key and we always split the node in half, we can use the `slot_count` field in the header to determine which slots are still part of the node and which slots were split off. Therefore, we do not need to keep any tracking information for the split off slots. Instead, we store the `slot_count` of the node at the time of eviction in the corresponding `Delta` array. When applying deltas to a node, we can use this information to determine which slots are still part of the node and which slots were split off. This way, we can discard split off nodes, freeing up space for new entries. To the new sibling node, the moved over slots are marked as `Inserted`. This is not necessary though when we create a new node, as new nodes are always written out to storage on eviction. At that point, all slots of the new node return to an `Unchanged` state.

Due to node splits, the `bytes_changed` field can become larger than the node's page size. Assume a node that is full on disk. When loading it into memory, we split it, counting the bytes of half of the slots that we split off. This should set the `bytes_changed` field to about 50% of the node size with fixed-sized entries. However, when we insert new entries into the node after the split, filling the freed space. This can increase the `bytes_changed` field to 100% of the node size. Assume that all these inserted entries are in the left half of the slots. This can happen because the slots are sorted by key and we might insert keys that are smaller than the keys in the right half. When splitting the

node again, we again count the bytes of half of the slots that we split off, exceeding the node size in the `bytes_changed` field. The key point here is the interpretation of the `bytes_changed` field. It is not a precise measurement of the actual bytes changed. It is an indicator of how much change we have carried on the page since the last write to storage. This helps us to decide whether a write is justified or not.

Tracking Inner Node Changes. As described above, when a child node splits, we need to insert the new fence key and new child pointer into the parent node. The key that is already present in the parent node remains unchanged, as it still forms the upper bound of that range. However, it is now the upper bound of the new sibling node. Therefore we perform an update on the existing slot, changing the child pointer to the new sibling node. The tracking information for that node changes according to the update operation described above. The new fence key is now the upper bound for the split node. Therefore, we insert a new slot into the parent node with the new fence key and the old child pointer. The tracking information for that node changes according to the insert operation described above. This shows that tracking changes in inner nodes is similar to tracking changes in leaf nodes.

Compactification

To reclaim free space, we compactify a node by defragmenting the data segment. Fragmentation in a node occurs through deletions, since we do not reclaim the space in the data segment eagerly. This would require moving possibly all entries in the data segment and updating the corresponding slots. This would be an expensive operation to perform on every deletion. Instead, we perform compactification lazily, for example after a node split. After a node split, half of the slots are removed from the node, freeing up a significant amount of space. More importantly, we split a node in particular to free up space for new entries.

First, we collect pointers to all slots that still point to valid entries. We also collect slots marked as `Deleted`, as we need to keep them in the node until the page is written back to storage to track the deletion as a delta. We then sort them by their offset in the data segment, starting with the highest offset. Then, we move the entries to the end of the data segment, updating the corresponding offsets in the slot accordingly. Finally, we update the header to point to the new start of the data segment.

Tracking. Since compactification only moves entries around in the data segment, we do not change the node logically. Therefore, we do not change any tracking information. However, compactification is an expensive operation and reclaiming space is important to keep the fanout of the tree high. We would like to maintain the space gains from

compactification also after discarding the page and loading it again from memory. Therefore it makes sense to always write out a page after a node split, as a node split usually carries enough information through its structural changes to justify the write. If we require more than 50% change on the page to perform a write-out, this would be a given, since we change half of the node during node splits. In Chapter 6 we will see that requiring a degree of change of less than 50% is a reasonable threshold to perform a write-out.

Eviction

When the buffer manager evicts a B-tree's node from memory, it evokes the injected Delta Tree. It needs to decide whether to write out the page to storage or not. To that end, we calculate the degree of change, by comparing the `bytes_changed` field in the header to the size of the node.

$$\text{degree_of_change} = \text{bytes_changed} / \text{page_size}$$

The Delta Tree is passed a threshold parameter *write_threshold* between 0.0 and 1.0. It determines the minimum *degree_of_change* required to justify a write-out of the page. *write_threshold* = 0.0 means that we always write out the page to storage and never store deltas. High thresholds (e.g. over 50%) are not expected to be useful in practice, as this will simply move write amplification to the Delta Tree. However, we want to evaluate all ranges of thresholds to understand the trade-offs in Chapter 6. Therefore, we allow the user to configure this threshold freely.

Resetting Deltas

If $\text{degree_of_change} > \text{write_threshold}$, we write the page to storage. In that case, we scan the slot array of the node and reset all tracking information: We set all slots to Unchanged state. We remove all Deleted slots from the node, as they are now actually deleted from the disk image of the node. We set the `bytes_changed` field in the header to 0. Finally, we erase any corresponding deltas for this page from the Delta Tree, as they are now obsolete. We can perform a standard B-tree deletion. We indicate to the buffer manager to continue writing the page to storage.

Extracting Deltas

If $\text{degree_of_change} \leq \text{write_threshold}$, we extract all deltas from the node and store them in the Delta Tree. We scan the slot array of the node and for each slot that is not Unchanged, we create a corresponding delta. The resulting delta array is then stored in

the Delta Tree with the node's PID as key. This is done with a standard B-tree insertion. Finally, we indicate to the buffer manager to discard the page without writing it to storage.

Applying Deltas

When the buffer manager loads a B-tree's node from storage, it invokes the injected Delta Tree to apply any stored deltas to the node. We first check whether there are any deltas stored for the node's PID in the Delta Tree. If not, we are done. Otherwise, we apply the deltas to the node. In the end we cut off any slots that were split off during a node split by using the stored `slot_count` in the delta array. Since we apply inserts and updates before cutting off split slots, we can ensure that we do not let any entries reappear that were actually split off. This must be correct, since we only store deltas for slots that are still part of the node at eviction time. Everything beyond the stored `slot_count` was split off and therefore cannot be part of the node.

Temporary Size Exceeding

When applying deltas to a node, we can exceed the node size temporarily. For example, we could have a node that is full on disk. In memory it had been split and then some insertions followed. When reconstructing the node from disk, we first load the full node from storage. We must first apply the deltas (insertions, updates, deletes) before we can cut off the split slots. This is because the `slot_count` only indicates which slots are still part of the node having applied the deltas. Therefore, we can exceed the node size while applying deltas and before cutting off split slots.

To address this, we allow exceeding the node size temporarily when a node becomes full while applying deltas: When inserting a new slot, we first check whether there is enough space in the node. If enough space is available, we proceed as usual. If not, we copy the current state of the node into a temporary buffer. The buffer is large enough to hold all deltas of the node. We then apply all remaining deltas into the temporary buffer. Once all deltas are applied, and split slots are identified, the original node size must be sufficient to hold all remaining slots. This is because the node was able to hold all remaining slots at eviction time. We compactify the temporary buffer to reclaim any space from deleted slots and then copy the compactified state back into the original node.

Deleting Deltas

After applying deltas to a node, we could delete the corresponding deltas from the Delta Tree. However, we decided against this for the following reasons: Assume a node

is written to in memory and then evicted. Its deltas are extracted and stored in the Delta Tree. Later, the node is loaded from storage again. Now, this node is needed again, loaded into memory but only read from until the next eviction. If we had deleted the deltas after applying them, we would need to extract and store them again, dirtying the page. This would introduce unnecessary overhead. Instead, by keeping the deltas in the Delta Tree after applying them, we can simply discard the page when evicting it again without any changes. We can keep the page in a clean state to the buffer manager. Therefore, after applying deltas to a node, we keep the corresponding deltas in the Delta Tree. Only when a node is written to again, we update the deltas in the Delta Tree accordingly during the next eviction. When a node is written to storage again, we delete the corresponding deltas from the Delta Tree.

5.3 Testing

All components of our system are covered by unit tests. We used the Google Test framework to write and run our tests. We tested the buffer manager, the slotted pages, the B-tree, and the 3B-tree separately. We also wrote integration tests to test the interaction between the components.

6 Evaluation

6.1 Experimental Setup

Since we are interested in write amplification, we observe the number of page writes to disk for different workloads and different memory limitations. This way, our results are not biased by the specific implementation, optimizations, and hardware that we run our experiments on. All experiments were conducted locally on a Apple MacBook Pro with the specification listed in Table 6.1.

Table 6.1: Hardware Specifications

Component	Specification
Device	Apple MacBook Pro (2021)
Processor (CPU)	Apple M1 Pro (8-core, up to 3.2 GHz)
GPU	Integrated 14-core Apple GPU
Memory (RAM)	16 GB
Storage	512 GB NVMe SSD
Operating System	macOS Sonoma 14.6.1

6.2 Workloads and Datasets

We evaluate our approach on synthetic and real-world datasets. The real-world dataset allows us to evaluate our approach on realistic data distributions and access patterns. With the synthetic dataset, we can control the data distribution to evaluate the performance of our approach under different scenarios. This allows us to identify the strengths and weaknesses of our approach.

We will be evaluating our system as a whole, benchmarking the database with the different indices to gain a holistic view of the performance. To take a closer look at the indices themselves, we will also be benchmarking the indices in isolation, without the overhead of the database system. For example, when benchmarking the whole database, we have to maintain the table data as well as the index, which introduces

additional overhead. When benchmarking the index in isolation, we can focus on the performance of the index itself.

Wikipedia Pageviews Workload

We use an augmented Wikipedia Pageviews dataset [7] as a real-world dataset for our evaluation. The primary goal of this dataset is to evaluate the performance of our approach on realistic data distributions and access patterns. The dataset contains pageview statistics for all Wikipedia articles within a certain time frame. It is publicly available and can be downloaded from the Wikimedia Dumps website¹. Each pageview record is of the form

en Google_Chrome 10406 0

consisting of the domain code, the page title, the number of views, and the total response size in bytes.

Data Augmentation

We use the hourly Pageview Wikipedia dataset from 1st of October 2025 at 00:00 UTC as our base dataset. We augment the dataset in the following way:

1. We filter out all non-English articles, i.e., we only keep articles with the domain code en.
2. For benchmarks with integer keys, we turn the page title into an integer key. For benchmarks with variable-sized keys, we use the original page title as key.
3. We create a lookup operation for each view of an article, i.e., if an article has 100 views, we create 100 lookups for that article.
4. To generate a mixed workload, we turn a certain percentage of the lookups into updates. This assumes that an article with more views is more likely to be updated.
5. We then shuffle the operations to create a mixed workload.
6. To create a smaller dataset, we take a random fraction of the articles as samples.

To populate the database, we insert all articles from filtered dataset once. We then run the workload on the database or on the indices directly.

¹<https://dumps.wikimedia.org/other/pageviews/>

Workload Characteristics

The resulting workload has the following characteristics:

- The dataset contains 59,240 distinct articles, translating to 59,240 distinct keys in the database.
- The workload contains 146,068 views in total.
- The keys follow a Zipf-like distribution, i.e. a small number articles are very popular and receive a large number of operations, while the majority of articles receive only a few.
- In fact, 40,670 articles (~69%) are viewed only once in the dataset. The most viewed article, *Jon_Stewart*, received 2,998 views (~10% of all views).
- **Update workload:** We transform 7,303 lookups into updates (~5%) by default. When mentioned, we vary the update ratio from 0% to 100%.
- With an update ratio of 5%, we update 5,724 distinct articles (~10% of all articles) in the generated workload, whereas the majority of articles (~86%) are only updated once. The most frequently updated article, *Jon_Stewart*, is updated 132 times (~10% of all updates).
- **Insert workload:** To evaluate the performance of our approach on insert-heavy workloads, we create a workload with 100% inserts as well. In this workload we insert all articles of the sample into an empty database or index.
- The keys are variable-sized strings with an average length of 20.5 characters, a maximum length of 236 characters and a minimum length of 1 character.

6.3 Results and Analysis

In this section, we present the results of our benchmark experiments and analyze the performance of the B-tree and 3B-tree indices. Our primary metric for this evaluation is the number of page writes to disk, which we aim to reduce. We also analyze the space overhead and read amplification introduced by our approach.

The goal of this evaluation is to determine whether the 3B-tree can reduce page writes compared to a traditional B-tree under different workloads and memory constraints. Additionally, we want to understand the trade-offs involved in using a 3B-tree.

6.3.1 Write Amplification

For a first analysis, we consider the write amplification of the B-tree and 3B-tree indices when running the mixed Wikipedia Pageviews workload on the database. We run the workload with 4 KB pages, a buffer pool of 500 pages, and a write threshold of 5% (i.e. we only write pages to disk if at least 5% of the page has been modified in the case of a 3B-tree index). We compare the number of page writes to disk for both indices. To gain a holistic view of the performance, we run the workload on the database as well as on the indices directly. The results are shown in Figure 6.1. When running the workload on the database as a whole (Figure 6.1a), we see a reduction in page writes of ~23% when using the 3B-tree compared to the B-tree. When running the workload on the indices directly (Figure 6.1b), we see a more significant reduction in page writes of ~66% when using the 3B-tree compared to the B-tree.

There are two main reasons for the difference in write amplification reduction between the two scenarios.

1. **Relative Impact:** Firstly and more obviously, when running the workload on the database, we have more pages in the system that are not affected by our method. Our method effects a smaller fraction of the total number of pages in the buffer, therefore our relative impact is naturally smaller. When running the workload on the indices directly, we can focus on the performance of the method itself without the overhead of maintaining the table data. Therefore, we will focus on the results when running the workload on the indices in isolation in the following analysis.
2. **Memory Constraints:** More importantly, the indices have different memory constraints in the two scenarios. When running the workload on the database, the indices have to share the buffer pool with the table data. When running isolated, the indices can use the full memory available in the system. In the metrics collected during the benchmark runs, we could see that we have 10-15% higher buffer hit rates when running the workload on the indices directly. While both indices have the same memory available and higher buffer hit rates when running isolated, the 3B-tree performs better in terms of write amplification reduction.

These findings indicate that the 3B-tree can significantly reduce write amplification compared to a traditional B-tree, especially when the index can effectively utilize the available memory. To investigate this further, we will run the workload under different memory constraints in the following section.

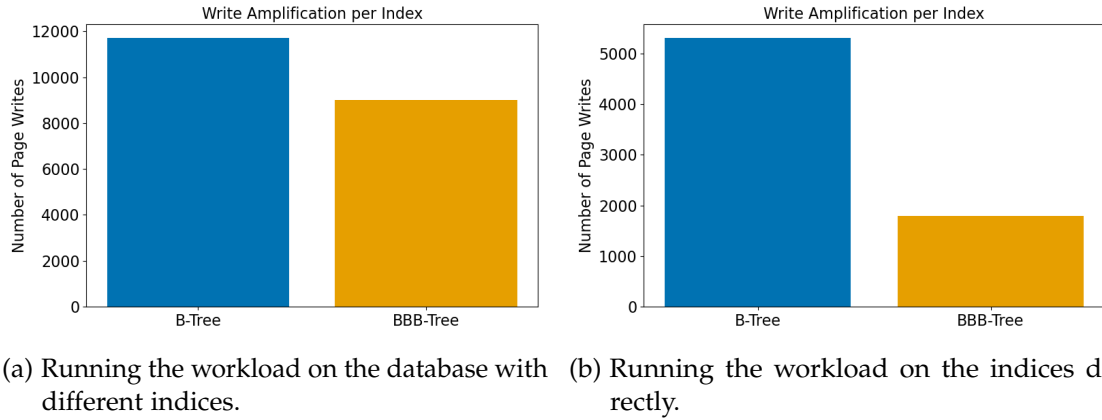


Figure 6.1: Running the mixed Wikipedia Pageviews workload with 5% updates, 4 KB pages, a buffer pool of 500 pages, and a write threshold of 5%. We see a significant difference in write amplification reduction when running the index as part of the database vs. running it in isolation.

Different Memory Constraints

To understand the impact of memory constraints on the performance of the 3B-tree, we run the same workload with different buffer pool sizes. The workload produces a B-tree of 606 nodes in total. We vary the buffer pool size from 50 to 700 pages, while keeping the page size at 4 KB. The results are shown in Figure 6.2.

Low Memory Capacity. With a buffer pool of 50 to 100 pages, we have little memory to cache changes. The 3B-tree suffers from the limited memory more than the B-tree and we even see an increase in page writes. This is, because with every load and eviction of a B-tree page, we have to perform operations on the Delta Tree, loading additional pages into memory. This reduces the chances of caching any updates in memory. Our method aims to only introduce overhead to the point in time of B-tree page swaps. If we constantly swap pages in and out of the buffer pool to perform any operation, we introduce more overhead.

For example, consider two temporally close updates to the same B-tree node. The traditional B-tree has a higher chance to batch these updates into a single page write. With the 3B-tree however, the first update is more likely to be written to disk before the second update arrives, since we have more page swaps, leading to two page writes instead of one. With very limited memory, we amplify the write amplification in the system.

Let us assume we do not cache any pages in memory, we only hold those pages that

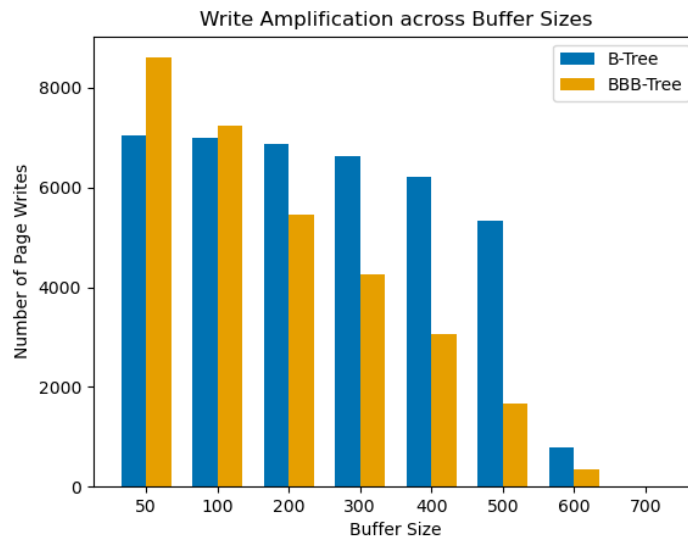


Figure 6.2: The impact of buffer pool size on the amount of page writes per index with a 4 KB page size and a 5% write threshold. The 3B-tree performs better with higher buffer pool sizes, as it can accumulate more changes in memory before writing them to disk. When the buffer fits the whole index, we perform no page writes at all.

we need to perform the current operation and evict them immediately afterwards. Given a B-tree of height h and a Delta Tree of height d , we can analyze the memory requirements for updating a leaf node in the B-tree. To update a leaf node in the B-tree, we have to fix h pages in memory (one for each level of the tree). For every node that we load from disk, we have to check the Delta Tree for any updates to apply. This means that we need a total of $h * d$ pages loads to perform an update. This is a worst case scenario that we approach when we have very limited memory. If we have a B-tree of height 3 and a Delta Tree of height 2, we need to load $3 * 2 = 6$ pages to perform any operation on the B-tree. With a sufficient amount of memory, we can assume that inner nodes are already in memory, reducing the number of page loads to $1 + 1 = 2$. As soon as we have enough space to cache pages effectively, we can start to accumulate changes in memory and reduce page writes.

This makes one trade-off of our method very clear: We sacrifice some space in memory to cache and batch changes. This means that we have less memory available to cache B-tree pages. Therefore, we need to swap B-tree pages more often, leading to more page writes. Only with the ability to hold changes in memory long enough to batch them, we can reduce the page writes in total. In a very low memory setting, we introduce more page writes than we save.

Full Memory Capacity. When the buffer pool can hold the whole B-tree (700 pages), we perform no page writes at all with the 3B-tree, as all changes can be accumulated in memory. In this scenario, the Delta Tree remains empty and the 3B-tree is obsolete. However, we noticed in our benchmarks that the 3B-tree does not introduce significant overhead when the whole index fits in memory. When initially loading pages into memory, we have to perform one lookup into the empty Delta Tree for each B-tree node. However, once the buffer cache is hot and all pages are loaded into memory, we do not have to perform any additional operations on the Delta Tree, as all changes can be applied directly to the B-tree nodes in memory. The only overhead that remains is tracking the changes to the B-tree nodes. In the benchmarks, we see that the 3B-tree is $\sim 0.67\%$ slower than the B-tree in this scenario.

Restricted Memory Capacity. With reasonably limited memory capacities (200-600 pages), we see a significant reduction in page writes with the 3B-tree compared to the B-tree. With a buffer pool of 500 pages, we see a reduction in page writes of $\sim 66\%$ with the 3B-tree compared to the B-tree. The larger the available memory, the more changes we can accumulate in our Delta Tree before writing them to disk. We achieve the batching effect that we are aiming for, leading to fewer page writes. This shows that our method can effectively utilize the available memory to reduce write amplification in memory-constrained settings. We require about $1/4$ of the index fit in memory to

see significant improvements and it defers page writes best when 2/3 of the index fit in memory.

Summary. To summarize, the 3B-tree aims to reduce write amplification in memory-constrained settings where the entire dataset cannot fit in memory. Its efficiency depends on caching mechanisms that group updates into fewer page writes. This optimization is achievable only when enough memory is available for effective caching.

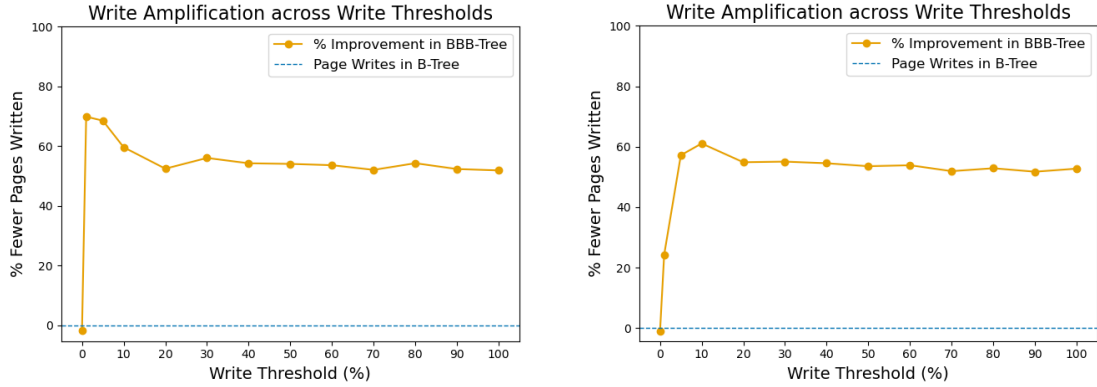
Different Write Thresholds

To understand the impact of the write threshold on the performance of the 3B-tree, we run the same workload with different write thresholds. We fixate the buffer pool size at 500 pages and the page size at 4 KB. To repeat, the write threshold defines the minimum percentage of a page that has to be modified before we write it to disk. When it is smaller than the threshold, we accumulate the changes in the Delta Tree and defer the write. For the baseline B-tree, the write threshold has no effect, as we always write every change to disk immediately. We vary the write threshold from 0% to 100%. The results are shown in Figure 6.3.

Without Buffering. With a write threshold of 0%, we write every changed page to disk immediately, just as a traditional B-tree would. We can see a few more page writes with the 3B-tree even, because we have a slightly smaller fanout due to the additional space required for tracking changes. We will analyze the space overhead of the 3B-tree in more detail below (see Subsection 6.3.2).

With Buffering. Starting from a write threshold of 1%, we can accumulate changes in the Delta Tree and reduce page writes significantly. In fact, 1% is the most significant step in reducing page writes of ~70% compared to the B-tree. With higher write thresholds, we accumulate more changes in the Delta Tree before writing them to disk, however the improvements become smaller. There are three reasons for the diminishing return with increasing write thresholds:

1. **Fewer Changes Fit into a Page:** We achieve our goal of reducing page writes when we can accumulate changes on y pages into a single page of the Delta Tree, where $y > 1$. We can then save up to $y - 1$ page writes. However, with larger write thresholds, fewer pages' changes fit into a single page. For example, with a 1% threshold, we can fit 100 pages' changes into a single 4 KB page, while with a 25% threshold, we can only fit 4 page's changes in the worst case. The maximum accumulation factor y decreases with larger write thresholds, leading to fewer potential savings in page writes.



(a) Workload: 5% updates & 95% lookups. Buffer Size: 500 pages. Page Size: 4 KB.
 (b) Workload: 100% inserts. Buffer Size: 300 pages. Page Size: 4 KB.

Figure 6.3: The impact of different write thresholds on the amount of page writes per index on two different workloads. At 0% threshold, we write every B-tree node to disk after every change, leading to no improvement in write amplification. With higher thresholds, we can accumulate changes before writing them to disk, leading to significantly fewer page writes. Both workloads show similar trends, with the 3B-tree performing best with small write thresholds.

2. **Less Likelihood to Batch Changes:** With fewer changes fitting into a single page, the likelihood of batching changes in between Delta Tree page writes decreases. For example, assume a Delta Tree node d that holds x delta arrays for x B-tree nodes. This means, at some point x B-tree nodes have been modified. However, this does not directly translate to x saved page writes, because d itself might have been written to disk before all x B-tree nodes were modified. Therefore, we only batch changes that happen between two writes of d . When d holds the changes of 100 B-tree nodes, the likelihood of batching changes is much higher than when d only holds the changes of 4 B-tree nodes. On average, we can save $\frac{y-1}{s}$ page writes per Delta Node d , where s is the number of times d has been written to disk.
3. **More Leaf Nodes in Delta Tree:** Additionally, with larger deltas, we require more leaf nodes in the Delta Tree to address all changes. This introduces more page overhead in the system, leading to more page writes. (The fanout itself is not affected, since inner nodes only hold fixed size PIDs as keys. The variable-sized deltas are only stored in the leaf nodes, so more pages need to be addressed by

the Delta Tree.)

Stagnating Improvements. For all three reasons, we should see smaller improvements, the larger the write threshold becomes. However, the improvements we see more or less stagnate after a write threshold of 20%. The reason is that we do not see many pages that are modified more than 20% between page writes. In Table 6.2, we can see the distribution of the modification degree for all modified B-tree nodes at the time of eviction. There are two reasons why we only see a small degree of change for most pages:

1. **Zipf-like Distribution:** Due to the Zipf-like distribution of the keys in the workload, a small number of very popular articles receive a large number of operations, while the majority of articles receive only a few. With an update ratio of 5% of all operations in the workload, most articles are not updated at all (~90%). Naturally, with updates scattered across the index, most pages are only slightly modified between page writes.
2. **Pages are Written Before They Reach the Write Threshold:** However, with a write threshold of 100%, we should never write a B-tree page to disk for the full workload (unless its new or it reaches a modification degree over 100%). We would expect at least some pages to be modified more than 20% within the workload. In Table 6.2, we can see the distribution of the modification degree for all modified B-tree nodes at the time they are unloaded to the Delta Tree. To emphasize, this table shows the degree of change for pages at the time they are evicted and the changes written to the Delta Tree. Therefore it only count the pages that are inserted into the Delta Tree, not the pages that bypass the Delta Tree and are directly written to disk. We can see that the Delta Tree only receives small deltas from the B-tree for the vast majority of nodes across workloads. Even in a workload with 100% inserts, where some nodes experience a lot of changes such as node splits, we see that they do not end up in the Delta Tree. One reason is that we write new pages to disk immediately at eviction. Another reason is that node splits combined with many inserts introduce change degrees over 100% for a page, which is higher than the write threshold of 100% and therefore is written to disk. Lastly, we sometimes have to write B-tree nodes to disk even though their degree of change is below the write threshold. Sometimes we have to lock the Delta Tree to protect against recursive evictions that want to modify the Delta Tree. For example, when a B-tree node is evicted and its delta is inserted into the Delta Tree, this might cause a split in the Delta Tree. The split causes a new node to be created, which has to be inserted into the B-tree. In this moment, the Delta

Tree is in an incomplete state and cannot be accessed by other operations. However, the newly created node can trigger another eviction in the buffer manager, which might evict a modified B-tree node. This modified B-tree node cannot insert its delta into the Delta Tree, as it is currently experiencing structure modifications and therefore is locked. In such cases, we force B-tree nodes to disk even though their degree of change is below the write threshold.

While investigating, we observed that every B-tree node is forced to disk at least once during the workloads for one of these reasons. Therefore, we never see high degrees of change for any page, as we write them to disk before they can accumulate more changes.

Modified	Num. Pages		
	5% Updates	100% Updates	100% Inserts
0–10%	5274	38530	6462
10–20%	670	1906	1892
20–30%	1	61	586
30–40%	0	1	129
40–50%	0	0	39
50–60%	0	0	156
60–70%	0	0	51
70–80%	0	0	3
80–90%	0	0	0
90–100%	0	0	0
>100%	0	0	0

Table 6.2: Distribution of B-tree pages by their modification degree (percentage intervals) when being unloaded to the Delta Tree with a Write Threshold of 100% for different workloads. The majority of pages are only slightly modified between writes, even with a workload of 100% inserts. Pages are unloaded to disk before they can accumulate more changes.

We would require a workload with more spatial locality to change many entries in the same page across the tree. However, this is not the case in the Wikipedia Pageviews workload. The workload has high temporal locality, as popular articles are viewed and updated more frequently. However, targeting the same article only modifies a single entry in a single page. Other updates likely refer to other pages, leaving the pages with small degrees of change. A situation where our method can reduce write amplification

significantly. For more sequential updates, the traditional B-tree already performs very well, as it can batch changes effectively due to the temporal and spatial locality of the workload. Therefore, we cannot expect to see significant improvements with very high write thresholds in such a workload.

Summary. Our method performs best with small write thresholds. The sweet spot for the write threshold is between 1% and 5%, where we can achieve significant reductions in page writes without introducing too much space overhead in the Delta Tree. We continue with a write threshold of 5% in the following experiments, as it leads to the highest write amplification reduction.

Different Read/Write Ratios

To understand the impact of different read/write ratios on the performance of the 3B-tree, we run the same workload with different update ratios. We fixate the buffer pool size at 500 pages, the page size at 4 KB, and the write threshold at 5%. We vary the update ratio from 0% to 100%, i.e. we run workloads with only lookups, only updates, and mixed workloads in between. The results are shown in Figure 6.4. We measure write amplification as the ratio of total bytes written to disk over the total bytes of the entries we modify in the index.

In a read-only workload we perform no page writes at all as expected. With writes present in the workload, we see a significant reduction in page writes with the 3B-tree compared to the B-tree. The write amplification itself is higher for fewer updates, as we scatter small writes across the index, leading to more pages written for a small set of updates. Here the 3B-tree can reduce write amplification by up to ~70% by batching them to fewer pages in the Delta Tree. With more updates, more entries are modified in the same pages, leading to lower write amplification. The 3B-tree can still reduce write amplification by ~50% in a workload with 100% updates. Even though we update every entry in the index with this workload, the 3B-tree can defer the page writes until more changes have accumulated, while the B-tree writes its pages to disk immediately upon eviction.

6.3.2 Space Utilization

To track changes we need to store additional metadata in the B-tree nodes. This introduces a fixed overhead per B-tree node.

Tracking Modified Entries. Firstly, we store the state of each entry in the B-tree node to track whether it has been modified or not. We inject this information into the slot of each entry. As mentioned in Chapter 5, we can use 2 bits to encode each

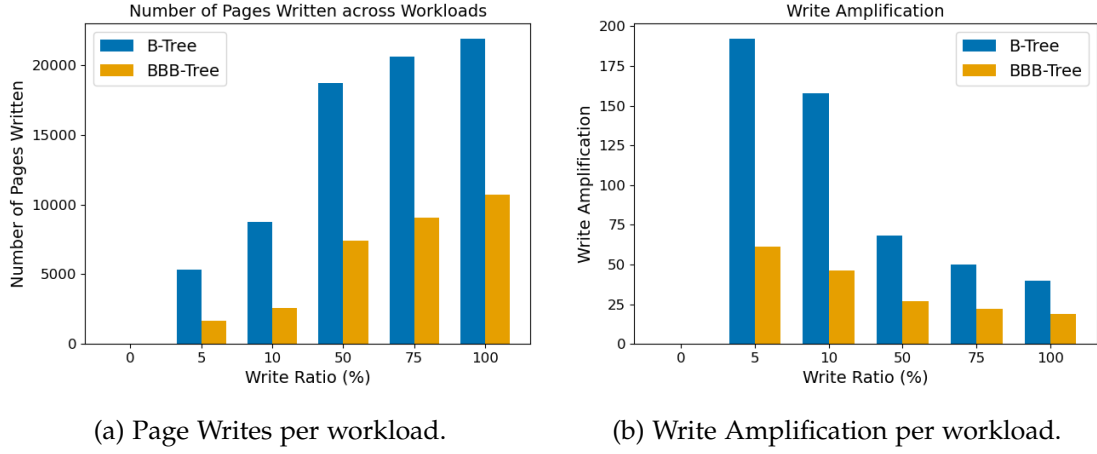


Figure 6.4: Page Writes and Write Amplification of the B-tree and 3B-tree with different write/read ratios in the workload. Without updates we have no page writes and therefore no write amplification. While page writes increase with more updates, write amplification decreases, as more changes happen in the same pages. The 3B-tree can reduce write amplification significantly across all workloads.

state (Unchanged, Inserted, Updated, Deleted). Since the slot data layout is critical to maximize fanout, we hide this information in the existing slot structure. We use the two most significant bits of the offset to store the state.

Tracking Degree of Change of Nodes. Secondly, we track the degree of change for each node. To that end we store a counter in each B-tree node that tracks the approximate number of bytes that have been modified since the last write to disk. This counter is used to determine whether the write threshold has been reached and the node needs to be written to disk. We use a 16-bit unsigned integer for this counter, which allows us to track changes up to 65535 bytes. This is sufficient for our use case, as we can track changes up to 100% of a 16 KB page. More realistically though, we do not want to track changes beyond 50% of a page, therefore we could even track larger page sizes with this counter.

This means that our implementation introduces a fixed overhead of 2 B per node. However, this does not affect the fanout of the index significantly. In some scenarios, it does not affect the fanout at all. For example, when we store entries of fixed size 16 B (8 B key, 8 B value) on 4 KB pages as we do in our previous benchmarks. On a leaf node, each entry requires 24 B, a slot of 8 B (4 B offset, 2 B key size, 2 B value size) and the data of 16 B (8 B key, 8 B value). Therefore, our B-tree leaf nodes can hold 170 entries on

a 4 KB page. With a header of 12 B, a full leaf node occupies $12B + 170 * 24B = 4092B$. With the additional overhead of 2 B per node, $4092B + 2B = 4094B < 4096B$, we can still fit the same amount of entries on a page. The same applies to inner nodes. In this scenario, we do not lose any fanout due to the additional overhead. However, in other scenarios we might lose one entry per node due to the additional overhead. With a 4 KB page and 170 entries per node, losing one entry means a loss of $\sim 0.6\%$ in fanout.

6.3.3 In-Memory Overhead

To analyze the memory overhead of tracking changes on the pages in memory, we run the mixed Wikipedia Pageviews workload purely in memory, once on a B-tree with tracking enabled and once on a B-tree without tracking. The B-tree without tracking does not have a Delta Tree attached, so we can see the pure overhead of tracking changes in the B-tree nodes. We fixate the buffer pool size to 600 pages to ensure that the whole index fits in memory. This way we can look at the pure memory overhead without the influence of page swaps. The results are shown in Table 6.3. We see that the overhead of tracking changes in memory is negligible.

Index Type	Time
B-tree without Tracking	13.54 ms
B-tree with Tracking	13.55 ms (+0.07%)

Table 6.3: Time to insert the Wikipedia Pageviews workload on an empty B-tree with and without tracking changes. The buffer manager fits the whole index in memory. The memory overhead of tracking changes is negligible.

6.3.4 Read Amplification

Looking at write amplification does not give the full picture of the performance of the 3B-tree. We need to consider the read amplification that we introduce as well. For the purpose of this analysis, we define read amplification as the ratio of page reads we add compared to the traditional B-tree.

We introduce read amplification in the following way: Everytime we load a B-tree page from disk, we have to check the Delta Tree for any changes that need to be applied. Everytime we unload a B-tree's dirty page, we either delete its delta from the Delta Tree (if the page is written to disk) or insert/update its delta in the Delta Tree (if the page is not written to disk). Since we have less space in memory for B-tree pages, we have to swap B-tree pages more often. Therefore, we have more operations on the Delta Tree.

Any of the nodes in the Delta Tree that we access might not be in memory, leading to additional page reads.

We have illustrated the page traffic in the buffer pool in Figure 6.5 for a mixed workload with 5% updates.

The Delta Tree is ~6% of the size of the B-tree (30 nodes vs. 502 nodes). We limited the buffer pool to 200 pages. As expected, the 3B-tree has more total buffer accesses due to the Delta Tree. The accesses by the B-tree are the same for both indices, since they process the same workload. Since the buffer pool is shared with the Delta Tree, the 3B-tree has slightly less space to cache B-tree pages, leading to slightly more buffer misses for B-tree accesses. Each B-tree page read is amplified further by the additional accesses to the Delta Tree that each B-tree page read causes. As we can see, most accesses to the Delta Tree are already buffered, since the Delta Tree is small in both cases. While the additional buffer misses seem small compared to the buffer hits, they are significant in absolute terms. After all, every buffer miss translates into an I/O operation to read the page from disk and potentially another I/O operation to write a dirty page back to disk to make space in the buffer pool.

For read amplification to remain low, we need to be able to cache the Delta Tree effectively in memory. If we can cache most of the Delta Tree pages in memory, we only introduce a small number of additional page reads. Therefore, the size of the Delta Tree compared to the available memory is critical to keep read amplification low. This is another reason to keep the write threshold small, as it keeps the Delta Tree small. We can analyze the maximum size of the Delta Tree given the write threshold and the size of the B-tree: Every node in the B-tree can produce deltas of the maximum size of $write_threshold * page_size$ that need to be stored in the Delta Tree. Therefore, the maximum size of all deltas is $write_threshold * page_size * num_btree_nodes$, which the Delta Tree has to store. Since the Delta Tree has the same page size as the B-tree, we can calculate the maximum number of leaf nodes in the Delta Tree (we neglect the space overhead of storing deltas in nodes for simplicity here):

$$num_delta_leaf_nodes = write_threshold * num_btree_nodes$$

With a write threshold of 5% for example, the number of leaf nodes in the Delta Tree are around 5% of the total nodes of the B-tree. If 1% of the B-tree nodes are inner nodes, we can assume that that inner nodes are always cached in memory. Therefore, we can simplify the number of Delta Tree nodes to:

$$num_delta_leaf_nodes = write_threshold * num_btree_leaf_nodes$$

We have shown in a previous section that the write threshold should be kept small to maximize write amplification reduction. Also, we have seen that the amount of change

per page usually remains small between page writes, leading to small deltas even with higher write thresholds. Therefore, we can keep the Delta Tree small compared to the B-tree, allowing us to cache it effectively in memory and keep read amplification low.

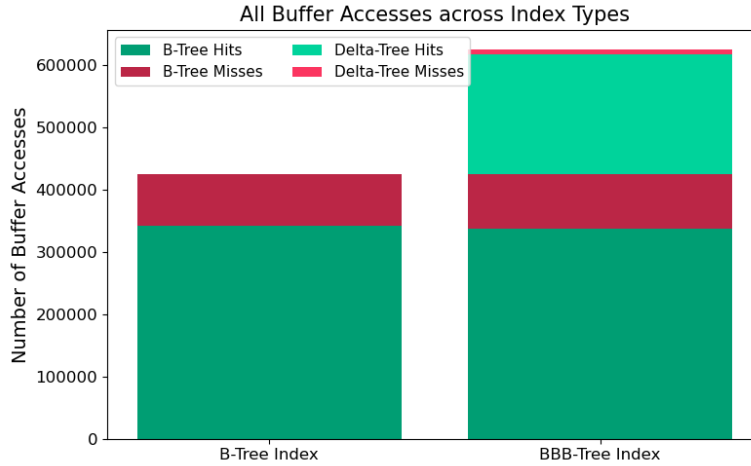


Figure 6.5: Total Buffer Accesses per index, separated into B-tree accesses and Delta Tree accesses and their respective buffer hits and misses. Both indices have the same amount of B-tree accesses (since they process the same workload), however the 3B-tree causes more buffer misses since it also buffers the Delta Tree. This benchmark runs with a buffer pool of 200 pages, a page size of 4 KB, and a write threshold of 5%. The B-tree has 502 nodes.

To repeat, while we can cache most of the Delta Tree in memory, we still introduce some additional page reads due to the introduced page overhead. We have illustrated the total I/O operations, separated in reads and writes, in Figure 6.6 for different update ratios in the workload. We can see that the baseline B-tree performs the same amount of reads across all workloads, since the workload size and the index size remain the same. We only change the amount of updates in the workload, which affects the amount of writes. In contrast, the 3B-tree perform more reads the higher the update threshold is, due to the read amplification we introduce. However, the more writes we have in the workload, the more writes we can save with the 3B-tree. The read amplification is up to ~33%, while the write reduction is up to ~62%.

These findings show that the 3B-tree is not always beneficial in every scenario. While we can reduce write amplification significantly, we introduce read amplification in the process. Only in workloads where we have enough writes to compensate for the additional reads, we can achieve a net reduction in I/O operations.

We can express this trade-off in a payoff condition for our method. Consider a workload

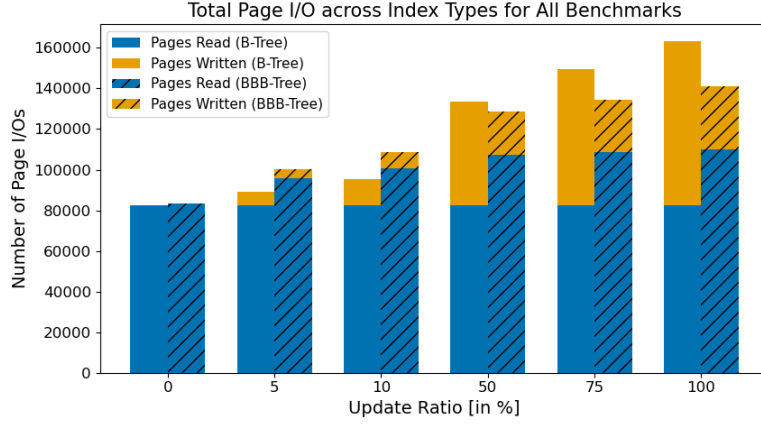


Figure 6.6: Total I/O operations per index, separated into reads and writes with different update ratios in the workload. When we introduce more page reads than we save page writes, we have more total I/O operations. This benchmark runs with a buffer pool of 200 pages, a page size of 4 KB, and a write threshold of 5%. The B-tree has 502 nodes.

consisting of *reads* read operations and *writes* write operations. The proposed method amplifies reads by a fraction *read_amplification* (expressed as a percentage) and reduces writes by a fraction *write_reduction* (also in percent).

$$\frac{\text{reads}}{\text{writes}} < \frac{\text{write_reduction}}{\text{read_amplification}} \quad (6.1)$$

For the case $c_w = c_r$ and the empirical values *read_amplification* = 33% and *write_reduction* = 62% from the insert workload, Equation 6.3 simplifies to:

$$\frac{\text{reads}}{\text{writes}} < \frac{62}{33} \approx 1.88 \quad (6.2)$$

Hence, the method pays off when the workload exhibits fewer than approximately 1.88 read operations per write. For example, in a workload where most pages are written to after being read from disk, we have one read per write most of the time < 1.88 . This is the pattern we see in the insert workload for example, building the index from scratch. Also in update-heavy workloads, we can see such patterns. For example in the 50% update workload shown in Figure 6.6, we have about 1.6 reads per write, so about 60% of all read pages are written to before being evicted. Since $1.6 < 1.88$, we reach a net reduction in I/O operations. A scenario where our method performs very well.

Depending on the underlying hardware, read and write operations can have different costs. In a setting where random writes are significantly more expensive than random

reads, as on the M1 Pro's SSD with 512 GB, we could see faster runs in the 3B-tree even in scenarios where we have more total I/O operations due to a high fraction of read operations but less write operations. However, some SSDs can be faster in writing than reading. We can extend this condition to account for different costs of read and write operations. Let c_r and c_w denote the cost per read and per write, respectively.

$$\frac{reads}{writes} < \frac{c_w}{c_r} \cdot \frac{write_reduction}{read_amplification} \quad (6.3)$$

To summarize, the 3B-tree is beneficial in workloads where the majority of pages are written to after being read from disk, i.e. workloads with a low read-to-write ratio. To keep read amplification low, we need to be able to cache the Delta Tree effectively in memory.

Variable-Sized Entries

To analyze the effect of variable-sized entries, we run the same Wikipedia Pageviews workload, but this time with the variable-sized `page_title` as key. As expected, the index size increases due to the larger average key size of ~20.5 B compared to the fixed size keys of 8 B. We observed that the B-tree has 757 nodes with variable-sized keys compared to 502 nodes with integer keys. To remove the influence of different index sizes, and therefore more pages, we run the benchmarks with a buffer pool that fits ~40% of the B-tree in memory respectively (300 pages for fixed-sized keys, 200 pages for variable-sized keys). We run the same workload with 100% insertions. The results are shown in Figure 6.7.

With the different buffer sizes we achieve similar page reads and writes for the baseline B-trees. However, with variable-sized keys, the 3B-tree achieves a smaller reduction in page writes compared to fixed-sized keys. With variable-sized keys, we can reduce page writes by ~56% compared to ~64% with fixed-sized keys. The reason is that with variable-sized keys, we have more B-tree nodes with more than 5% eviction time as shown in Table 6.4. Therefore, we buffer fewer page writes in the Delta Tree, leading to a smaller write reduction.

While a conclusion could be that variable sized keys require a larger write threshold to achieve similar write reductions, we could not confirm this hypothesis with our experiments. Just as with fixed-sized keys, we see diminishing returns with larger write thresholds, because the Delta Tree becomes larger, leading to higher read amplification. Both Delta Trees are ~3.8% of the size of their respective B-trees. Even though we might have larger deltas with variable-sized keys, we decide to produce a delta based on the percentage of the page size that has changed. The amount of bytes that can be accumulated in a delta are the same in both cases, since both have a write threshold

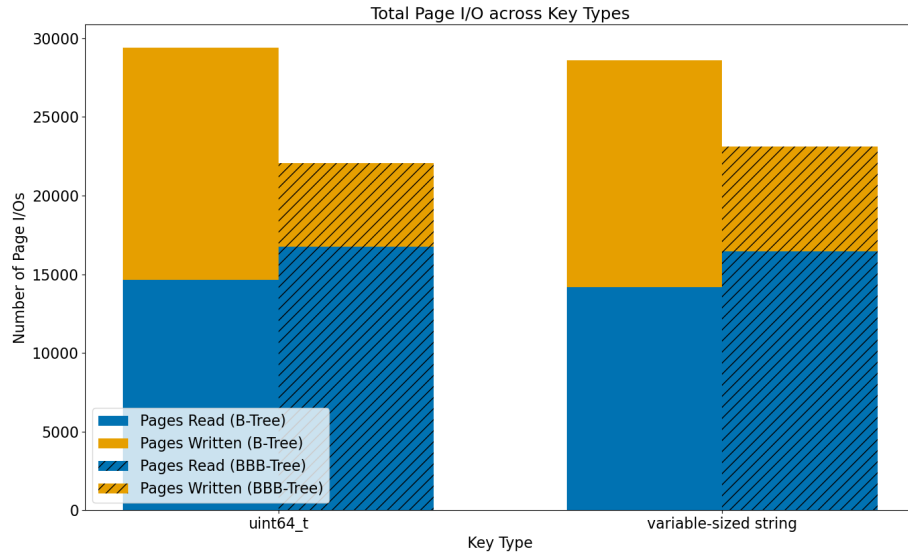


Figure 6.7: Total I/O operations per index, separated into reads and writes with 100% insertions of variable-sized string keys and fixed-sized integer keys. The buffer pool fits ~40% of the B-tree in memory, the page size is 4 KB and the write threshold is 5%. While we can reduce total I/O operations in both cases, the write reduction is smaller with variable-sized keys.

of 5% on 4 KB pages. Therefore, we do not increase the size of the Delta Tree with variable-sized keys.

Modified	Num. Pages	
	Fixed-Size Keys	Variable-Size Keys
0-5	12487	11013
5-10	2470	3303
10-15	64	180
15-20	5	26
20-25	1	4
25-30	0	2
30-35	0	0
35-40	0	1
40-45	0	10
45-50	104	239
50-55	446	477
55-60	59	139
60-65	15	43
65-70	13	23
70-75	11	19
75-80	5	16
80-85	2	13
85-90	7	9
90-95	6	11
95-100	9	13
≥ 100	109	163
Total Evictions	15813	15705

Table 6.4: Distribution of B-tree pages by their modification degree (percentage intervals) when being evicted with a Write Threshold of 5% for fixed-sized keys and variable-sized keys in a workload with 100% insertions. While both have similar number of page evictions, the variable-sized keys have more variance in the modification degree and less pages with a degree of change below the write threshold of 5%.

7 Discussion

This chapter discusses the results of the evaluation in the context of the research objectives. It summarizes the findings on how the proposed 3B-tree affects write amplification, read performance, and overall efficiency compared to traditional B-trees. Furthermore, it highlights the limitations of the current design and suggests areas for future research.

7.1 Summary of Findings

The proposed 3B-tree successfully reduces write amplification in traditional B-tree indices by buffering and batching updates in a secondary structure called the Delta Tree. The 3B-tree consistently demonstrates lower write amplification than the baseline B-tree while maintaining comparable space overhead and moderate read amplification. When evaluated on the mixed Wikipedia Pageviews workload, the 3B-tree achieved up to **70% fewer page writes** compared to the baseline.

Memory availability was found to be a decisive factor. In low-memory capacities ($\leq 10\%$ of the index fits in memory), the 3B-tree can produce more page writes since we cannot batch changes when constantly swapping pages in and out of memory. Batching is only possible when enough memory exists to cache the Delta Tree effectively. With **moderate memory capacities** ($>10\%$ of the index fits in memory), the 3B-tree can achieve substantial write reductions of up to 70%. With high memory capacities ($>99\%$ of the index fits in memory), the use of a 3B-tree is not meaningful, as the B-tree rarely performs page writes. This confirms that batching changes in memory is beneficial once memory is limited but sufficient space exists to cache updates.

The 3B-tree performed best with **small write thresholds** between 1% and 10%, balancing the number of buffered deltas per node and the size of the Delta Tree. At these thresholds, the structure accumulates small, scattered changes efficiently, avoiding unnecessary full page writes. Higher thresholds lead to larger Delta Trees, since each node fits less B-tree pages, diminishing the overall batching effect and introducing more page overhead.

An analysis of **read/write trade-offs** revealed that the 3B-tree introduces read amplification due to additional page reads for the Delta Tree whenever the B-tree reads or writes pages. This cost is offset when workloads exhibit enough page write savings,

i.e. in insert-heavy or update-intensive workloads. Under such conditions, total I/O operations are reduced, leading to net performance gains. Conversely, read-dominant workloads experience regressions since the small amount of page write savings cannot compensate for the introduced read overhead.

The experiments with **variable-sized keys** confirmed that the 3B-tree remains effective, although the write reduction was smaller (approximately 8% less compared to fixed-sized keys). Variance in key length increased the number of nodes exceeding the write threshold, reducing opportunities for batching. However, the Delta Tree size remained compact (same proportion to the respective B-tree) demonstrating that the overhead of managing variable-length entries is modest. Larger write thresholds do not improve write reduction for the reasons discussed above.

In summary, the 3B-tree reduces write amplification substantially across workloads. However, due to the introduced read amplification, the overall I/O reduction depends on the workload mix. The design achieves its intended balance between reduced writes, read amplification, and limited space overhead.

7.2 Limitations

While the 3B-tree demonstrates strong potential, some limitations constrain its current applicability:

1. **Memory Dependence.** The method's effectiveness relies on the ability to cache portions of the Delta Tree in memory. In extremely memory-limited environments, the additional lookups into the Delta Tree can increase total I/O activity and negate the intended benefits.
2. **Read Amplification.** By introducing an additional layer for change buffering, each page load may trigger additional Delta Tree page loads. Although the observed read amplification is moderate, it can increase total I/O in read-intensive workloads.
3. **Workload Diversity.** The experiments were running on a single dataset (Wikipedia Pageviews) with Zipf-like key distribution. Additional datasets with different locality and access patterns (such as sequential or uniformly random) would be needed to generalize the results.

7.3 Future Directions

The findings open several directions for further research and system development:

1. **Smart Eviction Policies.** Implementing page eviction strategies that consider the access patterns and update frequencies could enhance the performance of the 3B-tree. In our implementation, pages were evicted randomly, which do not reflect real-world buffer management strategies. More sophisticated policies, such as LFU or 2Q [19], could be explored to improve cache hit rates. Prioritizing Delta Tree pages that contain frequently updated nodes could reduce read amplification significantly.
2. **Alternative Buffering Data Structures.** The 3B-tree could benefit from exploring different data structures for the Delta Tree. We decided on a B-tree for simplicity, but other structures could offer better batching or lower overhead. For instance, one could write deltas into a log-structured format. We would naturally achieve higher locality for batching deltas. In a B-tree structure, we risk scattering deltas across multiple pages. More ideally, if temporally close deltas are also spatially close, we could achieve better batching. In contrast to an LSM-trees, where data is organized in levels, the 3B-tree only requires searching the Delta Tree during B-tree page reads and writes. However, it could incur higher read amplification, so a careful design would be necessary.
3. **Bloom Filters for Delta Tree Lookups.** Most read amplification arises from additional Delta Tree lookups during B-tree page reads. However, not all B-tree nodes have pending updates in the Delta Tree. In a read-dominant workload, many Delta Tree lookups may be unnecessary. A Bloom filter could be maintained in memory to quickly check whether a B-tree node has pending updates in the Delta Tree. A technique often applied to skip unnecessary LSM-trees level lookups. This would avoid unnecessary Delta Tree lookups when reading B-tree nodes that have no pending updates. An opportunity to reduce read amplification significantly.
4. **Tracking Updates in Table Data.** While this work focused on indexing structures, the same principles could be applied to the underlying table data. In write-intensive workloads, buffering updates to table pages in a similar Delta Tree structure could reduce write amplification at the data level.
5. **Levelled Delta Trees.** Another strategy to bring temporally close updates close together spatially is to introduce multiple levels of Delta Trees. Whenever a Delta Tree page itself is below a certain write threshold, it could be buffered into a higher-level Delta Tree. This would allow for multi-level batching of updates, potentially reducing the number of page writes even further. The tree on each level would become significantly smaller, making it easier to cache in memory.

The primary objective of future work should be to refine the 3B-tree design to minimize read amplification, the primary source of overhead in read-heavy workloads. Reducing read overhead would maximize the overall I/O savings across a broader range of workloads, establishing the 3B-tree as a robust replacement for traditional B-trees.

In conclusion, the 3B-tree demonstrates that *write amplification in B-trees can be significantly reduced through buffered batching without major structural changes*. Its design preserves the simplicity of B-trees while improving write efficiency, making it a practical foundation for future write-optimized indexing in modern storage environments. Uptaining read performance while minimizing write costs remains a key challenge.

8 Conclusion

This thesis set out to address the problem of excessive write amplification in traditional B-tree index structures, which impacts efficiency and storage longevity in modern database systems. While B-trees remain the most widely used indexing structure due to their efficient lookups and range queries, their page-oriented update model causes high write costs under random or mixed workloads. The objective of this work was therefore to design, implement, and evaluate a method that reduces write amplification in B-trees while preserving their core advantages: simplicity, concurrency, and read performance.

8.1 Recap of Contributions

To achieve this goal, this thesis introduced the 3B-tree, a lightweight, write-aware extension of the traditional B-tree. The key idea was to introduce an intermediate buffering structure, the Delta Tree, that intercepts page evictions and selectively batches modifications instead of performing immediate full-page writes to external storage. By deferring and consolidating small changes, the 3B-tree minimizes unnecessary I/O operations without altering the internal layout and fundamental operations of the B-tree.

The main contributions of this work can be summarized as follows:

- **A lightweight buffering layer for B-trees:** The Delta Tree acts as a transparent, non-intrusive extension between the B-tree and buffer manager, reducing write amplification through selective batching and deferred persistence.
- **A detailed implementation and evaluation:** The 3B-tree was implemented in C++ and benchmarked under realistic workloads derived from the Wikipedia Pageviews dataset. Experiments investigated write amplification, read overhead, and space utilization.
- **Empirical evidence of reduced write amplification:** Across a variety of configurations, the 3B-tree achieved up to 70% fewer page writes than a standard B-tree. This confirms that lightweight batching can significantly mitigate write amplification.

- **Identification of workload-dependent trade-offs:** Caching is the fundamental idea of this method, therefore a certain memory availability is required. Further, the evaluation revealed that the balance between write reduction and read amplification affects overall performance. The 3B-tree performs best in moderately sized buffer pools and update-heavy workloads.

The reason B-trees are so widely used is their balanced performance characteristics across a range of workloads. However, their random write performance lags behind the otherwise strong efficiency. With the 3B-tree we sacrifice some read performance but enable substantial write reductions in write-intensive scenarios. We argue that this evens out the performance landscape between read and write operations in traditional B-trees.

The goal of this thesis has thus been met by demonstrating that write amplification in B-trees can be substantially reduced through a simple buffering extension.

8.2 Significance of Results

The results of this work demonstrate that substantial write amplification reductions can be achieved without resorting to invasive structural changes, a limit on concurrency, or a prohibitive read overhead such as LSM-trees or B ϵ -trees. Moreover, by lowering write amplification, the 3B-tree indirectly mitigates device-level wear on SSDs, contributing to longer hardware lifespans and reduced operational cost.

8.3 Outlook and Final Thoughts

The promising results of the 3B-tree open multiple paths for future research. Extending the design to a fully concurrent, crash-consistent implementation would enable integration into production database systems. Additionally, levelled Delta Trees or log-structured buffers instead of trees could further optimize the trade-off between write reduction and read overhead.

In conclusion, this thesis demonstrates that *reducing write amplification in B-trees is feasible*. The 3B-tree is a step towards bridging the gap between high-performance and write-efficient indexing.

Abbreviations

LSM-trees Log-Structured-Merge-Trees

SSD Solid State Drive

DBMS Database Management Systems

DRAM Dynamic Random Access Memory

I/O Input/Output

TID Tuple ID

PID Page ID

CAS Compare-And-Swap

WAL Write-Ahead Log

DAM Disk-Access-Model

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Bibliography

- [1] A. Aggarwal and S. Vitter Jeffrey. “The Input/Output Complexity of Sorting and Related Problems.” In: *Communications of the ACM* 31.9 (1988), pp. 1116–1127.
- [2] R. Bayer and E. McCreight. “Organization and Maintenance of Large Ordered Indices.” In: *Proceedings of the 1970 ACM SIGFIDET (Now SIGMOD) Workshop on Data Description, Access and Control*. 1970, pp. 107–141.
- [3] M. A. Bender, M. Farach-Colton, W. Jannen, R. Johnson, B. C. Kuszmaul, D. E. Porter, J. Yuan, and Y. Zhan. “An Introduction to B^ε-trees and Write-Optimization.” In: *login; magazine* 40.5 (2015).
- [4] G. S. Brodal and R. Fagerberg. “Lower bounds for external memory dictionaries.” In: *SODA*. Vol. 3. 2003, pp. 546–554.
- [5] A. L. Buchsbaum, M. H. Goldwasser, S. Venkatasubramanian, and J. R. Westbrook. “On external memory graph traversal.” In: *SODA*. 2000, pp. 859–860.
- [6] F. Chang, J. Dean, S. Ghemawat, W. C. Hsieh, D. A. Wallach, M. Burrows, T. Chandra, A. Fikes, and R. E. Gruber. “Bigtable: A Distributed Storage System for Structured Data.” In: *ACM Transactions on Computer Systems (TOCS)* 26.2 (2008), pp. 1–26.
- [7] W. Foundation. *Wikimedia Pageview Dataset*. 2025. URL: <https://dumps.wikimedia.org/other/pageviews/2025/> (visited on 10/09/2025).
- [8] A. Gorrod. *Btree vs LSM*. 2017. URL: <https://github.com/wiredtiger/wiredtiger/wiki/Btree-vs-LSM> (visited on 09/15/2025).
- [9] G. Graefe. “Write-optimized B-trees.” In: *Proceedings of the Thirtieth international conference on Very large data bases-Volume 30*. 2004, pp. 672–683.
- [10] G. Graefe, H. Volos, H. Kimura, H. Kuno, J. Tucek, M. Lillibridge, and A. Veitch. “In-Memory Performance for Big Data.” In: *Proceedings of the VLDB Endowment* 8.1 (2014), pp. 37–48.
- [11] G. Haas, B. Lee, P. Bonnet, and V. Leis. “SSD-iq: Uncovering the Hidden Side of SSD Performance.” In: *Proceedings of the VLDB Endowment* 18.11 (2025), pp. 4295–4308.

- [12] G. Haas and V. Leis. “What Modern NVMe Storage Can Do, And How To Exploit It: High-Performance I/O for High-Performance Storage Engines.” In: *Proceedings of the VLDB Endowment* 16.9 (2023), pp. 2090–2102.
- [13] A. Kemper and T. Neumann. “HyPer: A hybrid OLTP&OLAP main memory database system based on virtual memory snapshots.” In: *2011 IEEE 27th International Conference on Data Engineering*. IEEE. 2011, pp. 195–206.
- [14] B. C. Kuszmaul. “A Comparison of Fractal Trees to Log-Structured Merge (LSM) Trees.” In: *Tokutek White Paper* (2014).
- [15] V. Leis. “LeanStore: A High-Performance Storage Engine for NVMe SSDs.” In: *Proceedings of the VLDB Endowment* 17.12 (2024), pp. 4536–4545.
- [16] V. Leis, M. Haubenschild, A. Kemper, and T. Neumann. “Leanstore: In-memory data management beyond main memory.” In: *2018 IEEE 34th International Conference on Data Engineering (ICDE)*. IEEE. 2018, pp. 185–196.
- [17] V. Leis, M. Haubenschild, and T. Neumann. “Optimistic Lock Coupling: A Scalable and Efficient General-Purpose Synchronization Method.” In: *IEEE Data Eng. Bull.* 42.1 (2019), pp. 73–84.
- [18] J. J. Levandoski, D. B. Lomet, and S. Sengupta. “The Bw-tree: A B-tree for new hardware platforms.” In: *2013 IEEE 29th International Conference on Data Engineering (ICDE)*. IEEE. 2013, pp. 302–313.
- [19] T. Neumann. *Database Systems on Modern CPU Architectures - Chapter 3: Access Paths*. 2024. URL: <https://db.in.tum.de/teaching/ss24/moderndbs/chapter3.pdf?lang=en> (visited on 09/14/2025).
- [20] P. O’Neil, E. Cheng, D. Gawlick, and E. O’Neil. “The Log-Structured Merge-Tree (LSM-tree).” In: *Acta informatica* 33.4 (1996), pp. 351–385.
- [21] Y. Qiao, X. Chen, N. Zheng, J. Li, Y. Liu, and T. Zhang. “Closing the b+-tree vs. {LSM-tree} write amplification gap on modern storage hardware with built-in transparent compression.” In: *20th USENIX Conference on File and Storage Technologies (FAST 22)*. 2022, pp. 69–82.
- [22] S. Sarkar and M. Athanassoulis. “Dissecting, designing, and optimizing LSM-based data stores.” In: *Proceedings of the 2022 International Conference on Management of Data*. 2022, pp. 2489–2497.
- [23] C. Sauer, G. Graefe, and T. Härder. “FineLine: log-structured transactional storage and recovery.” In: *Proceedings of the VLDB Endowment* 11.13 (2018), pp. 2249–2262.
- [24] F. R. team. *A Persistent Key-value Store for Fast Storage Environments*. 2021. URL: <https://rocksdb.org/> (visited on 09/15/2025).

- [25] Z. Wang, A. Pavlo, H. Lim, V. Leis, H. Zhang, M. Kaminsky, and D. G. Andersen. “Building a Bw-tree Takes More Than Just Buzz Words.” In: *Proceedings of the 2018 International Conference on Management of Data*. 2018, pp. 473–488.
- [26] W. Zhong, C. Chen, X. Wu, and S. Jiang. “REMIX: Efficient Range Query for LSM-trees.” In: *19th USENIX Conference on File and Storage Technologies (FAST 21)*. 2021, pp. 51–64.