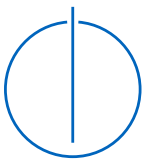
SCHOOL OF COMPUTATION, INFORMATION AND TECHNOLOGY — INFORMATICS

TECHNISCHE UNIVERSITÄT MÜNCHEN

Bachelor's Thesis in Informatics

Implementing an Efficient Shuffle Operator for Streaming Database Systems

Jonas Ladner



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Implementing an Efficient Shuffle Operator for Streaming Database Systems

Implementierung eines effizienten Shuffle-Operators für Streaming-Datenbanksysteme

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

Munich, 17.02.2025 Jonas Ladner

Acknowledgments

Abstract

Modern streaming database systems rely on efficient data partitioning to achieve scalability and high performance across processing nodes. Partitioned data shuffling is a crucial operation, as it is used to prepare and distribute data for further processing on distributed systems.

This thesis purposes and evaluates various partitioning implementations by simulating real-world usage of the shuffle operator. The implementations process incoming tuple batches and partition them into output buckets, which are based on slotted pages and can be passed to subsequent operators. The evaluation of the implementations is based on their performance, scalability and memory consumption.

The results demonstrate that using a lock- and Software Managed Buffers (SMB)-based approach yields the best overall performance, offering both efficiency and ease of implementation. Notably, the proposed locking mechanism minimizes the duration of holding a lock, ensuring minimal contention and contributing to the approach's superior performance.

TODO: quantify results
"As a result we implement a ... that is ?X faster than ..."
At the end: "Our approach uses software managed buffers, locking, ..."

Contents

1 Introduction

1.1 Motivation

Growing demand for real-time data analysis and increasing data volume create significant challenges [1–3]. Distributed and parallel systems like stream processing engines address these issues by distributing tasks across worker nodes [1, 4]. Data shuffling prepares and distributes tuples among worker nodes [5]. As a core streaming component, the shuffle operator must achieve high throughput and low latency to support efficient downstream processing. This thesis addresses these challenges by focusing on the most efficient implementations of the shuffle operator.

1.2 Streaming processing engines

Streaming processing engines are designed to process data as soon as it arrives rather than relying on traditional pre-computed information and index structures [1]. Their core operations include partitioning and distributing incoming traffic across worker nodes. The distribution process is frequently based on a partitioning function. These partitions can then improve the performance of further operators by ensuring the data locality of interdependent tuples [3, 6]. Data locality within the worker node is crucial for maintaining performance and scalability in large-scale deployments.

1.3 Shuffle operator

The shuffle operator provides a partitioned distribution of tuples, enabling downstream operators to leverage the data locality of partitioned data blocks. For instance, the throughput of the join operator can significantly be improved when tuples assigned to the same hash bucket are shuffled to the same worker node [3]. Implementing a shuffle operator involves addressing challenges like memory consumption, latency, and scalability. This thesis proposes and evaluates different implementations of the shuffle operator, focusing on their efficiency and performance.

1.4 Slotted pages

Slotted pages are a common way to store variable-size tuples within fixed size memory blocks [7]. These fixed size memory blocks can then be either stored on disk or easily be sent to worker nodes.

Typically, the pages consist of three sections: metadata, slots and a variable-size data section. The metadata area contains information like an identifier for the page, what fields the tuples have and the amount of tuples on this page. This fixed-size metadata section is then followed by the slot section. A single slot contains the fixed-size properties, the variable-size length and its start offset in the variable-size data section. In contrast to the previous two sections, the variable-size data section grows from the end of the page towards the slot section of the page.

1.5 Problem setting

The key contribution of this thesis is the creation and evaluation of the most efficient, multithreaded implementations of the shuffle operator. In order to simulate the real-world usage of the shuffle operator in a streaming system, the following three-step shuffle-simulation is proposed:

1. Tuple generation: The tuples are generated in a batched manner using a pseudo-random generator. Each implementation requests the ad-hoc generation of tuples, which contain a 32-bit key field and an optional variable-size data field.

2. Data shuffle: The requested, random-generated tuples are then processed using the different implementations and stored within partition buckets. Each partition bucket consists of slotted pages, where the tuple of this partition are stored.

3. Storing tuples on slotted pages: The implementations range from thread-local to shared slotted-page write-out strategies. The implementations using a shared write-out policy, can then be further categorized into locking and lock-free approaches.

This simulation is close to the real world usage of the shuffle operator, as streaming systems work on incoming tuple batches that are not materialized like in traditional relational databases.

Further, we use slotted pages as a communication format between nodes. This is an efficient and widely used format to transport tuples within fixed size data chunks. In contrast, sending each tuple as soon as it is processed, creates significant network overhead and makes downstreaming processing less efficient.

While the implementations are optimized for the simulated process above, the underlying algorithms can be transferred to any streaming system, that forwards data using slotted pages.

2 Related work

2.1 Radix Partitioning

2.2 Partitioned Joins

2.3 Software Managed Buffers

3 Implementations

This section explains the implementations and how to implement them efficiently. As the shuffle operator-simulation is based on fixed-size tuples, the explanations of the following implementation, are based on fixed-size tuples as well.

3.1 Slotted Pages

TODO: Explain tuple write out process.

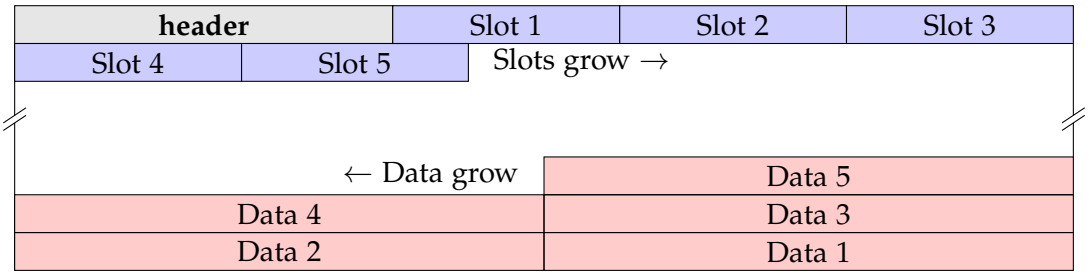

Figure 3.1: Slotted Page grow visualization

3.2 Slotted Page Managers

As some implementation share the same tuple write-out strategy, we propose the used write-out strategies here and reference them in the following explanations of the concrete implementations.

To further simplify the implementations, we intialize each partition with an empty slotted page. This significantly reduces the complexity of the page manager implementations.

3.2.1 Lock-based Page Manager

For each partition, we use a single lock and a vector for storing the slotted pages. As can be seen in Algorithm 1, the lock-based insertion process is straightforward. The

Algorithm 1: Lock-based Page Manager insert_tuple Algorithm

input : `tuple`: The tuple to be inserted, `partition`: The target partition index
output: Tuple inserted into the appropriate slotted page of the specified partition.

```
1 function insert_tuple(tuple, partition)
2 Acquire lock on partition_locks[partition]
3 if pages[partition].back().add_tuple(tuple) then
4 |   // Tuple added successfully
5 else
6 |   add_page(partition)
7 |   pages[partition].back().add_tuple(tuple)
8 end
9 Release lock
```

insertion on a given slotted page, can only fail if the page is full. This can easily be checked by reading the tuple count in the metadata section of the slotted page. If the current page is full, we just allocate and append a new slotted page to the page vector of this partition.

Tuple insertion in batches

Similarly, we can further optimize the write-out by using tuple-batches. In Algorithm 2,

Algorithm 2: Lock-based Page Manager insert_tuple_batch Algorithm

input : `tuples`: The tuple-batch to be inserted
`partition`: The target partition index
output: Tuples inserted into one or more slotted pages of the specified partition.

```
1  function insert_tuple_batch(tuples, partition)
2  Acquire lock on partition_locks[partition]
3  for tuple : tuples do
4  |   if pages[partition].back().add_tuple(tuple) then
5  |   |   // Tuple added successfully
6  |   else
7  |   |   add_page(partition)
8  |   |   pages[partition].back().add_tuple(tuple)
9  |   end
10 end
11 Release lock
```

we reuse the tuple insertion logic from Algorithm 1 but acquire the partition lock only once for the entire insertion process. Since acquiring and releasing the lock is expensive, this optimization significantly improves performance in multi-threaded scenarios.

3.2.2 Lock-free Page Manager

As holding a lock of a partition denies a second thread to also write out tuples, we propose a lock-free implementation. In comparision to the lock-based variant, we now have to store our slotted pages in a pointer-stable data structure. This is necessary to ensure threads can work simultanious, while a thread adds a new slotted page. Furthermore, we have to edit the slotted page metadata using compare-and-exchange operations to avoid losing writes from other threads.

Algorithm 3: Lock-free Slotted Page increment_and_fetch_opt_write_info Algorithm

```
1 function increment_and_fetch_opt_write_info()
2 current_tuple_count = header->tuple_count.load();
3 while !header->tuple_count.compare_exchange_strong(current_tuple_count,
    current_tuple_count + 1) do
4 |   if current_tuple_count >= get_max_tuples(page_size) then
5 |   |   return std::nullopt
6 |   end
7 end
8 return {page_data.get(), page_size, current_tuple_count}
```

In order to gather the information, where we can write a tuple, we increment the tuple count using compare-and-exchange. This index then acts as our location, where our tuple is placed on the page. In Algorithm 3, we also add an condition to stop attempting to further increase the count of tuples on the page, if the maximum is reached. This ensures that threads move to the next allocated page. Given the index, where the tuple is placed, we also append a pointer of the start of the page and the page size. This ensures we can write the page without requiring any further information.

Using the Algorithm 3, we retrieve the information to write the tuple in Algorithm 4. We read from an atomically-stored pointer to our current page, until we are assigned an index on a slotted page. If we are writing the last tuple on the page, we add a new page to this partition. This is necessary to create a unqiue condition, when a new page has to be allocated. With that write information at hand, we can write the tuple onto the slotted page.

Algorithm 4: Lock-free Page Manager insert_tuple Algorithm

input : `tuple`: The tuple to be inserted, `partition`: The target partition index
output: Tuple inserted into the appropriate slotted page of the specified partition.

```
1 function insert_tuple(tuple, partition)
2 wi = current_page[partition].load()->increment_and_fetch_opt_write_info()
3 while wi == std::nullopt do
4 |   wi = current_page[partition].load()->increment_and_fetch_opt_write_info()
5 end
6 if wi.tuple_index == LockFreeSlottedPage::get_max_tuples() - 1 then
7 |   add_page(partition)
8 end
9 LockFreeSlottedPage::add_tuple_using_index(wi, tuple)
```

3.2.3 Histogram-based Page Managers

Radix Page Manager

Ad-hoc Radix ("Hybrid") Page Manager

3.2.4 Thread-Local Pages and Merge-based Page Manager

3.2.5 Implementation-independent Optimizations

Padded atomics and locks

Minimal page-locking

Two-step buffered slotted page write out

3.3 On-Demand Partitioning

On-demand Partitioning is the simplest algorithm to implement the shuffle operator.

3.3.1 Overview

As soon as this implementation receives a batch of tuples, it processes each tuple individually. First, the hash-function is applied onto the tuple to gather information in which partition this tuple belongs. With this information, we only need to write out the tuple into the corresponding partition. The partition is now locked, and we check, if there is enough space left on the newest slotted page of this partition.

3.4 Software Managed Buffers-based Partitioning

3.4.1 Overview

3.4.2 Lock-based Implementations

3.4.3 Lock-free Implementations

3.5 Histogram-based Partitioning

3.5.1 Overview

3.5.2 Radix Partitioning

3.5.3 Ad-hoc Radix ("Hybrid") Partitioning

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3.6.1 Overview

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3.7.1 Overview

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4.2 Tuple Generation

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4.4 Shuffle Benchmark

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4.5 Comparison with Stream Processing Systems

5 Conclusion

5.1 Conclusion

5.2 Future Work

Abbreviations

SMB Software Managed Buffers

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