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

Author:	Jonas Ladner
Examiner:	Prof. Dr. Thomas Neumann
Supervisor:	Maximilian Rieger M.Sc.
Submission Date:	17.02.2025

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.

Furthermore, each implementation allocates a slotted page for each partition, as this simplifies the multithreaded-implementation of each algorithm.

3.1 On-Demand Partitioning

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

3.1.1 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.

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3.2.1 Overview

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5.1 Conclusion

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Abbreviations

SMB Software Managed Buffers

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