WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

CS 764: Topics in Database Management Systems

Lecture 3: Radix Join

Xiangyao Yu

9/14/2021

Today's Paper: Radix Join

Database Architecture Optimized for the new Bottleneck: Memory Access

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Abstract

In the past decade, advances in speed of commodity CPUs have far out-paced advances in memory latency. Main-memory access is therefore increasingly a performance bottleneck for many computer applications, including database systems. In this article, we use a simple scan test to show the severe impact of this bottleneck. The insights gained are translated into guidelines for database architecture; in terms of both data structures and algorithms. We discuss how vertically fragmented data structures optimize cache performance on sequential data access. We then focus on equi-join, typically a random-access operation, and introduce radix algorithms for partitioned hash-join. The performance of these algorithms is quantified using a detailed analytical model that incorporates memory access cost. Experiments that validate this model were performed on the Monet database system. We obtained exact statistics on events like TLB misses, L1 and L2 cache misses, by using hardware performance counters found in modern CPUs. Using our cost model, we show how the carefully tuned memory access pattern of our radix algorithms make them perform well, which is confirmed by experimental results.

*This work was carried out when the author was at the University of Amsterdam, supported by SION grant 612-23-431

Proceedings of the 25th VLDB Conference, Edinburgh, Scotland, 1999.

1 Introduction

Custom hardware – from workstations to PCs – has been experiencing tremendous improvements in the past decades. Unfortunately, this growth has not been equally distributed over all aspects of hardware performance and capacity. Figure 1 shows that the speed of commercial microprocessors has been increasing roughly 70% every year, while the speed of commodity DRAM has improved by little more than 50% over the past decade [Mow94]. Part of the reason for this is that there is a direct tradeoff between capacity and speed in DRAM chips, and the highest priority has been for increasing capacity. The result is that from the perspective of the processor, memory has been getting slower at a dramatic rate. This affects all computer systems, making it increasingly difficult to achieve high processor efficiencies.

Three aspects of memory performance are of interest: bandwidth, latency, and address translation. The only way to reduce effective memory latency for appli-

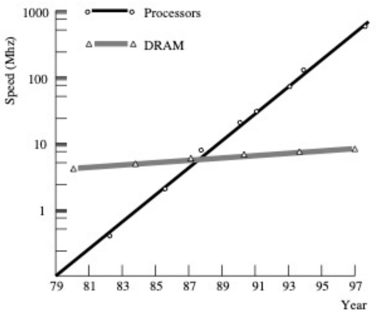

Figure 1: Hardware trends in DRAM and CPU speed

VLDB 1999

Agenda

Hardware background

In-memory partitioned hash join

Radix join

Experimental results

Radix join vs. non-partition hash join

Column-store and encoding

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Memory Wall

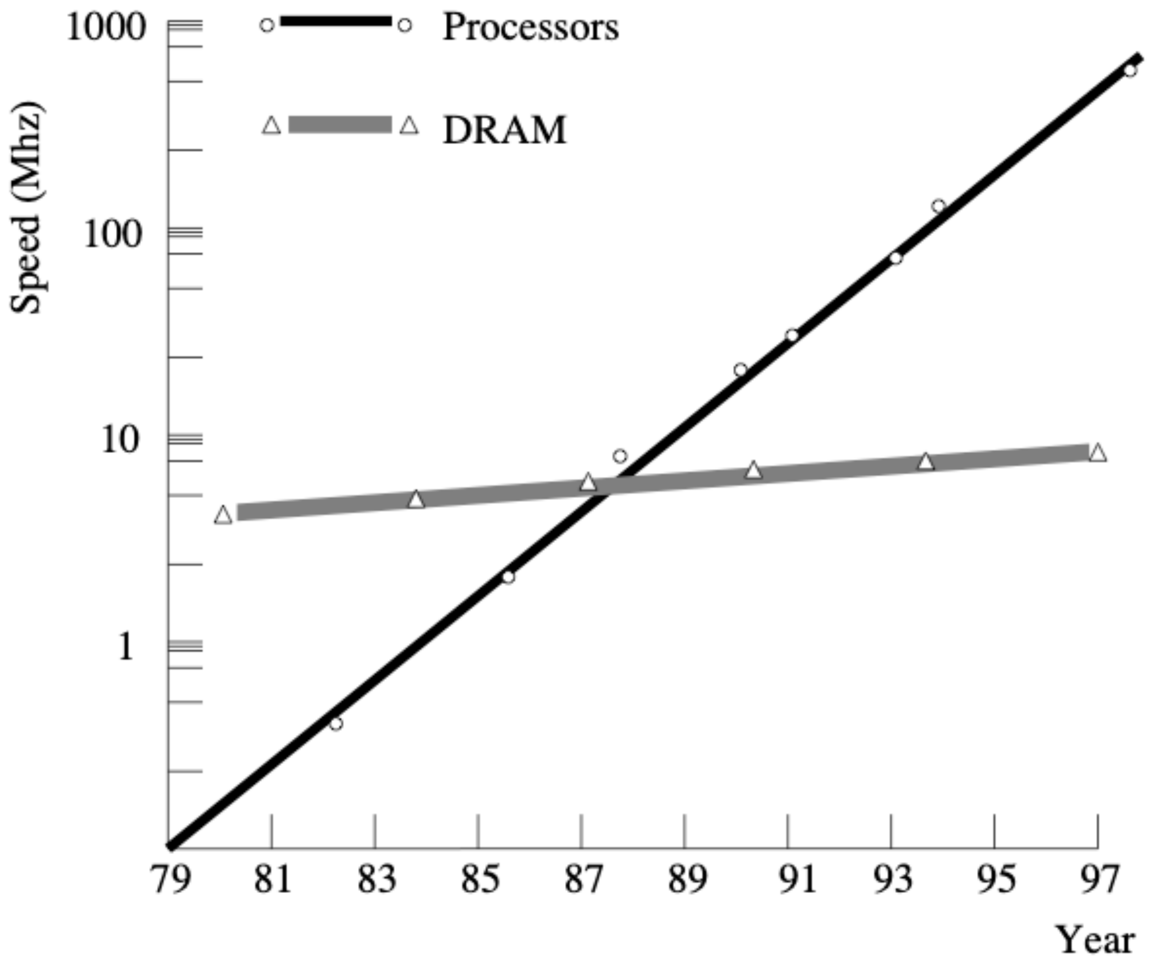


Figure 1: Hardware trends in DRAM and CPU speed

The growth of memory speed is slower than the growth of CPU speed

- Latency
- Bandwidth

Memory/Cache Hierarchy

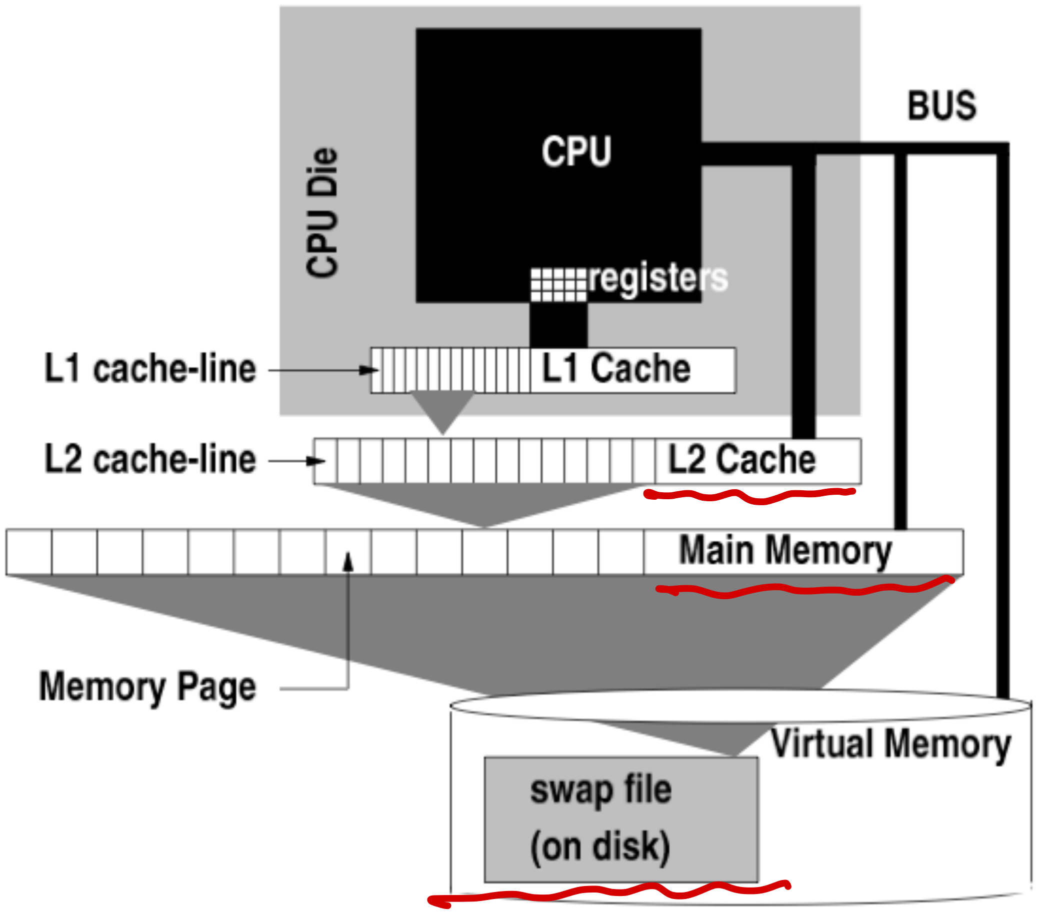
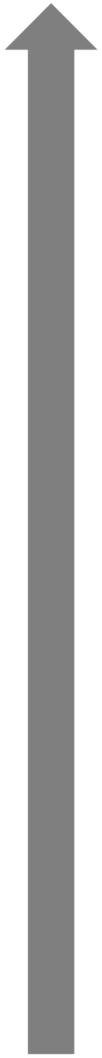
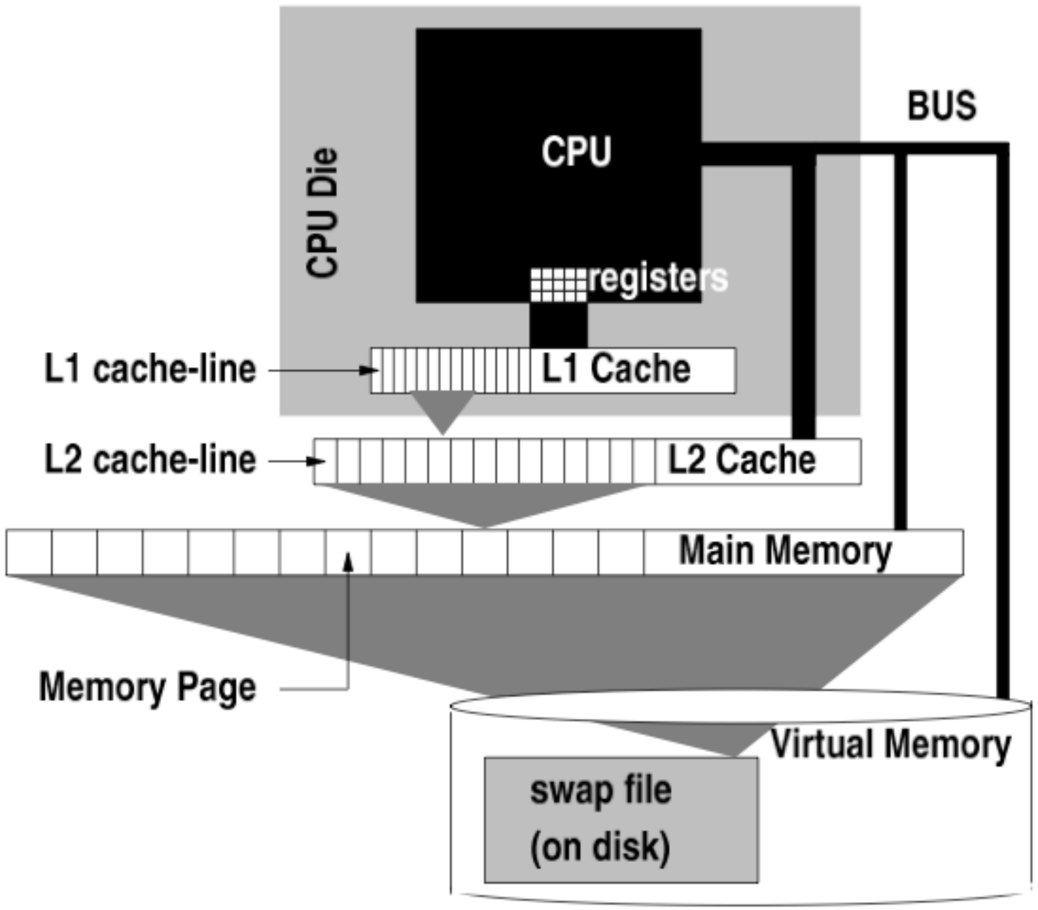


Figure 2: Hierarchical Memory System



Higher bandwidth
Lower access latency
Smaller capacity

Memory/Cache Hierarchy



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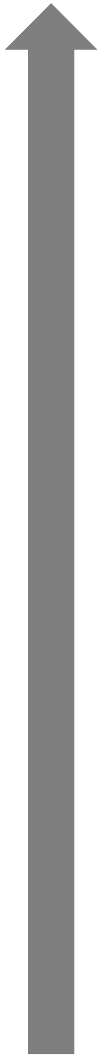


Higher bandwidth
Lower access latency
Smaller capacity

Optimizing join in DRAM/Disk system

- GRACE hash join

Optimizing join in SRAM/DRAM system?

Optimizing Join in Main-Memory DBMS

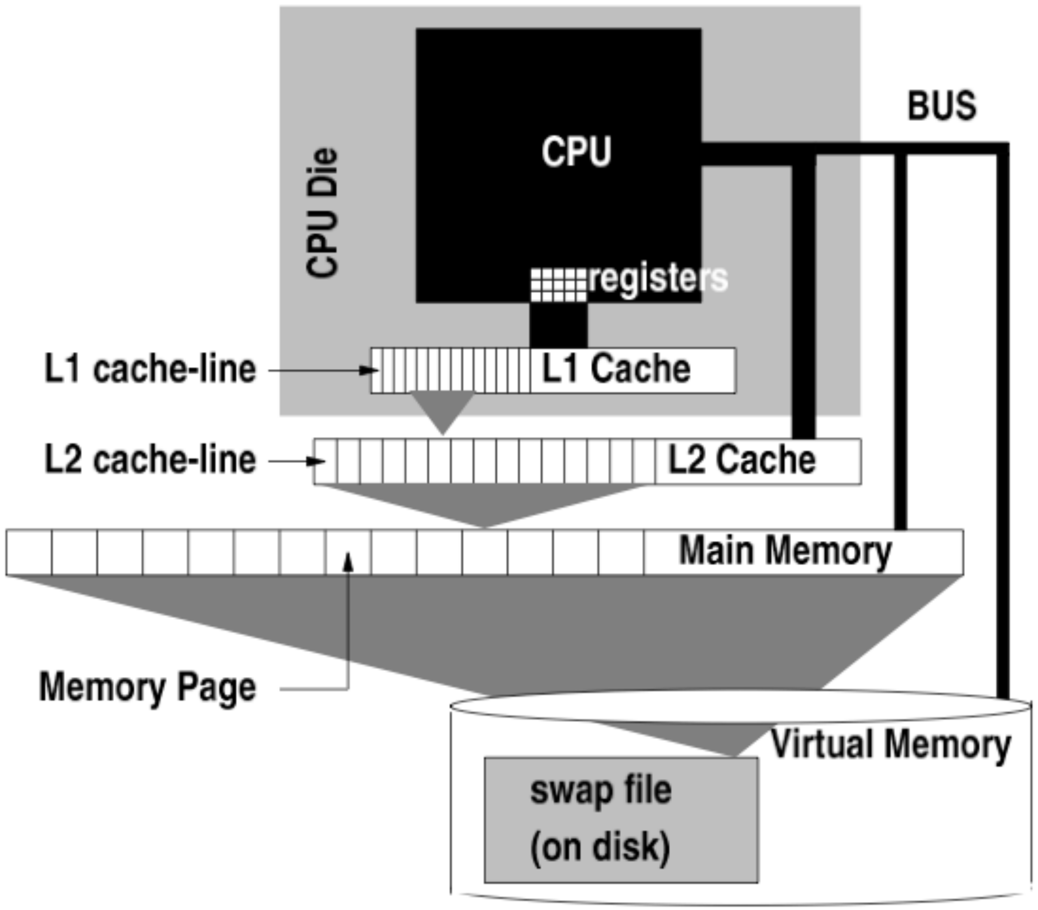


Figure 2: Hierarchical Memory System

Intuitive solution: Partition tables into shards that fit in SRAM cache

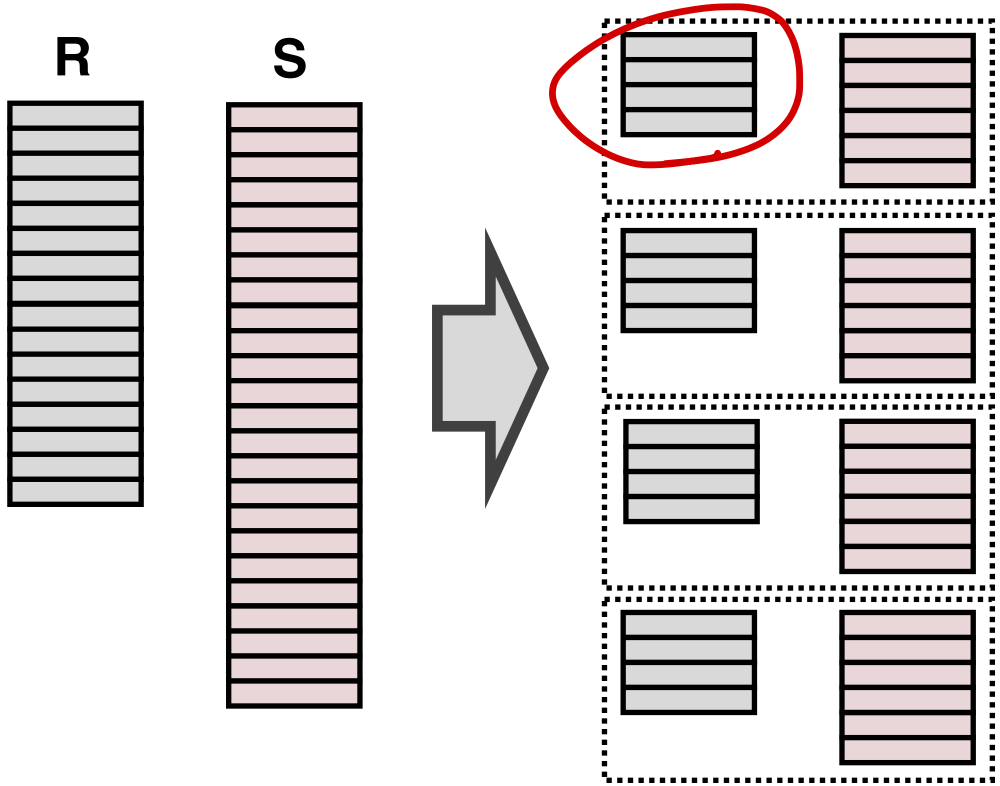
- Like GRACE hash join

Recap: GRACE Hash Join

Phase 1: Partition both R and S into pairs of k shards

- Each shard of R fits in CPU cache

Phase 2: Separately join each pairs of partitions



Group Discussion

In some modern in-memory DBMSs, the entire database can fit in memory. In such a system, can similar optimizations be applied to on-chip SRAM caches vs. DRAM? What are the key challenges compared to a DRAM vs. Disk setting?

Group Discussion

In some modern in-memory DBMSs, the entire database can fit in memory. In such a system, can similar optimizations be applied to on-chip SRAM caches vs. DRAM? What are the key challenges compared to a DRAM vs. Disk setting?

- Software does not have full control of CPU cache contents
- Disk access granularity is a block; DRAM access granularity is a cacheline
- CPU cache has very limited capacity

4KB 64B.

Optimizing Join in Main-Memory DBMS

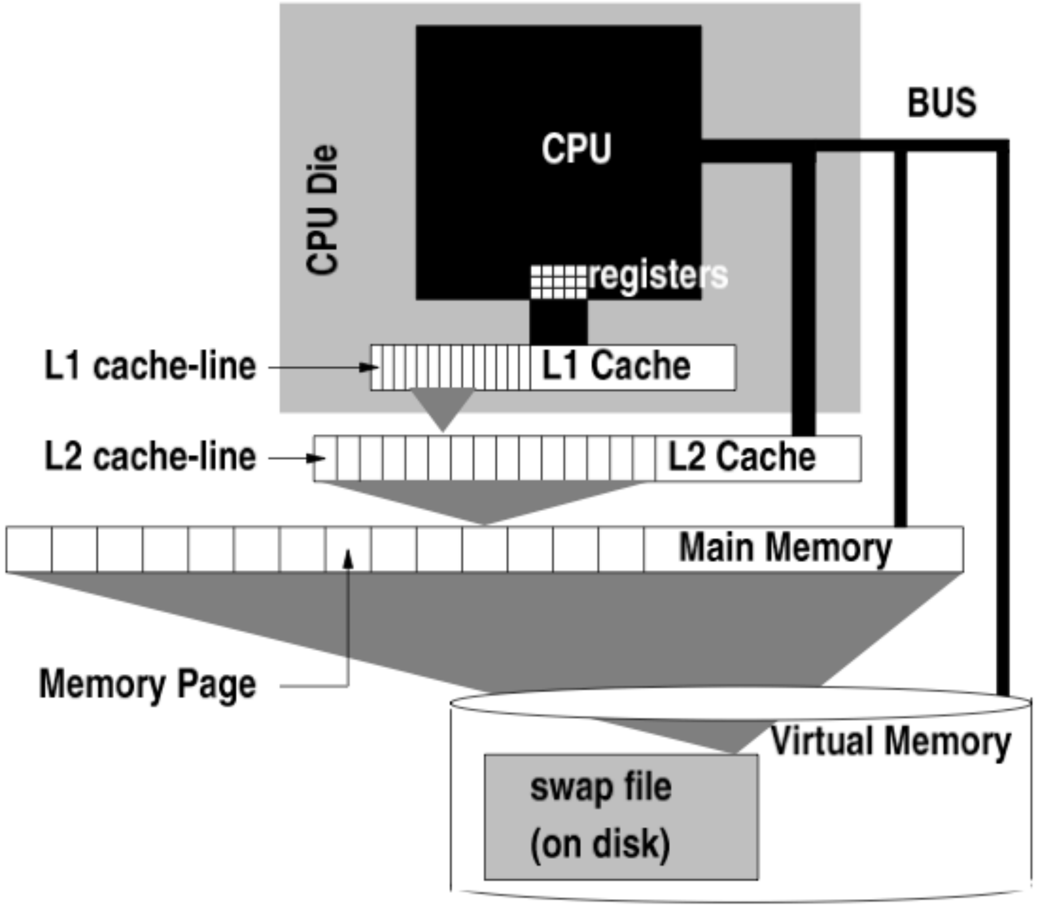


Figure 2: Hierarchical Memory System

Intuitive solution: Partition tables into shards that fit in SRAM cache

– Like GRACE hash join

Challenges:

– TLB becomes a performance bottleneck if too many partitions exist

– Determine the memory layout of data partitions (e.g., fragmentation)

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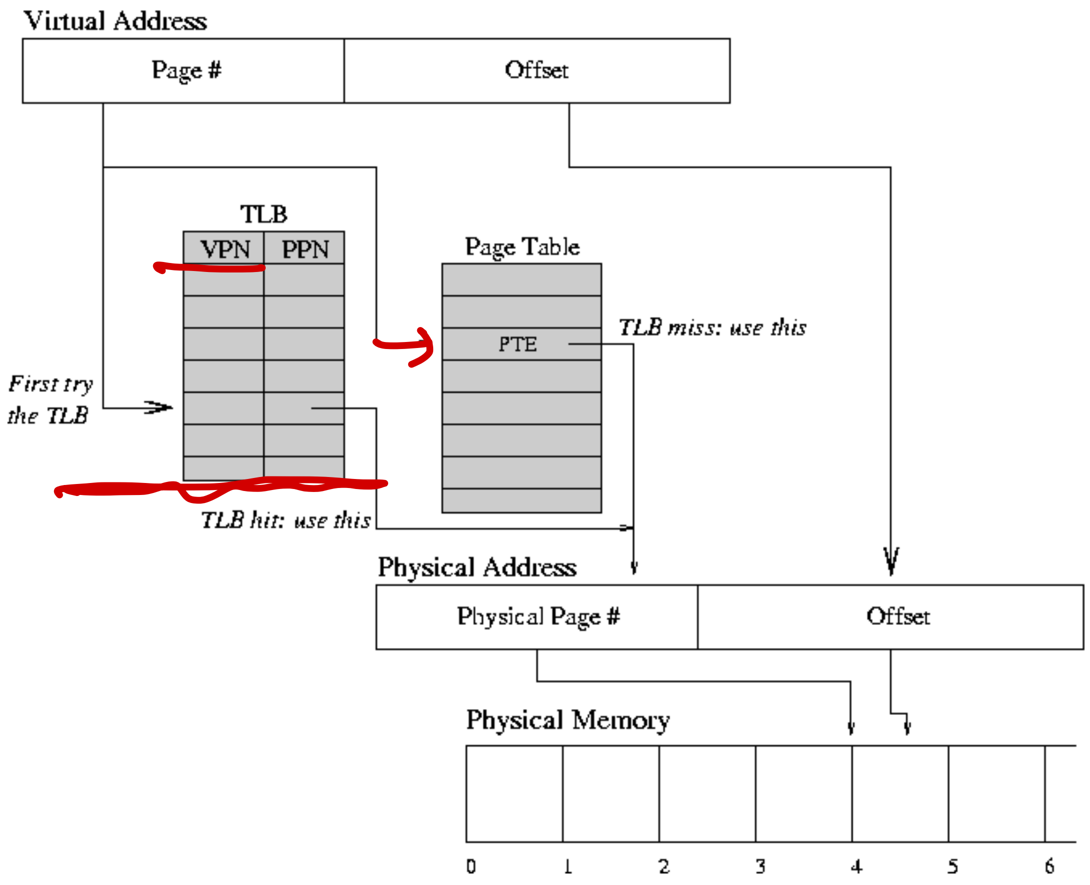
Translation Lookaside Buffer (TLB)



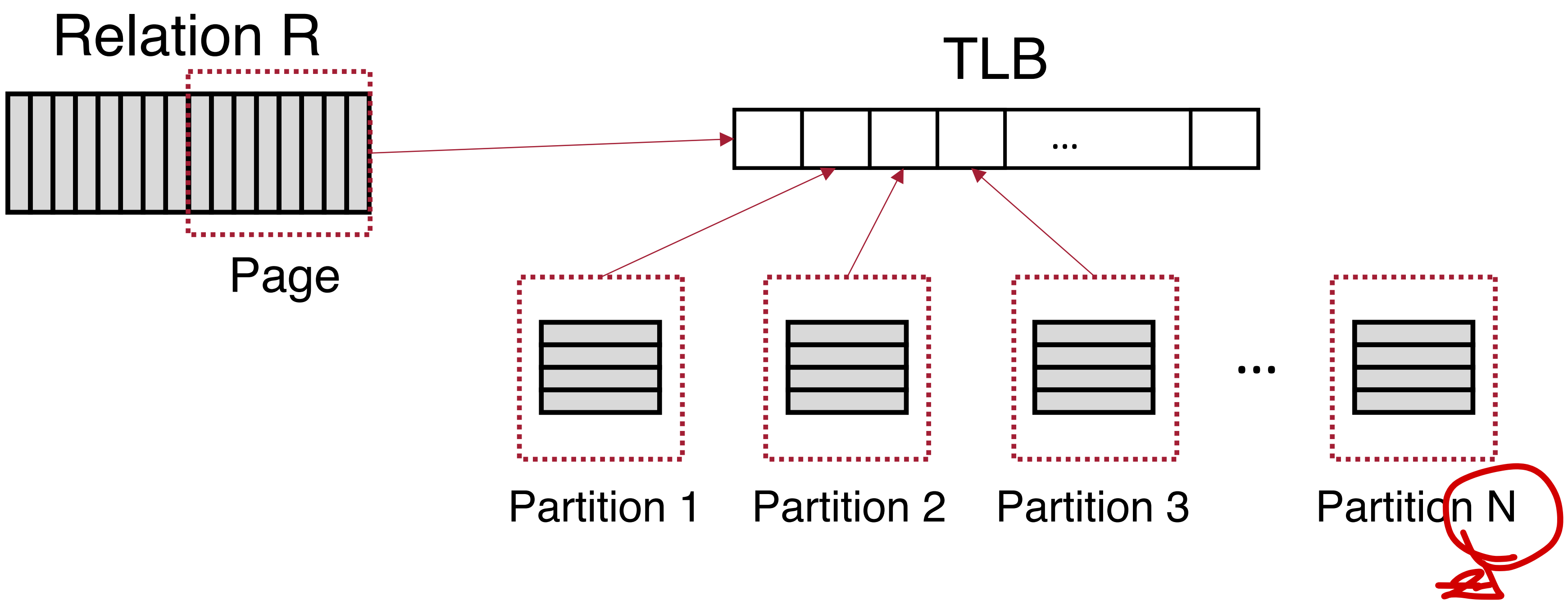
source: http://pages.cs.wisc.edu/~bart/537/lecturenotes/s17.html

A cache of OS page table to accelerate virtual address to physical address translation

- TLB hit has no cost
- TLB miss requires an expensive page table walk

TLB has a small number of entries

of Partitions vs. TLB size



If the number of partitions is greater than the number of TLB entries, the system experience **TLB thrashing**, i.e., many accesses lead to TLB misses

Thrashing

TLB thrashing: Number of accessed pages (i.e., number of partitions) is greater than the number of TLB entries in hardware

Cache thrashing: Number of accessed cachelines (i.e., number of partitions) is greater than the cache capacity

Page thrashing (in last lecture): Number of accessed pages (i.e., number of partitions) is greater than the memory capacity

Optimizing Join in Main-Memory DBMS

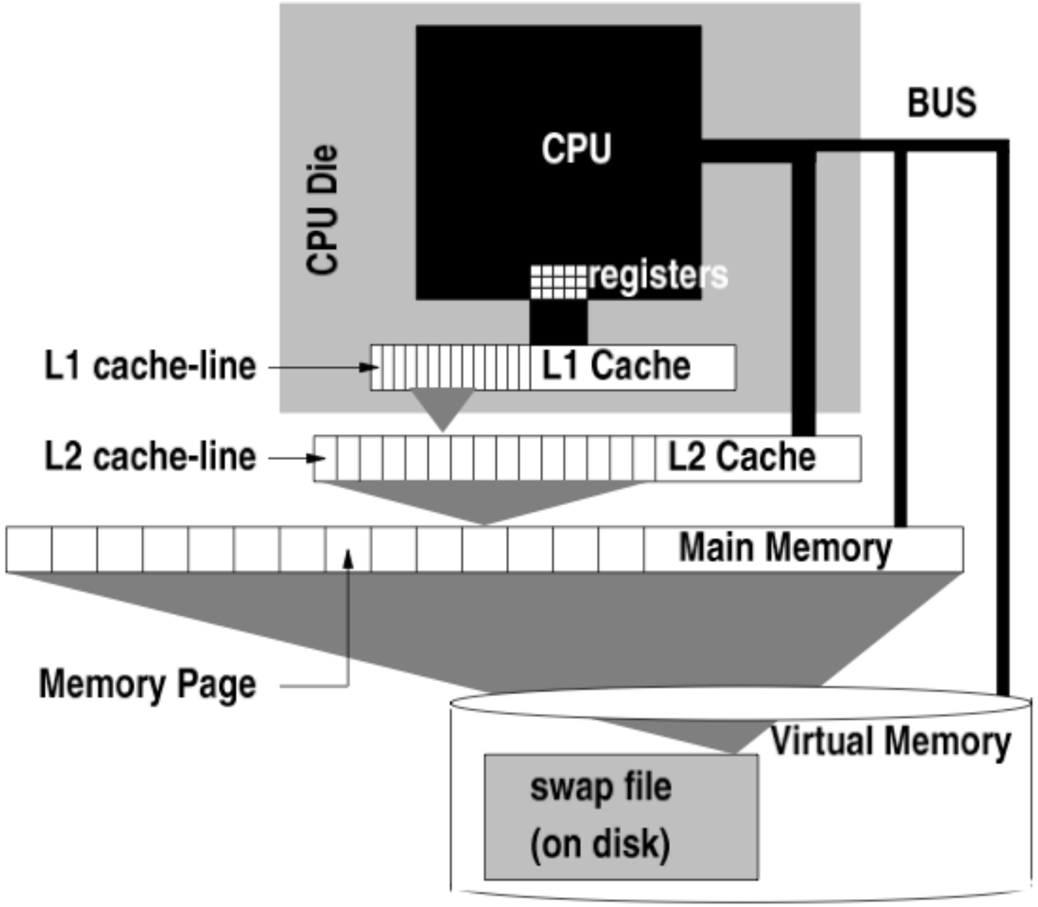


Figure 2: Hierarchical Memory System

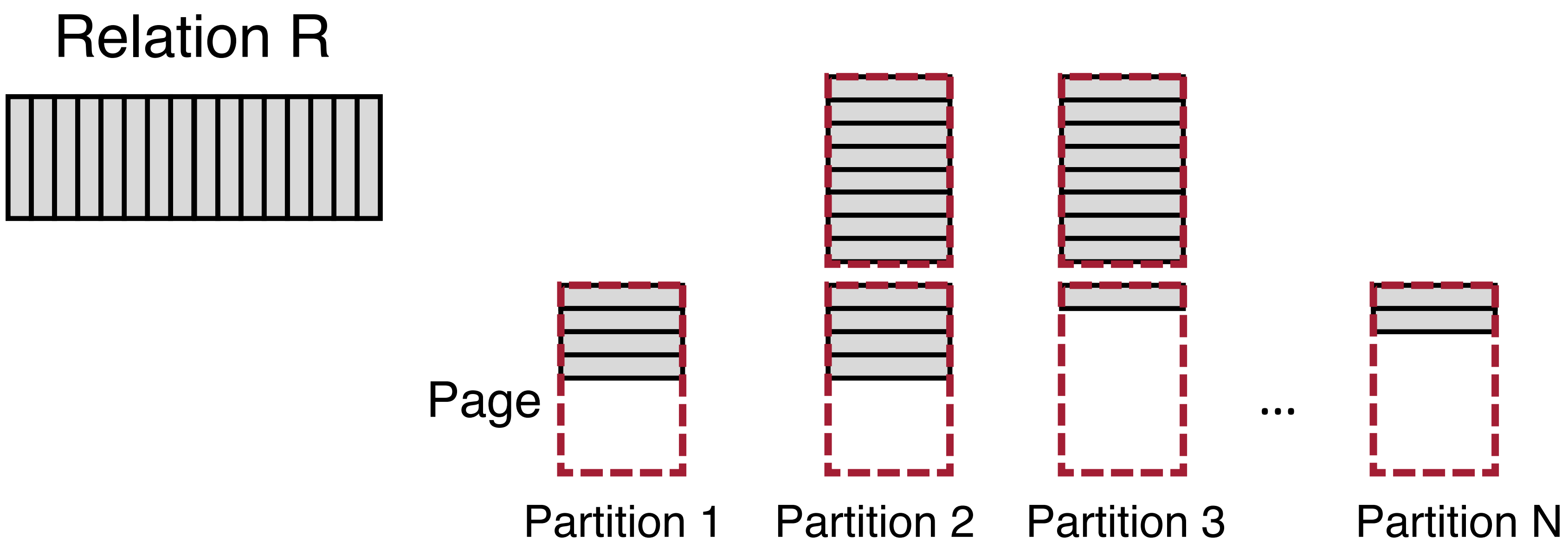
Intuitive solution: Partition tables into shards that fit in SRAM cache

Challenges:

- **TLB becomes a performance bottleneck if too many partitions exist**
- Determine the memory layout of data partitions (e.g., fragmentation)

Do not have too many partitions per round of partitioning. Limiting factor includes cache size and TLB size.

Fragmentation



How to track location and size for different partitions?

- Frequent memory allocation (e.g., malloc) is expensive
- Loss of memory capacity due to fragmentation
- Problem becomes worse if multiple passes of partitioning is needed

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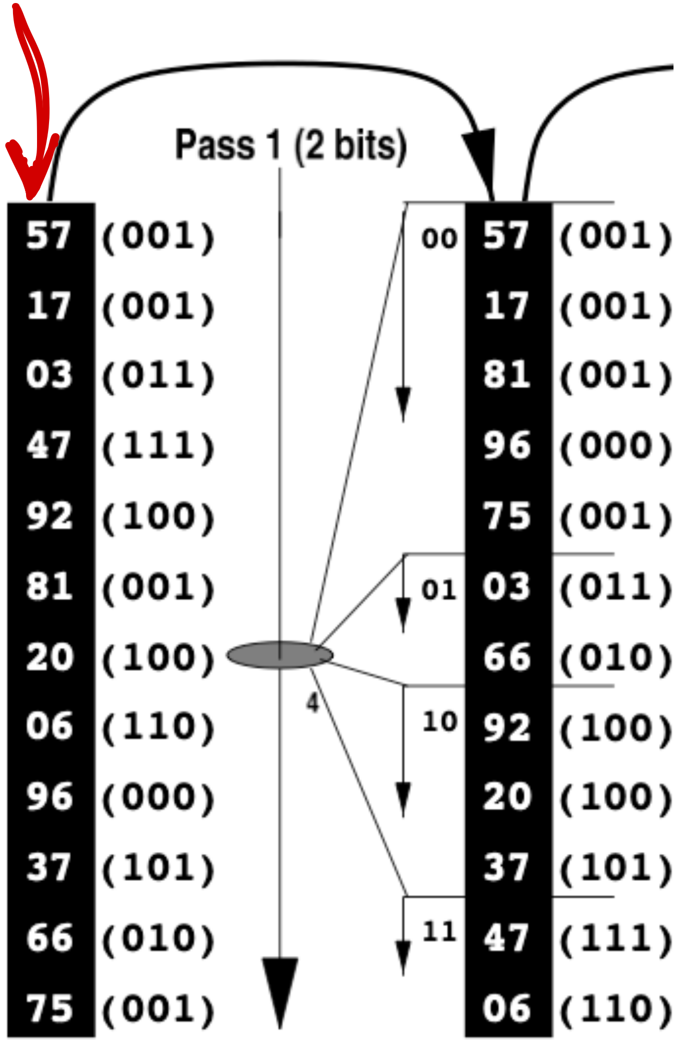
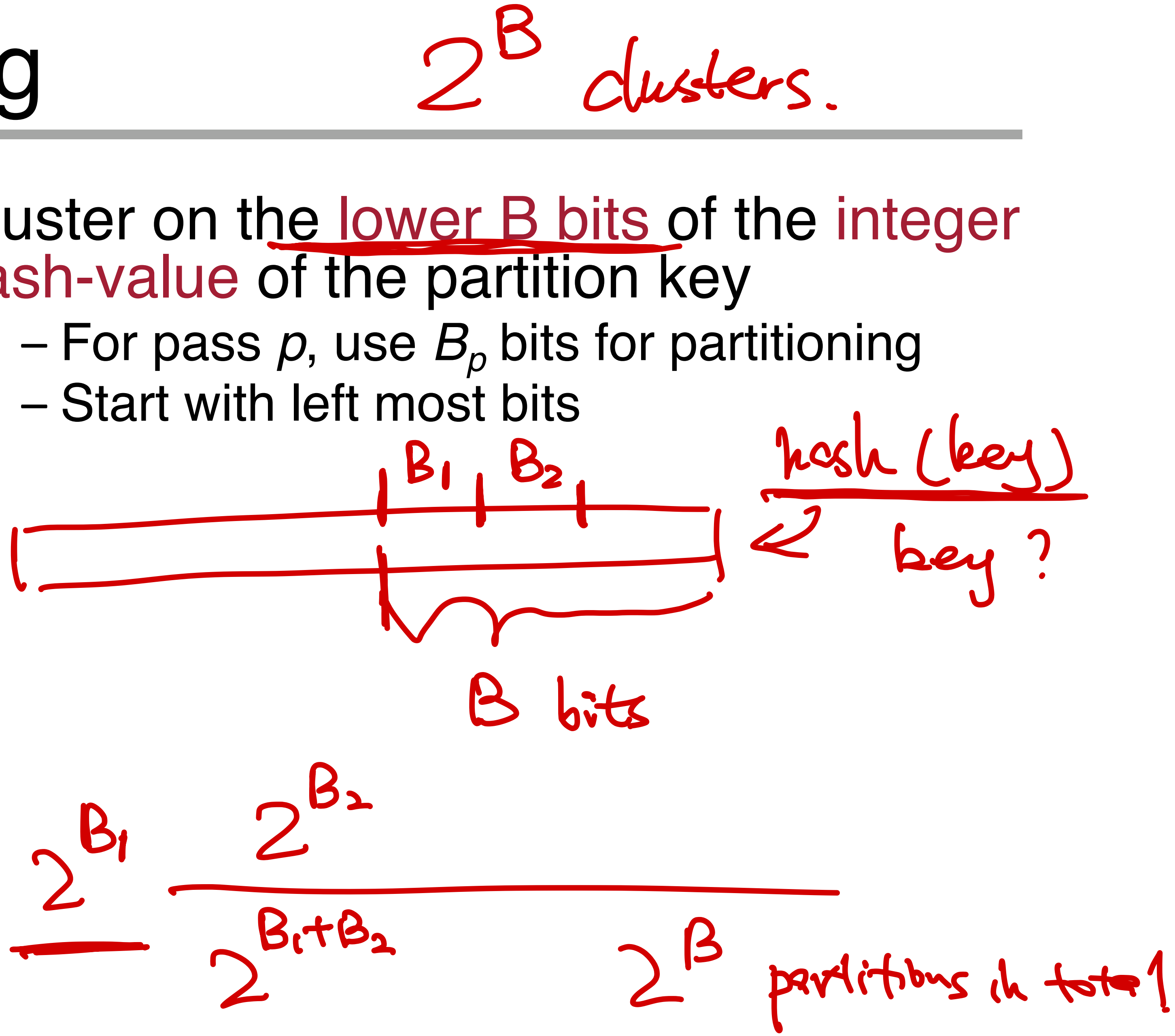
Radix Partitioning

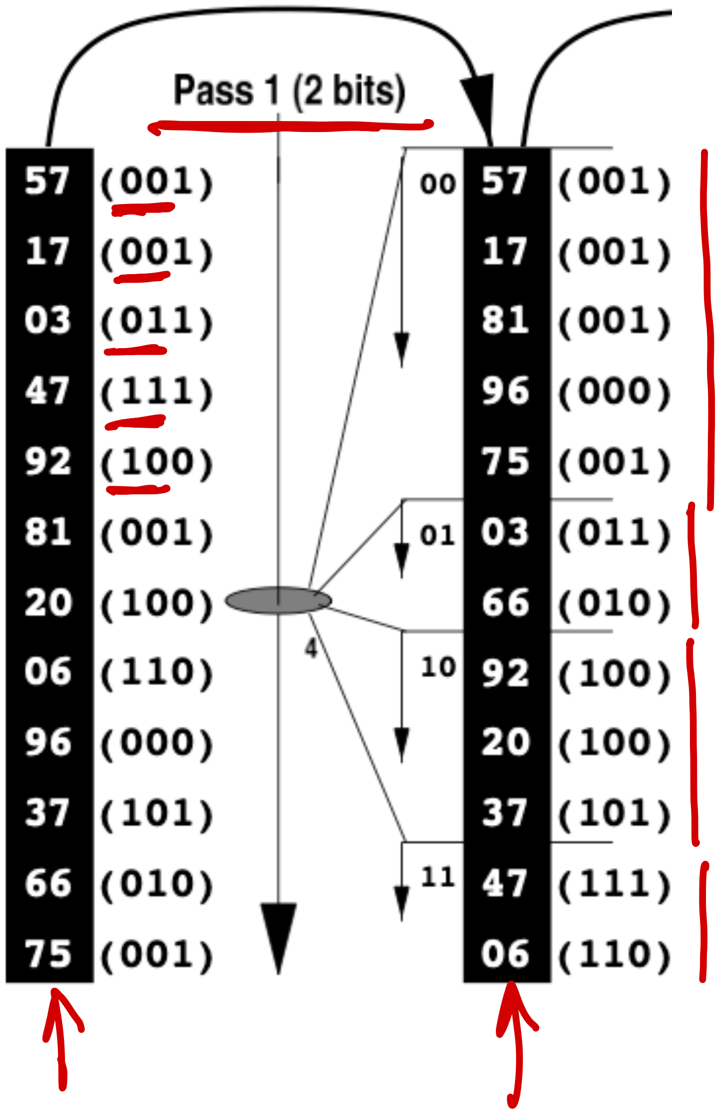


Cluster on the lower B bits of the integer hash-value of the partition key

- For pass p, use B_p bits for partitioning
- Start with left most bits



Radix Partitioning



Cluster on the lower B bits of the integer hash-value of the partition key

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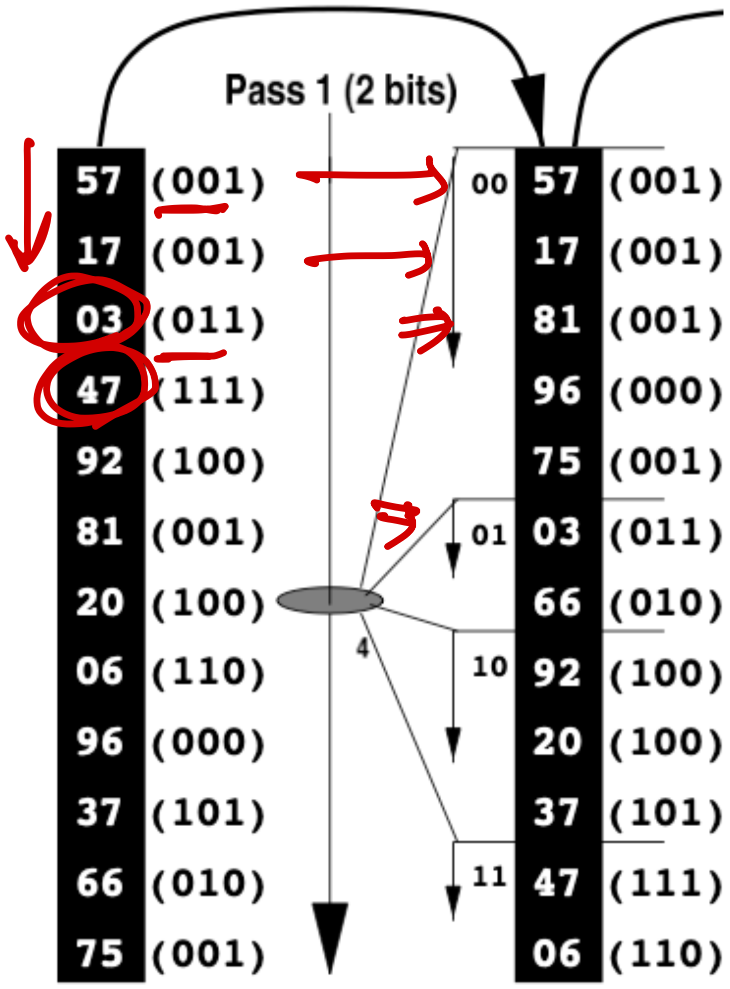
The output array of Radix partitioning has identical structure as the input array

- No complex memory allocation
- No fragmentation

Radix Partitioning



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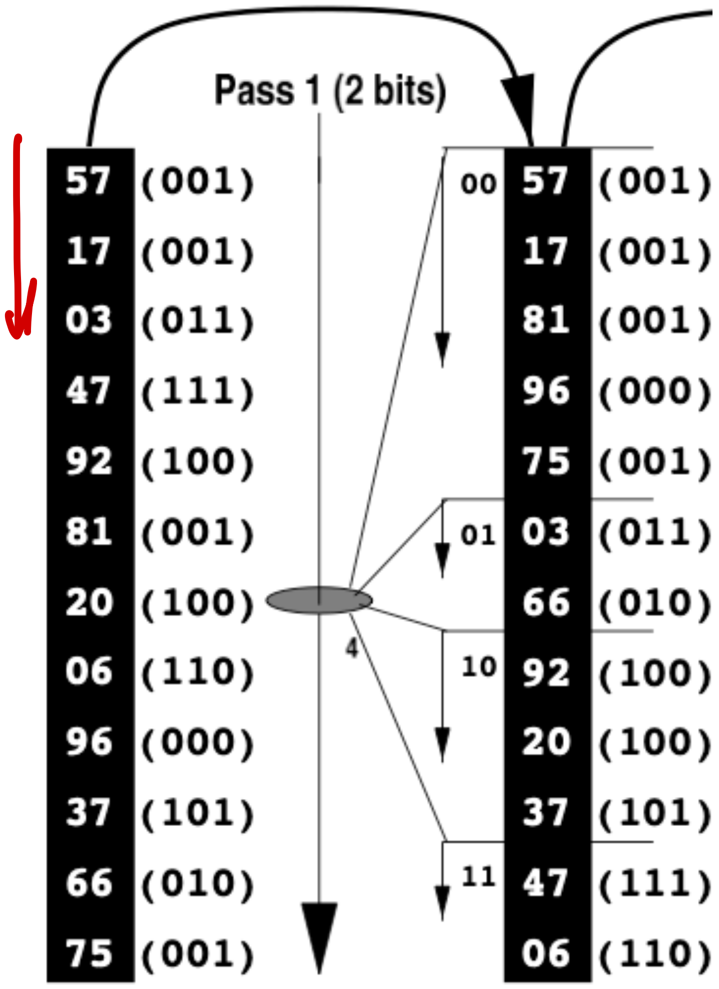
Q: How to know where to write in the output array? (e.g., 47 in the example)

- Need to scan the array twice; first time collect size per partition

Radix Partitioning



First scan

- “00”: 5 records
- “01”: 2 records
- “10”: 3 records
- “11”: 2 records

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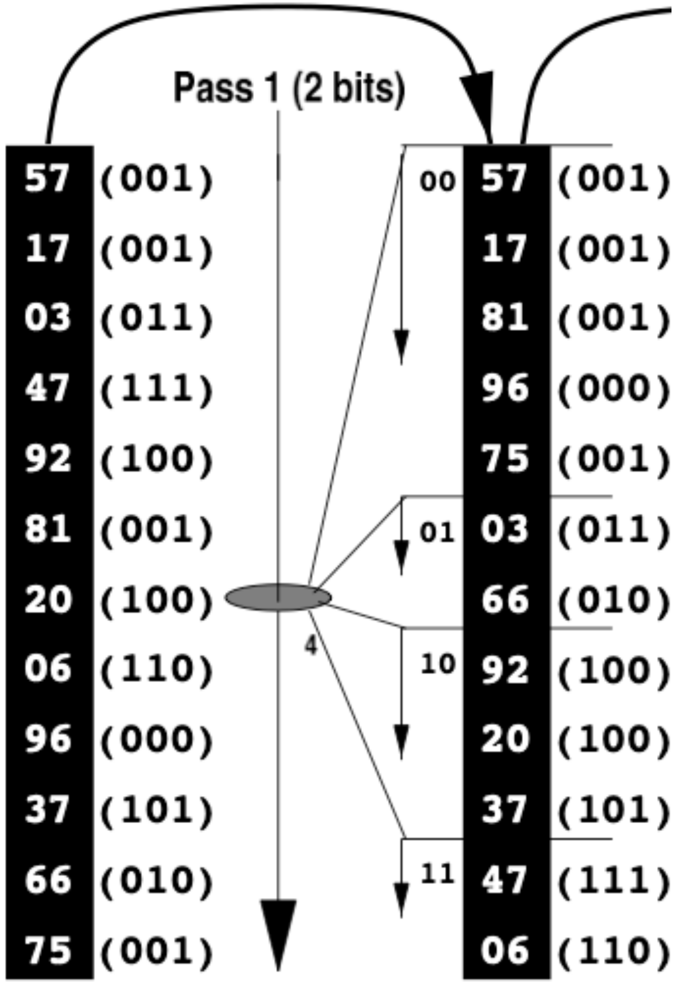
Radix Partitioning



First scan

- "00": 5 records
- "01": 2 records
- "10": 3 records
- "11": 2 records

Write location in output buffer

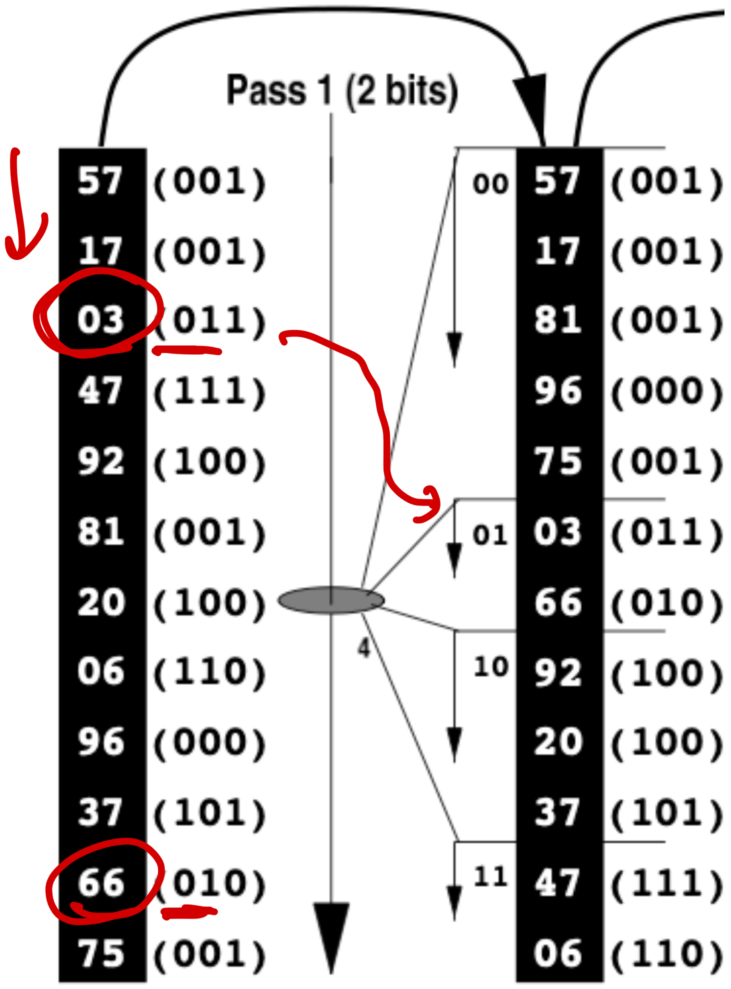
- "00": entry 0
- "01": entry 5
- "10": entry 5 + 2
- "11": entry 5 + 2 + 3

Prefix Sum

Q: How to know where to write in the output array? (e.g., 47 in the example)

- Need to scan the array twice; first time collect size per partition

Radix Partitioning



First scan

- "00": 5 records
- "01": 2 records
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- "11": 2 records

Write location in output buffer

- "00": entry 0
- "01": entry 5
- "10": entry 5 + 2
- "11": entry 5 + 2 + 3

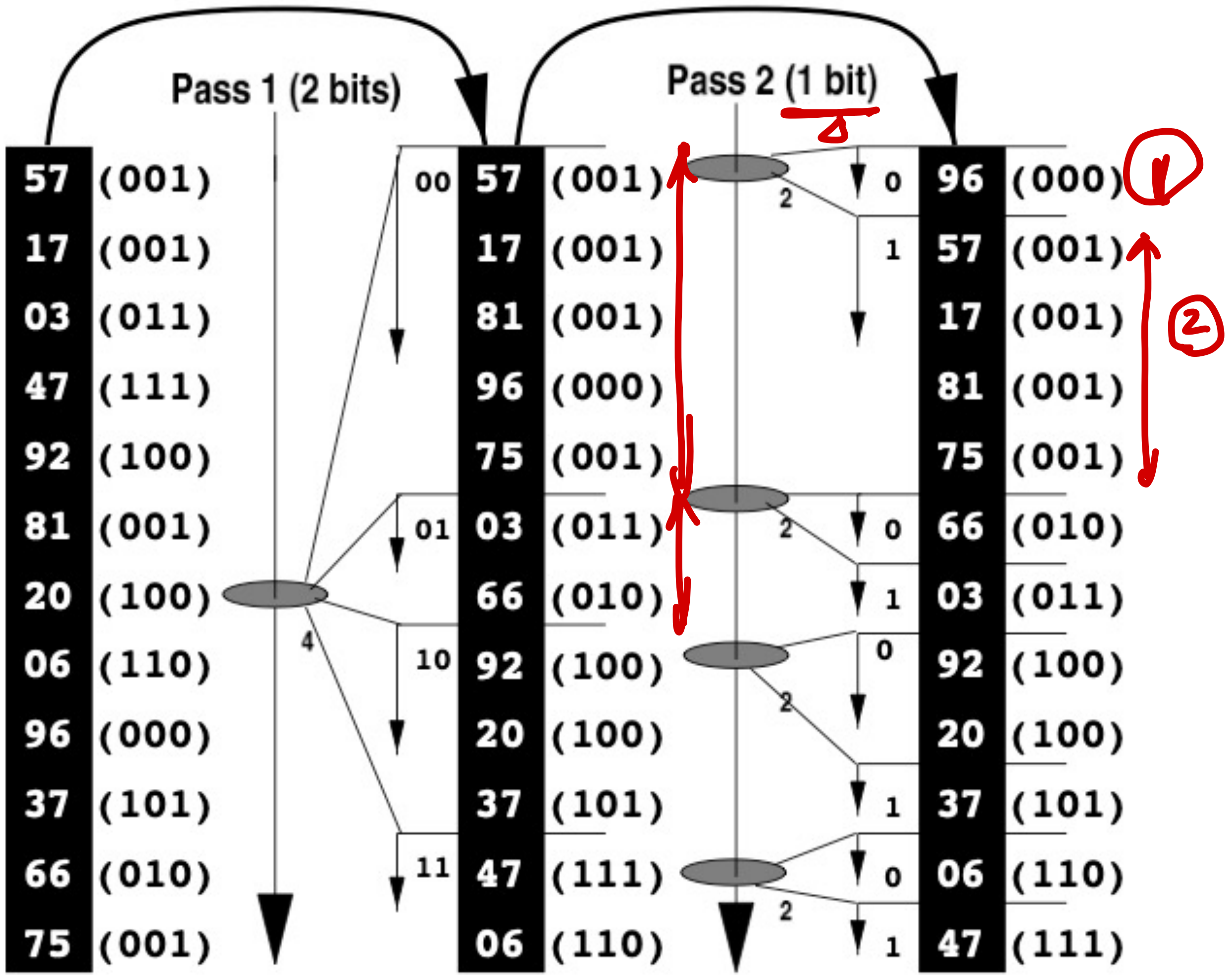
Prefix Sum

Second scan: write to corresponding location in the output buffer

Q: How to know where to write in the output array? (e.g., 47 in the example)

- Need to scan the array twice; first time collect size per partition

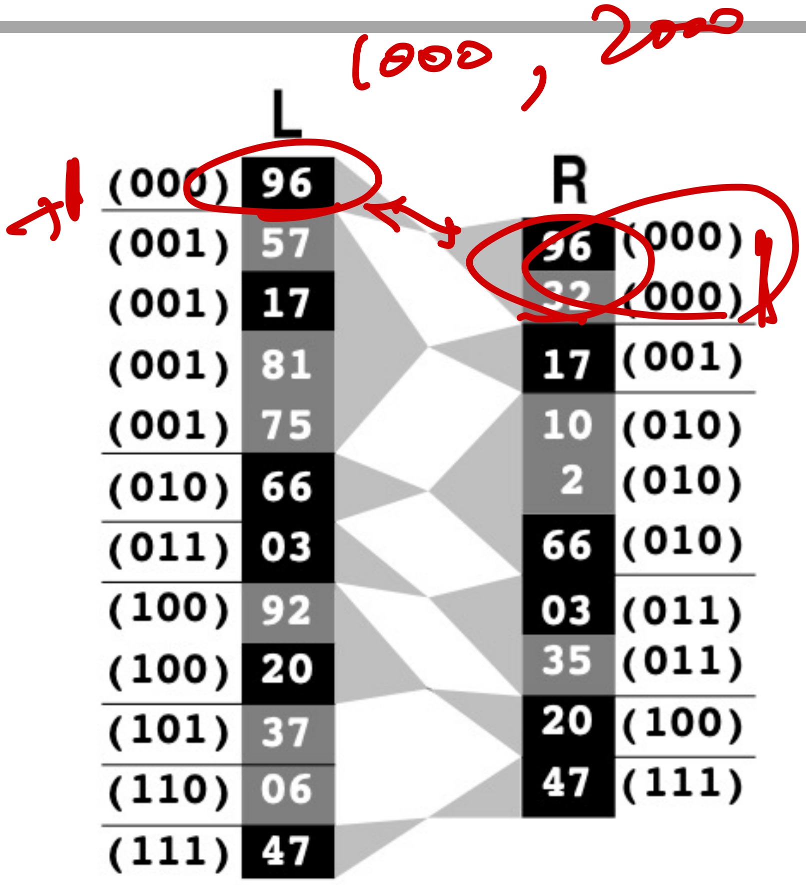
Radix Partitioning



Fully clustering *B* bits may require multiple passes

Number of partitions per pass is bounded by TLB and cache size

Join



Similar to GRACE hash join, join the corresponding partitions from the two relations

Can use either hash join or nested-loop join

Discussion Question:
Can we use sort merge join for the two relations?

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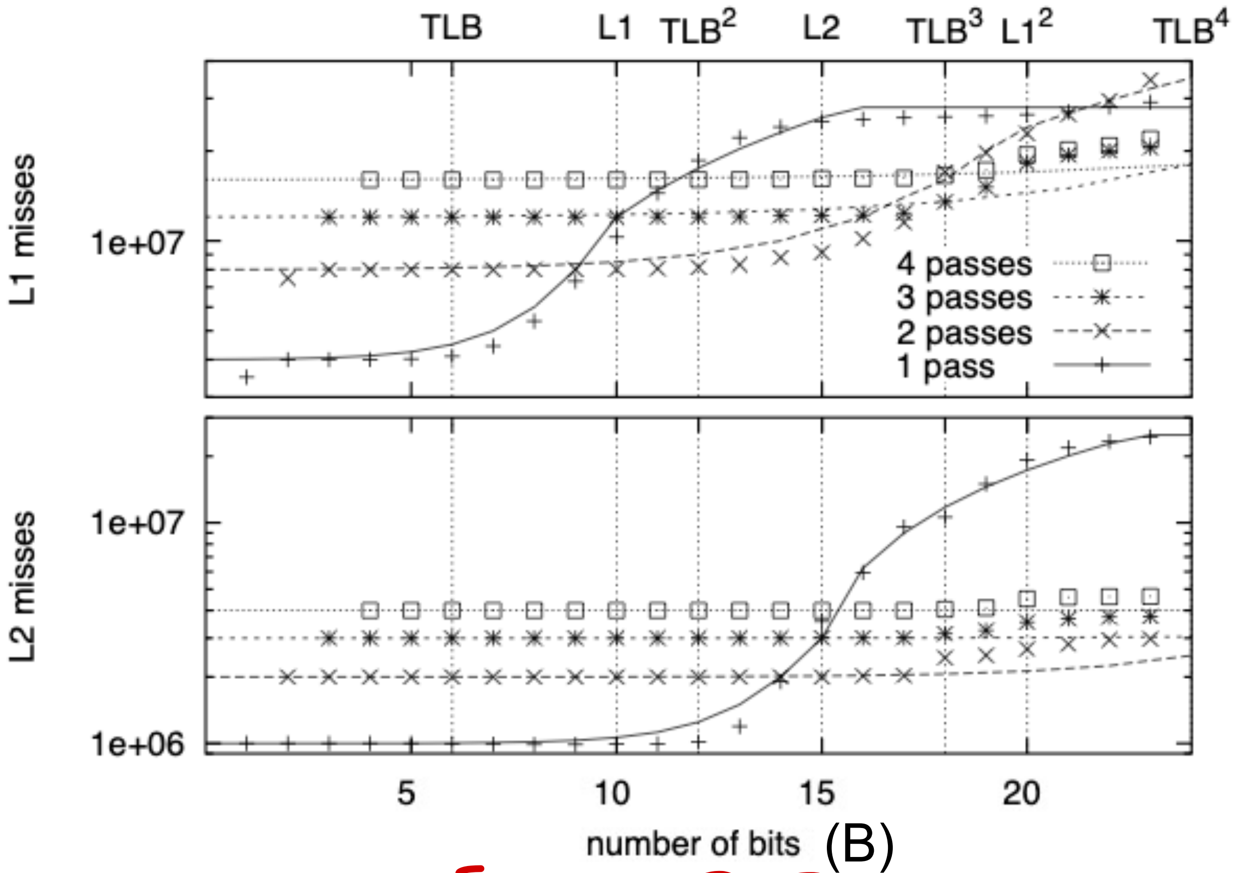
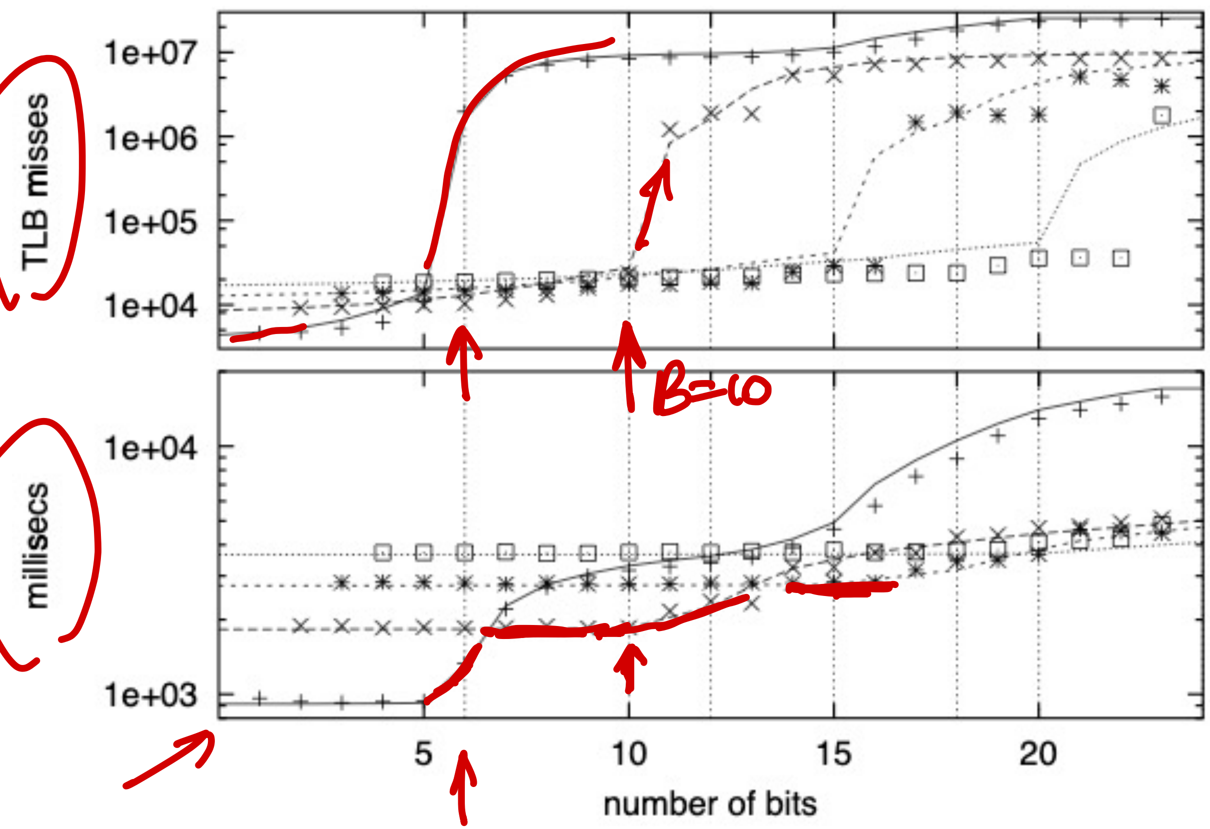
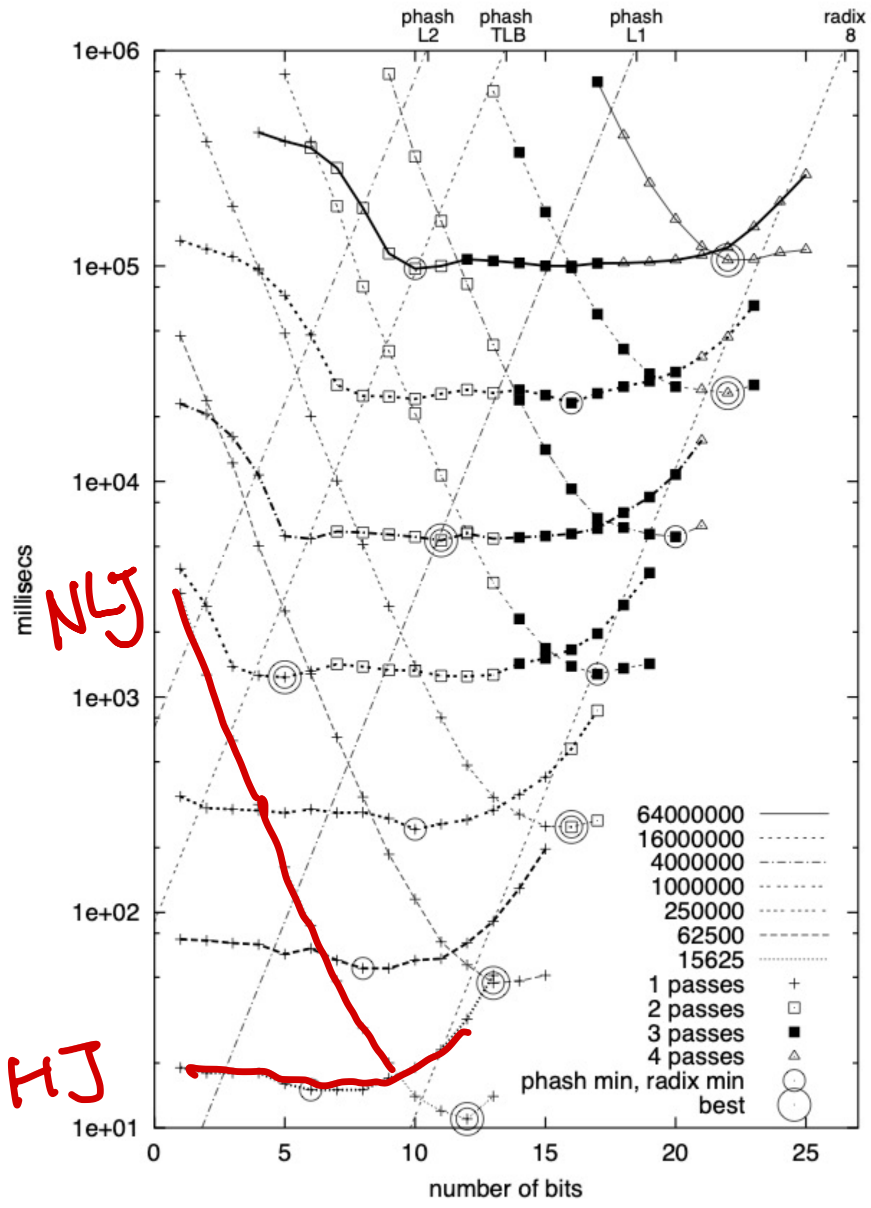
Evaluation: Radix Clustering





The machine's TLB has 64 entries

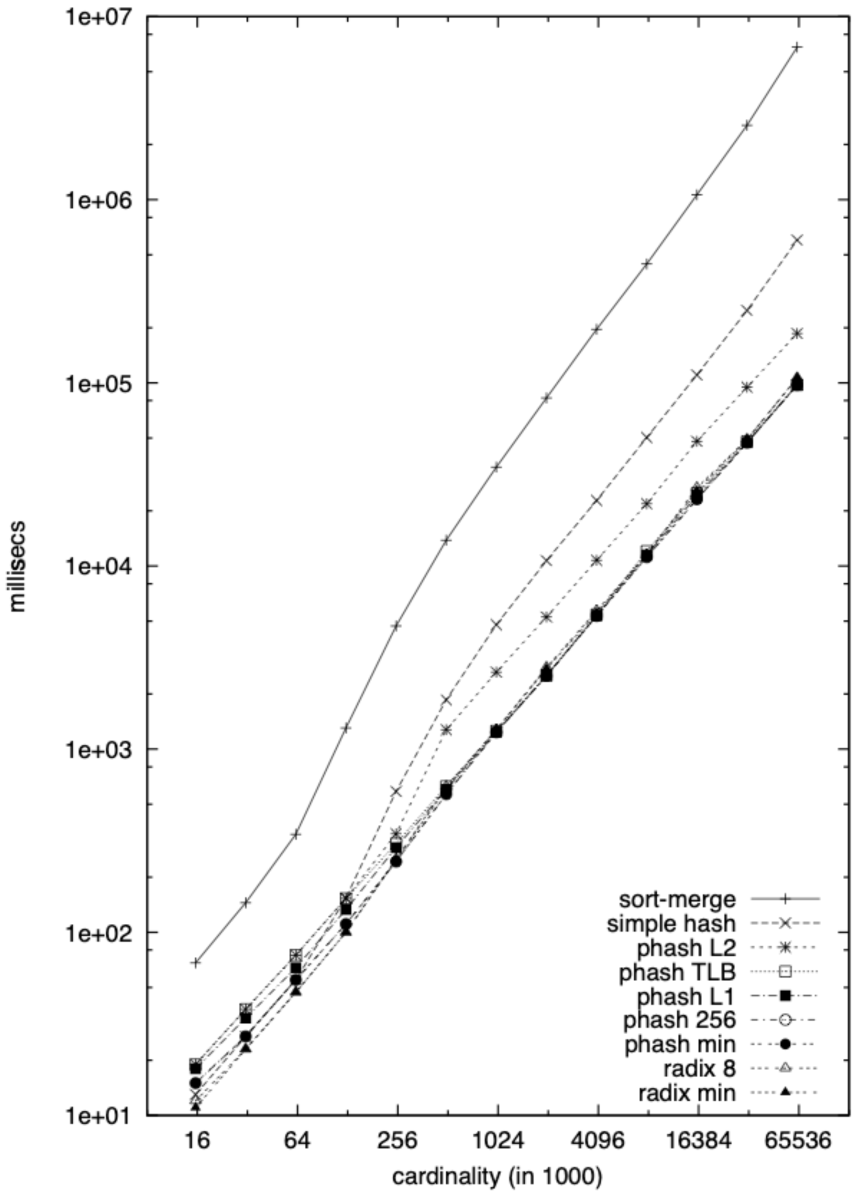
Evaluation: Join Performance



Nested-loop join prefers small partitions

Hash-join achieves similar performance for a range of partition sizes

Evaluation: Overall



Sort-merge < Simple hash < phash L2 < phash TLB and the rest

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A Different View Point

Design and Evaluation of Main Memory Hash Join Algorithms for Multi-core CPUs

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ABSTRACT

The focus of this paper is on investigating efficient hash join algorithms for modern multi-core processors in main memory environments. This paper dissects each internal phase of a typical hash join algorithm and considers different alternatives for implementing each phase, producing a family of hash join algorithms. Then, we implement these main memory algorithms on two radically different modern multiprocessor systems, and carefully examine the factors that impact the performance of each method.

Our analysis reveals some interesting results – a very simple hash join algorithm is very competitive to the other more complex methods. This simple join algorithm builds a shared hash table and does not partition the input relations. Its simplicity implies that it requires fewer parameter settings, thereby making it far easier for query optimizers and execution engines to use it in practice. Furthermore, the performance of this simple algorithm improves dramatically as the skew in the input data increases, and it quickly starts to outperform all other algorithms. Based on our results, we propose that database implementers consider adding this simple join algorithm to their repertoire of main memory join algorithms, or adapt their methods to mimic the strategy employed by this algorithm, especially when joining inputs with skewed data distributions.

Categories and Subject Descriptors

H.2.4. [**Database Management**]: Systems—*Query processing, Relational databases*

General Terms

Algorithms, Design, Performance

Keywords

hash join, multi-core, main memory

SIGMOD'11, June 12–16, 2011, Athens, Greece.

1. INTRODUCTION

Large scale multi-core processors are imminent. Modern processors today already have four or more cores, and for the past few years Intel has been introducing two more cores per processor roughly every 15 months. At this rate, it is not hard to imagine running database management systems (DBMSs) on processors with hundreds of cores in the near future. In addition, memory prices are continuing to drop. Today 1TB of memory costs as little as $25,000. Consequently, many databases now either fit entirely in main memory, or their working set is main memory resident. As a result, many DBMSs are becoming CPU bound.

In this evolving architectural landscape, DBMSs have the unique opportunity to leverage the inherent parallelism that is provided by the relational data model. Data is exposed by declarative query languages to user applications and the DBMS is free to choose its execution strategy. Coupled with the trend towards impending very large multi-cores, this implies that DBMSs must carefully rethink how they can exploit the parallelism that is provided by the modern multi-core processors, or DBMS performance will stall.

A natural question to ask then is whether there is anything new here. Beginning about three decades ago, at the inception of the field of parallel DBMSs, the database community thoroughly examined how a DBMS can use various forms of parallelism. These forms of parallelism include pure shared-nothing, shared-memory, and shared disk architectures [17]. If the modern multi-core architectures resemble any of these architectural templates, then we can simply adopt the methods that have already been designed.

In fact, to a large extent this is the approach that DBMSs have haven taken towards dealing with multi-core machines. Many commercial DBMSs simply treat a multi-core processor as a symmetric multi-processor (SMP) machine, leveraging previous work that was done by the DBMS vendors in reaction to the increasing popularity of SMP machines decades ago. These methods break up the task of a single operation, such as an equijoin, into disjoint parts and allow each processor (in an SMP box) to work on each part independently. At a high-level, these methods resemble variations of query processing techniques that were developed for parallel shared-nothing architectures [6], but adapted for SMP machines. In most commercial DBMSs, this approach is reflected across the entire design process, ranging from system internals (join processing, for example) to their pricing model, which is frequently done by scaling the SMP pricing model. On the other hand, open-source DBMSs have

12 years later

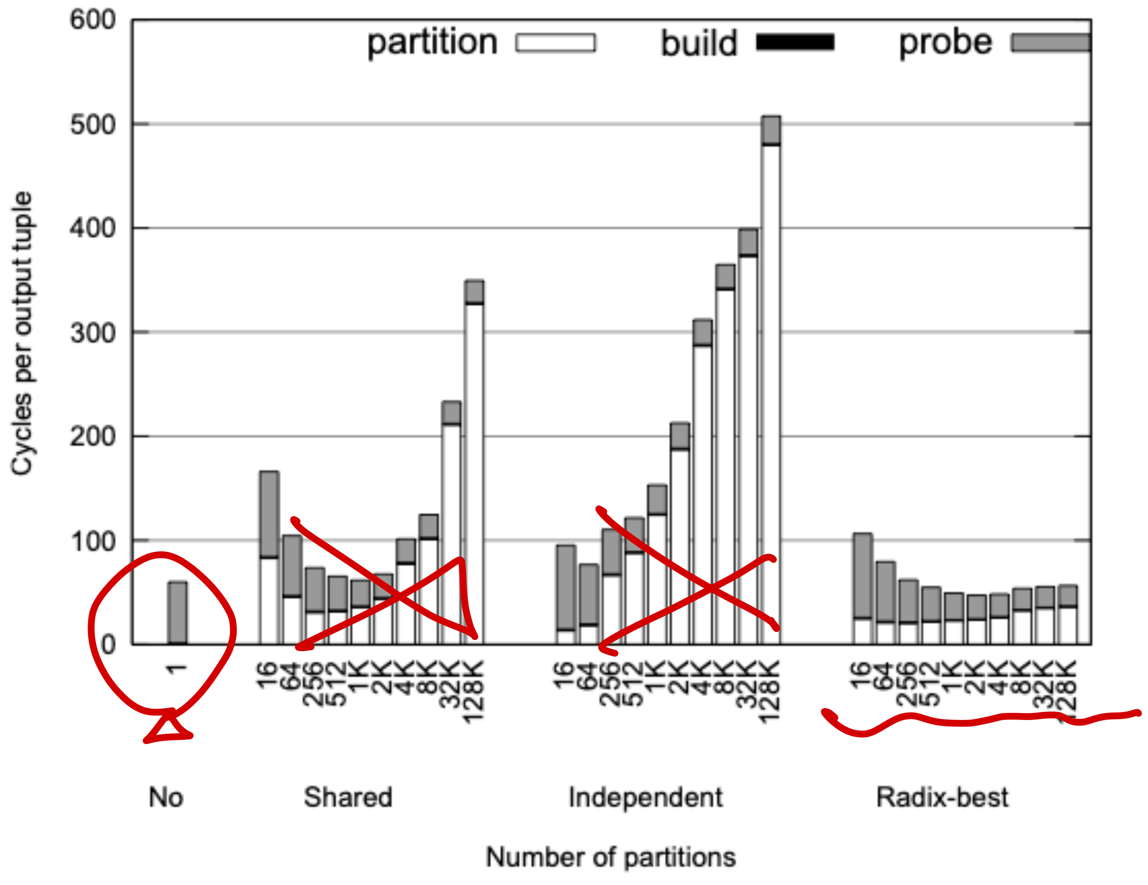
Multicore processors

Two design considerations

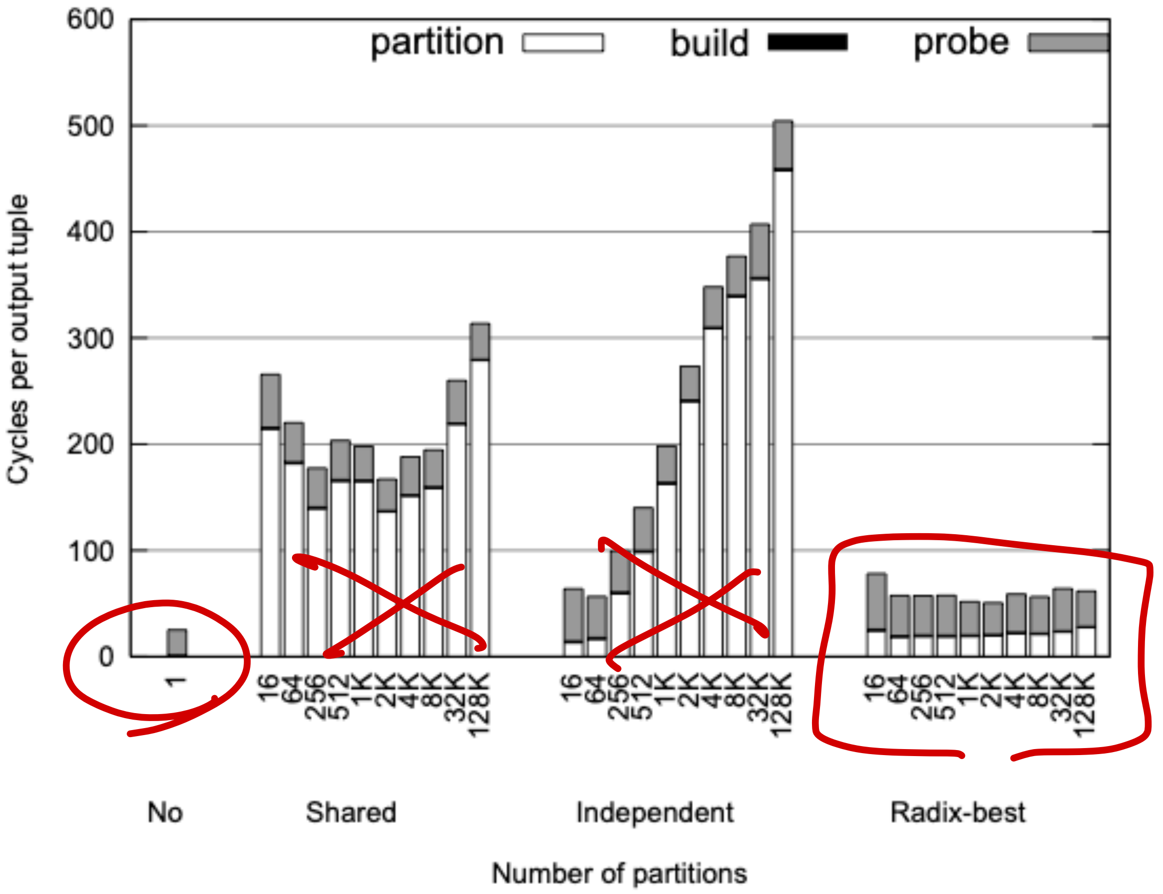
- minimizing the number of processor cache misses => **Radix Join**
- minimizing processor synchronization costs => **No partition hash join**

SIGMOD 2011

Evaluation on Multicore



Uniform dataset



Highly skewed dataset

Important to minimize synchronization overhead in multicore processors

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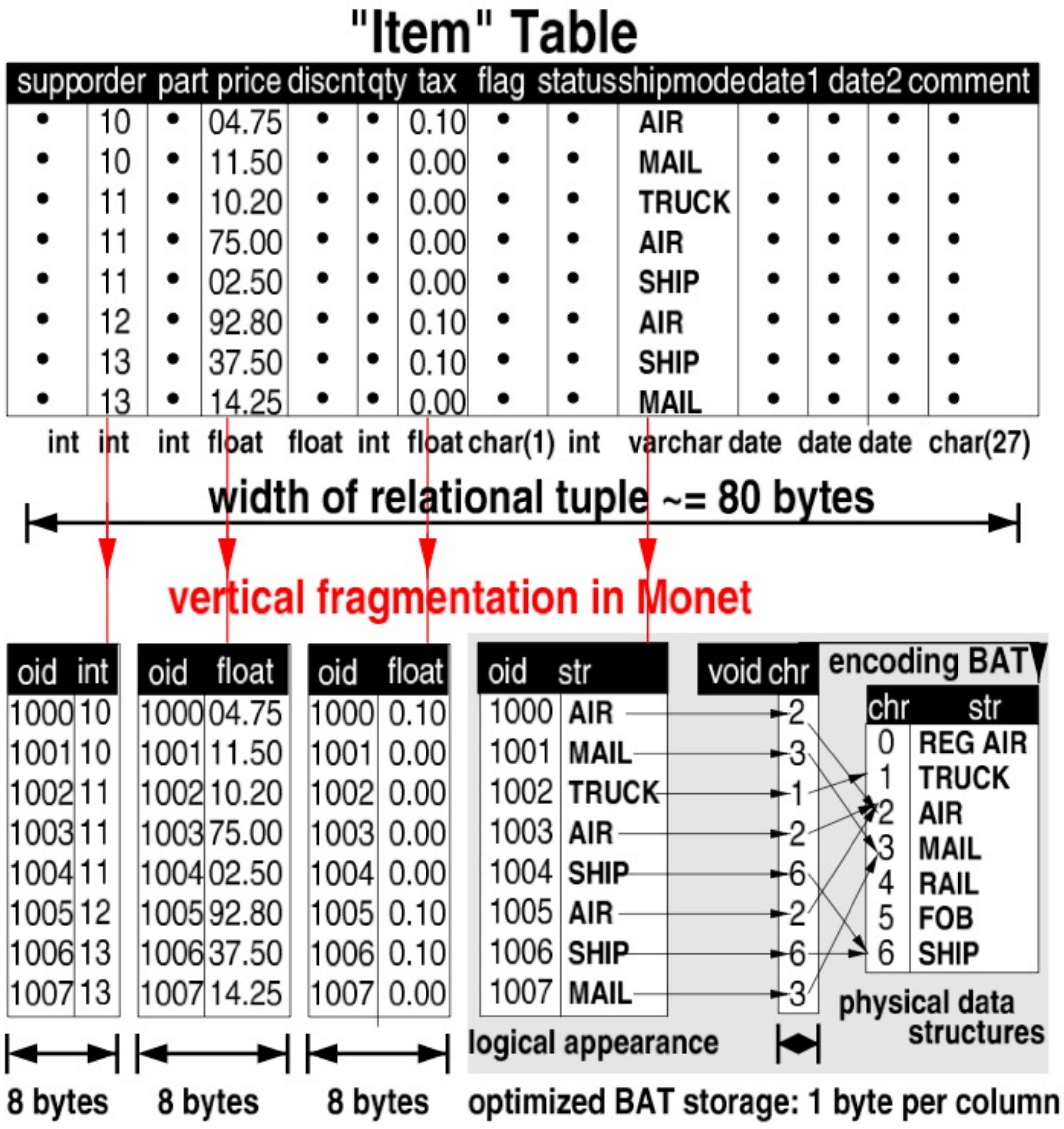
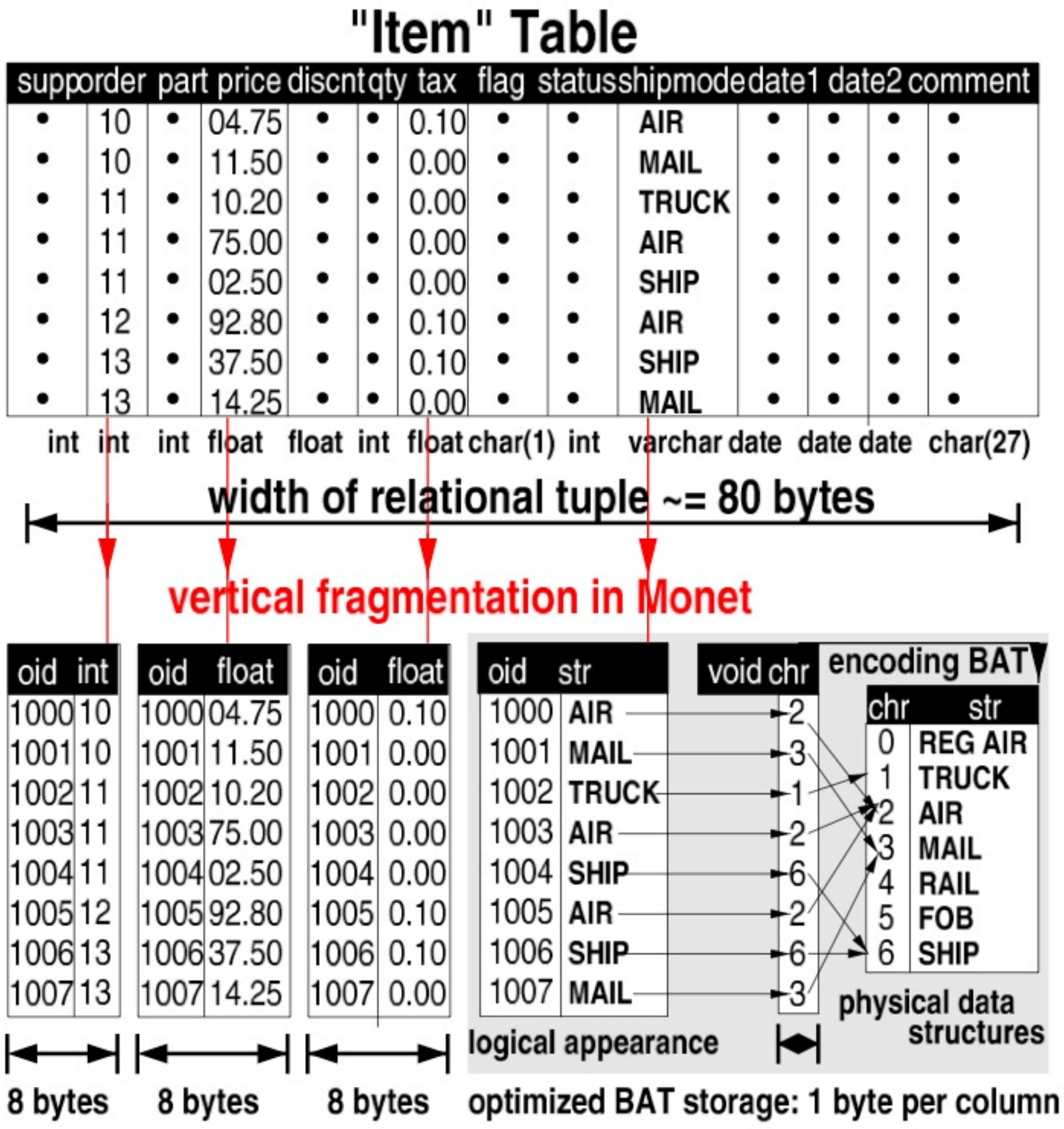
Other Topics



Column-store for analytical databases

- Stonebraker, Mike, et al. *C-store: a column-oriented DBMS*. VLDB 2005

Other Topics



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Dictionary encoding

- Many other encoding/compression schemes exist. E.g., bit-packing, delta encoding, RLE, etc.

Radix Join – Comments and Q/A

Radix join ensures tuples with same join key belong to same cluster?

Radix join assumes attributes stored as compact integer array?

Disadvantage of radix join?

Why having a shared hash table efficient for skewed data?

Common approach to use analytical model?

How to pick best parameters? (configurations vary across machines)

CPU speed improvement is also slowing down now.

Can radix join make use of modern hierarchical memory systems?

Core idea of radix-join portable to other operators?

Group Discussion

We want to join three tables, S ⋈ R ⋈ T. Assume S is large but R and T are relatively small (but larger than CPU cache). Assume the two joins are on different join keys. Would you use non-partitioned hash join or radix join for this query? Please justify your choice.

Before Next Lecture

Submit review for

Hong-Tai Chou, David DeWitt, An Evaluation of Buffer Management Strategies for Relational Database Systems. Algorithmica, 1986