DATA516/CSED516
Scalable Data Systems and Algorithms

Lecture 7
Column-store DBMSs

Announcements: General

- Project Feedback published last week
- No reading for next week

- HW4 released tonight
  - Datalog, Vertica, Materialize (next week)
  - Due Friday, December 2nd

- Project Milestones: Friday, November 25th

Project Milestone

- Hard deadline: Friday night!
- Preliminary draft of your final report
- 2-3 pages.
- Include Title and Author!
- Suggested structure/topics
  - Section 1: Goal and questions you want to ask
  - Section 2: Describe the system(s) and the data
  - Section 3: Briefly report what you have tried
  - Section 4: What do you need to do until 12/7?

Announcements: Project Dates

- Project Presentations:
  - November 29th + December 6th
  - Looking for Volunteers for the 29th
    - Perk: Those who present first will get their project feedback earlier
  - In person (contact me for exceptions)
    - For groups that've already reached out, please send an email to track
    - **Please show up in person even if not presenting**

- Final Paper due Friday December 9th

Project Presentation

Project presentations:

- You have 5 minutes (4 + 1 for questions)
- Prepare 4 - 5 slides in Google Slides. Suggestions:
  - Slide 1: Title slide: project title, your name,
  - Slide 2: Question: What question did you investigate?
  - Slide 3: Method: How did you go about answering it?
  - Slide 4: Results: What did you find?

- I will ask you to place your google slides on a shared drive; details TBD

Plan for Tuesday, Nov. 29th

- Start with Early Presentations
  - Snacks and Refreshments will be provided on both presentation days

- Remaining time depending on sign ups: OH to work on project and HW4

Today's Lecture

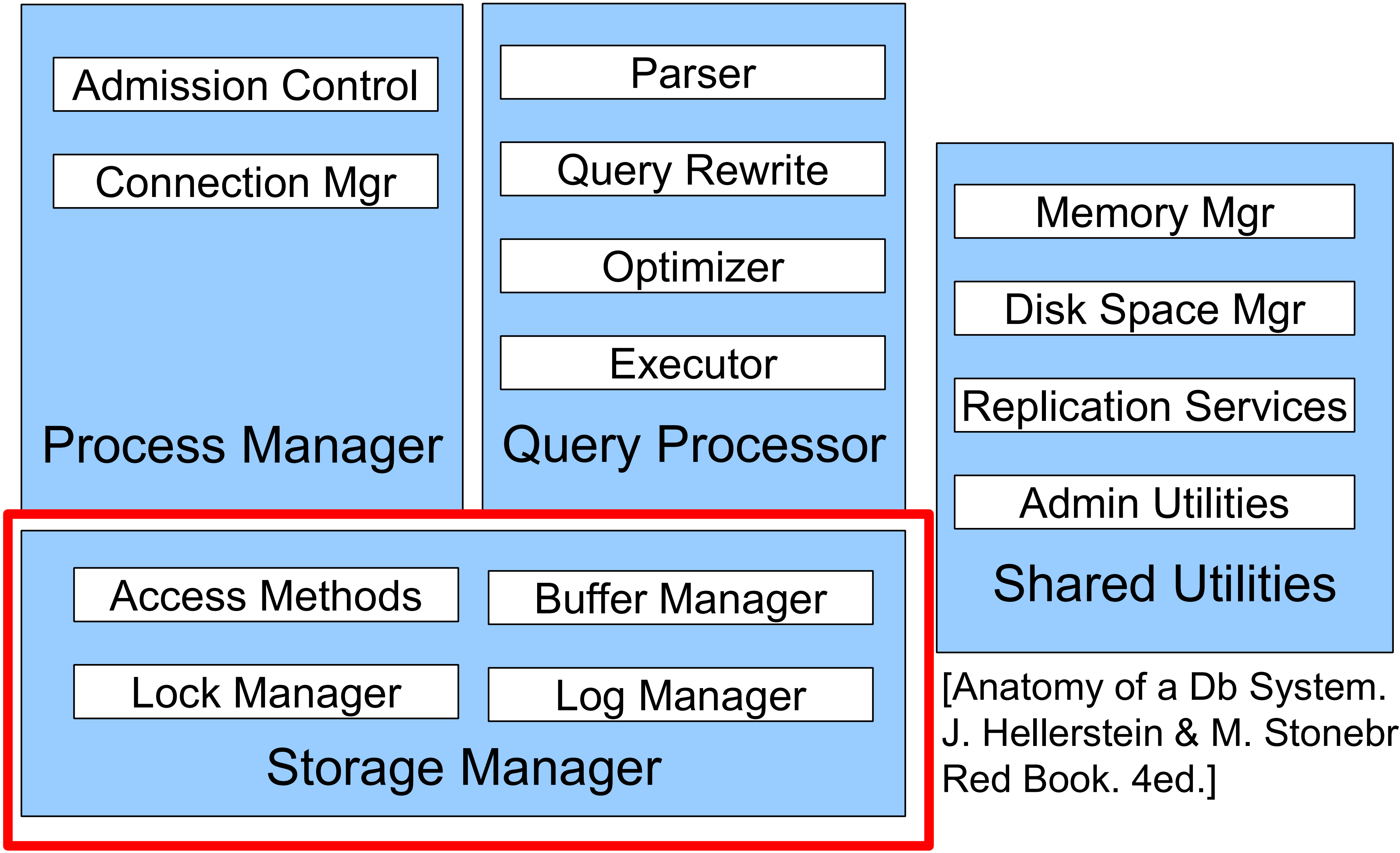
Columnar

Storage

Column-Oriented Storage

- C-store ideas and research since 1970’s
- **Circa 2000:** PAX (will discuss…)
- **2004**: C-store research prototype at MIT
  - Started by Mike Stonebraker
  - Lead graduate student Daniel Abadi
  - **2005**: Vertica founded by M. Stonebraker & A. Palmer
  - **2011**: Vertica acquired by HP
  - **2012**: As of VLDB’12 paper, 500 production deployments of Vertica, three over a PB in size
- **2013**: All major DB vendors include some column-store implementation
- **2016**: PAX adopted by Snowflake

DBMS Architecture



Process Manager
- Admission Control
- Connection Mgr

Query Processor
- Parser
- Query Rewrite
- Optimizer
- Executor

Storage Manager
- Access Methods
- Buffer Manager
- Lock Manager
- Log Manager

Shared Utilities
- Memory Mgr
- Disk Space Mgr
- Replication Services
- Admin Utilities

[Anatomy of a Db System.
J. Hellerstein & M. Stonebraker.
Red Book. 4ed.]

Review: Data Storage in a Row Store

Consider a relation storing tweets:

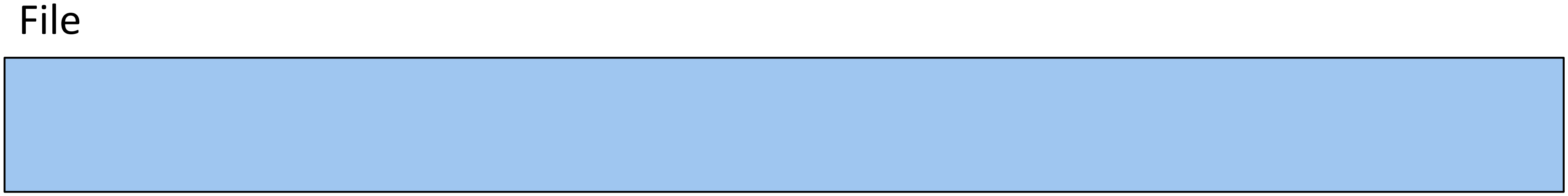
`Tweets(tid, user, time, content)`

How should we store it on disk?

Design Exercise

- Design choice: **One OS file for each relation**
  - Option 1: DBMS creates one big file with “files” inside
  - Option 2: DBMS uses disk directly, with “files” inside

- The OS (or DBMS) provides an API of the form
  - Seek to some position (or “skip” over B bytes)
  - Read/Write B bytes



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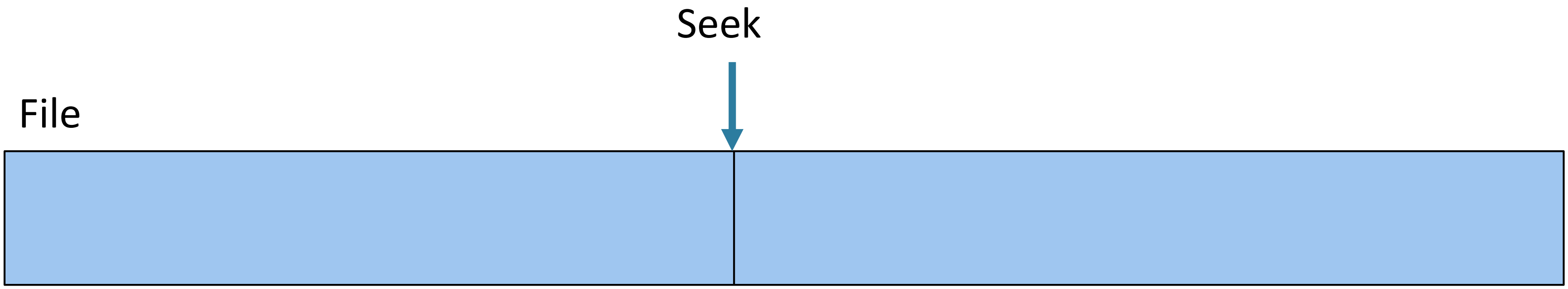

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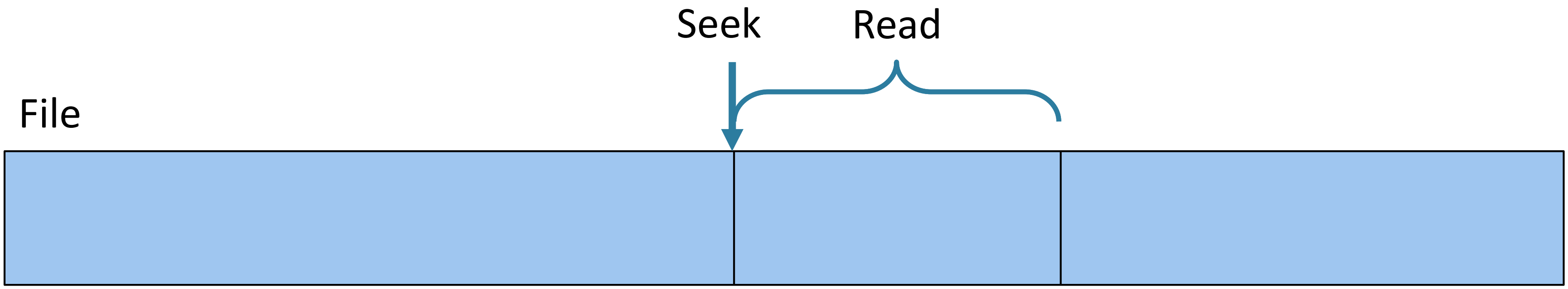
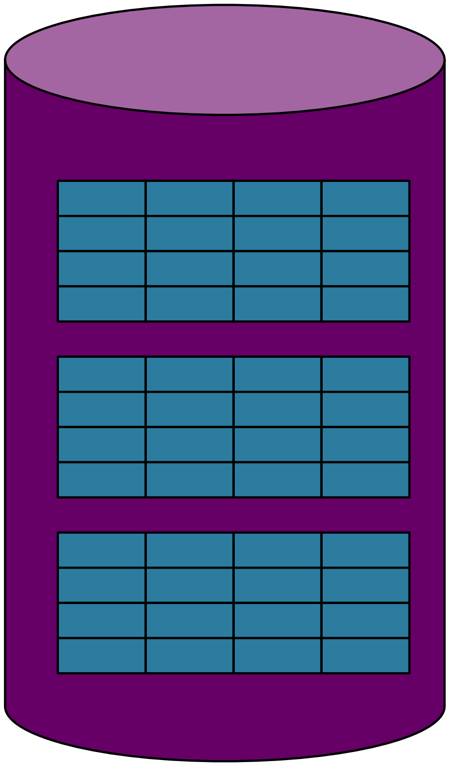


Working with Pages



- Reading/writing to/from disk
  - Seeking takes a long time!
  - Reading sequentially is fast
  - Read/write entire blocks

- 1 block = typically 4, 8, or 16 KB

- Buffer manager:
  - Caches a set of blocks in main memory
  - Blocks in MM are called pages
  - 1 page = 1 block

Working with Main Memory

- The Central Processing Unit (CPU) reads/writes data from/to main memory
  - Read/write entire bytes (= 8 bits)
  - Typically: 1 or 2 or 4 or 8 bytes
- CPU much faster than MM
- Solution: CPU cache
  - A very fast, associative memory
  - Cache line = aka cache block
  - Typically: 1 cache line = 64 bytes

Summary so far…

Two bottlenecks:

- The disk I/O bottleneck:
  - Disk is much slower than main memory
  - Read/write one block at a time (8KB-16KB)
  - Buffer pool in main memory: 1page=1block

Summary so far…

Two bottlenecks:

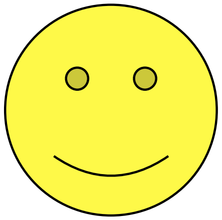
- The disk I/O bottleneck:
  - Disk is much slower than main memory
  - Read/write one block at a time (8KB-16KB)
  - Buffer pool in main memory: 1page=1block
- The main memory bottleneck
  - MM is much slower than CPU
  - Read/write one byte at a time (or 2/4/8)
  - CPU cache: 1 cache line = 64 bytes

Continuing our Design

Key question:

- How should we organize tuples on a page?

Design Exercise 1



- **Think how you would store tuples on a page**
  - Fixed length tuples
  - Variable length tuples

- **Requirements**
  - Insert a new tuple
  - Look up a tuple given a RID (= Record ID)
  - Remove a tuple given a RID
  - Modify a tuple
  - Enumerate all tuples

Page Formats

Issues to consider:

- 1 page = 1 disk block = fixed size (e.g. 8KB)
- Records:
  - Fixed length
  - Variable length
- Record id = RID
  - Typically **RID = (PageID, SlotNumber)**

Why do we need RID’s in a relational DBMS ?

Page Formats

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- Records:
  - Fixed length
  - Variable length
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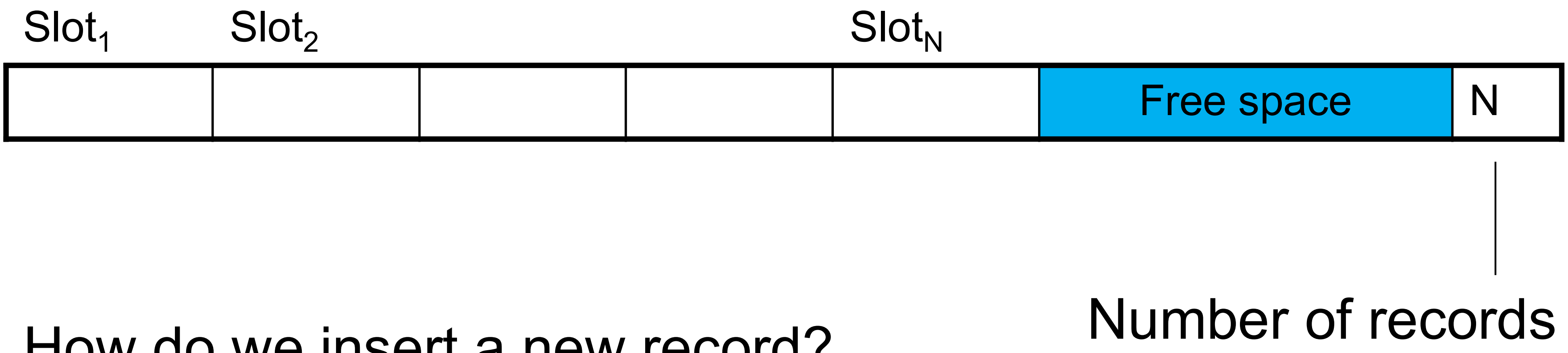
Why do we need RID's in a relational DBMS ?

For indexes, and for transactions

Page Format Approach 1

Fixed-length records: packed representation
Divide page into **slots**. Each slot can hold one tuple
Record ID (RID) for each tuple is **(PageID,SlotNb)**



How do we insert a new record?

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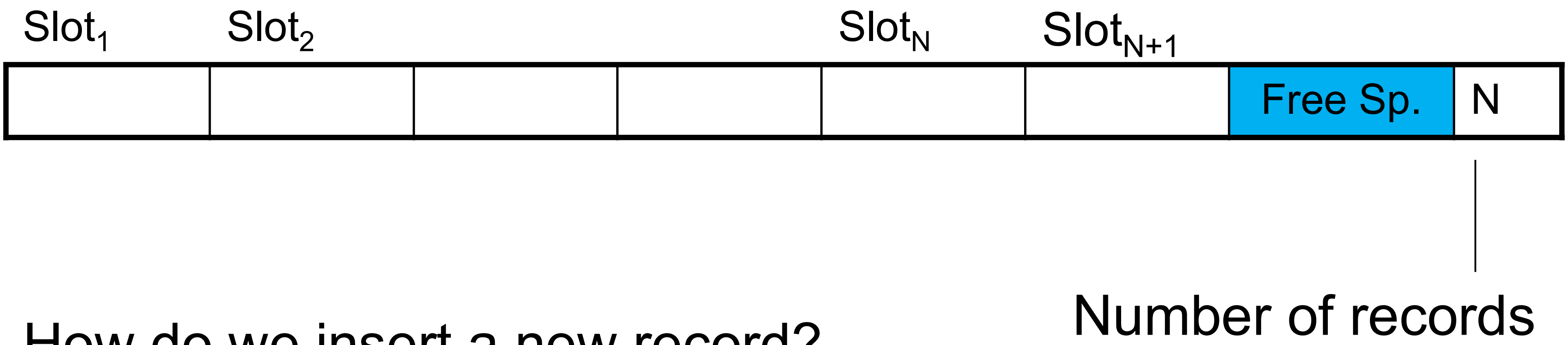

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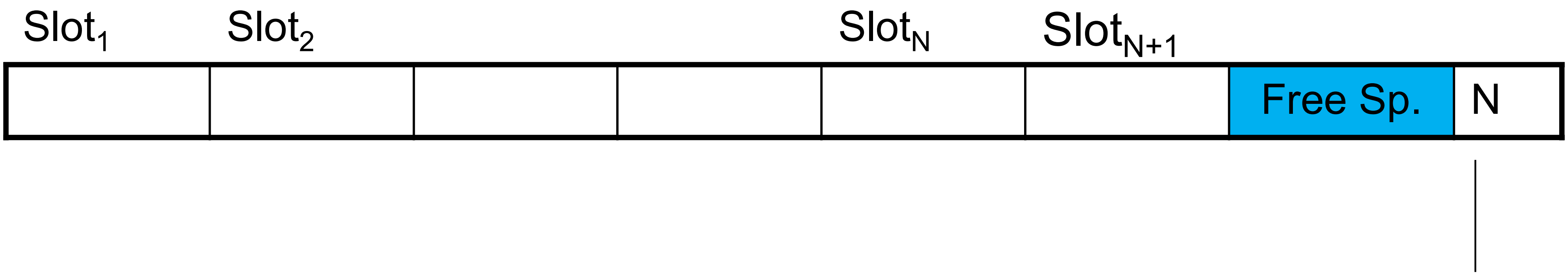

Number of records

How do we insert a new record?

How do we delete a record?

Page Format Approach 1

Fixed-length records: packed representation
Divide page into **slots**. Each slot can hold one tuple
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Number of records

How do we insert a new record?

How do we delete a record? Cannot remove record (why?)

Page Format Approach 1

Fixed-length records: packed representation
Divide page into **slots**. Each slot can hold one tuple
Record ID (RID) for each tuple is **(PageID,SlotNb)**

Number of records

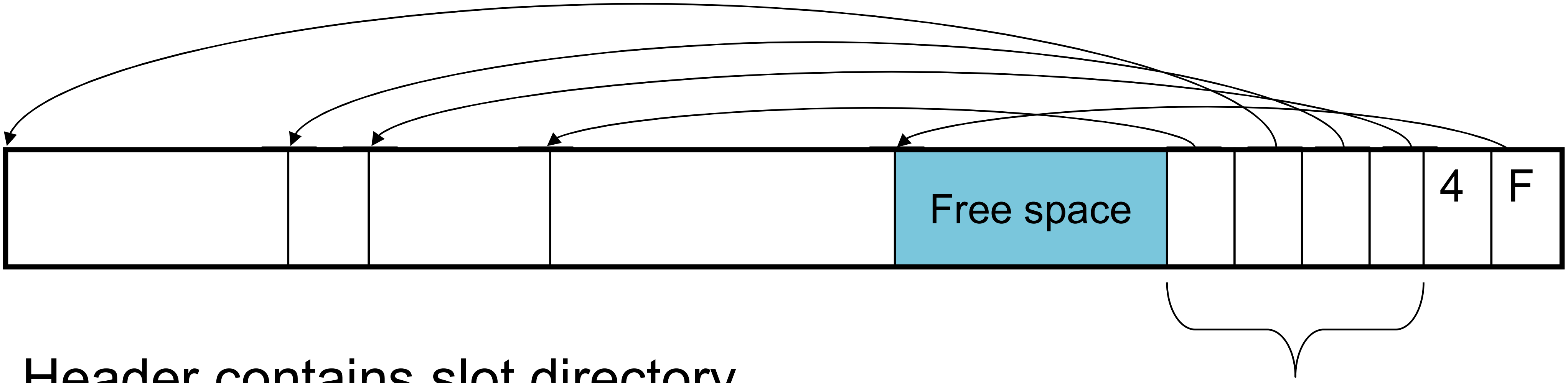
How do we insert a new record?

How do we delete a record? Cannot remove record (why?)

How do we handle variable-length records?

Page Format Approach 2

Record ID (RID) for each tuple is **(PageID,SlotNb)**



Slot directory

Header contains slot directory
+ Need to keep track of nb of slots
+ Also need to keep track of free space (F)

Can handle variable-length records
Can move tuples inside a page without changing RIDs

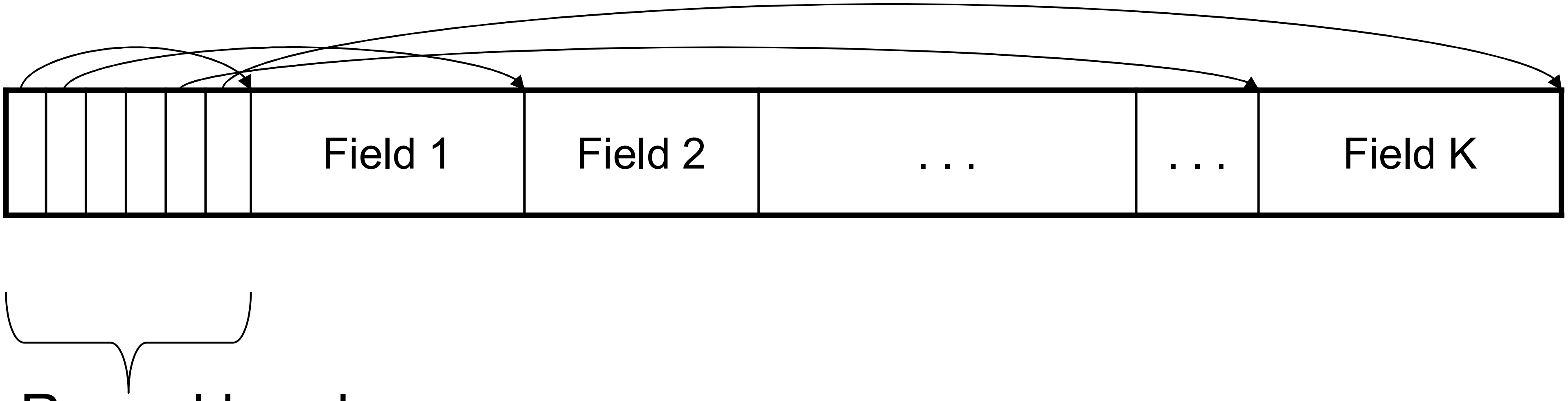
Record Formats

Fixed-length records => Each field has a fixed length (i.e., it has the same length in all the records)

Information about field lengths and types is in the catalog

Record Formats

Variable length records



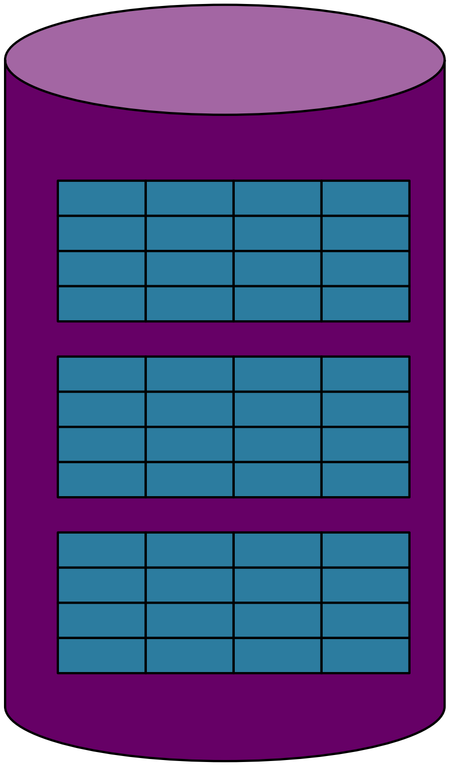
Record header

Remark: NULLS require no space at all (why ?)

Summary so far…

- Page format:
  - Page header
  - Record
  - Record
  - …
- Record format:
  - Record header
  - Field
  - Field
  - …

From Row-Store to Column-Store



Rows stored
contiguously on disk
(+ tuple headers)

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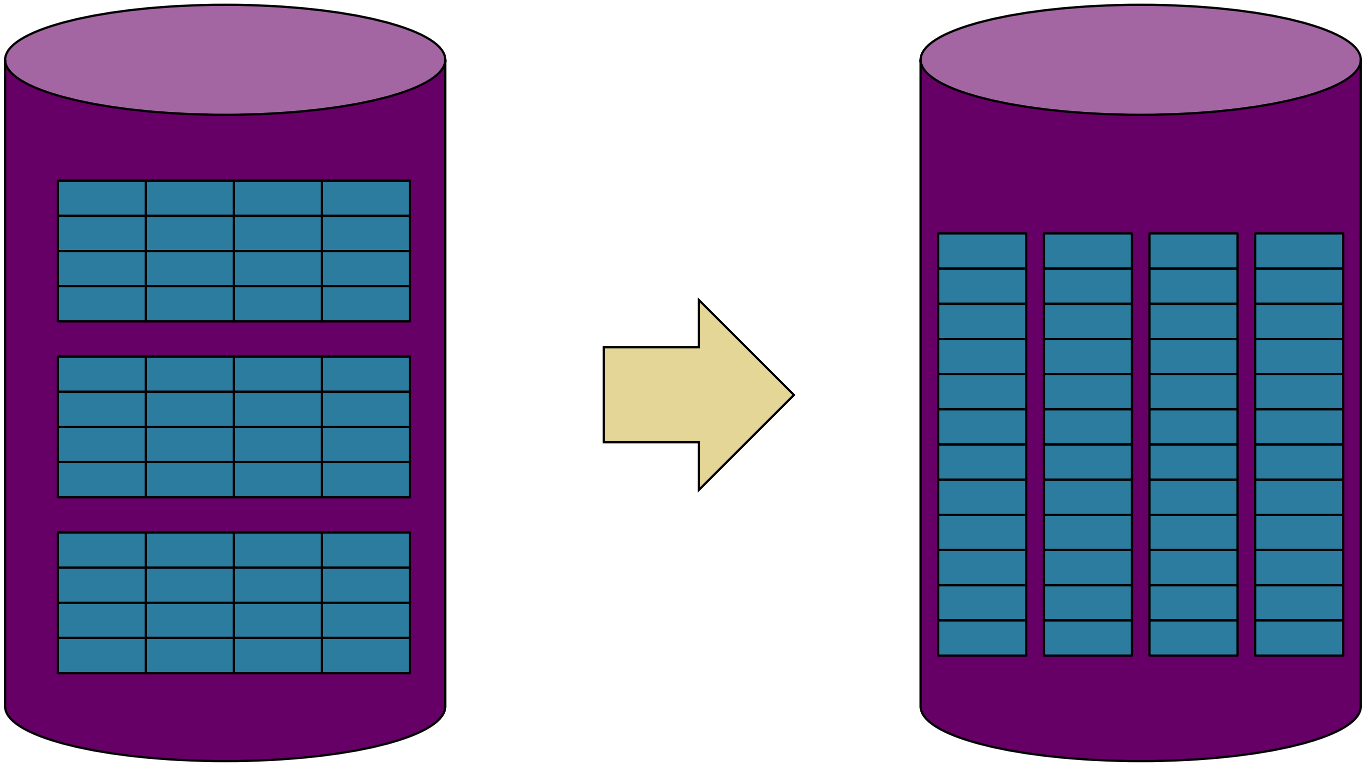

Rows stored
contiguously on disk
(+ tuple headers)

Columns stored
contiguously on disk
(no tuple headers needed)

Two Options

Column Store:

- 1 column = 1 file
- Requires a complete rewrite of query engine
- Potential for major performance gain for <u>*some*</u> queries, but need need a lot of work to get there (will see this)

Two Options

Column Store:

- 1 column = 1 file
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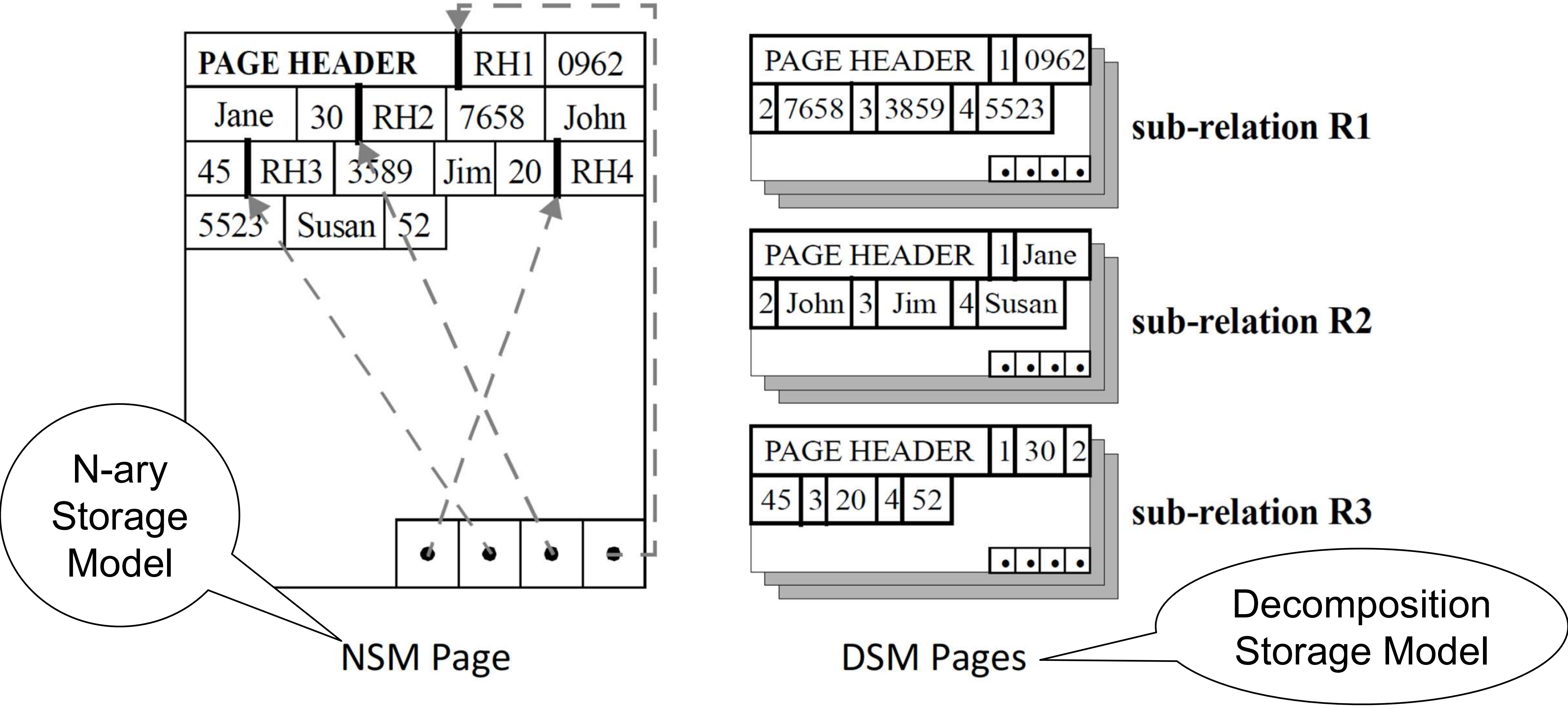
PAX:

- Split the table into blocks (original PAX) or chunks (Snowflake)
- Inside each chunk, store the attribute column-wise
- Obtain most of the performance gain, with very little update to the query engine

An Intermediate Format: PAX

- PAX = Partition Attributes Across
- Addresses memory access bottleneck (not the disk bottleneck)

From Row to Column Storage (Initial Designs - 1985)



N-ary Storage Model

Decomposition Storage Model

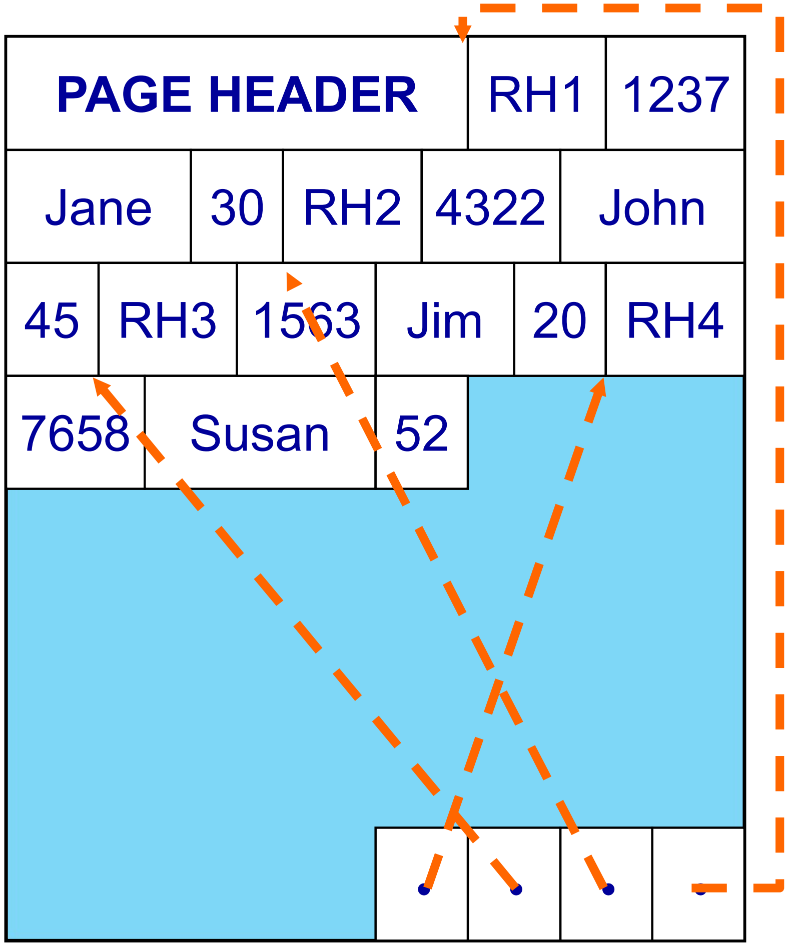
Figure 2.1: Storage models for storing database records inside disk pages: NSM (row-store) and DSM (a predecessor to column-stores). Figure taken from [5].

Current Scheme: Slotted Pages

Formal name: NSM (N-ary Storage Model)

R

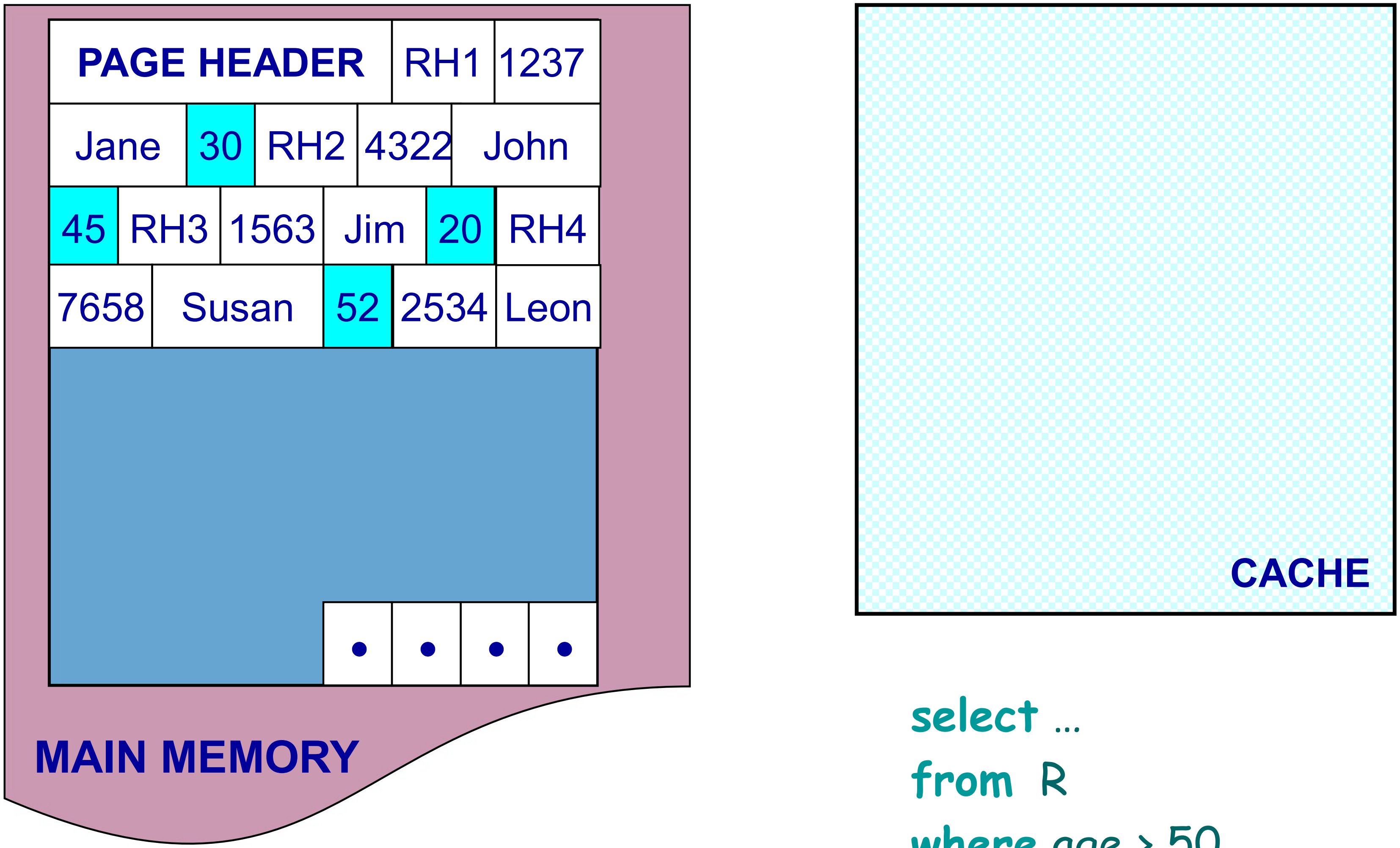
RID	SSN	Name	Age
1	1237	Jane	30
2	4322	John	45
3	1563	Jim	20
4	7658	Susan	52
5	2534	Leon	43
6	8791	Dan	37



- Records are stored sequentially
- Offsets to start of each record at end of page

Ailamaki VLDB’01 http://research.cs.wisc.edu/multifacet/papers/vldb01_pax_talk.ppt

Predicate Evaluation using NSM



PAGE HEADER RH1 1237
Jane 30 RH2 4322 John
45 RH3 1563 Jim 20 RH4
7658 Susan 52 2534 Leon
• • • •

MAIN MEMORY

CACHE

select …
from R
where age > 50

NSM pushes non-referenced data to the cache

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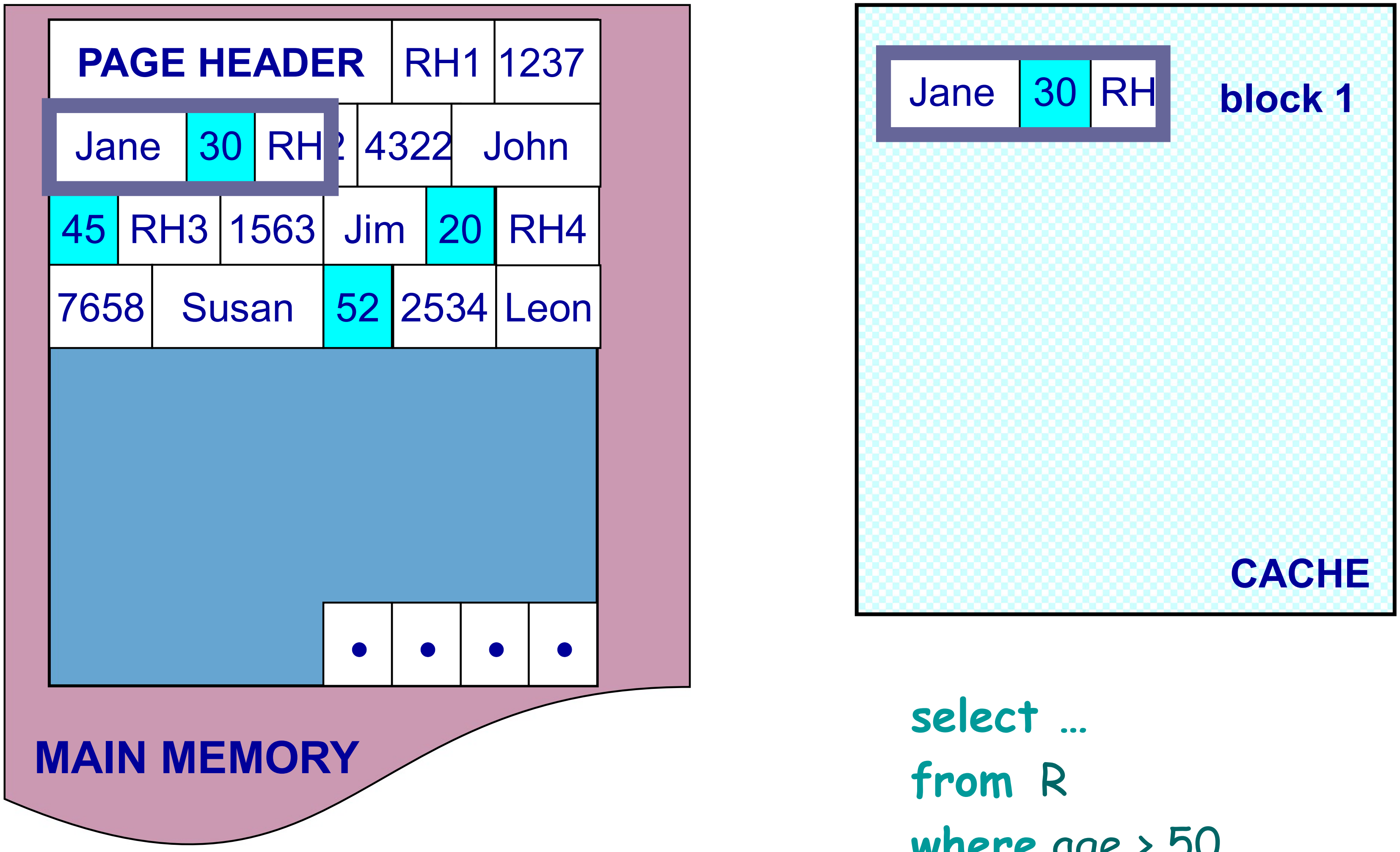

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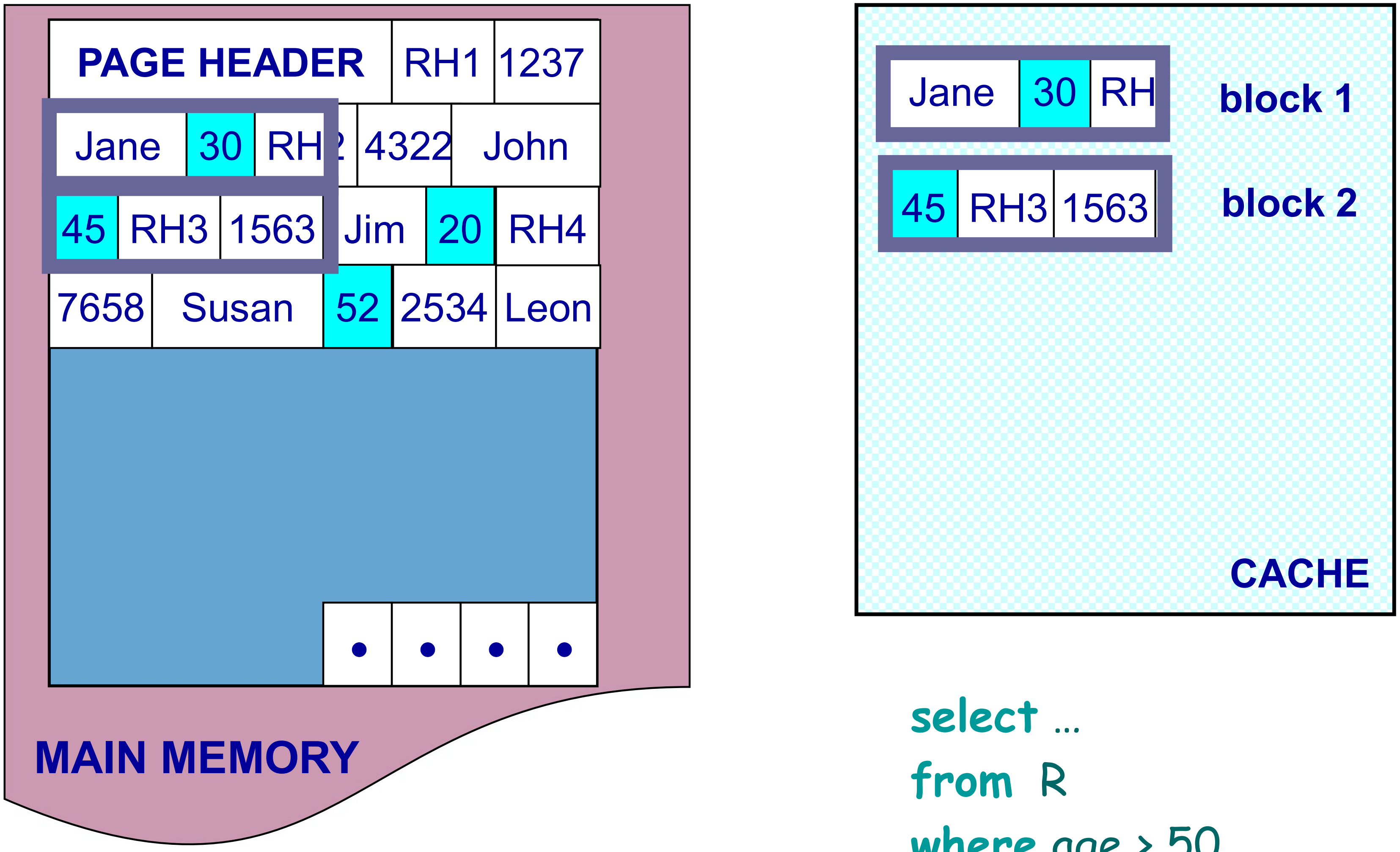

PAGE HEADER			RH1	1237
Jane	30	RH2	4322	John
45	RH3	1563	Jim	20	RH4
7658	Susan	52	2534	Leon

• • • •

MAIN MEMORY

Jane 30 RH **block 1**

45 RH3 1563 **block 2**

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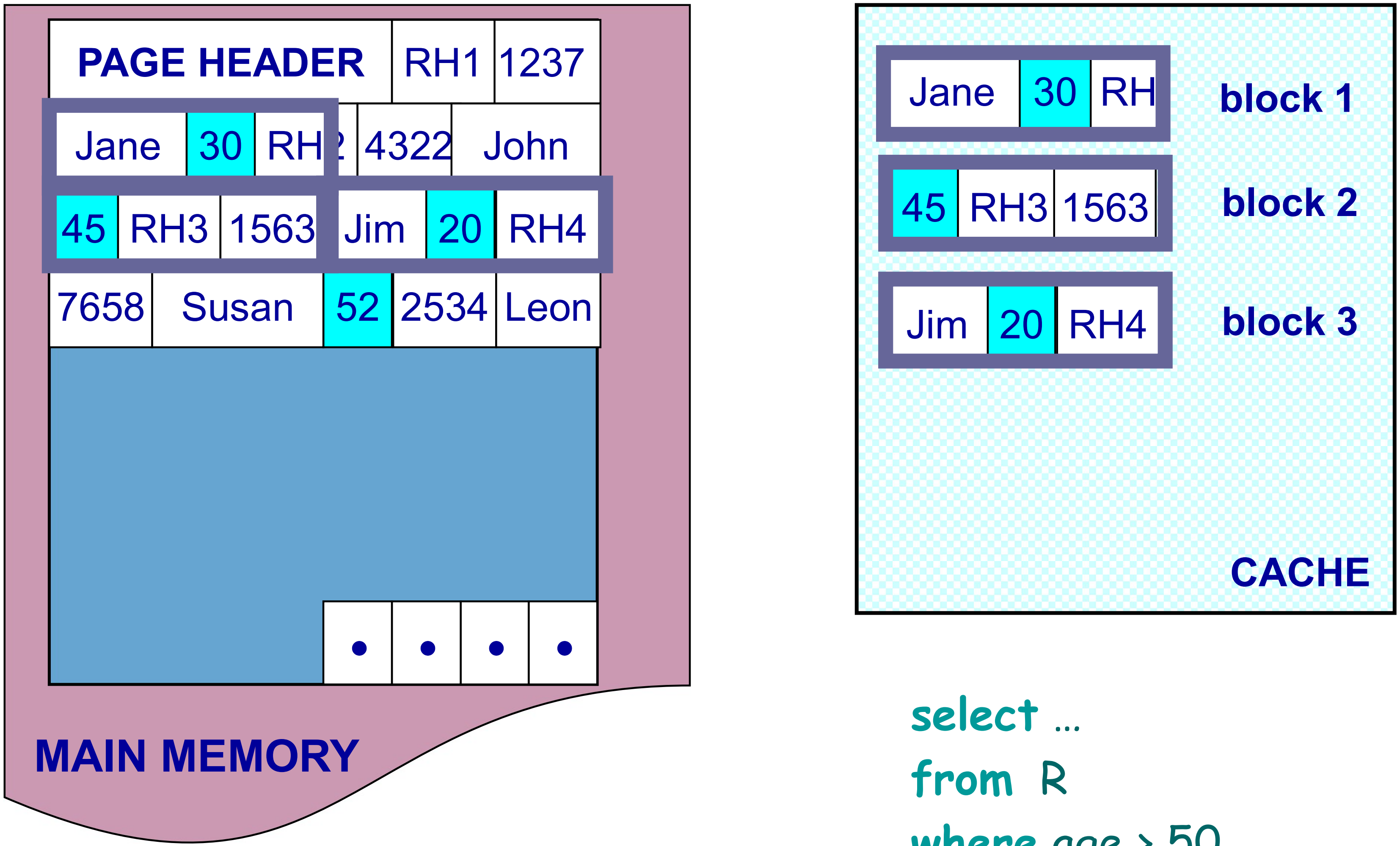

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MAIN MEMORY

Jane | 30 | RH — block 1

45 | RH3 | 1563 — block 2

Jim | 20 | RH4 — block 3

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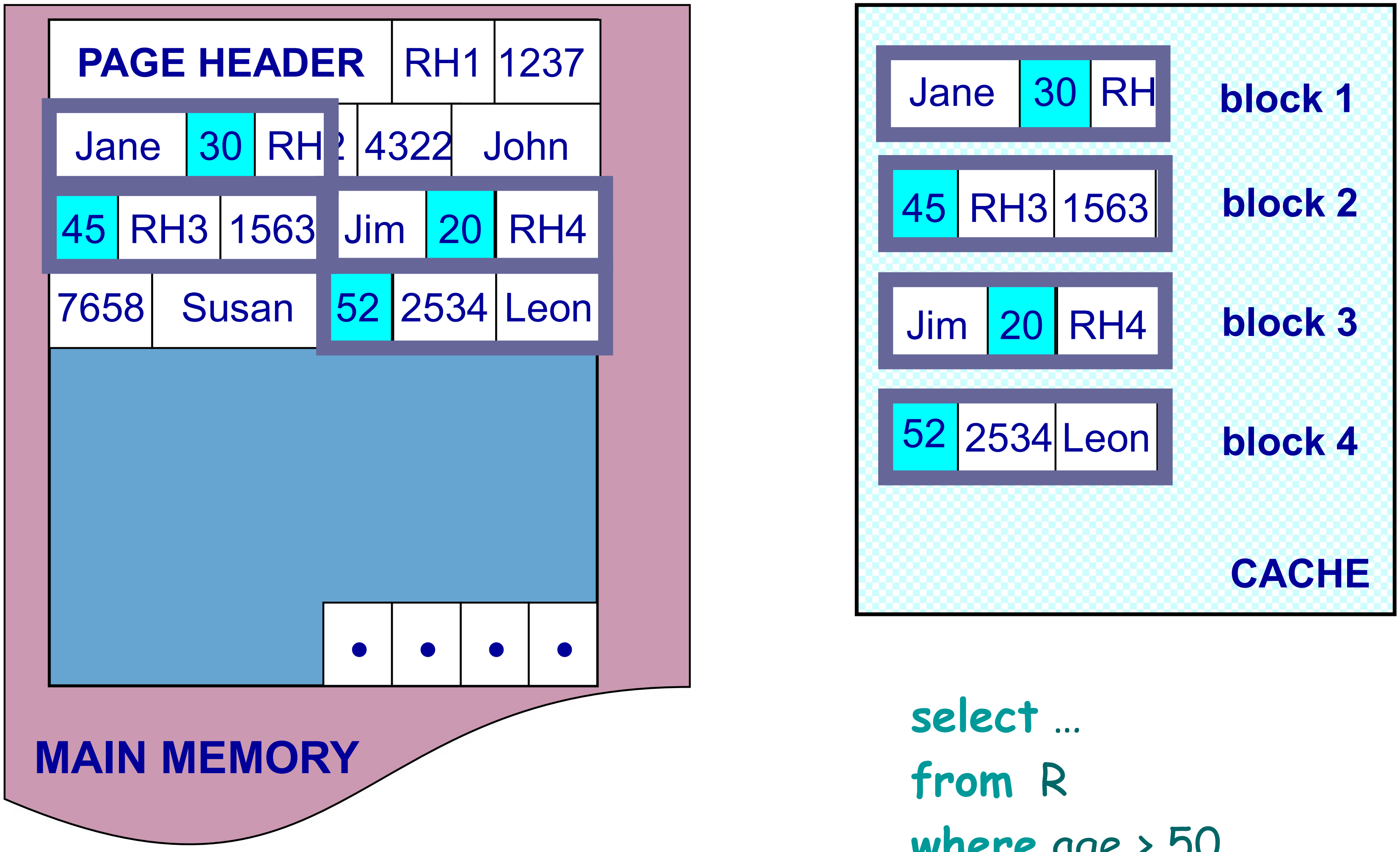

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Need New Data Page Layout

- Eliminates unnecessary memory accesses
- Improves inter-record locality
- Keeps a record’s fields together
- Does not affect I/O performance

and, most importantly, is…

low-implementation-cost, high-impact

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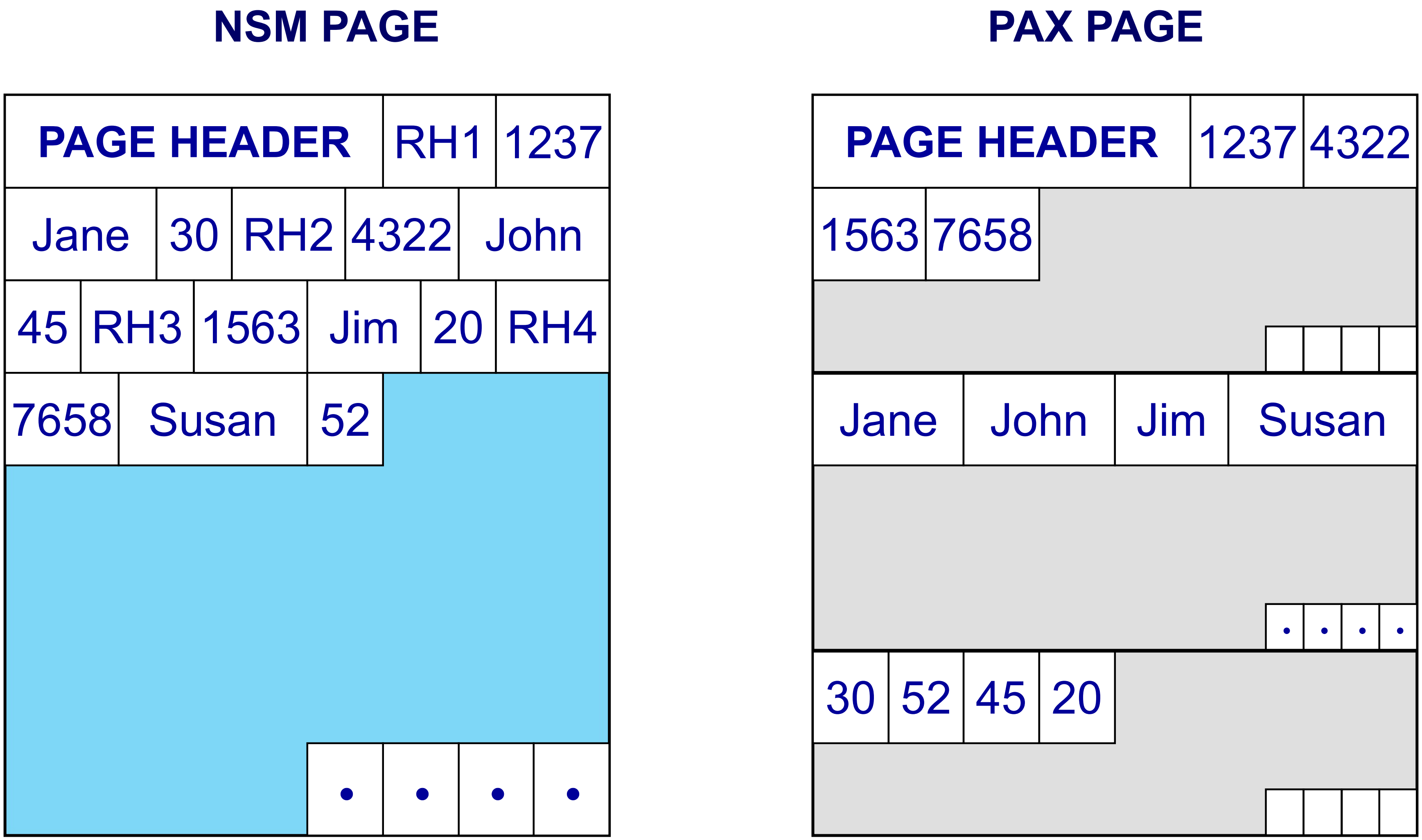
Partition Attributes Across (PAX)



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PAX PAGE

PAGE HEADER 1237 4322

1563 7658

Jane John Jim Susan

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Partition data *within* the page for spatial locality

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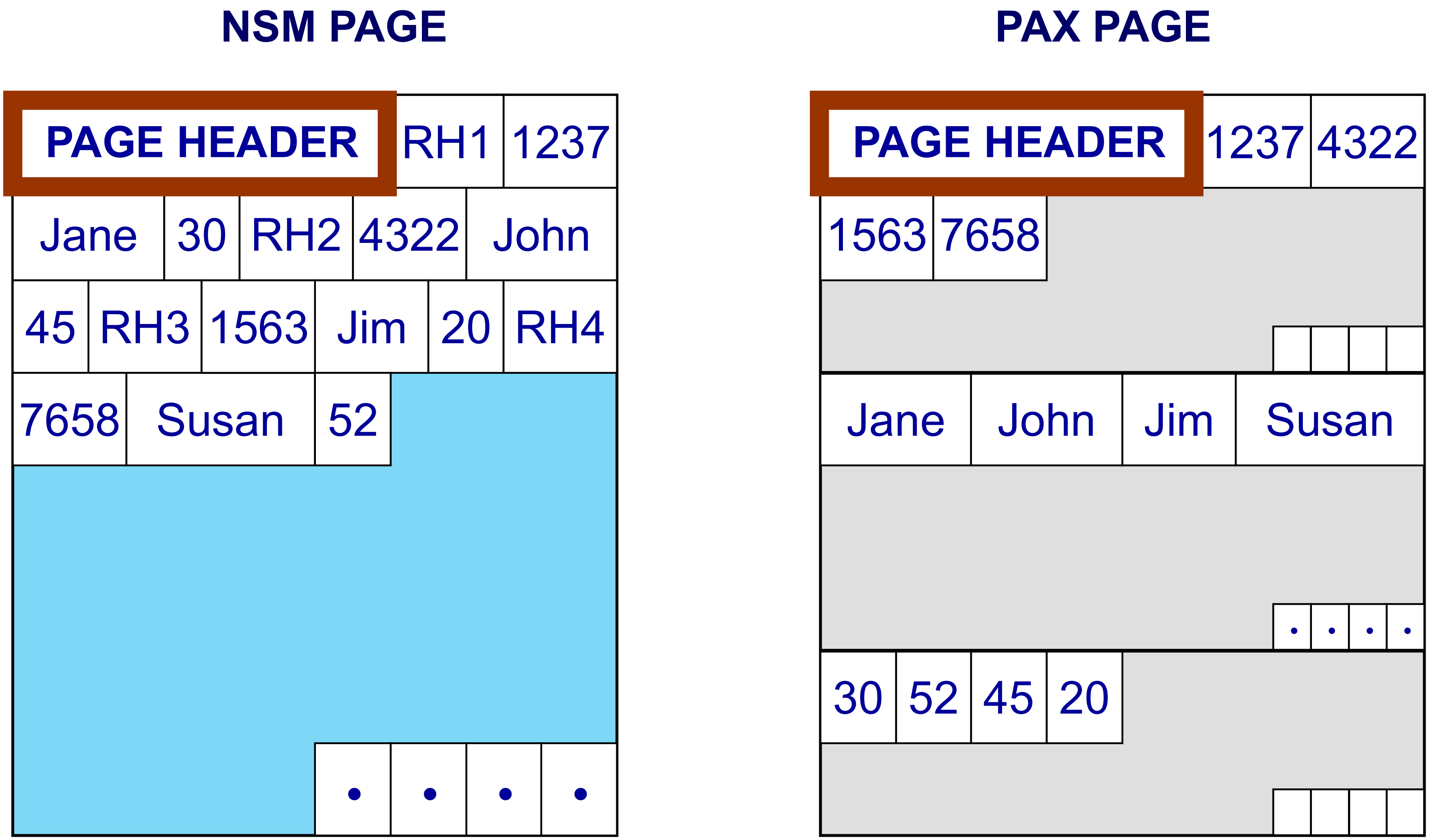

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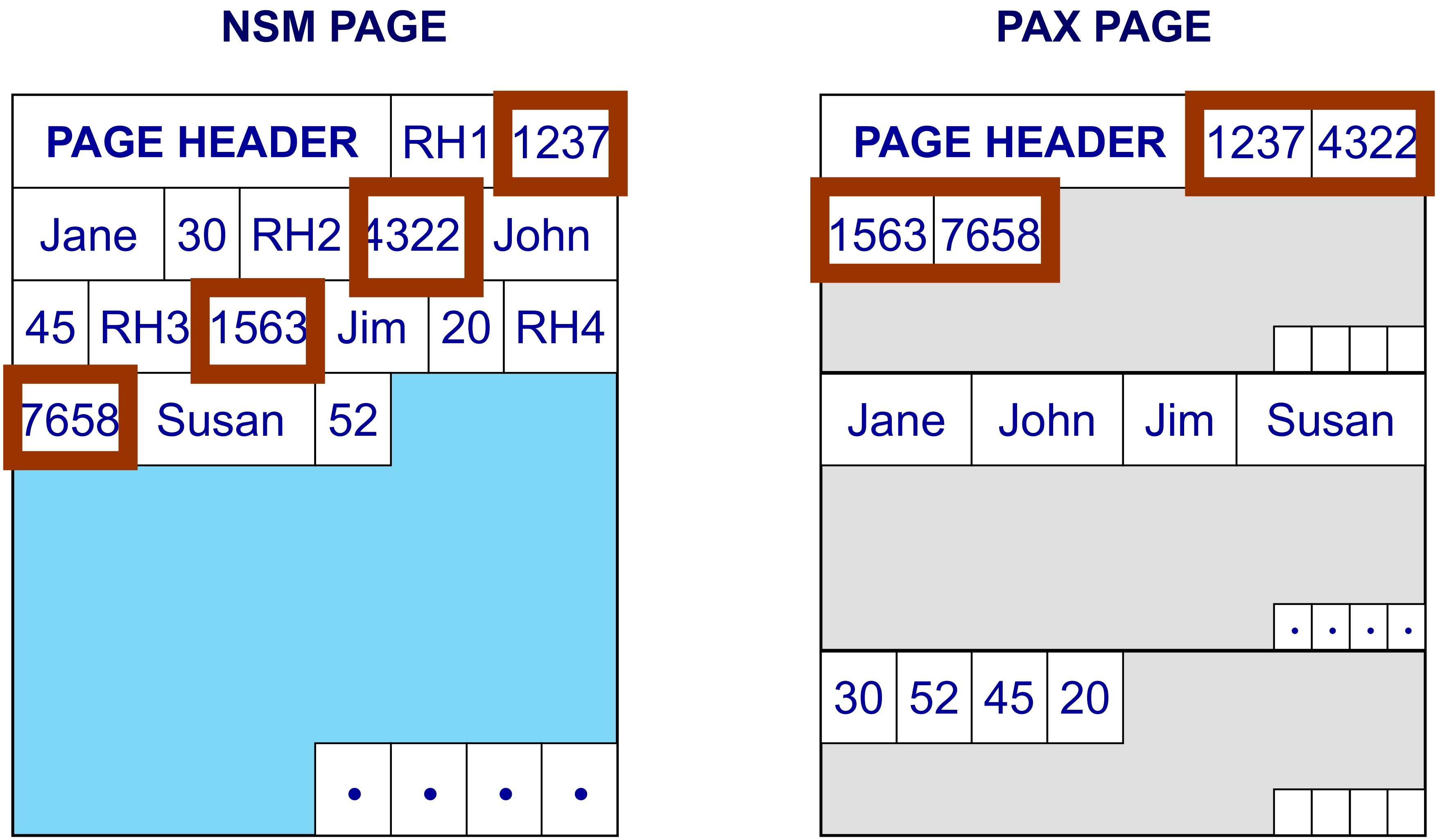

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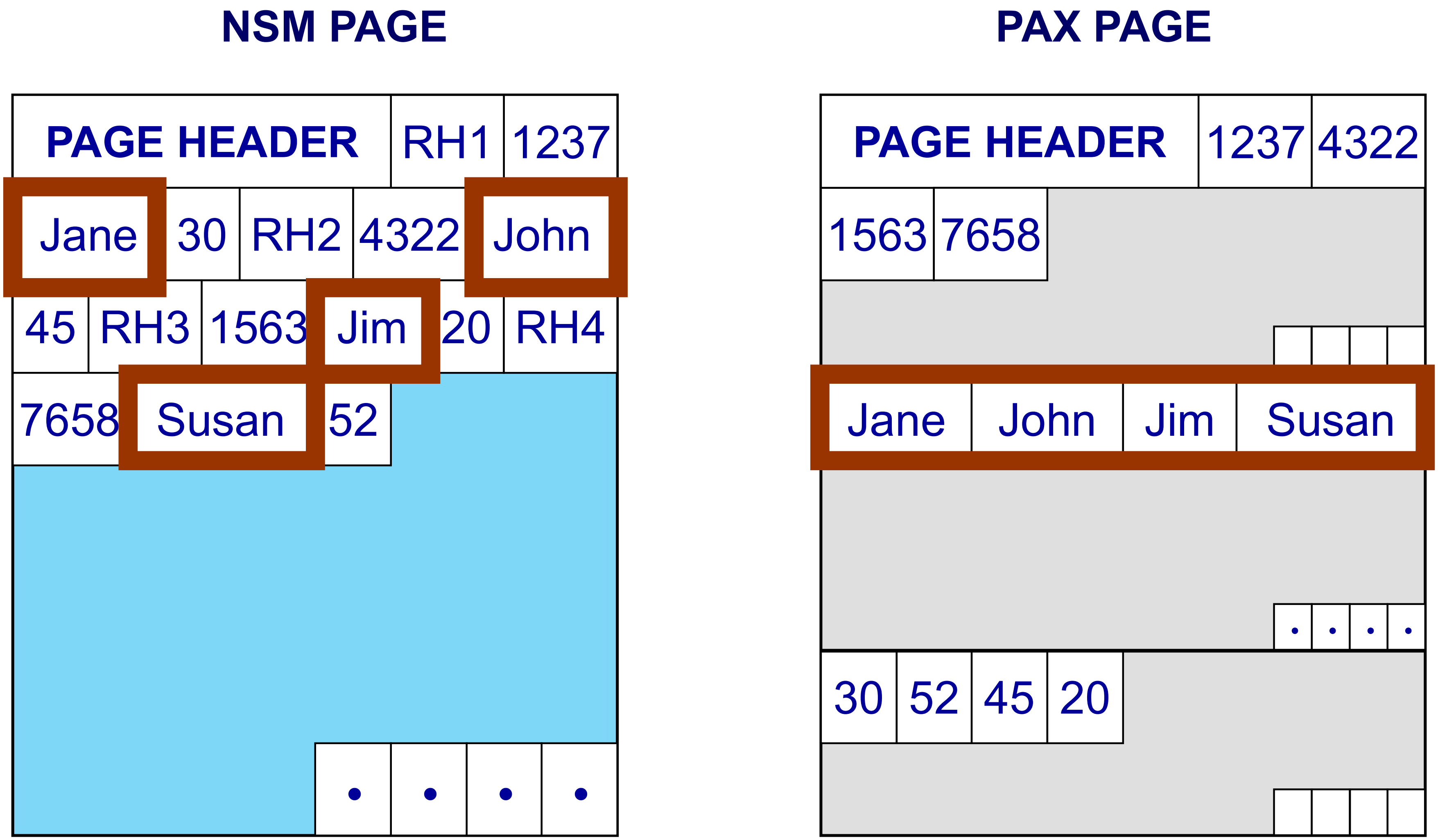

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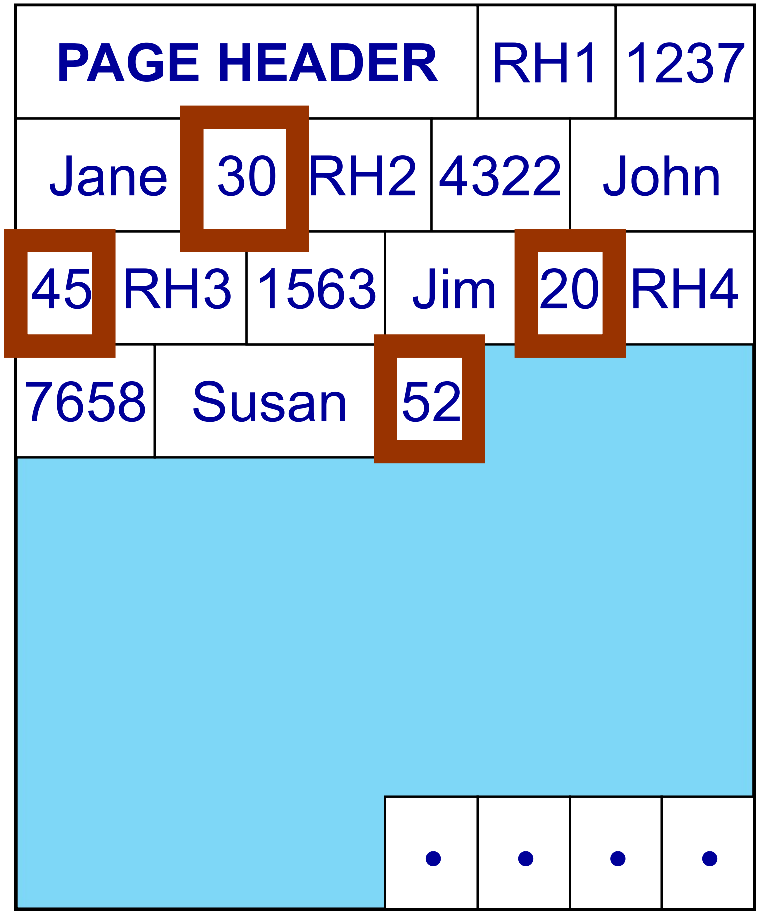
NSM PAGE



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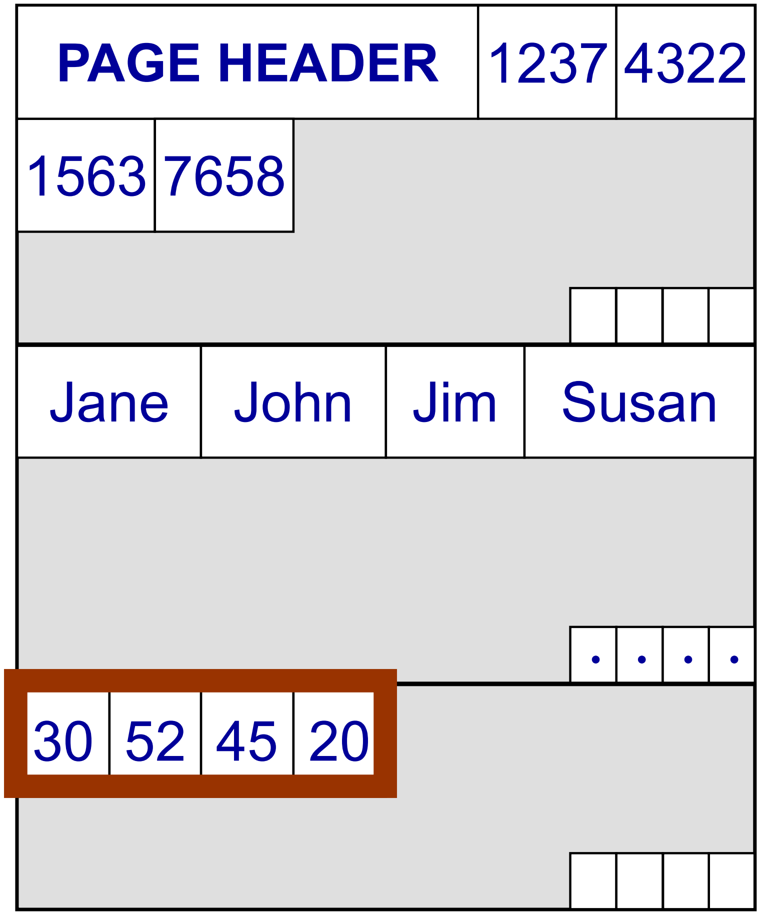

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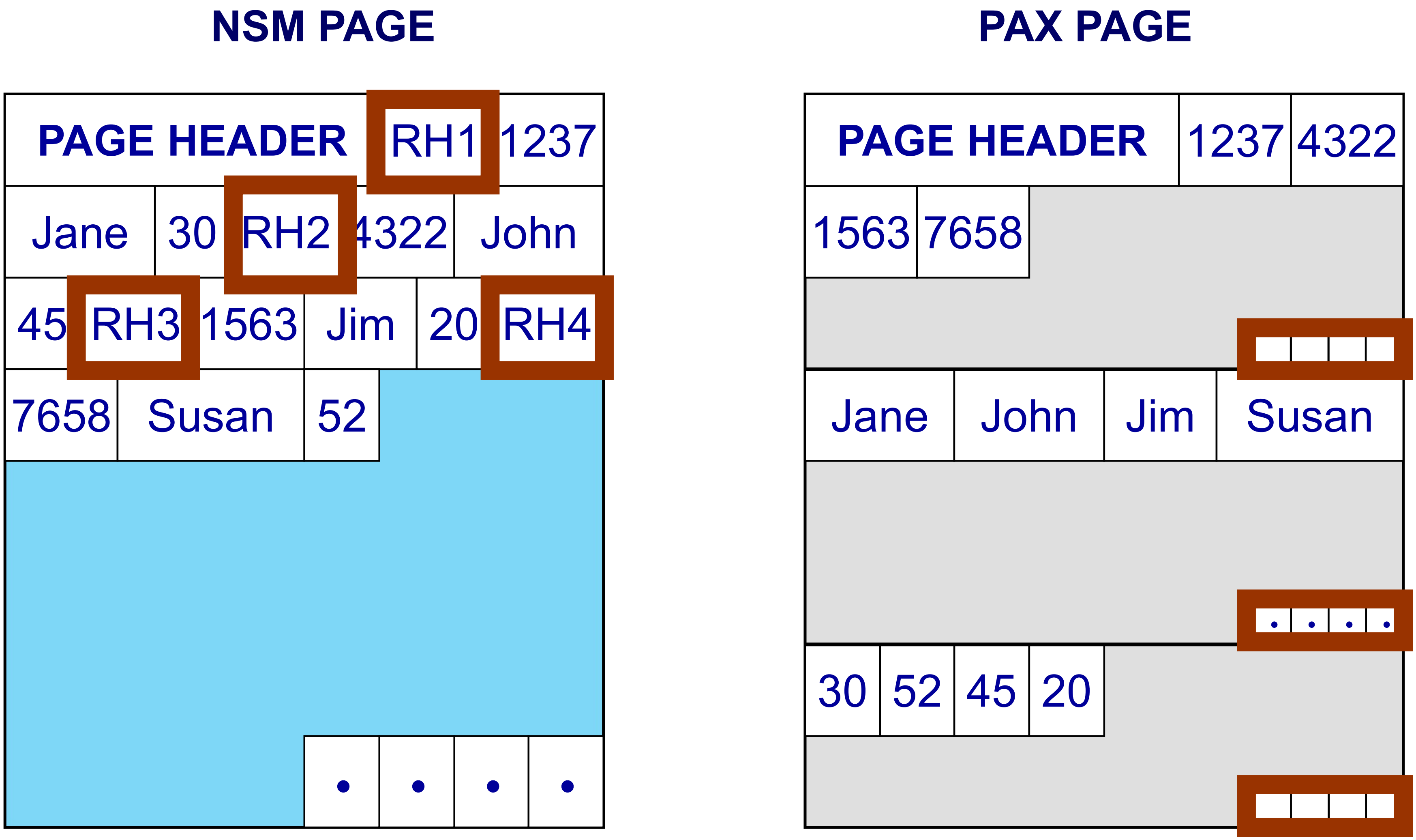

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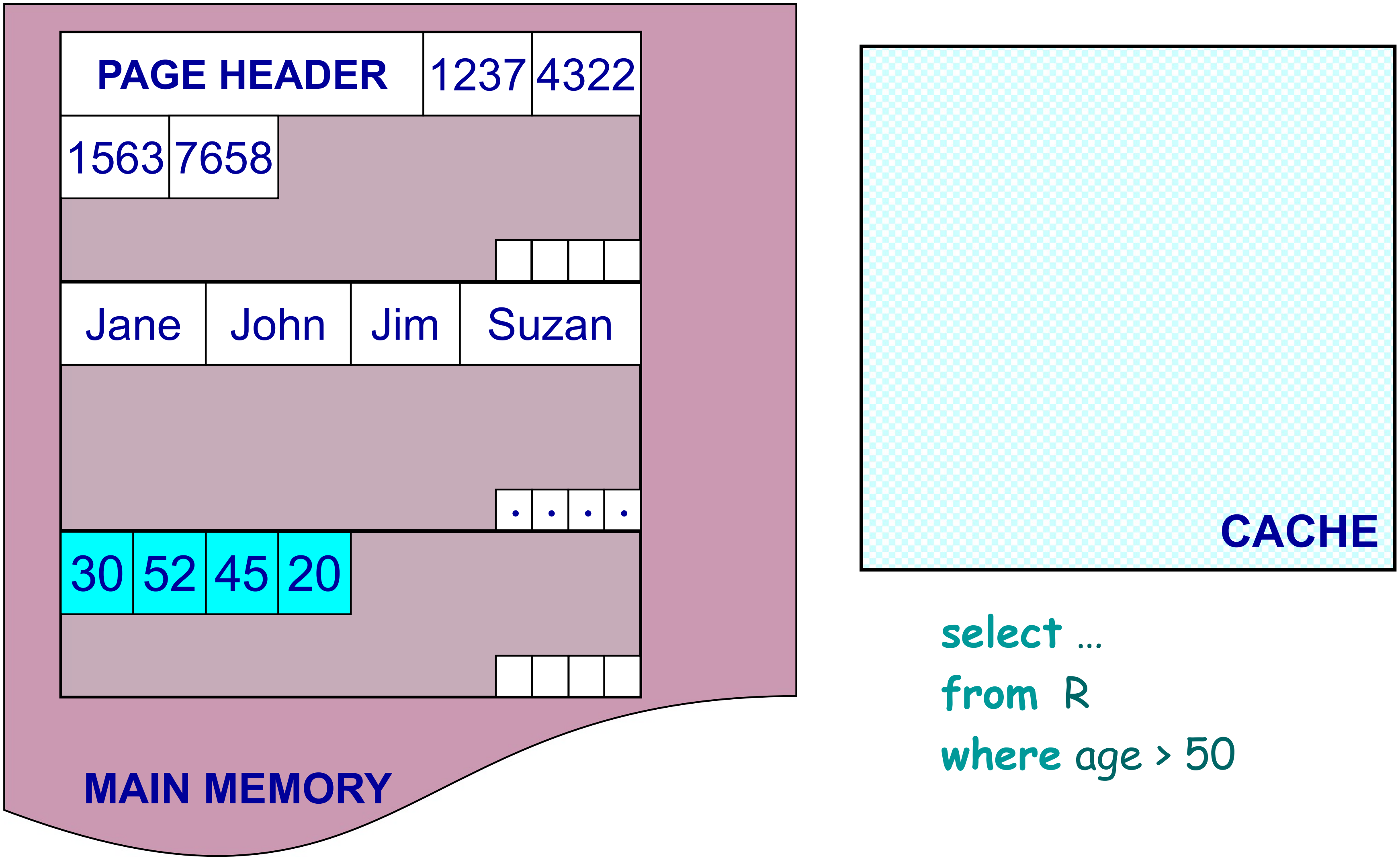

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Fewer cache misses, low reconstruction cost

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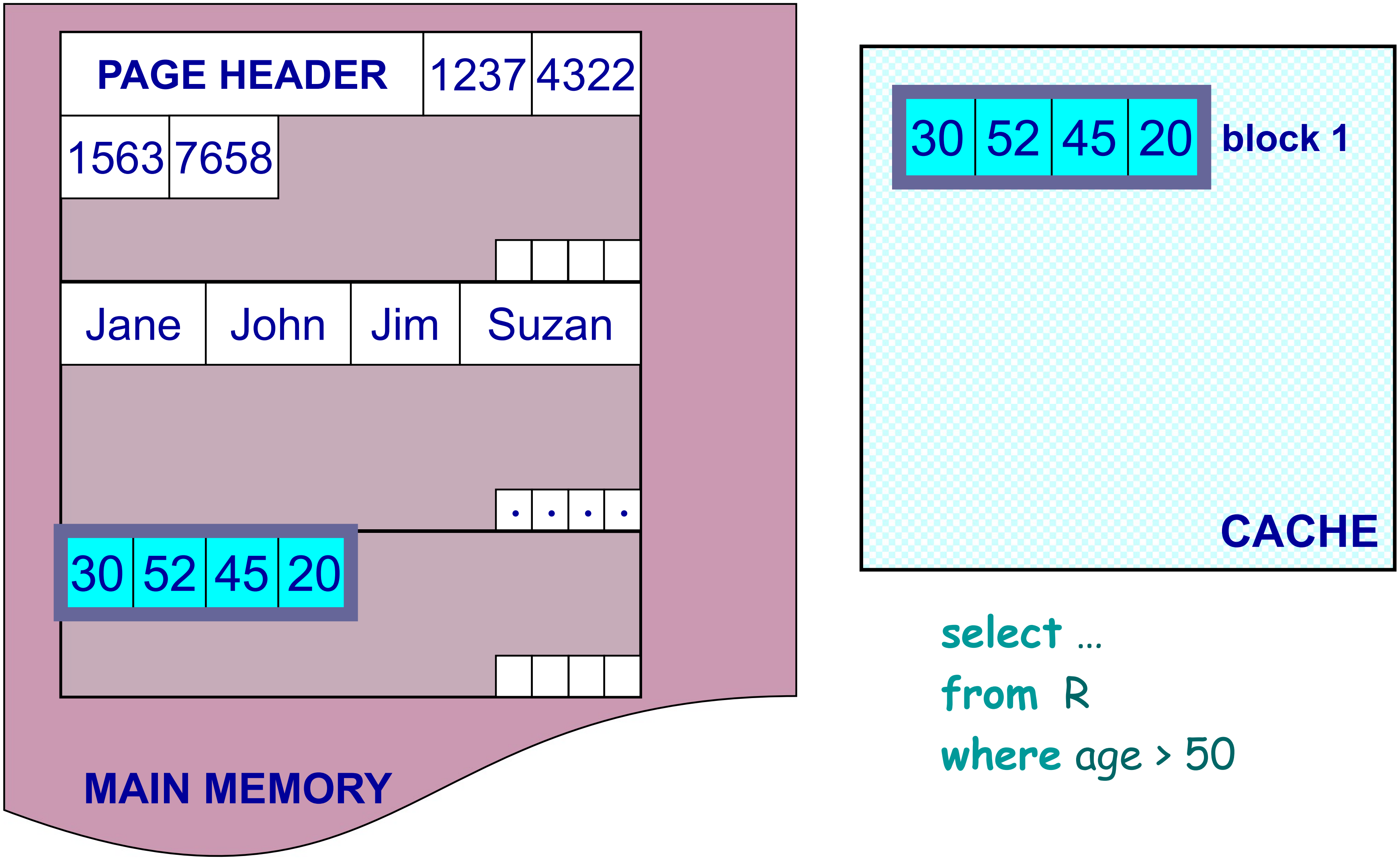

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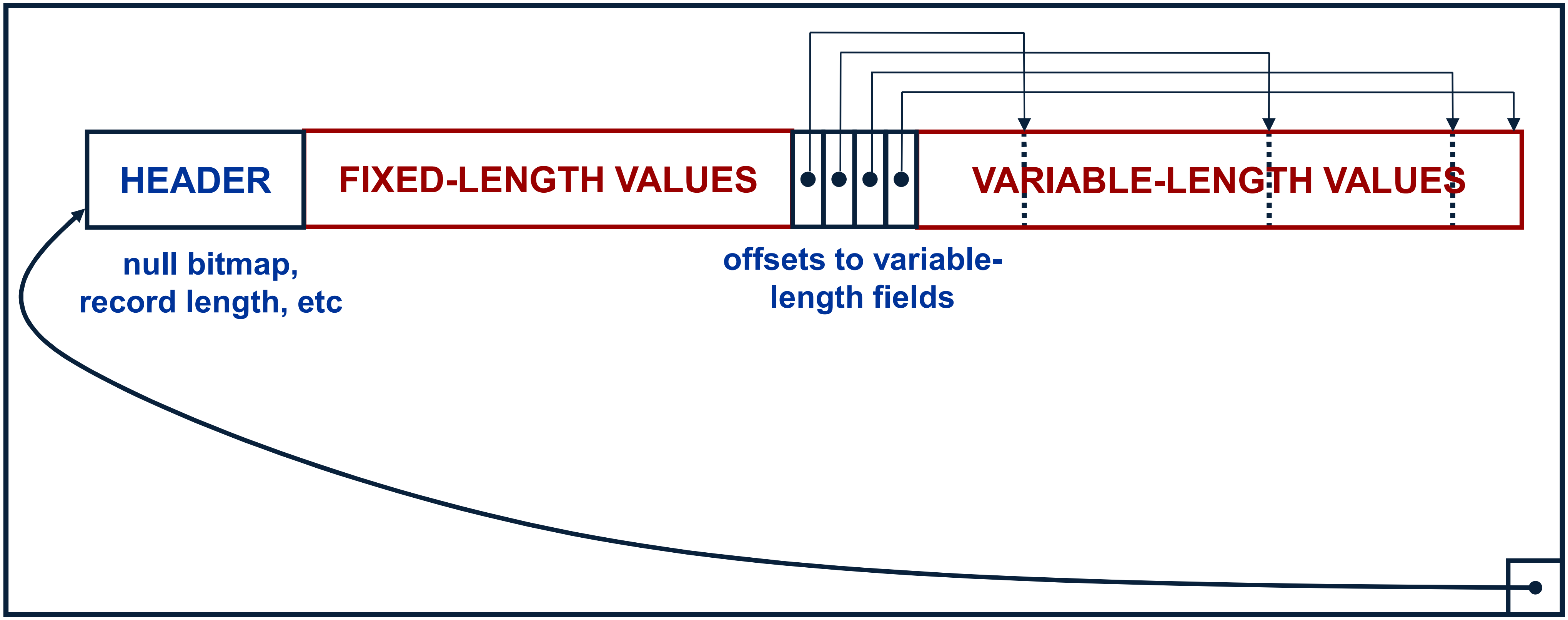
A Real NSM Record



NSM: All fields of record stored together + slots

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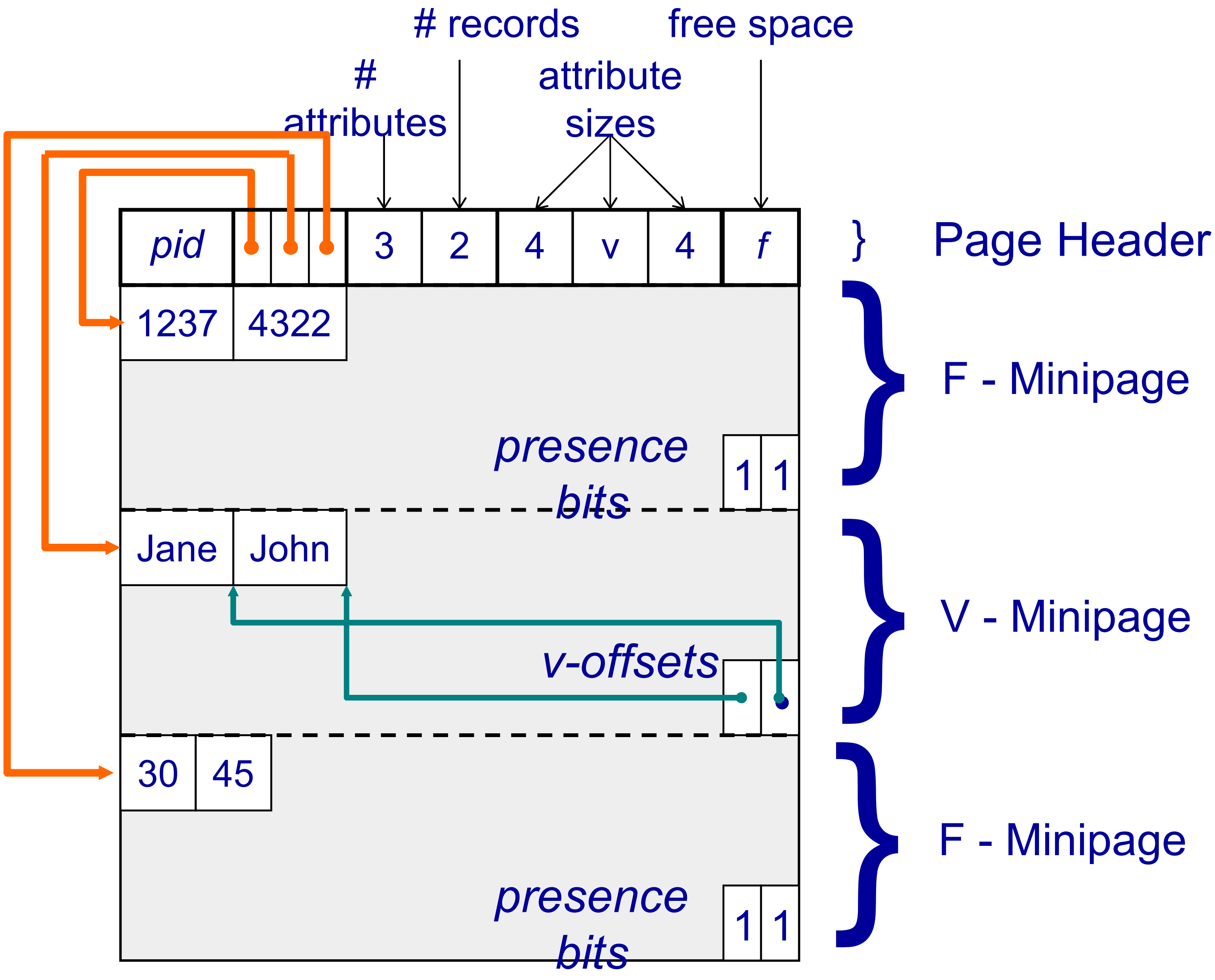
PAX: Detailed Design



PAX: Group fields + amortizes record headers

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PAX - Summary

- Improves processor cache locality
- Does not affect I/O behavior
  - Same disk accesses for NSM or PAX storage
  - No need to change the buffer manager

- Today:
  - Most (all?) commercial engines use a PAX layout of the disk
  - Beyond disk: Snowflake partitions tables horizontally into files, then uses column-store inside each file (hence, PAX)

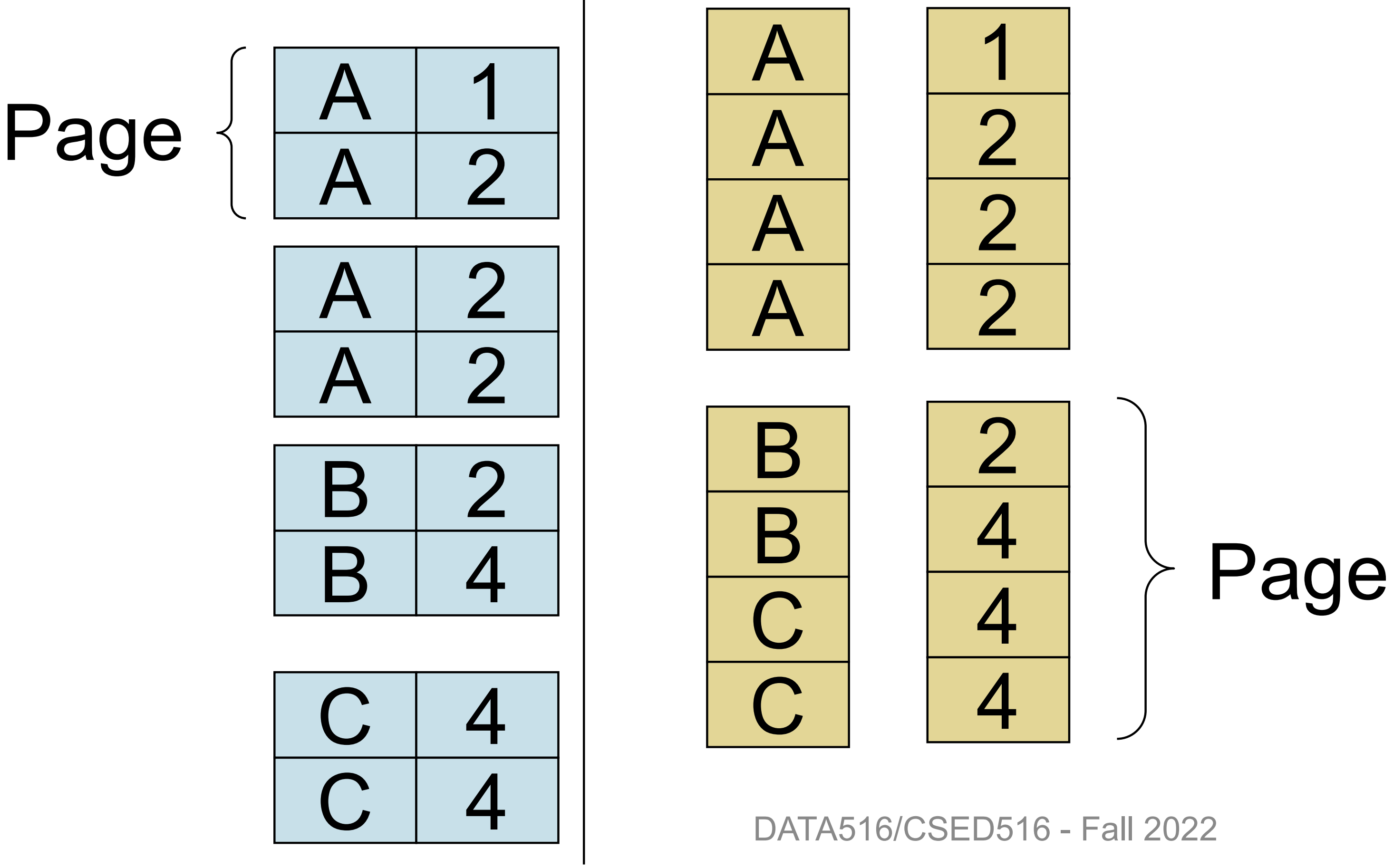
Column-Store

- Store an entire attribute in a different file
- While the idea had been around before PAX, getting all the details right in order to extract the extra performance took a long time

C-Store Illustration

Row-based
(4 pages)

Column-based
(4 pages)



C-Store also
avoids large
tuple headers

Column-Oriented Databases

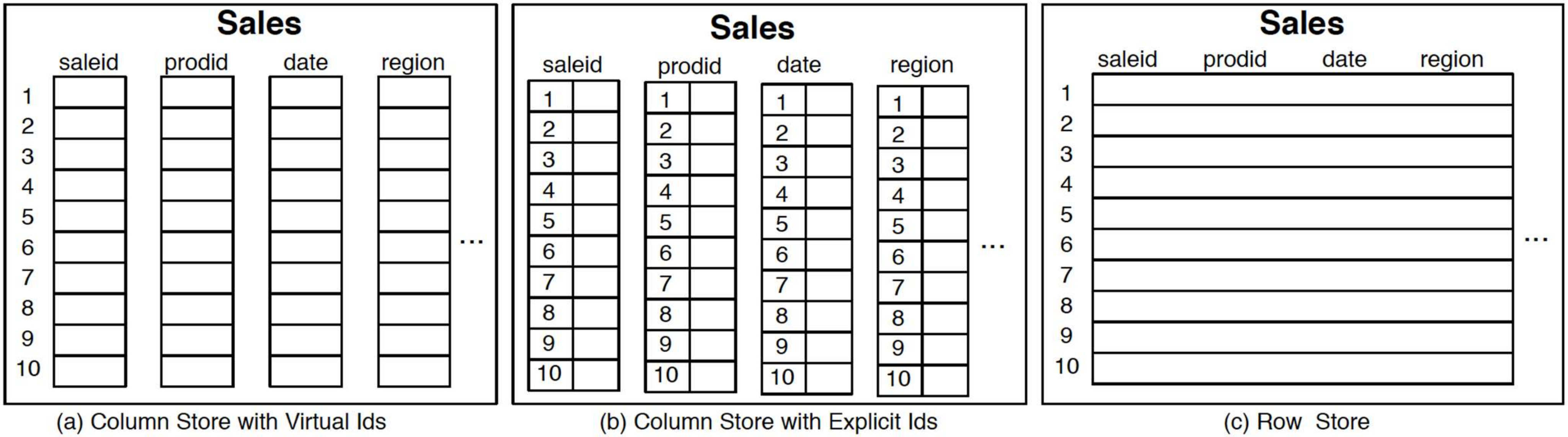
- Main idea:
  - Physical storage: complete vertical partition; each column stored separately: R.A, R.B, R.A
  - Logical schema: remains the same R(A,B,C)

- Main advantage:
  - Improved transfer rate: disk to memory, memory to CPU, better cache locality

Basic Trade-Off

- Row stores
  - Quick to update entire tuple (1 page IO)
  - Quick to access a single tuple
- Column stores
  - Avoid reading unnecessary columns
  - Better compression
- Entire system needs a different design
  - Not only storage manager
  - To achieve high performance

From Row to Column Storage (Modern Designs)



(a) Column Store with Virtual Ids

(b) Column Store with Explicit Ids

(c) Row Store

Figure 1.1: Physical layout of column-oriented vs row-oriented databases.

Basic tradeoffs:

- Reading all attributes of one records, v.s.
- Reading some attributes of many records

Fig. 1.2

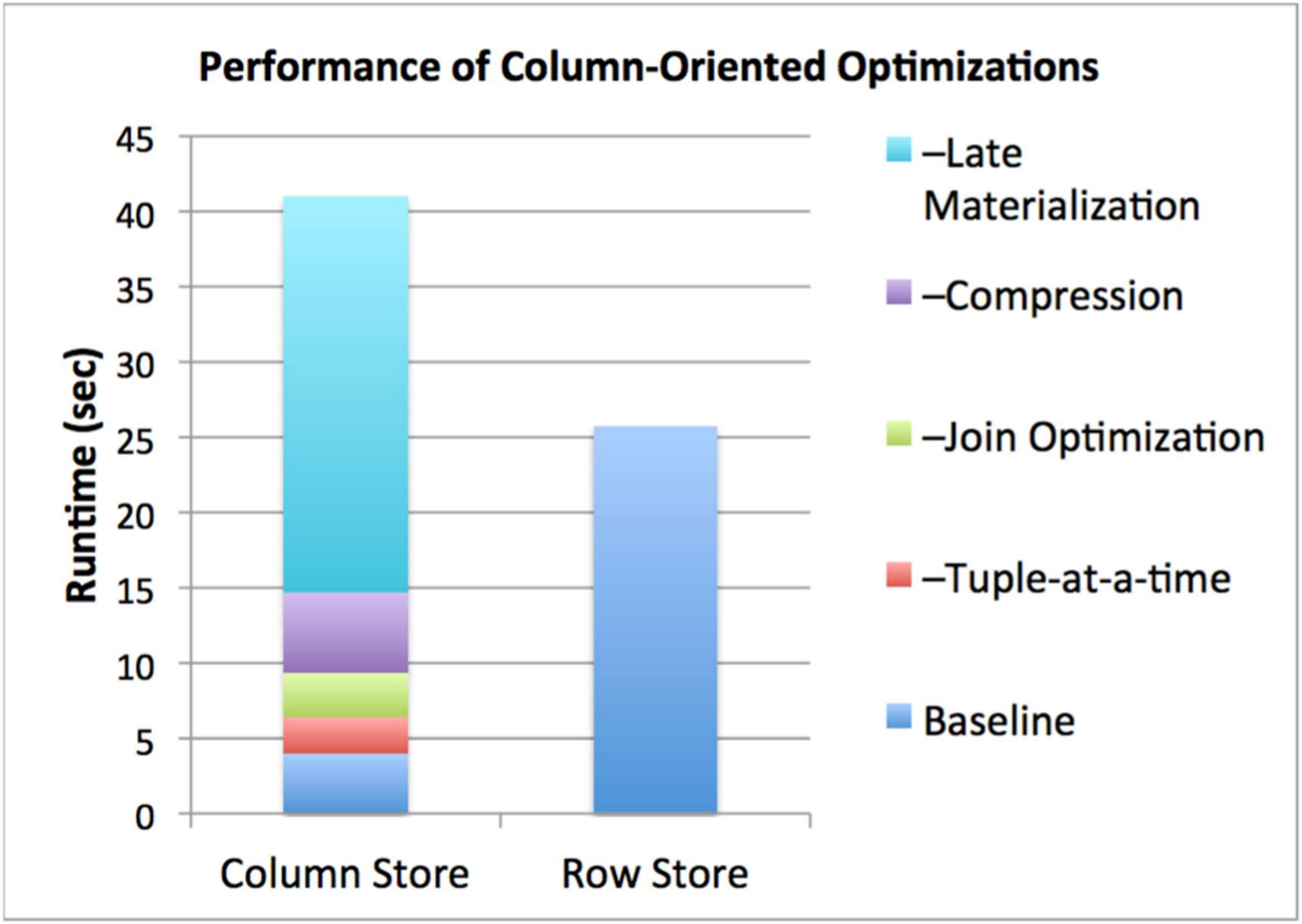


Figure 1.2: Performance of C-Store versus a commercial database system on the SSBM benchmark, with different column-oriented optimizations enabled.

Key Architectural Trends (Sec.1)

- Virtual IDs
- Block-oriented and vectorized processing
- Late materialization
- Column-specific compression

Key Architectural Trends (Sec.1)

- Virtual IDs
  - Offsets (arrays) instead of keys
- Block-oriented and vectorized processing
  - Iterator model: one tuple→one block of tuples
- Late materialization
  - Postpone tuple reconstruction in query plan
- Column-specific compression
  - Much better than row-compression (why?)

Vectorized Processing

Review:

- Volcano-style iterator model
  - Next() method
  - Pipelining
- Materialization of all intermediate results
- Discuss in class:

```
select avg(A) from R where A < 100
```

Vectorized Processing

- Vectorized processing:
  - Next() returns a block of tuples (e.g. N=1000) instead of single tuple
- Pros:
  - No more large intermediate results
  - Tight inner loop for selection and/or avg
- Discuss in class:

```
select avg(A) from R where A < 100
```

Compression (Sec. 4)

- What is the advantage of compression in databases?

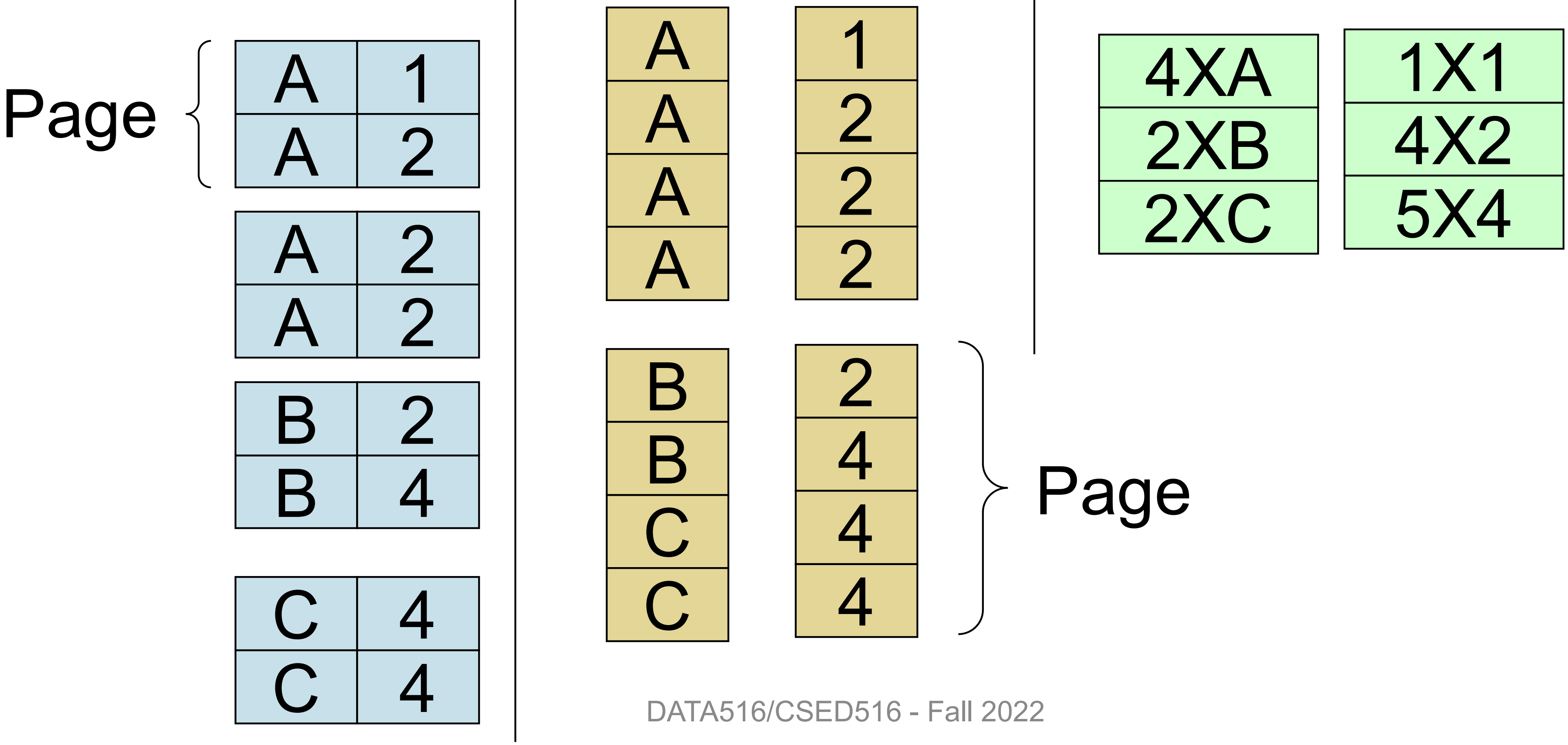
- Main column-at-a-time compression techniques

Compression (Sec. 4)

- What is the advantage of compression in databases?

- Main column-at-a-time compression techniques
  - Row-length encoding: F,F,F,F,M,M→4F,2M
  - Bit-vector (see also bit-map indexes)
  - Dictionary. More generally: Ziv-Lempel

Compression (Sec. 4)



Row-based
(4 pages)

Page

A	1
A	2

A	2
A	2

B	2
B	4

C	4
C	4

Column-based
(4 pages)

A
A
A
A

1
2
2
2

B
B
C
C

2
4
4
4

Page

Compressed
(2 pages)

4XA
2XB
2XC

1X1
4X2
5X4

Late Materialization (Sec. 4)

- What is it?
- Discuss $\Pi_B(\sigma_{A=\text{'a'} \wedge D=\text{'d'}}(R(A,B,C,D,\ldots))$

Late Materialization (Sec. 4)

- What is it?
- Discuss $\Pi_B(\sigma_{A='a' \wedge D='d'}(R(A,B,C,D,\ldots))$
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  - Retrieve positions with ‘a’ in column A: 2, 4, 5, 9, 25…

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  - Retain only positions with ‘d’:   4, 9, ...

Late Materialization (Sec. 4)

- What is it?
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  - Retrieve those values in column D: ‘x’, ‘d’, ‘y’, ‘d’, ‘d’,...
  - Retain only positions with ‘d’: 4, 9, ...
  - Lookup values in column B: B[4], B[9], …

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Late Materialization (Sec. 4)

- What is it?
- Discuss $\Pi_B(\sigma_{A=\text{'a'} \wedge D=\text{'d'}}(R(A,B,C,D,\ldots))$
- Early materialization:
    - Retrieve positions with ‘a’ in column A: 2, 4, 5, 9, 25…
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    - Lookup values in column B: B[4], B[9], …
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    - Retrieve positions with ‘a’ in column A: 2, 4, 5, 9, 25…
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    - Intersect: 4, 9, …

Late Materialization (Sec. 4)

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  - Lookup values in column B: B[4], B[9], …
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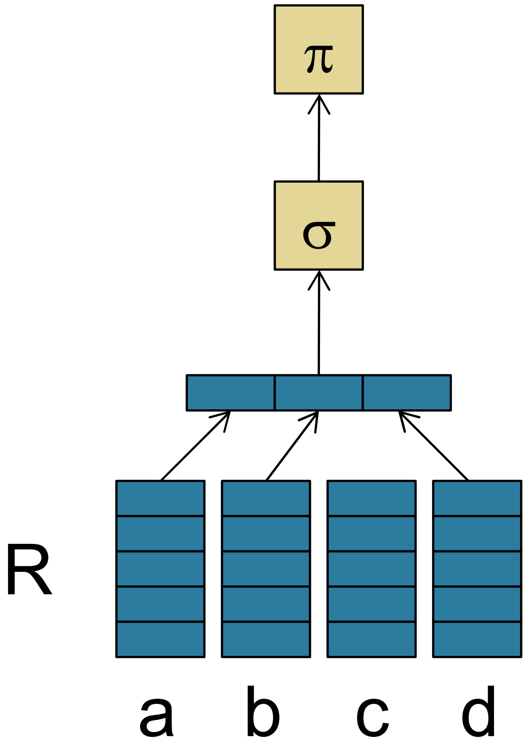
  - Retrieve positions with ‘a’ in column A: 2, 4, 5, 9, 25…
  - Retrieve positions with ‘d’ in column D: 3, 4, 7, 9,12,..
  - Intersect: 4, 9, …
  - Lookup values in column B: B[4], B[9], …

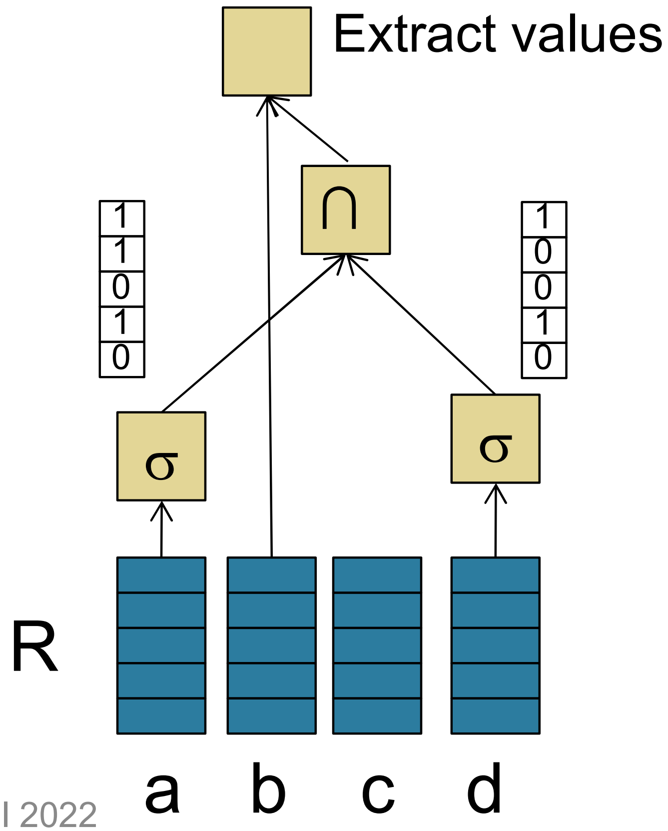
Late Materialization (Sec. 4)

Ex: `SELECT R.b from R where R.a=X and R.d=Y`

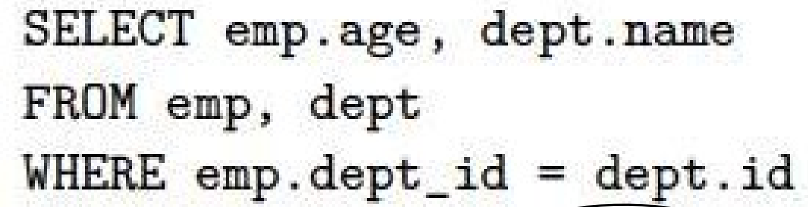
Early materialization



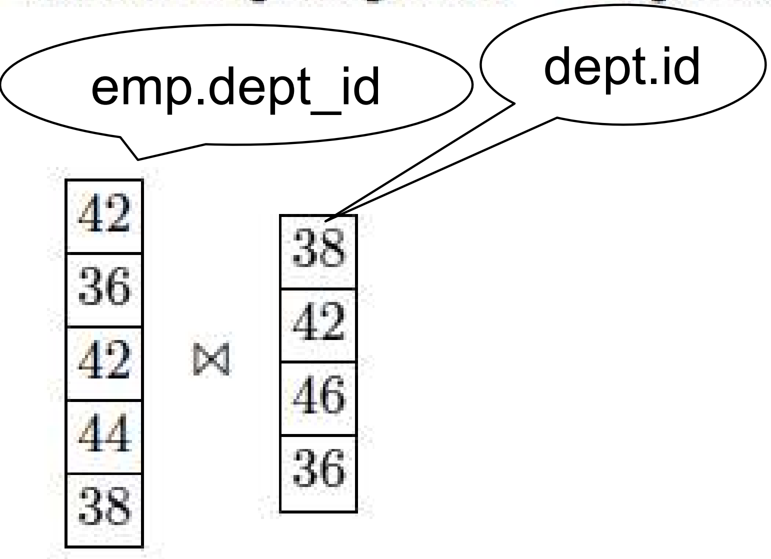
Late materialization



Jive Join (Sec. 4)



```
SELECT emp.age, dept.name
FROM emp, dept
WHERE emp.dept_id = dept.id
```



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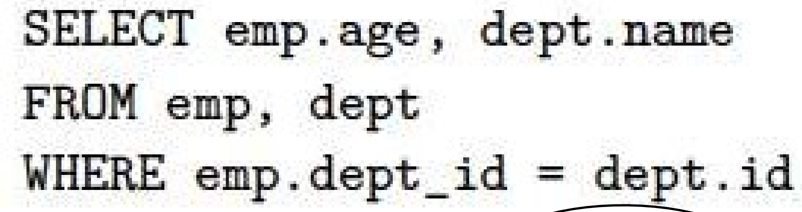

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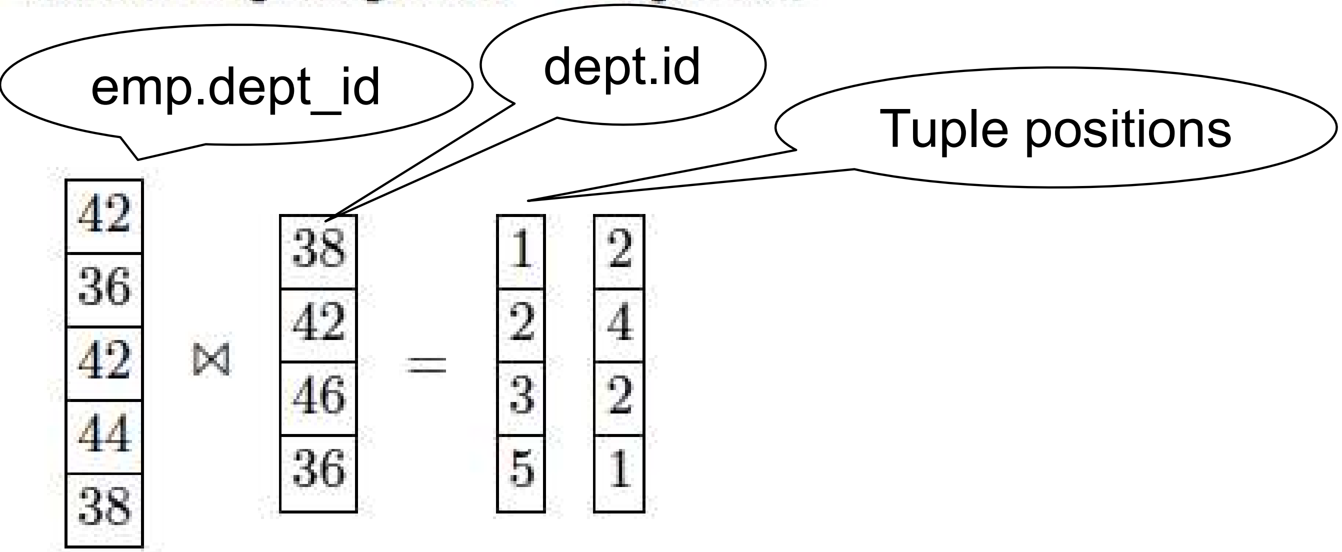
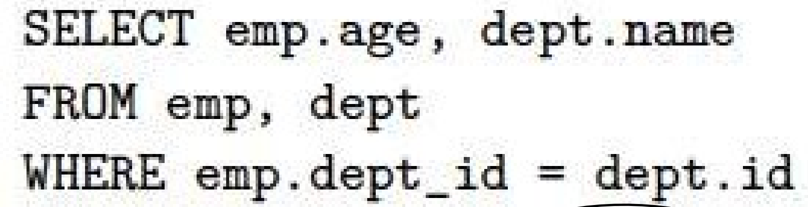


Jive Join (Sec. 4)



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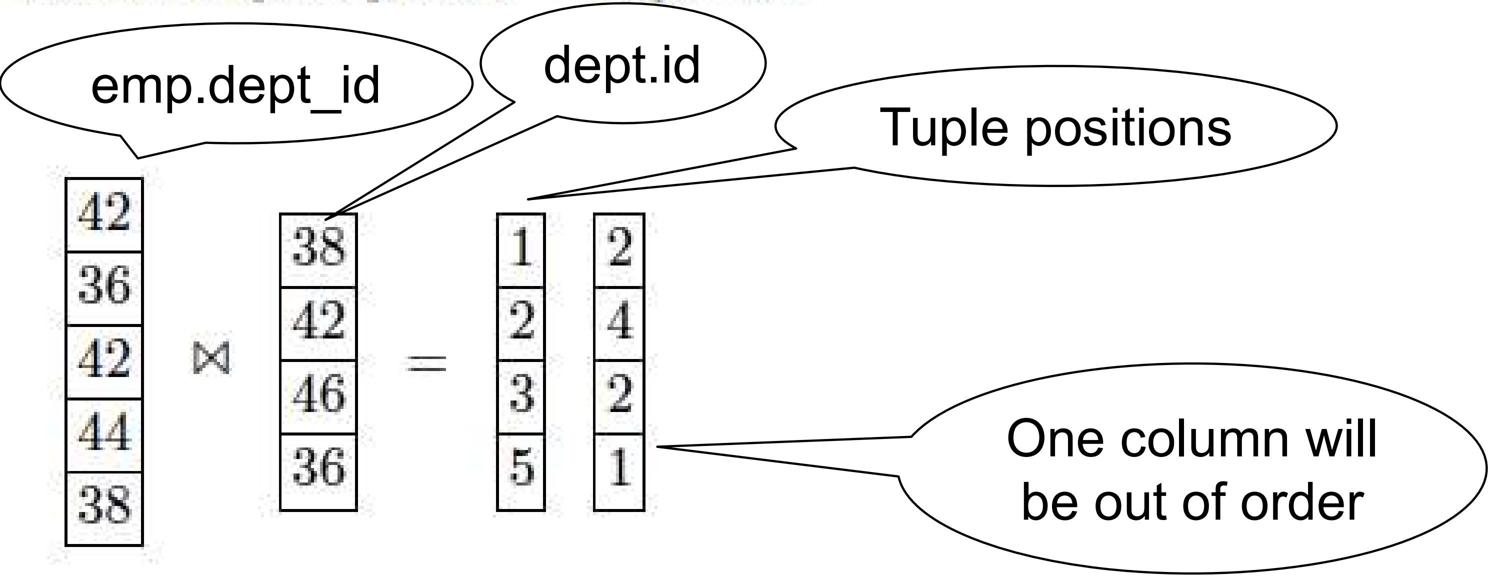
emp.dept_id

dept.id

Tuple positions

One column will be out of order

Jive Join (Sec. 4)

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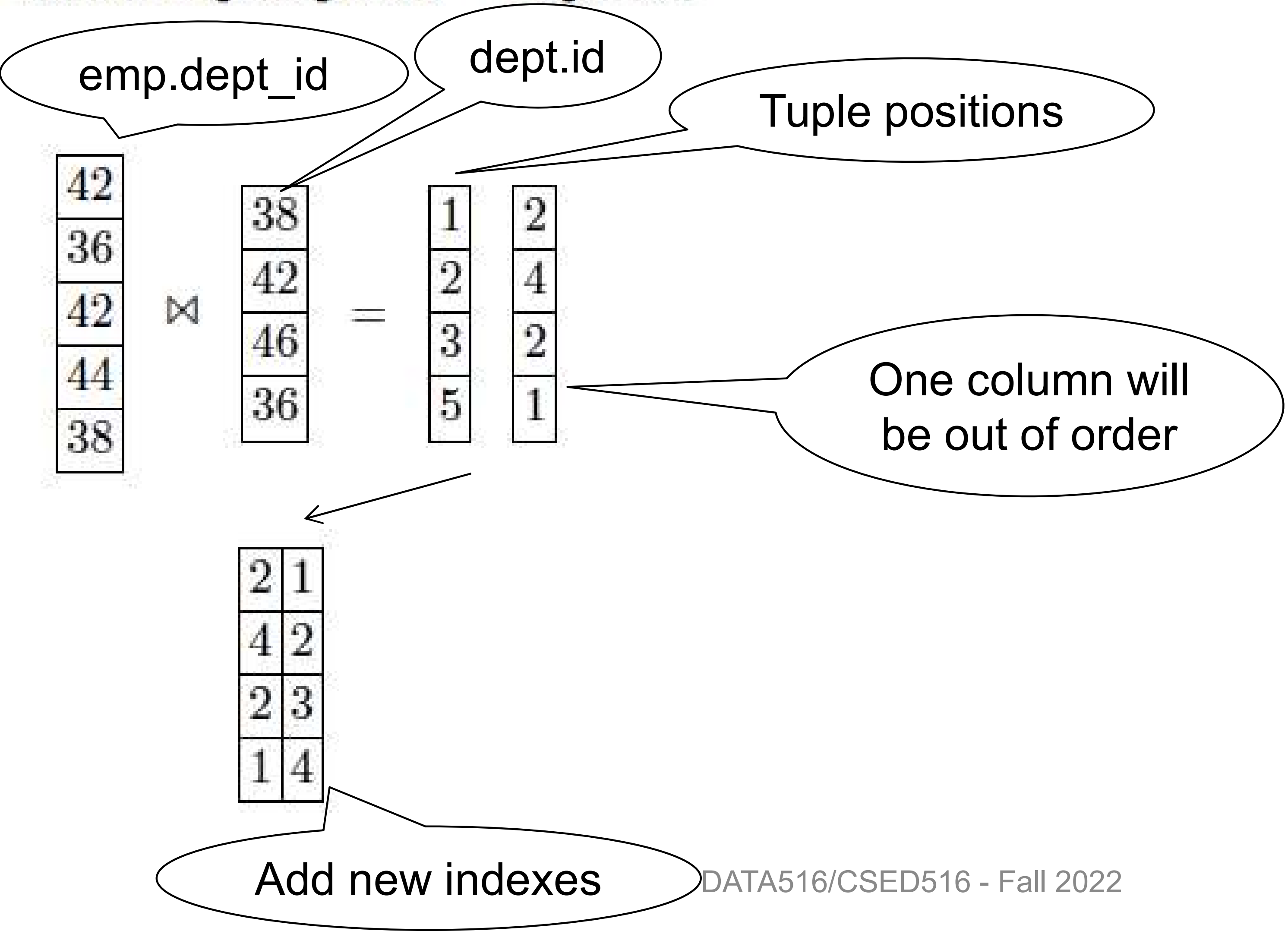
```



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Tuple positions

One column will be out of order

Add new indexes

Jive Join (Sec. 4)

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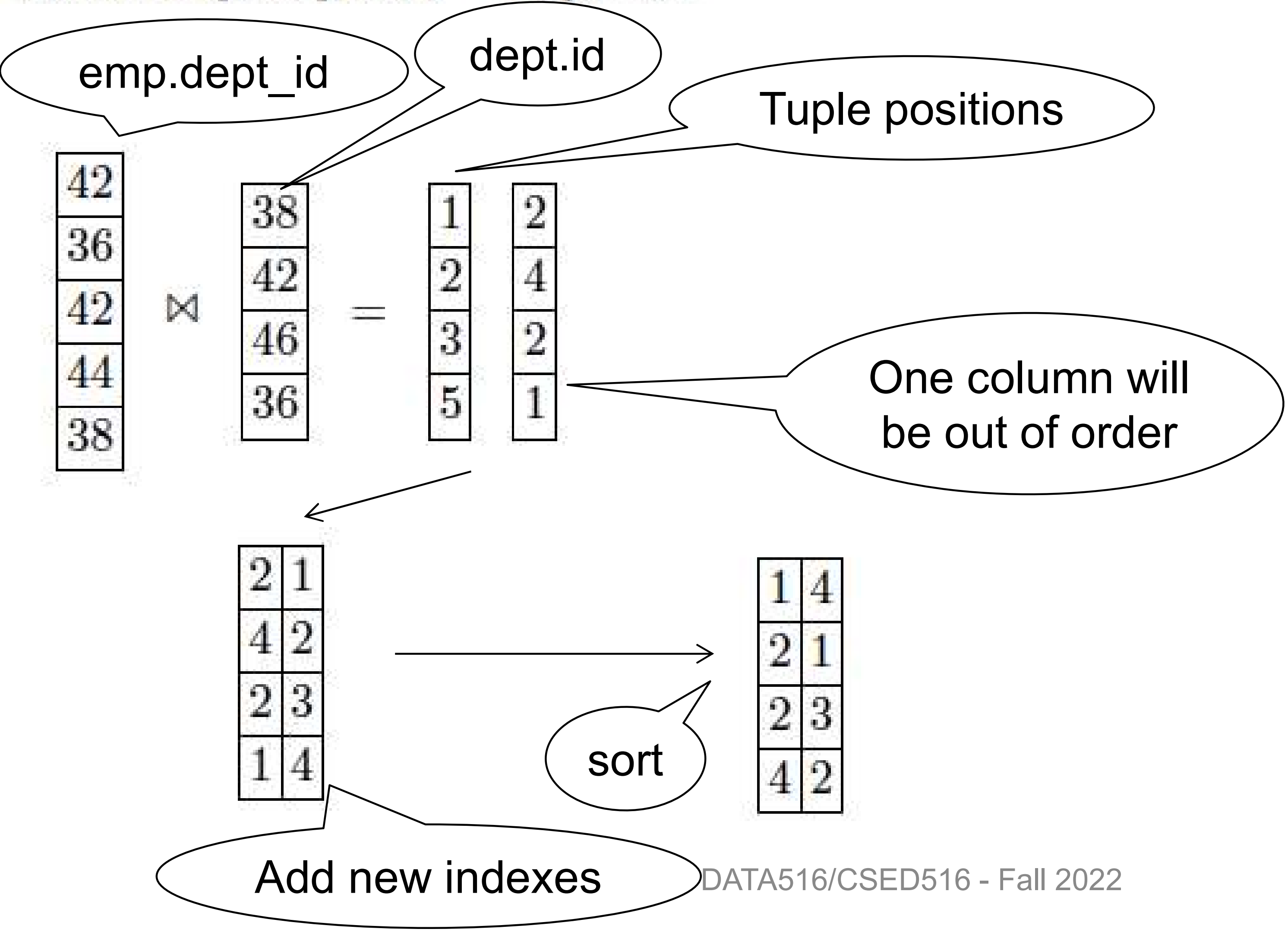

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dept.id

Tuple positions

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Add new indexes

sort

Jive Join (Sec. 4)

```
SELECT emp.age, dept.name
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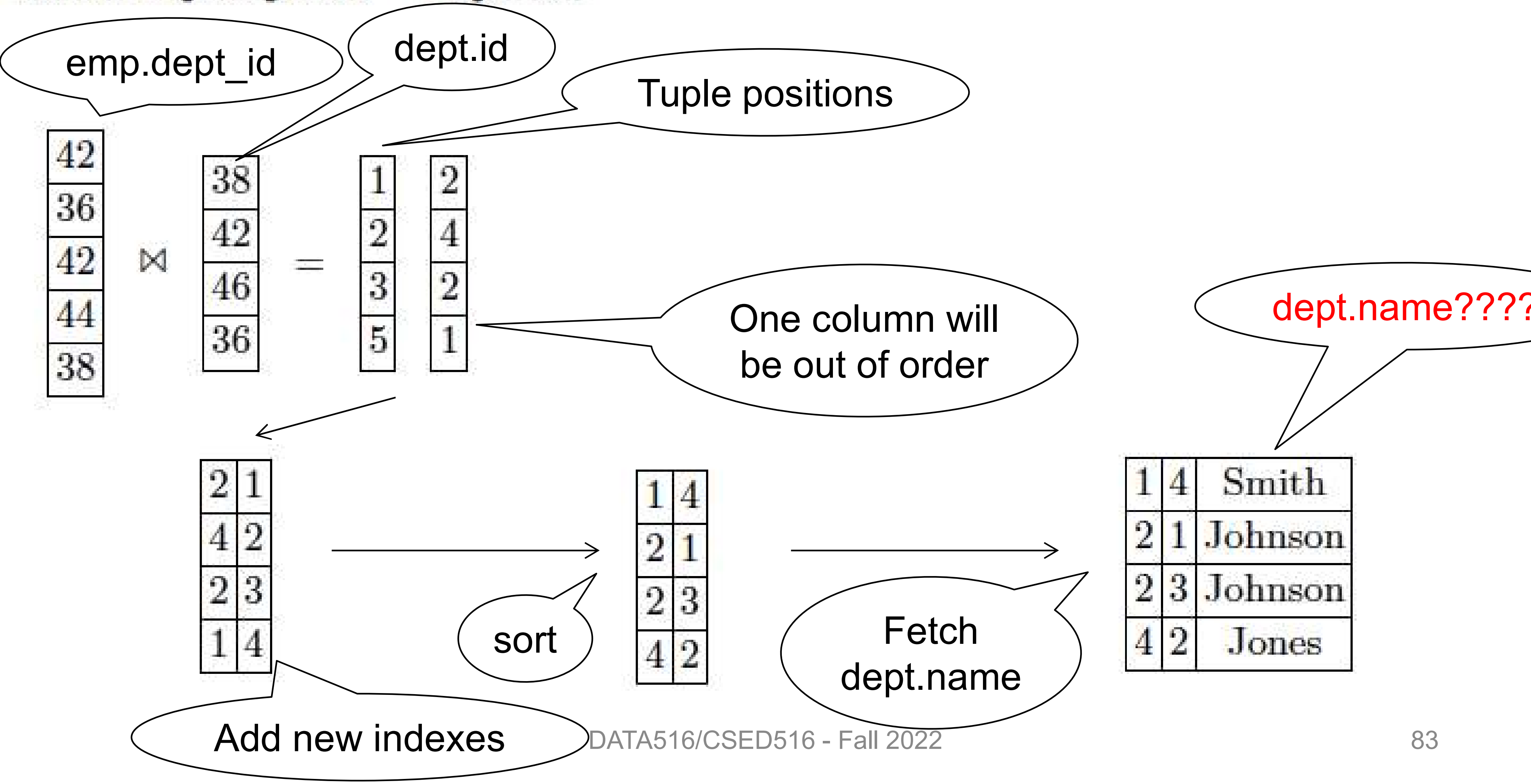

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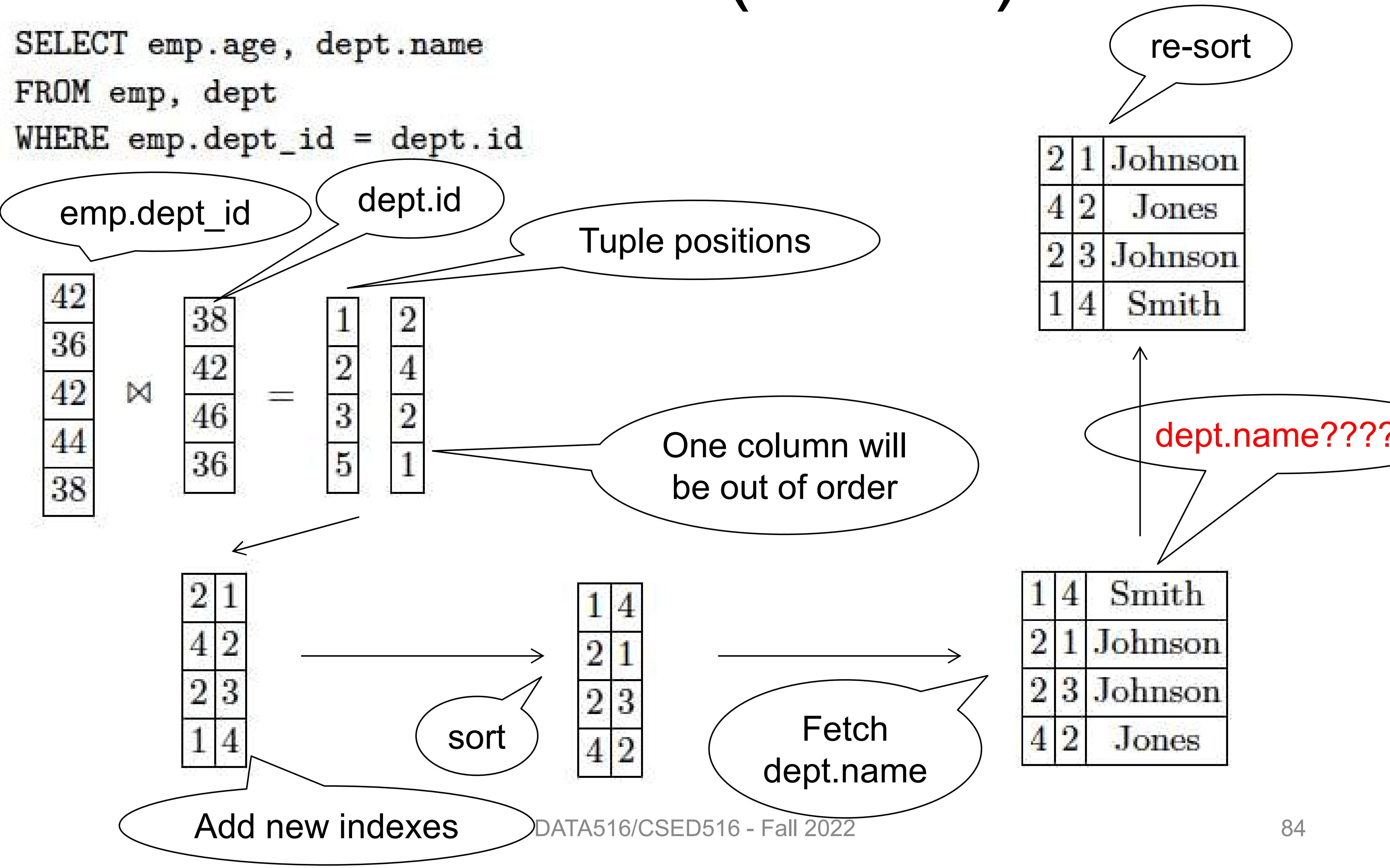


42
36
42
44
38

⋈

38
42
46
36

=

1	2
2	4
3	2
5	1

2	1
4	2
2	3
1	4

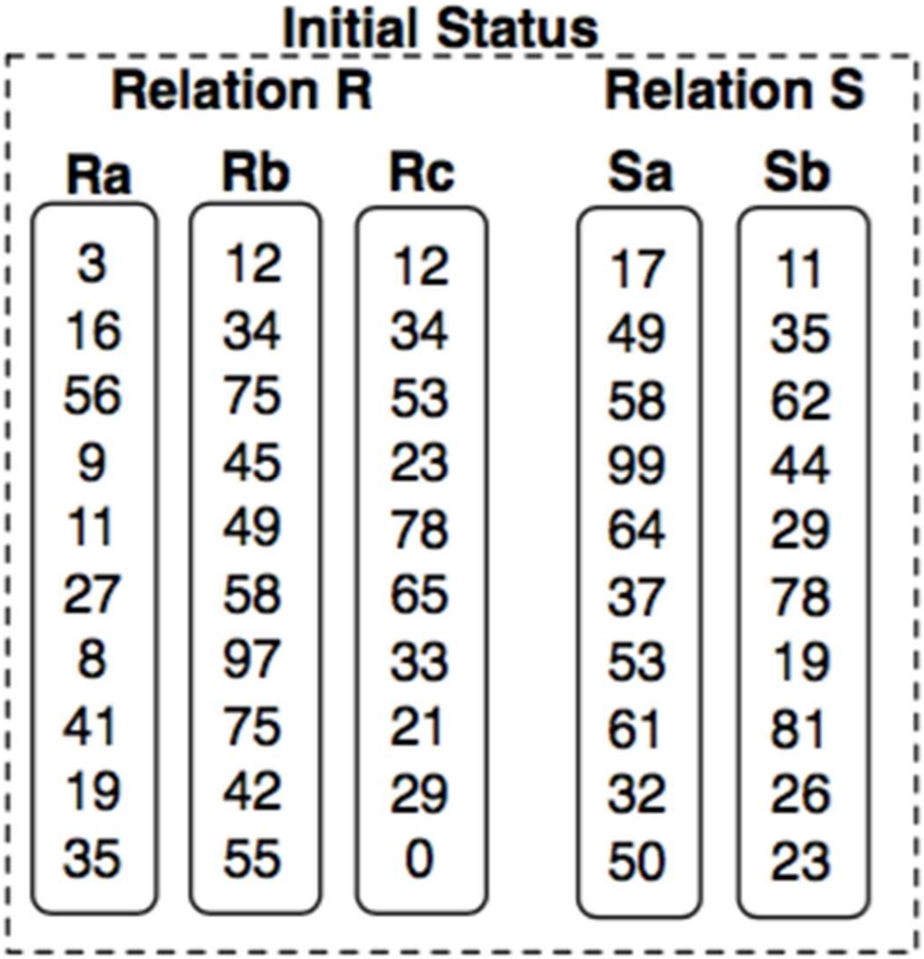
1	4
2	1
2	3
4	2

1	4	Smith
2	1	Johnson
2	3	Johnson
4	2	Jones

2	1	Johnson
4	2	Jones
2	3	Johnson
1	4	Smith

Late Materialization

```
select sum(R.a) from R, S
where R.c = S.b
  and 5<R.a<20 and 40<R.b<50
 and 30<S.a<40
```



Initial Status

Relation R			Relation S	
Ra	**Rb**	**Rc**	**Sa**	**Sb**
3	12	12	17	11
16	34	34	49	35
56	75	53	58	62
9	45	23	99	44
11	49	78	64	29
27	58	65	37	78
8	97	33	53	19
41	75	21	61	81
19	42	29	32	26
35	55	0	50	23

Late Materialization

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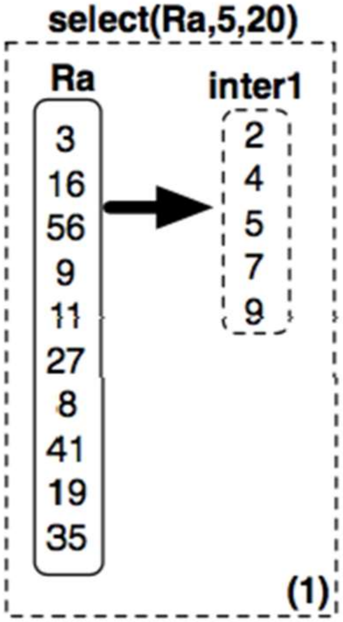

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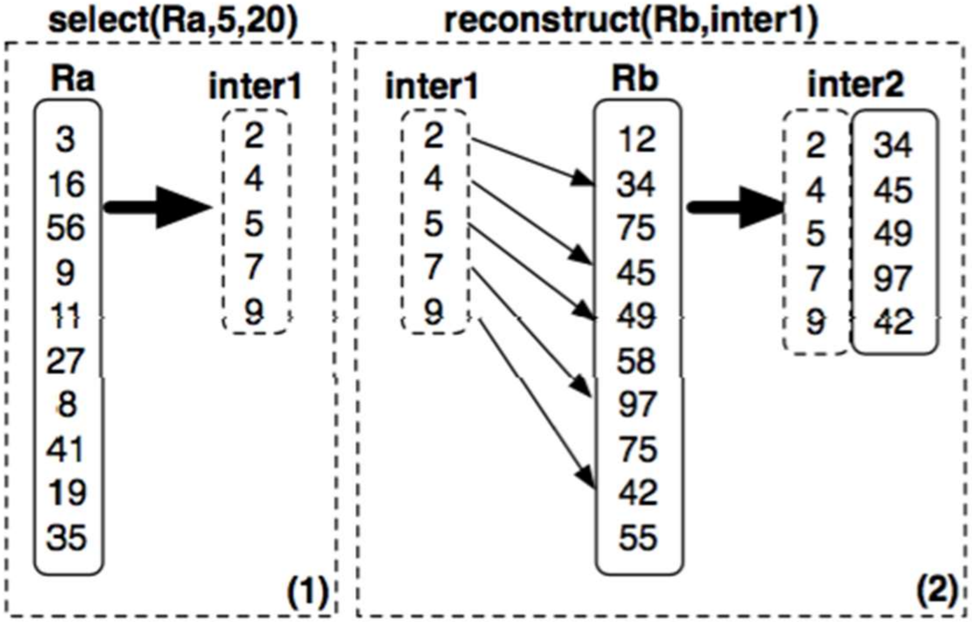

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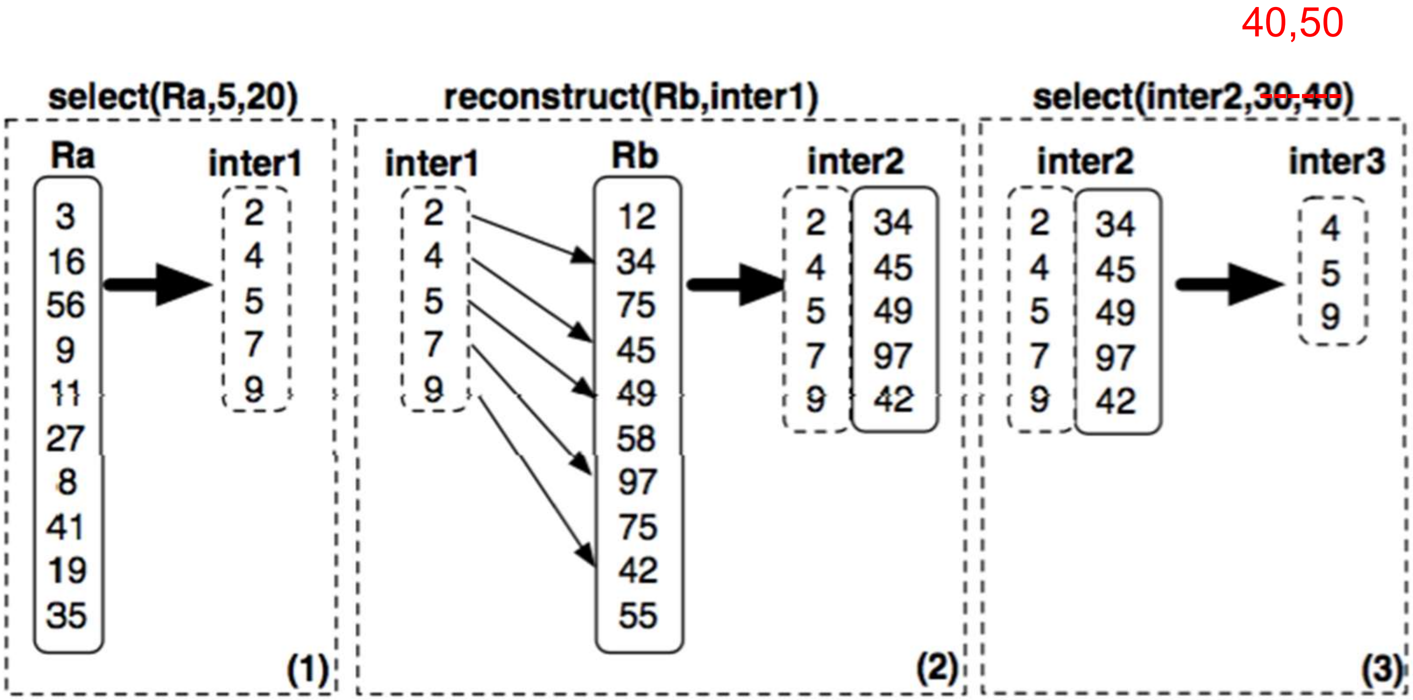

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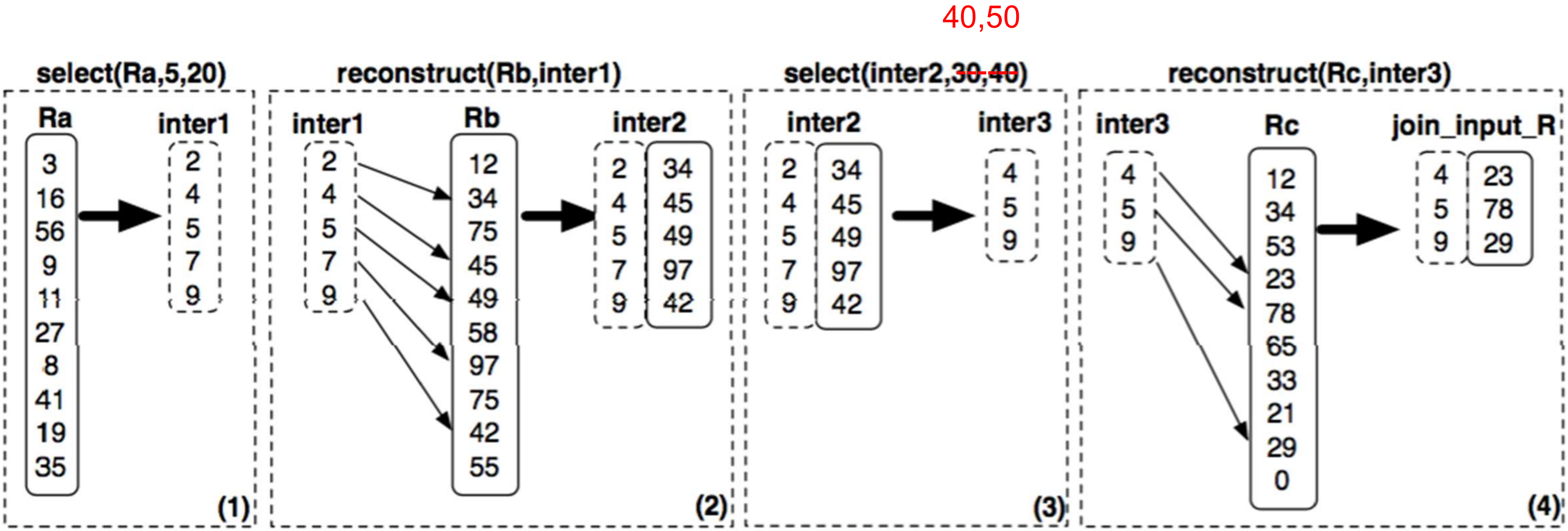

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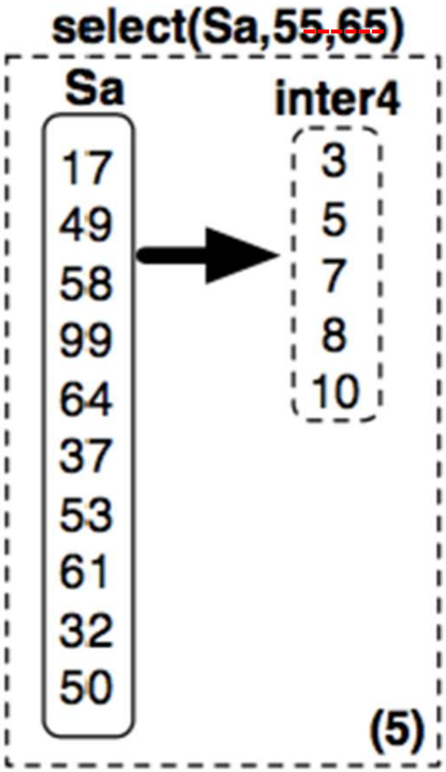
???



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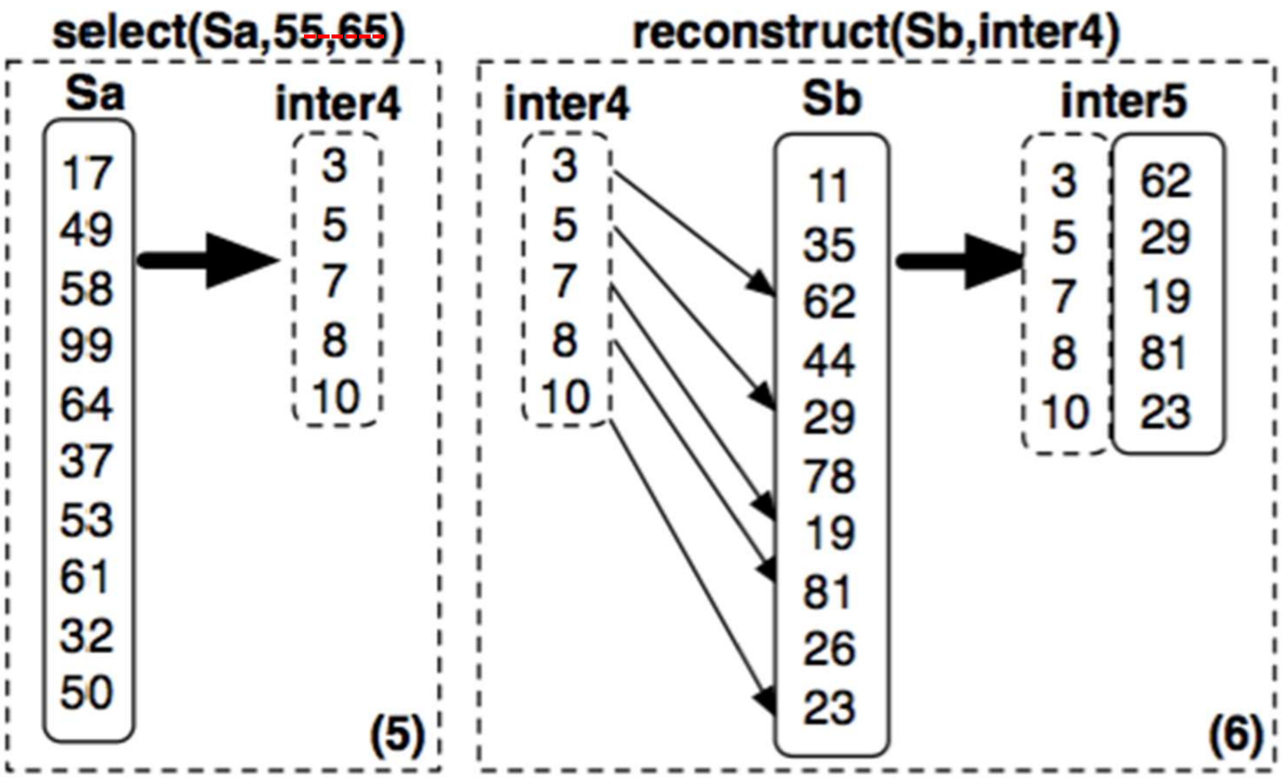

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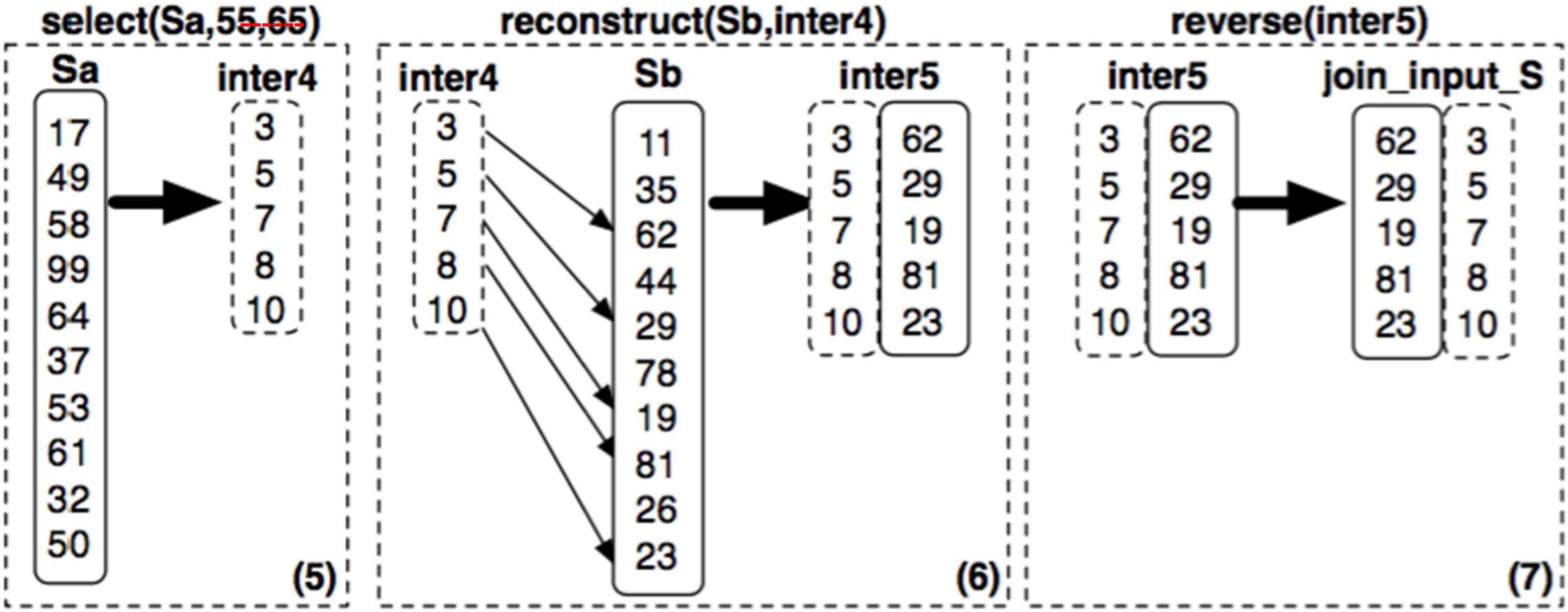

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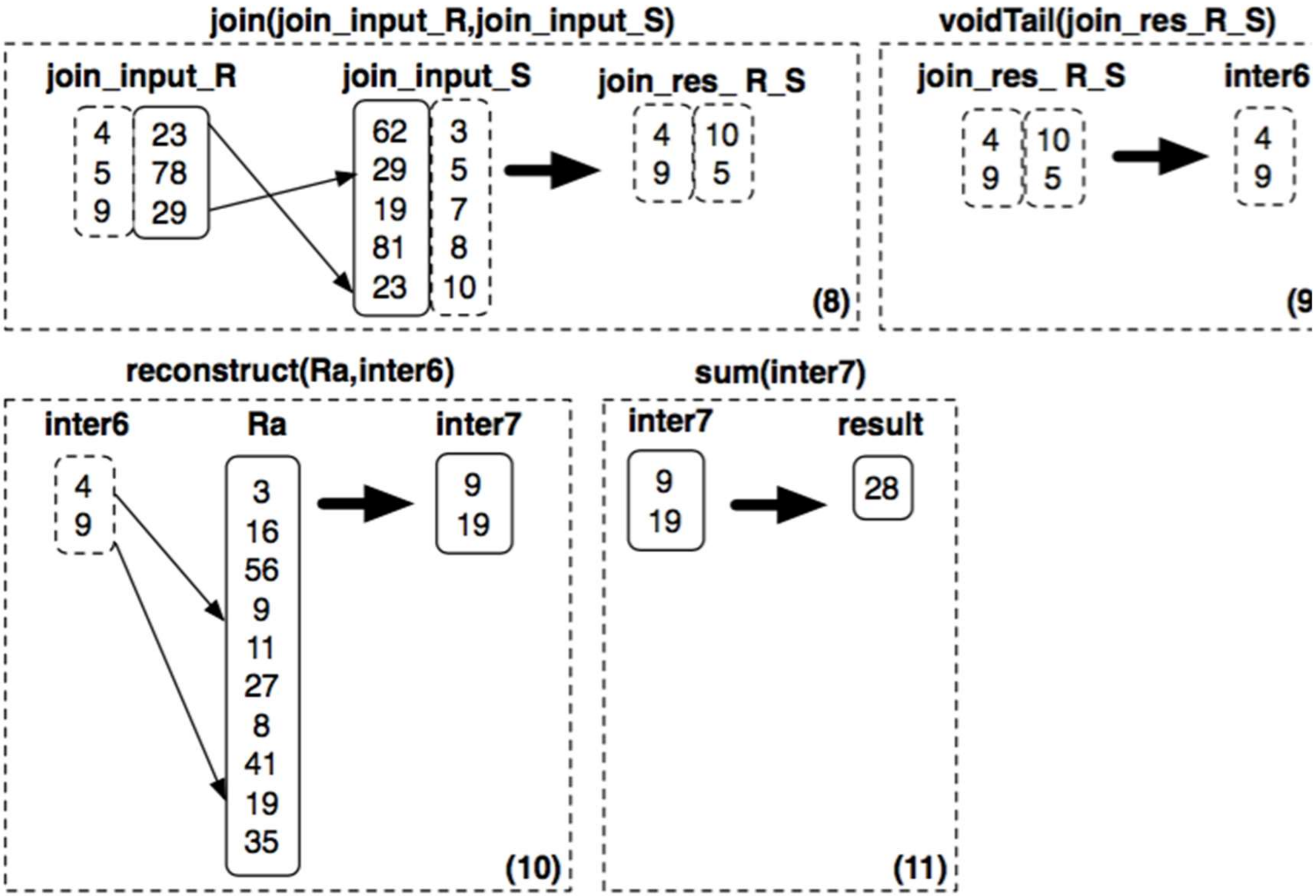


More Details

- Sort columns according to some criterion
  - Helps with range queries on that column
  - Helps compressing that column
  - But need to sort all the other columns the same way
- Create additional (redundant) ”views”, called “projections”, by sorting on different columns

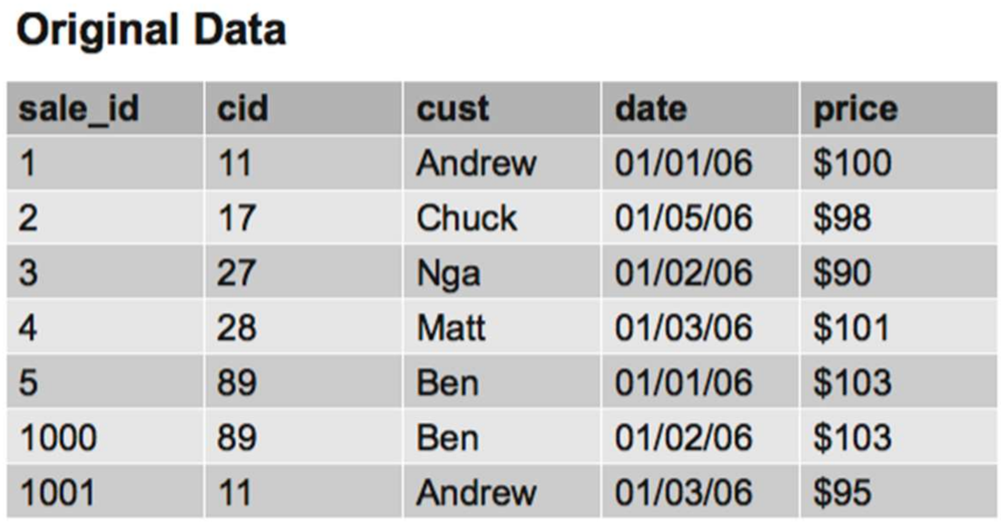
Vertica Data Model Details

Data organized into ***projections***:

Sorted subsets of the attributes

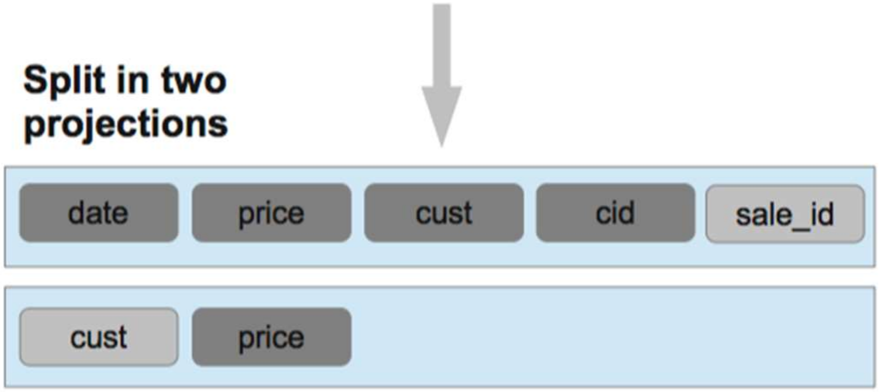
Each table has one super projection

- Includes all table attributes



Original Data

sale_id	cid	cust	date	price
1	11	Andrew	01/01/06	$100
2	17	Chuck	01/05/06	$98
3	27	Nga	01/02/06	$90
4	28	Matt	01/03/06	$101
5	89	Ben	01/01/06	$103
1000	89	Ben	01/02/06	$103
1001	11	Andrew	01/03/06	$95



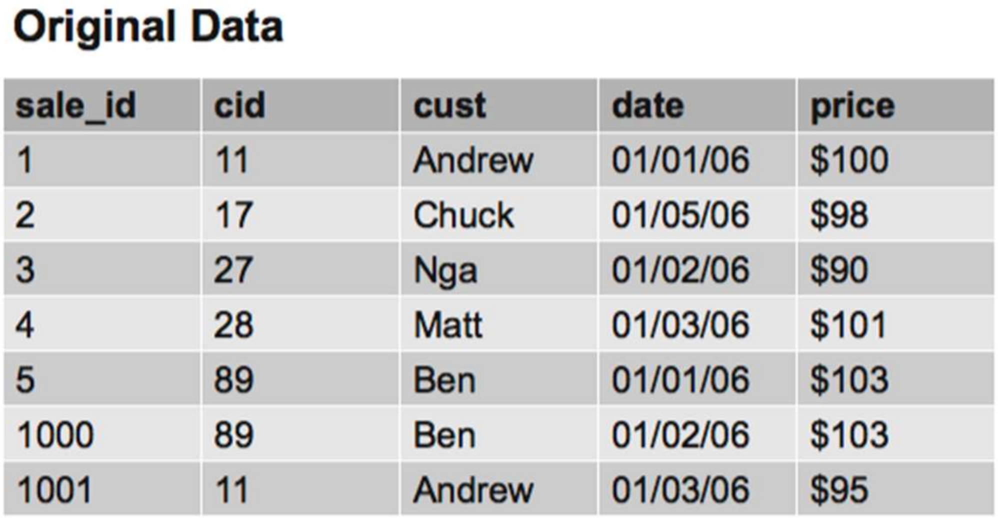
Super projection sorted by date

Non-super projection containing only(cust, price)
attributes, sorted by cust

From: The Vertica Analytic Database: CStore 7 Years Later. Lamb et. Al. VLDB’12

Parallel Processing

- Segment data horizontally across nodes
- Organize as column store on each node



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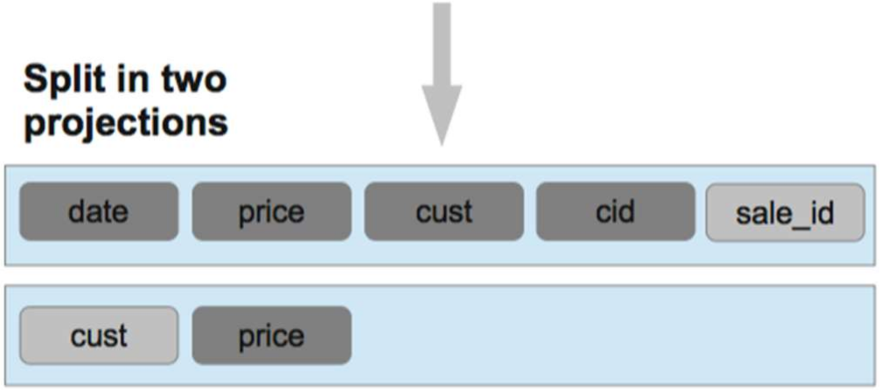
1000	89	Ben	01/02/06	$103
1001	11	Andrew	01/03/06	$95



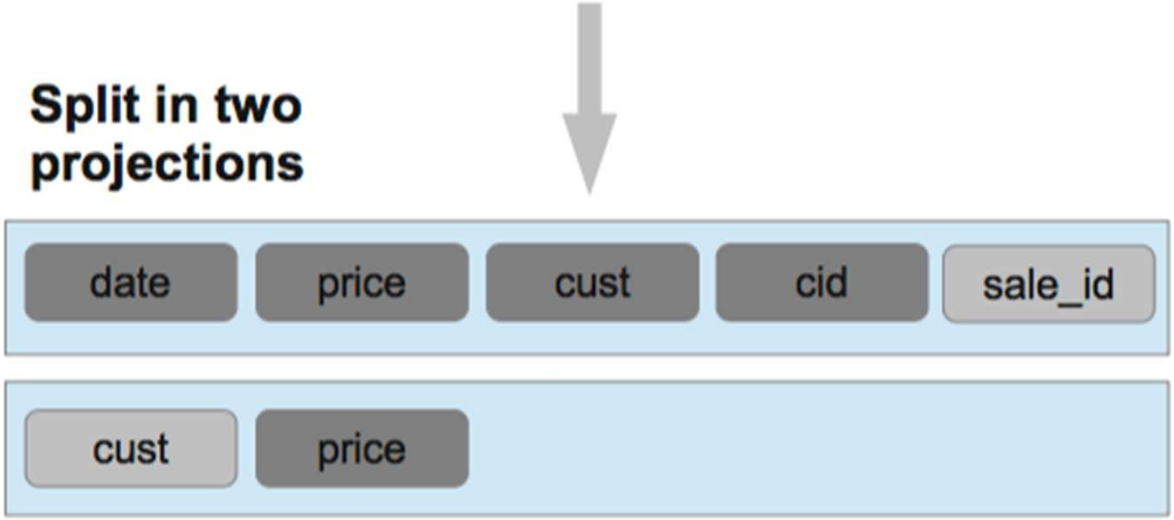
Split in two projections

Super projection sorted by date & segmented by hash(sale_id)

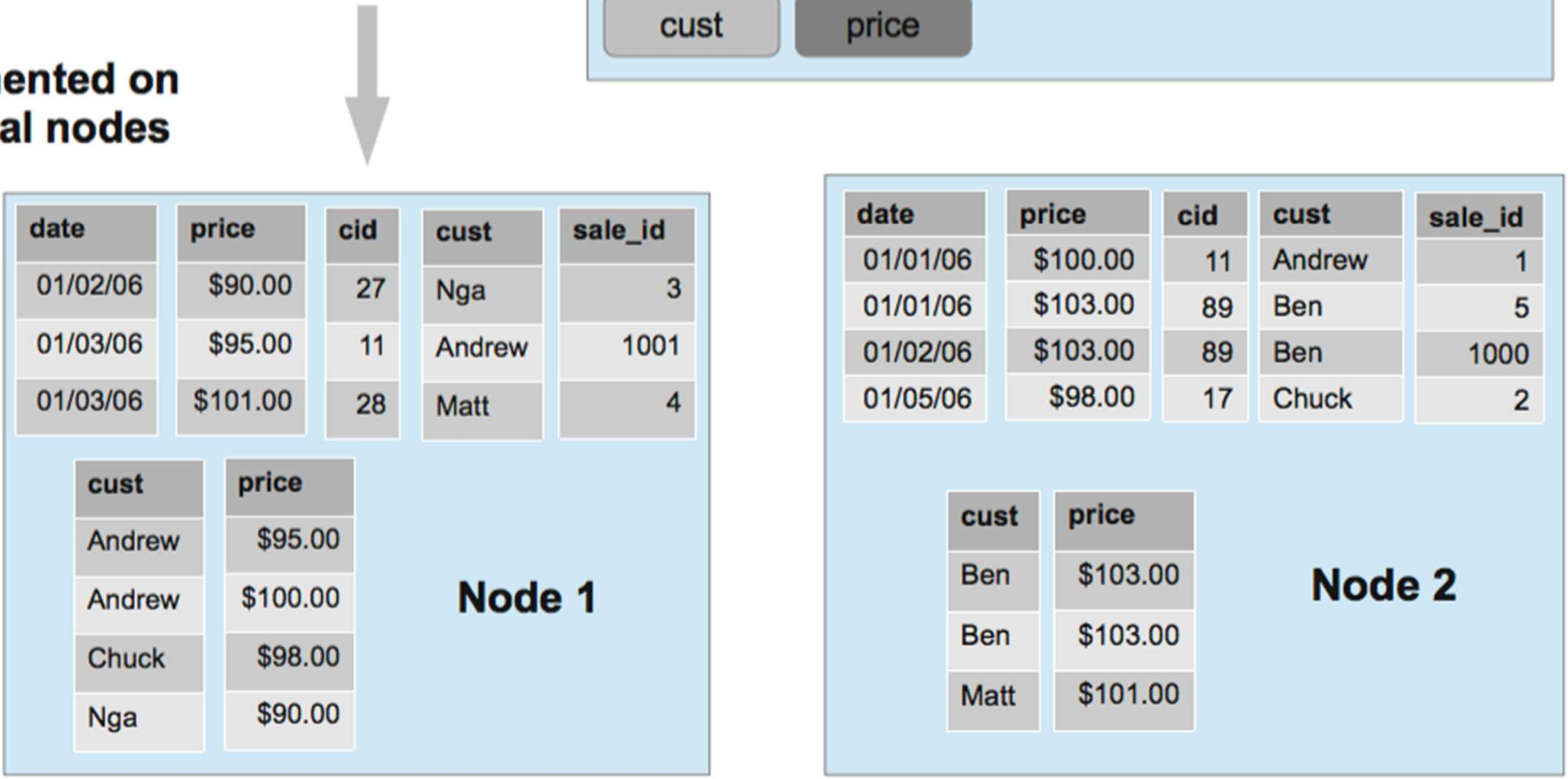
Non-super projection containing only(cust, price) attributes, sorted by cust, segmented by hash(cust)

Vertica Data Model Details

Split in two projections



Segmented on several nodes



Node 1

date	price	cid	cust	sale_id
01/02/06	$90.00	27	Nga	3
01/03/06	$95.00	11	Andrew	1001
01/03/06	$101.00	28	Matt	4

cust	price
Andrew	$95.00
Andrew	$100.00
Chuck	$98.00
Nga	$90.00

Node 2

date	price	cid	cust	sale_id
01/01/06	$100.00	11	Andrew	1
01/01/06	$103.00	89	Ben	5
01/02/06	$103.00	89	Ben	1000
01/05/06	$98.00	17	Chuck	2

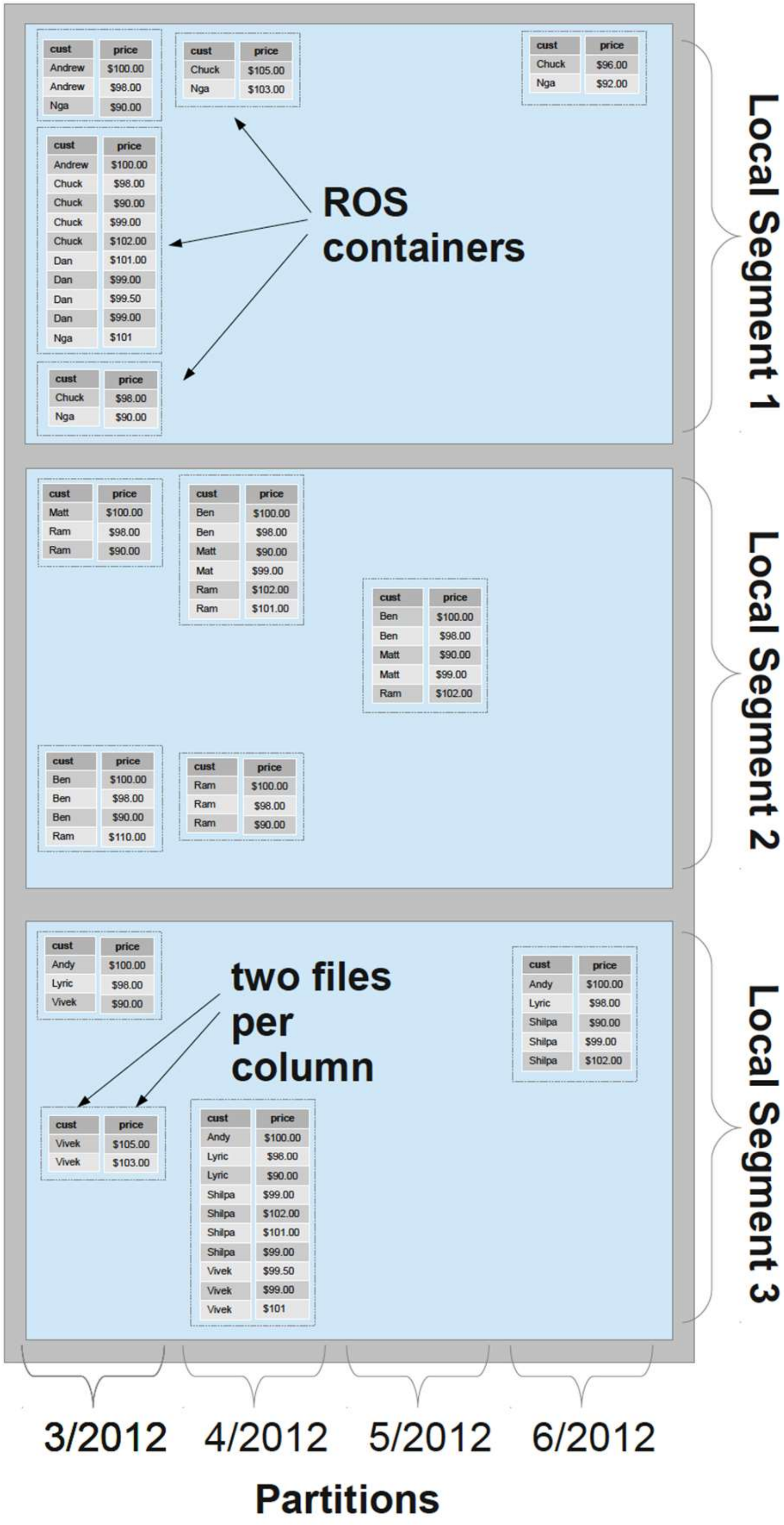
cust	price
Ben	$103.00
Ben	$103.00
Matt	$101.00

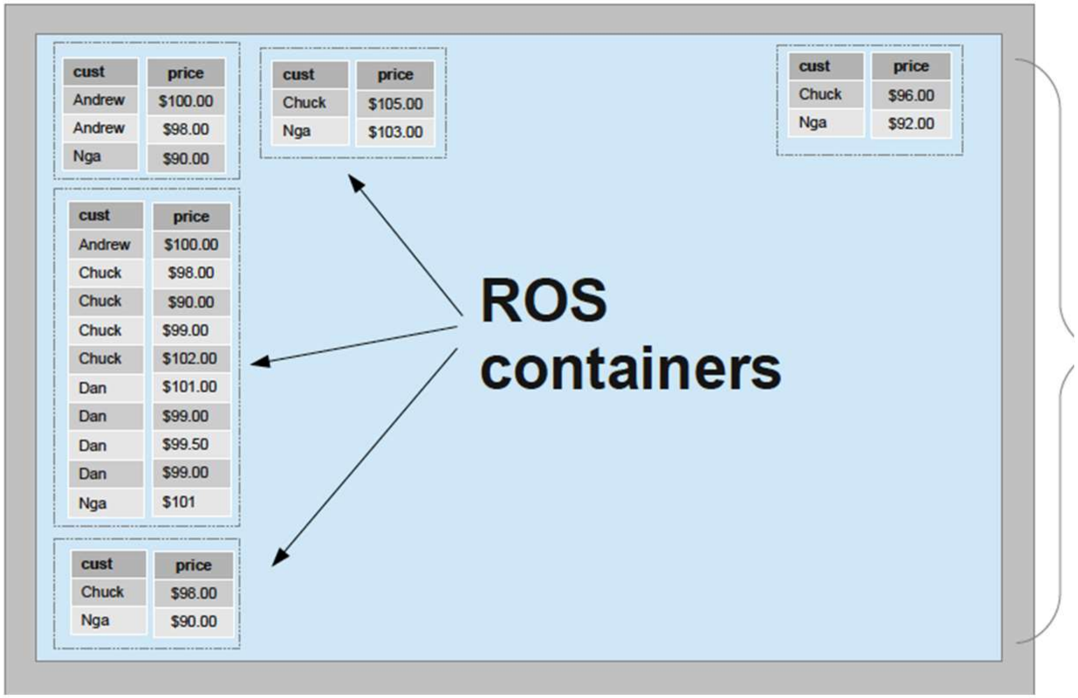
Vertica Data Partitioning

- Cross-node partitioning called “segmentation”
  - Hash-partitioning
  - Other expression
- Each node assigned multiple local segments
  - To facilitate elasticity
  - Enables moving segments as cluster size changes
- Can also replicate all tuples in projection

Vertica Intra-Node Partitioning

- Vertica divides each on-disk structure into logical regions at runtime and processing the regions in parallel
- Vertica also supports explicit data partitioning
  - Partitions segments within nodes into smaller pieces
  - CREATE TABLE … PARTITION BY <expr>
  - Benefits:
    - Fast deletion
    - Pruning of partitions during query execution





Segmentation = horizontal partitioning *across* nodes

→ Each projection has own segmentation

→ More segments than nodes for elasticity

Partition = horizontal *within* a node

→ Same partition for all projections & nodes

ROS = Read Optimized Store

Each column's data within its ROS container is stored as a single file

Updates

- What is the question?

- How does the paper address this?

Updates

- What is the issue?
  - Updates in a sorted column require reordering of the entire column, and the other columns as well

- How does the paper address this?

Updates

- What is the issue?
  - Updates in a sorted column require reordering of the entire column, and the other columns as well

- How does the paper address this?
  - Update to Write Optimized Store (WOS)
  - Queries on Read Optimized Store (ROS)

C-Store/Vertica Design

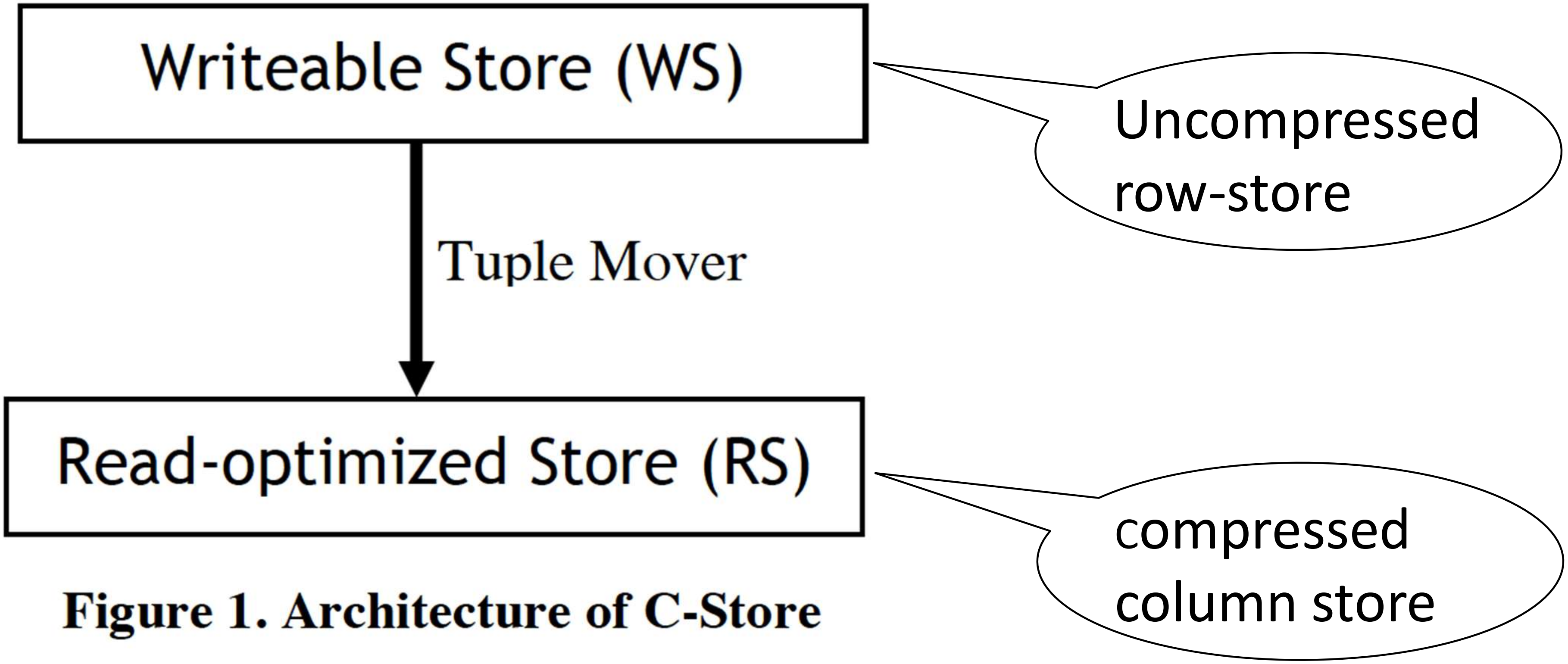


Figure 1. Architecture of C-Store

Uncompressed row-store

compressed column store

From: C-Store: A Column-oriented DBMS. Stonebraker et. Al. VLDB’05

Read and Write Optimized Stores

- Write Optimized Store (WOS)
  - In memory data: buffer delete/insert/update operations
  - Column vs row does not matter
- Tuples never modified in place
  - Use “delete vector” to track deleted tuples
  - Eventually removed by tuple mover during ROS merge
- Tuple mover
  - Move between WOS and ROS
  - When moving tuples out, creates a new ROS container
  - Merges ROS files together
    - Better compression & faster processing (fewer files to merge)

Read and Write Optimized Stores

- Read Optimized Store (ROS)
  - Multiple ROS containers
  - Stored on standard file system
  - Logically contains some number of complete tuples sorted by the *projection's* sort order, stored as a pair of files per column: position index & data
    - The position index = only metadata per disk block
  - Column files may be independently retrieved

Final Thoughts

Simulating a Column-Store in a Row-Store DBMS:

- Vertical partitioning
  - Two-column tables: (key, attribute)
- Index-only plans
  - Create a B+ tree index on each attribute
  - Answer queries using indexes only, without reading actual data
- Materialized views
  - Each view contains a subset of columns

References

- Ailamaki et al. *Weaving Relations for Cache Performance,* VLDB'2001
- The Design and Implementation of Modern Column-Oriented Database Systems Daniel Abadi, et al., Foundations and Trends in Databases
- Also:
  - C-Store: A Column-oriented DBMS. Stonebraker et al. VLDB'05
  - The Vertica Analytic Database: CStore 7 Years Later. Lamb et. al. VLDB'12