CSE544
Data Management

Lectures 6: PAX and C-Store

Reminder

- HW1 due on Friday

Hints for HW1

Triple-representation of data:

- T(subject, predicate, object)
  - E.g. (“Alice”, “age”, 30)

Hints for HW1

Triple-representation of data:

- T(subject, predicate, object)
  - E.g. (“Alice”, “age”, 30)
- Convenient for *semistructured data*:
  - Some attributes may be missing
  - Some subjects have extra attributes
  - Some attributes may be duplicates

Hints for HW1

Triple-representation of data:

- T(subject, predicate, object)
  - E.g. (“Alice”, “age”, 30)
- Convenient for *semistructured data*:
  - Some attributes may be missing
  - Some subjects have extra attributes
  - Some attributes may be duplicates

Structured data:

- Known schema: Person(name, age, city, …)
- How do we map semistructured to structured?

Hints for HW1

```
test=# select * from triples;
 key |    attr    |   val
-----+------------+----------
   1 | name       | Alice
   1 | age        | 20
   1 | city       | Seattle
   2 | name       | Bob
   2 | age        | 30
   2 | city       | Portland
   1 | profession | SE
(7 rows)
```

Hints for HW1

```
test=# select * from triples;
 key |    attr    |   val
-----+------------+----------
   1 | name       | Alice
   1 | age        | 20
   1 | city       | Seattle
   2 | name       | Bob
   2 | age        | 30
   2 | city       | Portland
   1 | profession | SE
(7 rows)
```

?

```
test=# select * from Person;
 id | name  | age |   city
----+-------+-----+----------
  1 | Alice | 20  | Seattle
  2 | Bob   | 30  | Portland
(2 rows)
```

Hints for HW1

```
test=# select * from triples;
 key |    attr    |   val
-----+------------+----------
   1 | name       | Alice
   1 | age        | 20
   1 | city       | Seattle
   2 | name       | Bob
   2 | age        | 30
   2 | city       | Portland
   1 | profession | SE
(7 rows)
```

```
create table Person as
  (select x.key as id,
            x.val as name,
            y.val as age,
            z.val as city
    from triples x,
          triples y,
          triples z
    where x.key = y.key
      and x.key = z.key
      and x.attr='name’
      and y.attr='age’
      and z.attr='city');
```

Hints for HW1

Other options are possible:

- E.g. insert only the keys first, then update, separately, each field:

```
update Person set name = … where …
update Person set age = … where …
update Person set city = … where …
```

Hints for HW1

```
test=# select * from triples;
 key |    attr    |   val
-----+------------+----------
   1 | name       | Alice
   1 | age        | 20
   1 | city       | Seattle
   2 | name       | Bob
   2 | age        | 30
   2 | city       | Portland
   1 | profession | SE
(7 rows)
```

?

```
test=# select * from Empl;
 id | name    | profession
----+---------+------------
  1 | Alice   | SE
  2 | Bob     |
(2 rows)
```

Hints for HW1

```
test=# select * from triples;
 key |    attr    |   val
-----+------------+----------
   1 | name       | Alice
   1 | age        | 20
   1 | city       | Seattle
   2 | name       | Bob
   2 | age        | 30
   2 | city       | Portland
   1 | profession | SE
(7 rows)
```

```
create table Empl as
  (select x.key as id,
          x.val as name,
          y.val as profession
   from triples x left outer join
        triples y
     on x.key=y.key
    and y.attr='profession'
   where x.attr='name');
```

Hints for HW1

- Data is not code!
  - There is no perfect way to import DBLP
  - Where it’s ambiguous, use common sense

Hints for HW1

- Data is not code!
  - There is no perfect way to import DBLP
  - Where it's ambiguous, use common sense
- NULLs or No-data: choose your poison
  - NULLs are bad: drop records that need NULL
  - Dropping records is bad: insert NULLs if needed

Hints for HW1

- Data is not code!
  - There is no perfect way to import DBLP
  - Where it's ambiguous, use common sense
- NULLs or No-data: choose your poison
  - NULLs are bad: drop records that need NULL
  - Dropping records is bad: insert NULLs if needed
- Data cleaning = hacking of the worst kind
  - How to you check if a field is a homepage?
  - Use some regular expression…

Outline for Today

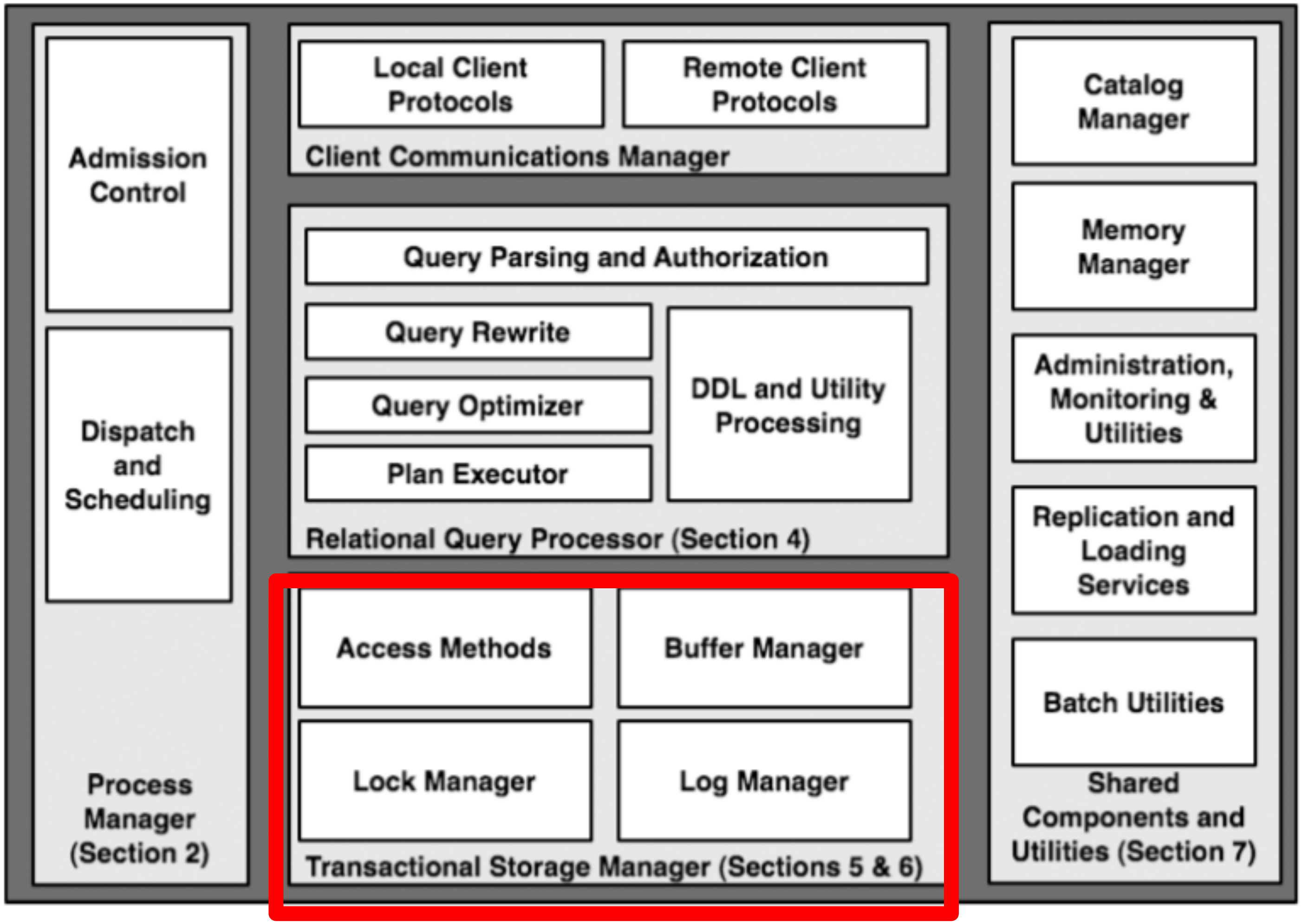
- Quick review of page/record formats
- PAX paper
- C-Store paper
  - Sec. 1,2 only
  - Will discuss the slides concerning Sec. 4 some other time
- Go back to last lecture (lecture 5):
  - finish discussing indexes

References

- Ailamaki et al. *Weaving Relations for Cache Performance,* VLDB'2001
- Daniel Abadi, et al., *The Design and Implementation of Modern Column-Oriented Database Systems* Foundations and Trends in Databases

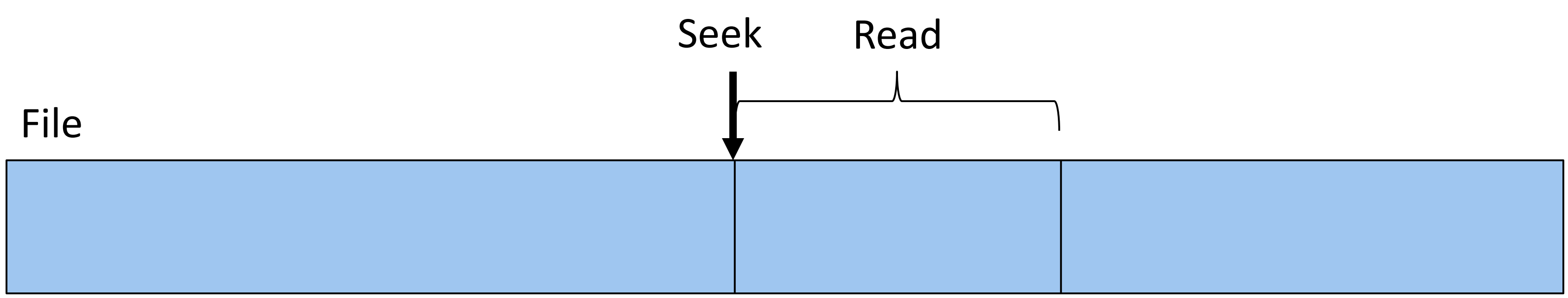
[Architecture of a Database System, Hellerstein, Stonebraker, Hamilton]

Storage

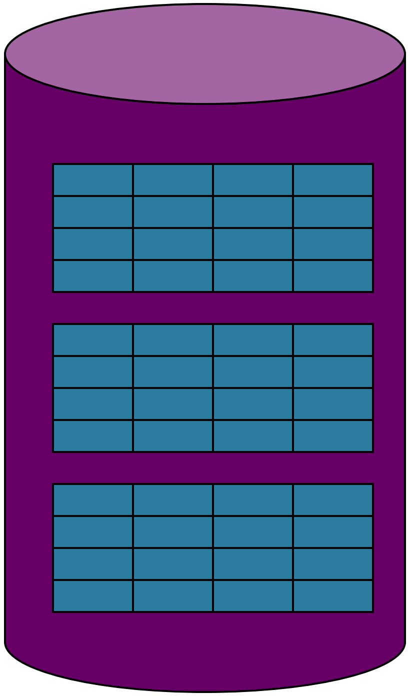


Review

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



Review: Working with Pages



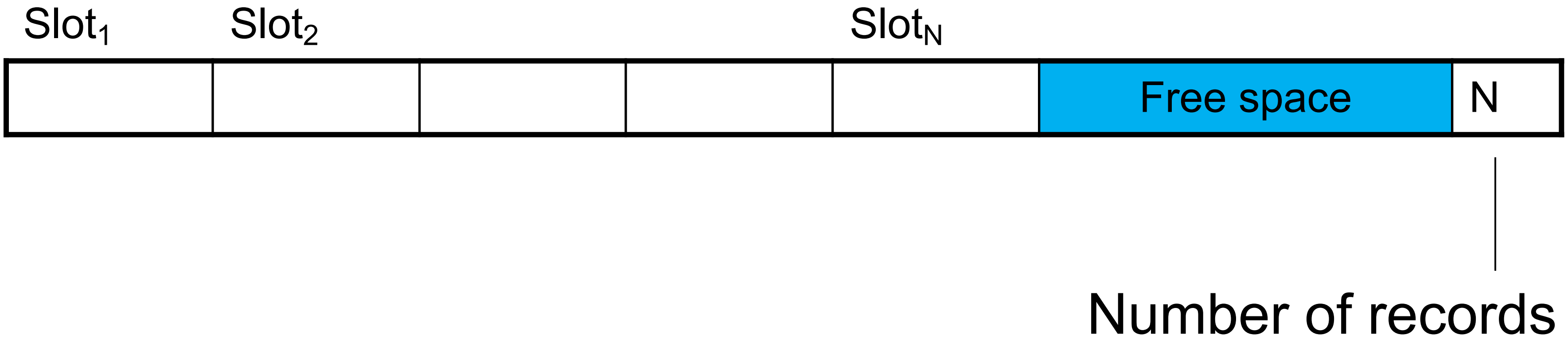
- Reading/writing to/from disk
  - Seeking takes a long time!
  - Reading sequentially is fast
- To simplify buffer manager, want to cache a collection of same-sized objects
- Solution: Read/write **pages** of data
  - A page should correspond to a disk block

Review: Page Formats

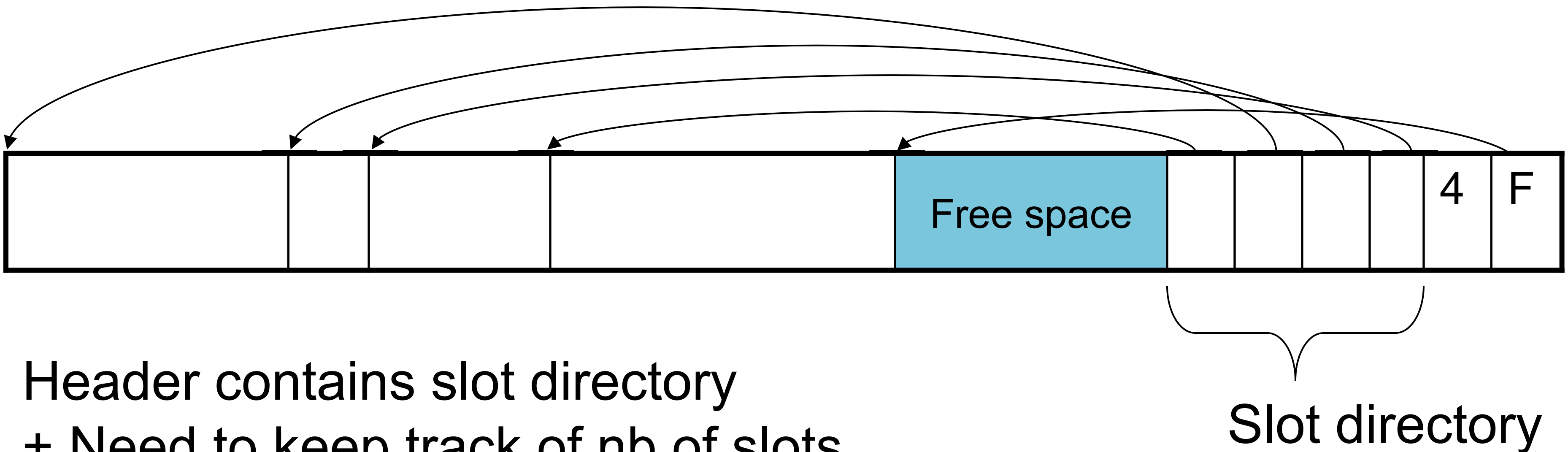
- 1 page = 1 disk block = fixed size (e.g. 8KB)
- Records:
  - Fixed length
  - Variable length
- Record id = RID
  - Typically RID = (PageID, SlotNumber)

Page Format: Fixed-length Records

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



Page Format: Variable-length Records



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

Record Formats: Fixed-length Fields

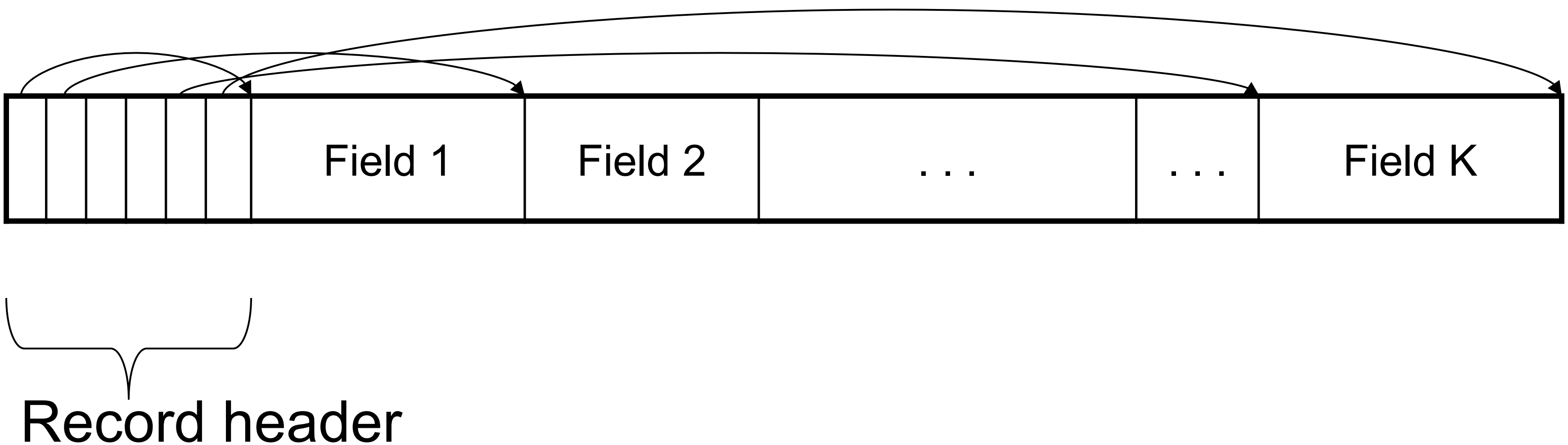
Fixed-length records => Each field has a fixed length (i.e., it has the same length in all the records)

Field 1	Field 2	. . .	. . .	Field K

Information about field lengths and types is in the catalog

Record Formats: Variable-length Fields

Variable length records



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

An Intermediate Format: PAX

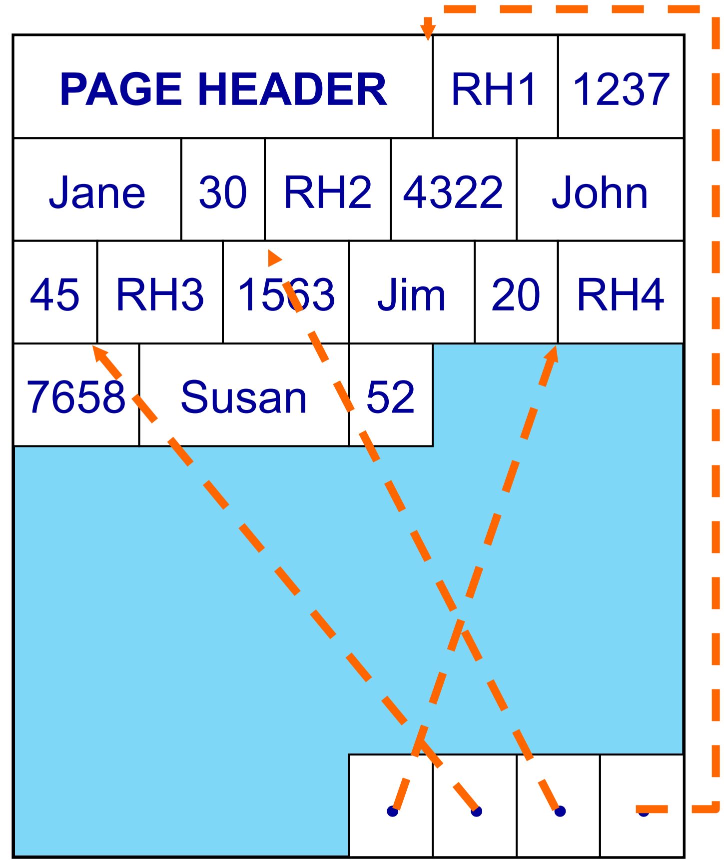
- PAX = Partition Attributes Across
- Addresses memory access bottleneck (not the disk bottleneck)

Current Scheme: Slotted Pages

Formal name: NSM (N-ary Storage Model)

R

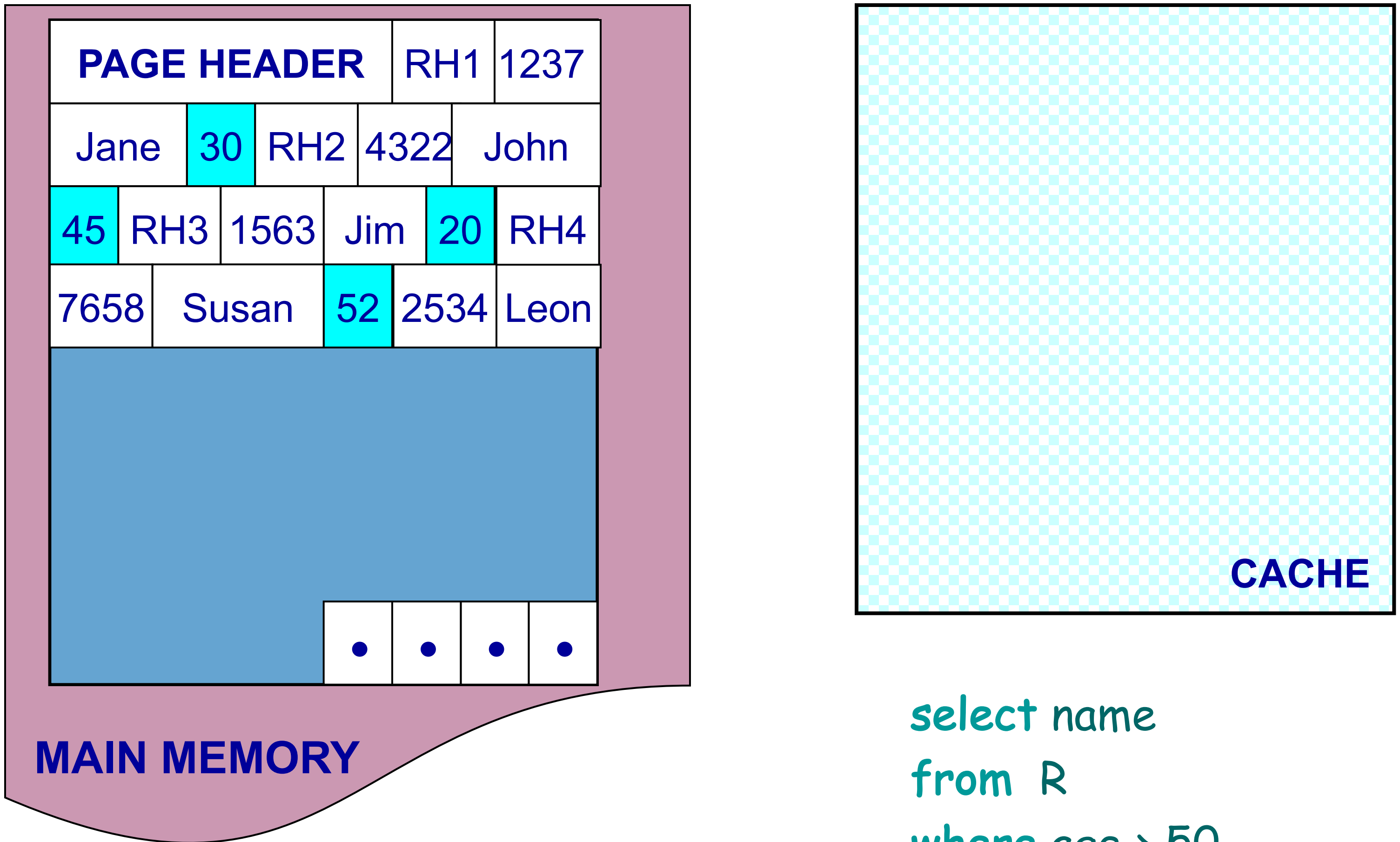
RID	SSN	Name	Age
1	1237	Jane	30
2	4322	John	45
3	1563	Jim	20
4	7658	Susan	52
5	2534	Leon	43
6	8791	Dan	37



- 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

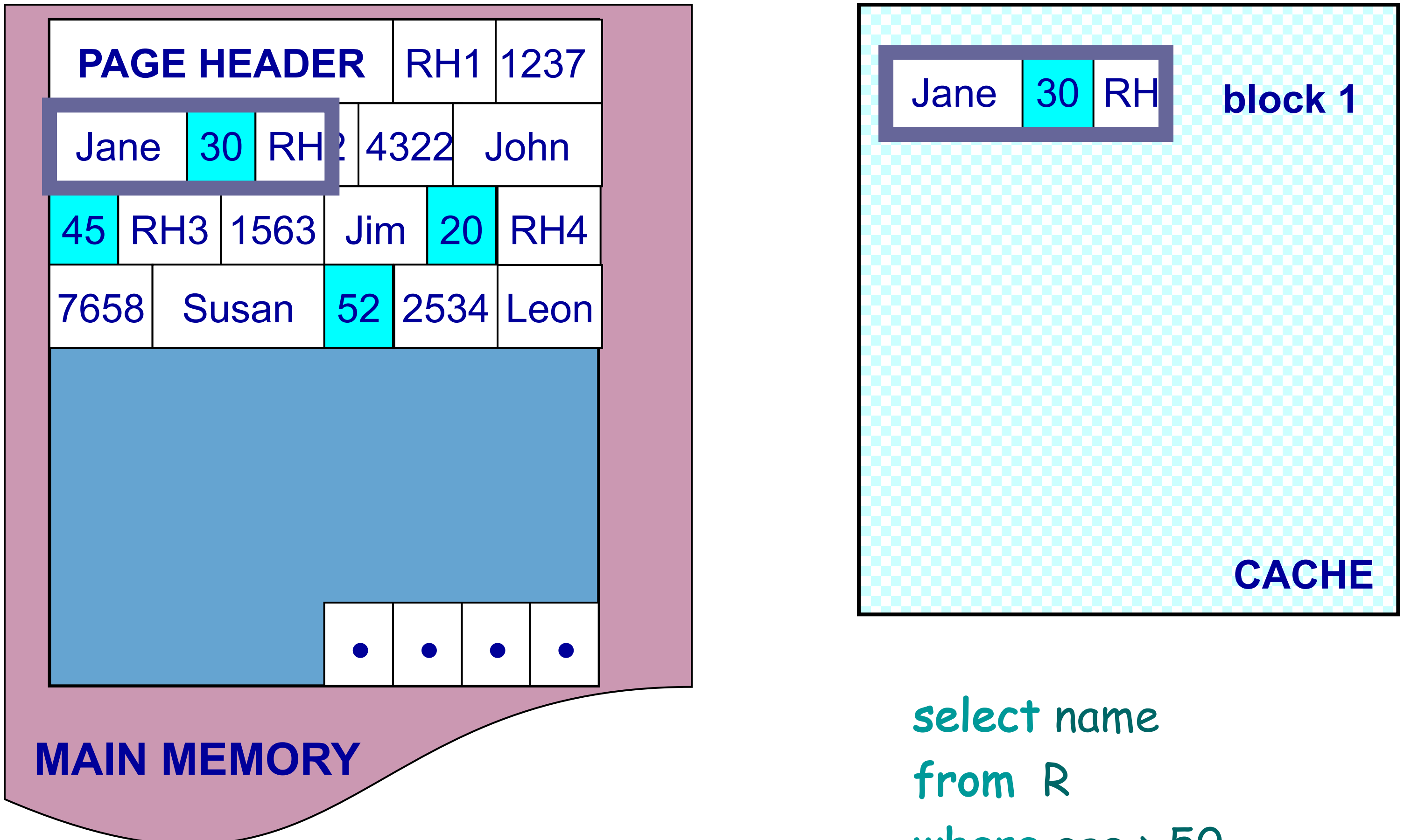


select name
from R
where age > 50

NSM pushes non-referenced data to the cache

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

Predicate Evaluation using NSM

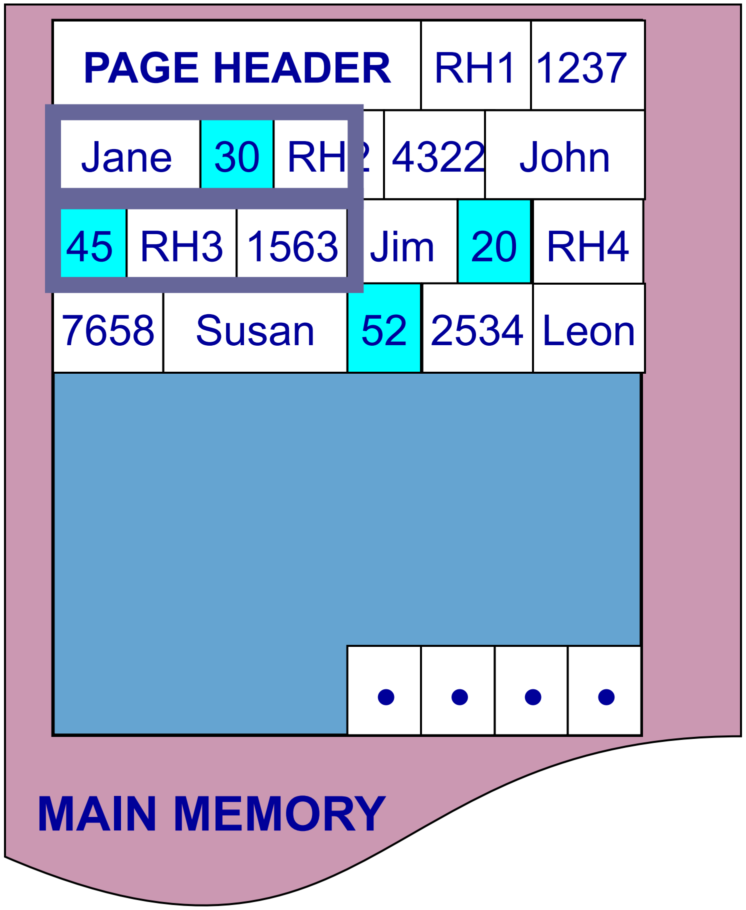


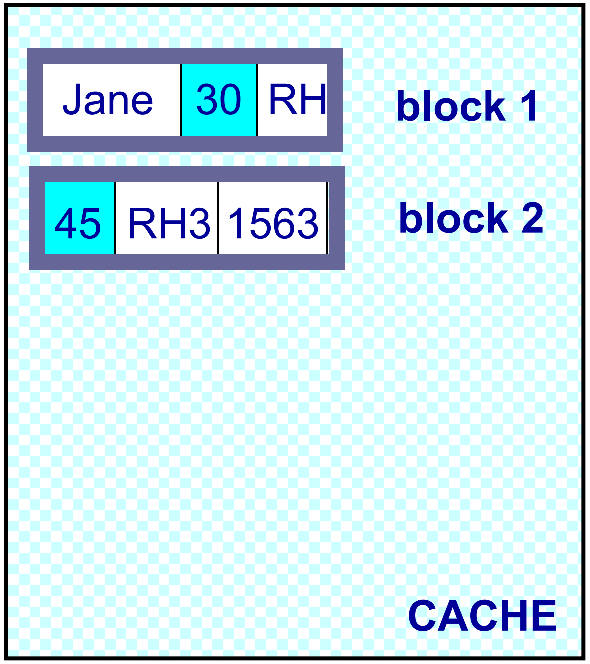
select name
from R
where age > 50

NSM pushes non-referenced data to the cache

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

Predicate Evaluation using NSM



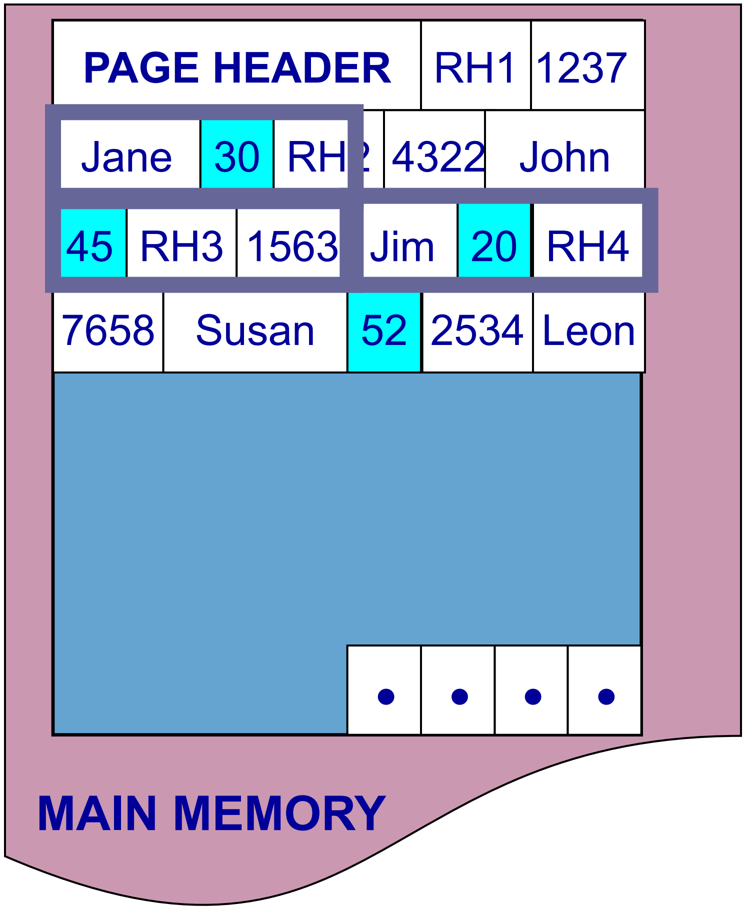


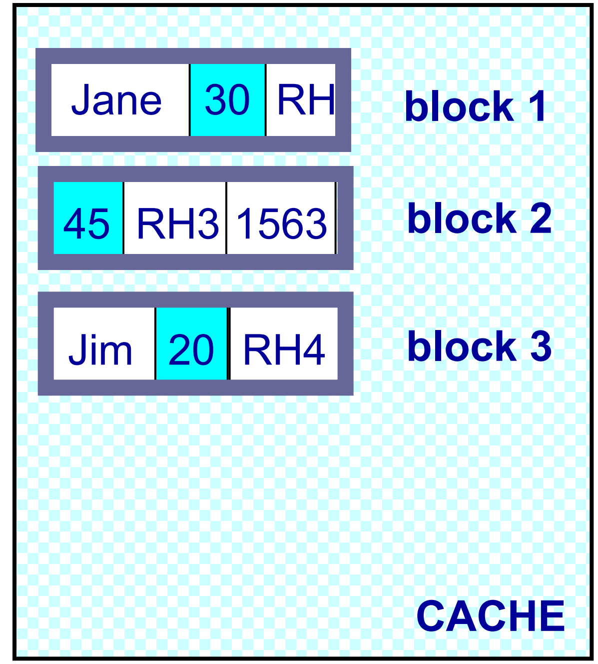
select name
from R
where age > 50

NSM pushes non-referenced data to the cache

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

Predicate Evaluation using NSM



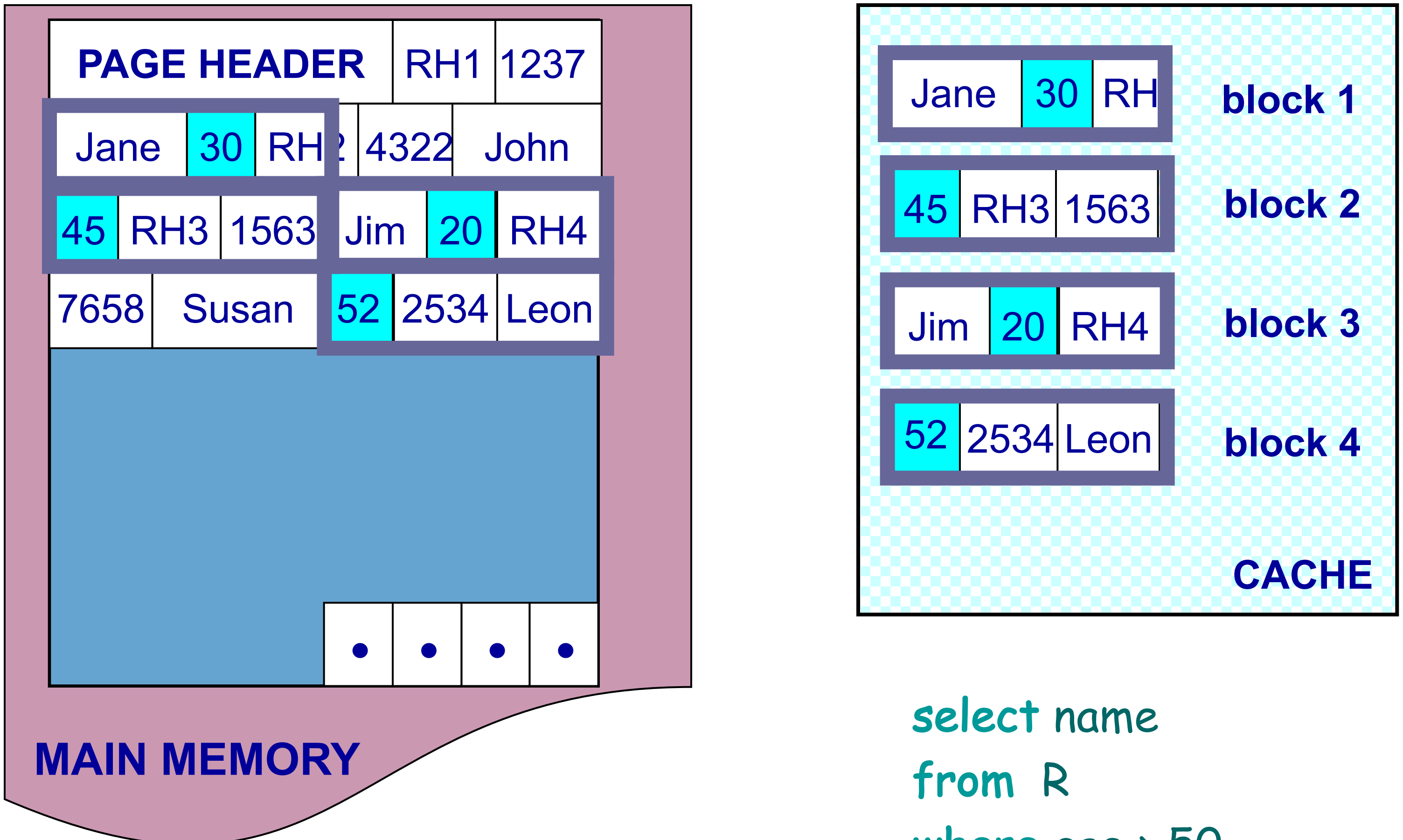



```
select name
from R
where age > 50
```

NSM pushes non-referenced data to the cache

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

Predicate Evaluation using NSM



select name
from R
where age > 50

NSM pushes non-referenced data to the cache

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

Need New Data Page Layout

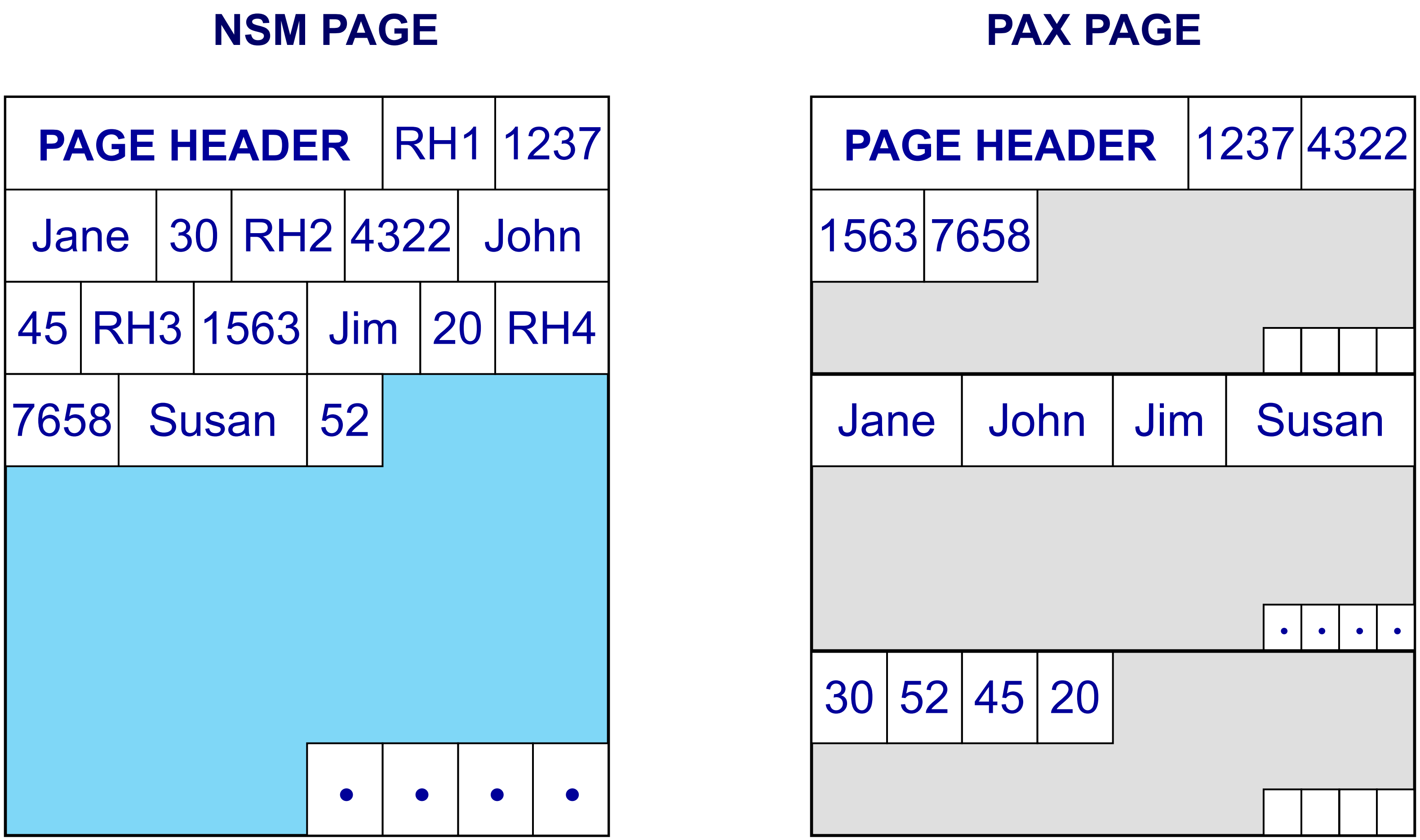
- Eliminates unnecessary memory accesses
- Improves inter-record locality
- Keeps a record's fields together
- Does not affect I/O performance

and, most importantly, is…

low-implementation-cost, high-impact

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

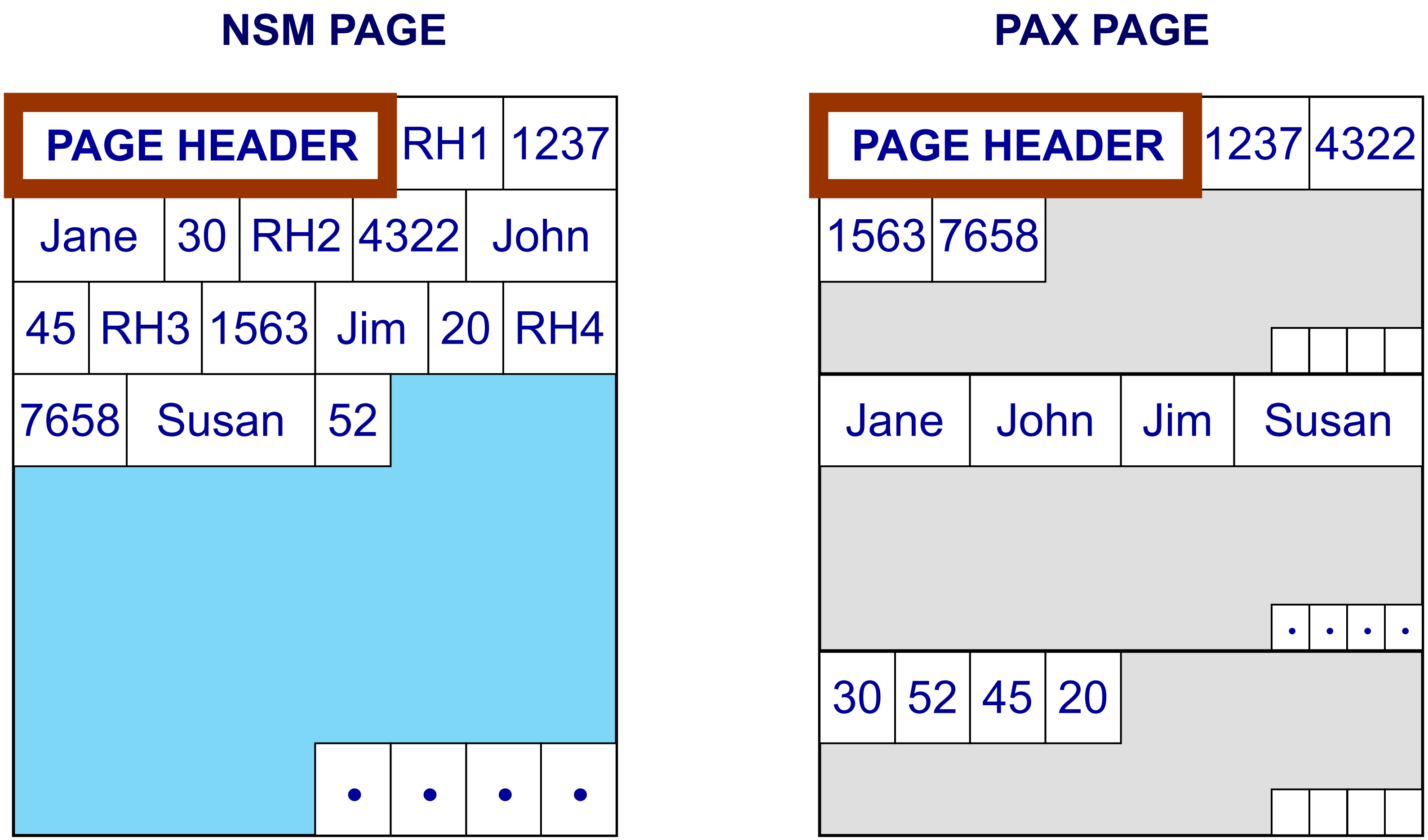
Partition Attributes Across (PAX)



Partition data *within* the page for spatial locality

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

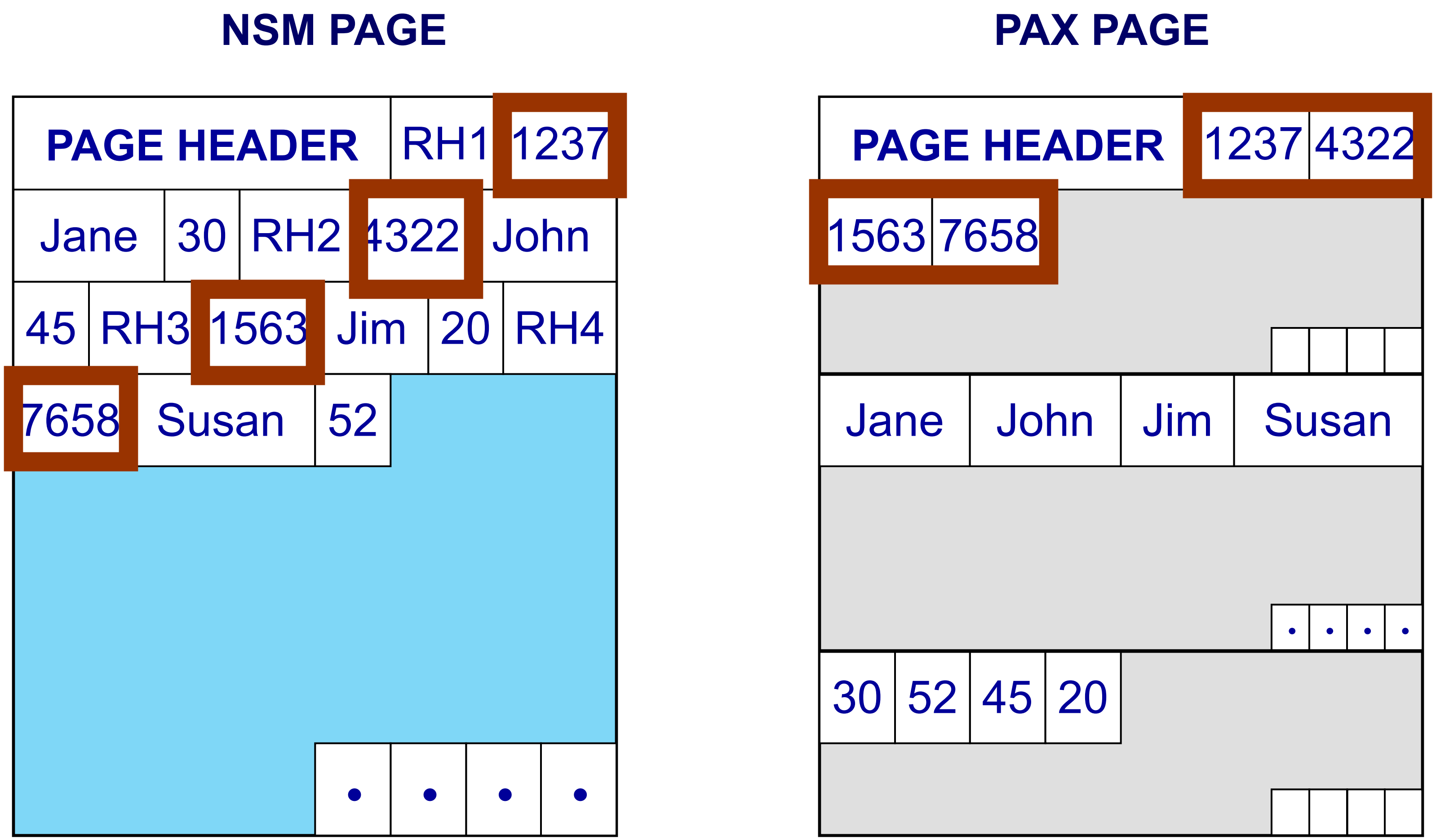
Partition Attributes Across (PAX)



Partition data *within* the page for spatial locality

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

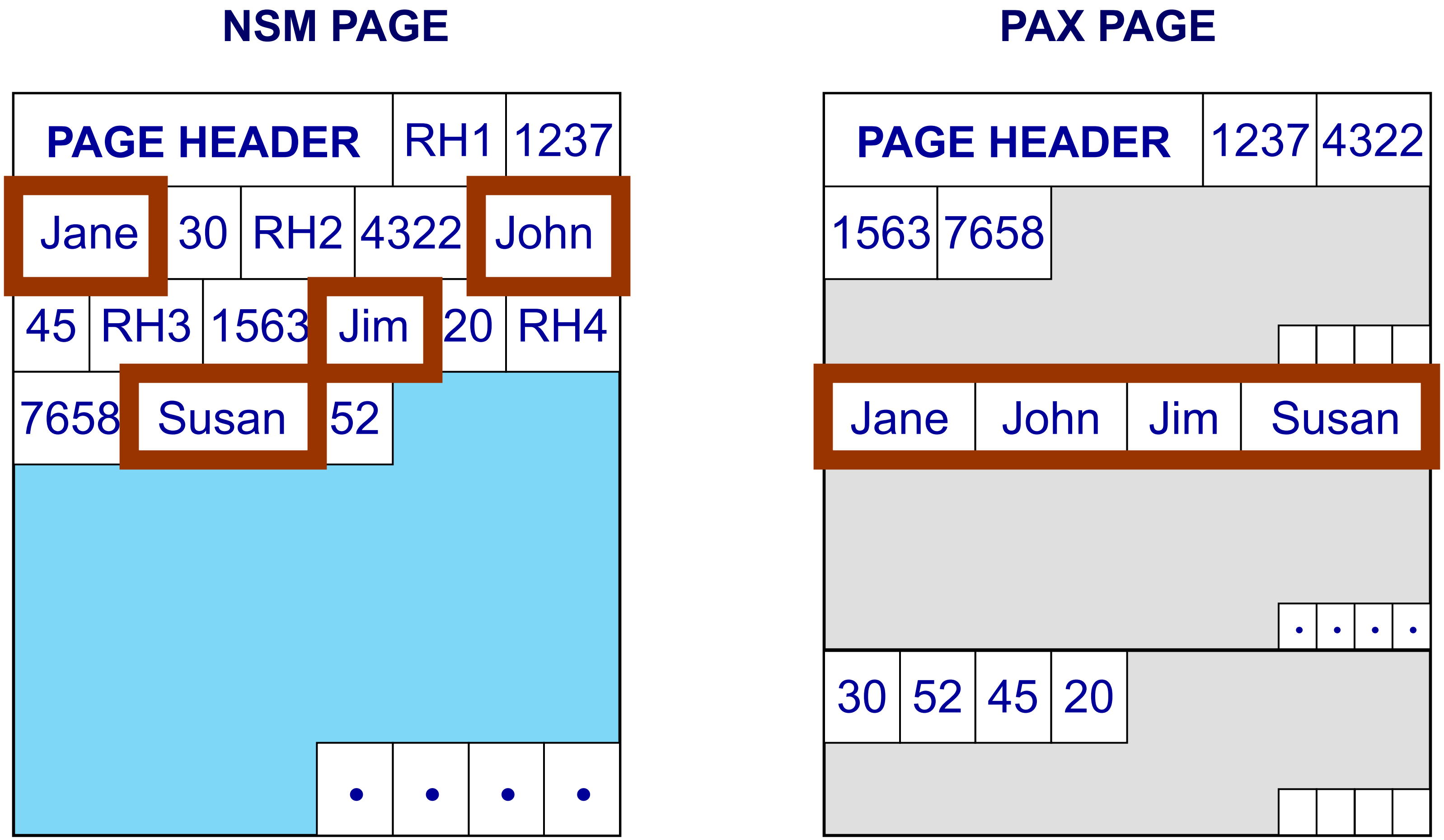
Partition Attributes Across (PAX)



Partition data *within* the page for spatial locality

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

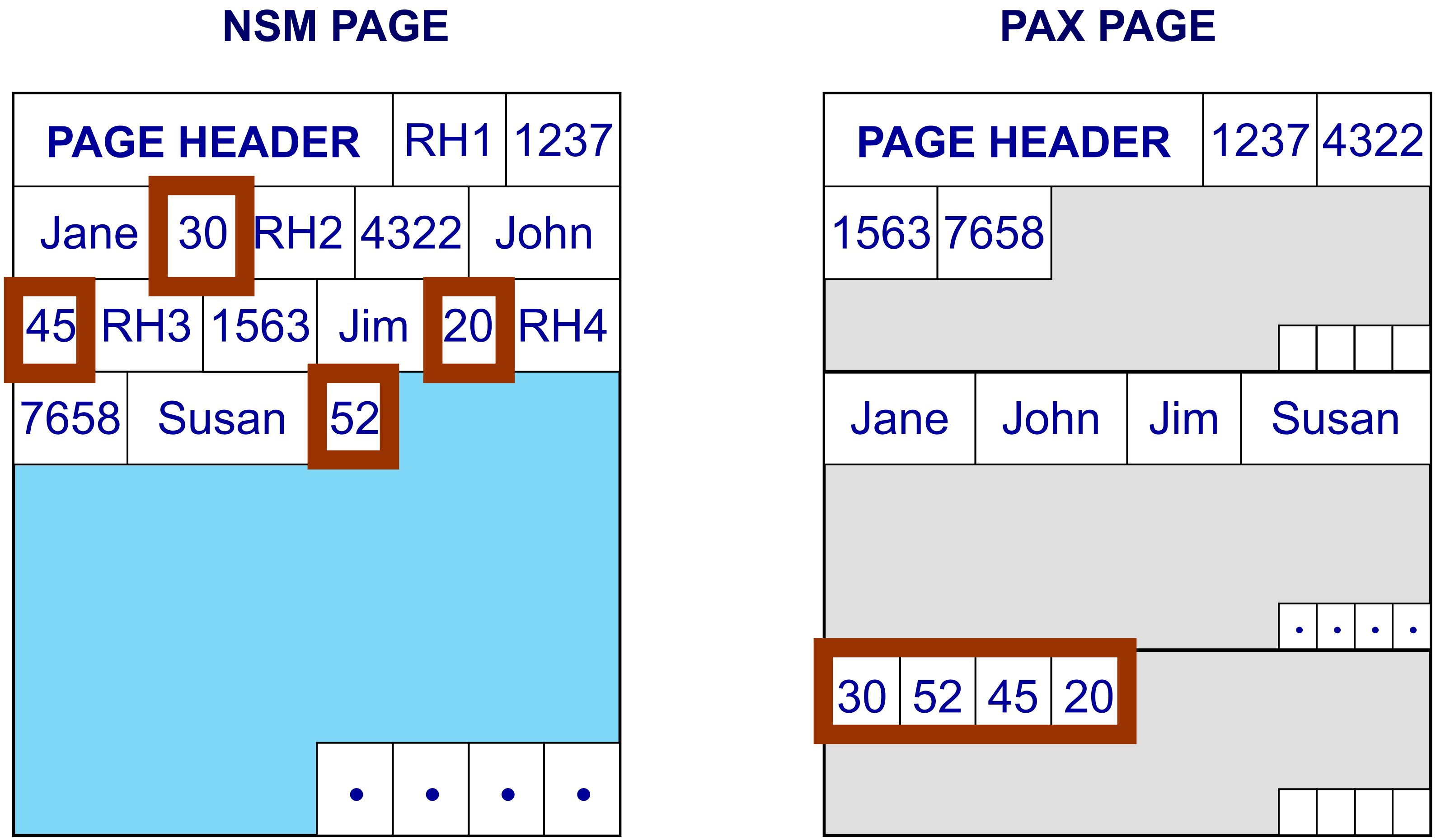
Partition Attributes Across (PAX)



Partition data *within* the page for spatial locality

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

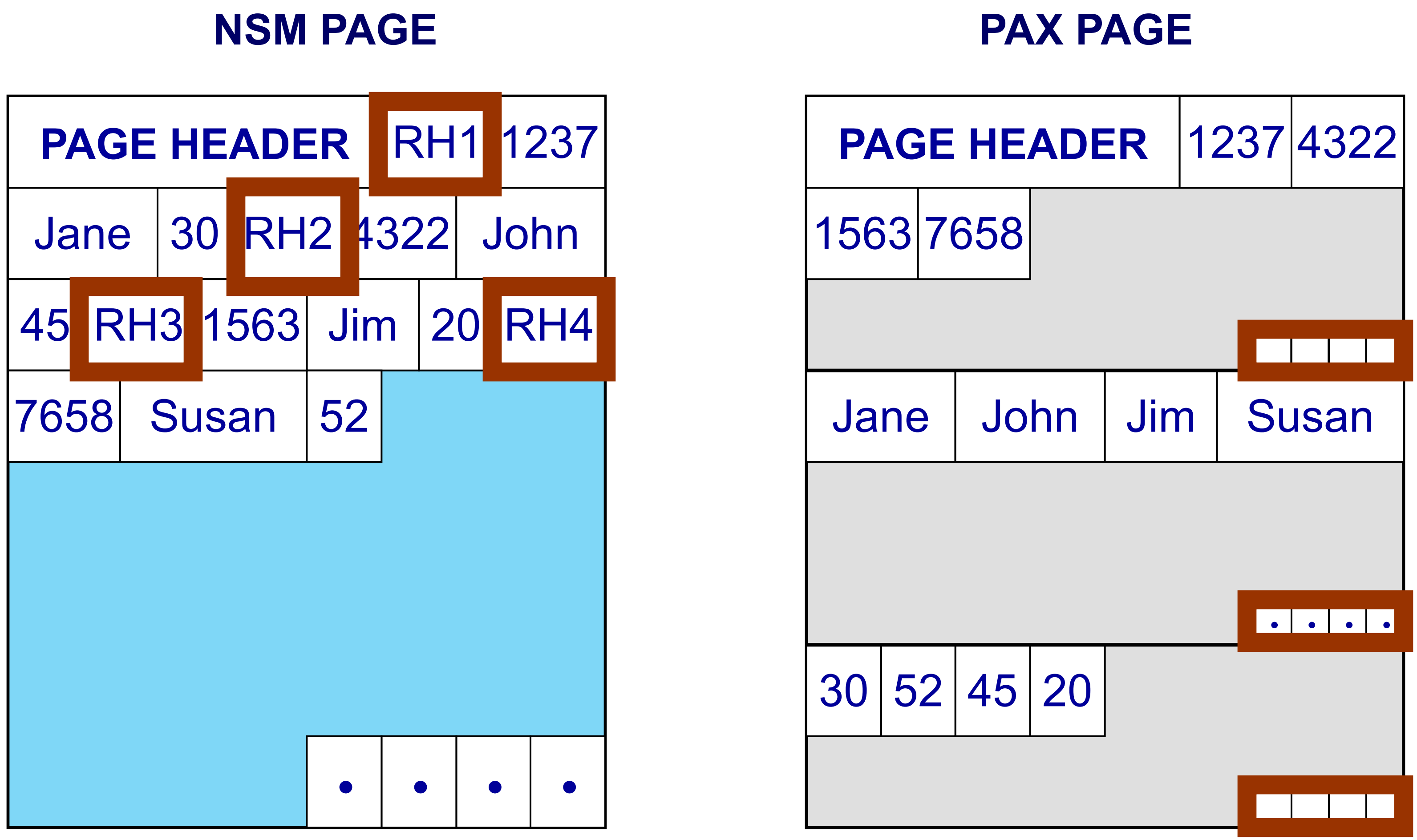
Partition Attributes Across (PAX)



Partition data *within* the page for spatial locality

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

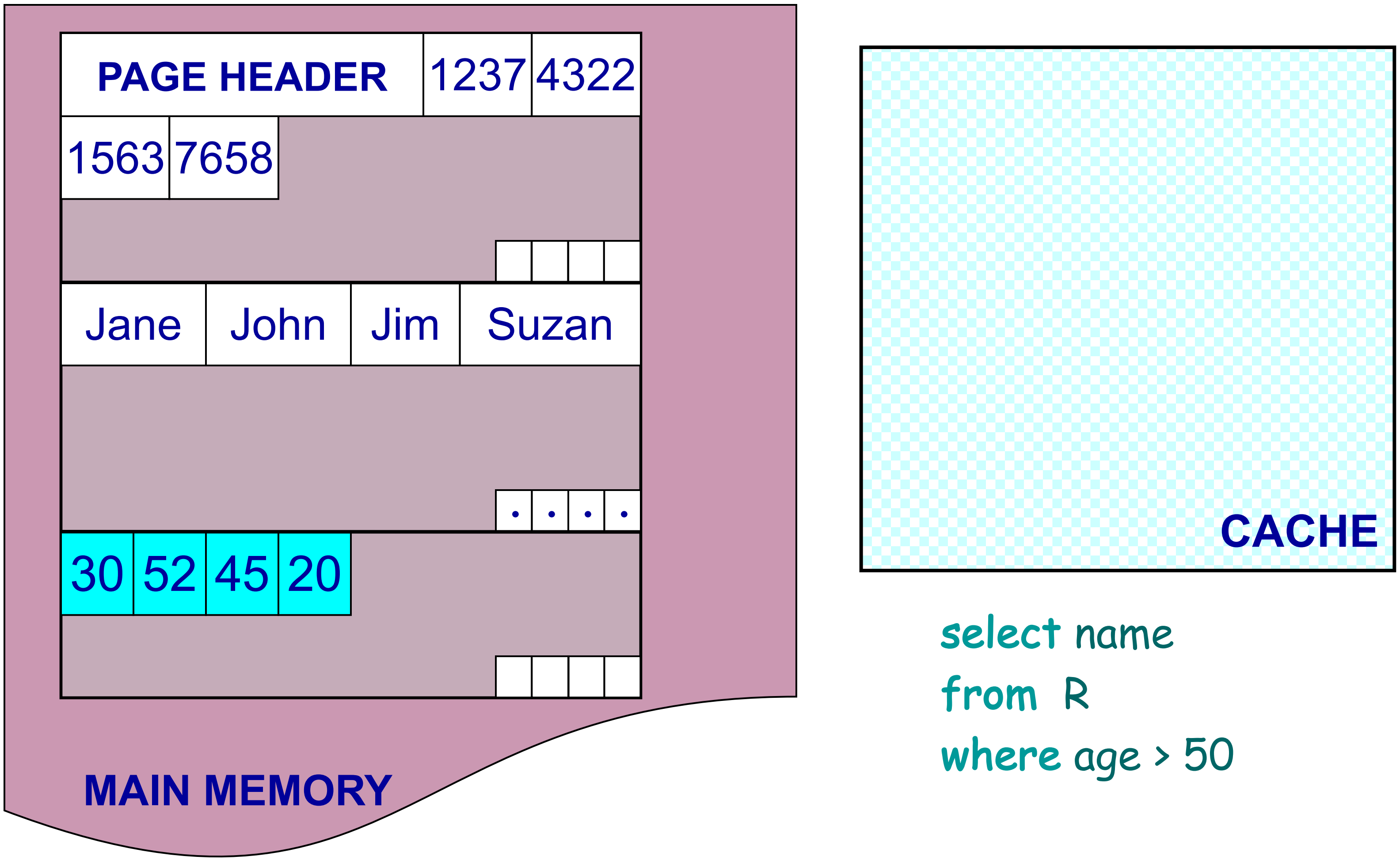
Partition Attributes Across (PAX)



Partition data *within* the page for spatial locality

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

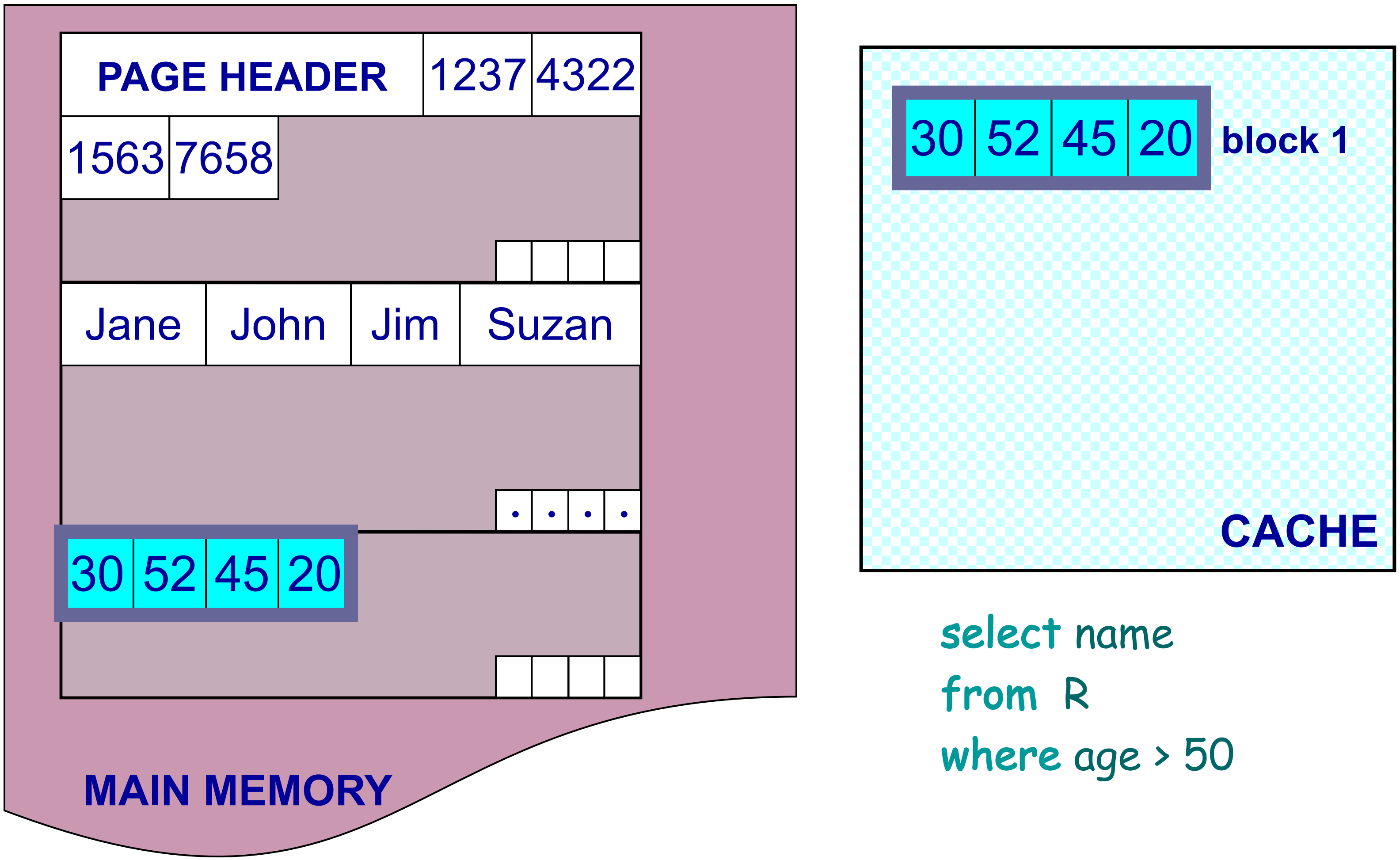
Predicate Evaluation using PAX



select name
from R
where age > 50

Fewer cache misses, low reconstruction cost

Predicate Evaluation using PAX

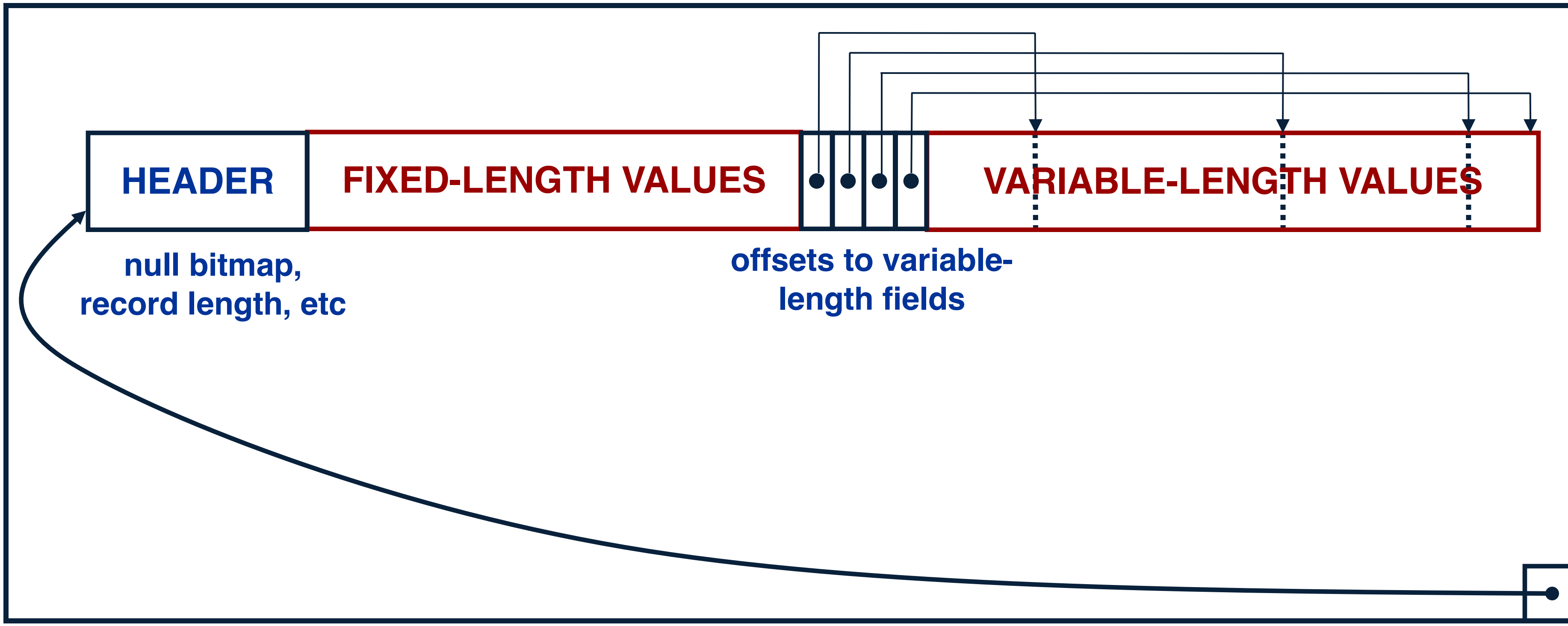


select name
from R
where age > 50

Fewer cache misses, low reconstruction cost

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

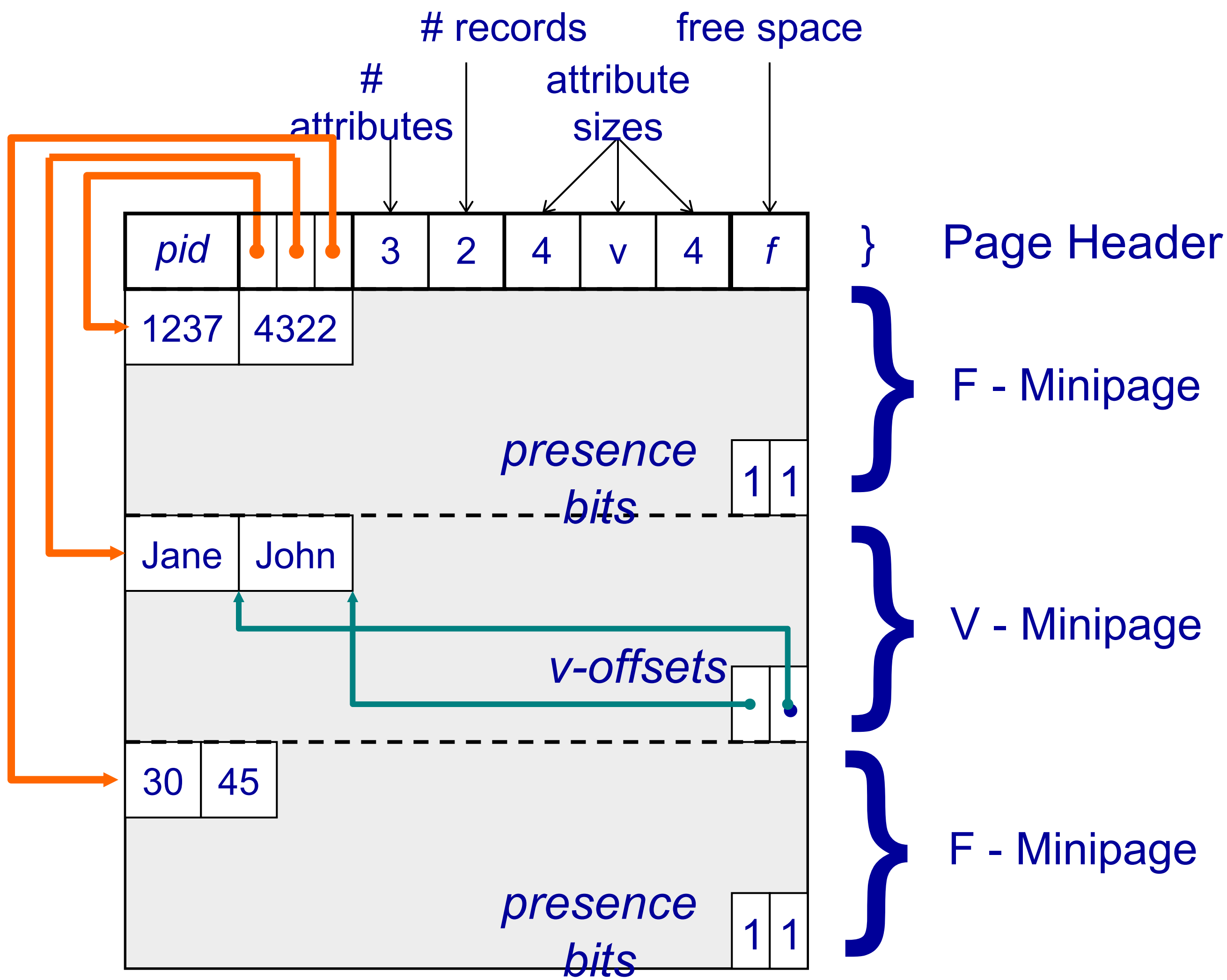
A Real NSM Record



NSM: All fields of record stored together + slots

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

PAX: Detailed Design



PAX: Group fields + amortizes record headers

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

PAX - Summary

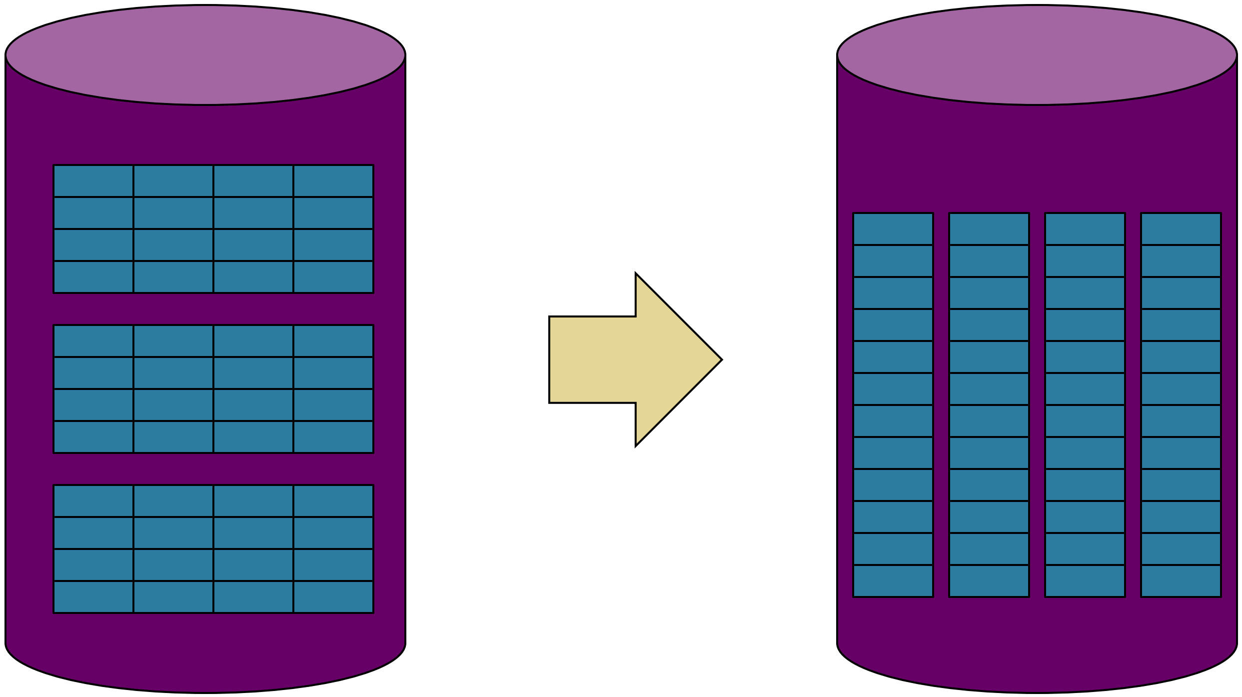
- Improves processor cache locality
- Does not affect I/O behavior
  - Same disk accesses for NSM or PAX storage
  - No need to change the buffer manager

- 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

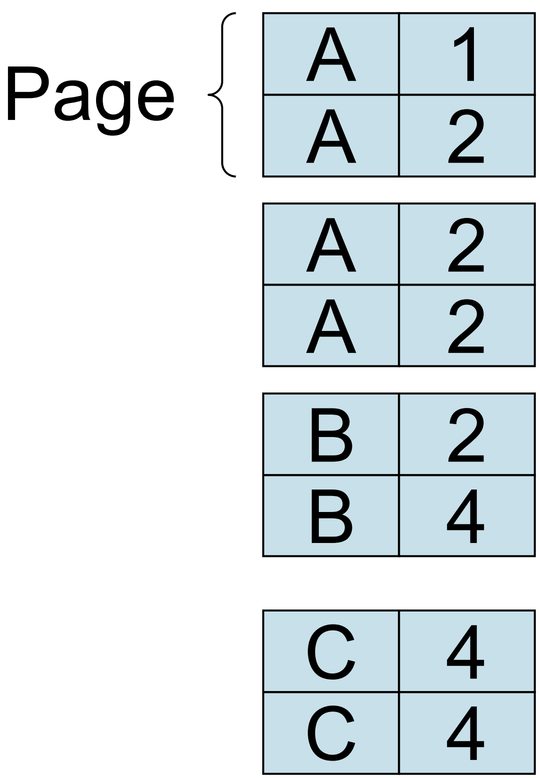
From Row-Store to Column-Store



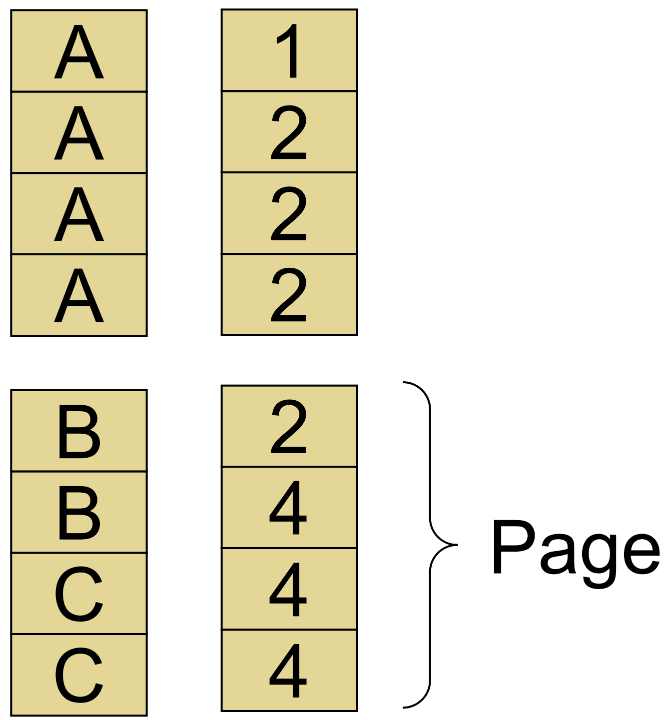
Rows stored contiguously on disk (+ tuple headers)	Columns stored contiguously on disk (no headers needed)

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)

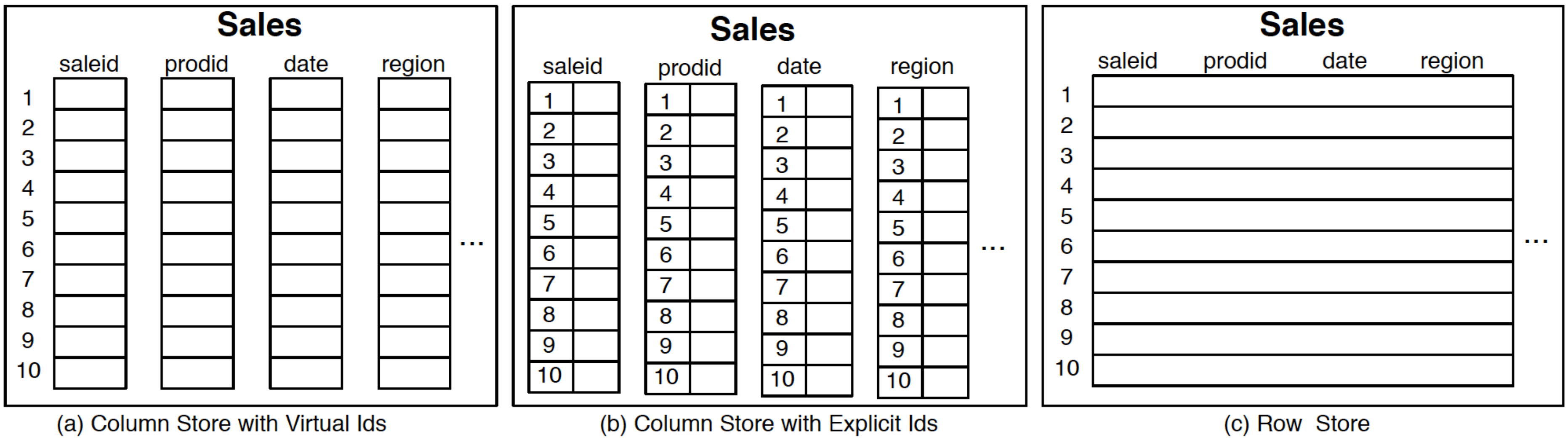


Figure 1.1: Physical layout of column-oriented vs row-oriented databases.

Basic tradeoffs:

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

Fig. 1.2

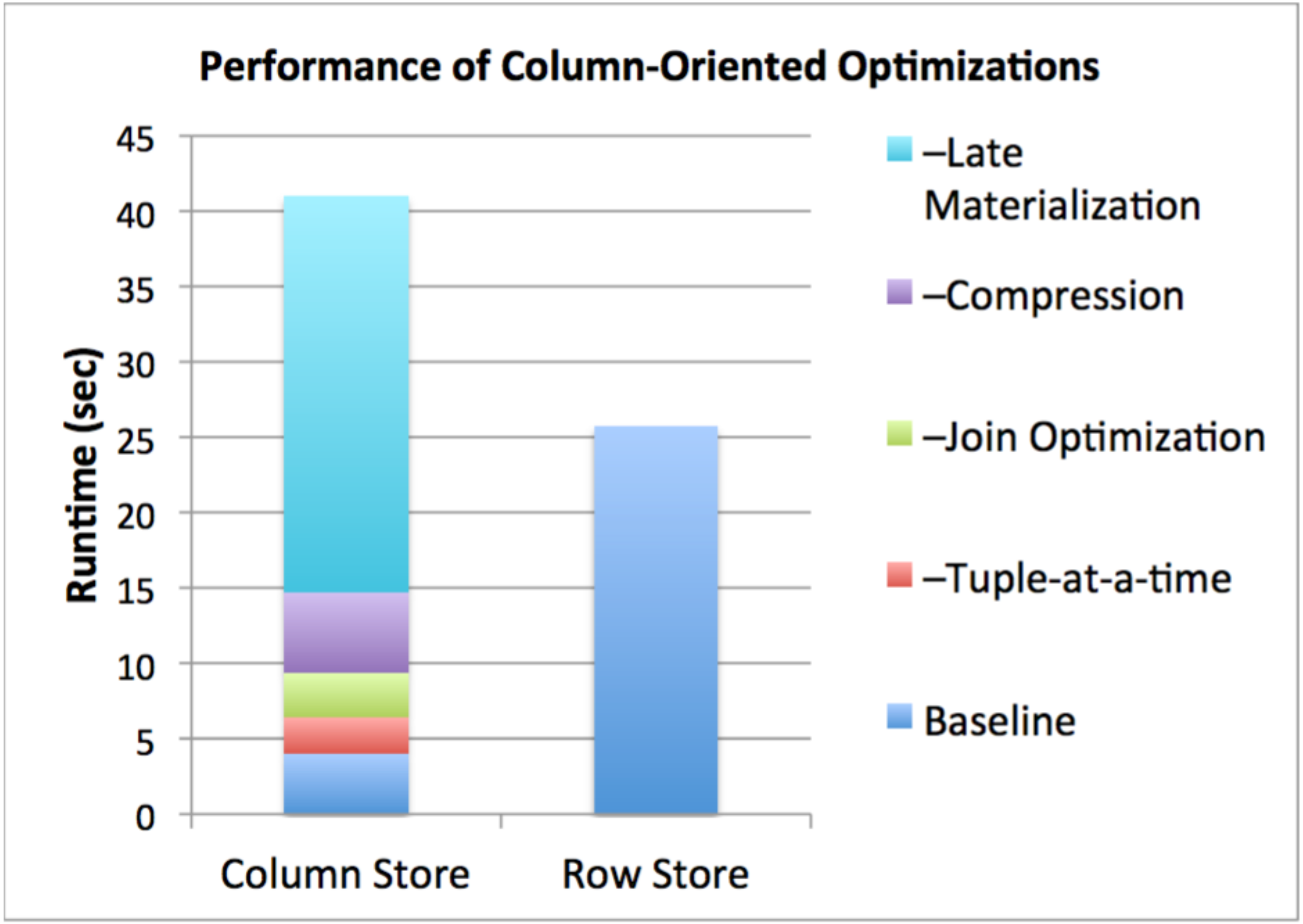


Figure 1.2: Performance of C-Store versus a commercial database system on the SSBM benchmark, with different column-oriented optimizations enabled.

Architectural Changes in C-Store

- We will discuss the remaining slides in a later lecture, after we study the query processor for a row-store

Key Architectural Trends (Sec.1)

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

Key Architectural Trends (Sec.1)

- Virtual IDs
  – Offsets (arrays) instead of keys
- Block-oriented and vertical 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?
- Discuss main column-at-a-time compression techniques

Compression (Sec. 4)

- What is the advantage of compression in databases?

- Discuss 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	1
A	2
A	2
A	2

B	2
B	4
C	4
C	4

Page

Compressed (2 pages)

4XA	1X1
2XB	4X2
2XC	5X4

Late Materialization (Sec. 4)

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

Late Materialization (Sec. 4)

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

Late Materialization (Sec. 4)

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

Late Materialization (Sec. 4)

- What is it?
- Discuss $\Pi_B(\sigma_{A='a' \land D='d'}(R(A,B,C,D,\ldots))$
- Early materialization:
  - Retrieve positions with ‘a’ in column A: 2, 4, 5, 9, 25…
  - Retrieve those values in column D: ‘x’, ‘d’, ‘y’, ‘d’, ‘d’,...
  - Retain only positions with ‘d’: 4, 9, ...

Late Materialization (Sec. 4)

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

Late Materialization (Sec. 4)

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

Late Materialization (Sec. 4)

- What is it?
- Discuss $\Pi_B(\sigma_{A='a' \wedge D='d'}(R(A,B,C,D,\ldots))$
- Early materialization:
  - Retrieve positions with ‘a’ in column A: 2, 4, 5, 9, 25…
  - 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], …
- Late materialization
  - Retrieve positions with ‘a’ in column A: 2, 4, 5, 9, 25…
  - Retrieve positions with ‘d’ in column D: 3, 4, 7, 9,12,..

Late Materialization (Sec. 4)

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

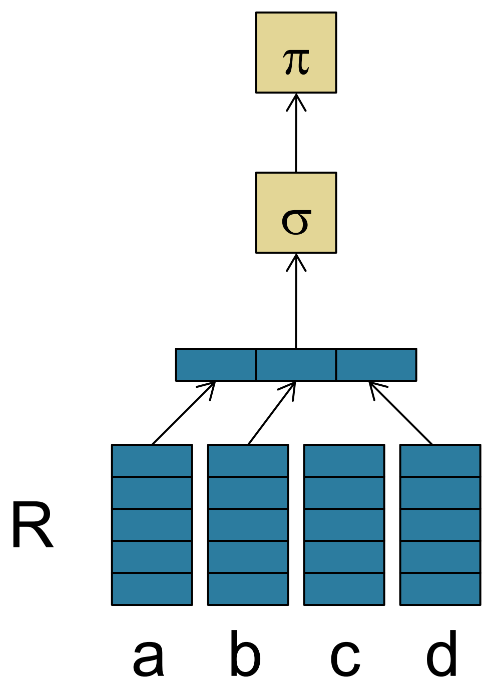
Late Materialization (Sec. 4)

- 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…
  - 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], …
- Late materialization
  - 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], …

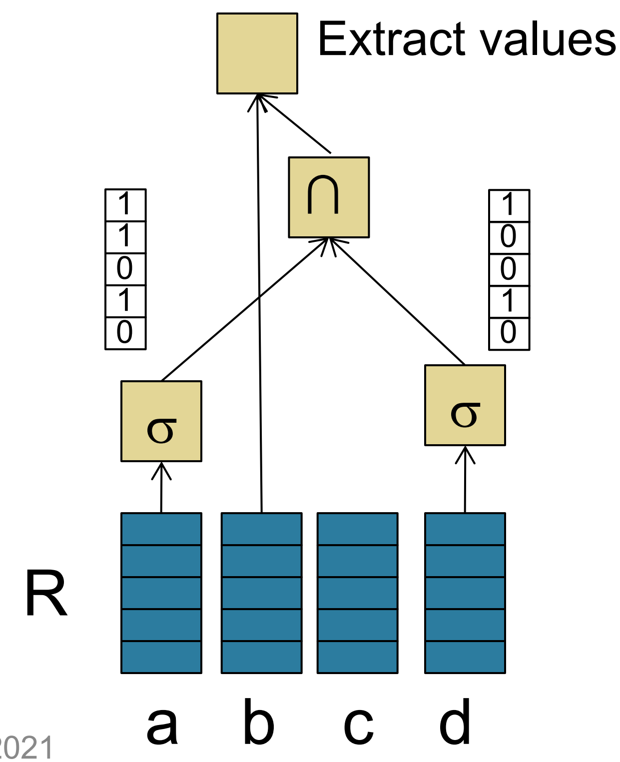
Late Materialization (Sec. 4)

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

Early materialization

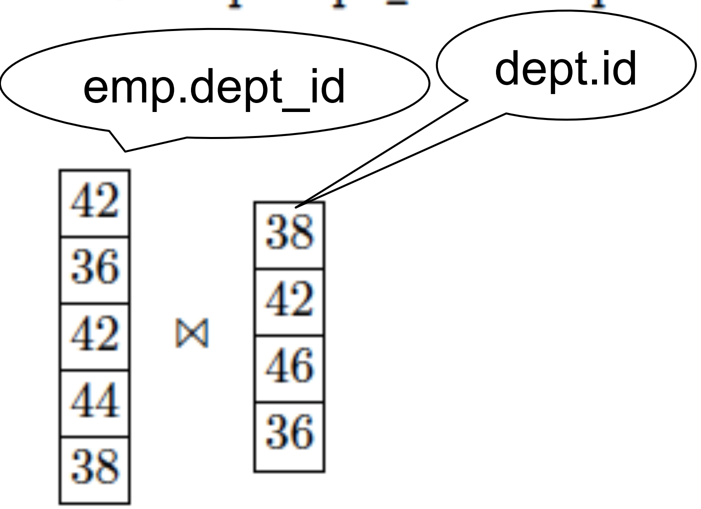


Late materialization



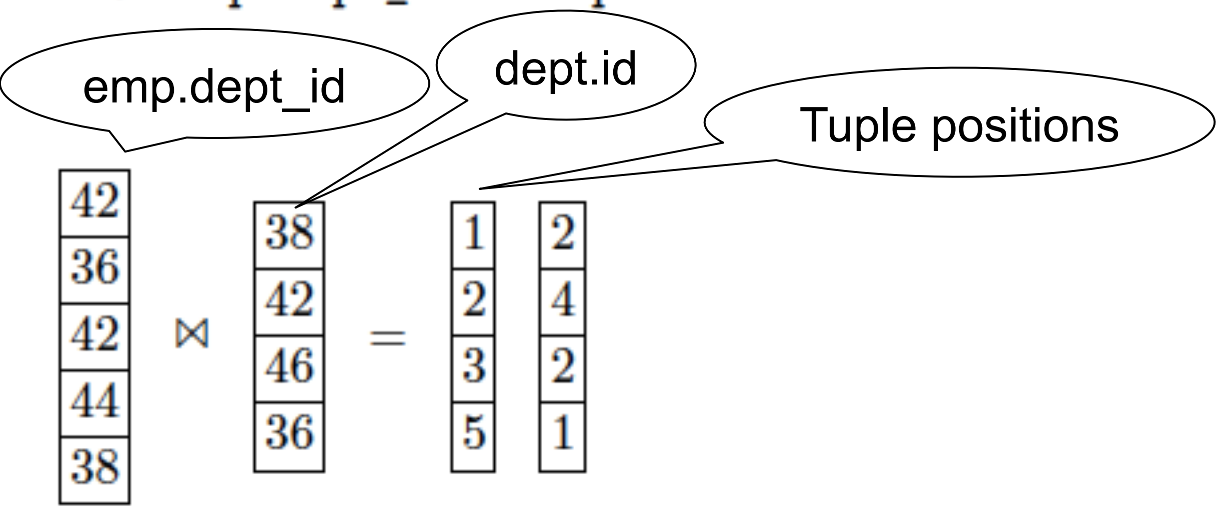
Jive Join (Sec. 4)

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



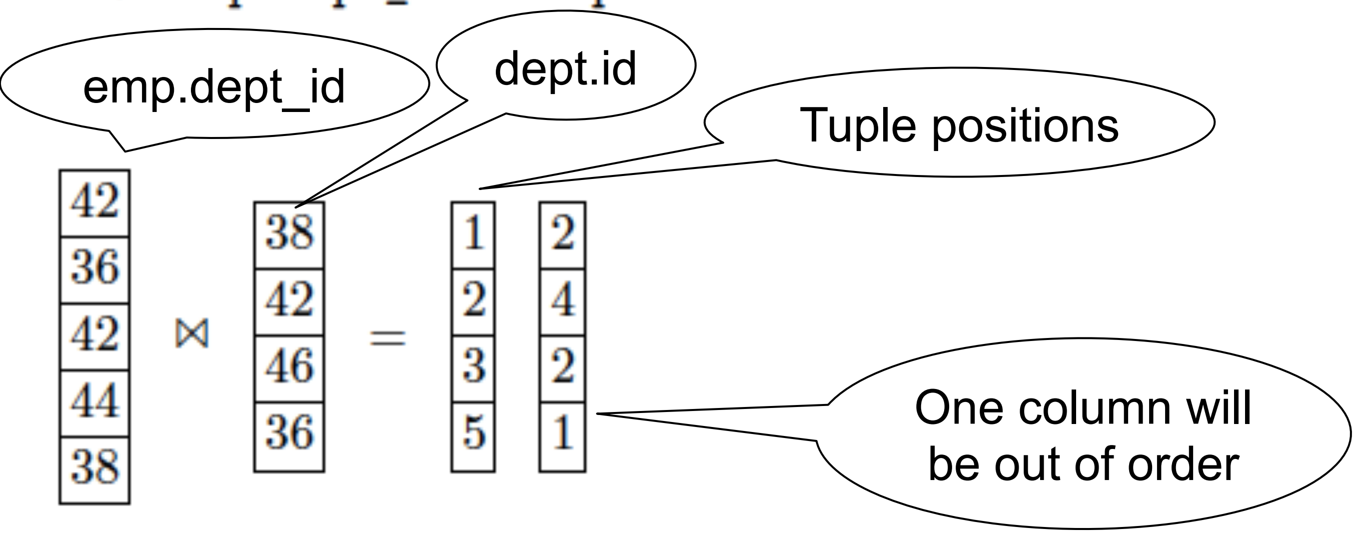
Jive Join (Sec. 4)

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



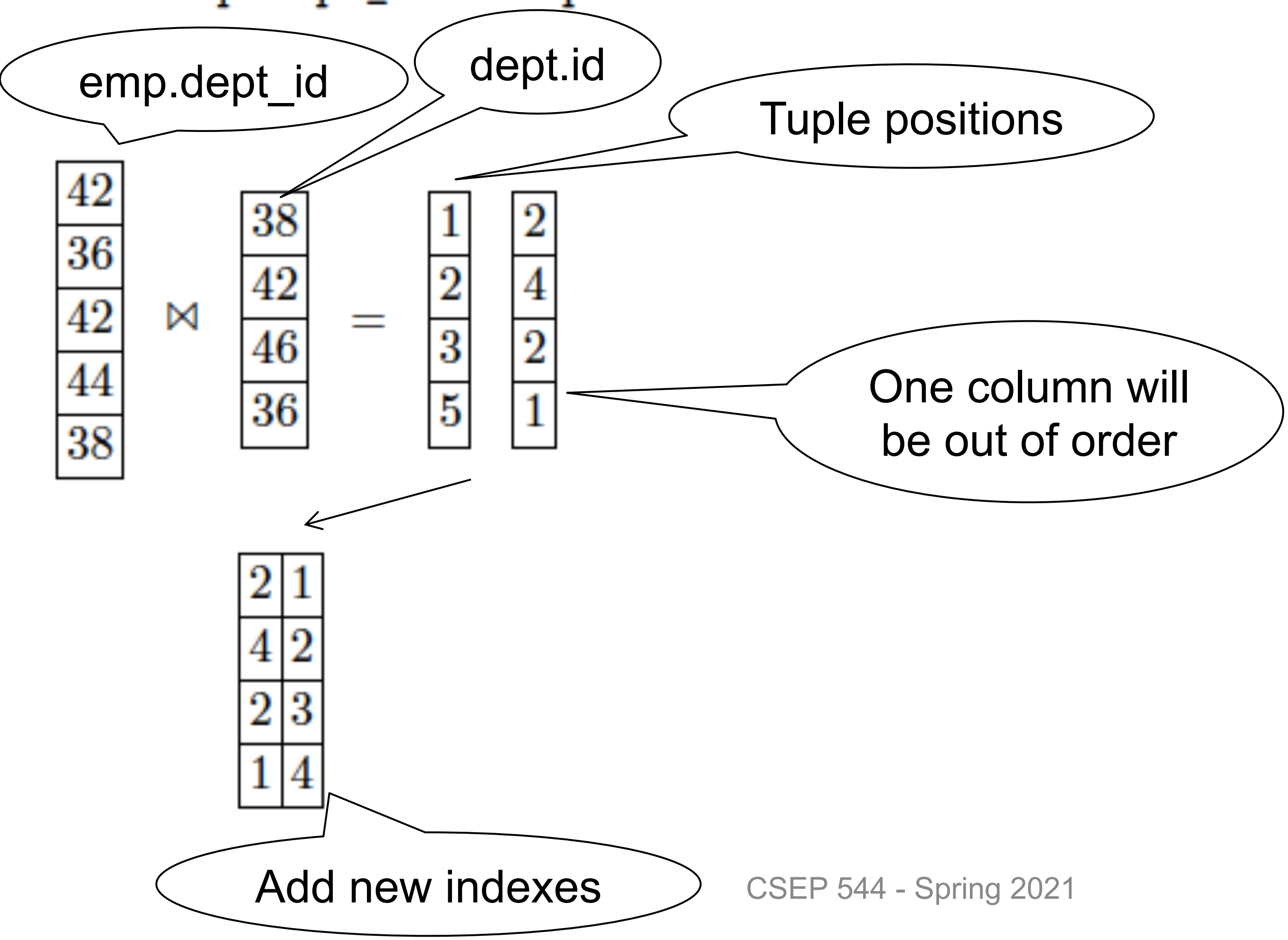
Jive Join (Sec. 4)

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



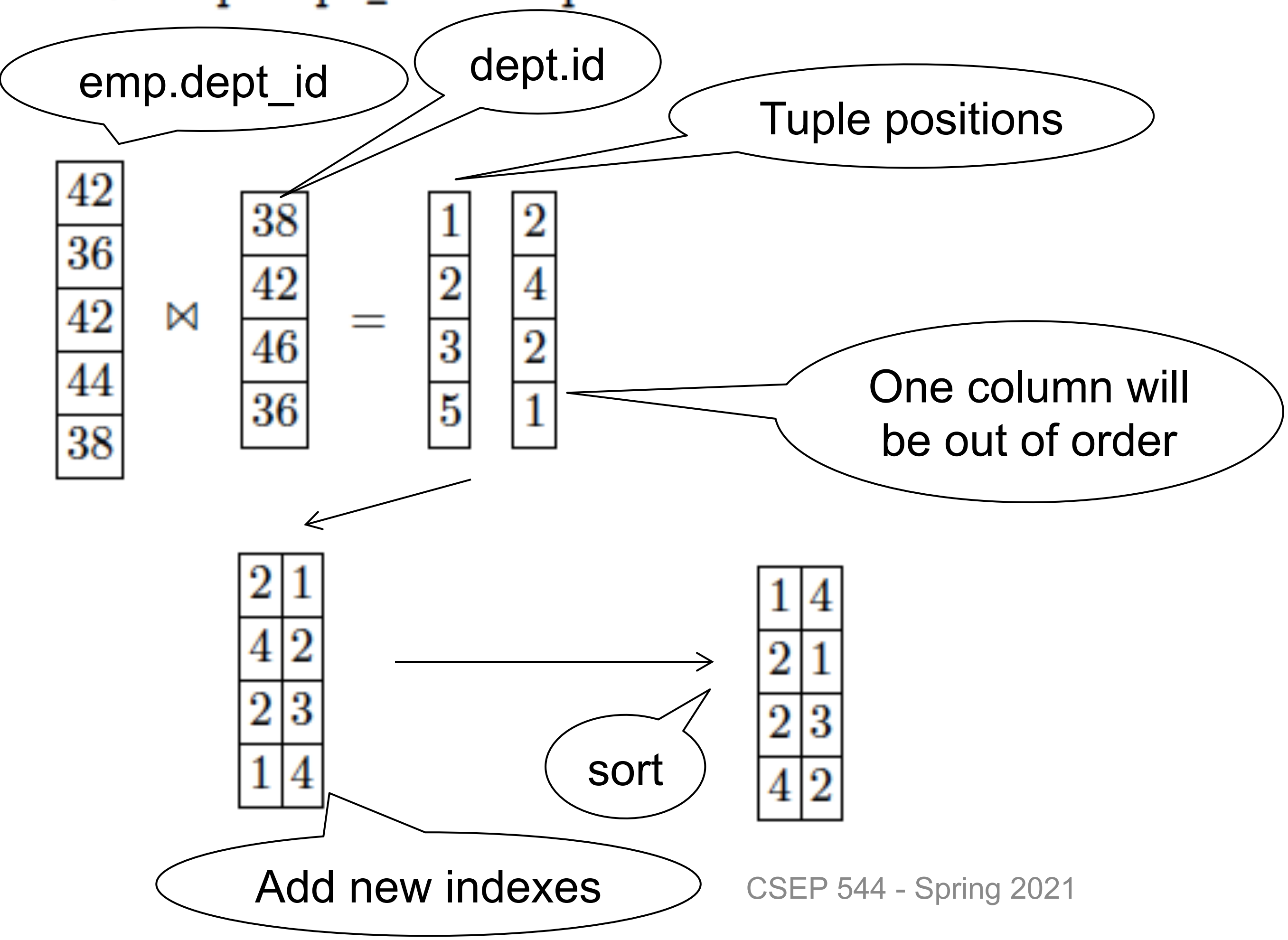
Jive Join (Sec. 4)

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



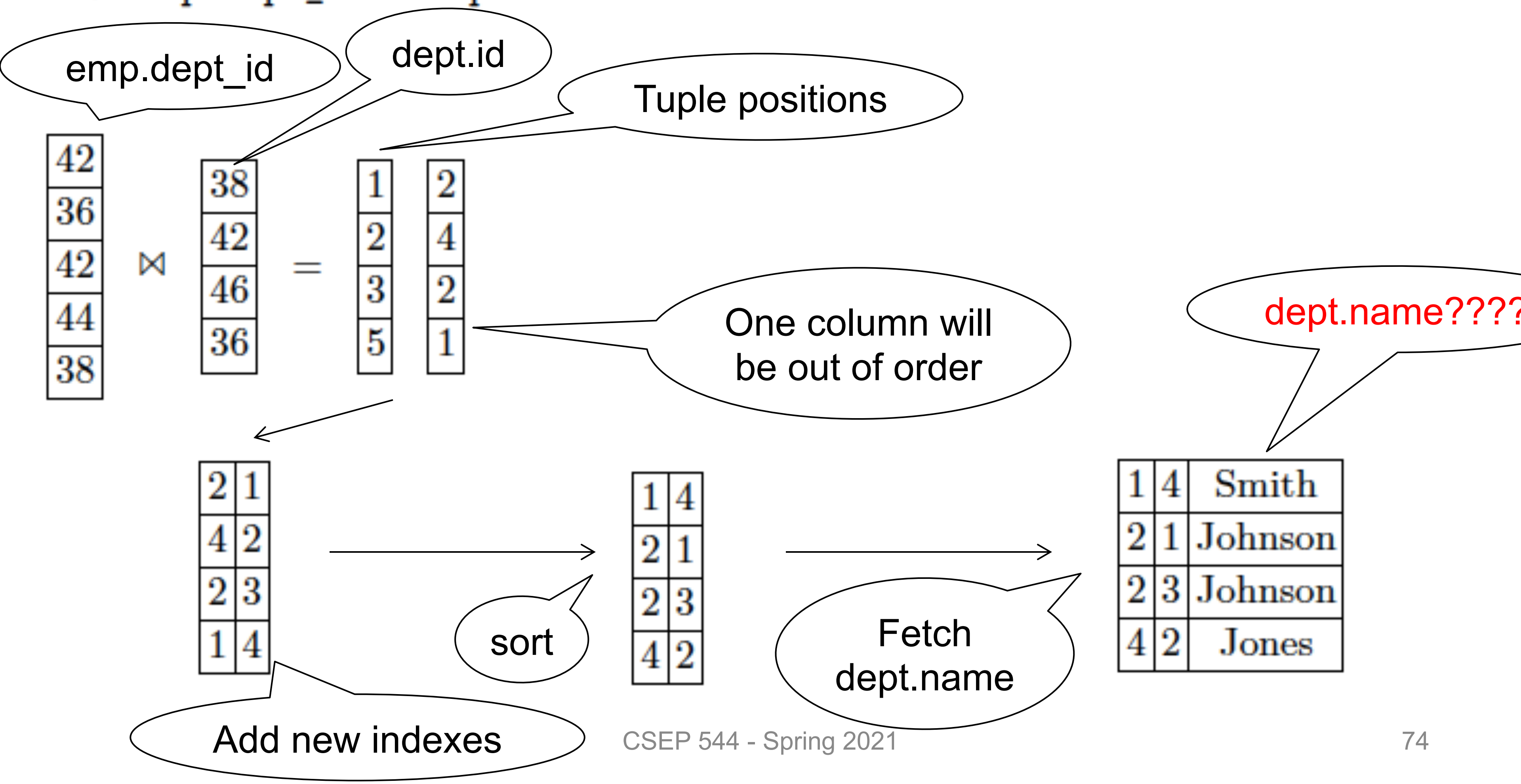
Jive Join (Sec. 4)

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



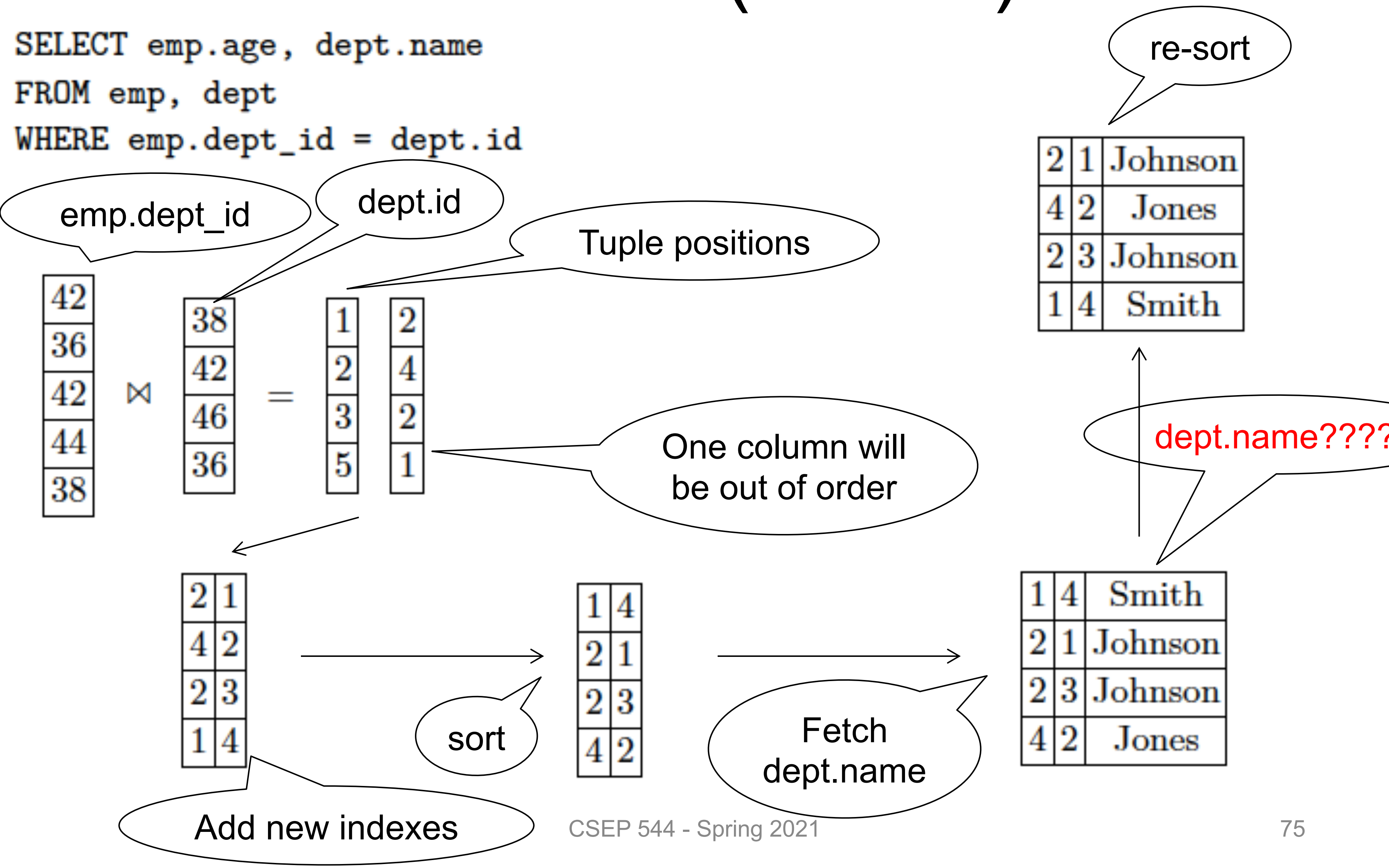
Jive Join (Sec. 4)

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



Jive Join (Sec. 4)

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



Late Materialization

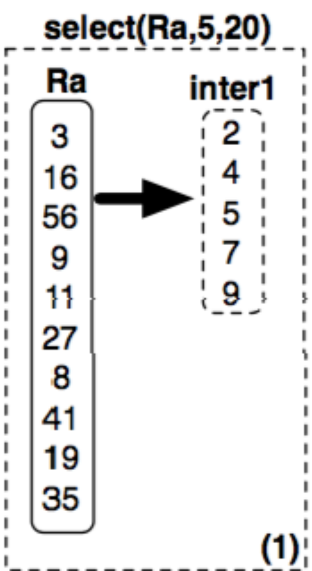
```
select sum(R.a) from R, S
where R.c = S.b
  and 5<R.a<20 and 40<R.b<50
 and 30<S.a<40
```

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

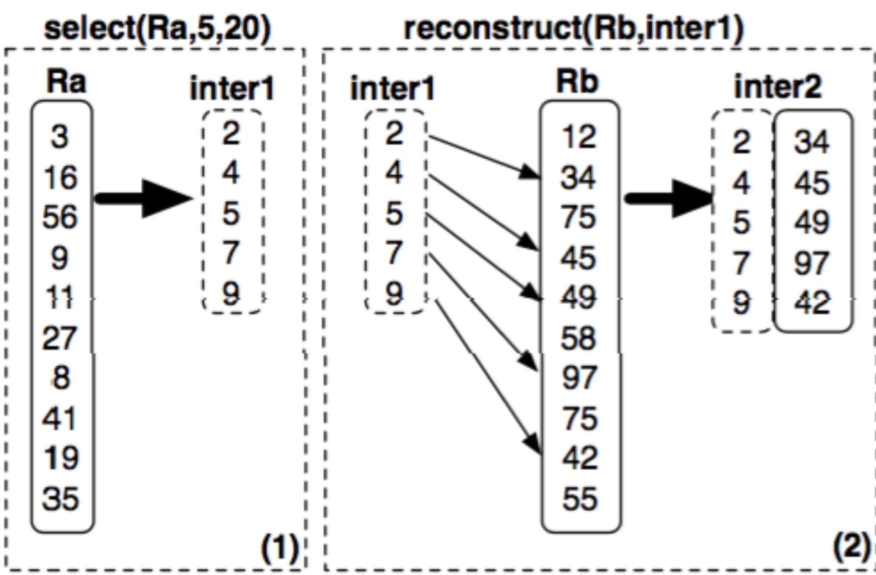
Late Materialization

```
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
```



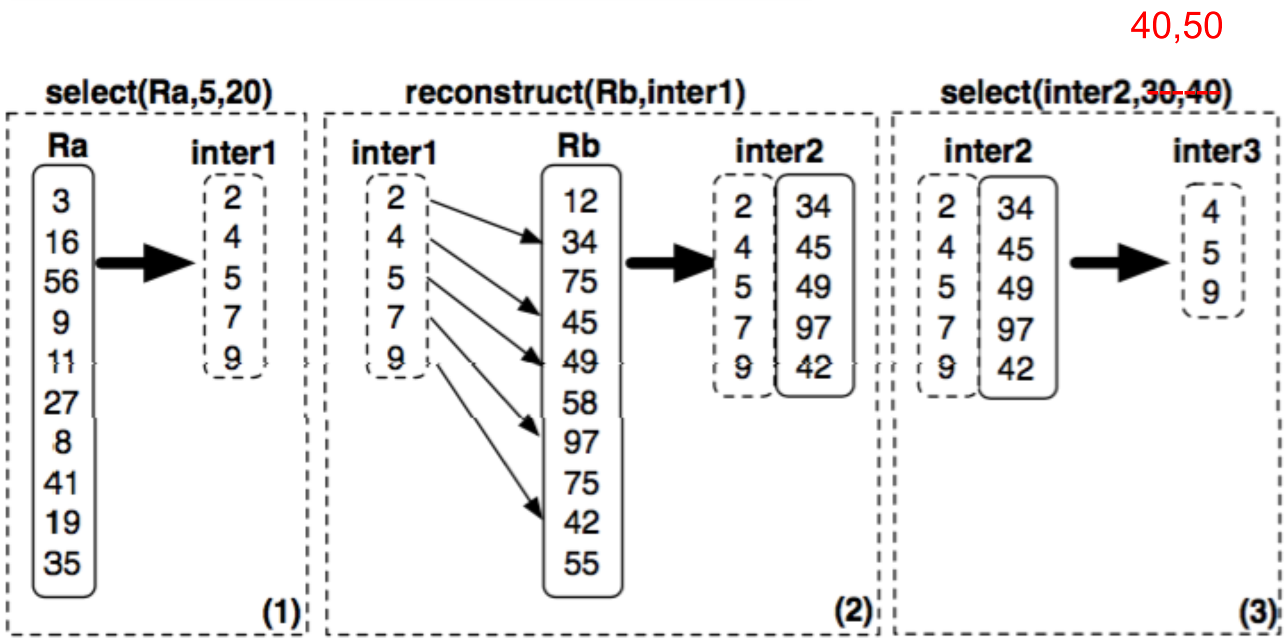
Late Materialization

```
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
```



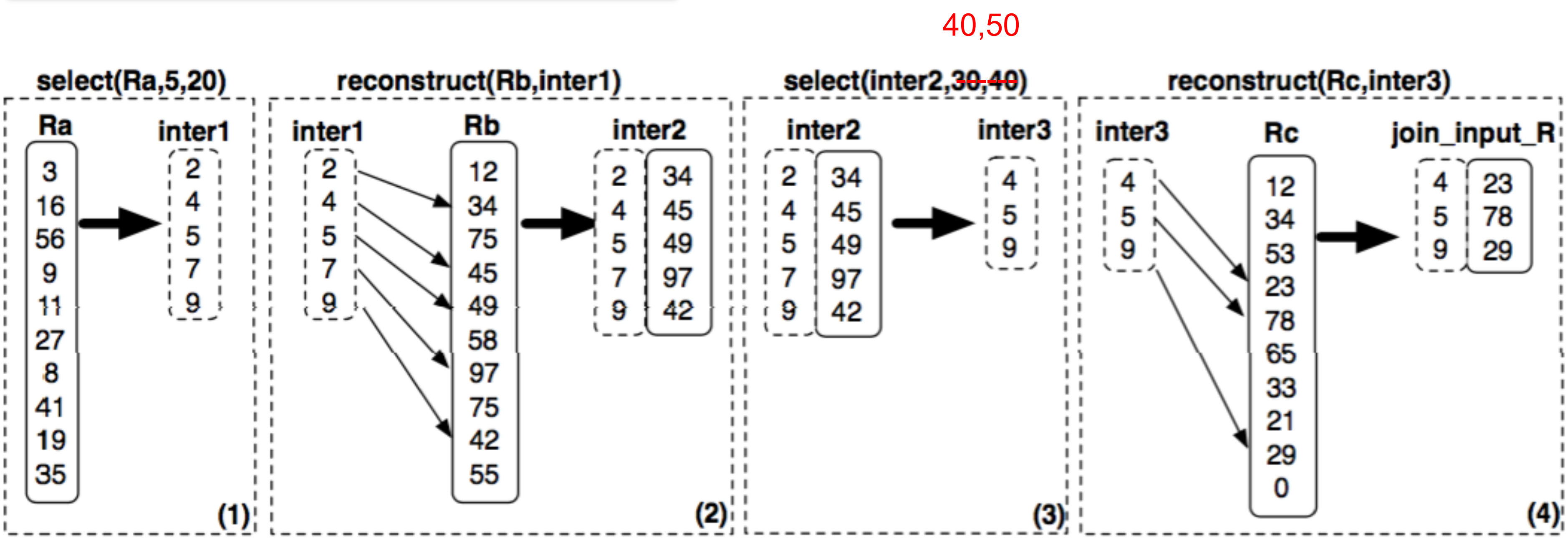
Late Materialization

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



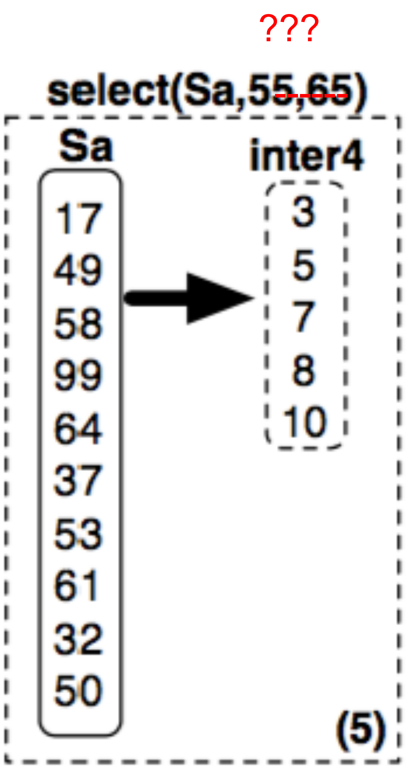
Late Materialization

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



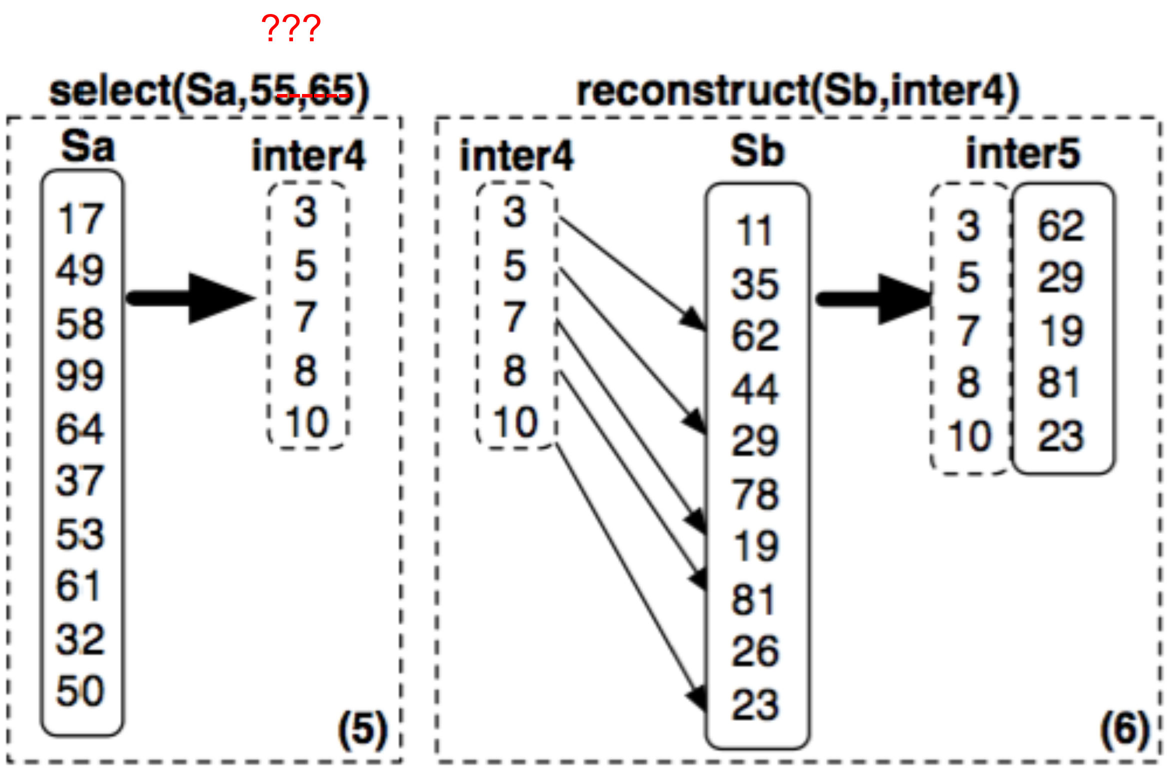
Late Materialization

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



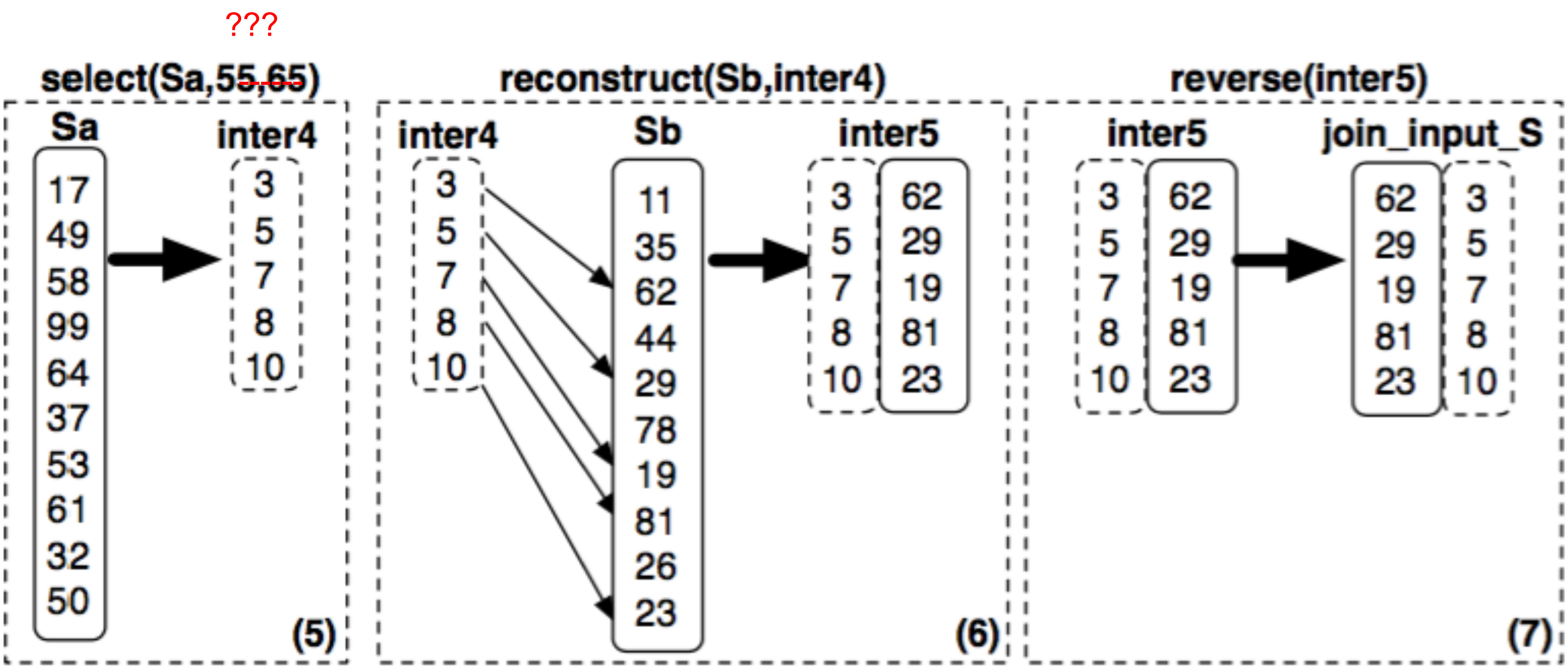
Late Materialization

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



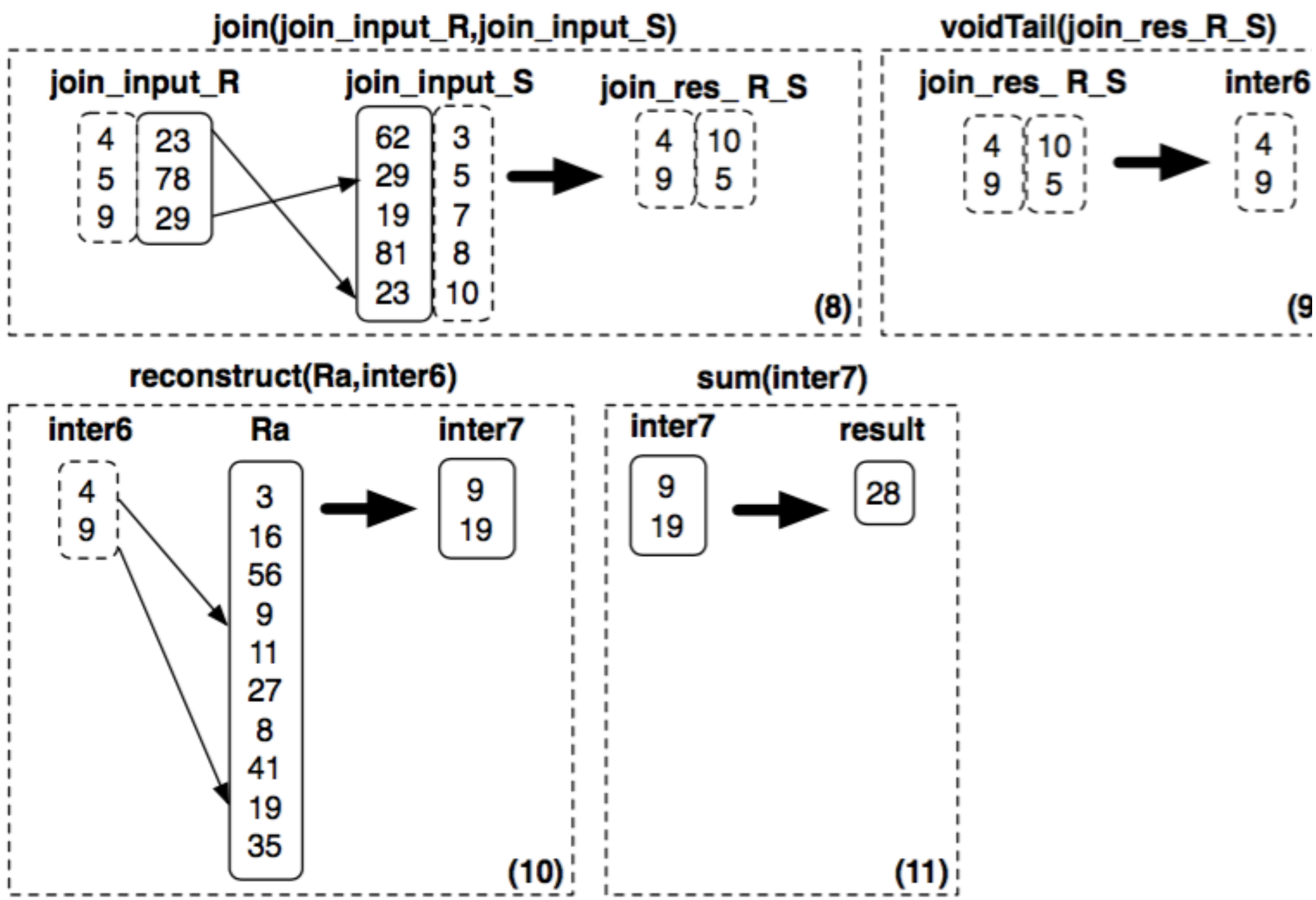
Late Materialization

```
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
```



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



More Details

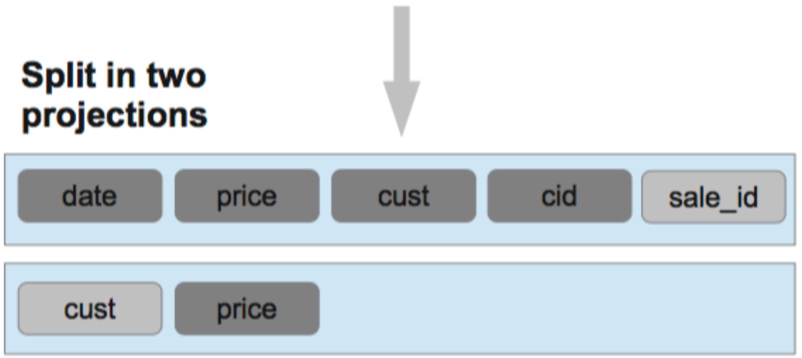
- Sort columns according to some criterion
  - Helps with range queries on that column
  - Helps compressing that column
  - But need to sort all the other columns the same way
- Create additional (redundant) ”views”, called “projections”, by sorting on different columns

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

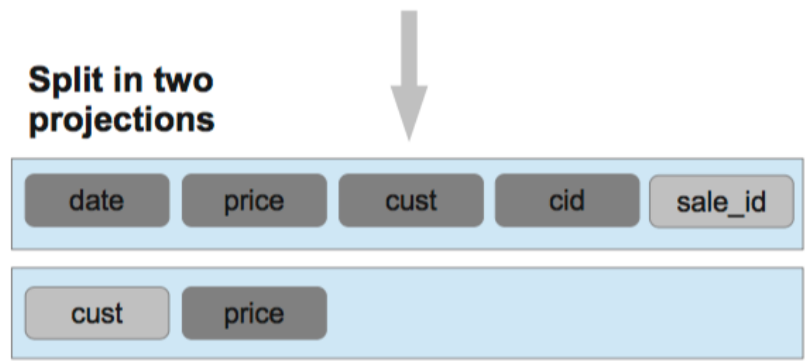
From: The Vertica Analytic Database: CStore 7 Years Later. Lamb et. Al. VLDB'12

Parallel Processing

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

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

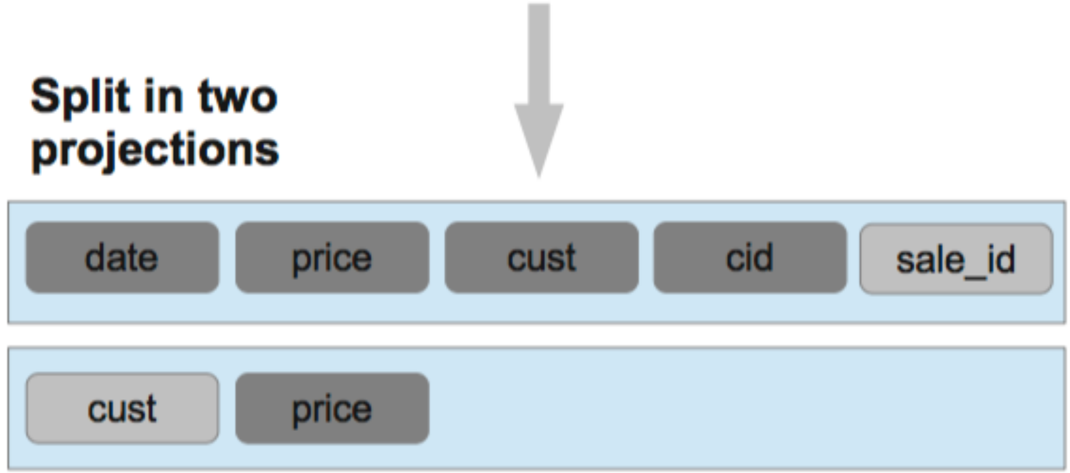


Super projection sorted by date & segmented by hash(sale_id)

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

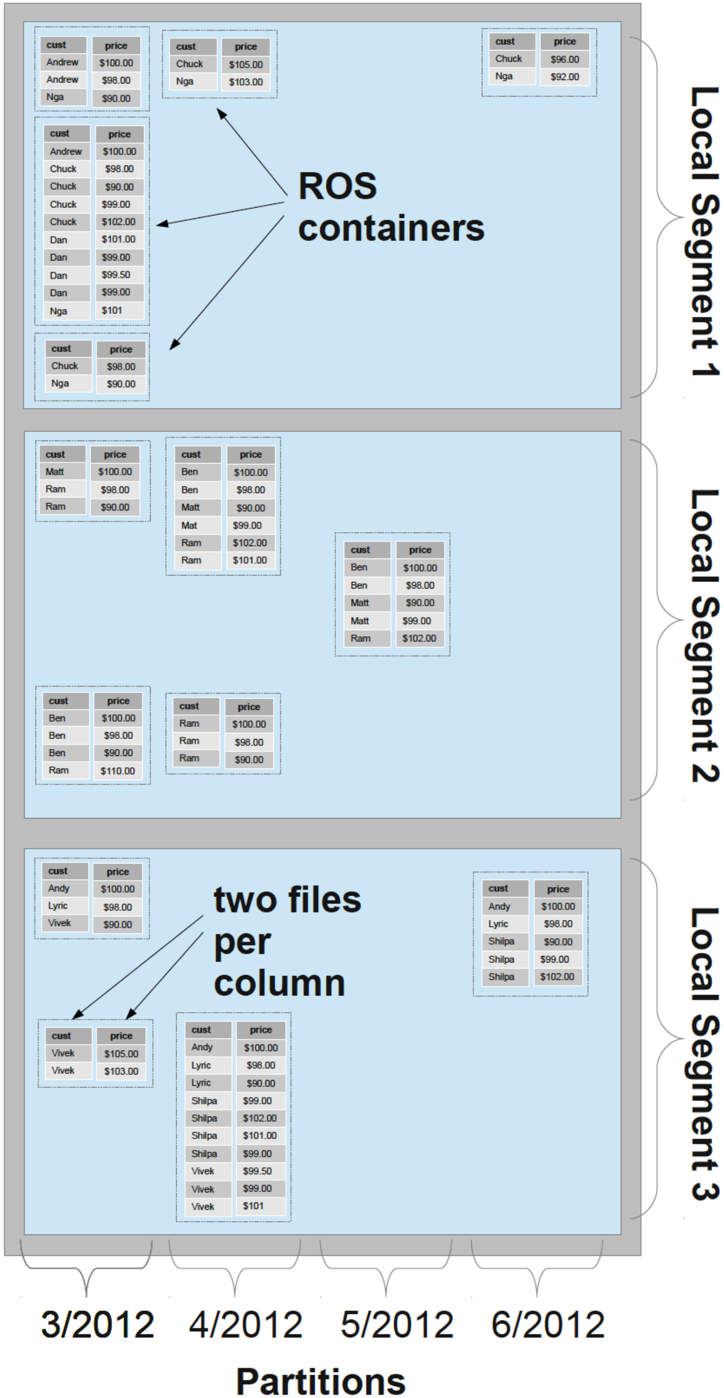
cust	price
Ben	$103.00
Ben	$103.00
Matt	$101.00

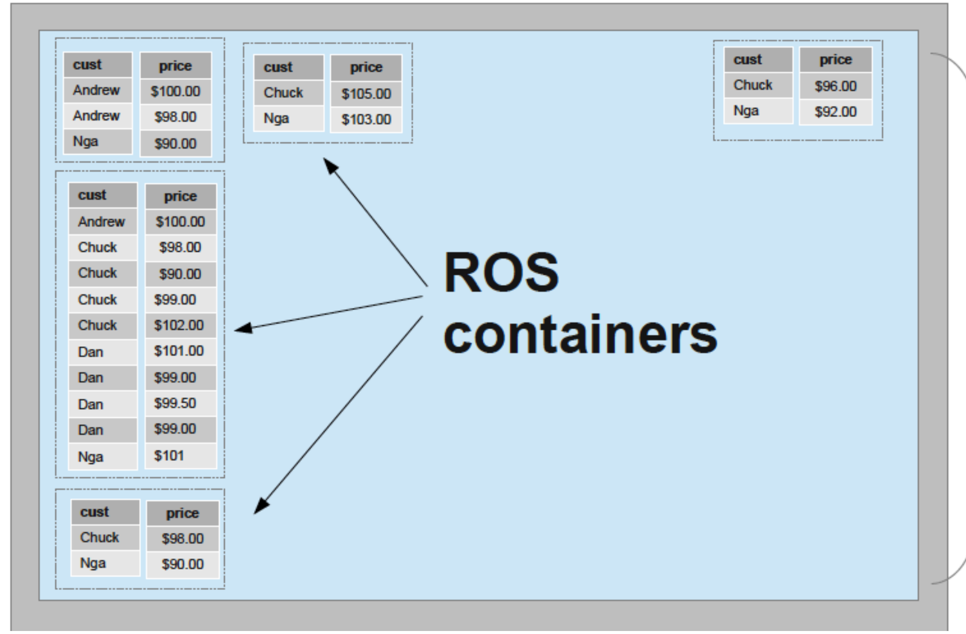
Vertica Data Partitioning

- 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

- C-store proposed intra-node data partitioning
  - Similar to other parallel DBMS such as Teradata
- In contrast, 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

→ Total of 28 files of user data

Updates

- What is the issue?

- 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

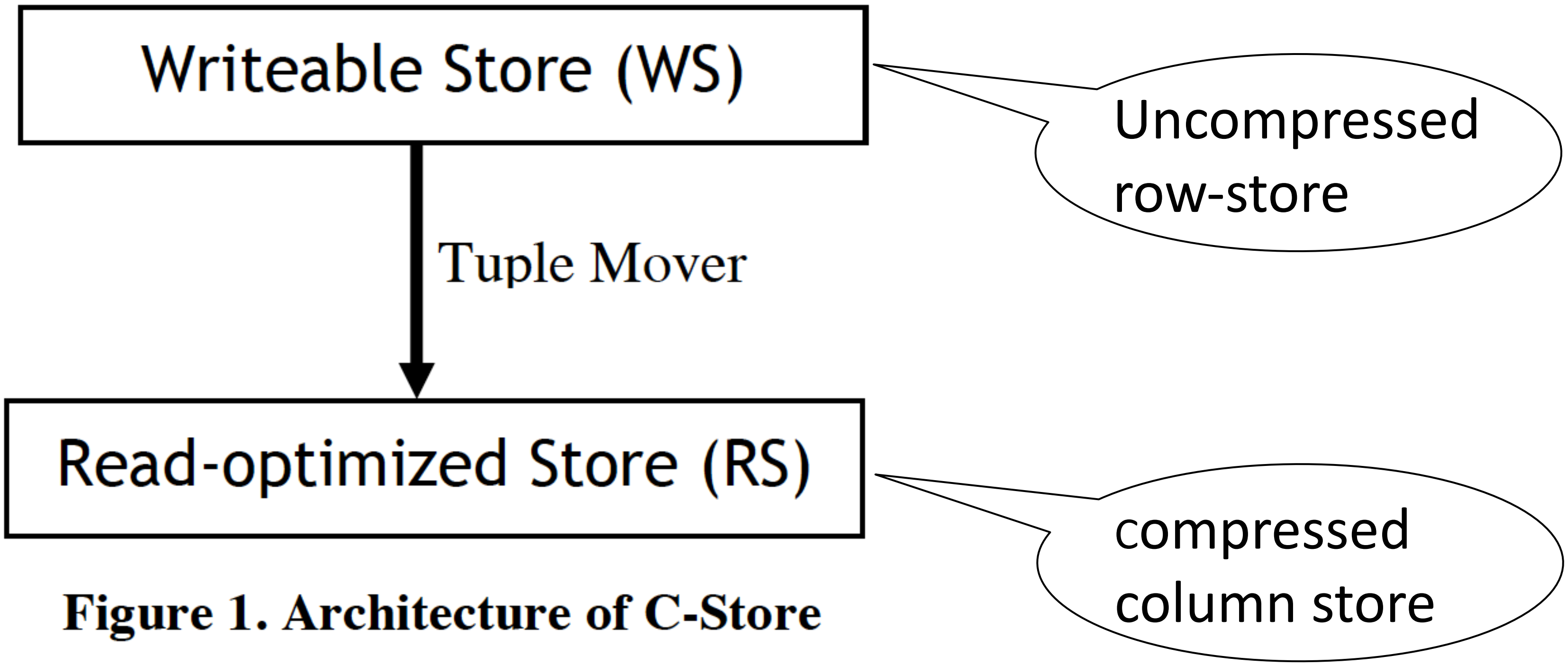


Figure 1. Architecture of C-Store

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