

# Database System Internals

## Data Storage and (more) Buffer Management

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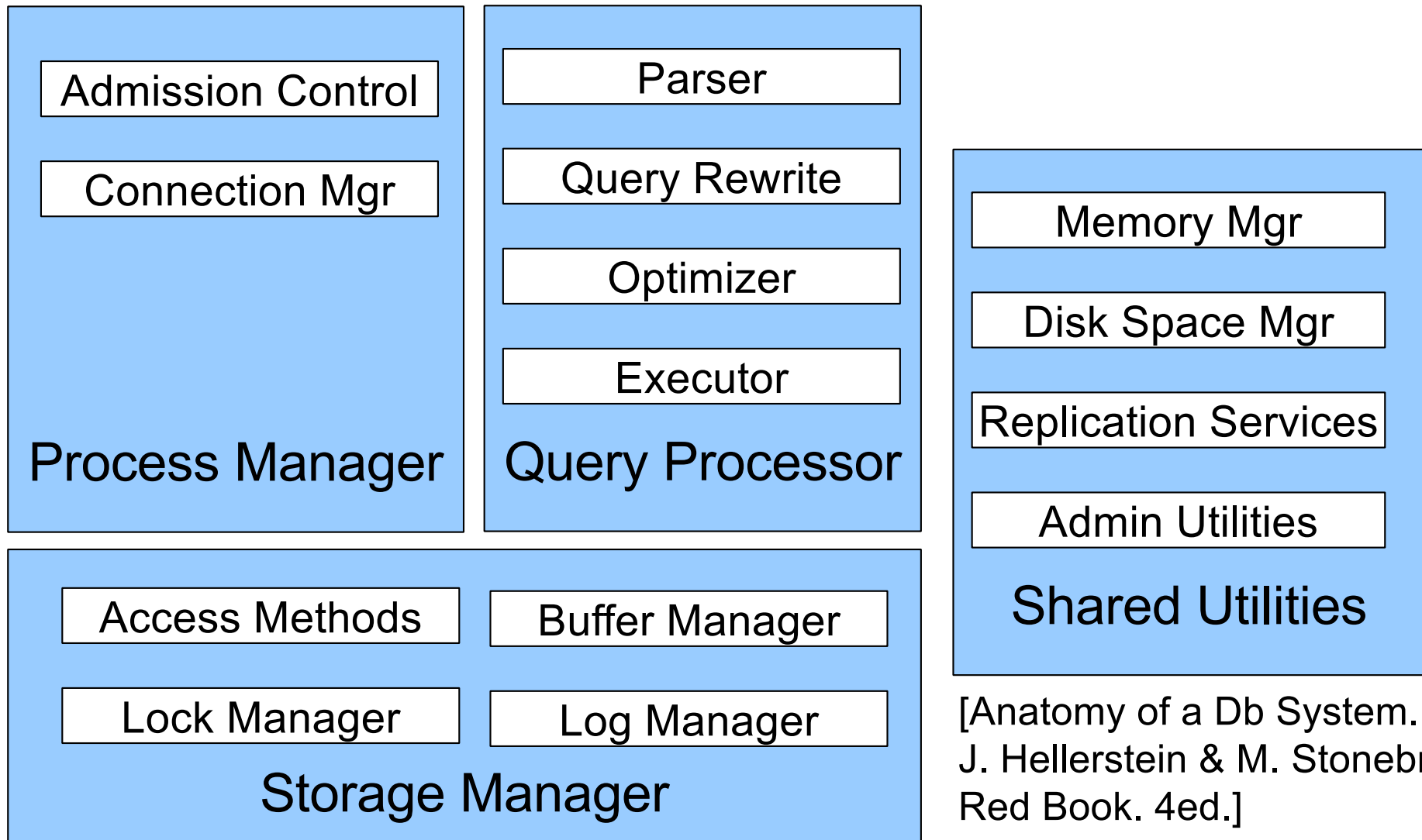
# Announcements

- Lab 1 part 1 is due Wednesday at 11pm
  - Don't worry about passing exact tests and implementing everything as completely as possible for intermediate stage
  - We are not grading according to tests-passed for part 1, just that the functions asked for are complete.
- Homework 1:
  - Due Friday at 11pm

# Important Note

- Lectures show principles
- Homeworks + Quizzes test the principles
- You need to think through what you will actually implement in SimpleDB!
  - Try to implement the simplest solutions
- If you are confused, tell us!
  - Thursday section this week will be extra lab help, Q/A office hours style
- SimpleDB not designed to be bullet-proof software

# DBMS Architecture



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

The diagram illustrates the layers of a database system. It consists of four main components arranged vertically. The top component is a light blue rectangle containing a white box with the text 'Operators: Sequential Scan, etc.' and the text 'Query Processor' below it. The second component is a larger light blue rectangle containing a white box with 'Access Methods: HeapFile, etc.', a smaller white box with 'Buffer Manager' below it, and the text 'Storage Manager' at the bottom. The third component is a smaller light blue rectangle containing a white box with 'Disk Space Mgr'. The bottom component is a white cylinder with 'Data on disk' written inside. All components are centered horizontally.

Operators: Sequential Scan, etc.  
Query Processor

Access Methods: HeapFile, etc.  
Buffer Manager  
Storage Manager

Disk Space Mgr

Data on disk

# Today: Starting at the Bottom

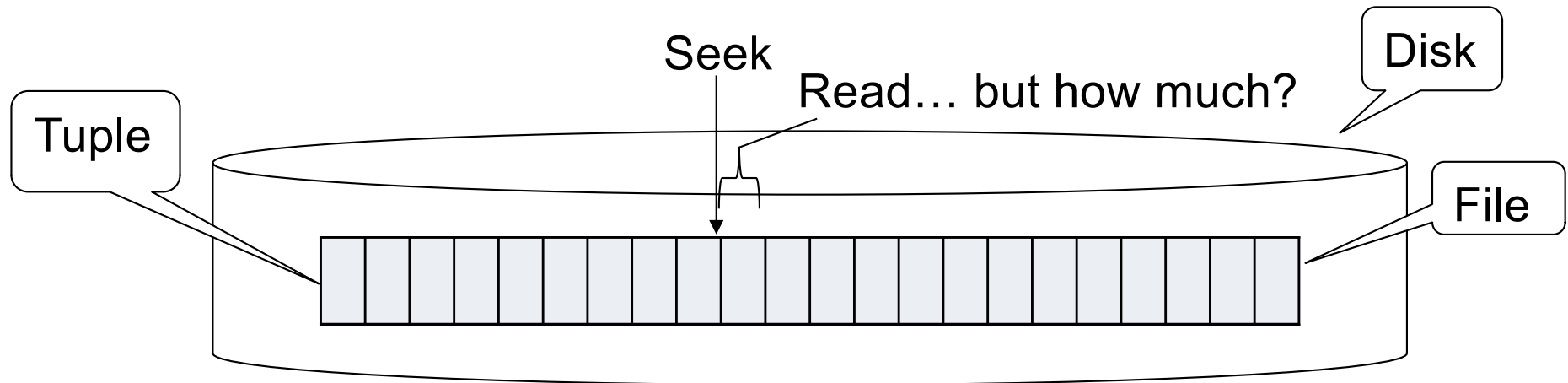
**Consider a relation storing tweets:**

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

**How should we store it on disk?**

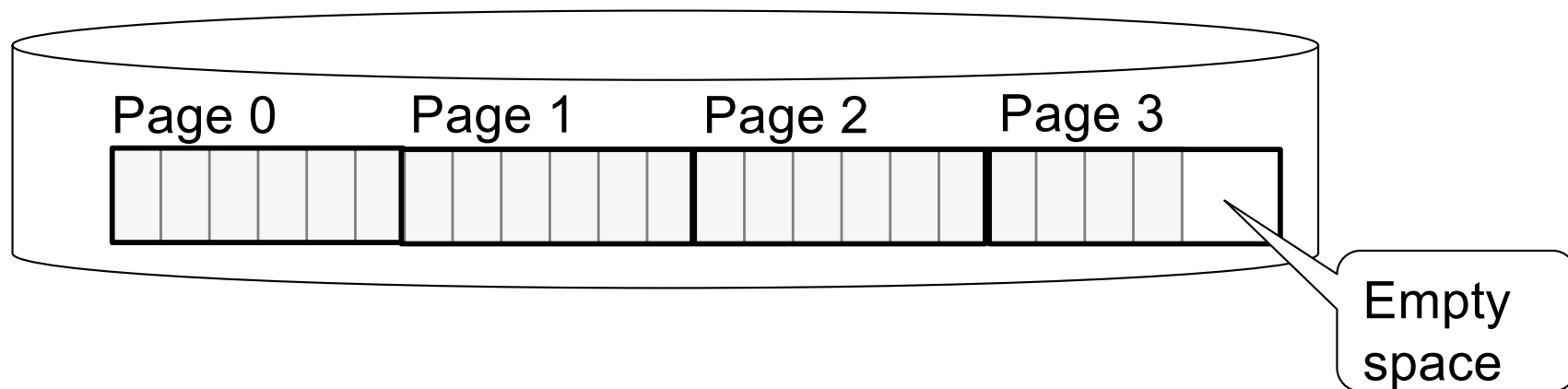
# Design Exercise

- One design choice: **One OS file for each relation**
  - This does not always have to be the case! (e.g., SQLite uses one file for whole database)
  - DBMSs can also use disk drives directly
- An OS file provides an API of the form
  - Seek to some position (or “skip” over B bytes)
  - Read/Write B bytes



# First Principle: Work with Pages

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





# Continuing our Design

Key questions:

- How do we organize pages into a file?
- How do we organize data within a page?

First, **how could we store some tuples on a page?**

Let's first assume all tuples are of the same size:

```
Tweets(tid int, user char(10),  
        time int, content char(140))
```

# Page Formats

## Issues to consider

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

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

See future discussion on indexes and transactions

# Page Formats

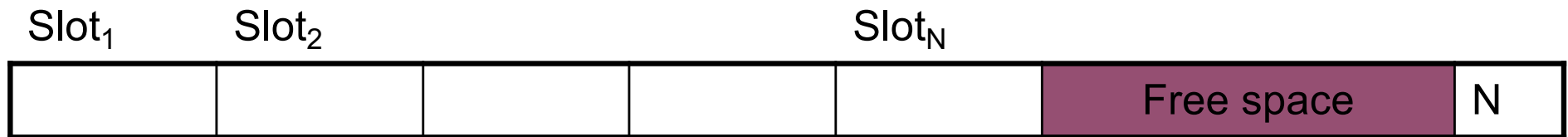
- Think how you would store tuples on a page
  - Fixed length tuples
  - Variable length tuples
- Compare your solution with your neighbor's

# 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?

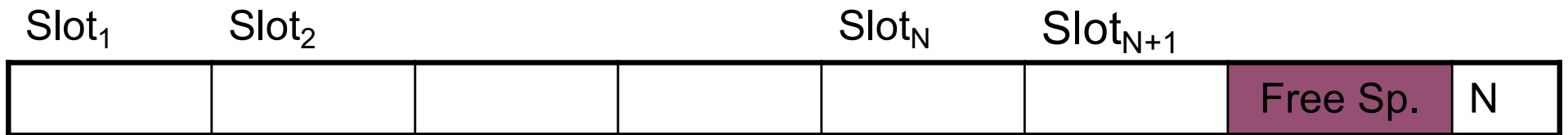
Number of records

# Page Format Approach 1

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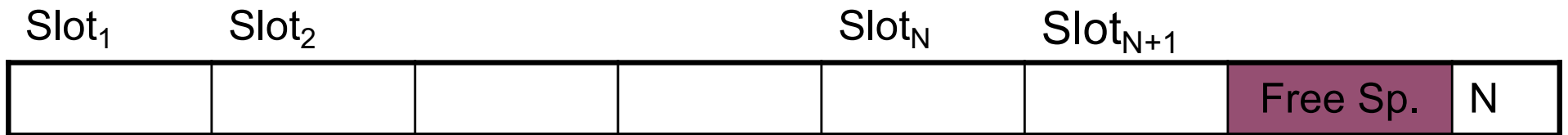
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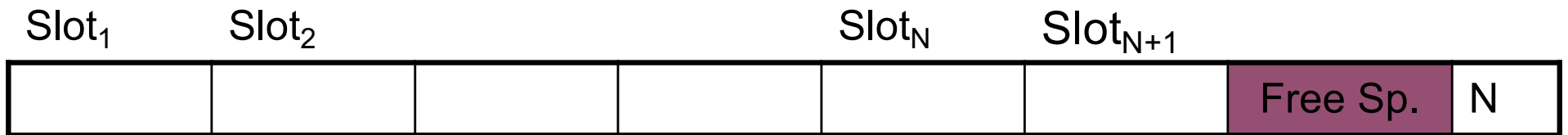
How do we delete a record?

# Page Format Approach 1

Fixed-length records: packed representation

Divide page into slots. Each slot can hold one tuple

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



How do we insert a new record?

Number of records

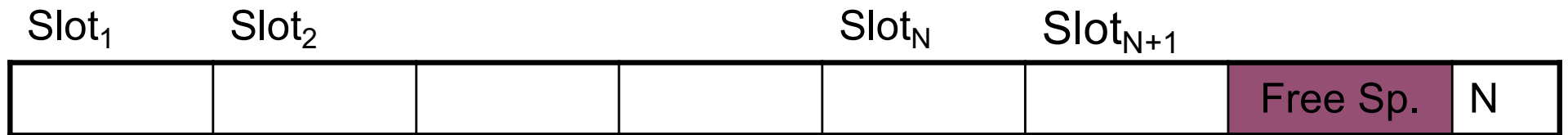
How do we delete a record? What is the problem?

# 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?

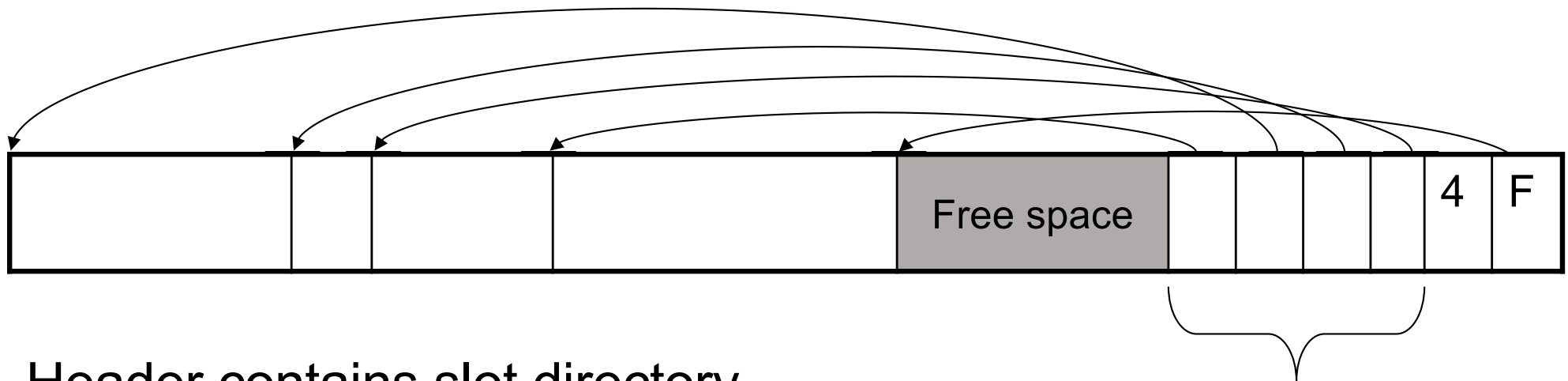
Number of records

How do we delete a record? Cannot move records! (Why?)

How do we handle variable-length records?



# Page Format Approach 2



Header contains slot directory

- + Need to keep track of # of slots

- + Also need to keep track of free space pointer (F)

Slot directory

Each slot contains  
<record offset, record length>

Can handle variable-length records

Can move tuples inside a page without changing RIDs

RID is (PageID, SlotID) combination

# Record Formats

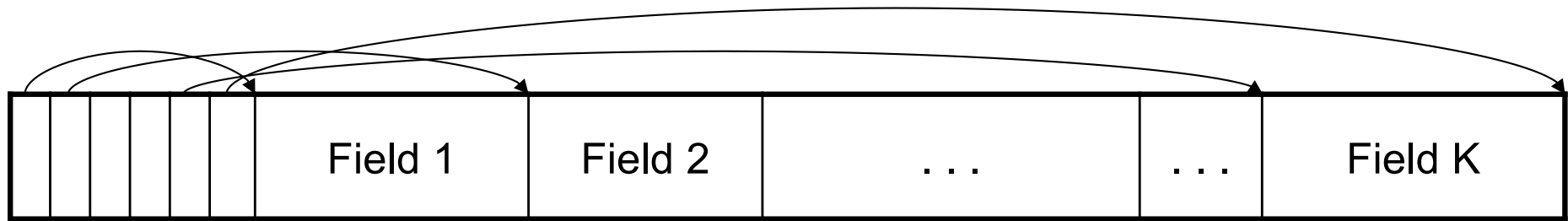
Fixed-length records => Each field has a fixed length  
(i.e., it has the same length in all the records)

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

Information about field lengths and types is in the catalog

# Record Formats

Variable length records



Record header

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

- Large objects
  - Binary large object: BLOB
  - Character large object: CLOB
- Supported by modern database systems
- E.g. images, sounds, texts, etc.
- Storage: attempt to cluster blocks together

# Continuing our Design

Our key questions:

- How do we organize pages into a file?
- How do we organize data within a page?

Now, **how should we group pages into files?**

# Heap File Implementation 1

A sequence of pages (implementation in SimpleDB)

Data page	Data page	Data page	Data page	Data page	Data page	Data page	Data page
--------------	--------------	--------------	--------------	--------------	--------------	--------------	--------------

Some pages have space and other pages are full

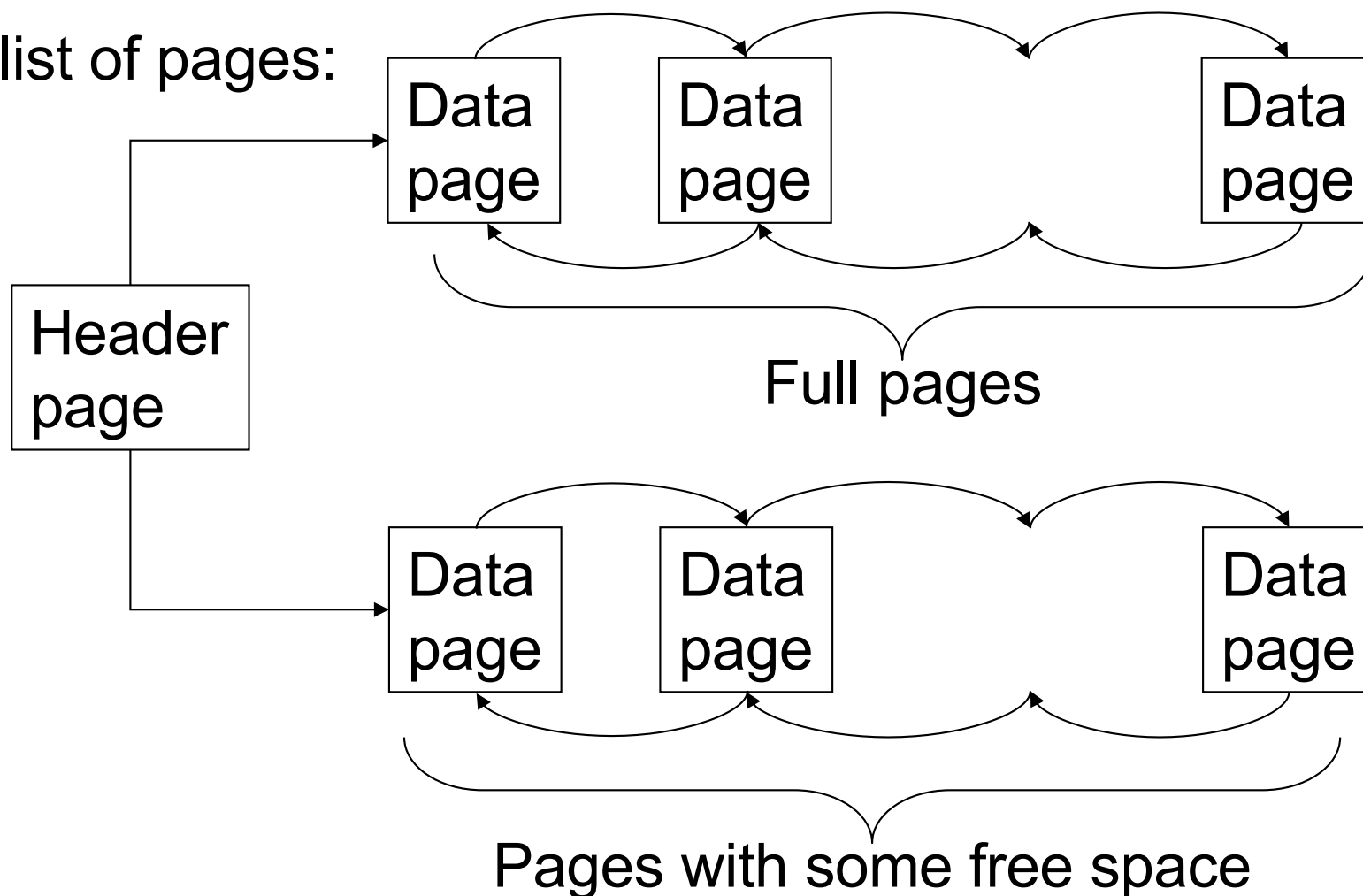
Add pages at the end when need more space

Works well for small files

But finding free space requires scanning the file...

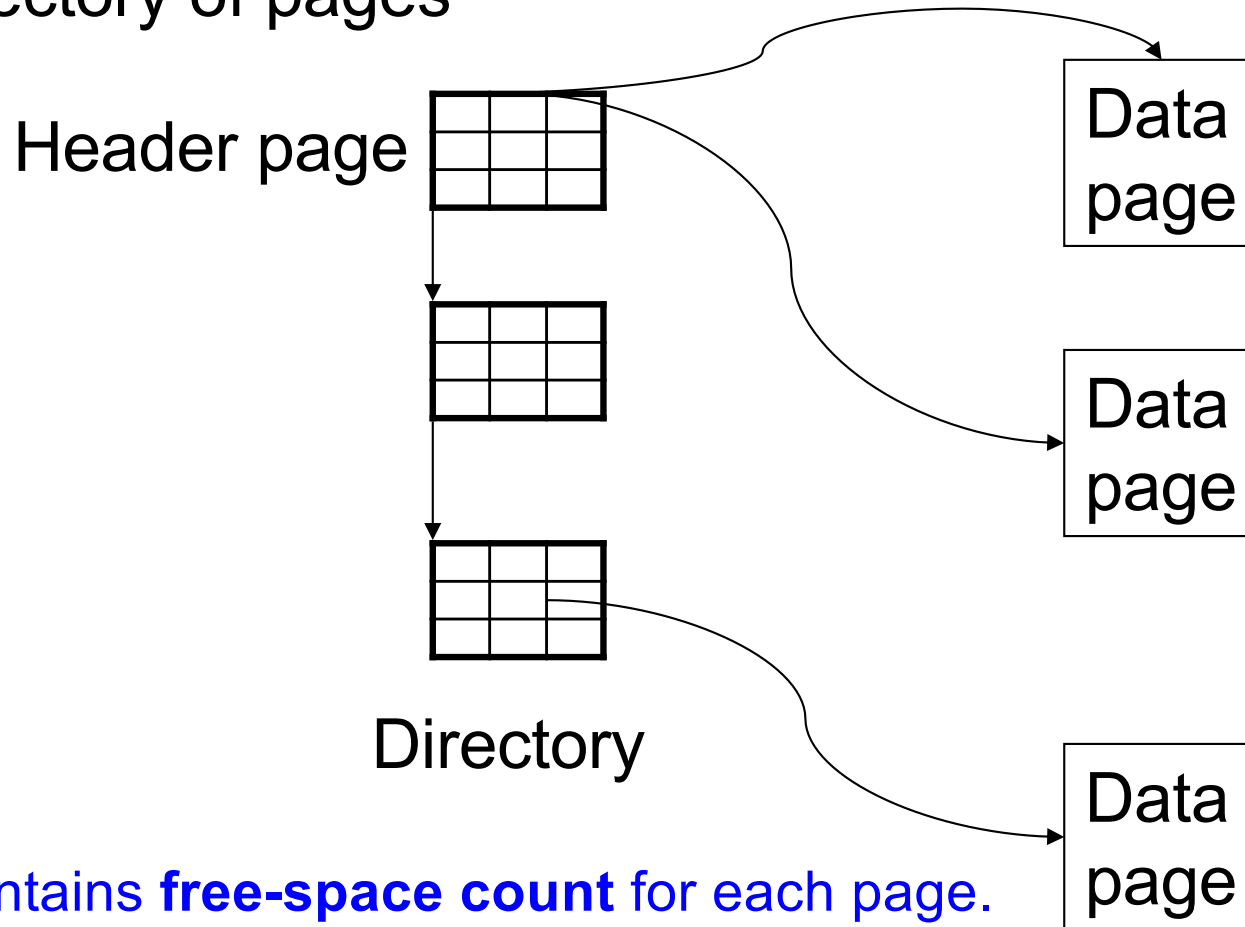
# Heap File Implementation 2

Linked list of pages:



# Heap File Implementation 3

Better: directory of pages



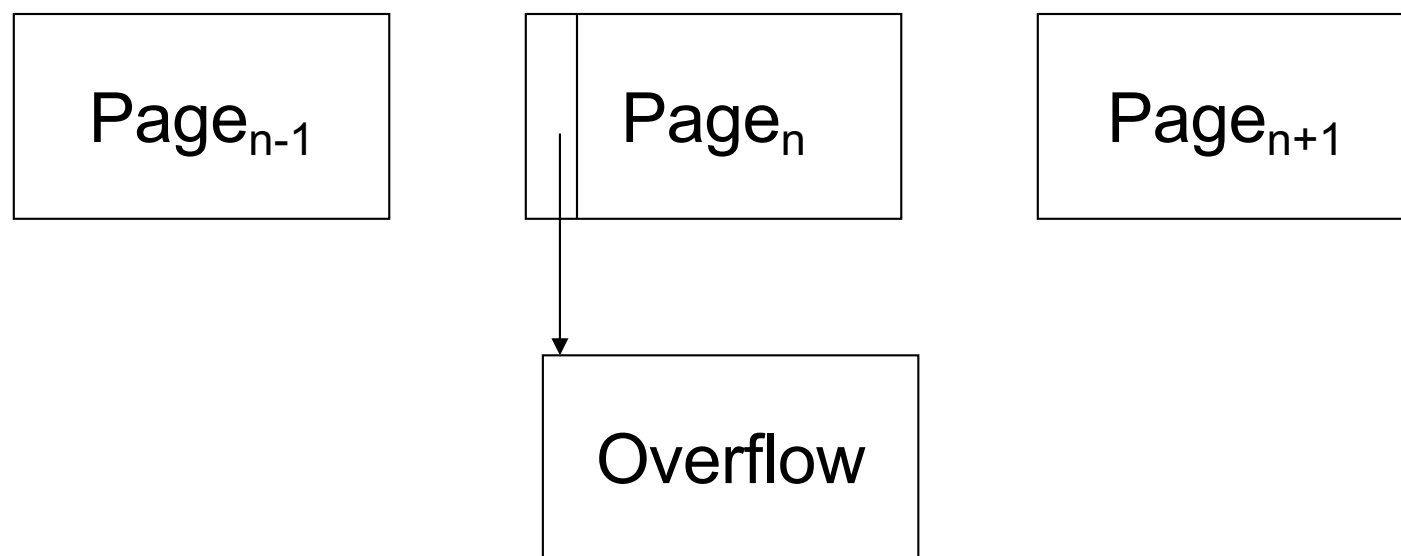
Directory contains **free-space count** for each page.  
Faster inserts for variable-length records



# Modifications: Insert Tuple

- File is unsorted (= *heap file*)
  - add it wherever there is space (easy 😊)
  - add more pages if out of space
- File is sorted
  - Is there space on the right page ?
    - Yes: we are lucky, store it there
  - Is there space in a neighboring page ?
    - Look 1-2 pages to the left/right, shift records
  - If anything else fails, create **overflow page**

# Overflow Pages



- After a while the file starts being dominated by overflow pages: time to reorganize

# Modifications: Deletions

- Free space by shifting records within page
  - Be careful with slots
  - RIDs for remaining tuples must NOT change
- May be able to eliminate an overflow page

# Modifications: Updates

- If new record is shorter than previous, easy 😊
- If it is longer, need to shift records
  - May have to create overflow pages

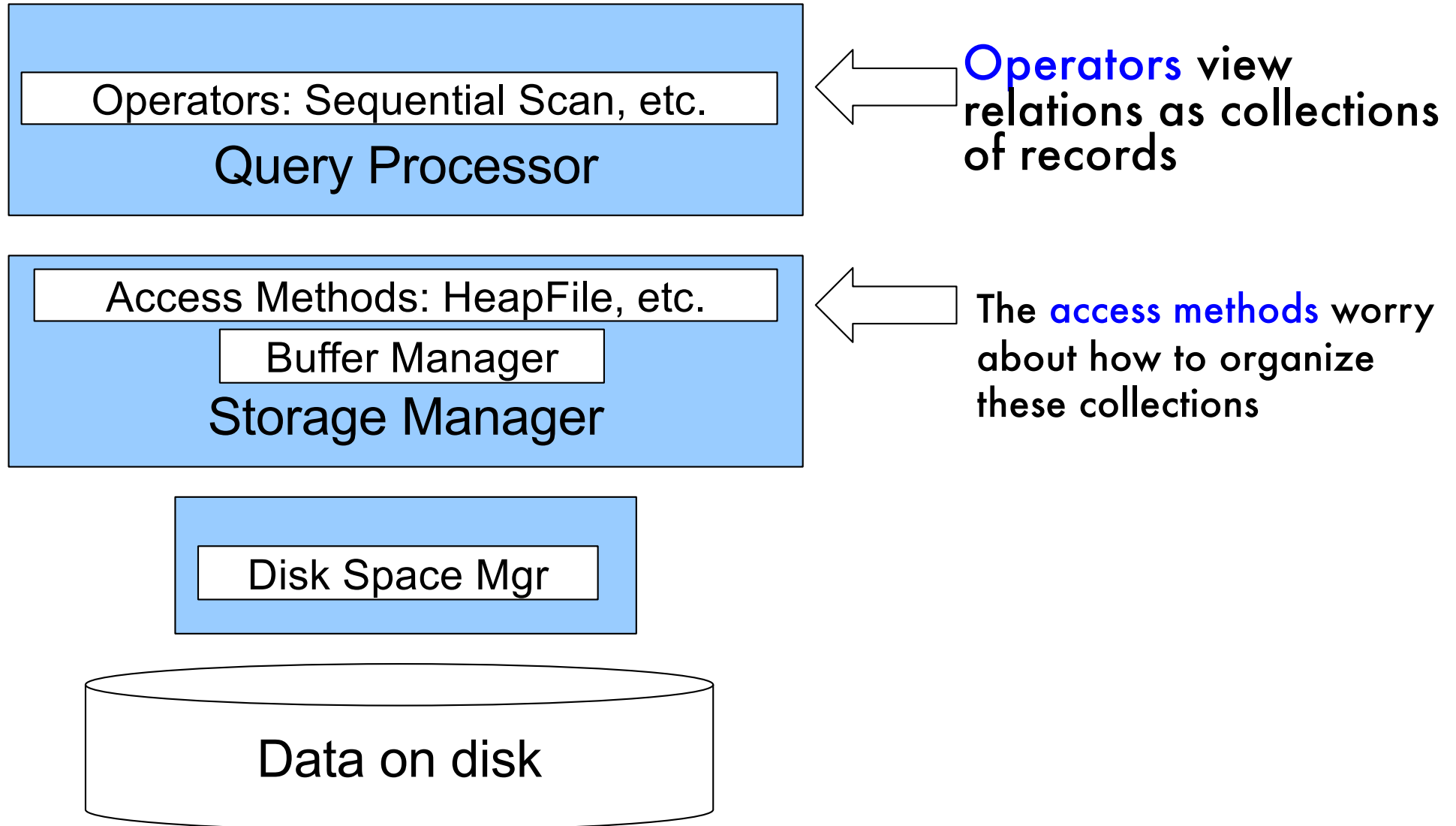
# Continuing our Design

We know how to store tuples on disk in a heap file

How do these files interact with rest of engine?

- Let's look back at lecture 3

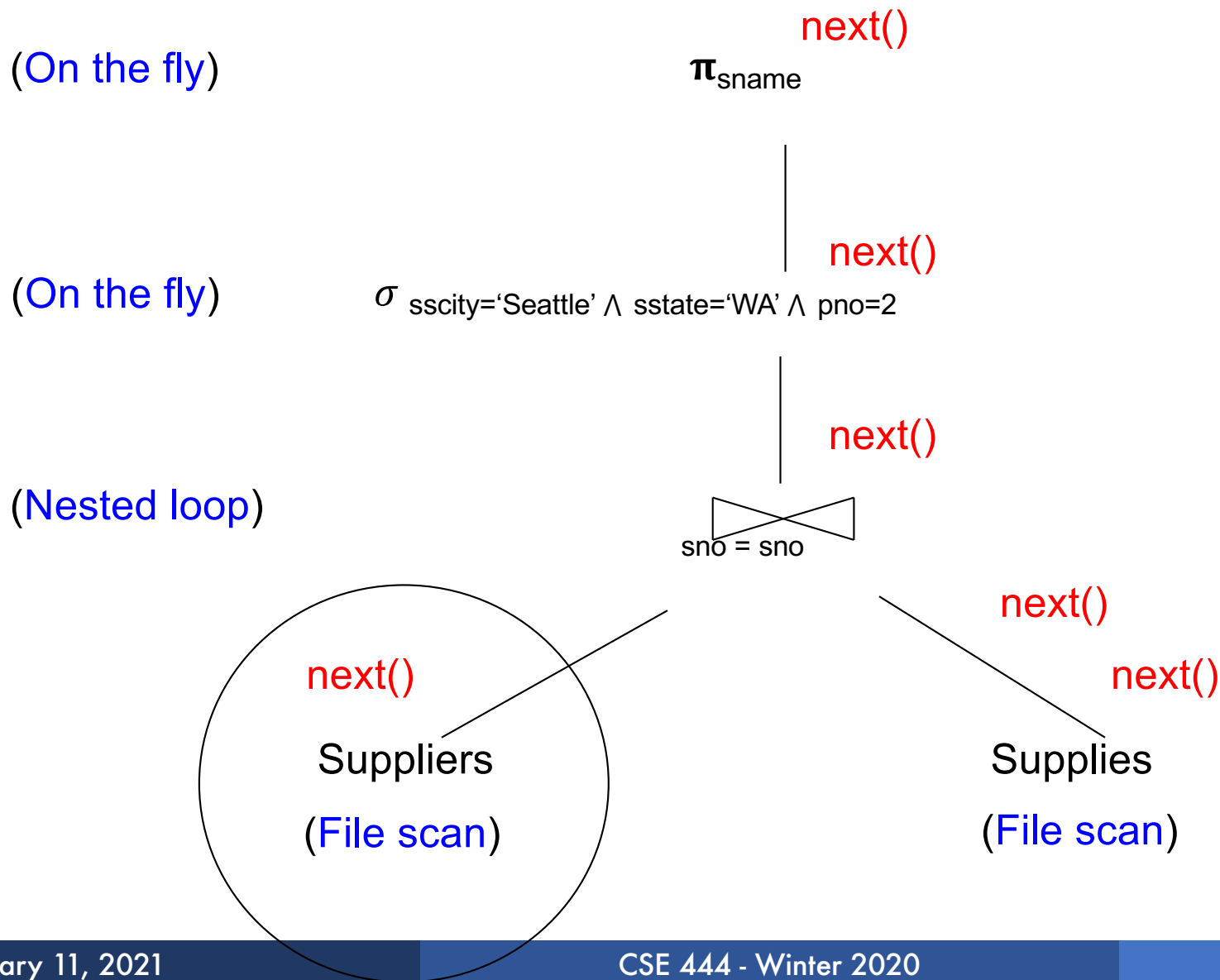
# How Components Fit Together



# Heap File Access Method API

- **Create** or **destroy** a file
- **Insert** a record
- **Delete** a record with a given rid (rid)
  - rid: unique tuple identifier (more later)
- **Get** a record with a given rid
  - Not necessary for sequential scan operator
  - But used with indexes (more next lecture)
- **Scan** all records in the file

# Query Execution





# Query Execution In SimpleDB

open()

next()

**SeqScan**

Operator at  
bottom of plan

open()

next()

**Heap File Access Method**

In SimpleDB, SeqScan can  
find HeapFile in Catalog

Offers iterator interface

open()

next()

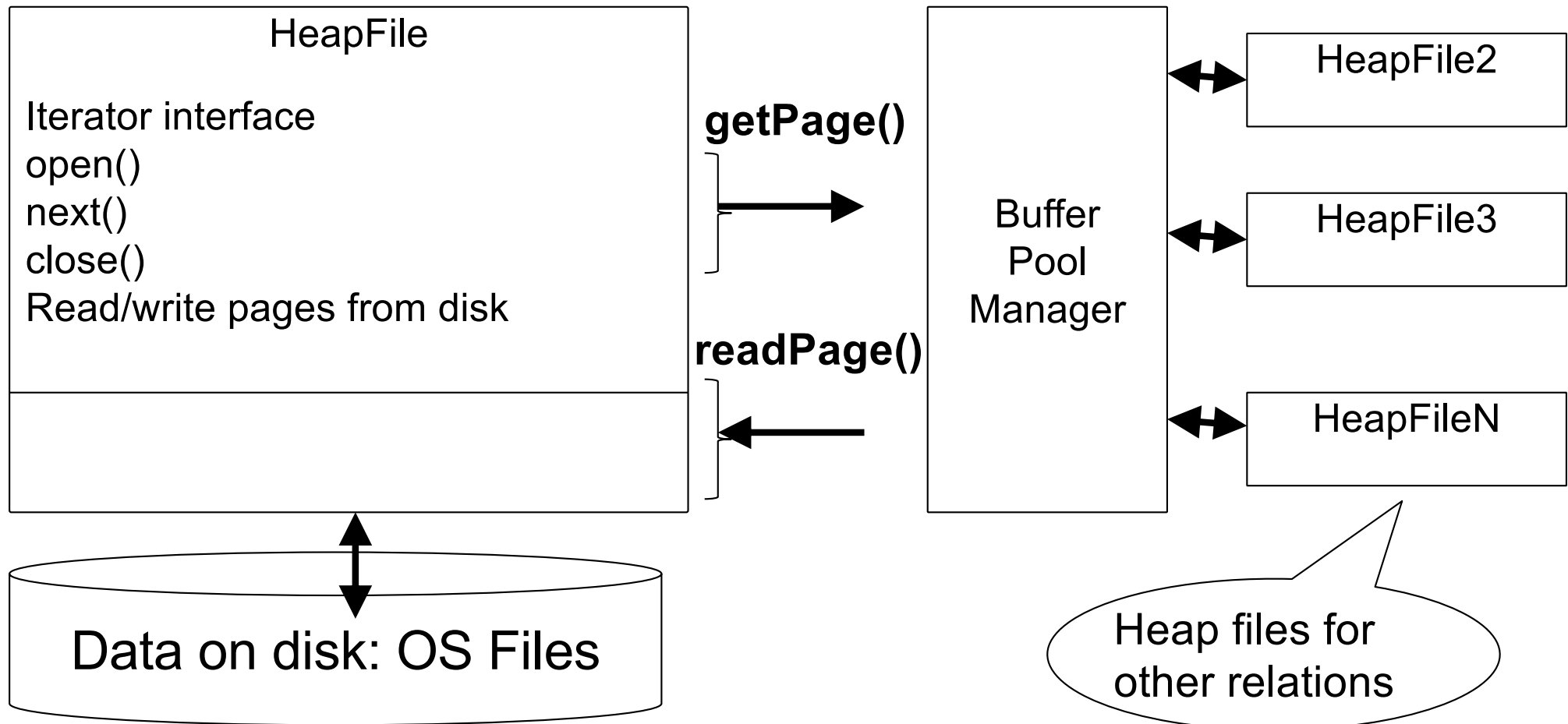
close()

Knows how to read/write pages from disk

But if Heap File reads data  
directly from disk, it will not  
stay cached in Buffer Pool!

# Query Execution In SimpleDB

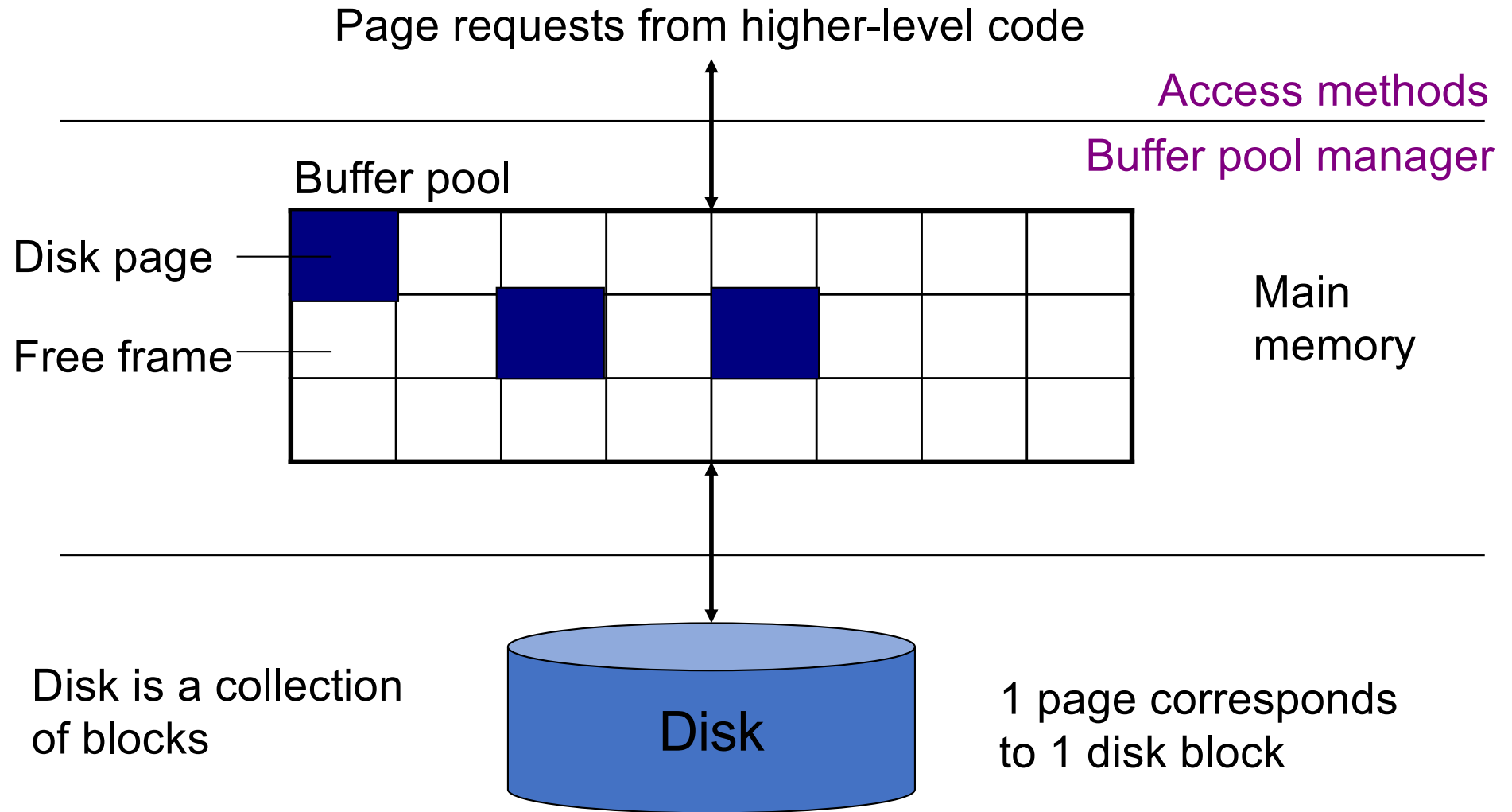
Everyone shares  
a single cache



# Buffer Manager

- Brings pages in from memory and caches them
- Eviction policies
  - Random page (ok for SimpleDB)
  - Least-recently used
  - The “clock” algorithm
- Keeps track of which **pages are dirty**
  - A dirty page has changes not reflected on disk
  - Implementation: Each page includes a dirty bit

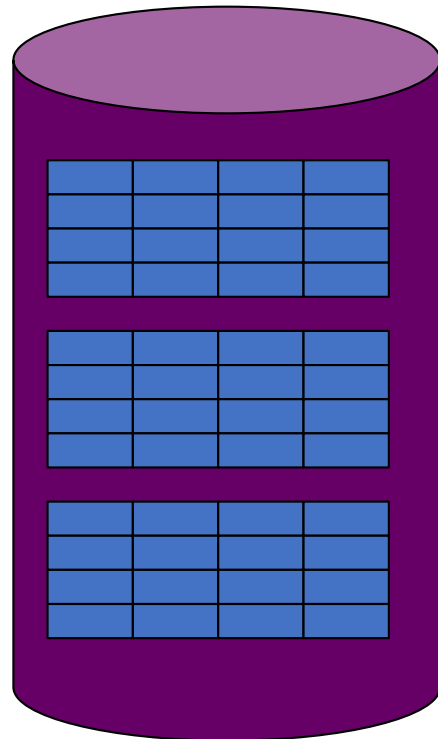
# Buffer Manager



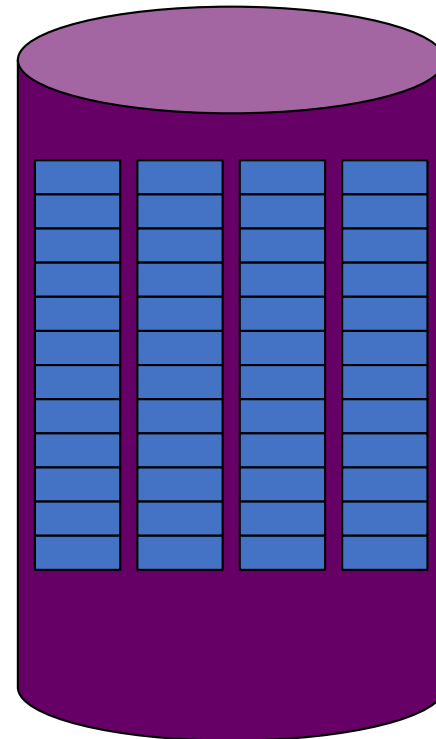
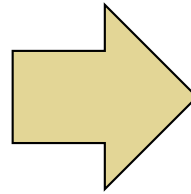
# Pushing Updates to Disk

- When **inserting a tuple**, HeapFile inserts it on a page but does not write the page to disk
- When **deleting a tuple**, HeapFile deletes tuple from a page but does not write the page to disk
- The buffer manager worries when to write pages to disk (and when to read them from disk)
- When need to **add new page** to file, HeapFile adds page to file on disk and then reads it through buffer manager

# Alternate Design: Column Store



Rows stored  
contiguously on disk  
(+ tuple headers)



Columns stored  
contiguously on disk  
(no headers needed)

# Column Store Illustration

Row-based  
(4 pages)

Page {

A	1
A	2
A	2
A	2
B	2
B	4
C	4
C	4

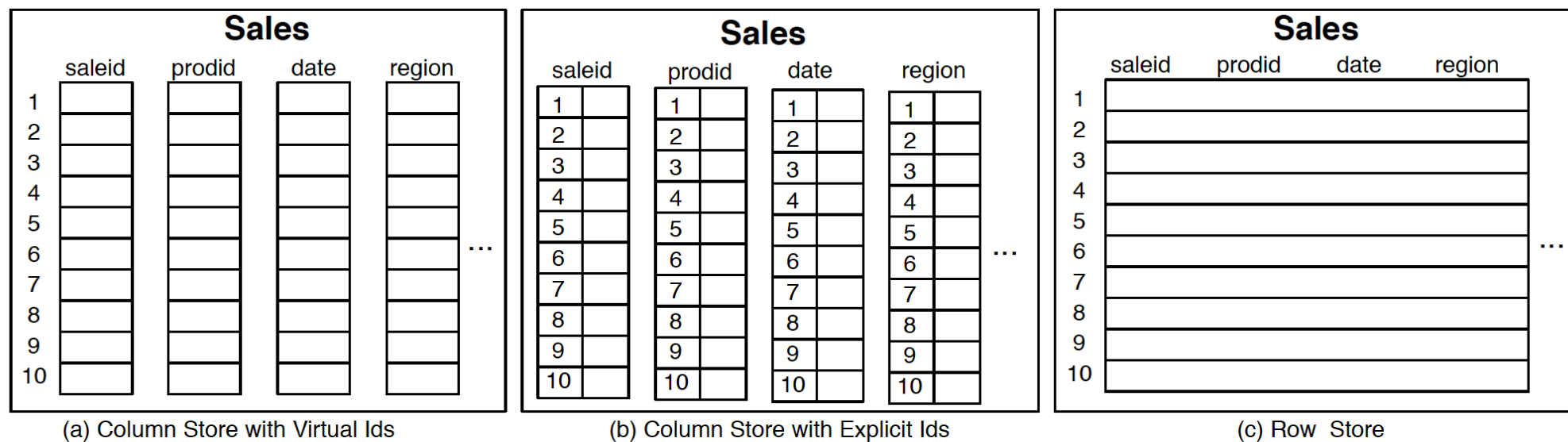
Column-based  
(4 pages)

A	1
A	2
A	2
A	2
B	2
B	4
C	4
C	4

} Page

C-Store also  
avoids large  
tuple headers

# Column Store Example



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

The Design and Implementation of Modern Column-Oriented Database Systems Daniel Abadi, Peter Boncz, Stavros Harizopoulos, Stratos Idreos, Samuel Madden. Foundations and Trends® in Databases (Vol 5, Issue 3, 2012, pp 197-280)



# Conclusion

- Row-store storage managers are most commonly used today for OLTP systems
  - They offer high-performance for transactions
  - But column-stores win for analytical workloads
  - They are widely used in OLAP
- 
- [Optional] Final discussion: OS vs DBMS
    - OS files vs DBMS files
    - OS buffer manager vs DBMS buffer manager