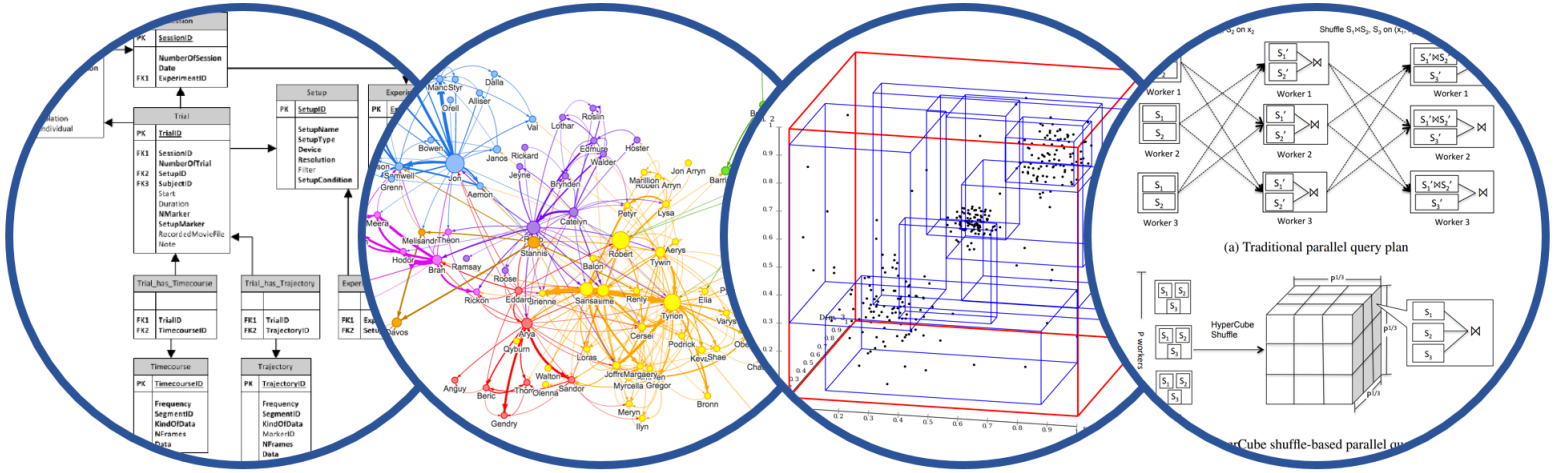



# Database System Internals

# Data Storage and (more) Buffer Management

Paul G. Allen School of Computer Science and Engineering
University of Washington, Seattle

# Announcements

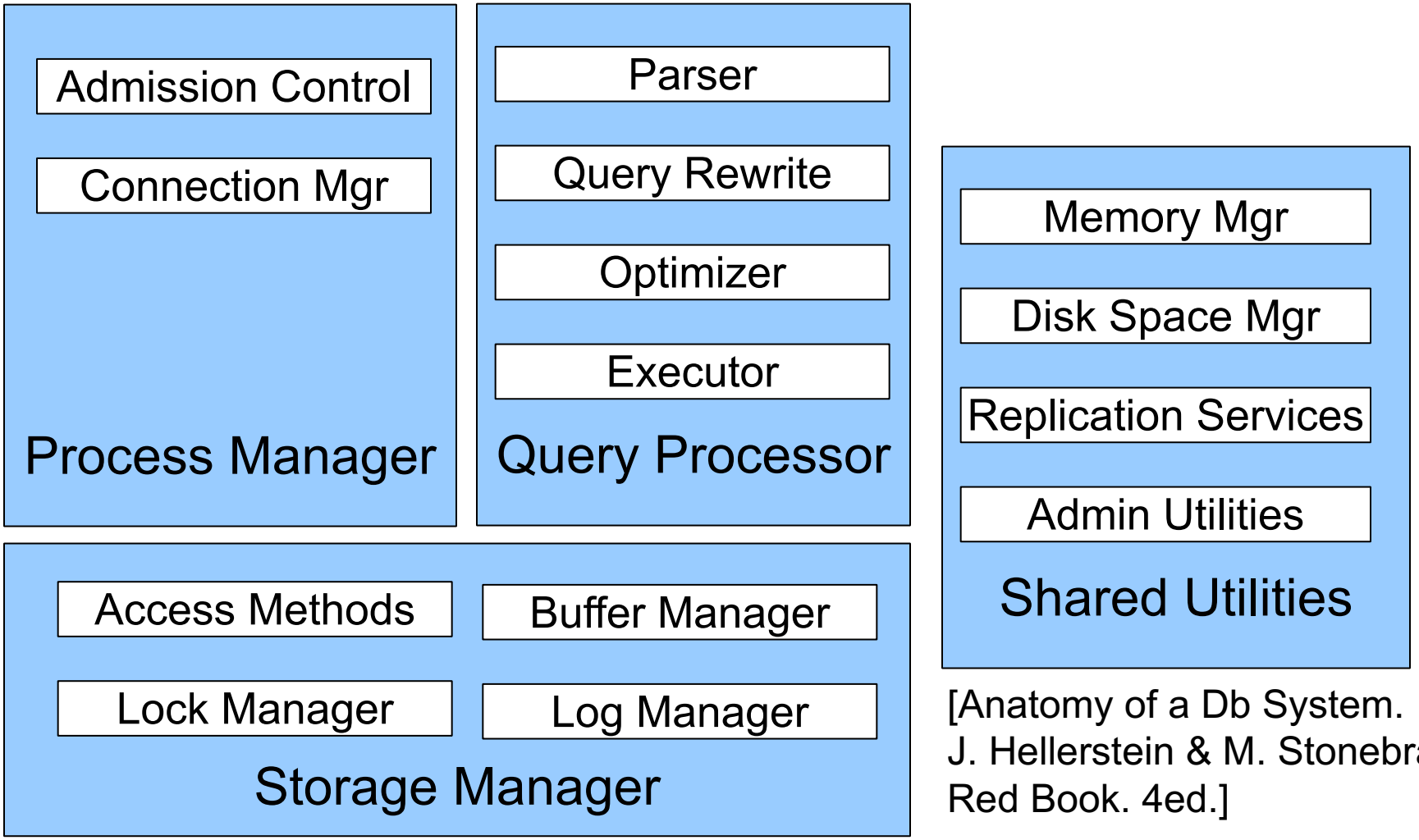
- Lab 1 part 1 is due on tonight at 11pm
  - Don't worry about implementing everything completely and passing all tests
  - We are not grading according to tests-passed for part 1, just that the functions asked for are complete.

- Homework 1:
  - Submit by Gradescope

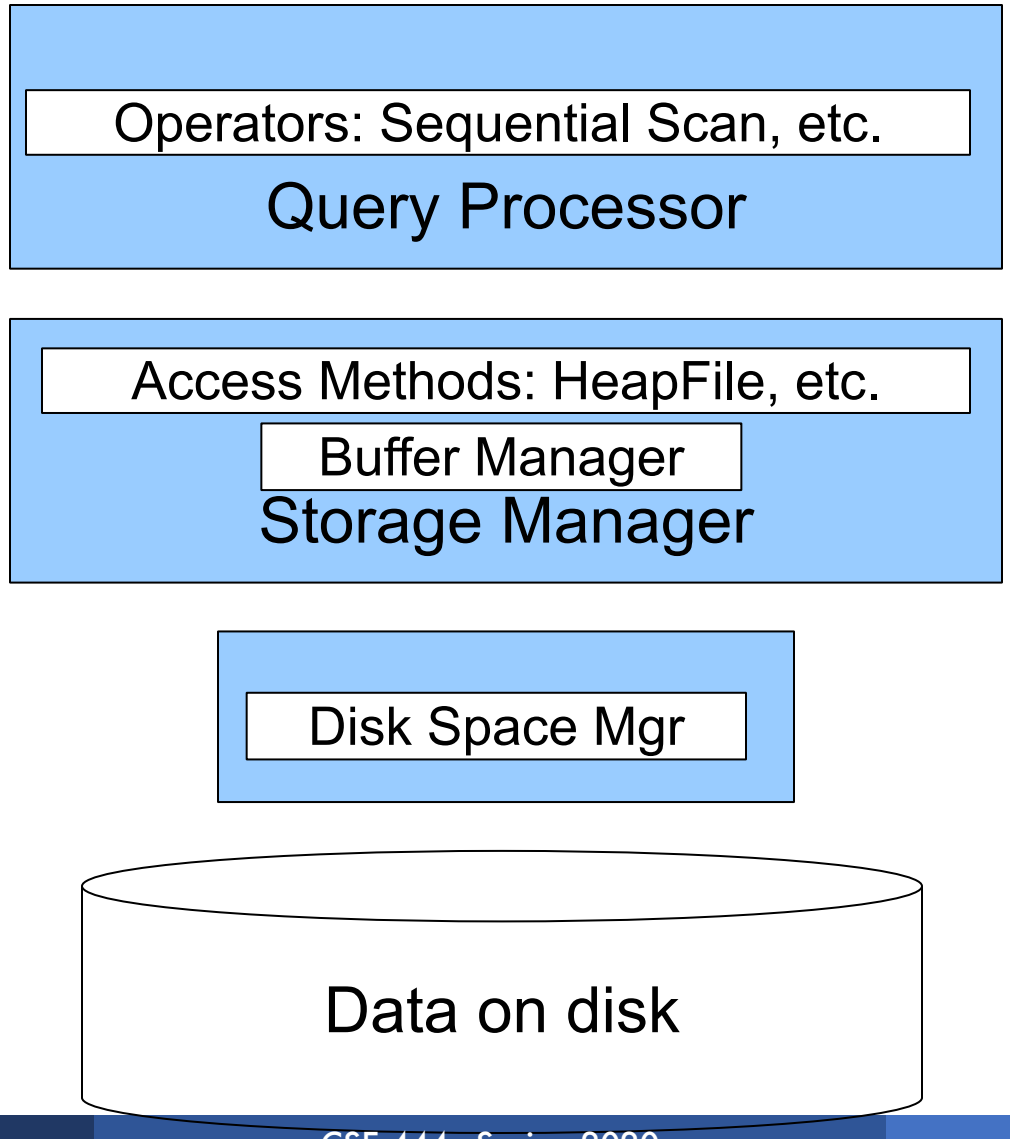
# Important Note

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

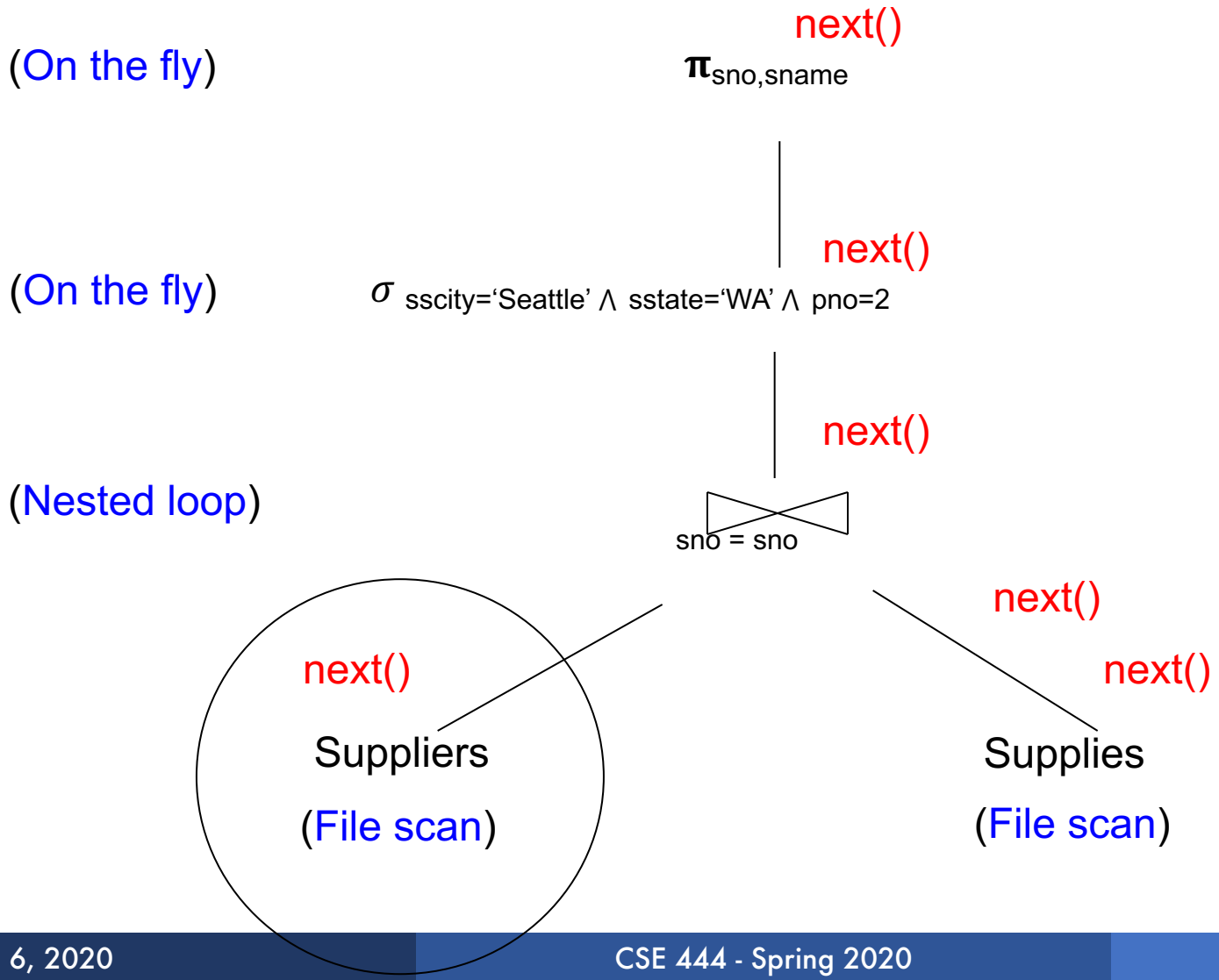
# DBMS Architecture



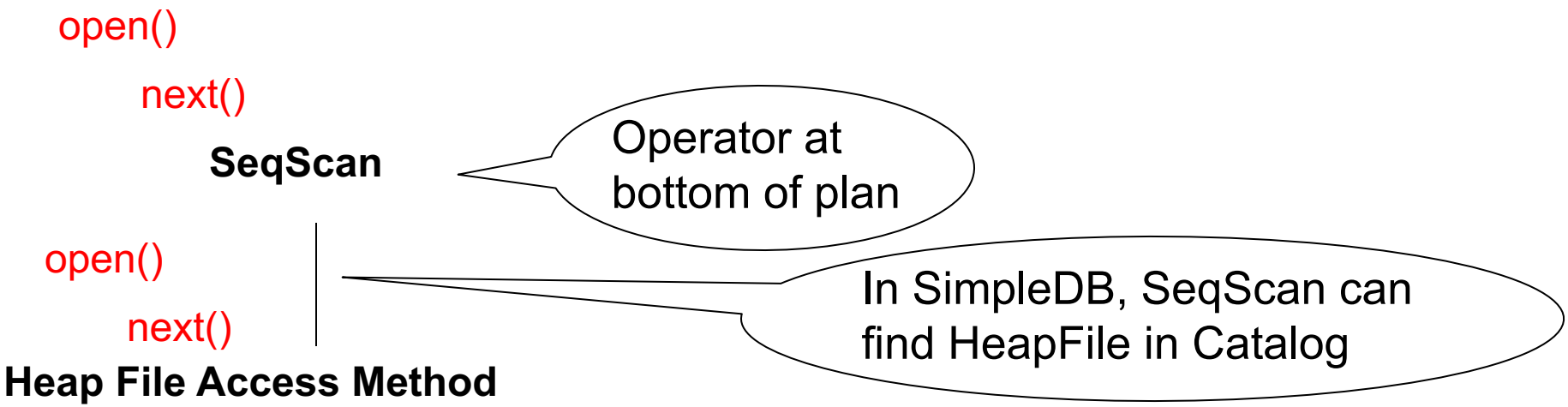

[Anatomy of a Db System. J. Hellerstein & M. Stonebraker. Red Book. 4ed.]


Operators: Sequential Scan, etc.
Query Processor
Access Methods: HeapFile, etc.
Buffer Manager
Storage Manager
Disk Space Mgr
Data on disk

# Recap: Query Execution



# Recap: Execution In SimpleDB



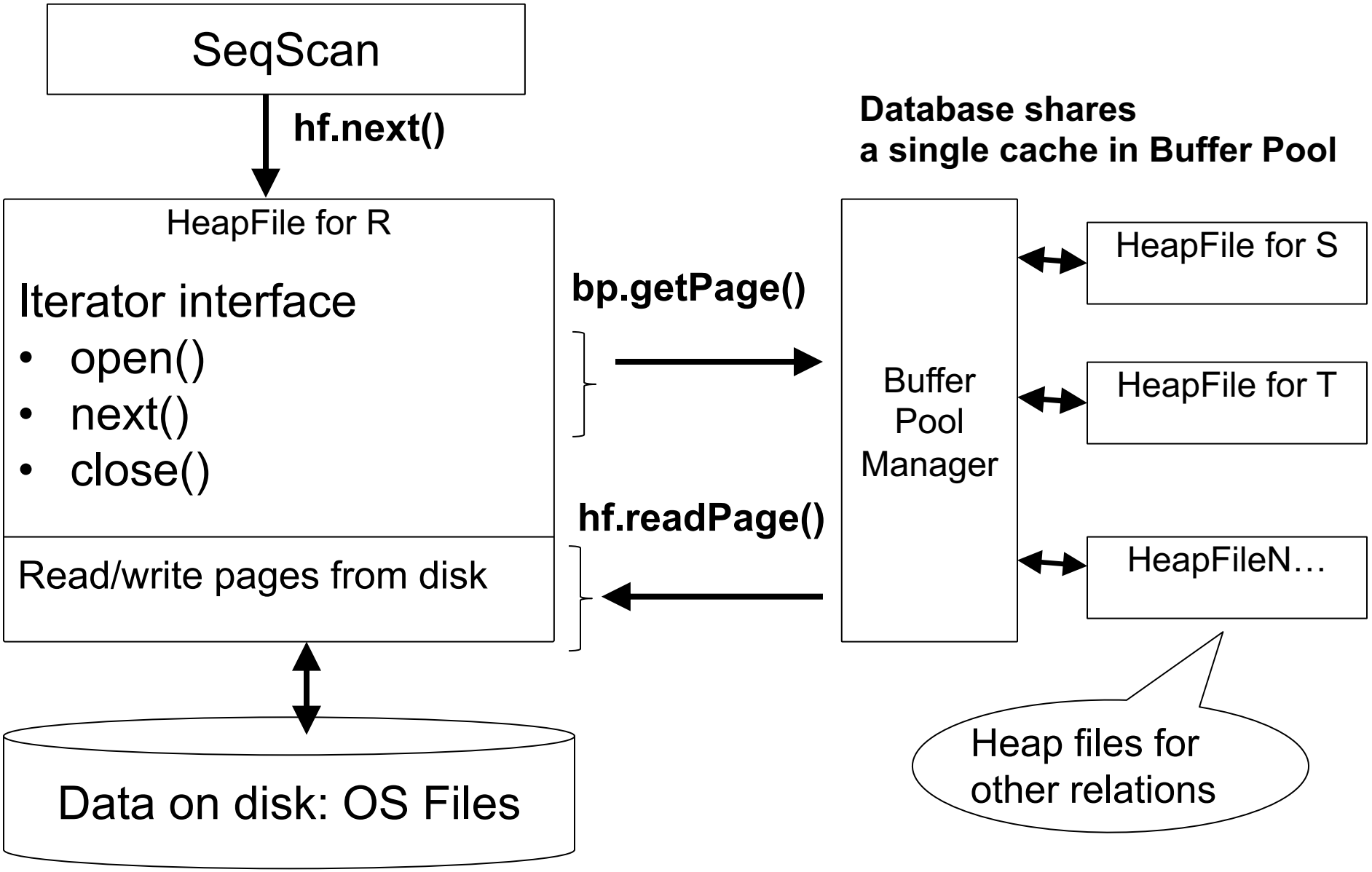

Offers iterator interface

- 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!

# Recap: Execution In SimpleDB



# Today: Starting at the Bottom

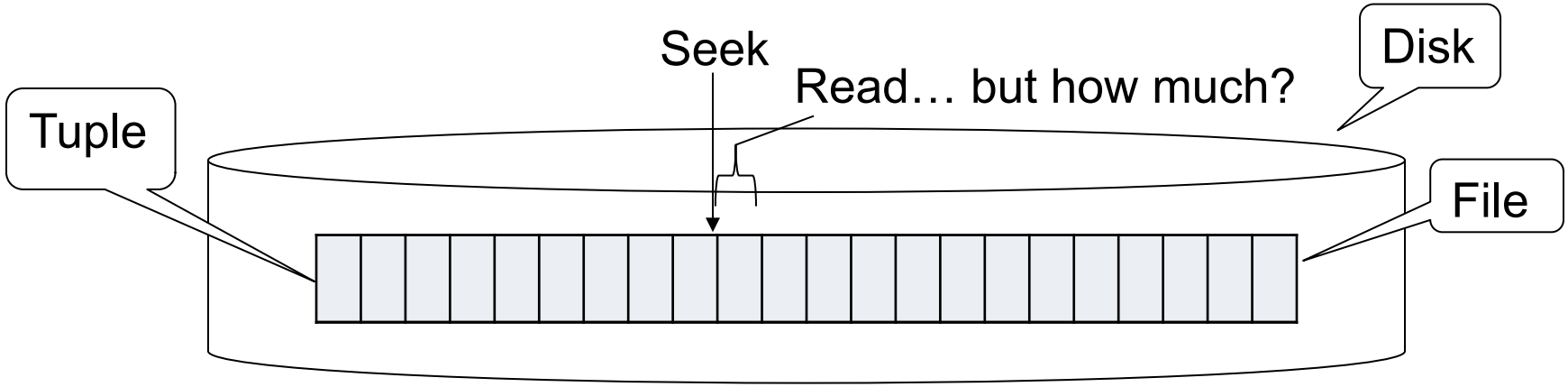
Consider a relation storing tweets:

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

How should we store it on disk?

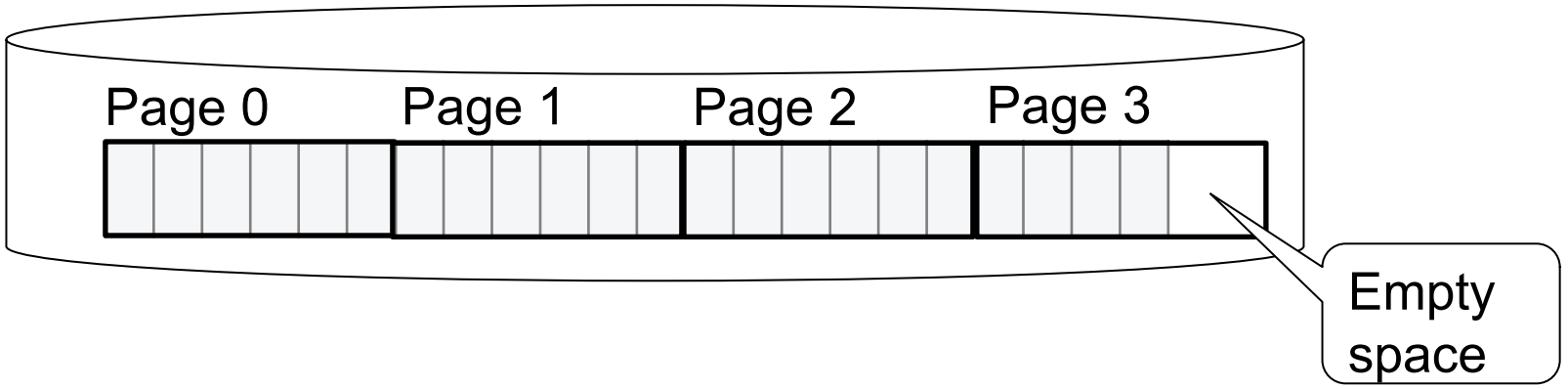
# Design Exercise

- One design choice: **One OS file for each relation**
  - Alternative: SQLite uses one file for whole database
  - Alternative: some DBMSs use disk drives directly
- An OS file provides an API of the form
  - Seek to some position (or "skip" over S 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



# Continuing our Design

Key questions:

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

Start with: 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

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

## Issues to consider

- 1 page = 1 disk block = fixed size (e.g. 8KB)
- Records:
  - Fixed length
  - Variable length

# Page Formats

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- Records:
  - Fixed length
  - Variable length

- **Record id = RID**
  - Like a pointer to a tuple
  - Typically RID = (PageID, SlotNumber)

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

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  - 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 ?

Needed by indexes and transactions

# Page Format Approach 1

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

Fixed-length records: packed representation

Divide page into slots. Each slot can hold one tuple

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

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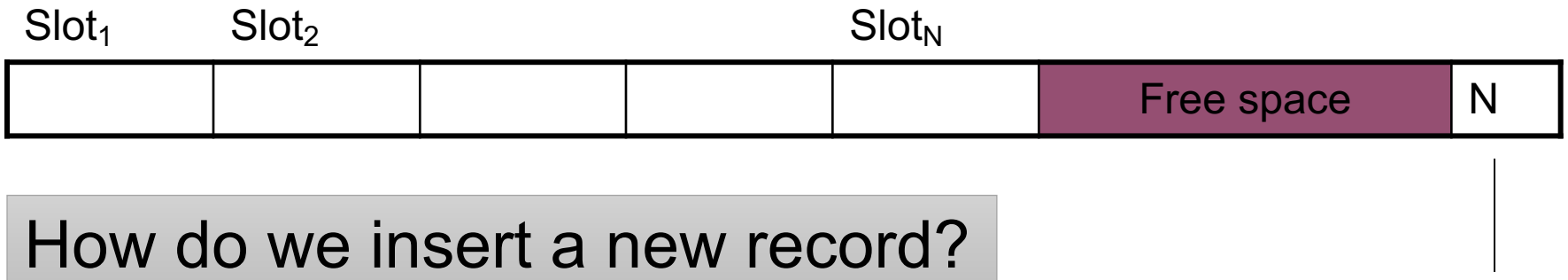


How do we insert a new record?

Number of records

# Page Format Approach 1

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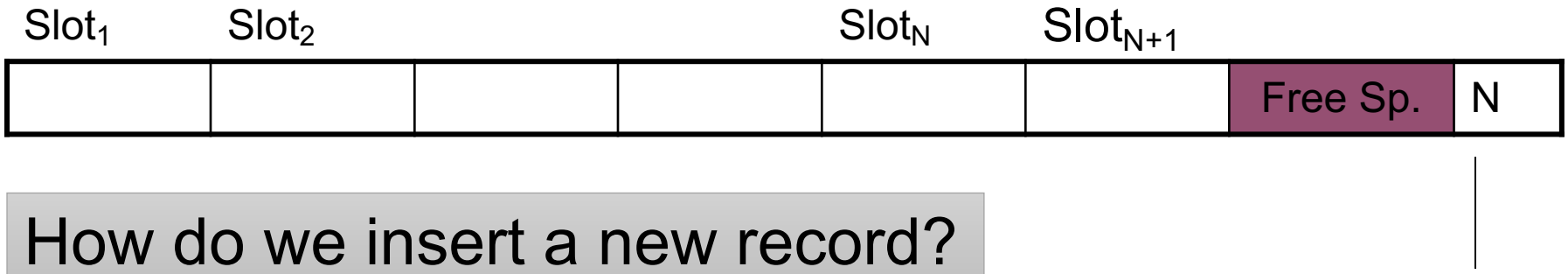


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Number of records

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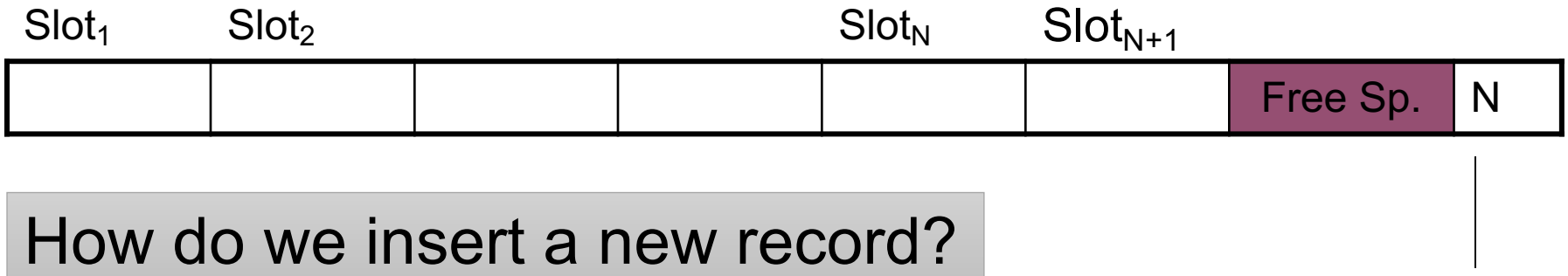


How do we insert a new record?

How do we delete a record?

Number of records

# Page Format Approach 1

**Tweets**(tid int, user char(10),
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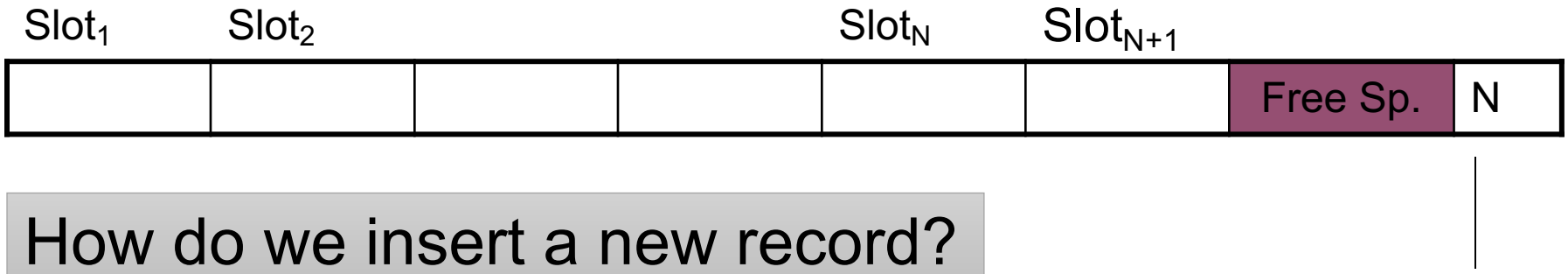


How do we insert a new record?

Number of records

How do we delete a record?

What is the problem?

# Page Format Approach 1

**Tweets**(tid int, user char(10),
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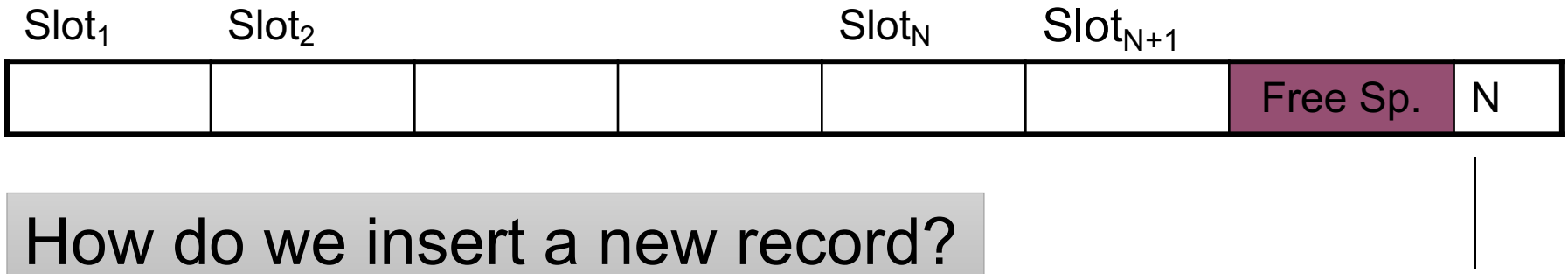
Fixed-length records: packed representation

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?

How do we delete a record?

Cannot move records! (Why?)

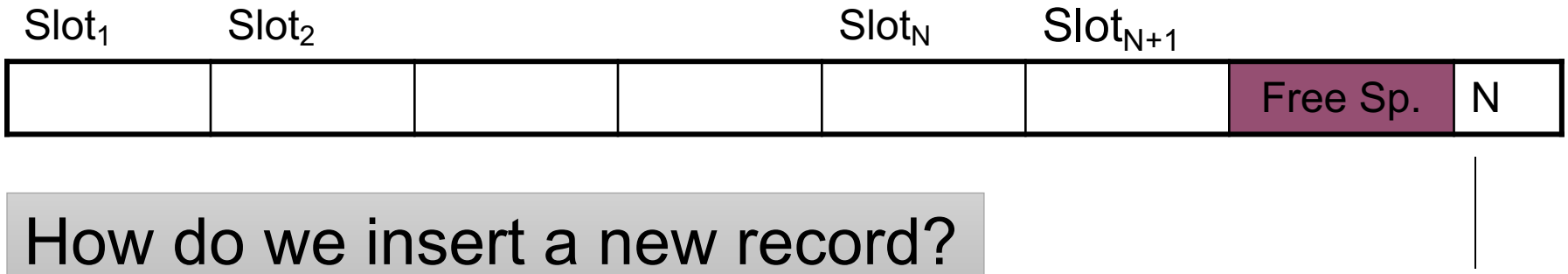
# Page Format Approach 1

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

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?

How do we delete a record?

How do we handle variable-length records?

# Page Format Approach 2

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

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**Tweets**(tid int, user char(10),
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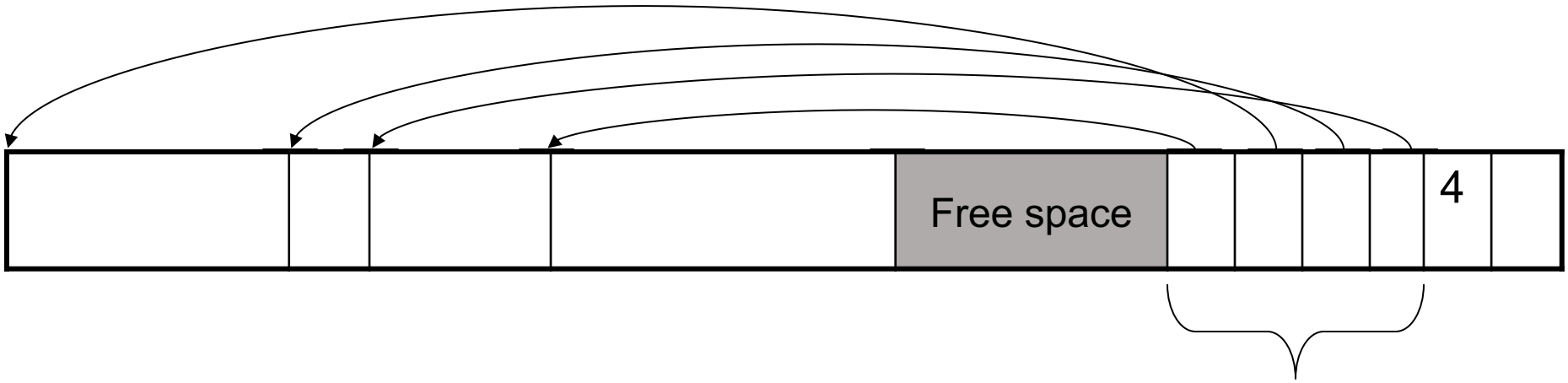


Slot directory

Each slot contains
<record offset, record length>

# Page Format Approach 2

**Tweets**(tid int, user char(10),
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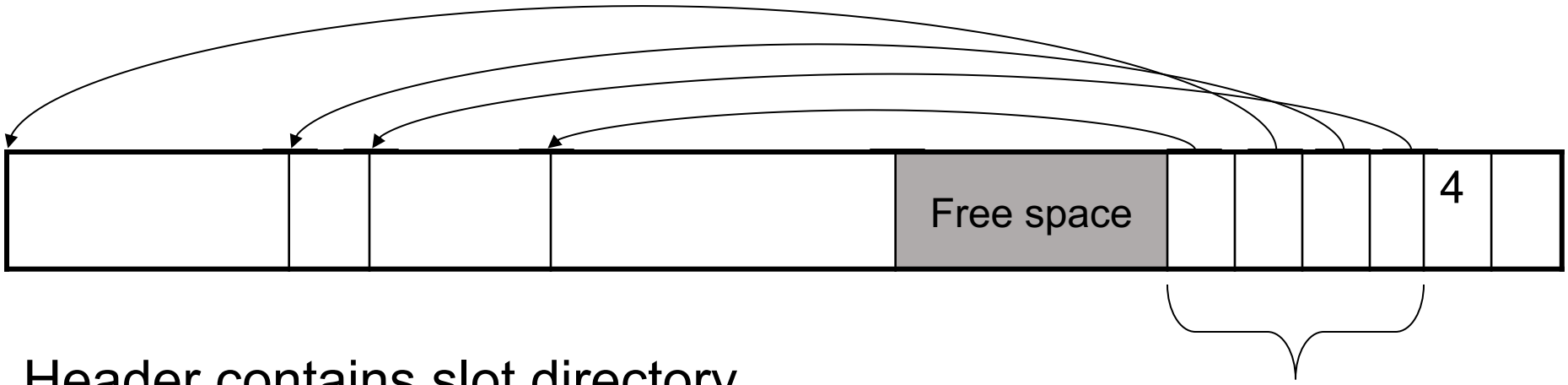


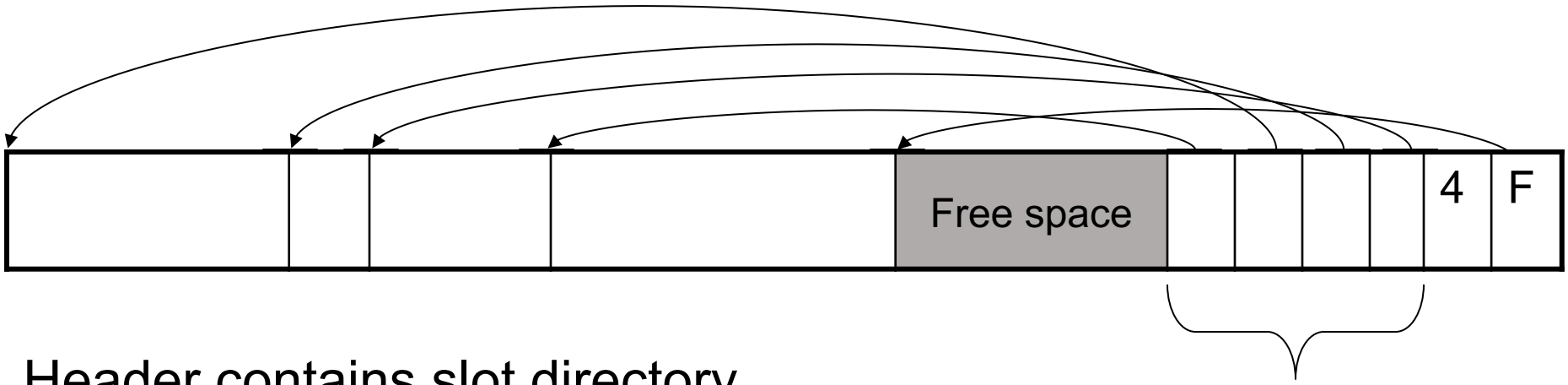

Header contains slot directory
+ Need to keep track of # of slots

Slot directory

Each slot contains
<record offset, record length>

# Page Format Approach 2

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




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>

# Page Format Approach 2

**Tweets**(tid int, user char(10),
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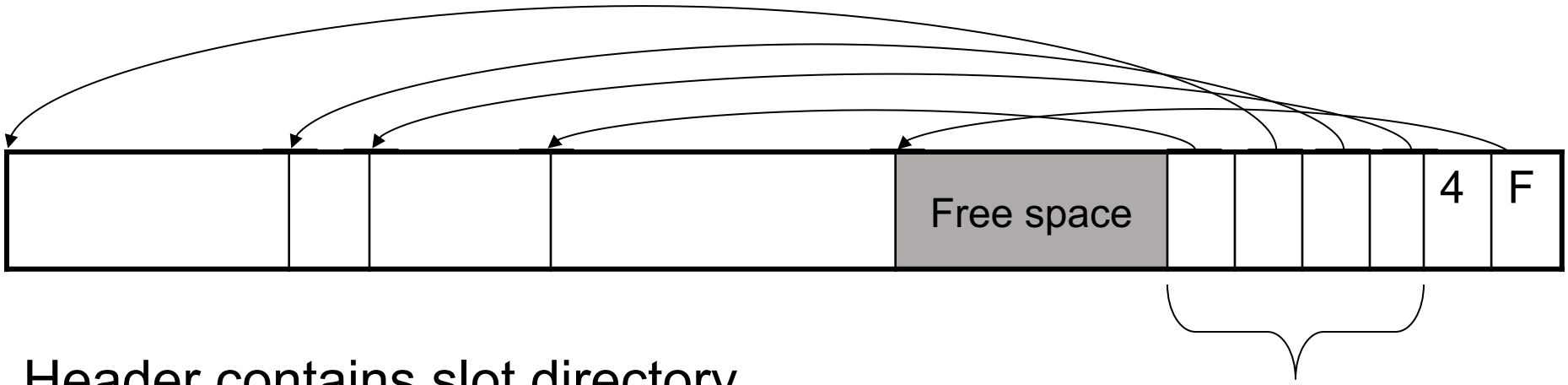


Header contains slot directory

+ 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

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

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

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time int, content char(140))

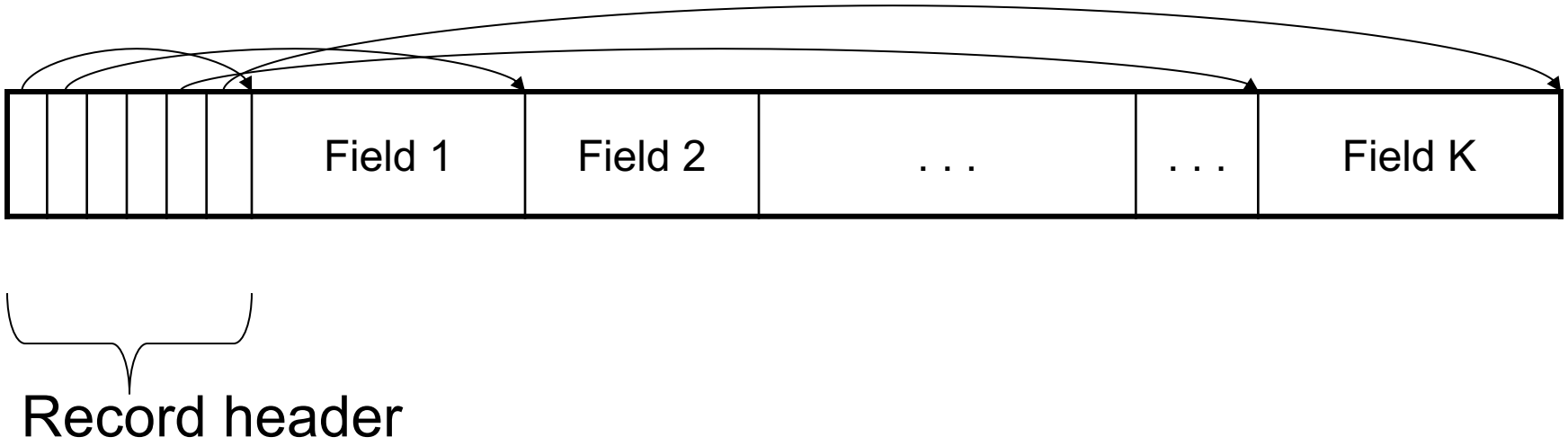
Fixed-length records => Each field has a fixed length
(i.e., it has the same length in all the records)


Information about field lengths and types is in the catalog

# Record Formats

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

Variable length records




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

# LOB

- 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 tuples within a page?

Now, how should we group pages into files?

# Heap File Implementation 1

A sequence of pages (implementation in SimpleDB)

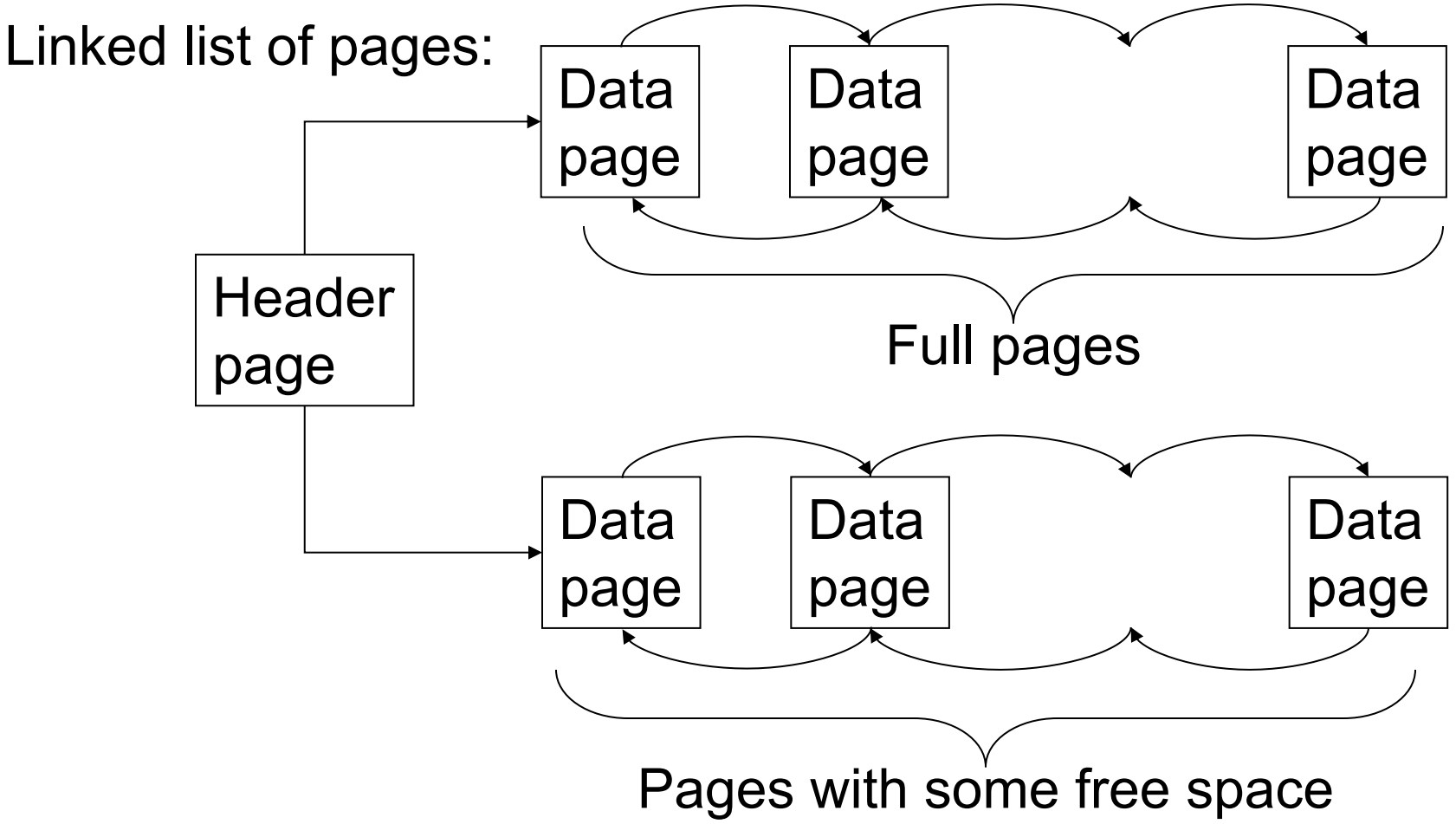

Some pages have space and other pages are full

Add pages at the end when need more space

Works well for small files

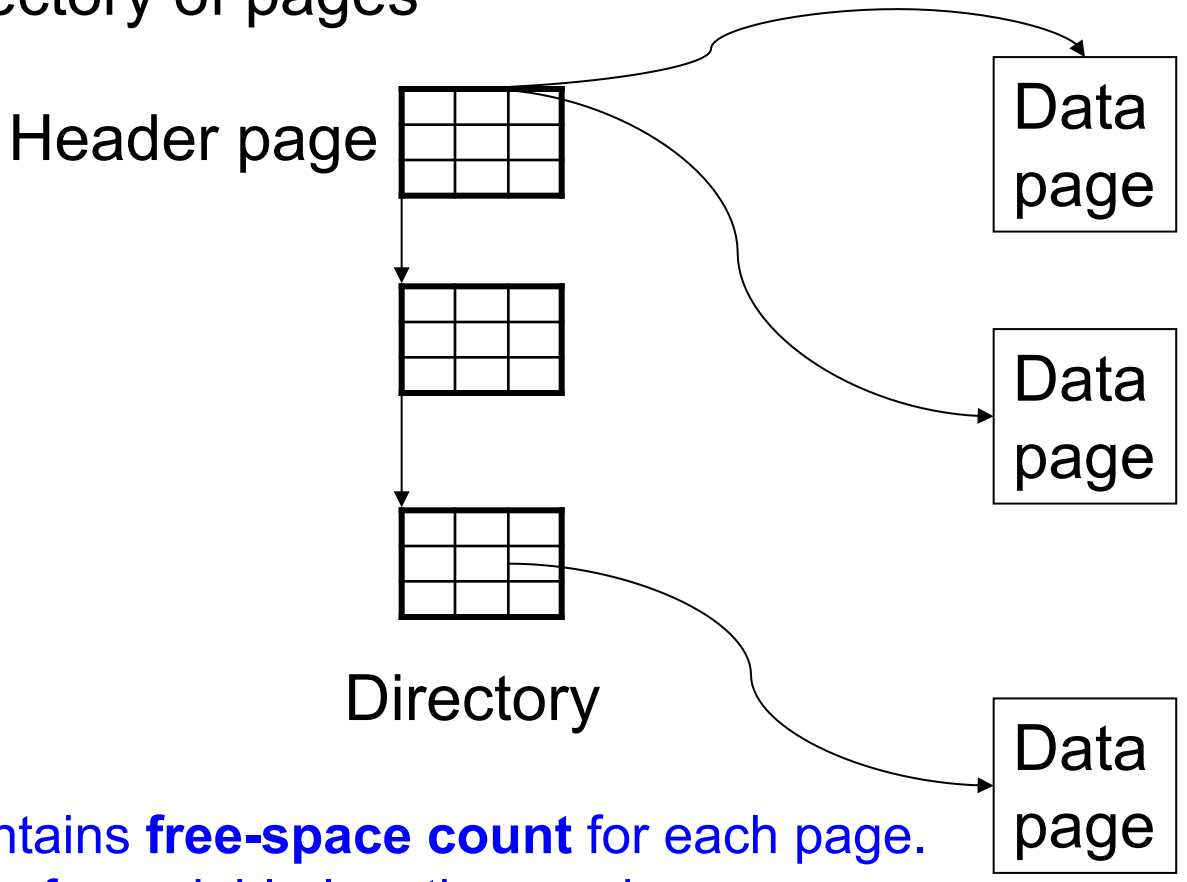
But finding free space requires scanning the file…

# Heap File Implementation 2



# Heap File Implementation 3

Better: directory of pages



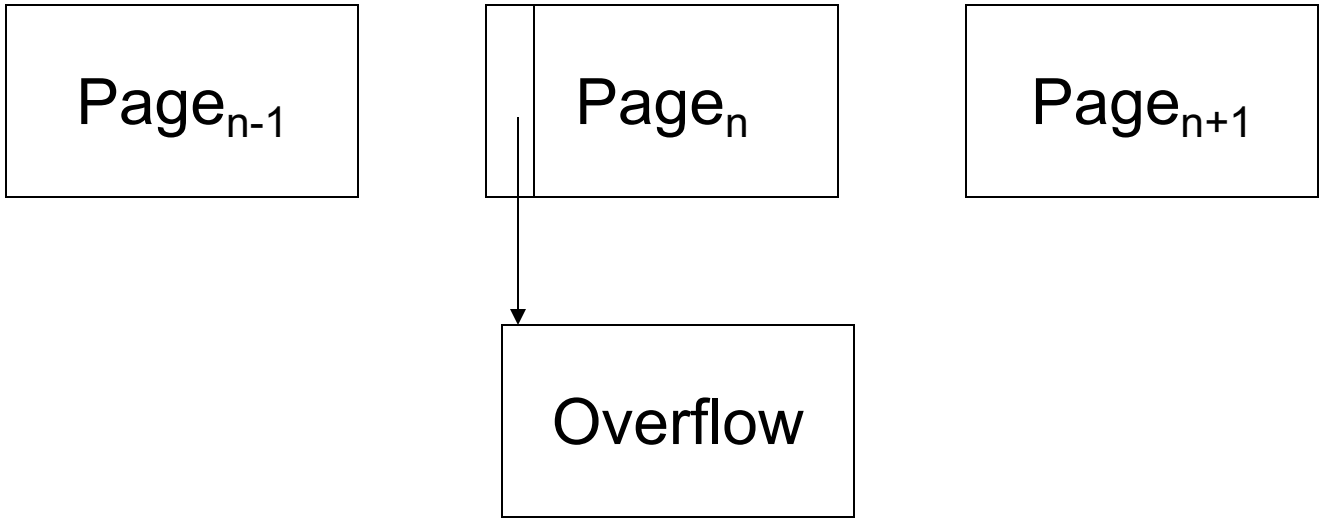

Directory contains **free-space count** for each page.
Faster inserts for variable-length records

# 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

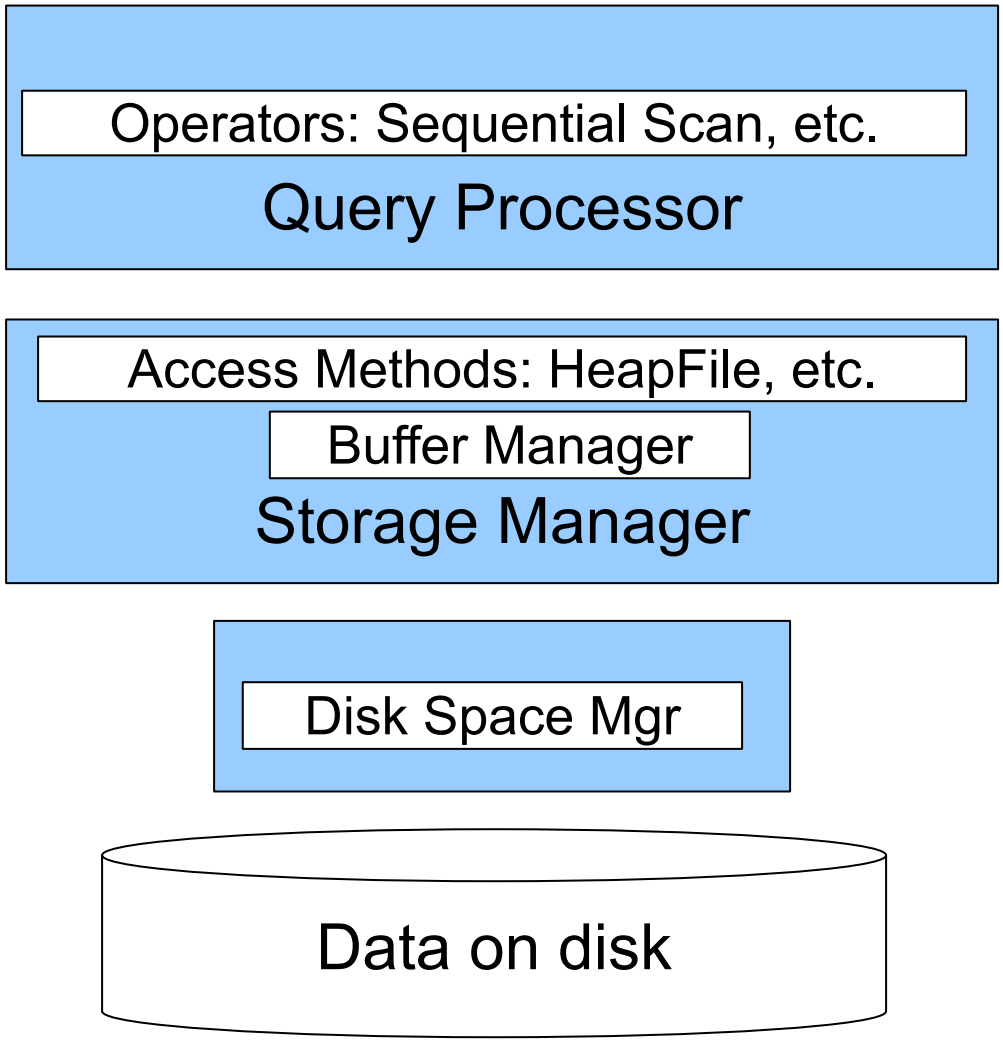
- If new record is shorter than previous, easy ☺
- If it is longer, need to shift records
  - May have to create overflow pages

# Continuing our Design

We know how to store tuples in a heap file

How do heap files interact with rest of engine?

# How Components Fit Together



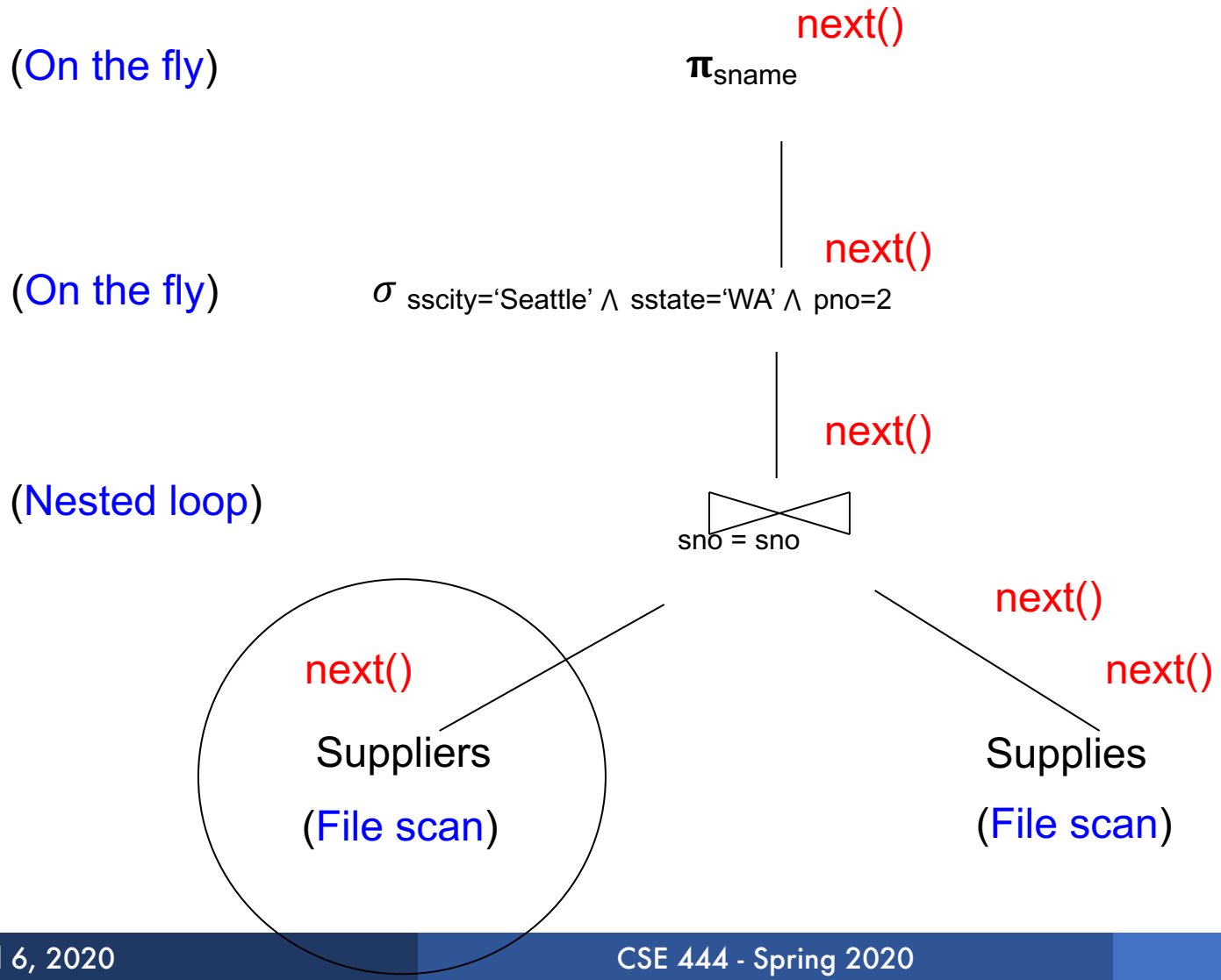

Operators view relations as collections of records

The access methods worry about how to organize these collections

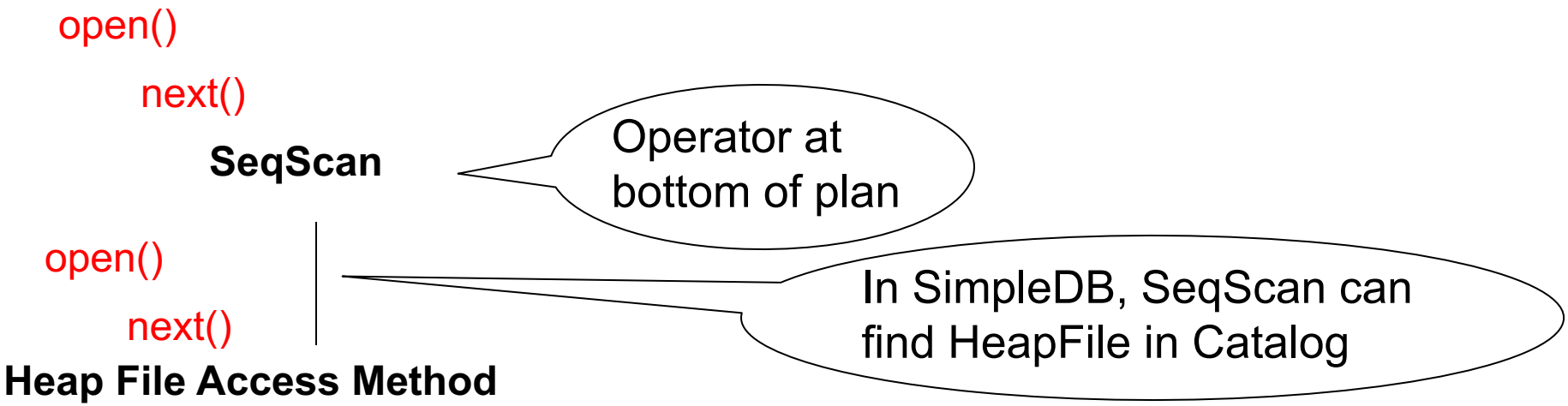
# Heap File Access Method API

- **Create** or **destroy** a file
- **Insert** a record
- **Delete** a record with a given rid
  - rid: unique tuple identifier
- **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




Offers iterator interface
open()
next()
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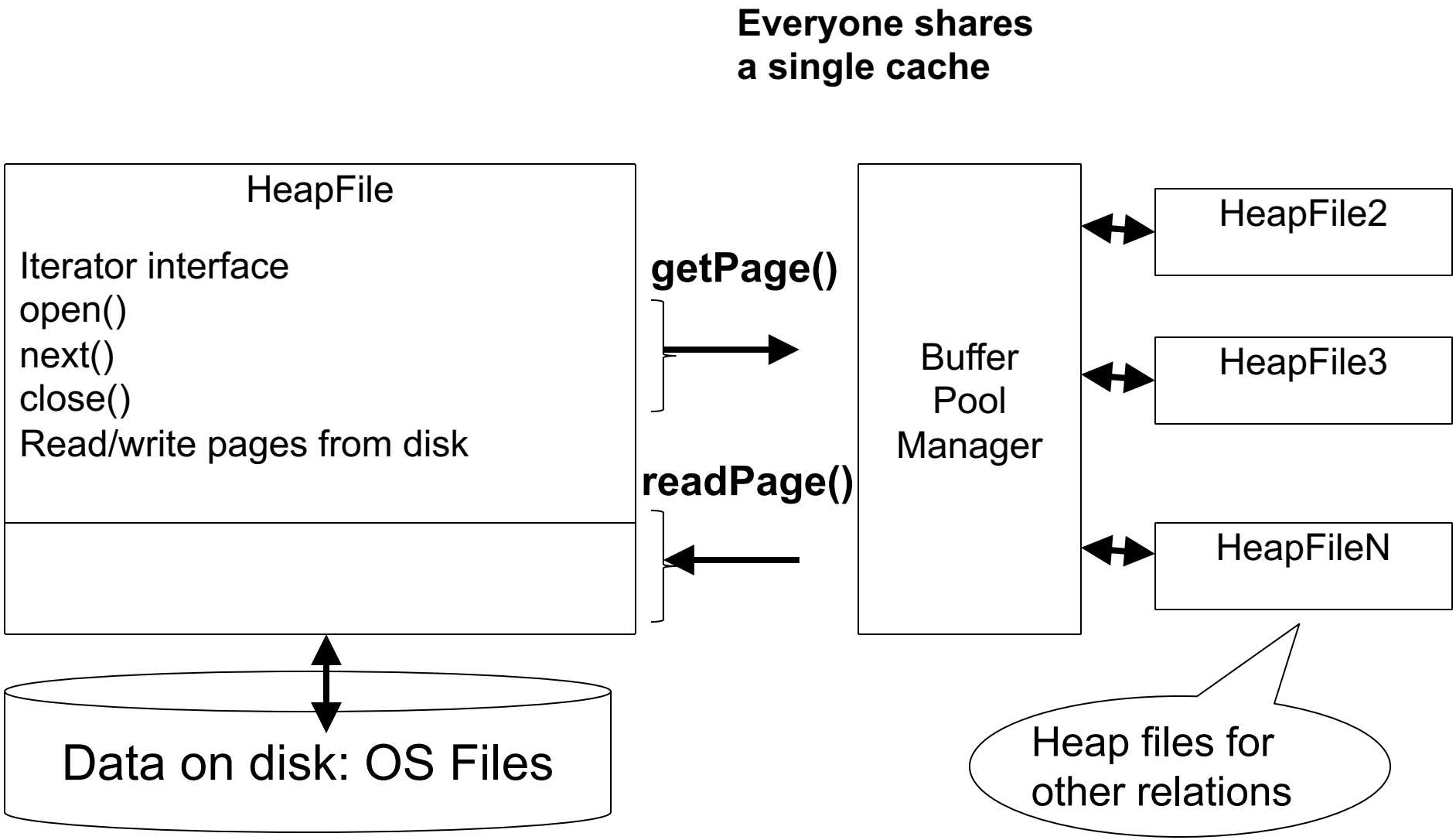
Knows how to read/write pages from disk

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

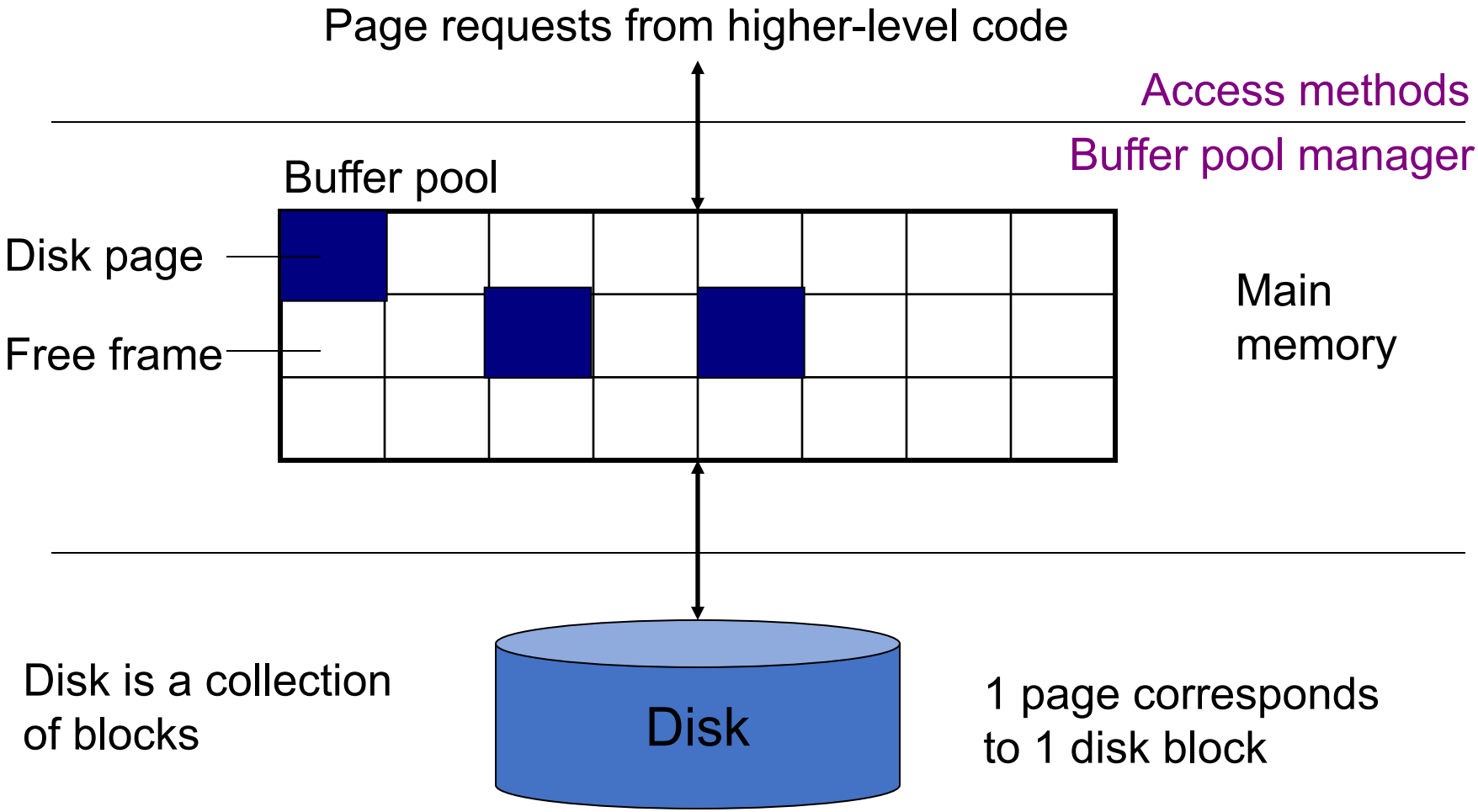
# Query Execution In SimpleDB



# Buffer Manager

- Brings pages in from memory and caches them
- Eviction policies
  - Random page (ok for SimpleDB)
  - Least-recently used (LRU)
  - 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

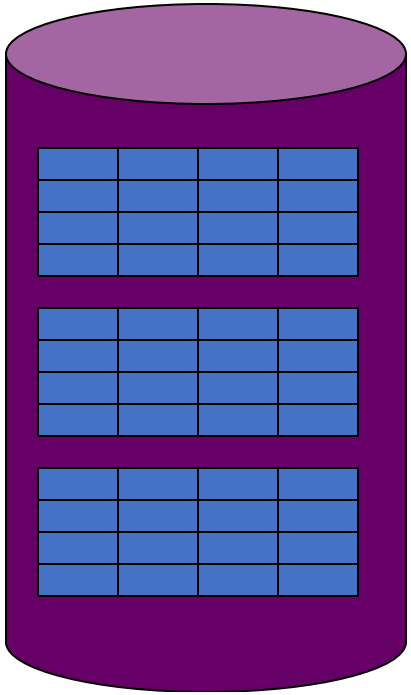
# Buffer Manager



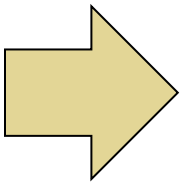
# Pushing Updates to Disk

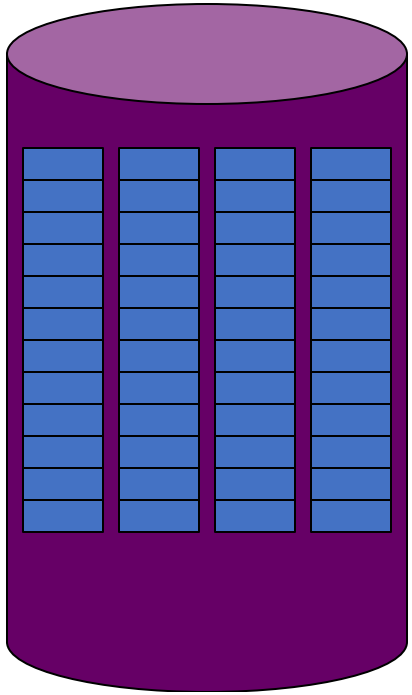
- When inserting a tuple, HeapFile inserts it on a page but does not write the page to disk
- When deleting a tuple, HeapFile deletes tuple from a page but does not write the page to disk
- The buffer manager worries when to write pages to disk (and when to read them from disk)
- When need to add new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

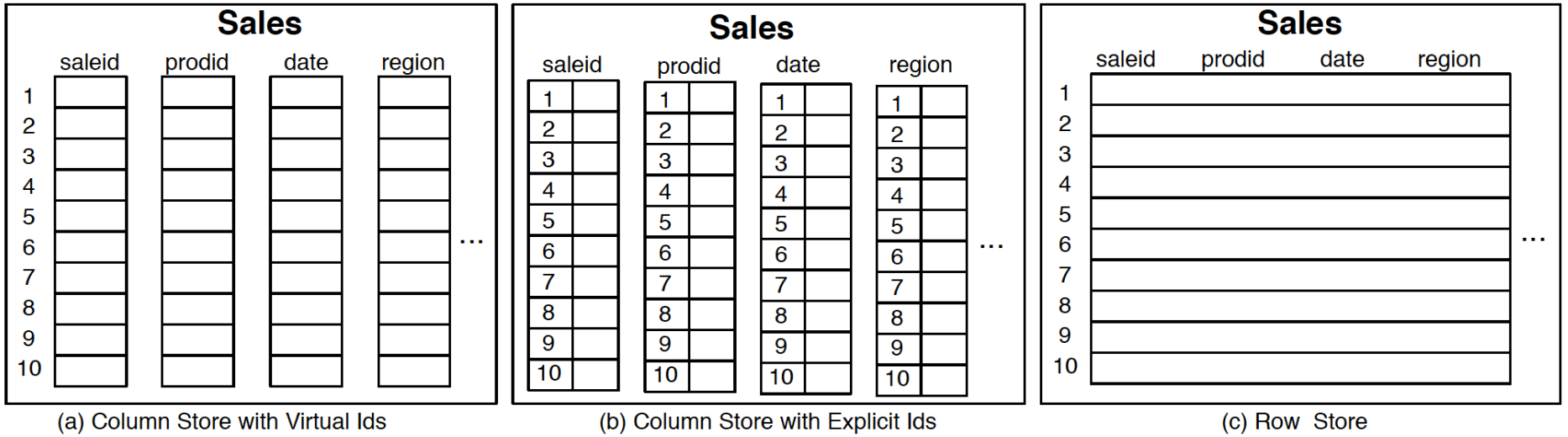



**Figure 1.1:** Physical layout of column-oriented vs row-oriented databases.

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