Intro to Database Systems (15-445/645)

03 Database Storage *Part 1*

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ADMINISTRIVIA

Project 0 due Sunday. Quick adaptation to C++ is a prerequisite for this course!

Homework 1 available, due Friday Feb 3rd.

Project 1 will be released next Monday, January 30th.

LAST CLASS

We now understand what a database looks like at a logical level and how to write queries to read/write data (e.g., using SQL).

Unfinished business: Window functions.

WINDOW FUNCTIONS

Performs a "sliding" calculation across a set of tuples that are related.

Like an aggregation but tuples are not grouped into a single output tuples.

How to "slice" up data
Can also sort

```
SELECT ... FUNC-NAME(...) OVER (...)
  FROM tableName
```

Aggregation Functions
Special Functions

WINDOW FUNCTIONS

Aggregation functions:

→ Anything that we discussed earlier

Special window functions:

→ ROW_NUMBER()→ # of the current row

→ RANK()→ Order position of the current row.

sid	cid	grade	row_num
53666	15-445	C	1
53688	15-721	A	2
53688	15-826	B	3
53655	15-445	B	4
53666	15-721	C	5

```
SELECT *, ROW_NUMBER() OVER () AS row_num
  FROM enrolled
```

WINDOW FUNCTIONS

The OVER keyword specifies how to group together tuples when computing the window function.

There are many ways to define a window, e.g., PARTITION BY to specify a group.

cid	sid	row_number
15-445	53666	1
15-445	53655	2
15-721	53688	1
15-721	53666	2
15-826	53688	1

```
SELECT cid, sid,
    ROW_NUMBER() OVER (PARTITION BY cid)
  FROM enrolled
 ORDER BY cid
```

WINDOW FUNCTIONS

You can also include an ORDER BY in the window grouping to sort entries in each group.

```
SELECT *,
    ROW_NUMBER() OVER (ORDER BY cid)
  FROM enrolled
 ORDER BY cid
```

WINDOW FUNCTIONS

Find the student(s) with the second highest grade for each course.

Group tuples by cid
Then sort by grade

```
SELECT * FROM (
  SELECT *, RANK() OVER (PARTITION BY cid
                ORDER BY grade ASC) AS rank
    FROM enrolled) AS ranking
 WHERE ranking.rank = 2
```

LAST CLASS

We now understand what a database looks like at a logical level and how to write queries to read/write data (e.g., using SQL).

Unfinished business: Window functions

We will next learn how to build software that manages a database (i.e., a DBMS).

COURSE OUTLINE

Relational Databases
Storage
Execution
Concurrency Control
Recovery
Distributed Databases
Potpourri

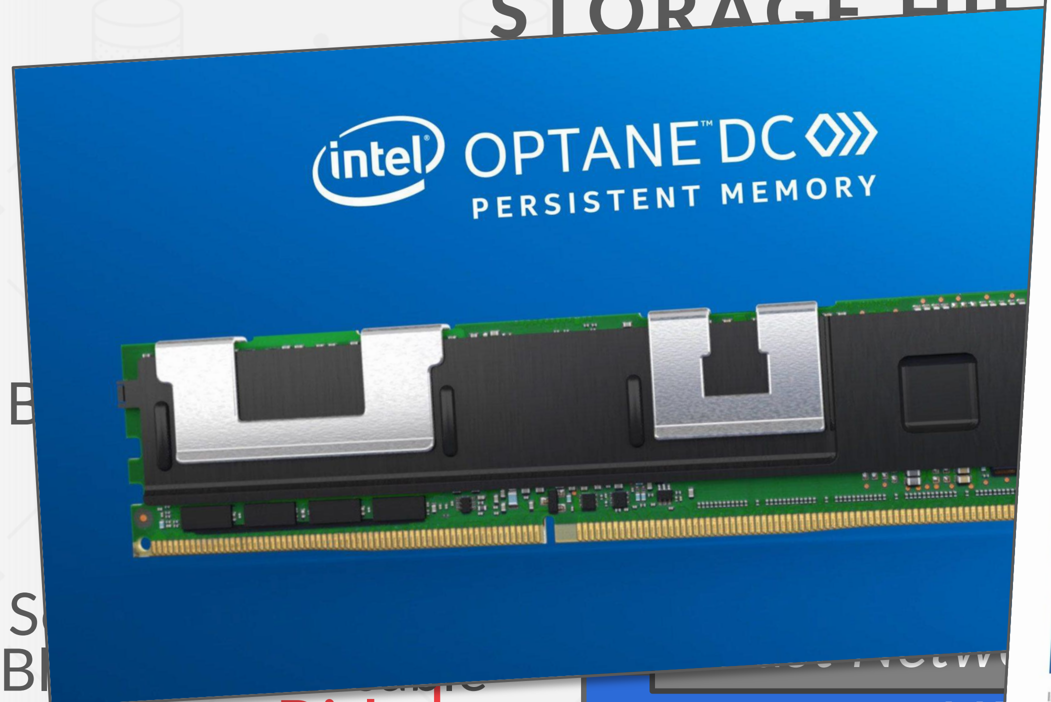
Query Planning
Operator Execution
Access Methods
Buffer Pool Manager
Disk Manager

DISK-BASED ARCHITECTURE

The DBMS assumes that the primary storage location of the database is on non-volatile disk.

The DBMS's components manage the movement of data between non-volatile and volatile storage.

STORAGE HIE



PCWorld
NEWS BEST PICKS REVIEWS HOW-TO DEALS

NEWS

Intel kills the remnants of Optane memory

The speed-boosting storage tech was already on the ropes.

By Michael Crider
Staff Writer, PCWorld | JUL 29, 2022 6:59 AM PDT

Image: Intel

If you haven't built a super-high-end workstation in a while, you might not have heard of Intel's Optane memory caching tech. Optane also powered ultra-fast SSDs for consumers and businesses alike. Not that it matters much now. After a disastrous second-quarter earnings call in which it missed expected revenue by billions of dollars, the company announced its plans to end its Optane memory business entirely.

Disk

HI

Networ

ACCESS TIMES

Latency Numbers Every Programmer Should Know

1 ns	L1 Cache Ref
4 ns	L2 Cache Ref
100 ns	DRAM
16,000 ns	SSD
2,000,000 ns	HDD
~50,000,000 ns	Network Storage
1,000,000,000 ns	Tape Archives

Source: Colin Scott

SEQUENTIAL VS. RANDOM ACCESS

Random access on non-volatile storage is almost always much slower than sequential access.

DBMS will want to maximize sequential access.
- → Algorithms try to reduce number of writes to random pages so that data is stored in contiguous blocks.
- → Allocating multiple pages at the same time is called an extent.

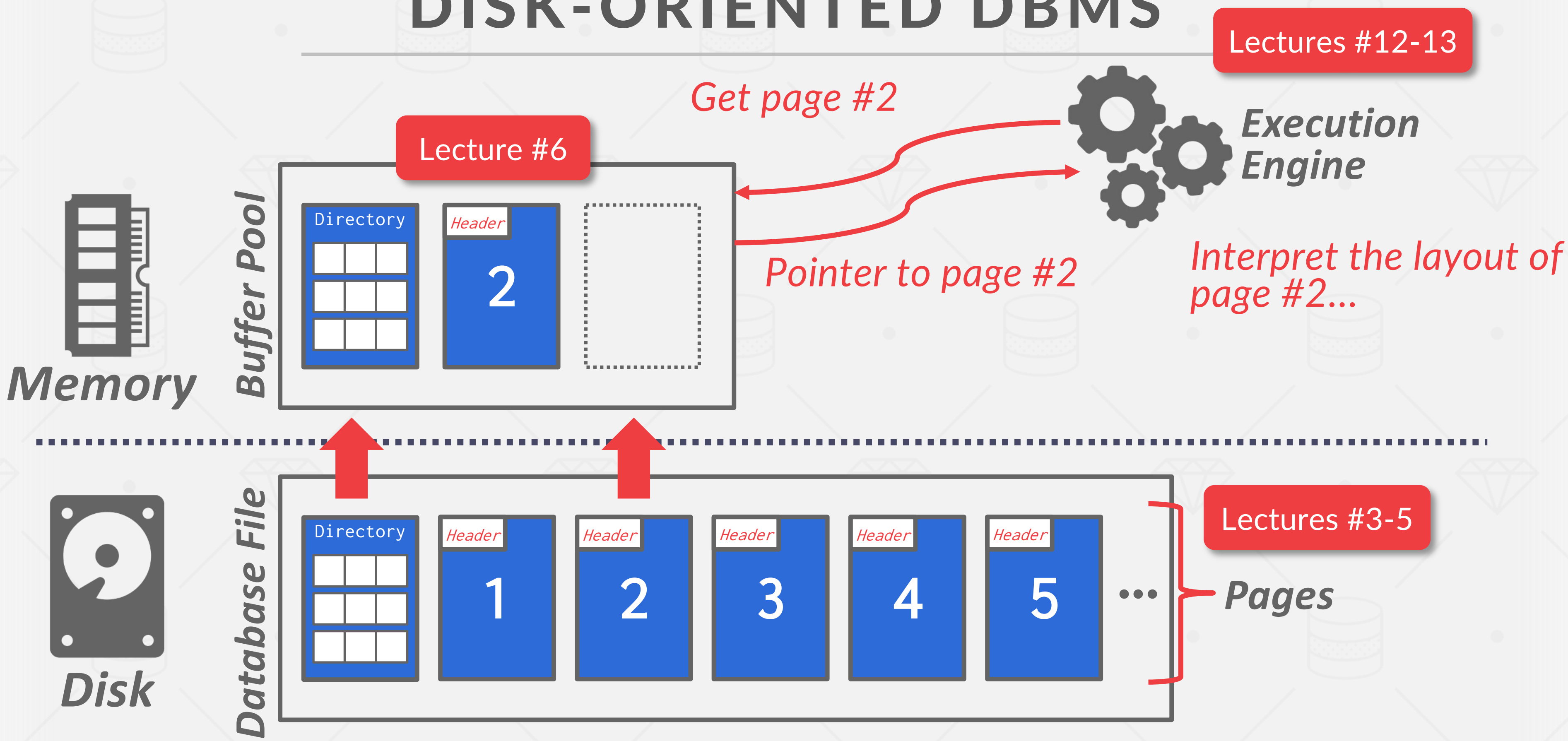
SYSTEM DESIGN GOALS

Allow the DBMS to manage databases that exceed the amount of memory available.

Reading/writing to disk is expensive, so it must be managed carefully to avoid large stalls and performance degradation.

Random access on disk is usually much slower than sequential access, so the DBMS will want to maximize sequential access.

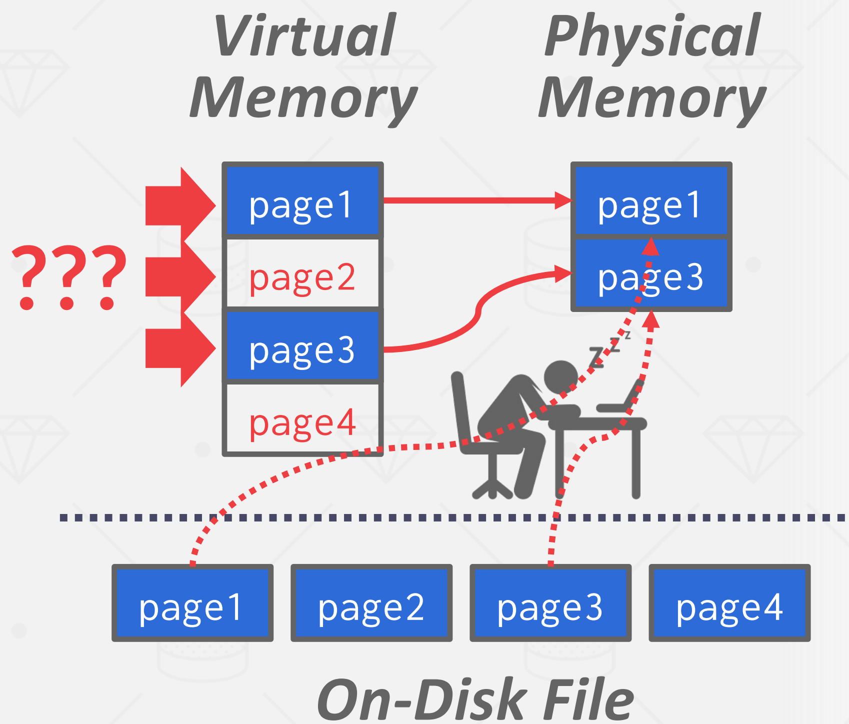
DISK-ORIENTED DBMS



WHY NOT USE THE OS?

The DBMS can use memory mapping (**mmap**) to store the contents of a file into the address space of a program.

The OS is responsible for moving the pages of the file in and out of memory, so the DBMS doesn't need to worry about it.



MEMORY MAPPED I/O PROBLEMS

Problem #1: Transaction Safety
→ OS can flush dirty pages at any time.

Problem #2: I/O Stalls
→ DBMS doesn't know which pages are in memory. The OS will stall a thread on page fault.

Problem #3: Error Handling
→ Difficult to validate pages. Any access can cause a `SIGBUS` that the DBMS must handle.

Problem #4: Performance Issues
→ OS data structure contention. TLB shootdowns.

WHY NOT USE THE OS?

There are some solutions to some of these problems:

→ **madvise**: Tell the OS how you expect to read certain pages.

→ **mlock**: Tell the OS that memory ranges cannot be paged out.

→ **msync**: Tell the OS to flush memory ranges out to disk.

Full Usage

monetdb
LMDB
RAVENDB
levelDB
elasticsearch
QuestDB

Partial Usage

mongoDB
SingleStore
SQLite
influxdb

WHY NOT USE THE OS?

DBMS (almost) always wants to control things itself and can do a better job than the OS.

→ Flushing dirty pages to disk in the correct order.
→ Specialized prefetching.
→ Buffer replacement policy.
→ Thread/process scheduling.

The OS is **not** your friend.

DATABASE STORAGE

Problem #1: How the DBMS represents the database in files on disk. ← Today

Problem #2: How the DBMS manages its memory and moves data back-and-forth from disk.

TODAY'S AGENDA

File Storage
Page Layout
Tuple Layout

FILE STORAGE

The DBMS stores a database as one or more files on disk typically in a proprietary format.
→ The OS doesn't know anything about the contents of these files.

Early systems in the 1980s used custom filesystems on raw storage.
→ Some DBMSs still support this.
→ Most newer DBMSs do not do this.

STORAGE MANAGER

The storage manager is responsible for maintaining a database's files.

→ Some do their own scheduling for reads and writes to improve spatial and temporal locality of pages.

It organizes the files as a collection of pages.

→ Tracks data read/written to pages.
→ Tracks the available space.

DATABASE PAGES

A page is a fixed-size block of data.
→ It can contain tuples, meta-data, indexes, log records…
→ Most systems do not mix page types.
→ Some systems require a page to be self-contained.

Each page is given a unique identifier.
→ The DBMS uses an indirection layer to map page IDs to physical locations.

DATABASE PAGES

There are three different notions of "pages" in a DBMS:
→ Hardware Page (usually 4KB)
→ OS Page (usually 4KB)
→ Database Page (512B-16KB)

A hardware page is the largest block of data that the storage device can guarantee failsafe writes.

4KB
SQLite
IBM DB2
ORACLE

8KB
Microsoft SQL Server
PostgreSQL

16KB
MySQL

PAGE STORAGE ARCHITECTURE

Different DBMSs manage pages in files on disk in different ways.

→ Heap File Organization
→ Tree File Organization
→ Sequential / Sorted File Organization (ISAM)
→ Hashing File Organization

At this point in the hierarchy we don't need to know anything about what is inside of the pages.

HEAP FILE

A heap file is an unordered collection of pages with tuples that are stored in random order.

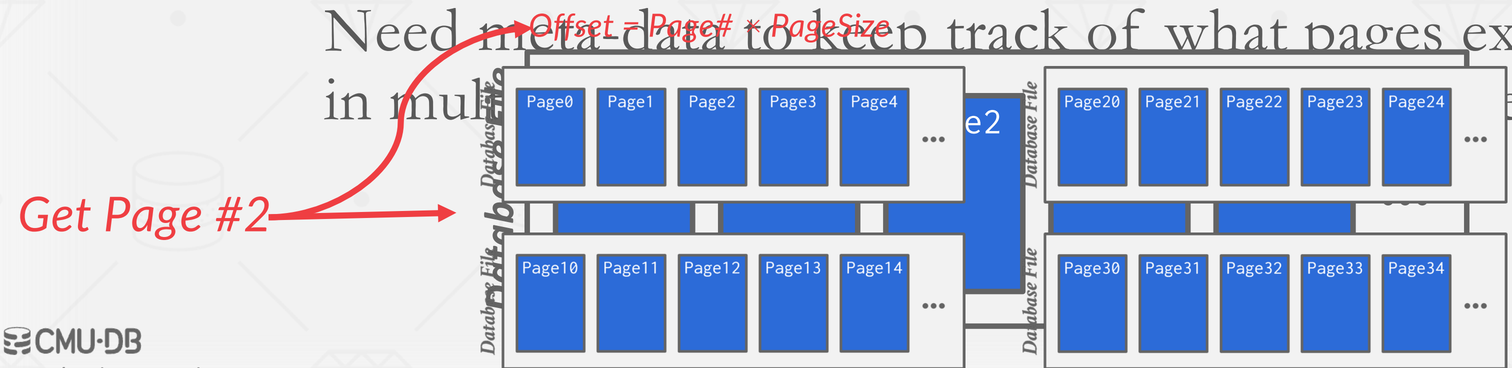
→ Create / Get / Write / Delete Page

→ Must also support iterating over all pages.

It is easy to find pages if there is only a single file.

Need meta-data to keep track of what pages exist

in mul e.



HEAP FILE: PAGE DIRECTORY

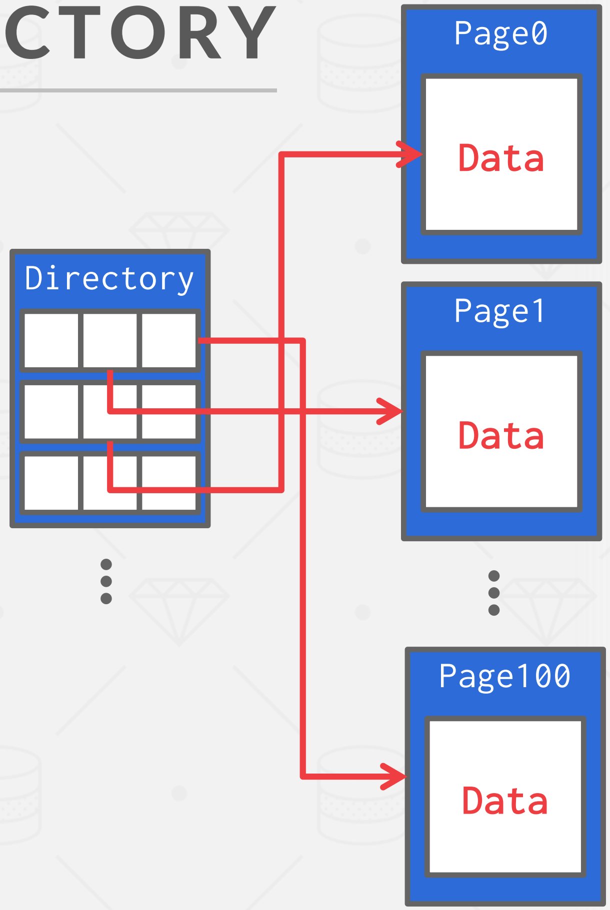
The DBMS maintains special pages that tracks the location of data pages in the database files.

→ Must make sure that the directory pages are in sync with the data pages.

The directory also records meta-data about available space:

→ The number of free slots per page.

→ List of free / empty pages.



TODAY'S AGENDA

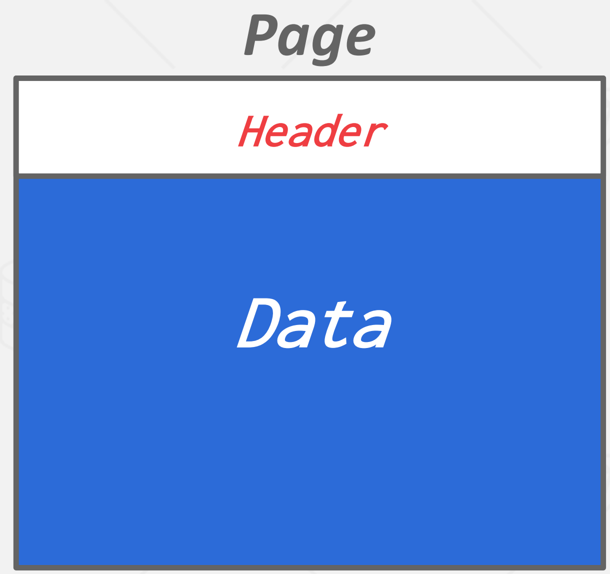
File Storage
Page Layout
Tuple Layout

PAGE HEADER

Every page contains a header of meta-data about the page's contents.

→ Page Size
→ Checksum
→ DBMS Version
→ Transaction Visibility
→ Compression Information

Some systems require pages to be self-contained (e.g., Oracle).



PAGE LAYOUT

For any page storage architecture, we now need to decide how to organize the data inside of the page.

→ We are still assuming that we are only storing tuples.

Two approaches:

→ Tuple-oriented

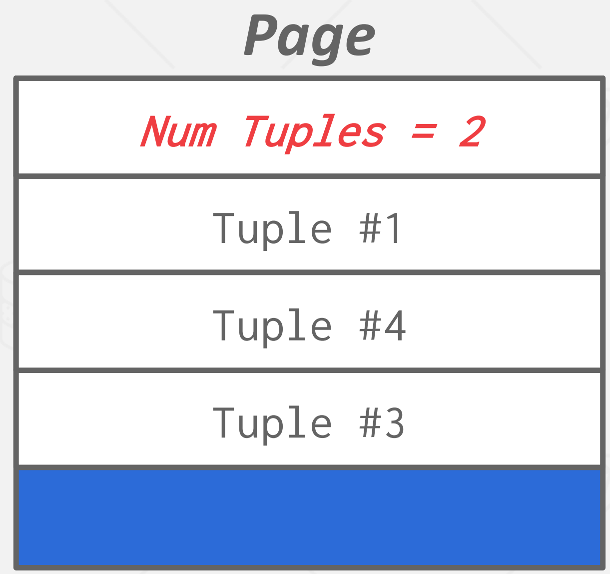
→ Log-structured ← Next Class

TUPLE STORAGE

How to store tuples in a page?

Strawman Idea: Keep track of the number of tuples in a page and then just append a new tuple to the end.

→ What happens if we delete a tuple?
→ What happens if we have a variable-length attribute?

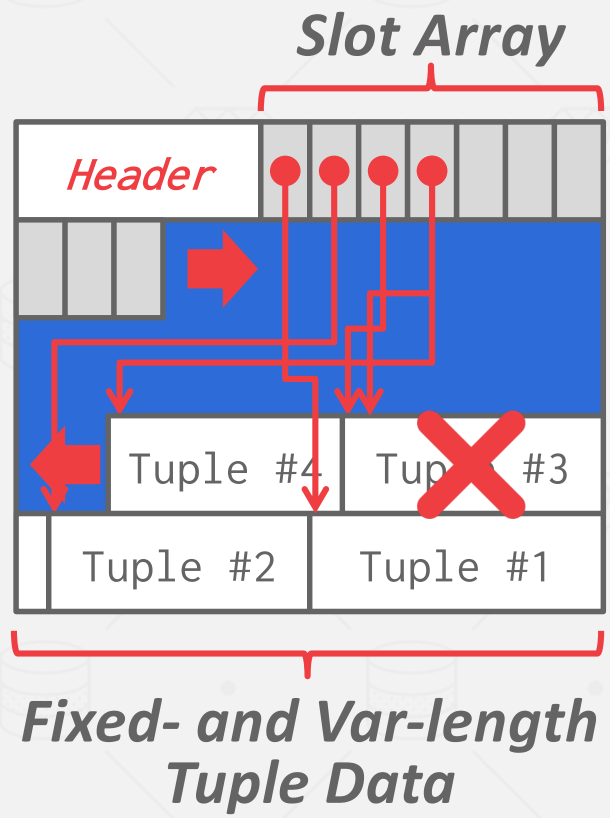


SLOTTED PAGES

The most common layout scheme is called slotted pages.

The slot array maps "slots" to the tuples' starting position offsets.

The header keeps track of:
→ The # of used slots
→ The offset of the starting location of the last slot used.



RECORD IDS

The DBMS needs a way to keep track of individual tuples.

Each tuple is assigned a unique record identifier.
→ Most common: **page_id** + **offset/slot**
→ Can also contain file location info.

An application cannot rely on these IDs to mean anything.

PostgreSQL
CTID (6-bytes)

SQLite
ROWID (8-bytes)

ORACLE
ROWID (10-bytes)

TODAY'S AGENDA

File Storage
Page Layout
Tuple Layout

TUPLE LAYOUT

A tuple is essentially a sequence of bytes.

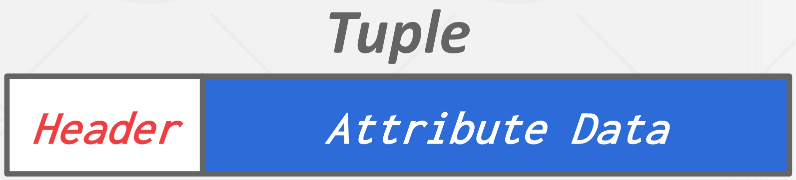
It's the job of the DBMS to interpret those bytes into attribute types and values.

TUPLE HEADER

Each tuple is prefixed with a header that contains meta-data about it.

→ Visibility info (concurrency control)
→ Bit Map for NULL values.

We do not need to store meta-data about the schema.



TUPLE DATA

Attributes are typically stored in the order that you specify them when you create the table.

This is done for software engineering reasons (i.e., simplicity).

However, it might be more efficient to lay them out differently.

Tuple

Header	a	b	c	d	e

```
CREATE TABLE foo (
  a INT PRIMARY KEY,
  b INT NOT NULL,
  c INT,
  d DOUBLE,
  e FLOAT
);
```

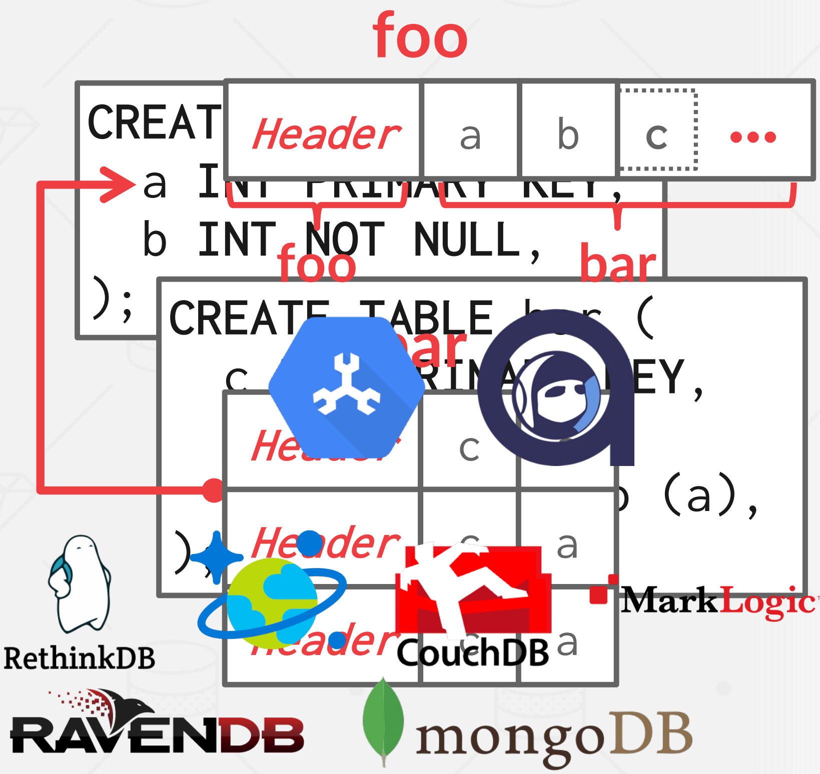
DENORMALIZED TUPLE DATA

DBMS can physically ***denormalize*** (e.g., "pre join") related tuples and store them together in the same page.

→ Potentially reduces the amount of I/O for common workload patterns.
→ Can make updates more expensive.

Not a new idea.

→ IBM System R did this in the 1970s.
→ Several NoSQL DBMSs do this without calling it physical denormalization.



CONCLUSION

Database is organized in pages.
Different ways to track pages.
Different ways to store pages.
Different ways to store tuples.

NEXT CLASS

Log-Structured Storage
Value Representation
Catalogs