Carnegie Mellon University

Database Systems

Database Storage: *Files & Pages*

15-445/645 FALL 2024 » PROF. ANDY PAVLO

ADMINISTRIVIA

Homework #1 is due September 8th @ 11:59pm

Project #0 is due September 8th @ 11:59pm

Project #1 will be released on September 9th

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).

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

COURSE OUTLINE

- Relational Databases
- → Storage
- Query Execution
- Concurrency Control
- Database Recovery
- Distributed Databases
- Potpourri

TODAY'S AGENDA

Background
File Storage
Page Layout
Tuple Layout
DB Flash Talk: Neon

DISK-BASED ARCHITECTURE

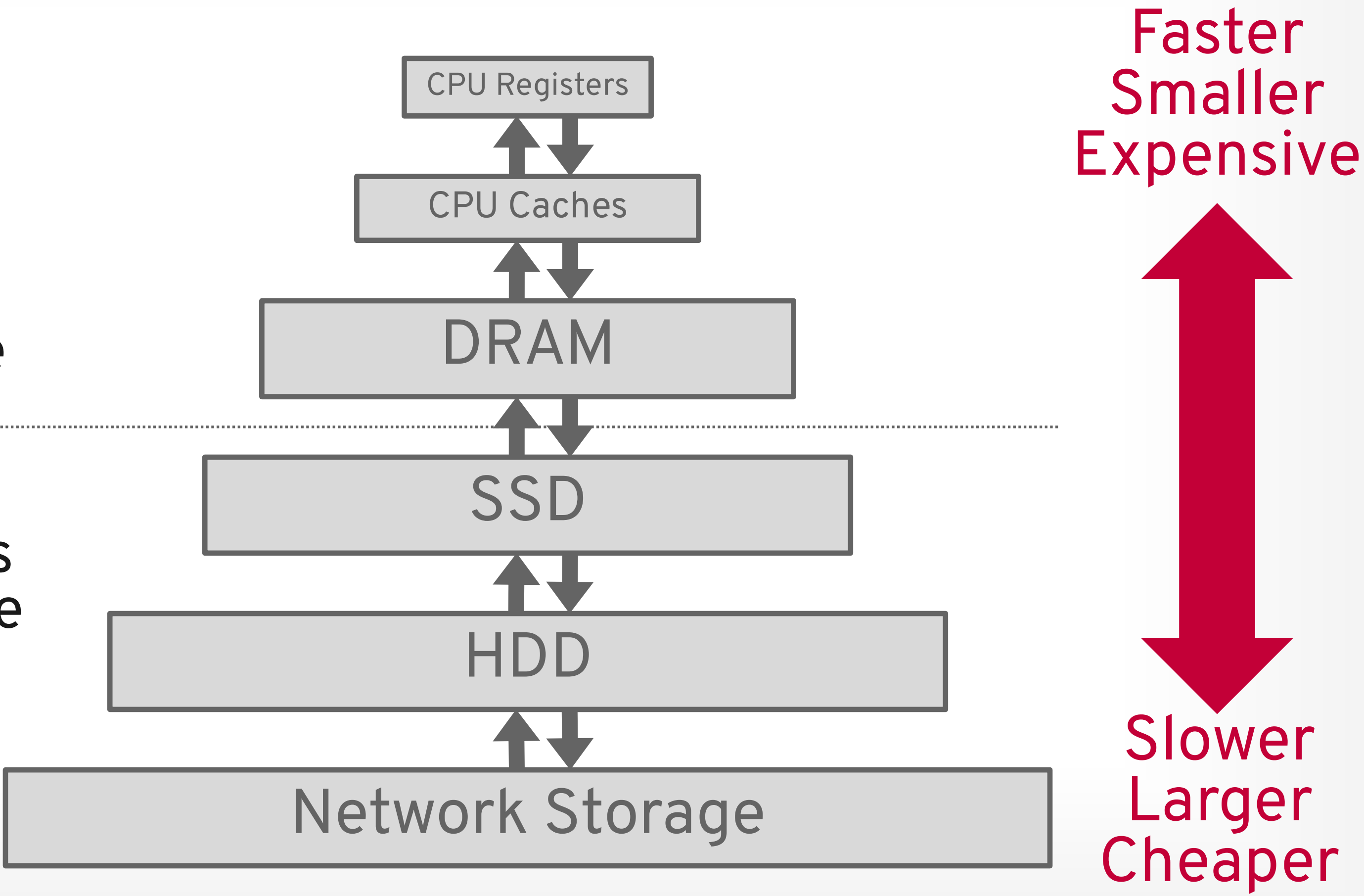
The DBMS assumes that the primary storage location of the database is on non-volatile disk.

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

STORAGE HIERARCHY

Volatile
Random Access
Byte-Addressable

Non-Volatile
Sequential Access
Block-Addressable



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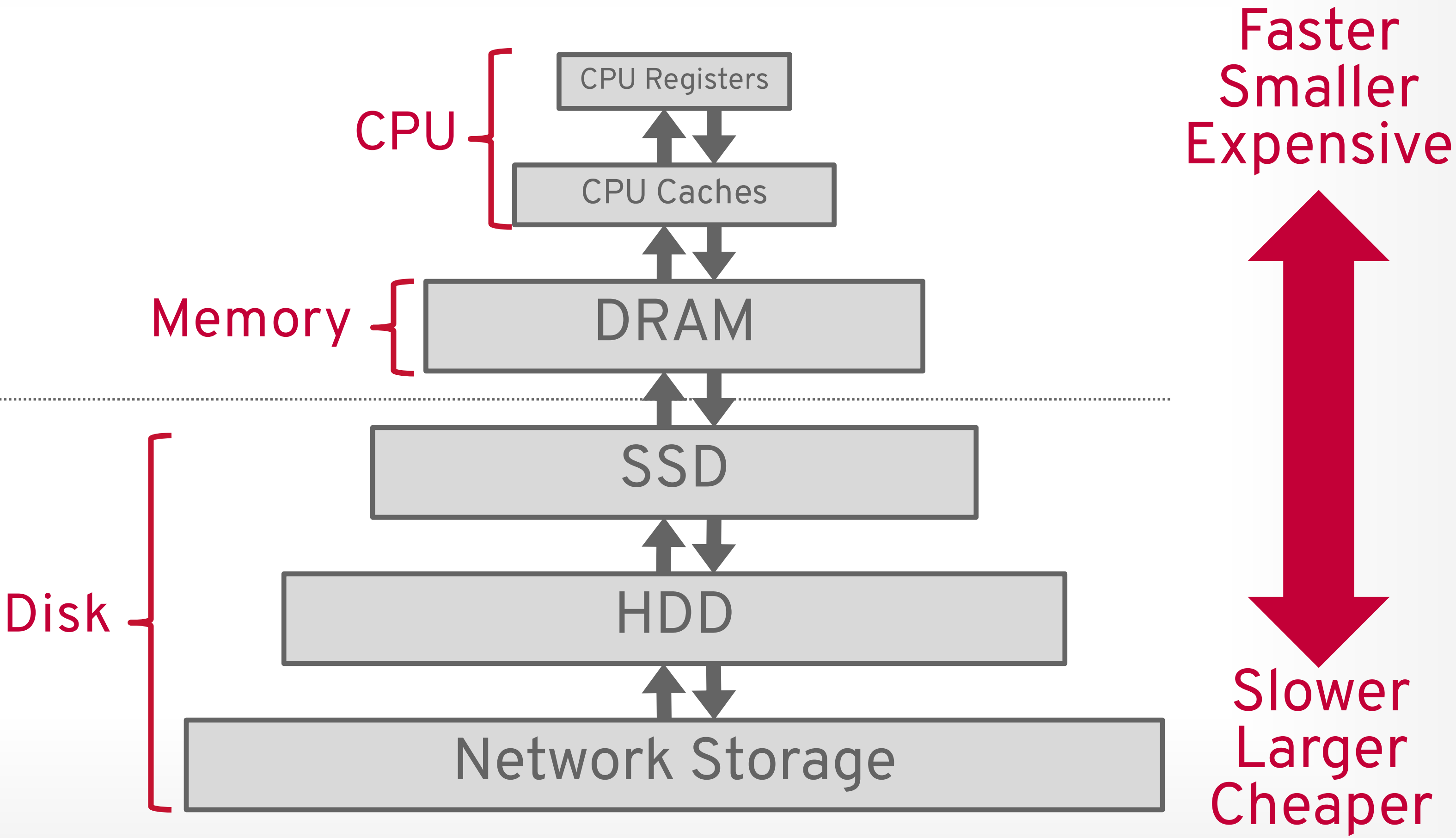

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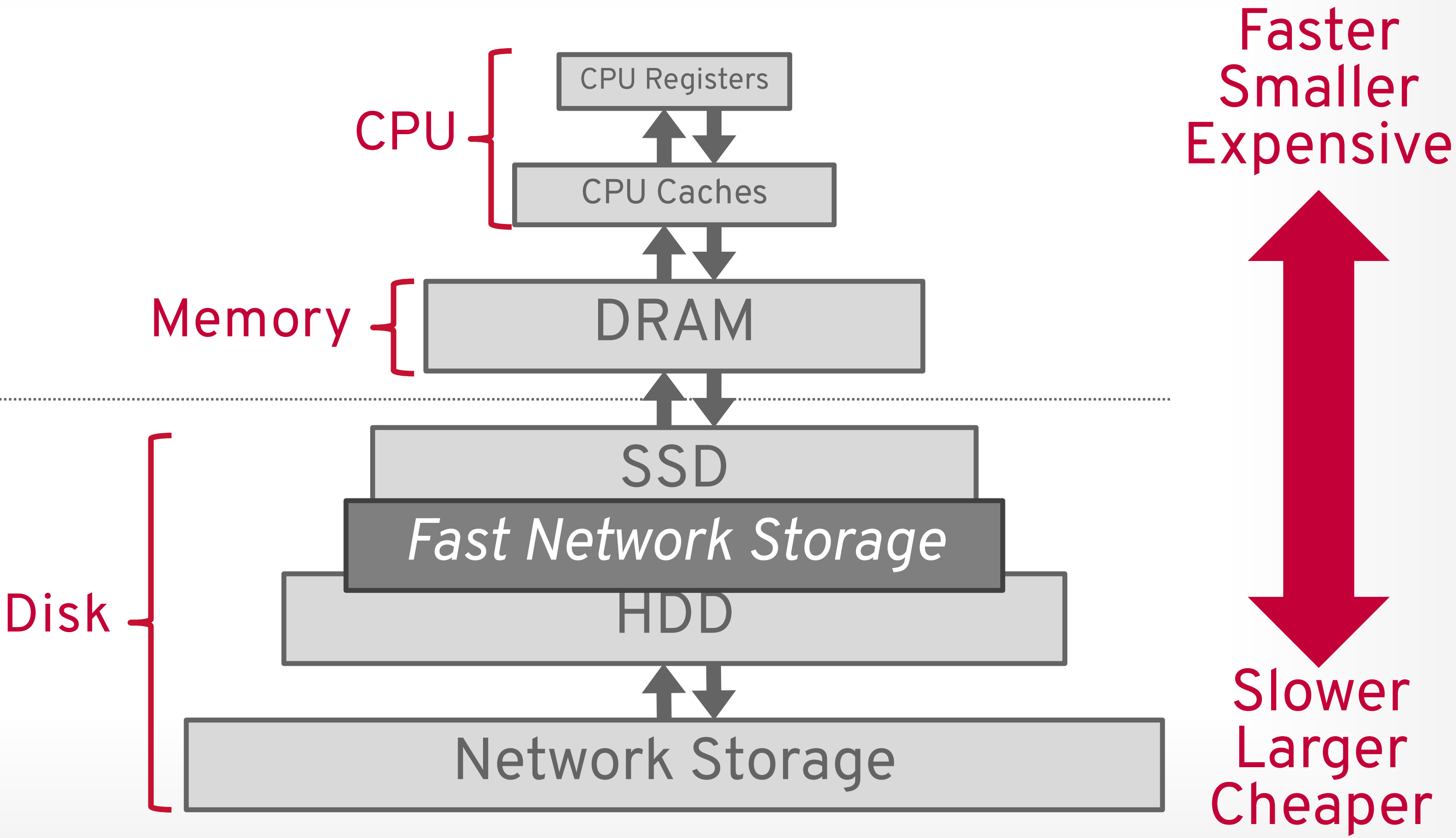

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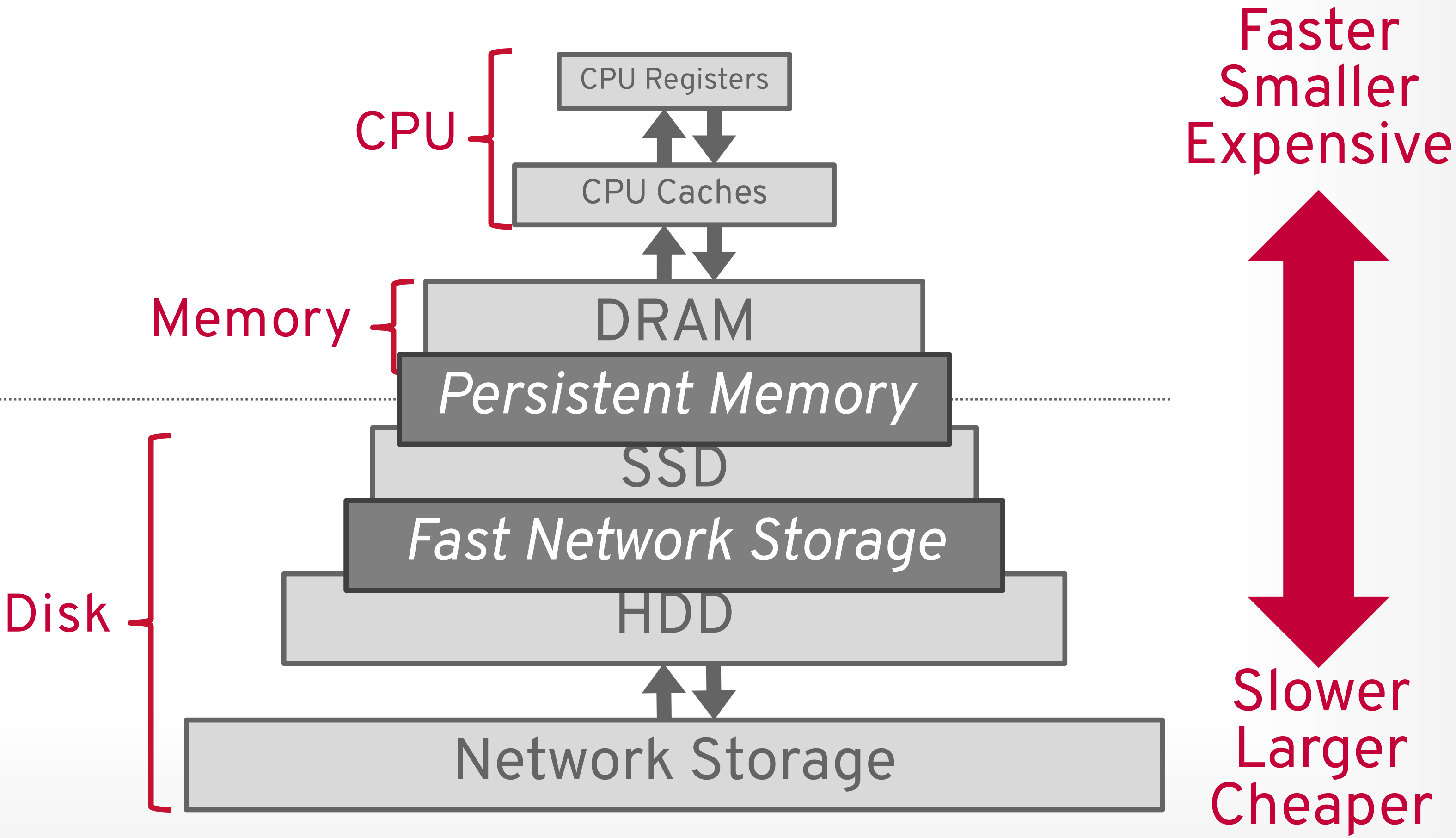

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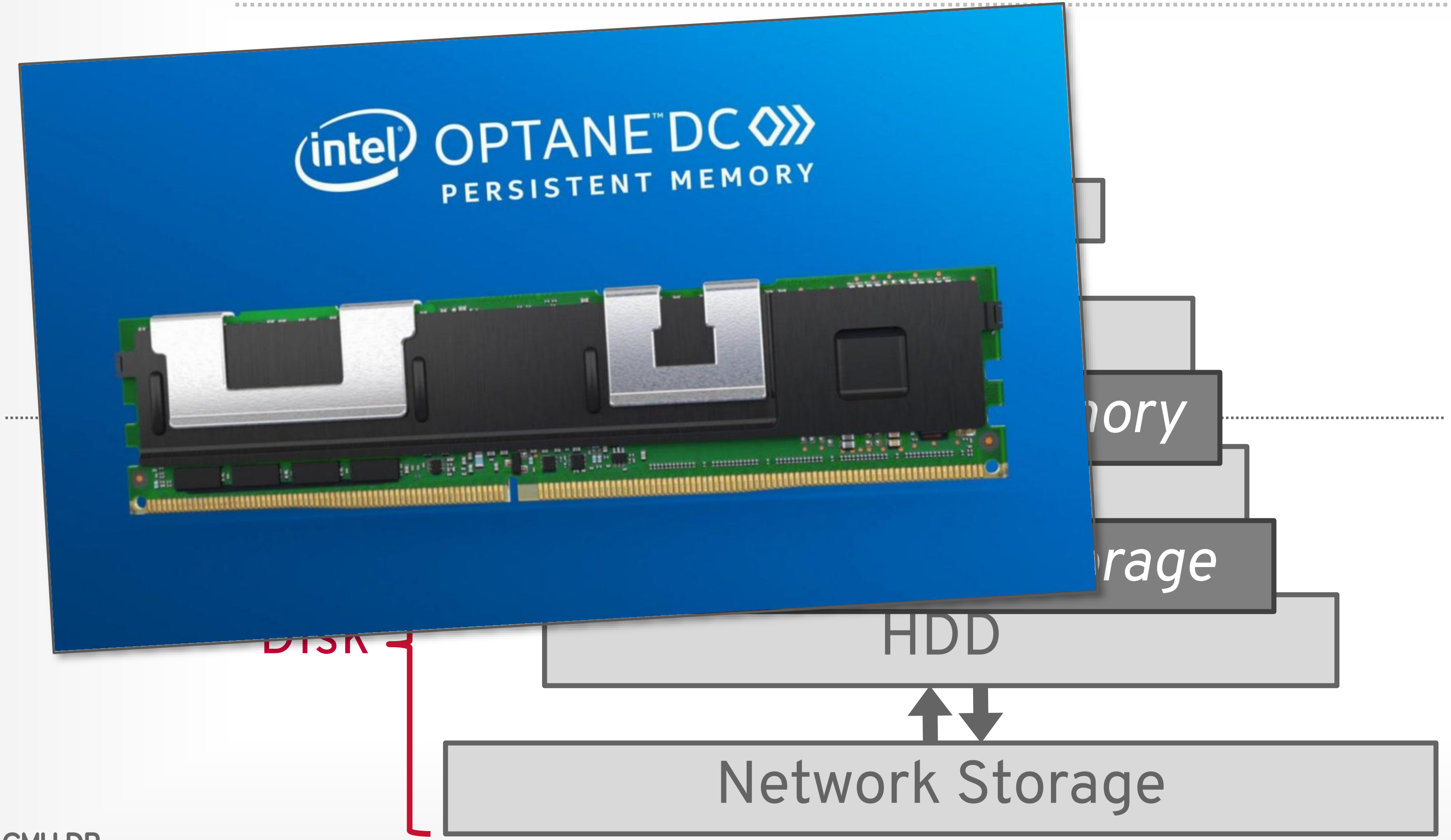
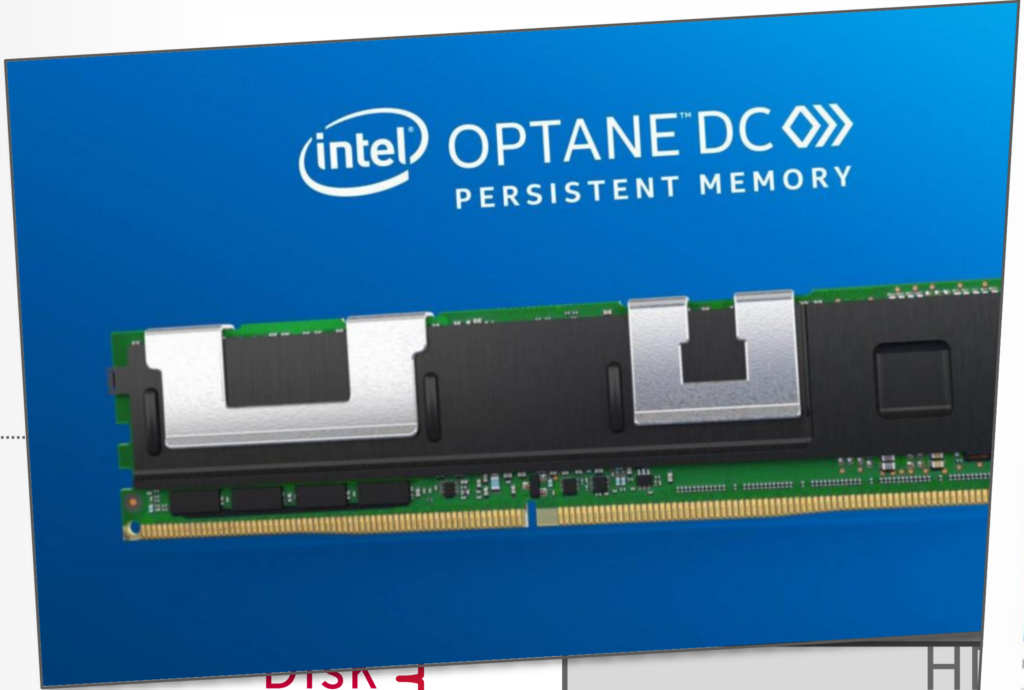
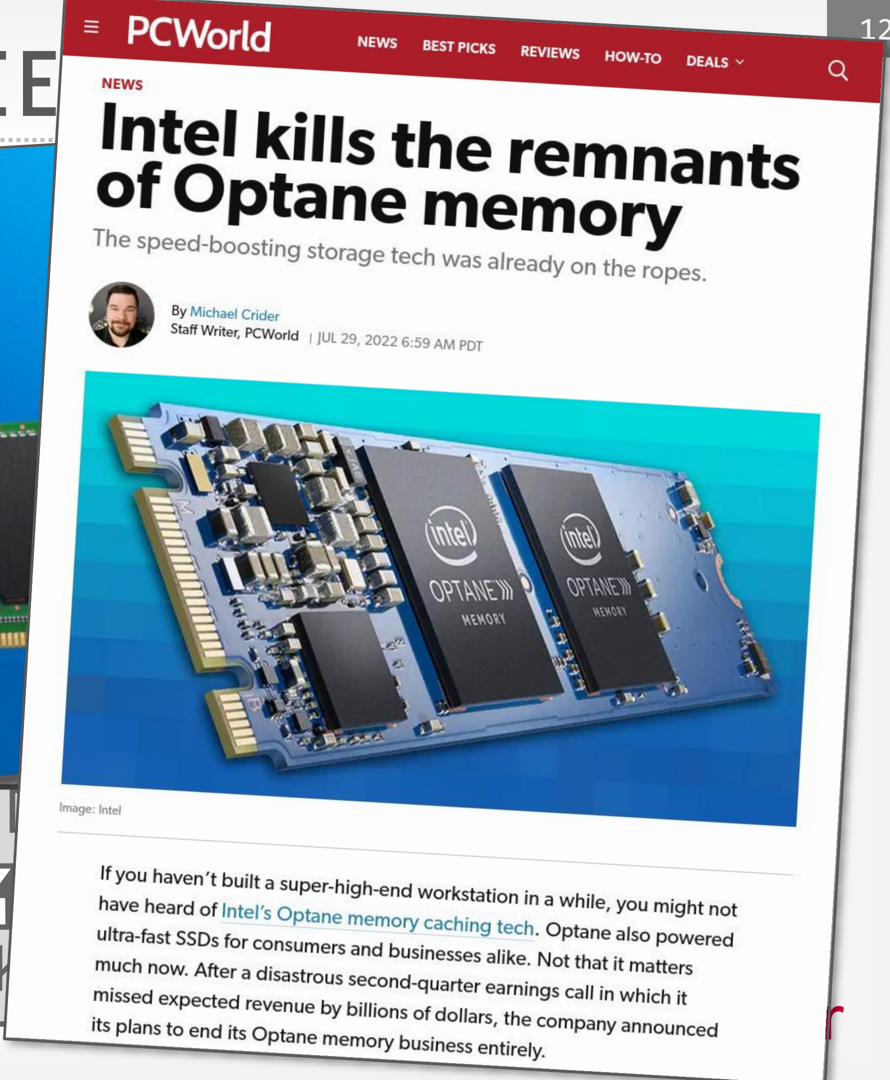


Faster
Smaller
Expensive

Slower
Larger
Cheaper

STORAGE HIE





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

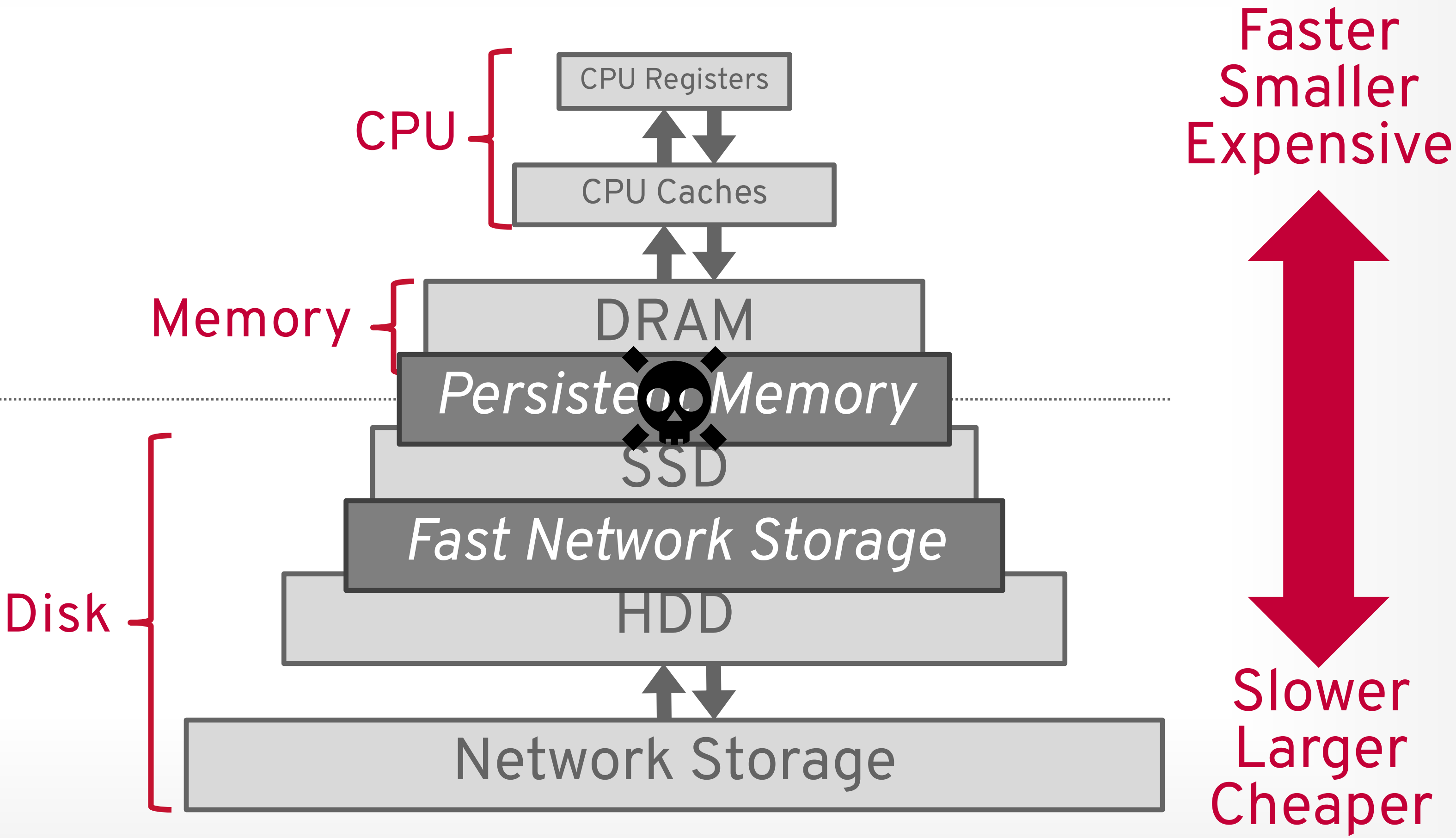
If you haven't built a super-high-end workstation in a while, you might not have heard of Intel's Optane memory caching tech. Optane also powered ultra-fast SSDs for consumers and businesses alike. Not that it matters much now. After a disastrous second-quarter earnings call in which it missed expected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

Disk

HI

Network

STORAGE HIERARCHY



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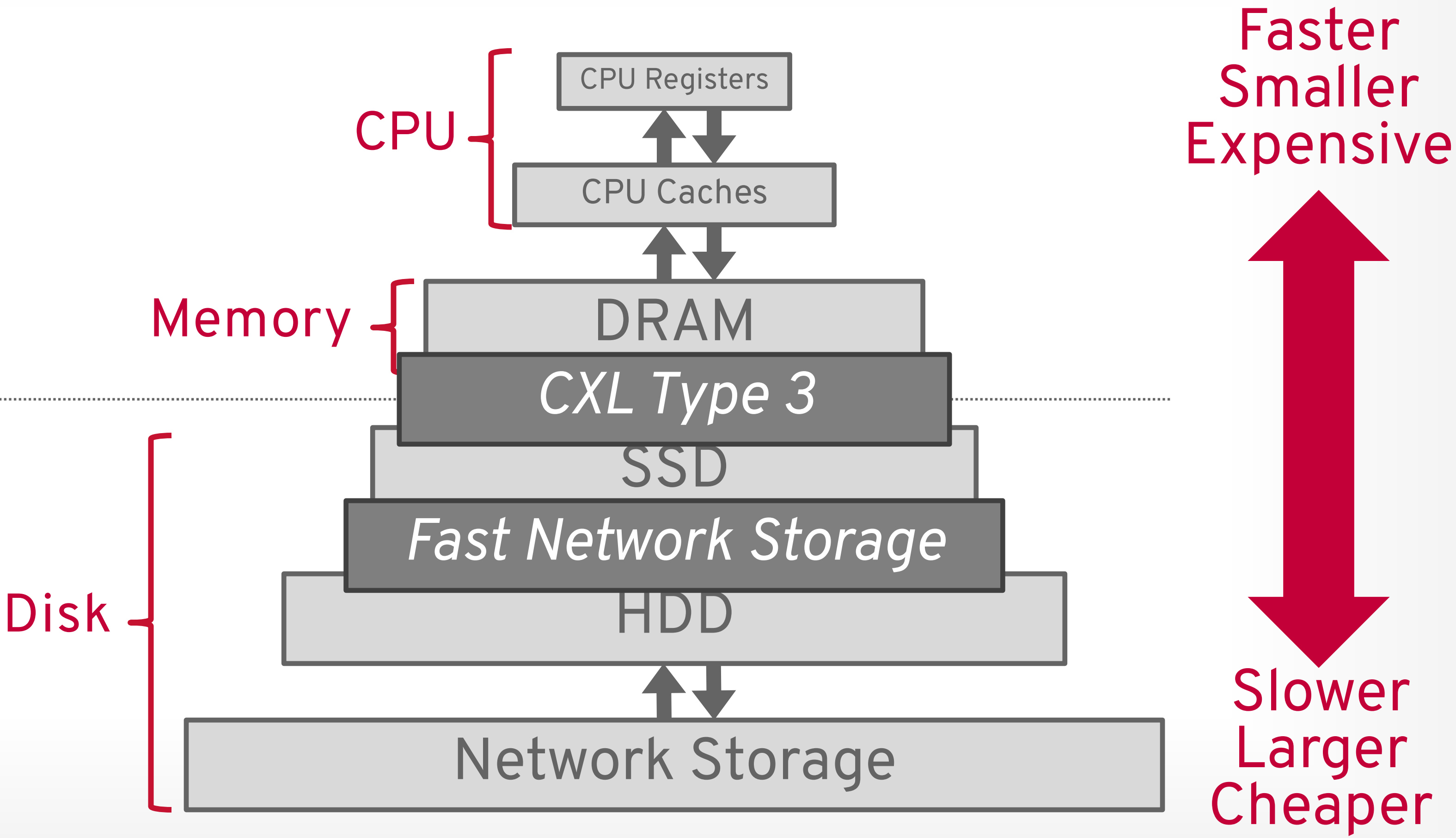

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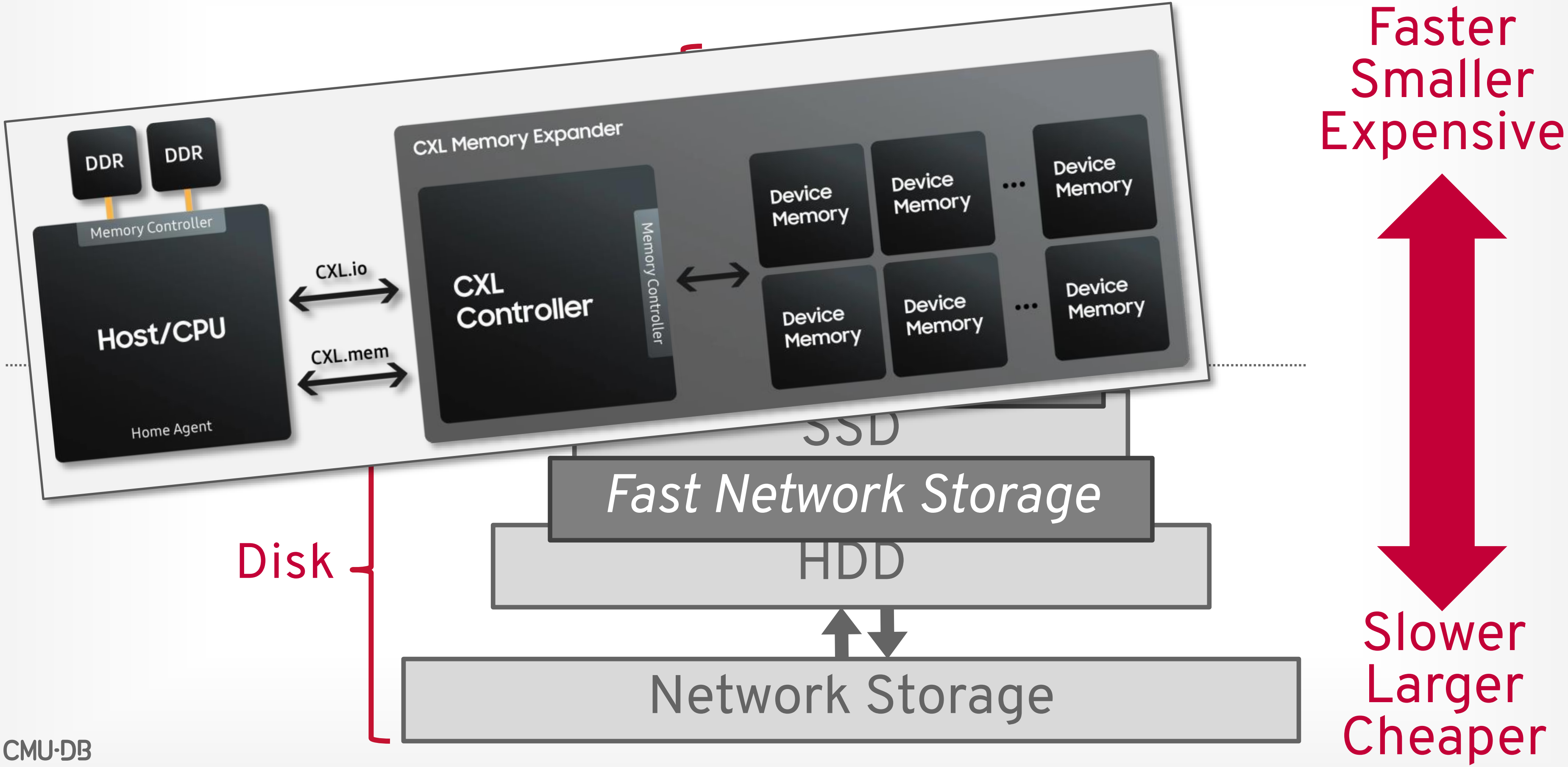

ACCESS TIMES

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

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4 ns	L2 Cache Ref	⬅	**4 sec**
100 ns	DRAM	⬅	**100 sec**
16,000 ns	SSD	⬅	**4.4 hours**
2,000,000 ns	HDD	⬅	**3.3 weeks**
~50,000,000 ns	Network Storage	⬅	**1.5 years**
1,000,000,000 ns	Tape Archives	⬅	**31.7 years**

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.

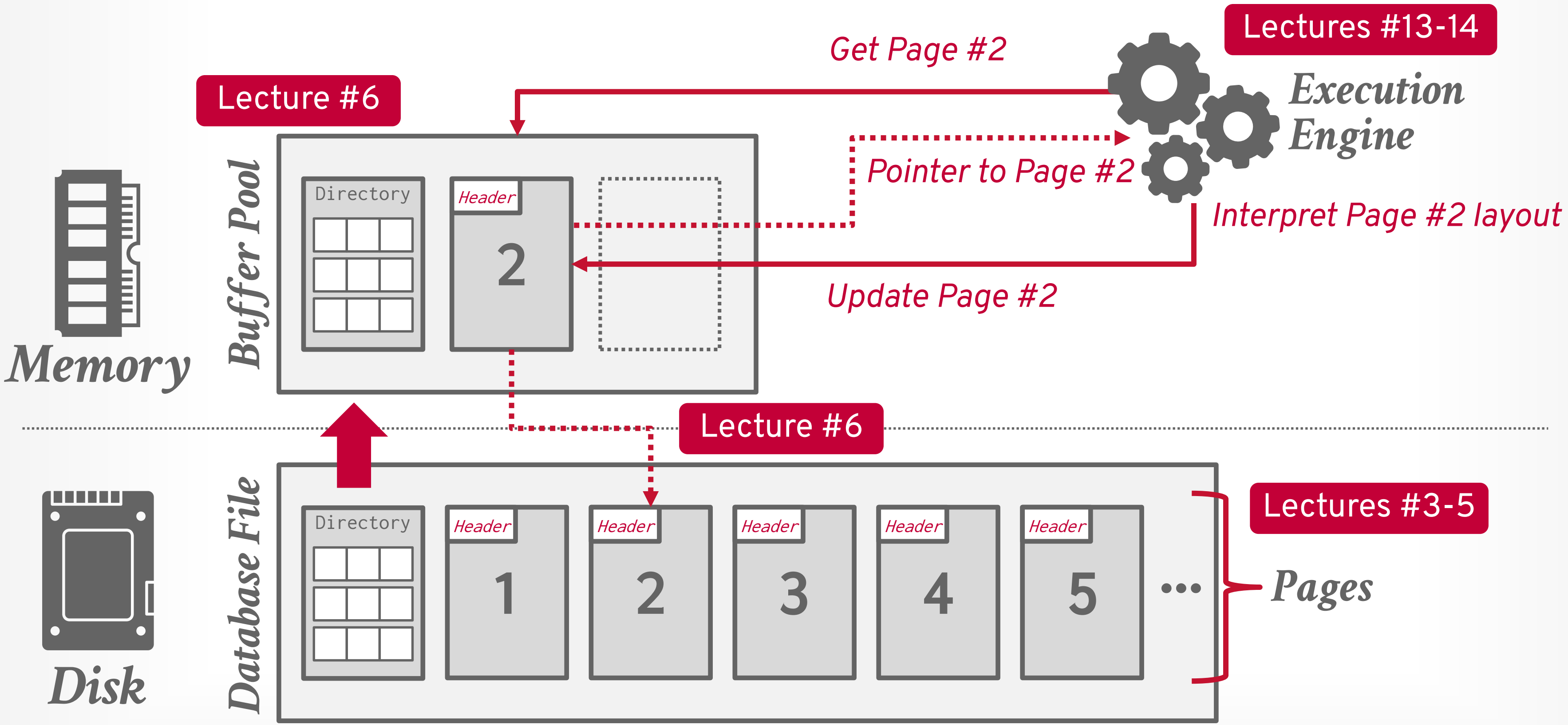
SYSTEM DESIGN GOALS

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



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.

FILE STORAGE

The DBMS stores a database as one or more files on disk typically in a proprietary format.

→ The OS does not know anything about the contents of these files.
→ We will discuss portable file formats next week…

Early systems in the 1980s used custom filesystems on raw block storage.

→ Some "enterprise" 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.

A DBMS typically does not maintain multiple copies of a page on disk.

→ Assume this happens above/below storage manager.

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 (**page ID**).
→ A page ID could be unique per DBMS instance, per database, or per table.
→ 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, x64 2MB/1GB)

→ Database Page (512B-32KB)

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

DBMSs that specialize in read-only workloads have larger page sizes.

Default DB Page Sizes

Size	DBMS
4KB	SQLite, ORACLE, IBM DB2, RocksDB, WIREDTIGER
8KB	Microsoft SQL Server, PostgreSQL
16KB	MySQL

PAGE STORAGE ARCHITECTURE

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

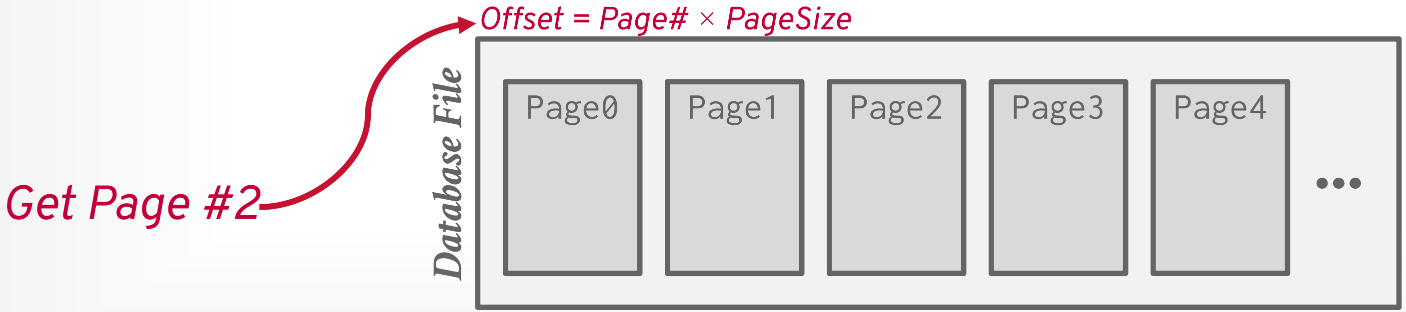
- → Heap File Organization
- → Tree File Organization
- → Sequential / Sorted File Organization (ISAM)
- → Hashing File Organization

At this point in the hierarchy, we do <u>not</u> 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.

Need additional meta-data to track location of files and free space availability.



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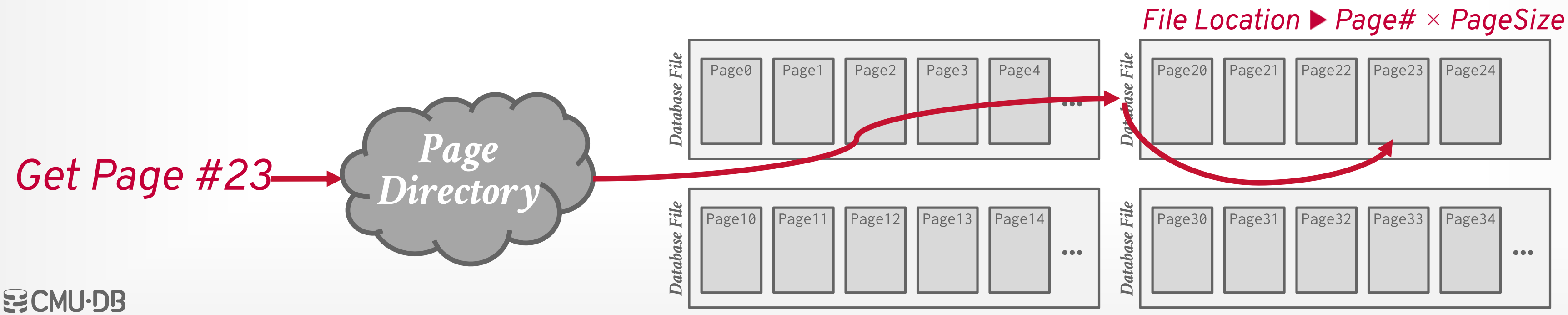


HEAP FILE: PAGE DIRECTORY

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

→ One entry per database object.

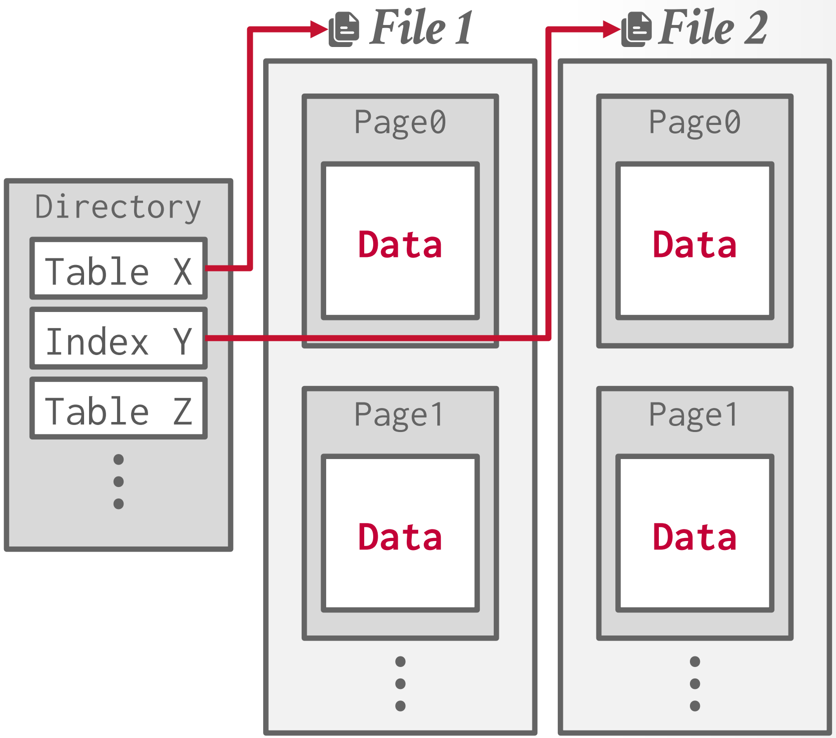
→ Must make sure that the directory pages are in sync with the data pages.

DBMS also keeps meta-data about pages' contents:

→ Amount of free space per page.

→ List of free / empty pages.

→ Page type (data vs. meta-data).



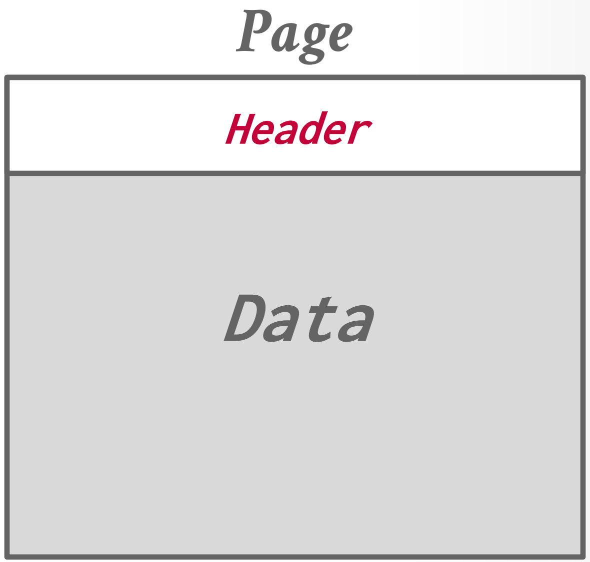
TODAY'S AGENDA

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 / Encoding Meta-data
→ Schema Information
→ Data Summary / Sketches



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 in a row-oriented storage model.

Lecture #5

Approach #1: Tuple-oriented Storage ← Today

Approach #2: Log-structured Storage

Approach #3: Index-organized Storage

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Approach #2: Log-structured Storage

Approach #3: Index-organized Storage

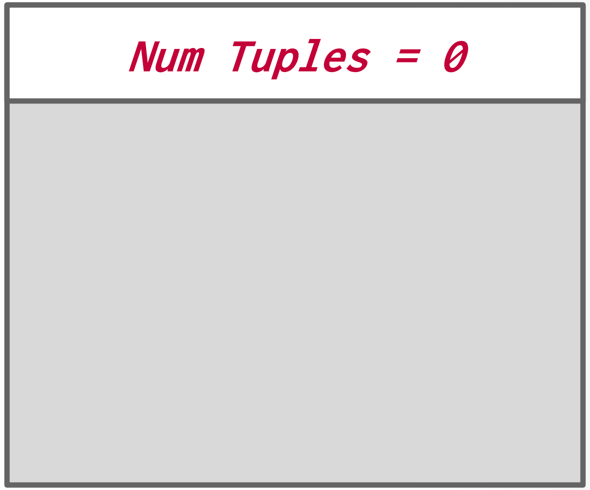
Lecture #4

TUPLE-ORIENTED 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.

Page



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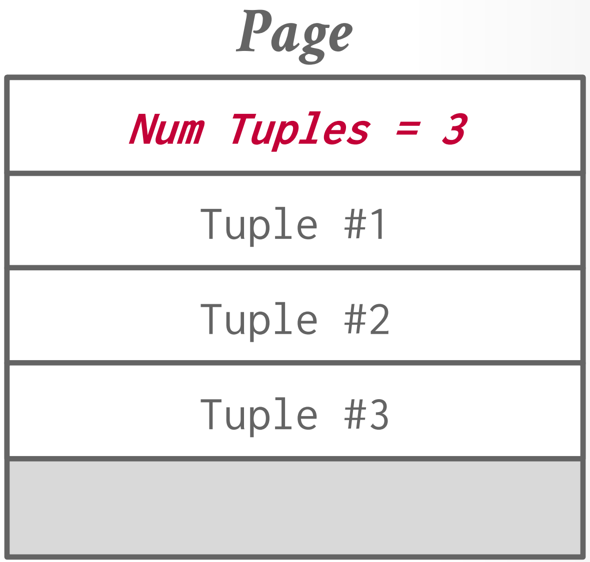
→ What happens if we delete a tuple?



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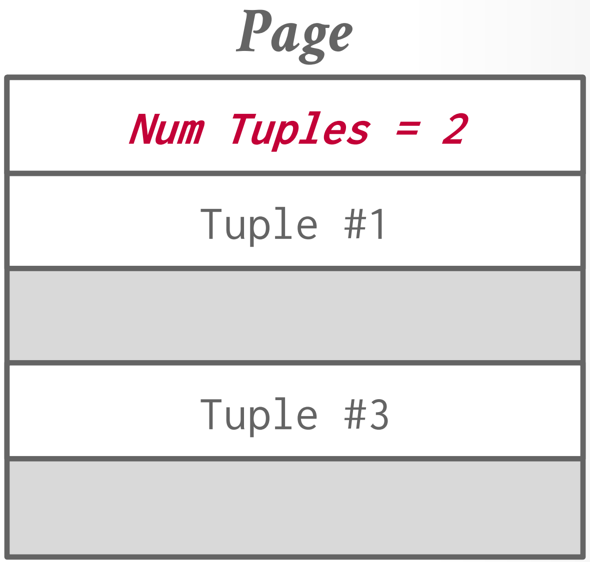

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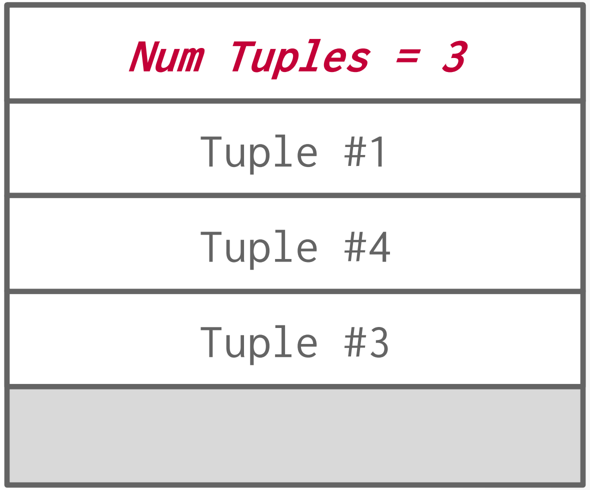

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How to store tuples in a page?

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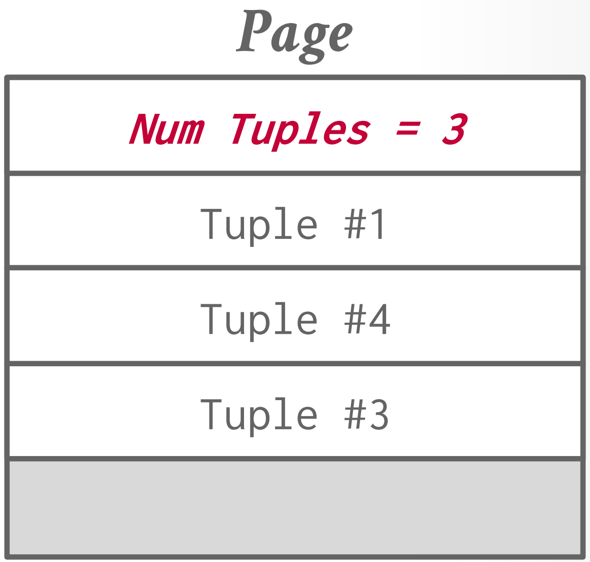
→ What happens if we delete a tuple?
→ What happens if we have a variable-length attribute?

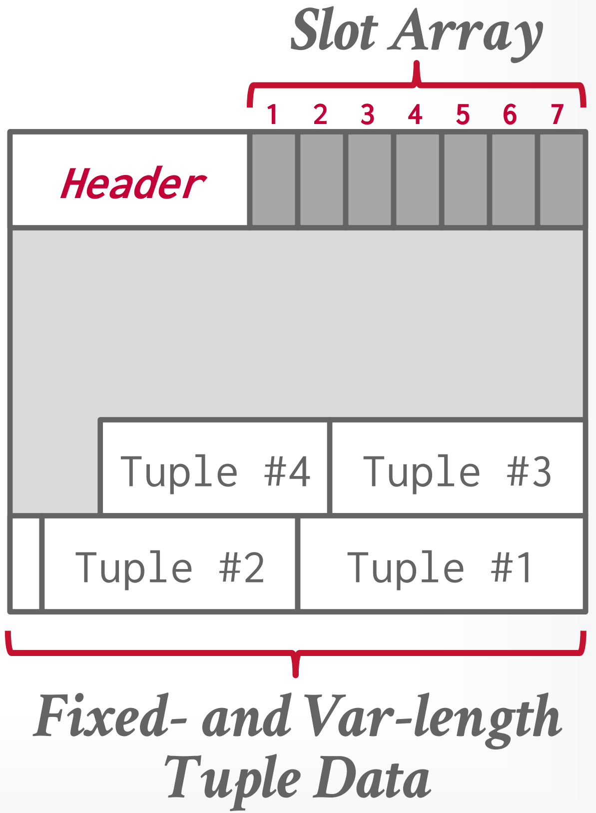


SLOTTED PAGES

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.



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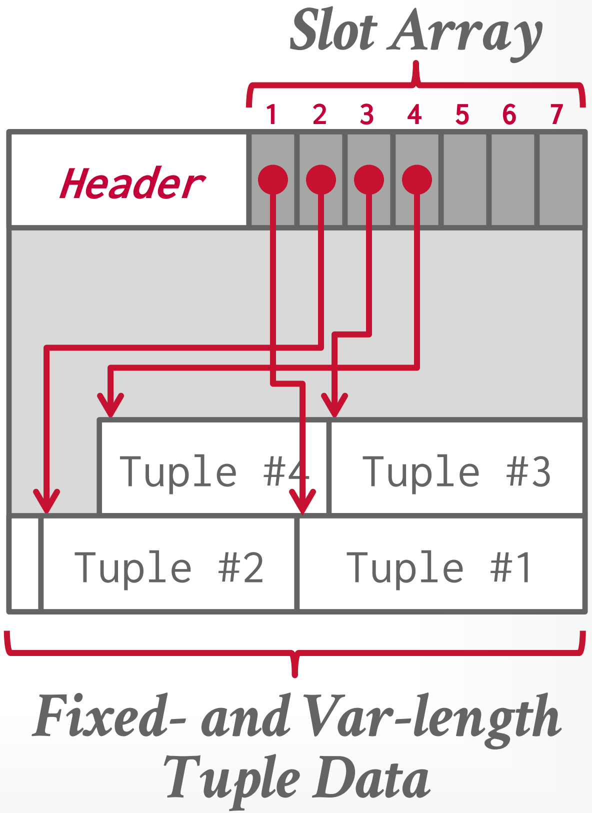

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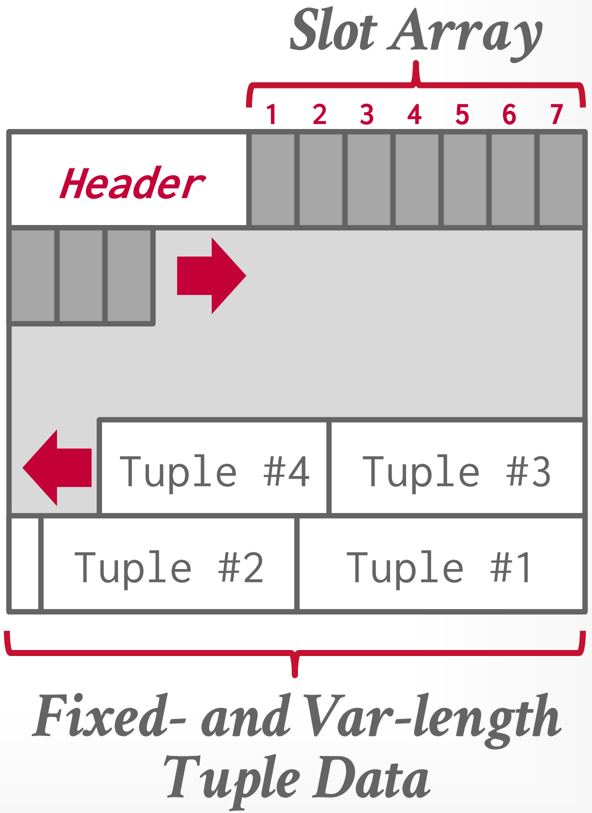

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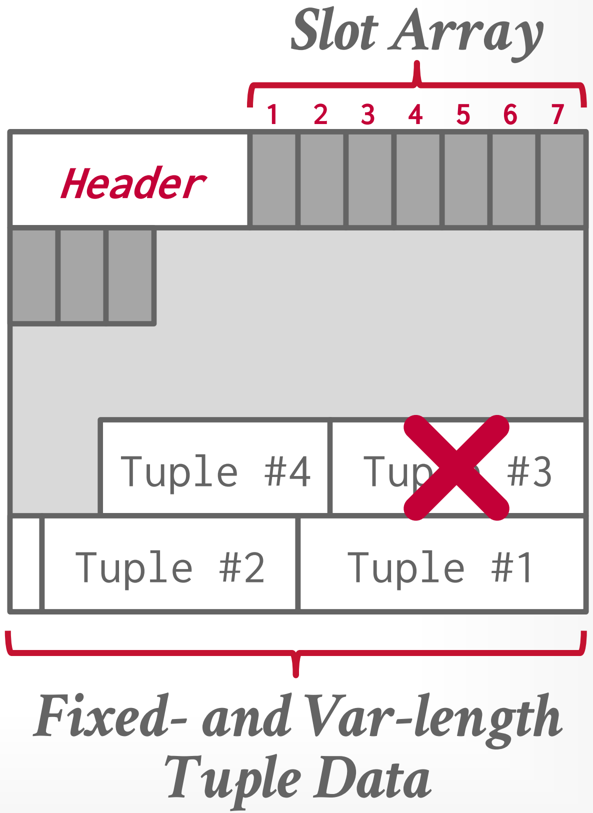

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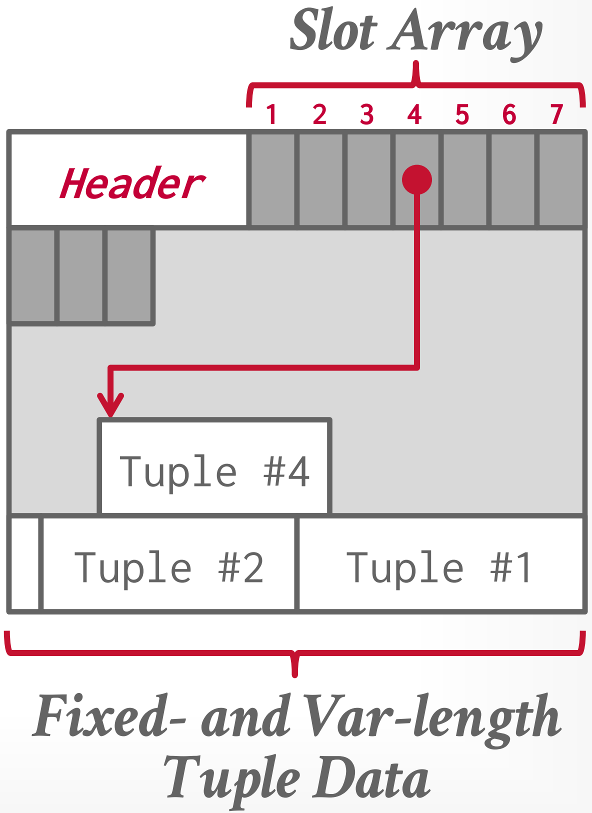

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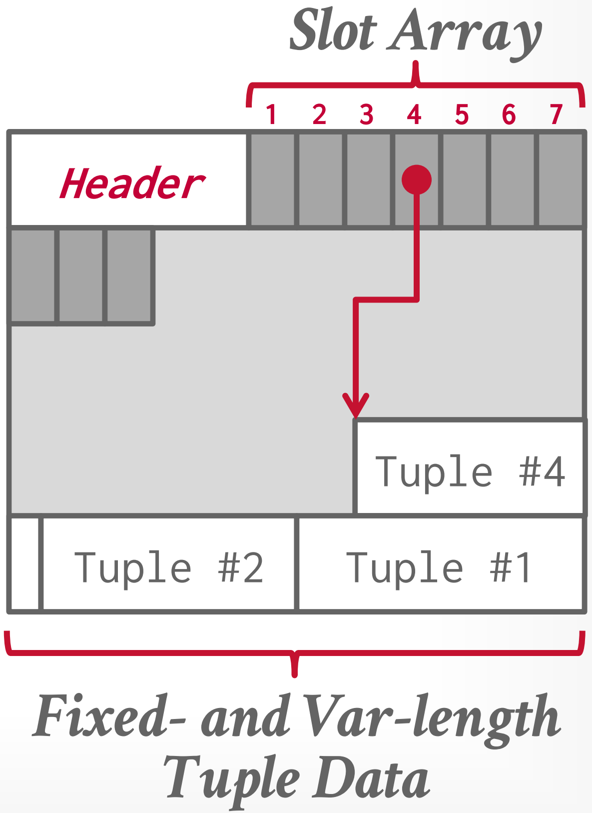


RECORD IDS

The DBMS assigns each logical tuple a unique record identifier that represents its physical location in the database.

→ File Id, Page Id, Slot #
→ Most DBMSs do not store ids in tuple.
→ SQLite uses ROWID as the true primary key and stores them as a hidden attribute.

Applications should never rely on these IDs to mean anything.

PostgreSQL
CTID (6-bytes)

SQLite
ROWID (8-bytes)

Microsoft SQL Server
%%physloc%% (8-bytes)

ORACLE
ROWID (10-bytes)

TODAY'S AGENDA

File Storage
Page Layout
Tuple Layout

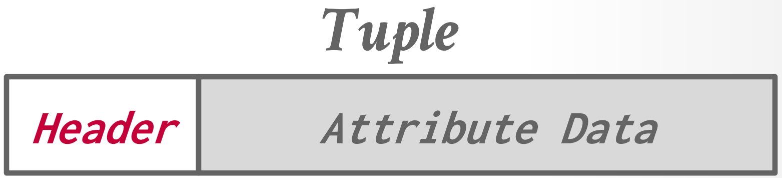
TUPLE LAYOUT

A tuple is essentially a sequence of bytes.
→ These bytes do not have to be contiguous.

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

TUPLE HEADER

Each tuple is prefixed with a <u>header</u> that contains meta-data about it.
→ Visibility info (concurrency control)
→ Bit Map for **NULL** values.



We do <u>not</u> 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

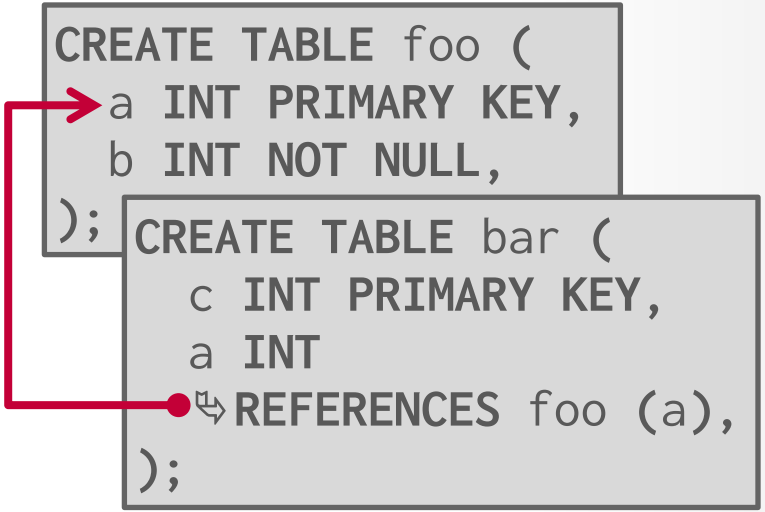
```
CREATE TABLE foo (
  a INT PRIMARY KEY,
  b INT NOT NULL,
  c INT,
  d DOUBLE,
  e FLOAT
);
```

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.



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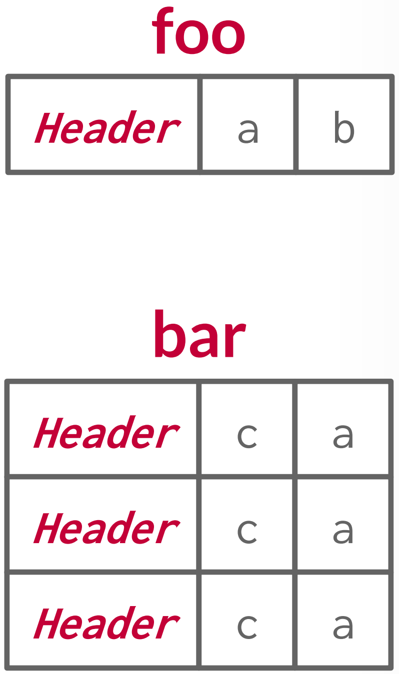

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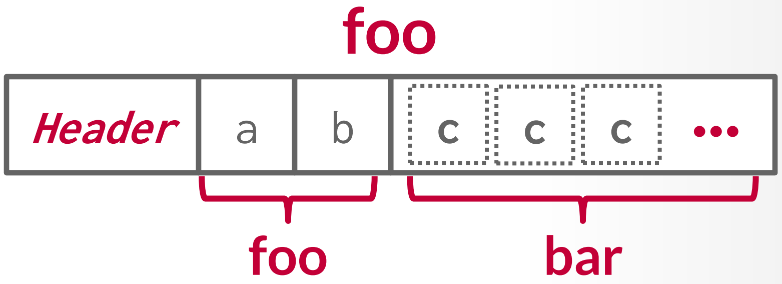


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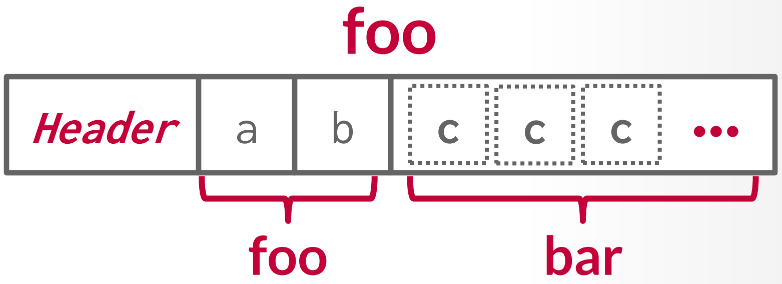

Not a new idea.

→ 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
Index-Organized Storage
Value Representation
Catalogs