Lecture 2: Storage Management

- Exercise Sheet
- Assignment

Recap

Why you should take this course?

- You want to learn how to make database systems **scalable**, for example, to support web or mobile applications with millions of users.
- You want to make applications that are highly **available** (*i.e.*, minimizing downtime) and operationally robust.
- You have a natural curiosity for the way things work and want to know what goes on inside major websites and online services.
- You are looking for ways of making systems easier to maintain in the long run,even as they grow and as requirements and technologies change.
- If you are good enough to write code for a database system, then you can write code on almost anything else.

History of Database Systems

- **1960s**: Hierarchical data model (Tree)
- **1970s**: Network data model (Graph)
- **1980s**: Relational data model (Relation)
- **1990s**: Object-Oriented Data Model
- **2000s**: Data Warehouses – OLAP workload
- **2000s**: NoSQL systems
- **2010s**: NewSQL systems
- **2010s**: Hybrid systems – OLTP + OLAP workload
- **2010s**: Cloud systems
- **2020s**: Specialized systems (*e.g.*, Time Series DBMSs, GPU-based DBMSs)

Performance
Features

Specialization
vs
Generalization

Today's Agenda

- Programming Assignments
- Anatomy of a DBMS
- Hardware Properties
- Storage Management

Programming Assignments

Machine Setup

- Operating System (OS): Ubuntu 18.04
- **Build System**: cmake
- Testing Library: Google Testing Library (gtest)
- **Continuous Integration (CI)** System: Gradescope
- Memory Error Detector: valgrind memcheck

memory leaks

C++ Topics

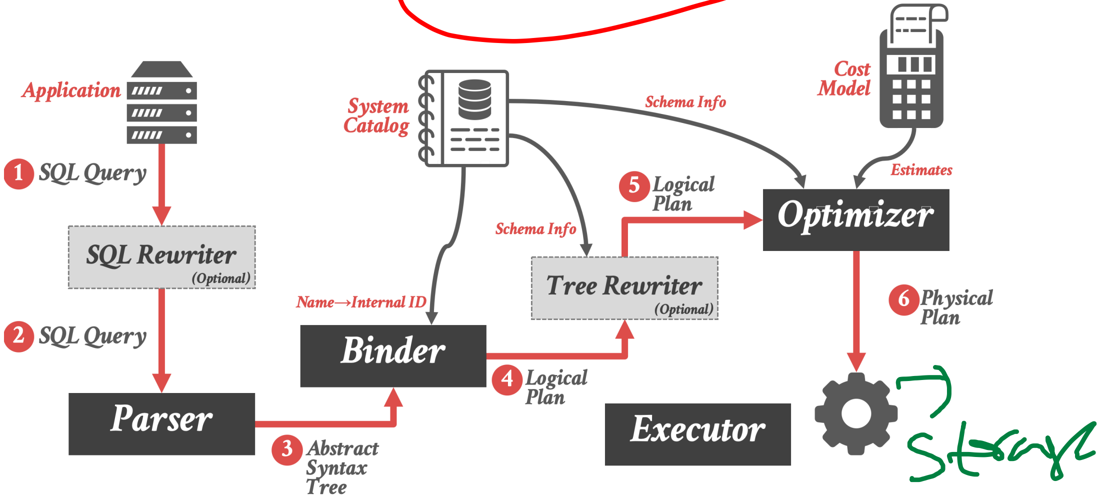
- STL map
- File I/O
- Threading (later assignments)
- Smart Pointers (later assignments)

Assignment 1

- **Goal:** Help brush up your C++ programming skills
- Design a program to locate the occurences of a word in a **text file**.
- Knowledge of basic data structures and algorithm design

Anatomy of a DBMS

Anatomy of a Database System [Monologue]



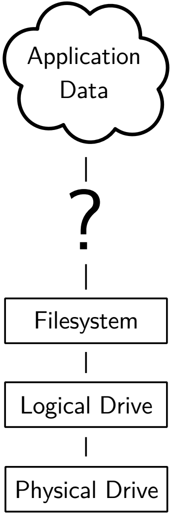
Anatomy of a Database System [Monologue]

- Process Manager
  - Manages client connections
- Query Processor
  - Parse, plan and execute queries on top of storage manager
- Transactional Storage Manager
  - Knits together buffer management, concurrency control, logging and recovery
- Shared Utilities
  - Manage hardware resources across threads

Anatomy of a Database System [Monologue]

- Process Manager
  - Connection Manager + Admission Control
- Query Processor
  - Query Parser
  - Query Optimizer (*a.k.a.*, Query Planner)
  - Query Executor
- Transactional Storage Manager
  - Lock Manager
  - Access Methods (*a.k.a.*, Indexes)
  - Buffer Pool Manager
  - Log Manager
- Shared Utilities
  - Memory, Disk, and Networking Manager

The Problem


Application
Data
?
Filesystem
Logical Drive
Physical Drive

Requirements

There are different classes of requirements:

- Data Independence
  - application logic must be shielded from physical storage implementation details
  - physical storage can be reorganized
  - hardware can be changed
- Scalability
  - must scale to (nearly) arbitrary data size
  - efficiently access to individual tuples
  - efficiently update an arbitrary subset of tuples
- Reliability
  - data must never be lost
  - must cope with hardware and software failures
- ...

Layered Architecture

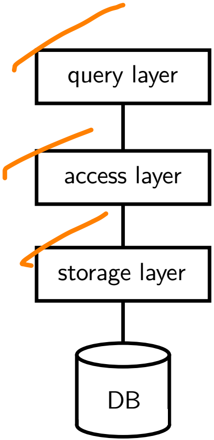
- implementing all these requirements on “bare metal” is hard
- and not desirable
- a DBMS must be maintainable and extensible

Instead: use a **layered architecture**

- the DBMS logic is split into levels of functionality
- each level is implemented by a specific layer
- each layer interacts only with the next lower layer
- simplifies and modularizes the code

A Simple Layered Architecture

Purpose	Access Granularity
	declarative queries sets of records
query translation and optimization	
managing records and access paths	records
DB buffer and hardware interface	page

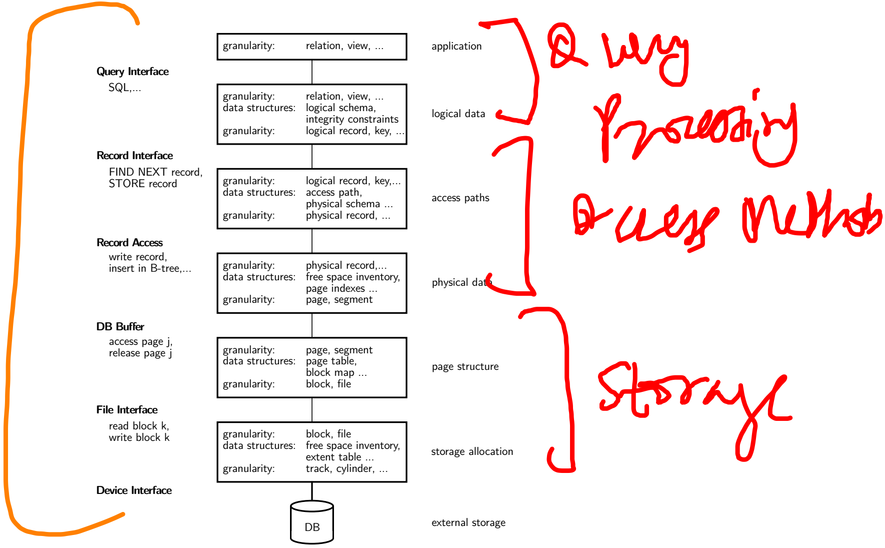


A Simple Layered Architecture (2)

- layers can be characterized by the data items they manipulate
- lower layer offers functionality for the next higher level
- keeps the complexity of individual layers reasonable
- rough structure: physical → low level → high level

This is a reasonable architecture, but simplified.
A more detailed architecture is needed for a complete DBMS.

A More Detailed Architecture



Hardware Properties

Impact of Hardware

Must take hardware properties into account when designing a storage system.

For a long time dominated by **Moore's Law**:

The number of transistors on a chip doubles every 18 month.

Indirectly drove a number of other parameters:

- main memory size
- CPU speed
  - no longer true!
- HDD capacity
  - start getting problematic, too. density is very high
  - only capacity, not access time

Memory Hierarchy

capacity
latency

bytes
1ns

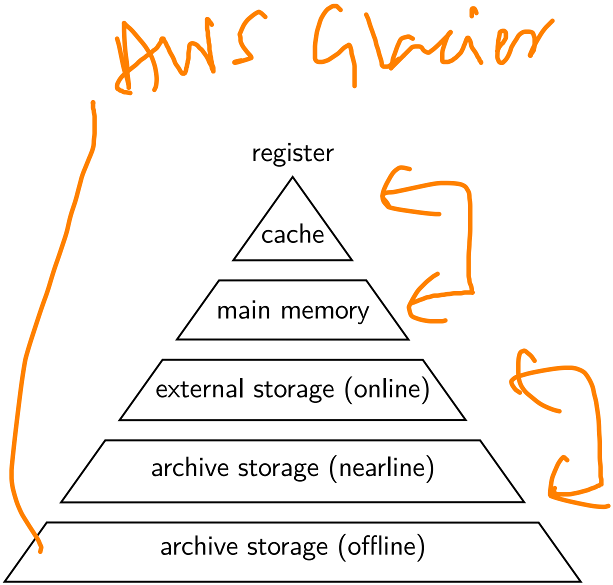
K-M bytes
<10ns

G bytes
<100ns

T bytes
ms

T bytes
sec

T-P bytes
sec-min



Memory Hierarchy (2)

There are huge gaps between hierarchy levels

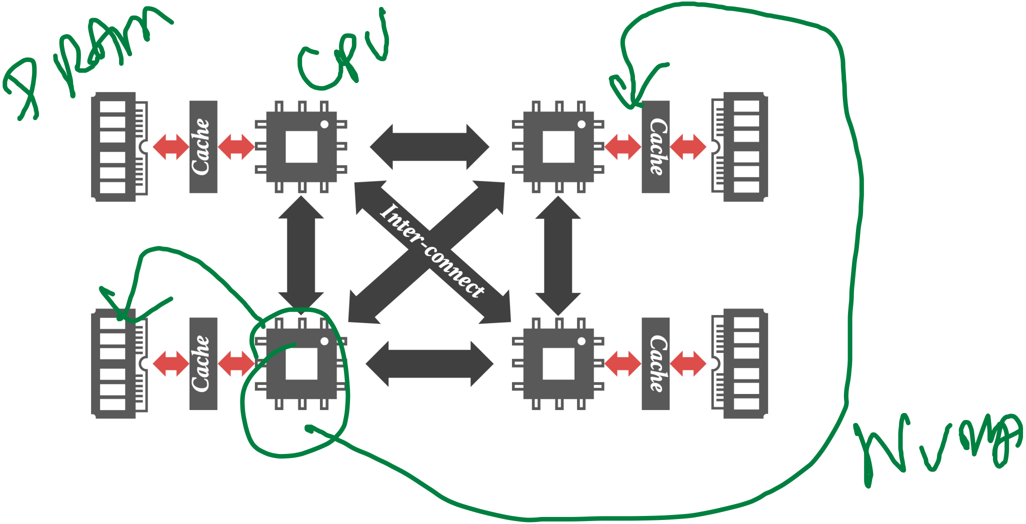
- traditionally, main memory vs. disk is most important
- but memory vs. cache etc. also relevant

The DBMS must aim to maximize locality.

spatial

temporal

Non-Uniform Memory Access



Hard Disk Access

Hard Disks are still the dominant external storage:

- rotating platters, mechanical effects
- transfer rate: ca. 150MB/s
- seek time ca. 3ms
- huge imbalance in random vs. sequential I/O!

Hard Disk Access (2)

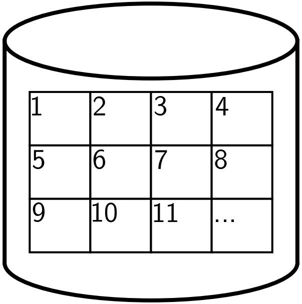
The DBMS must take these effects into account

- sequential access is much more efficient
- traditional DBMSs are designed to maximize sequential access
- gap is growing instead of shrinking
- even SSDs are slightly asymmetric (and have other problems)
- DBMSs try to reduce number of writes to random pages by organizing data in **contiguous blocks**.
- Allocating multiple pages at the same time is called a **segment**

Hard Disk Access (3)

Techniques to speed up disk access:

- do not move the head for every single tuple
- instead, load larger chunks. typical granularity: one **page**
- page size varies. traditionally 4KB, nowadays often 16K and more (**trade-off**)



Hard Disk Access (4)

The page structure is very prominent within the DBMS

- granularity of I/O
- granularity of buffering/memory management
- granularity of recovery

Page is still too small to hide random I/O though

- sequential page access is important
- DBMSs use read-ahead techniques
- asynchronous write-back

Database System Architectures

Storage Management

Disk-Centric Database System

- The DBMS assumes that the primary storage location of the database is HDD.

Memory-Centric Database System (**MMDB**)

- The DBMS assumes that the primary storage location of the database is DRAM.

Buffer Management

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

Access Times

Access Time	Hardware	Scaled Time
0.5 ns	L1 Cache	0.5 sec
7 ns	L2 Cache	7 sec
100 ns	DRAM	100 sec
350 ns	NVM	6 min
150 us	SSD	1.7 days
10 ms	HDD	16.5 weeks
30 ms	Network Storage	11.4 months
1 s	Tape Archives	31.7 years

Source: Latency numbers every programmer should know

Storage Management

Storage Manager

- The **storage manager** is responsible for maintaining a database's files.
  - Some do their own **scheduling** of I/O operations to improve spatial and temporal locality of pages.
- It organizes the files as a collection of pages.
  - Tracks data being read from and written to pages.
  - Tracks the available free 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. Why?
- Each page is given a unique identifier.
  - The DBMS uses an **indirection layer** to map page ids to physical locations.
  - This is implemented as a page directory table.

 Storage Management

Database Pages

- There are three different notions of "pages" in a DBMS:
  - Hardware Page (usually 4 KB)
  - OS Page (usually 4 KB)
  - Database Page (512 B – 16 KB)
- By hardware page, we mean at what level the device can guarantee a "failsafe write".

Checksum

TORN WRITES

Disk Block Mapping

The units of database space allocation are **disk blocks, extents, and segments**.

- A disk block is the smallest unit of data used by a database.
- An extent is a logical unit of database storage space allocation made up of a number of **contiguous** disk blocks.
- A segment is made up of one or more extents (and is hence not always **contiguous** on disk).

System Catalog

- A DBMS stores **meta-data** about databases in its internal catalog.
  - List of tables, columns, indexes, views
  - List of users, permissions
  - Internal statistics (*e.g.*, disk reads, storage space allocation)
- Almost every DBMS stores their catalog as a **private database**.
  - Wrap object abstraction around tuples.
  - Specialized code for "bootstrapping" catalog tables. Why?

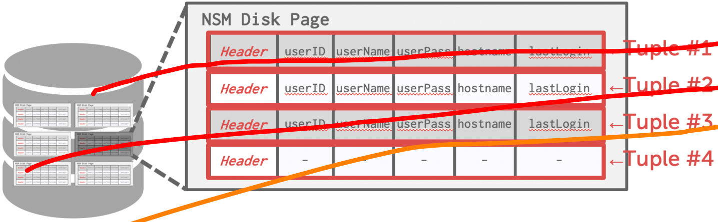
Data Representation

- INTEGER/BIGINT/SMALLINT/TINYINT
  - C/C++ Representation
- FLOAT/REAL vs. NUMERIC/DECIMAL
  - IEEE-754 Standard / Fixed-point Decimals
- VARCHAR/VARBINARY/TEXT/BLOB
  - Header with length, followed by data bytes.
- TIME/DATE/TIMESTAMP
  - 32/64-bit integer of (micro)seconds since Unix epoch

1970

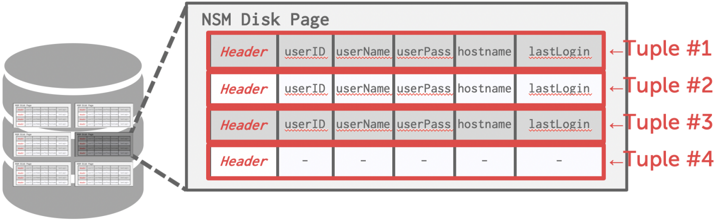
N-ary Storage Model (NSM)

- The DBMS stores all attributes for a single tuple contiguously in a page.



row store

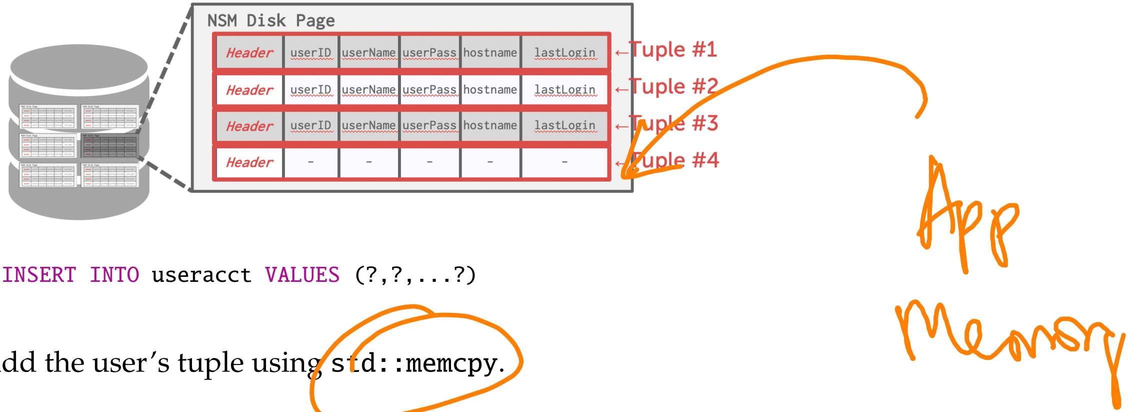
N-ary Storage Model (NSM)




```sql
SELECT * FROM useracct
WHERE userName = ? AND userPass = ?
```

Use index to access the particular user's tuple.

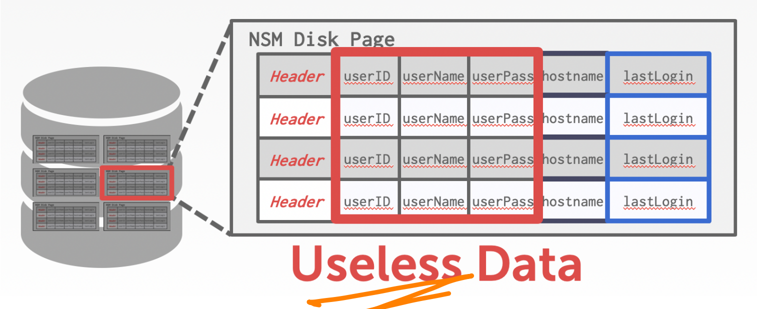
N-ary Storage Model (NSM)




```
INSERT INTO useracct VALUES (?,?,...?)
```

Add the user's tuple using `std::memcpy`.

N-ary Storage Model (NSM)




```
SELECT COUNT(U.lastLogin), EXTRACT(month FROM U.lastLogin) AS month
FROM useracct AS U
WHERE U.hostname LIKE '%.gov'
GROUP BY EXTRACT(month FROM U.lastLogin)
```

Useless data accessed for this query.

 Storage Management

N-ary Storage Model (NSM)

- Advantages
  - Fast inserts, updates, and deletes.
  - Good for queries that need the entire tuple.
- Disadvantages
  - Not good for scanning large portions of the table and/or a subset of the attributes.

OLAP

Decomposition Storage Model (DSM)

- The DBMS stores the values of a **single attribute** for all tuples contiguously in a page.
  - Also known as a "column store"
- Ideal for OLAP workloads where read-only queries perform large scans over a subset of the table's attributes.

Decomposition Storage Model (DSM)

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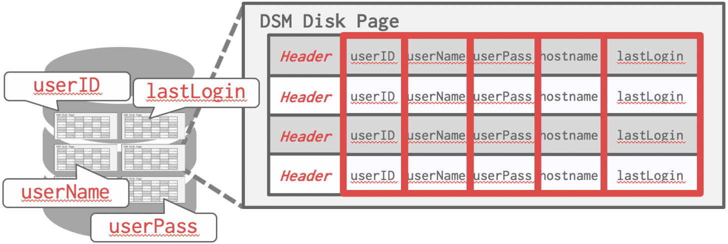
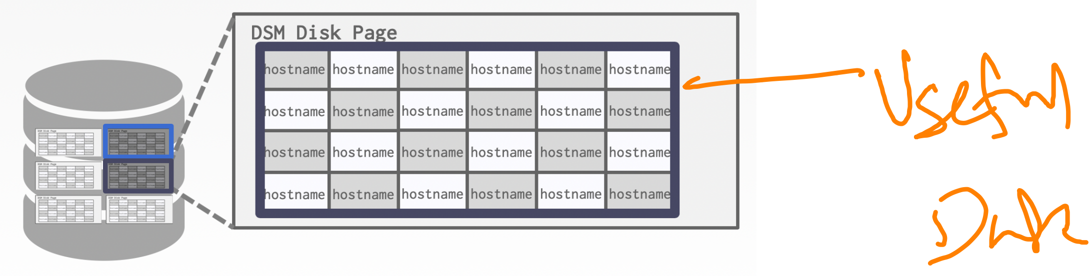


Decomposition Storage Model (DSM)

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 Storage Management

Workload Characterization

- On-Line Transaction Processing (OLTP)
  - Fast operations that only read/update a small amount of data each time.
  - OLTP Data Silos
- On-Line Analytical Processing (OLAP)
  - Complex queries that read a lot of data to compute aggregates.
  - OLAP Data Warehouse
- Hybrid Transaction + Analytical Processing
  - OLTP + OLAP together on the same database instance

Workload Characterization

Workload	Operation Complexity	Workload Focus
OLTP	Simple	Writes
OLAP	Complex	Reads
HTAP	Medium	Mixture

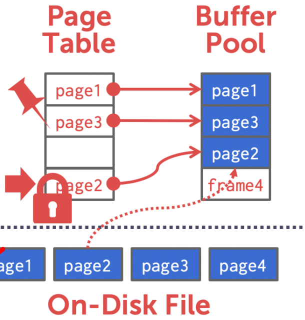
Source

Storage Models

- A DBMS encodes and decodes the tuple's bytes into a set of attributes based on its schema.
- It is important to choose the right storage model for the target workload
  - OLTP $\longrightarrow$ Row-Store
  - OLAP $\longrightarrow$ Column-Store

Buffer Pool Meta-Data

- The **page table** keeps track of pages that are currently in memory.
- Also maintains additional meta-data per page:
  - **Dirty Flag**
  - **Pin/Reference Counter**



Buffer Replacement Policies

- When the DBMS needs to free up a frame to make room for a new page, it must decide which page to evict from the buffer pool.
- Policies:
  - FIFO
  - LFU
  - LRU
  - CLOCK
  - LRU-k
  - 2Q

Conclusion

Parting Thoughts

- Database systems have a layered architecture.
- Design of database system components affected by hardware properties.
- Database is physically organized as a collection of pages on disk.
- The units of database space allocation are disk blocks, extents, and segments
- The DBMS can manage that sweet, sweet memory better than the OS.
- Leverage the semantics about the query plan to make better decisions.
- It is important to choose the right storage model for the target workload

Next Class

- Recap of access methods
- Submit exercise sheet #1 via Gradescope.