Advanced Database Systems

Spring 2025

Lecture #04:

HW & Disk Space Management

R&G: Chapters 1, 9.1, 9.3

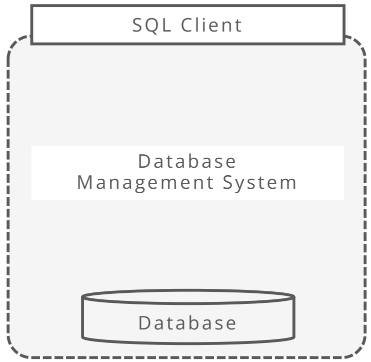
1

DBMS: Big Picture

SQL clients interact with a DBMS

You know how to write a SQL query

How is a SQL query executed?



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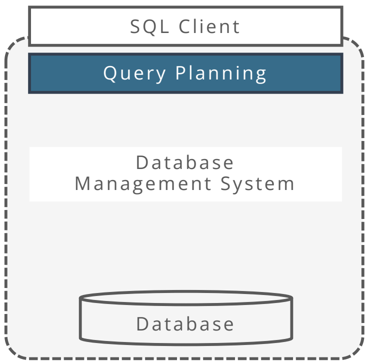
DBMS: Query Planning

Parse, check, and verify the SQL query

```
SELECT S.name
  FROM Student S JOIN Enrolled E
    ON S.sid = E.sid
 WHERE E.cid = 'INF-11199'
```

Translate into an efficient relational query plan that can be executed



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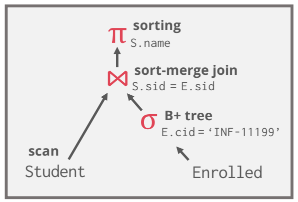
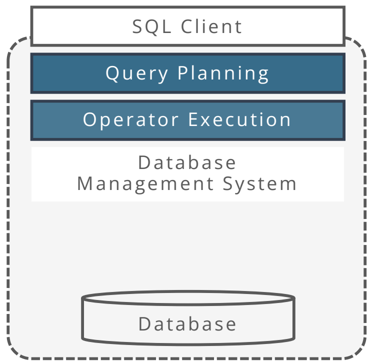
DBMS: Operator Execution

Execute a dataflow by operating on *records* and *files*





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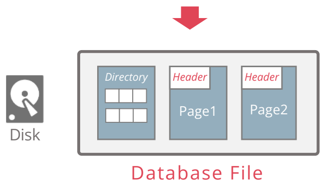
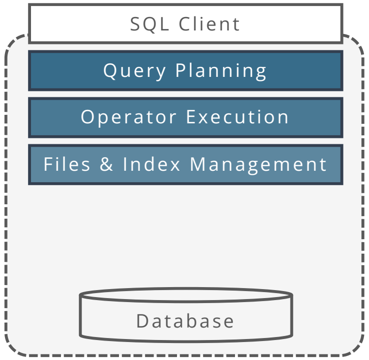
DBMS: Files & Index Management

Organise tables and records as groups of pages in a logical file

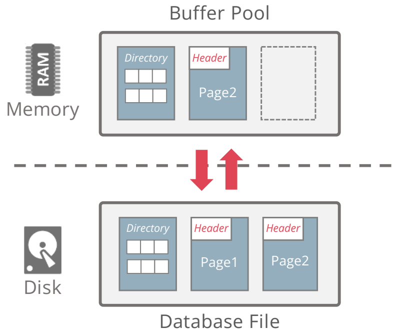
sid	name	dept	age
12344	Jones	CS	18
12355	Smith	Physics	23
12366	Gold	CS	21

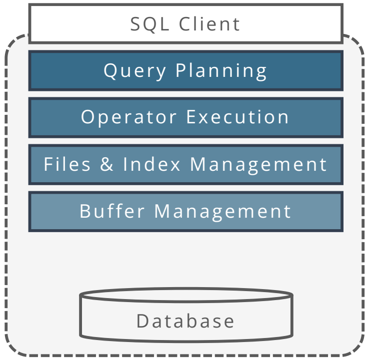




DBMS: Buffer Management

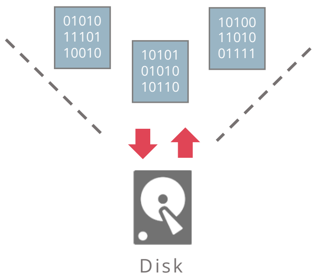
Transfer data between disk and memory

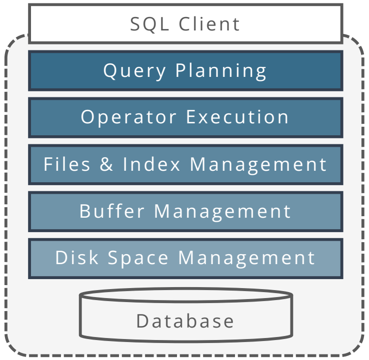




DBMS: Disk Space Management

Translate page requests into reading & writing physical bytes on devices





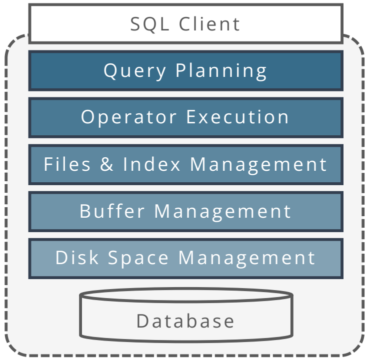
Architecture of a DBMS

Organised in layers

Each layer abstracts the layer below

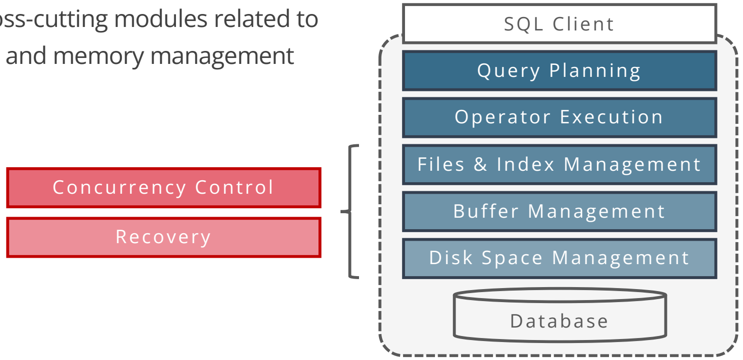
- Manage complexity
- Performance assumptions

Example of good systems design



DBMS: Concurrency & Recovery

Two cross-cutting modules related to storage and memory management



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Outline

Storage Media

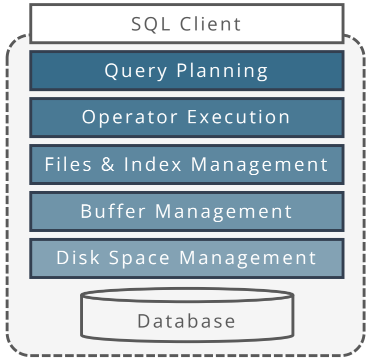
Disk Space Management

Buffer Management

File Layout

Page Layout

Record Layout



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Disk-Oriented Architecture

Most database systems are designed for non-volatile **disk storage***

- The primary location of the database is on disks (HDD and/or SSD)
- Data processing happens in volatile **main memory**
- The DBMS responsible for moving data between disk and main memory

Major implications

- Data stored on disk is not byte addressable. Instead, an API:
  - READ: transfer "page" of data from disk to RAM
  - WRITE: transfer "page" of data from RAM to disk
- Disk reads & writes are **very, very slow**! ⇒ Must plan carefully!

* Volatile storage only maintains its data while the device is powered

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Why Not Store All in Main Memory?

Costs too much

- Cost of 1TB storage (2020): 50$ for HDD, 200$ for SSD, 6000$ for RAM
- High-end databases today in the petabyte range!
- Roughly 60% of the cost of a production system is in the disks

Main memory is volatile

- Obviously important if DB stops/crashes. We want data to be saved!

Some specialised systems <u>do</u> store entire databases in main memory

- Faster than disk-oriented but with much higher cost/GB
- Suitable for small databases

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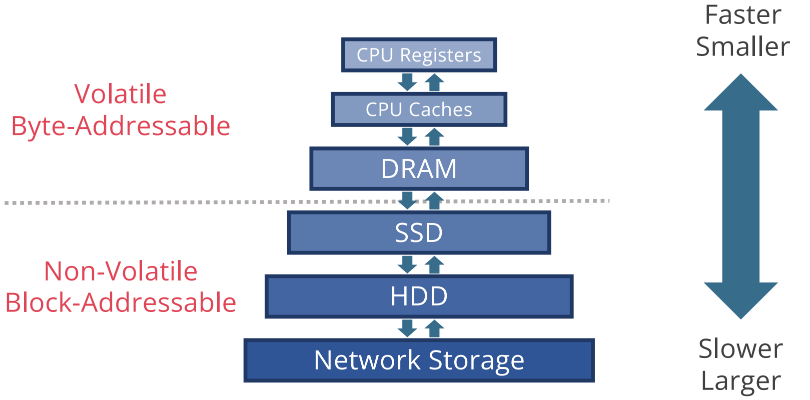
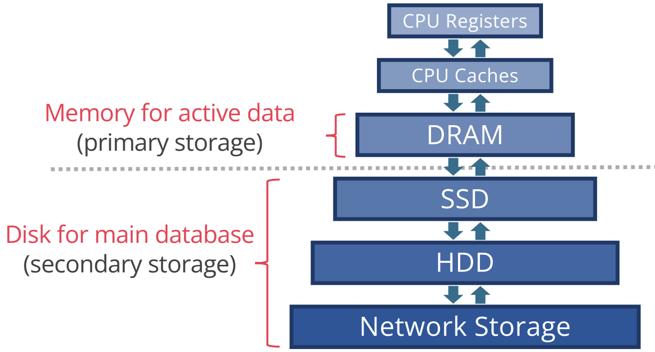
Storage Hierarchy



Storage Hierarchy



Latency	Capacity
< 1ns	B
< 10ns	KB/MB
100ns	GB
0.1ms	GB/TB
10ms	TB
30ms	PB

Anatomy of a Disk

Platters rotate (say 15000 rpm)

Disk arm moves in or out to position **disk heads** on a desired **track**

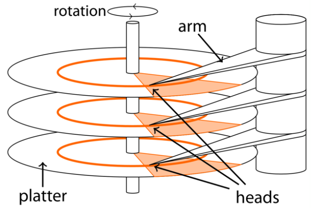
Tracks under heads make a “cylinder”

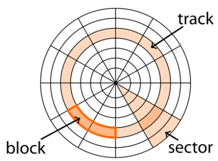
Only one head reads/writes at any one time

Block size is a multiple of (fixed) **sector** size

Sector = minimum storage unit (512B or 4KB)

[Video on how disk drives work]





Accessing a Disk Page

Data is stored and retrieved in units called **disk blocks**

Block size is determined by the filesystem (usually 4KB, sometimes up to 64KB)

Unlike RAM, time to retrieve a block depends on its location

Time to access (read/write) a disk block:

Seek time: moving disk arm to position disk heads on track

Rotational delay: waiting for target block to rotate under a head

Transfer time: actually moving data to/from disk surface

Seagate Cheetah 15K.7

4 disks, 8 heads, avg. 512 KB/track, 600GB capacity

rotational speed: 15 000 rpm

average seek time: 3.4 ms

transfer rate ≈ 163 MB/s

Access time to read one block of size 8KB

Average seek time		3.40 ms
Average rotational delay	1/2 · 1/15000 min	2.00 ms
Transfer time	8KB / 163 MB/s	0.05 ms
Total access time		**5.45 ms**

Seek time and rotational delay dominate!

Sequential vs. Random Access

What about accessing 1000 blocks of size 8 KB

Random: 1000 · 5.45 ms = 5.45 s

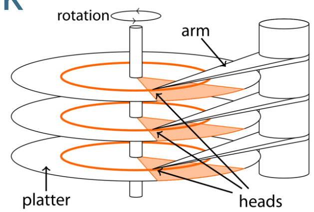
Sequential: 3.4 ms + 2 ms + 1000 · 0.05 ms ≈ 55 ms

tracks store only 512KB ⟹ some additional (< 5 ms) track-to-track seek time

Sequential I/O orders of magnitude faster than random I/O

avoid random I/O at all cost

Arranging Blocks on Disk



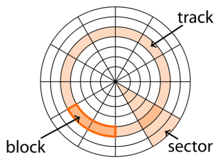
'**Next**' block concept:

- sequential blocks on same track, followed by
- blocks on same cylinder, followed by
- blocks on adjacent cylinder

Arrange file pages sequentially by 'next' on disk

- Minimize seek and rotational delay

For a **sequential scan**, pre-fetch several blocks at a time!



Reading large consecutive blocks

- "Amortises" seek time and rotational delay

Solid State Drives

Alternative to conventional hard disks

- Data accessed in pages, internally pages are organised into blocks
- Fine-grain reads (4-8KB pages), coarse-grain writes (1-2MB blocks)

Issues in current generation (NAND)

- **Write amplification:** Writing data in small pages causes erasing big blocks
- **Limited endurance:** Only 2K-3K erasures before cell failure
- **Wear levelling:** SSD controller needs to keep moving hot write units around
- **Price:** SSD is 2-5x more expensive than HDD

Solid State Drives

Read is fast and predictable
- Single read access time: 30 μs
- 4KB random reads: ~500 MB/sec
- Sequential reads: ~525 MB/sec

But write is not! Slower for random
- Single write access time: 30 μs
- 4KB random writes: ~120 MB/sec
- Sequential writes: ~480 MB/sec

Random access **still slower** than sequential access

SSD vs. HDD

SSD can achieve 1-10x the bandwidth (bytes/sec) of ideal HDD
- Note: Ideal HDD spec numbers are hard to achieve
- Expect 10-100x bandwidth for non-sequential reads

Locality matters for both
- Reading/writing to “far away” blocks on HDD requires slow seek/rotation delay
- Writing 2 “far away” blocks on SSD can require writing multiple much larger units
- High-end flash drives are getting much better at this

And don’t forget
- SSD is 2-5x more expensive than HDD

Bottom Line

Very large DBs: relatively traditional
- Disk still offers the best cost/GB by a lot
- SSDs improve performance and performance variance

Smaller DB story is changing quickly
- SSDs win at the low end (modest DB sizes)
- Many interesting databases fit in RAM

Lots of change brewing on the HW storage tech side
- Non-volatile memory likely to affect the design of future systems

We will focus on traditional RAM and disk

Database Storage

Most DBMSs store data as one or more **files** on disk
- Files consist of **pages** (loaded in memory), pages contain **records**

Data on disk is read & written in large chunks of sequential bytes
- **Block** = Unit of transfer for disk read/write
- **Page** = A common synonym for “block”
  - In some textbooks, “page” = a block-sized chunk of RAM
  - We will treat “block” and “page” as synonyms
- **I/O operation** = read/write disk operation

Sequential pages: reading “next” page is fastest

System Design Goals

Goal: allow the DBMS to manage databases > available main memory

Disk reads/writes are expensive ⟹ must be managed carefully

- Minimise disk I/O, maximise usage of data per I/O

Spatial control

- Where to write pages on disk
- **Goal:** keep pages often used together as physically close as possible on disk

Temporal control

- When to read pages into memory and when to write them to disk
- **Goal:** minimise the number of CPU stalls from having to read data from disk

Disk Space Management

Lowest layer of DBMS, manages space on disk

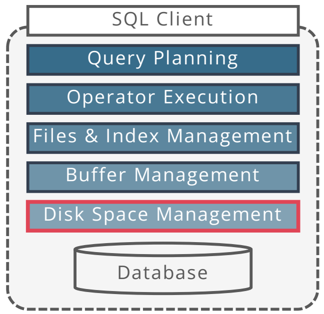
- Map pages to locations on disk
- Load pages from disk to memory
- Save pages back to disk

Introduces the concept of a **page**

- Typical page size: 4 – 64KB (a multiple of 4KB)
- Each page has a unique identifier: **page ID**

Higher levels call upon this layer to:

- Allocate/de-allocate a page
- Read/write a page



Disk Space Management: Page Requests

Disk space manager can get requests for a **sequence of pages**

- E.g., when higher levels execute a scan operator on a relation

Such requests are best satisfied by pages stored sequentially on disk

- Physical details hidden from higher levels of system
- Higher levels may "safely" assume **Next Page** is fast, so they will simply expect sequential runs of pages to be quick to scan

Disk space manager aims to intelligently lay out data on disk

- to meet the performance expectation of higher levels as best as possible

Disk Space Management: Implementation

Using local filesystem (FS)

- Allocate one large "contiguous" file on an empty disk
- Rely on OS and FS that sequential pages in this file are physically contiguous on disk
- A logical database "file" may span multiple FS files on multiple disks/machines
- Disk space manager maintains a **mapping** from page IDs to physical locations
  - physical location = filename + offset within that file

The OS and other apps know nothing about the contents of these files

- Only the DBMS knows how to decipher their contents
- Early DBMSs in the 1980s used custom 'filesystems' on raw storage

SUMMARY

- Magnetic disk and flash storage
  - Random access vs. sequential access (10x)
  - Physical data placement is important
- Disk space management
  - Exposes data as a collection of pages
  - Pages: block-level organisation of bytes on disk
  - API to read/write pages to disk
  - Provides “next” locality
  - Abstracts device and file system details