THE UNIVERSITY *of* EDINBURGH

Advanced Database Systems

Spring 2025

Lecture #04:

HW & Disk Space Management

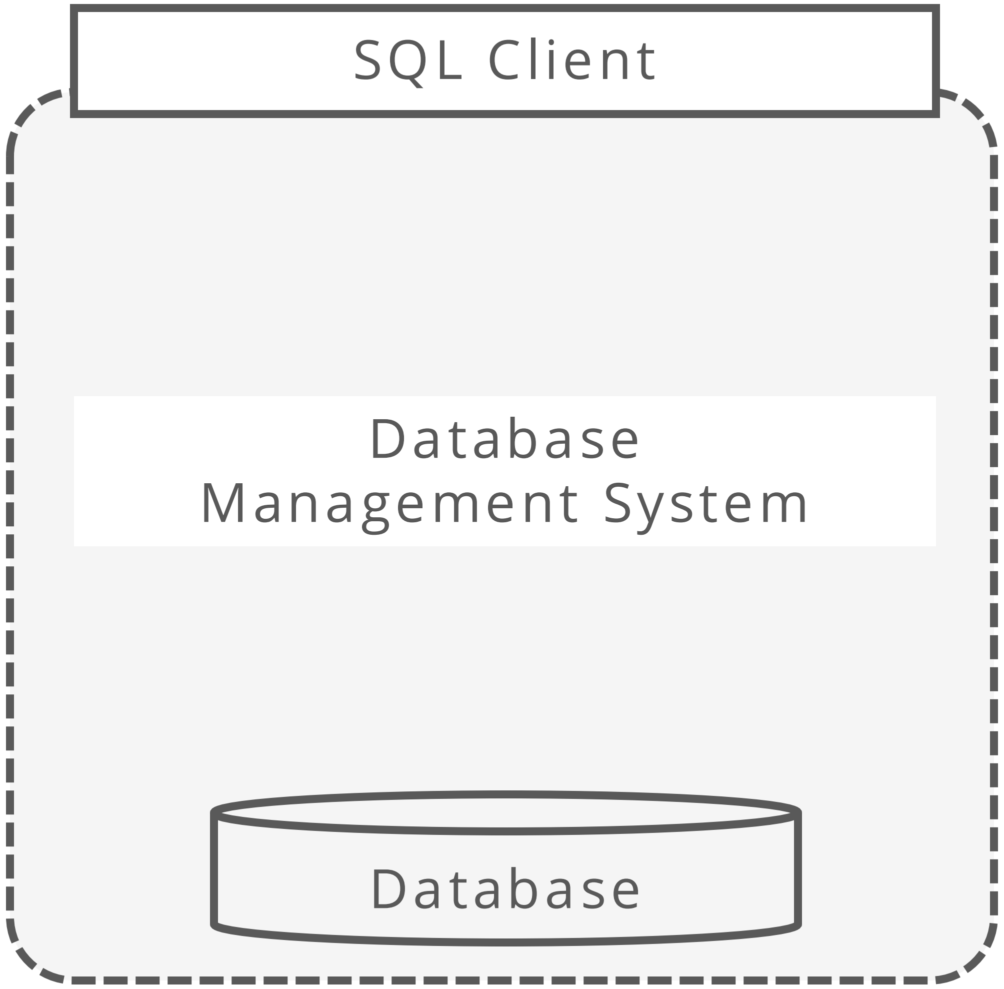
R&G: Chapters 1, 9.1, 9.3

DBMS: Big Picture

SQL clients interact with a DBMS

You know how to write a SQL query

How is a SQL query executed?

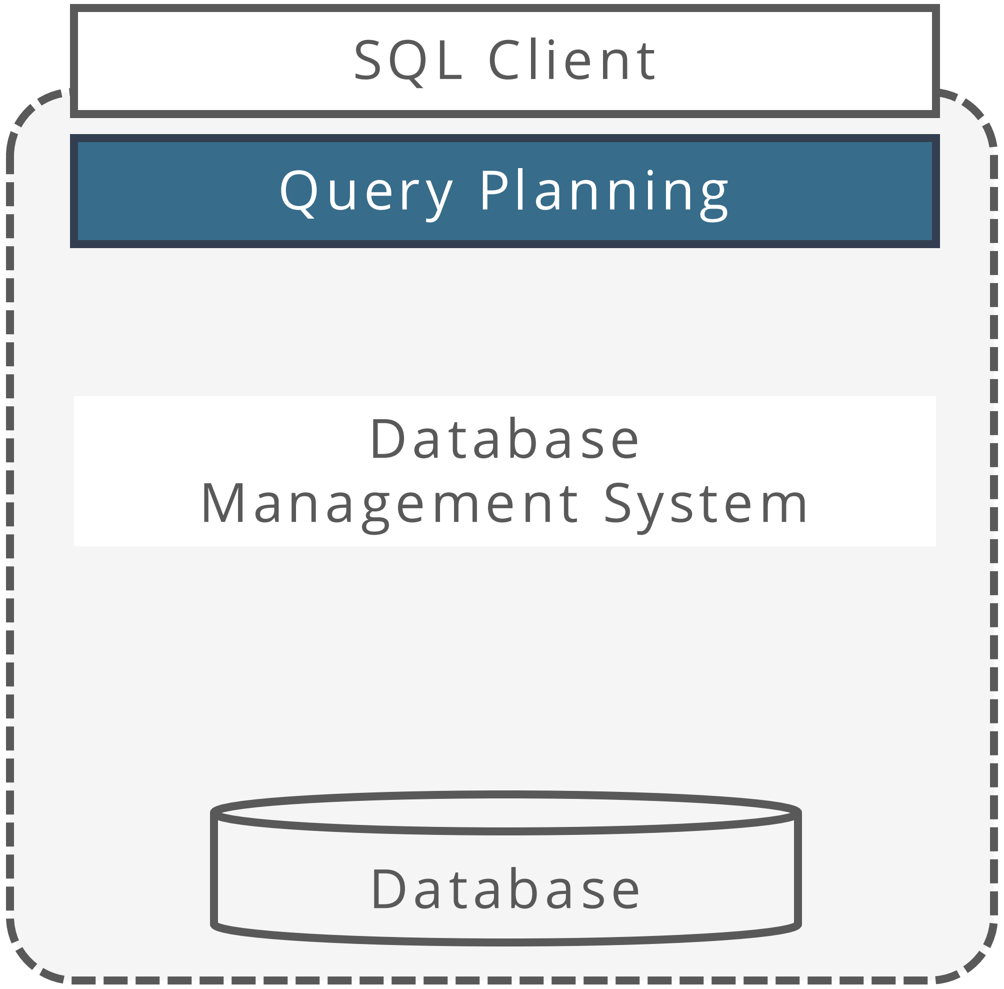


DBMS: Query Planning

Parse, check, and verify the SQL query

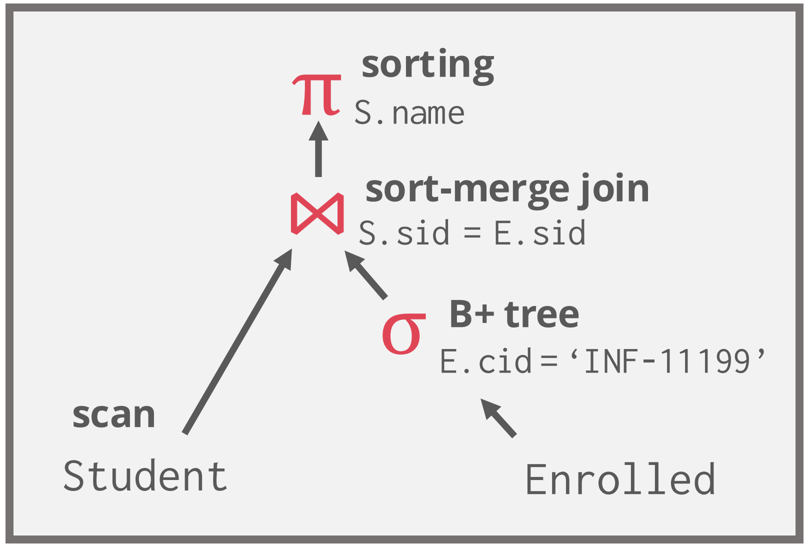
```
SELECT S.name
  FROM Student S JOIN Enrolled E
    ON S.sid = E.sid
 WHERE E.cid = ‘INF-11199’
```

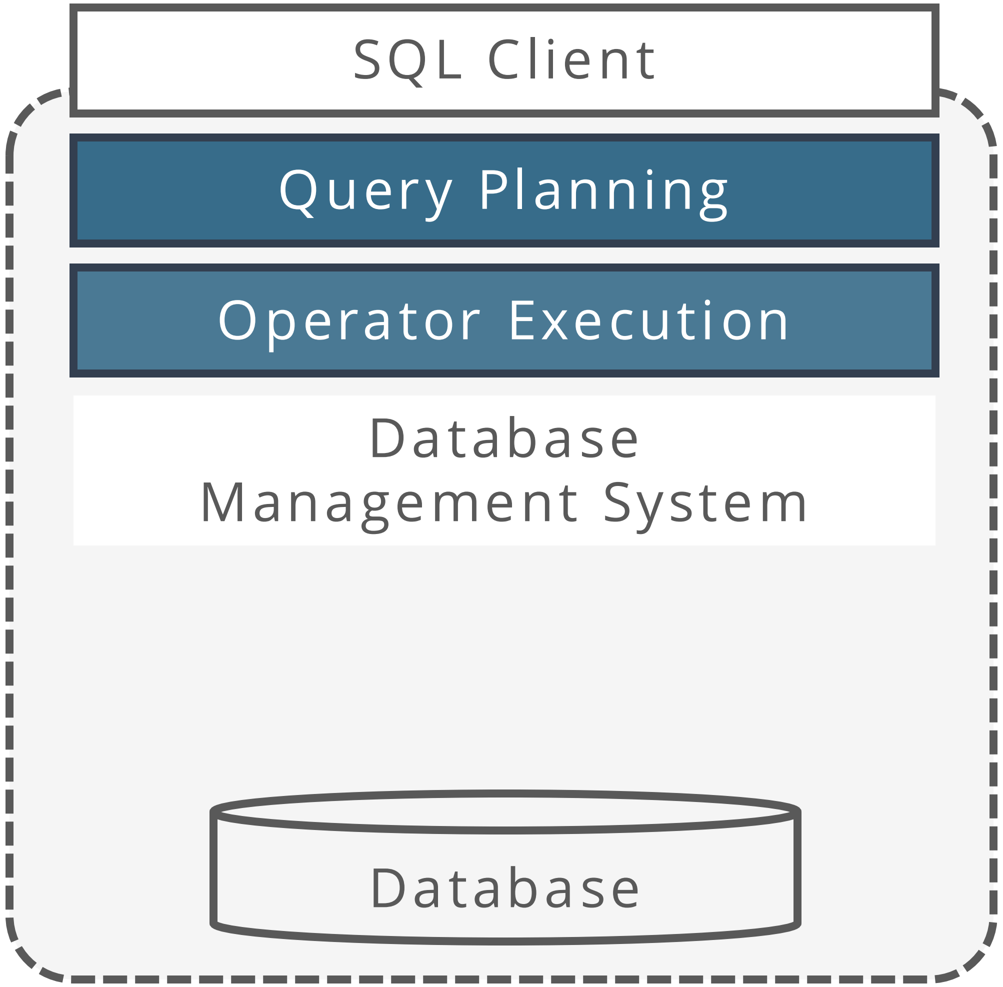
Translate into an efficient relational query plan that can be executed



DBMS: Operator Execution

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

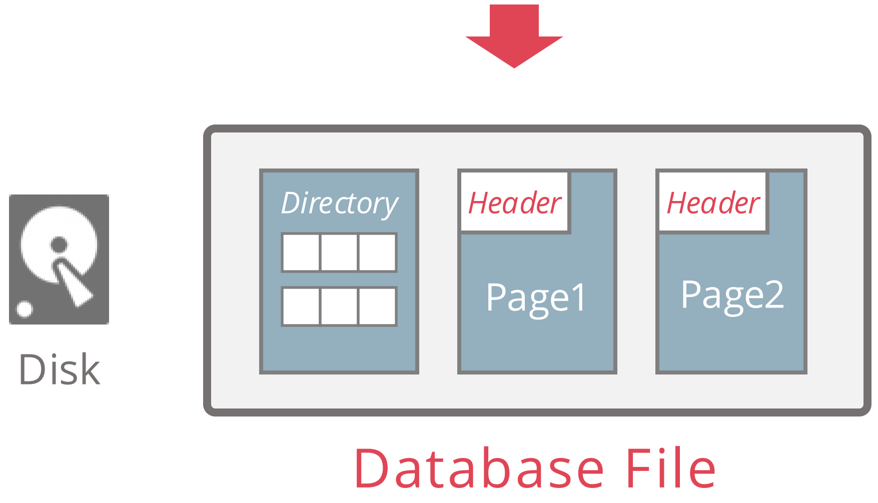


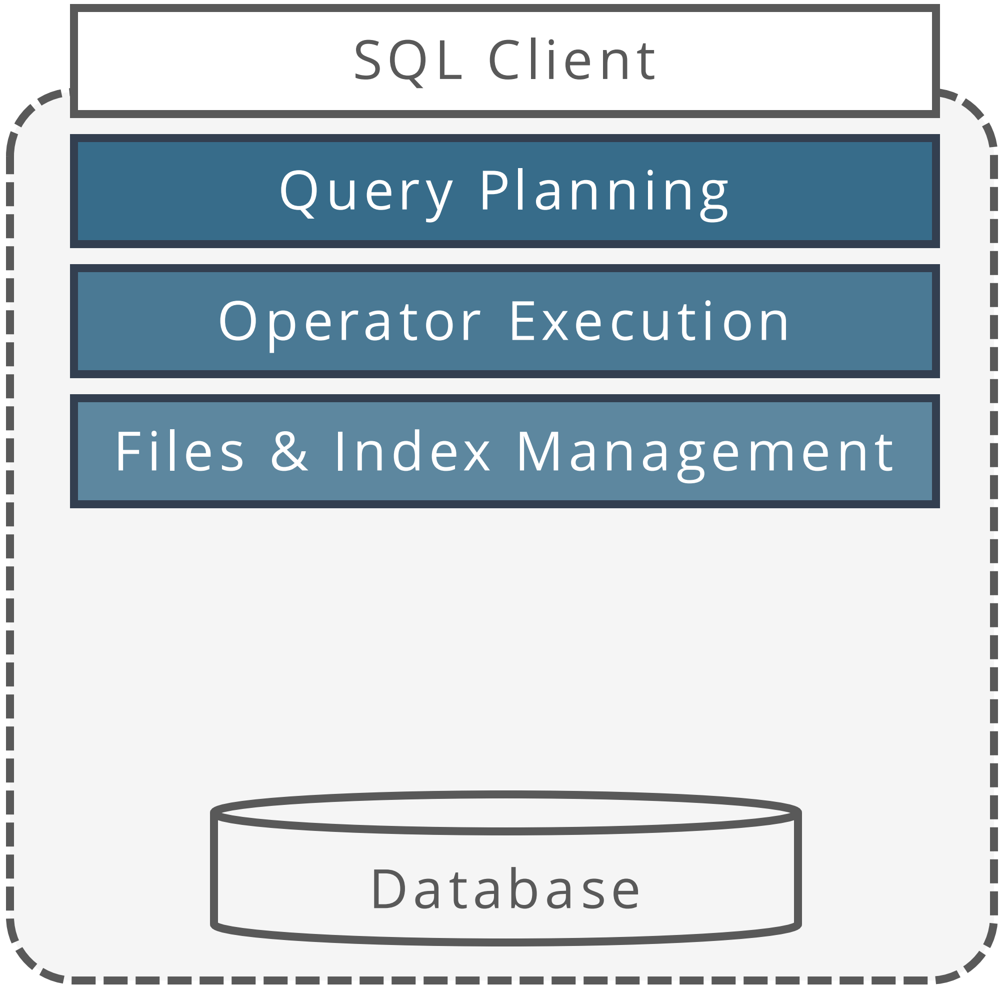


DBMS: Files & Index Management

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

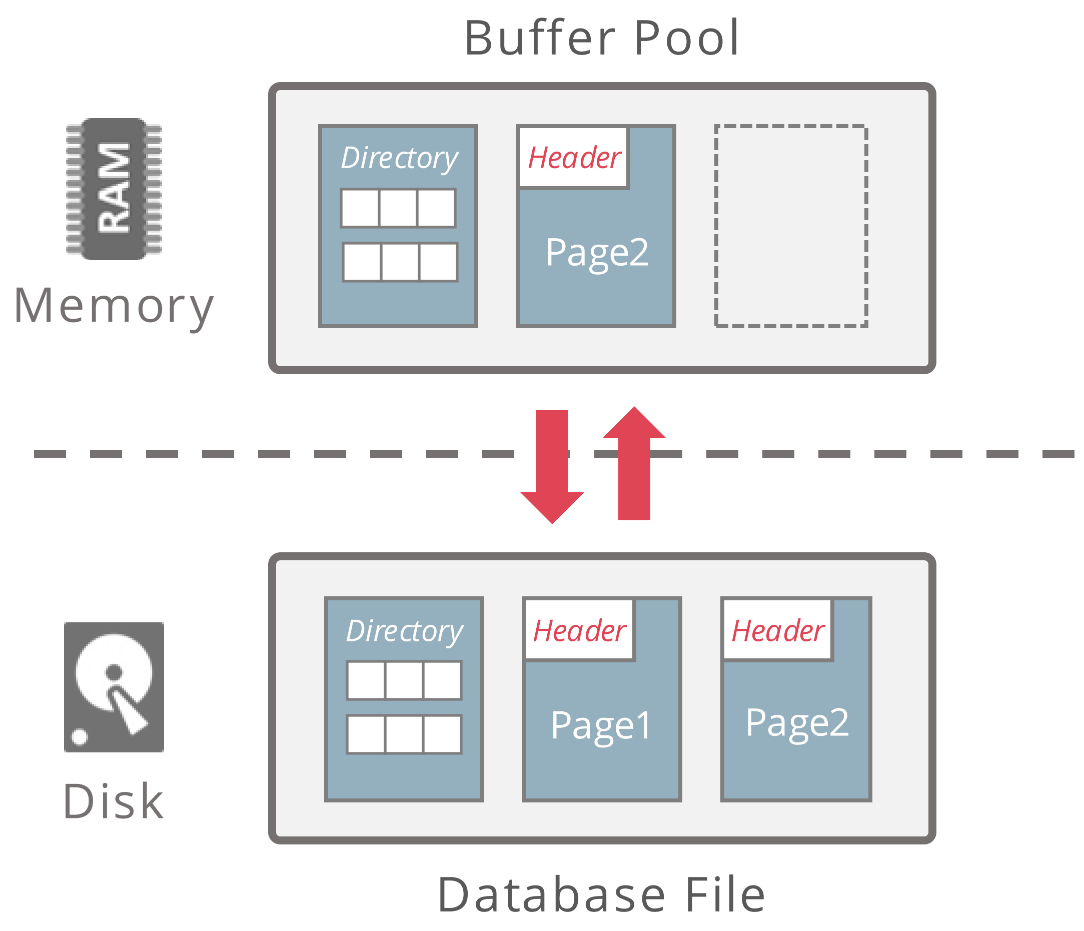
sid	name	dept	age
12344	Jones	CS	18
12355	Smith	Physics	23
12366	Gold	CS	21

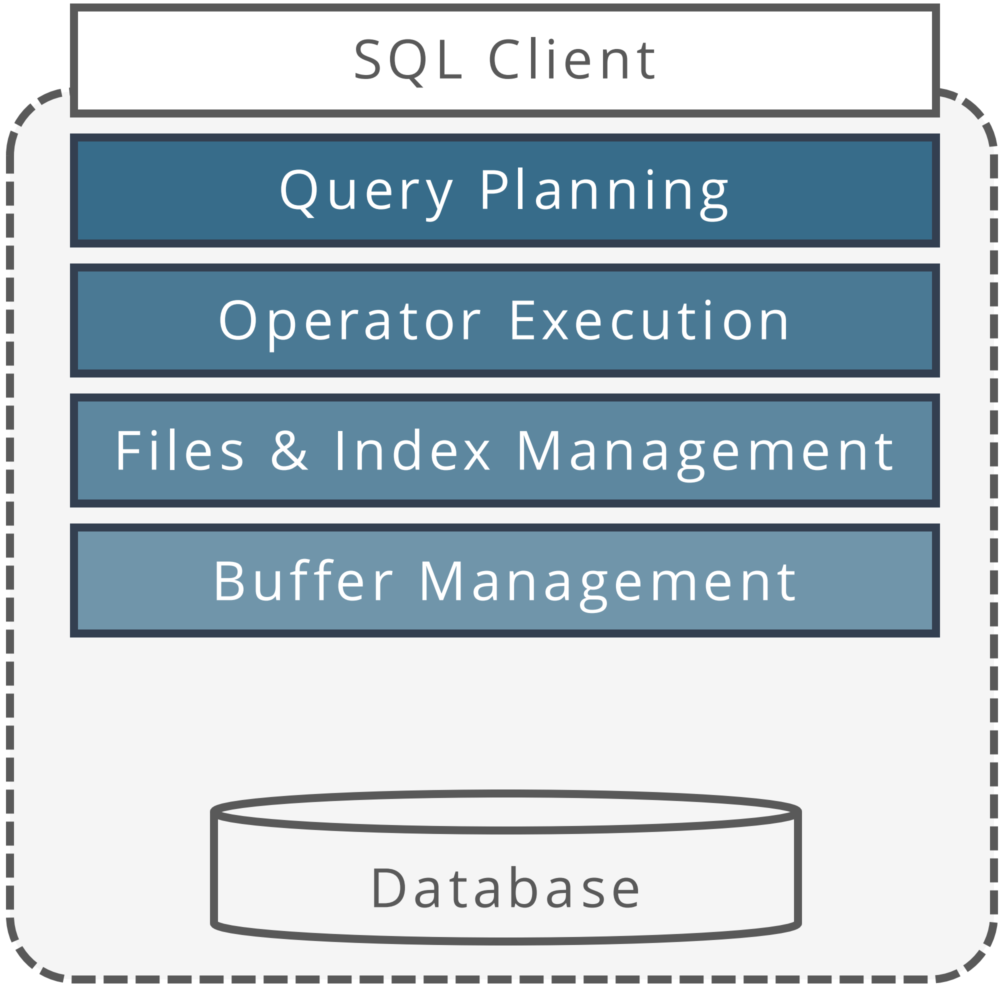




DBMS: Buffer Management

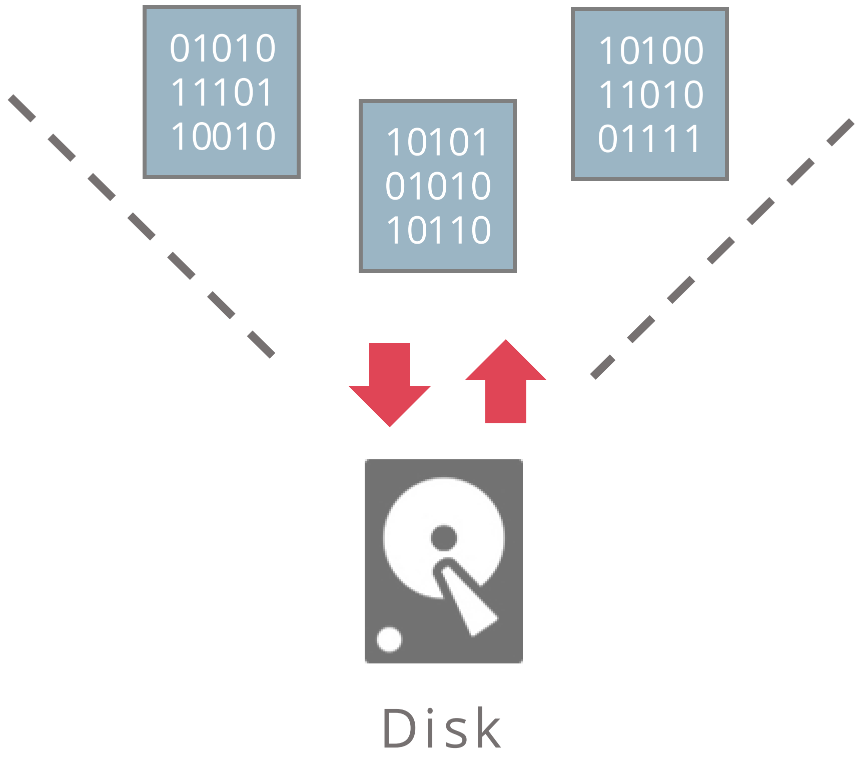
Transfer data between disk and memory

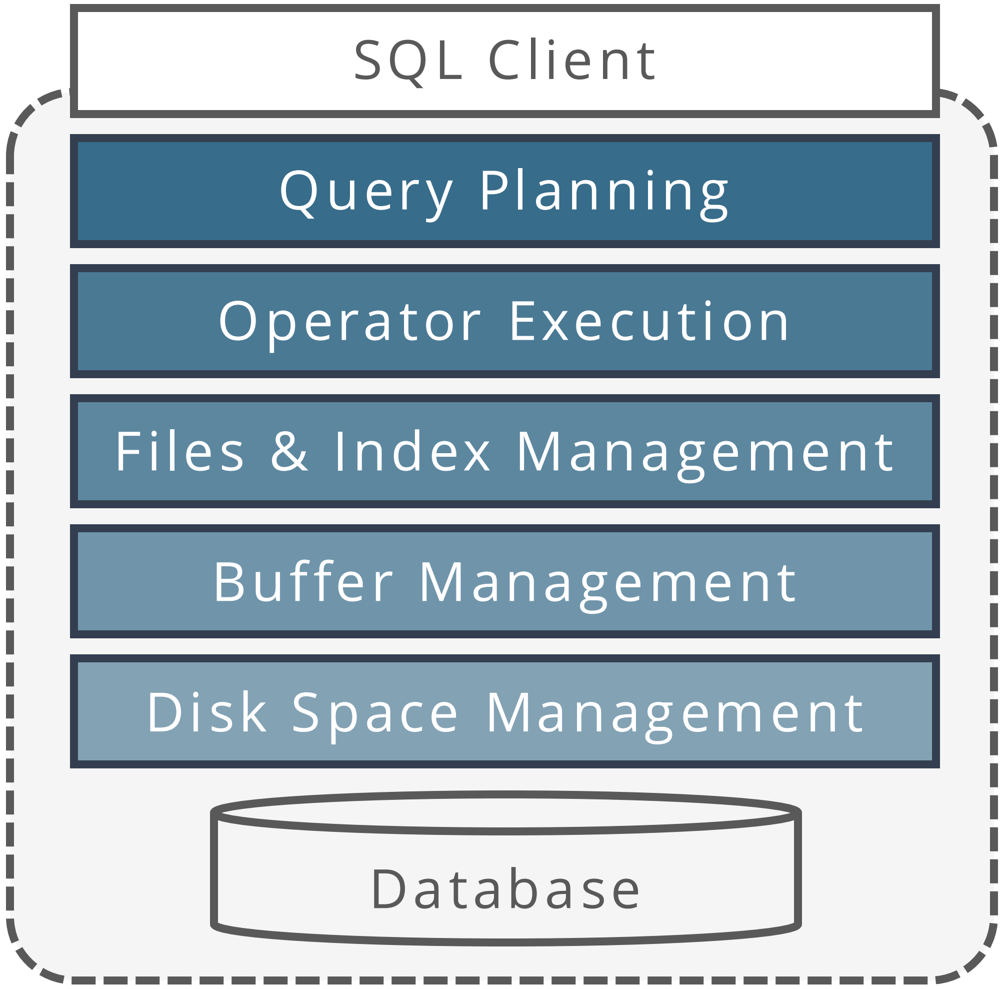




DBMS: Disk Space Management

Translate page requests into reading & writing physical bytes on devices





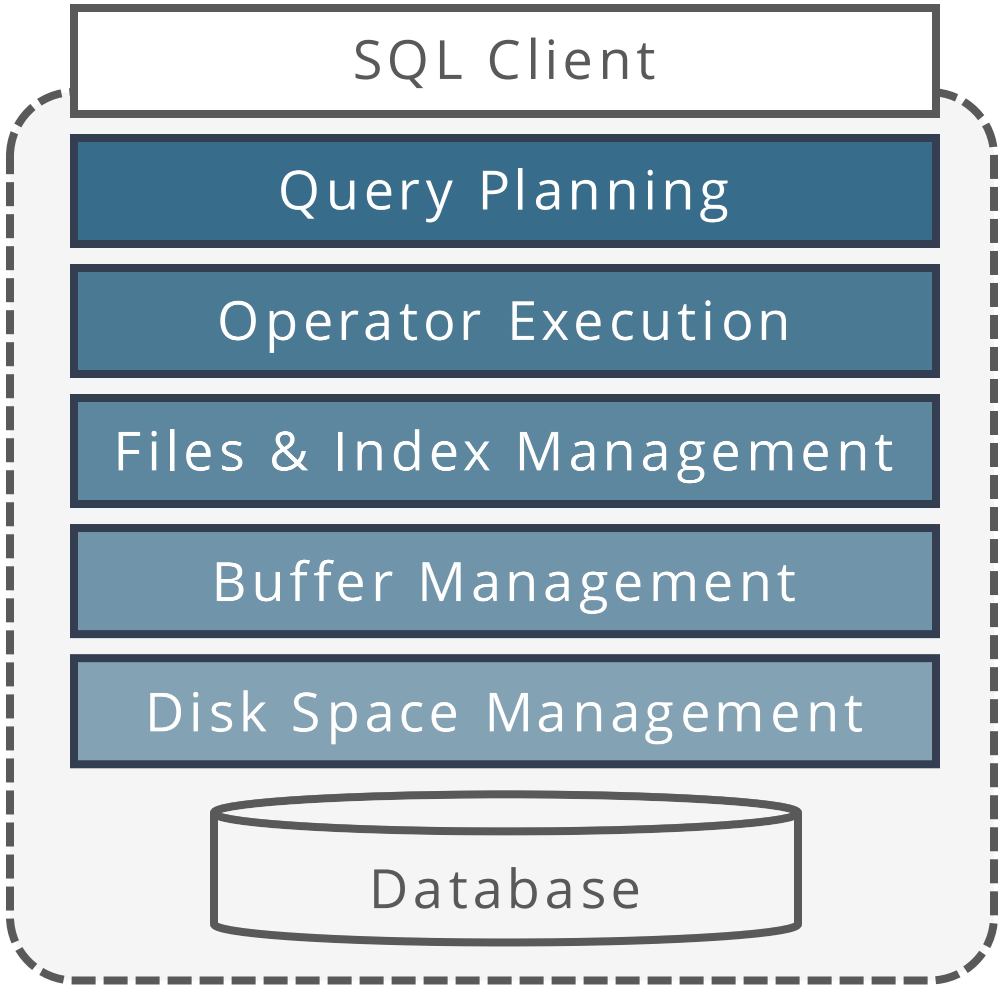
Architecture of a DBMS

Organised in layers

Each layer abstracts the layer below

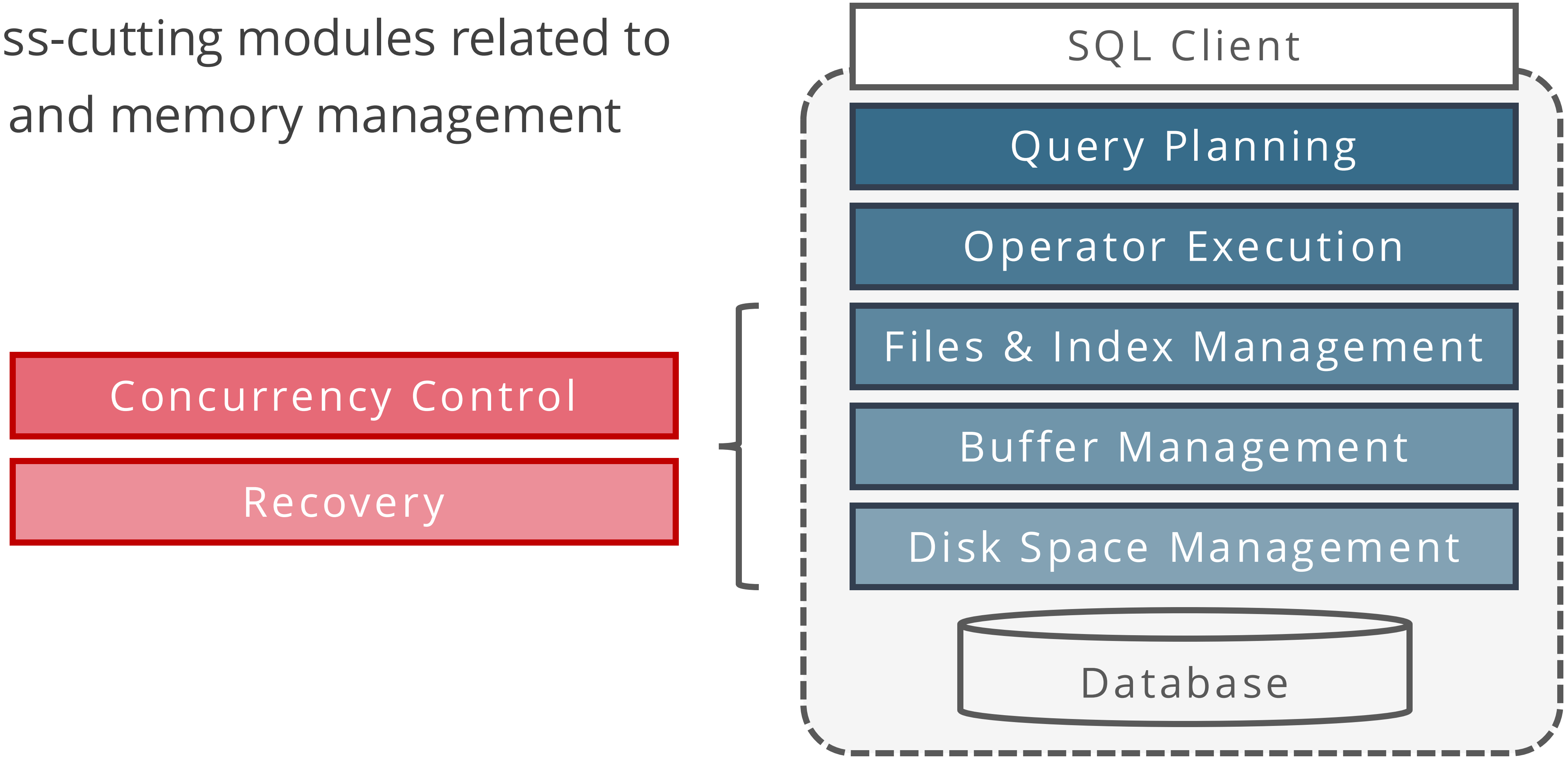
- Manage complexity
- Performance assumptions

Example of good systems design



DBMS: Concurrency & Recovery

Two cross-cutting modules related to storage and memory management



Outline

Storage Media

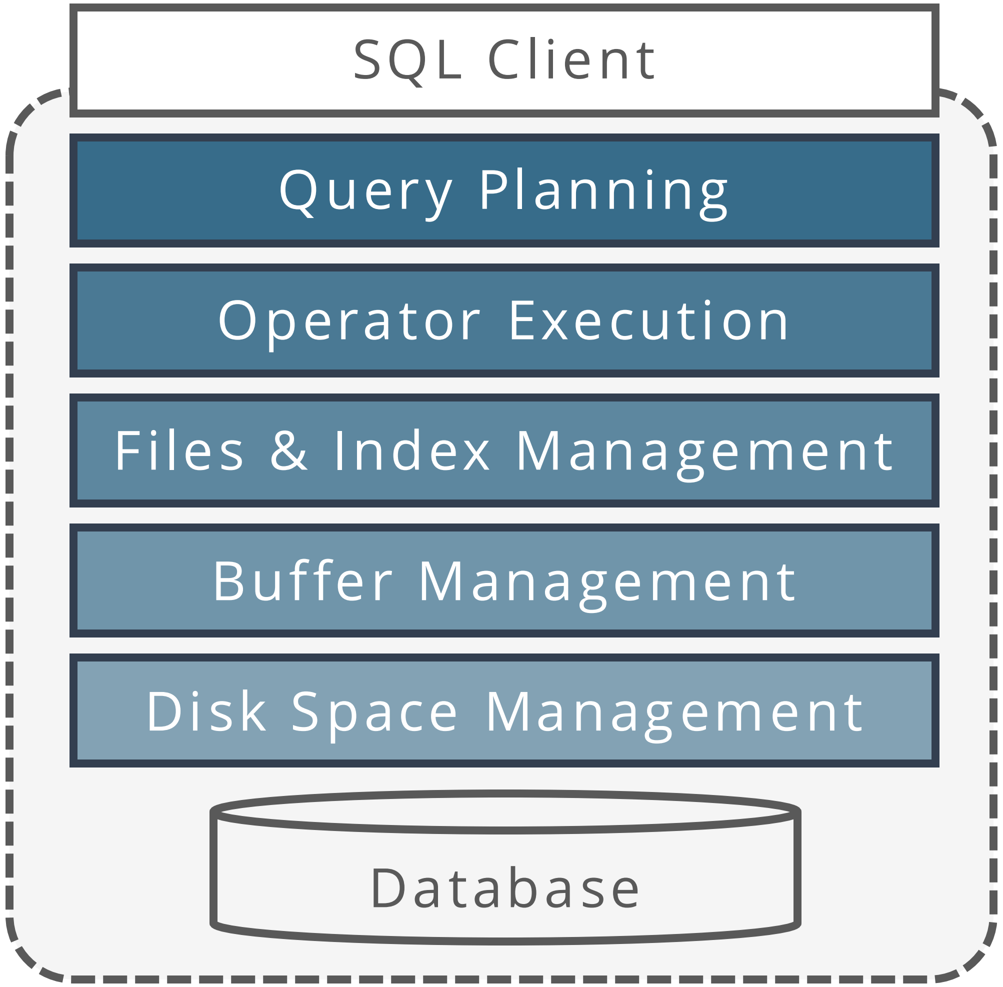
Disk Space Management

Buffer Management

File Layout

Page Layout

Record Layout



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

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

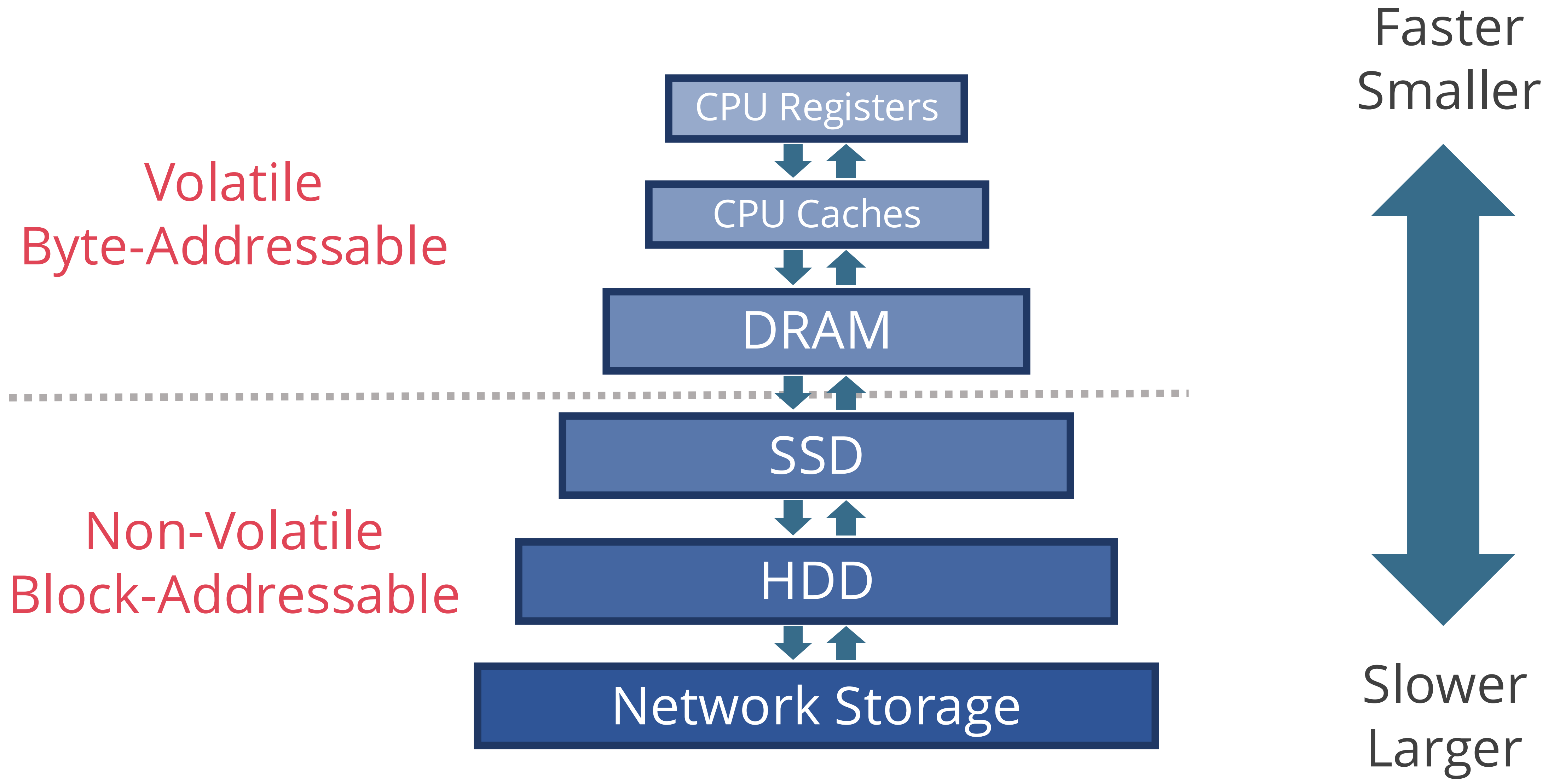
Main memory is volatile

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

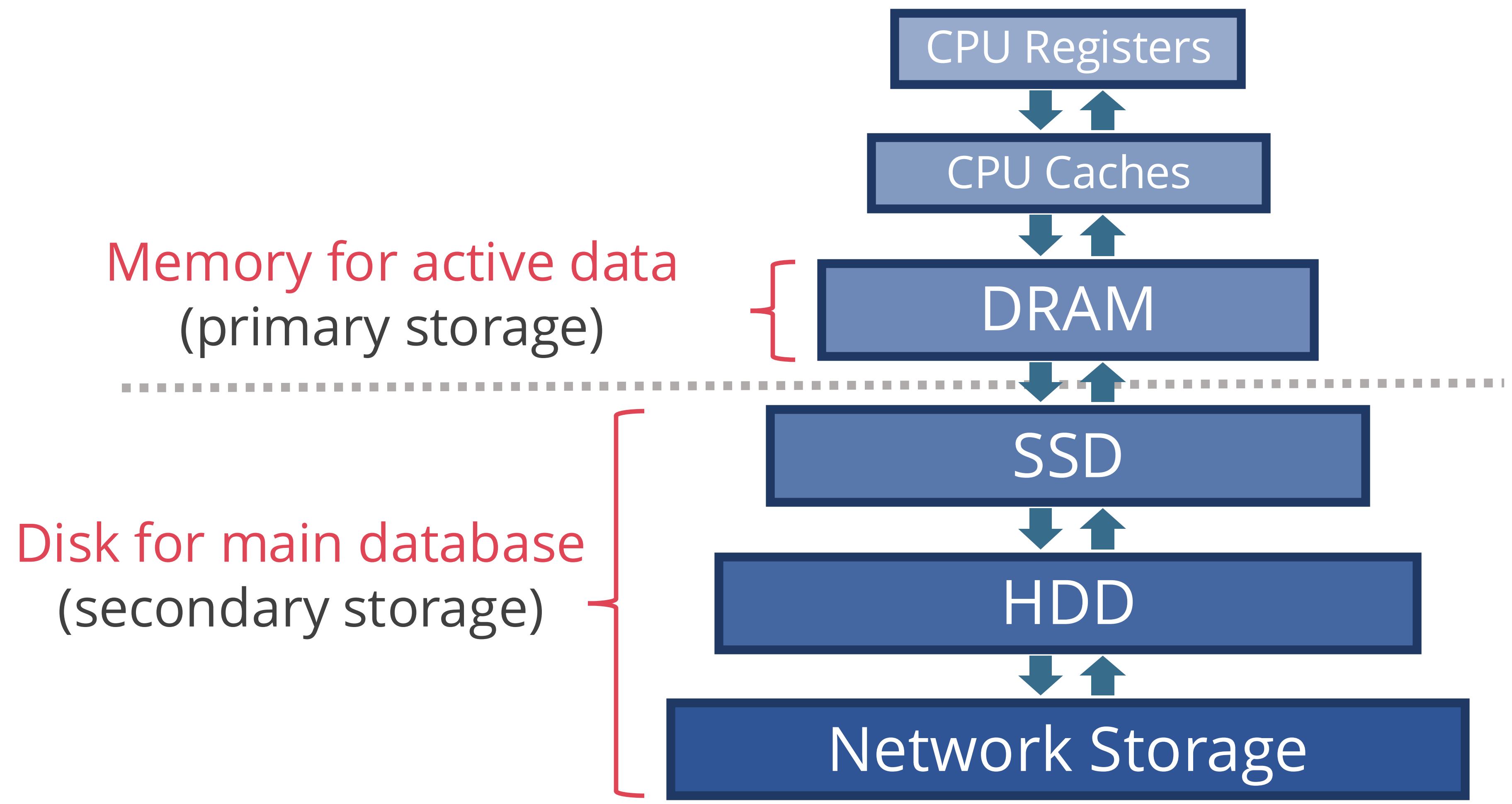
Some specialised systems <u>do</u> store entire databases in main memory

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

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**

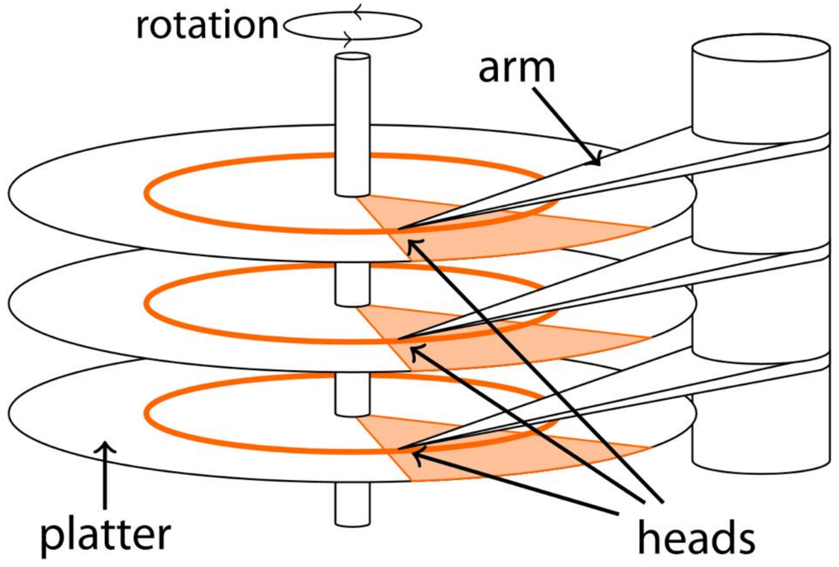
- Tracks under heads make a “cylinder”

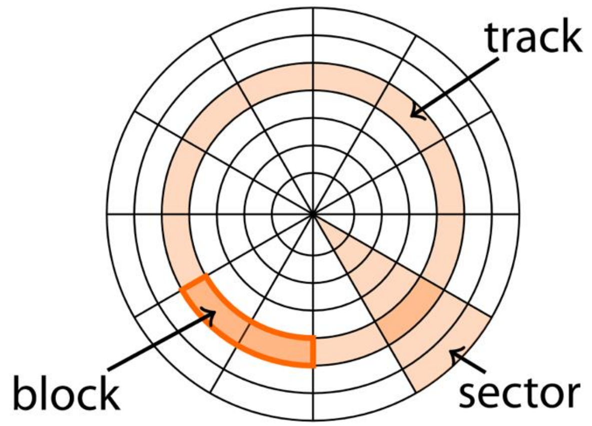
Only one head reads/writes at any one time

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:** $1000 \cdot 5.45\,\text{ms} = 5.45\text{ s}$
- **Sequential:** $3.4\,\text{ms} + 2\,\text{ms} + 1000 \cdot 0.05\,\text{ms} \approx 55\,\text{ms}$
  - tracks store only 512KB $\Longrightarrow$ some additional ($< 5\,\text{ms}$) track-to-track seek time

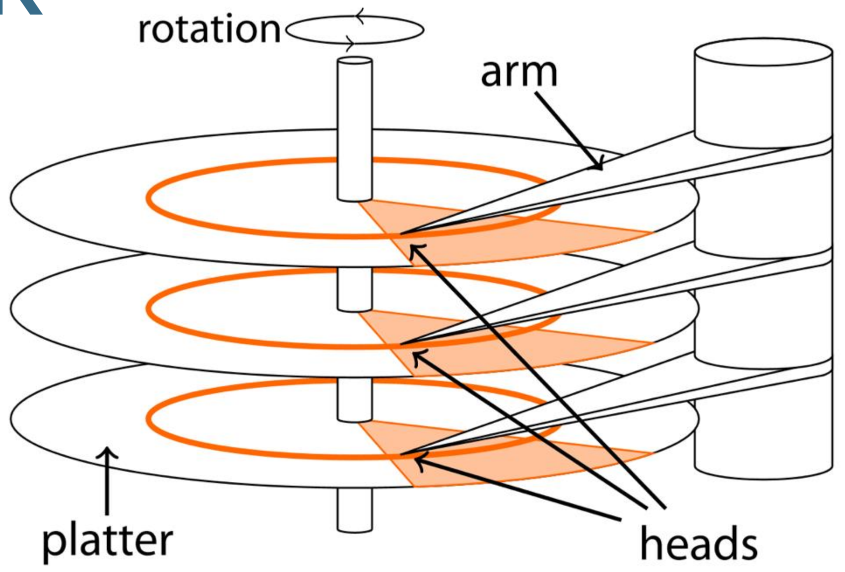
Sequential I/O orders of magnitude faster than random I/O

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



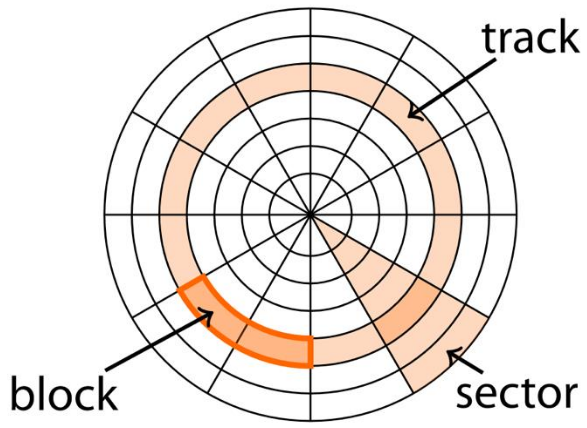
Arrange file pages sequentially by ‘next’ on disk

- 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 $\Longrightarrow$ 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

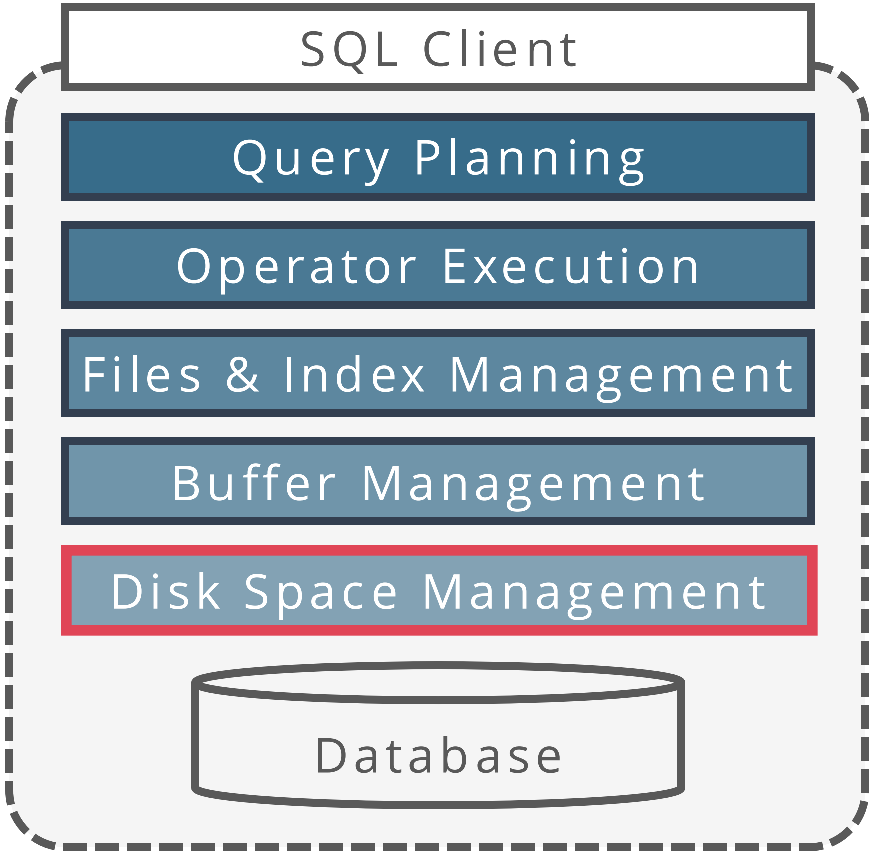
- Map pages to locations on disk
- Load pages from disk to memory
- Save pages back to disk

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

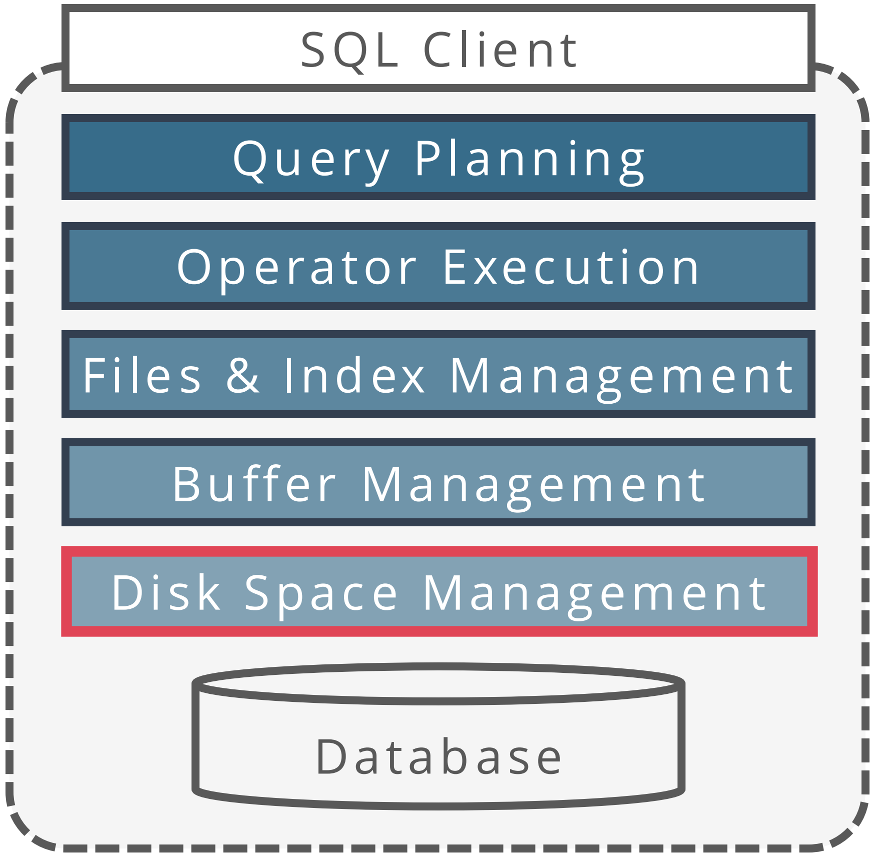
SUMMARY

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


SQL Client
Query Planning
Operator Execution
Files & Index Management
Buffer Management
Disk Space Management
Database