Systems Infrastructure for Data Science

Web Science Group
Uni Freiburg
WS 2012/13

Lecture I: Storage

Storage

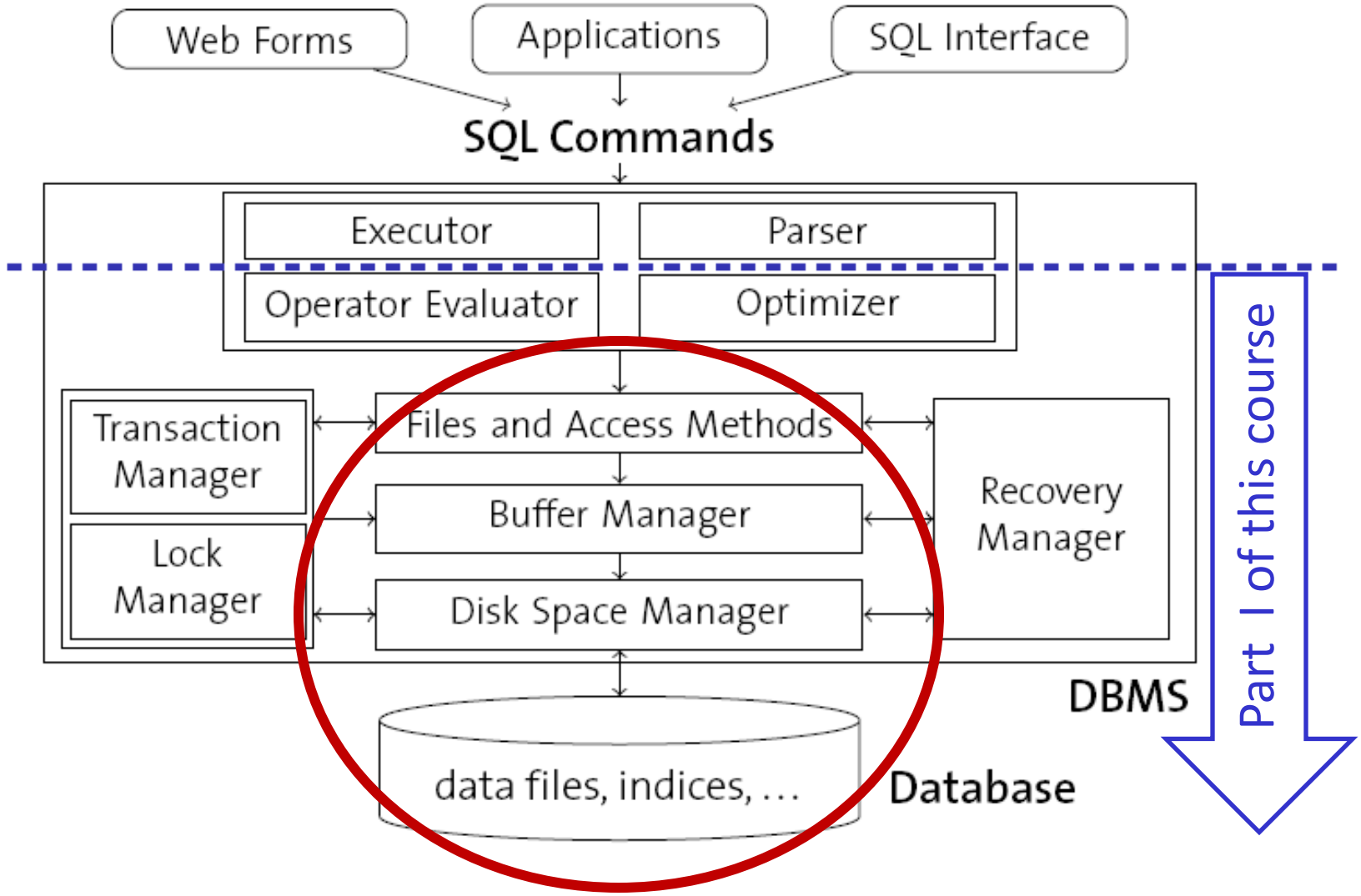
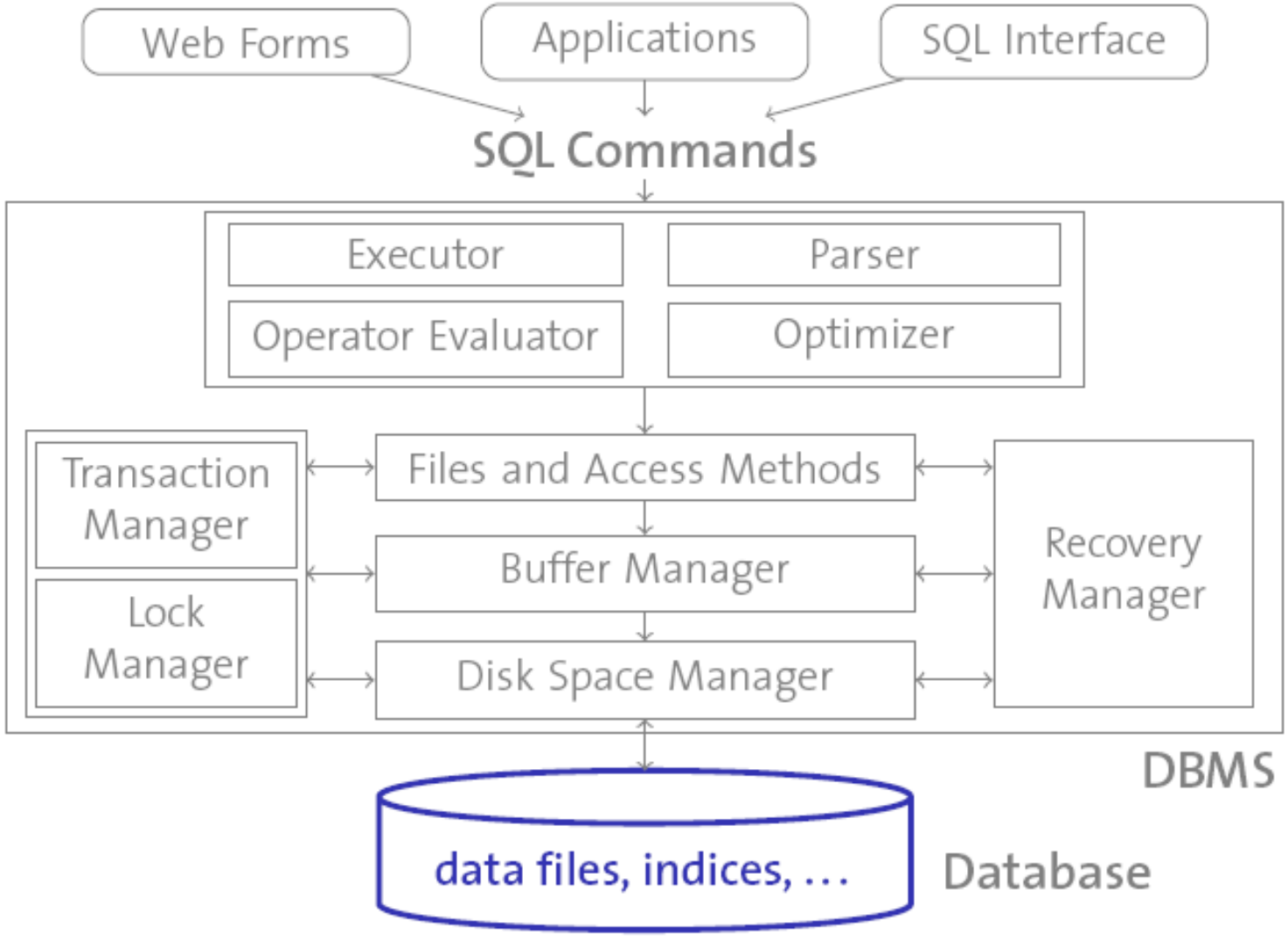
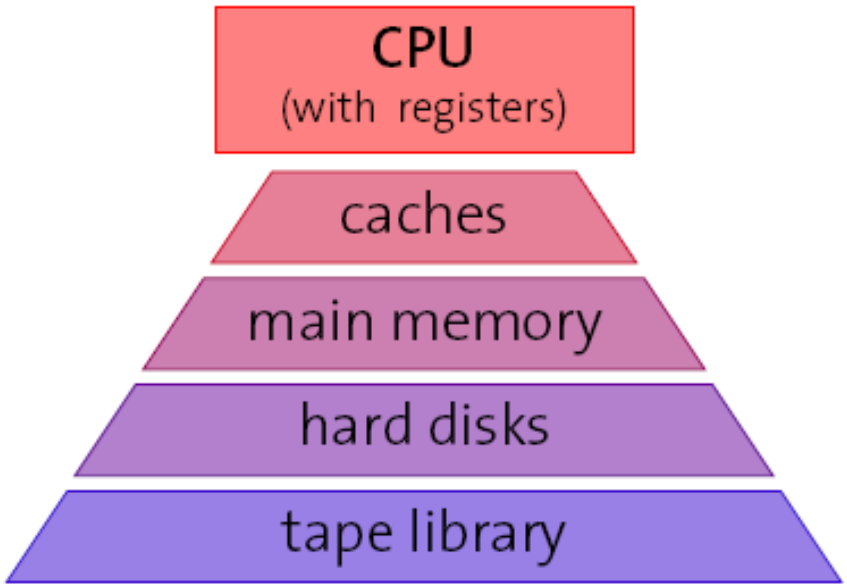


Figure inspired by Ramakrishnan/Gehrke: "Database Management Systems", McGraw-Hill 2003.

The Physical Layer



The Memory Hierarchy



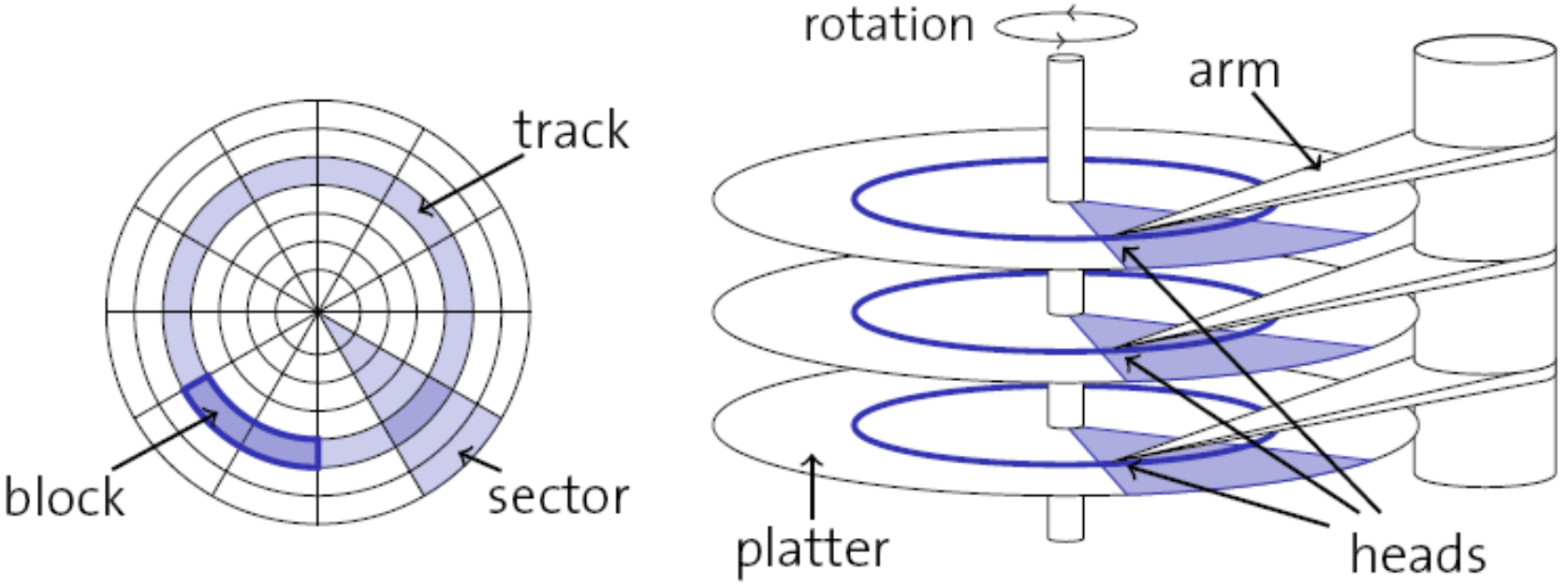
	capacity	latency
CPU (with registers)	bytes	< 1 ns
caches	kilo-/megabytes	< 10 ns
main memory	gigabytes	70–100 ns
hard disks	terabytes	3–10 ms
tape library	petabytes	varies

- Fast, but expensive and small memory close to CPU
- Larger, slower memory at the periphery
- We'll try to hide latency by using the fast memory as a **cache**.

Observations and Trends

- For which gaps were systems designed traditionally?
- Within the same technology:
  - Storages capacities grow fastest
  - Transfer speeds grow moderately
  - Latencies only see minimal changes
- Between the level
  - Widening latency gap

Magnetic Disks



- A stepper motor positions an array of disk heads on the requested track.
- Platters (disks) steadily rotate.
- Disks are managed in blocks: the system reads/writes data one block at a time.

Photo: http://www.metallurgy.utah.edu/

Access Time

- This design has implications on the **access time** to read/write a given block:
  1. Move disk arms to desired track (**seek time** t_s).
  2. Wait for desired block to rotate under disk head (**rotational delay** t_r).
  3. Read/write data (**transfer time** t_{tr}).

access time $t = t_s + t_r + t_{tr}$

Example

Notebook drive Hitachi TravelStar 7K200

- 4 heads, 2 disks, 512 bytes/sector, 200 GB capacity
- average seek time = **10 ms**
- rotational speed = **7200 rpm** (**r**evolutions **p**er **m**inute)
- transfer rate = ≈ **50 MB/s**

➢ What is the access time to read an **8 KB** data block?

$t = t_s + t_r + t_{tr}$

$t_s = 10$ ms

$t_r = (60{,}000/7200)/2 = 4.17$ ms ← max = 60,000/7200 ms; avg = max/2

$t_{tr} = (8/50{,}000)*1{,}000 = 0.16$ ms

$t = 10 + 4.17 + 0.16 = 14.33$ ms

Sequential vs. Random Access

➢ What is the access time to read **1000 blocks** of size **8 KB**?

- Random access:

$t_{rnd} = 1000 * t$

$= 1000 * (t_s + t_r + t_{tr})$

$= 1000 * (10 + 4.17 + 0.16) = 1000 * 14.33 =$ **14330 ms**

- Sequential access:

$t_{seq} = t_s + t_r + 1000 * t_{tr} + N * t_{\text{track-to-track seek time}}$

$= t_s + t_r + 1000 * 0.16 \text{ ms} + (16 * 1000)/63 * 1 \text{ ms}$

$= 10 \text{ ms} + 4.17 \text{ ms} + 160 \text{ ms} + 254 \text{ ms} \approx$ **428 ms**

// N: number of tracks

// TravelStar 7K200: There are 63 sectors per track.
Each 8 KB block occupies 16 sectors.
$t_{\text{track-to-track seek time}} = 1$ ms

Sequential vs. Random Access

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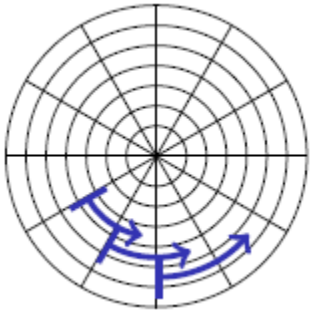
➢ Sequential I/O is **much** faster than random I/O.

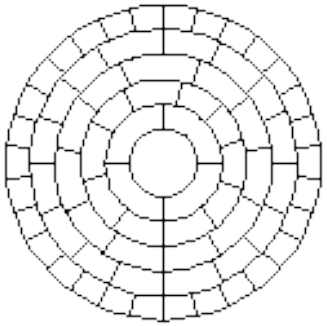
➢ Avoid **random I/O** whenever possible.

Performance Tricks

- System builders play a number of tricks to improve performance:
  - **Track skewing:** Align sector 0 of each track to avoid rotational delay during sequential scans.



  - **Request scheduling:** If multiple requests have to be served, choose the one that requires the smallest arm movement (SPTF: **S**hortest **P**ositioning **T**ime **F**irst).
  - **Zoning:** Outer tracks are longer than the inner ones. Therefore, divide outer tracks into more sectors than inners.



Evolution of Hard Disk Technology

- Disk latencies have only marginally improved over the last years (≈ 10% per year).
- **But:**
  - Throughput (i.e., transfer rates) improve by ≈ 50% per year.
  - Hard disk capacity grows by ≈ 50% every year.
- **Therefore:**
  - Random access cost hurts even more as time progresses.

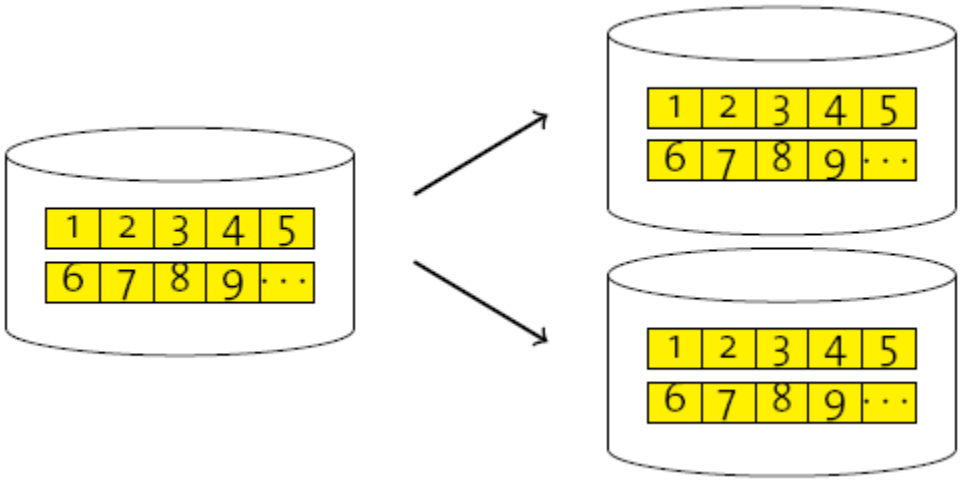
Ways to Improve I/O Performance

- The latency penalty is hard to avoid.
- **But:**
  - Throughput can be increased rather easily by exploiting **parallelism.**
  - **Idea**: Use multiple disks and access them in parallel.

➢ **TPC-C: An industry benchmark for OLTP**
➢ The #1 system in 2008 (an IBM DB2 9.5 database on AIX) uses:
  - 10,992 disk drives (73.4 GB each, 15,000 rpm) **(!)**
  - connected with 68 x 4 Gbit Fibre Channel adapters,
  - yielding 6M transactions per minute.

Disk Mirroring

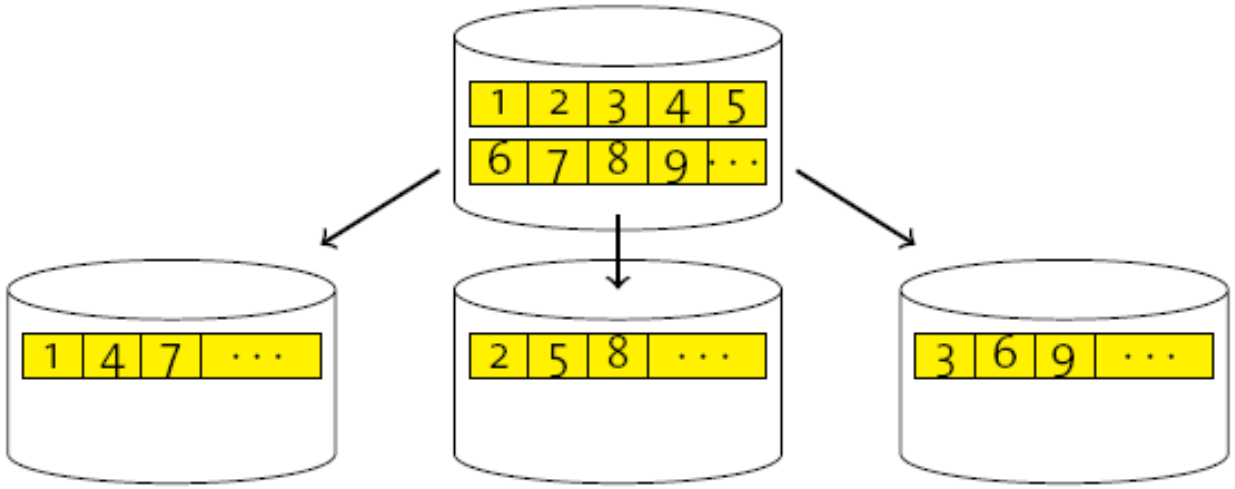
- Replicate data onto multiple disks:



- I/O parallelism only for **reads** (writes must be sequential to keep consistency).
- Improved **failure tolerance** (can survive one disk failure).
- **No parity** (no extra information kept to recover from disk failures).
- This is also known as **RAID 1** ("mirroring without parity").
  (RAID = **R**edundant **A**rray of **I**nexpensive **D**isks)

Disk Striping

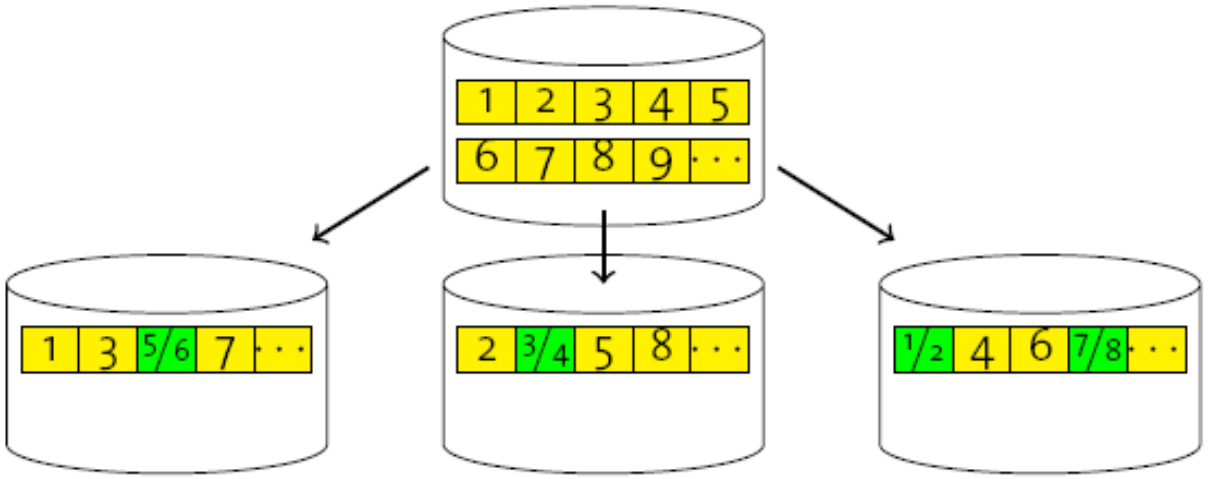
- Distribute data into equal-size partitions over multiple disks:



- Full I/O parallelism (both reads and writes).
- No parity.
- High failure risk (here: 3 times risk of single disk failure)!
- This is also known as **RAID 0** ("striping without parity").

Disk Striping with Parity

- Distribute data and parity information over disks:



- High I/O parallelism.
- Fault tolerance: one disk can fail without data loss.
- This is also known as **RAID 5** ("striping with distributed parity").

Other RAID Levels

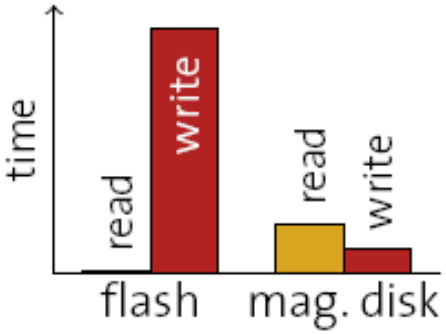
- **RAID 0**: block-level **striping** without parity or mirroring
- **RAID 1**: **mirroring** without parity or striping
- RAID 2: bit-level striping with dedicated parity
- RAID 3: byte-level striping with dedicated parity
- RAID 4: block-level striping with dedicated parity
- **RAID 5**: block-level striping with **distributed parity**
- RAID 6: block-level striping with double distributed parity

Modern Storage Alternatives

- (Flash-based) Solid-State Disk (SSD)
- Phase-Change Memory (PCM)
- Storage-Area Network (SAN)
- Cloud-based Storage (e.g., Amazon S3)

Solid-State Disks

- Solid-State Disks (SSDs), mostly based on flash memory chips, have emerged as an alternative to conventional hard disks.
  - SSDs provide **very low-latency random read access**.
  - **Random writes**, however, are significantly **slower** than on traditional magnetic drives.
    - Pages have to be **erased** before they can be updated.
    - Once pages have been erased, sequentially writing them is almost as fast as reading.
  - Adapting databases to these characteristics is a current research topic.



➢ Koltsidas and Viglas, “Flashing up the Storage Layer”, VLDB Conference, 2008.

Phase-Change Memory

- More recently, Phase-Change Memory (PCM) has been emerging as an alternative to flash.
- It incurs lower read and write latency compared to both flash memory and magnetic disks.
- Currently mostly used in mobile devices; is expected to become more common in the near future.

➢ Chen, Gibbons, Nath, “Rethinking Database Algorithms for Phase Change Memory”, CIDR Conference, 2011.

Network-based Storage

- The network is **not** a bottleneck any more:
  - Hard disk: 150 MB/s
  - Serial ATA: 600 MB/s
    Ultra-640 SCSI: 640 MB/s
  - 10 gigabit Ethernet: 1,250 MB/s (latency ~ µs)
    Infiniband QDR: 12,000 MB/s (latency ~ µs)
  - For comparison:
    PC2-5300 DDR2-SDRAM (dual channel) = 10.6 GB/s
    PC3-12800 DDR3-SDRAM (dual channel) = 25.6 GB/s

➢ Why not use the network for database storage?

Storage Area Network (SAN)

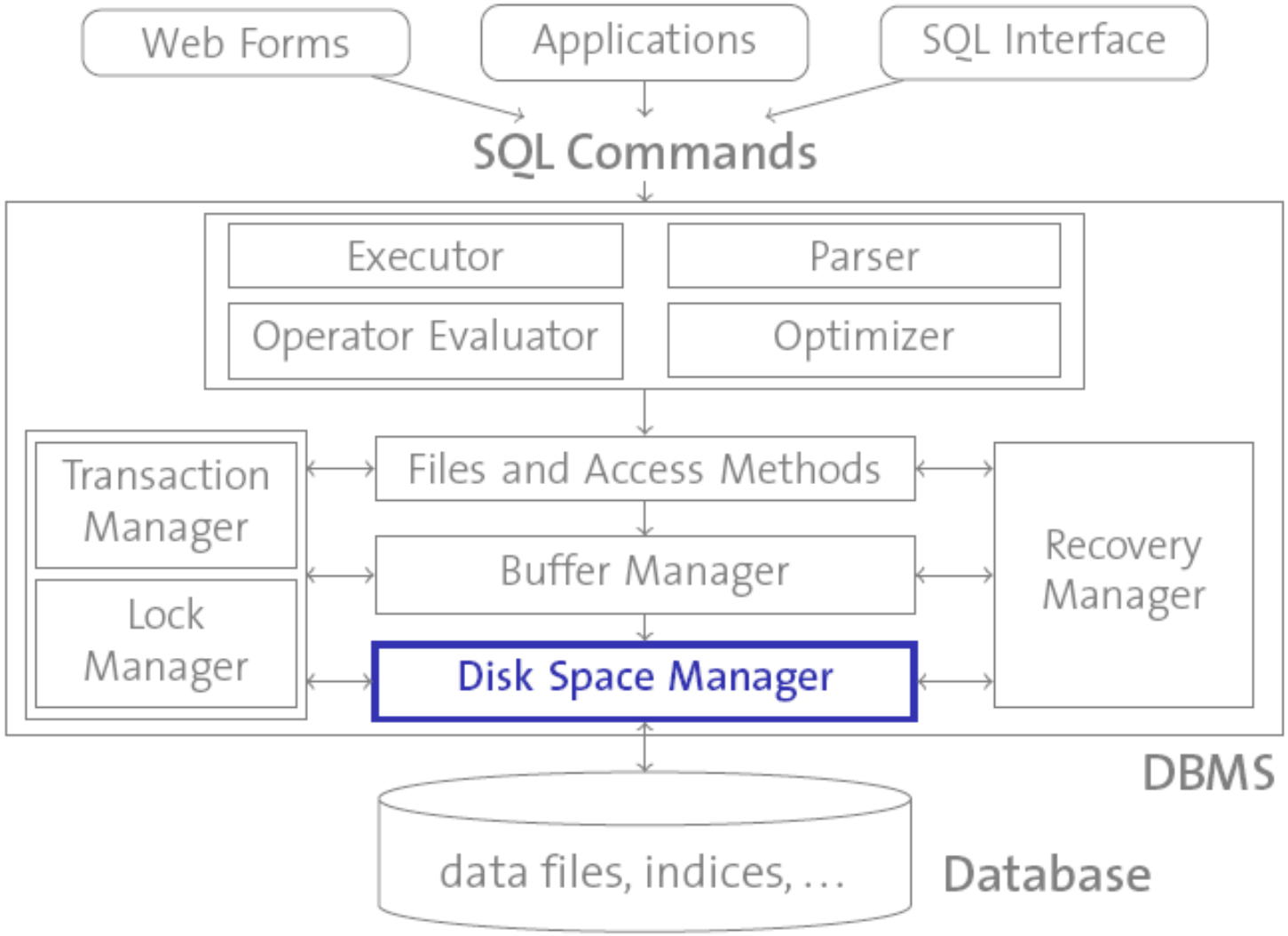
- **Block-based** network access to storage
  - Seen as logical disks ("Give me block 4711 from disk 42.")
  - Unlike network file systems (e.g., NFS)
- SAN storage devices typically abstract from RAID or physical disks, and present logical drives to the DBMS.
  - Hardware acceleration and simplified maintainability
- Typically local networks with multiple servers and storage resources participating
  - Failure tolerance and increased flexibility

Grid or Cloud Storage

- Some big enterprises employ clusters with **thousands** of commodity PCs (e.g., Google, Amazon):
  - **system cost** $\leftrightarrow$ **reliability** and **performance**
  - use **massive replication** for data storage
- Spare CPU cycles and disk space can be sold as a **service**.
- Amazon's "Elastic Computing Cloud (EC2)"
  - Use Amazon's compute cluster by the hour (~ 10 cents/hour).
- Amazon's "Simple Storage Systems (S3)"
  - "Infinite" store for objects between 1 Byte and 5 GB in size, with a simple key $\rightarrow$ value interface.
  - Latency: 100 ms to 1 s (not impacted by load)
  - Pricing ≈ disk drives (but additional cost for access)

➢ Build a database on S3? (Brantner et al., SIGMOD'08 Conference)

Managing Space



Managing Space

- The **disk space manager**
  - abstracts from the gory details of the underlying storage
  - provides the concept of a **page** (typically 4–64 KB) as a unit of storage to the remaining system components
  - maintains the mapping

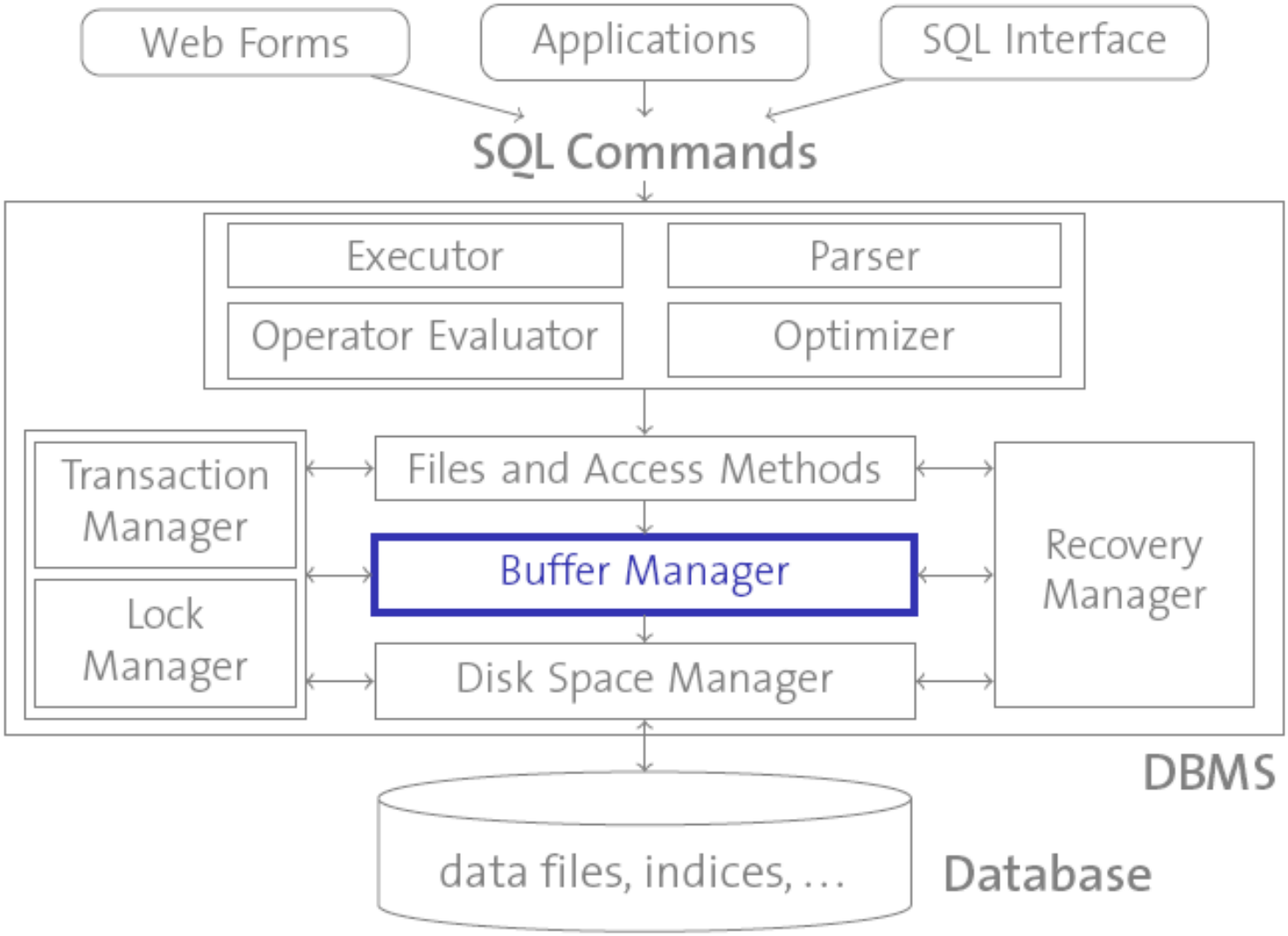
    page number $\rightarrow$ physical location

    where a physical location could be, e.g.,
    - an OS file name and an offset within that file, or
    - head, sector, and track of a hard drive, or
    - tape number and offset for data stored in a tape library.

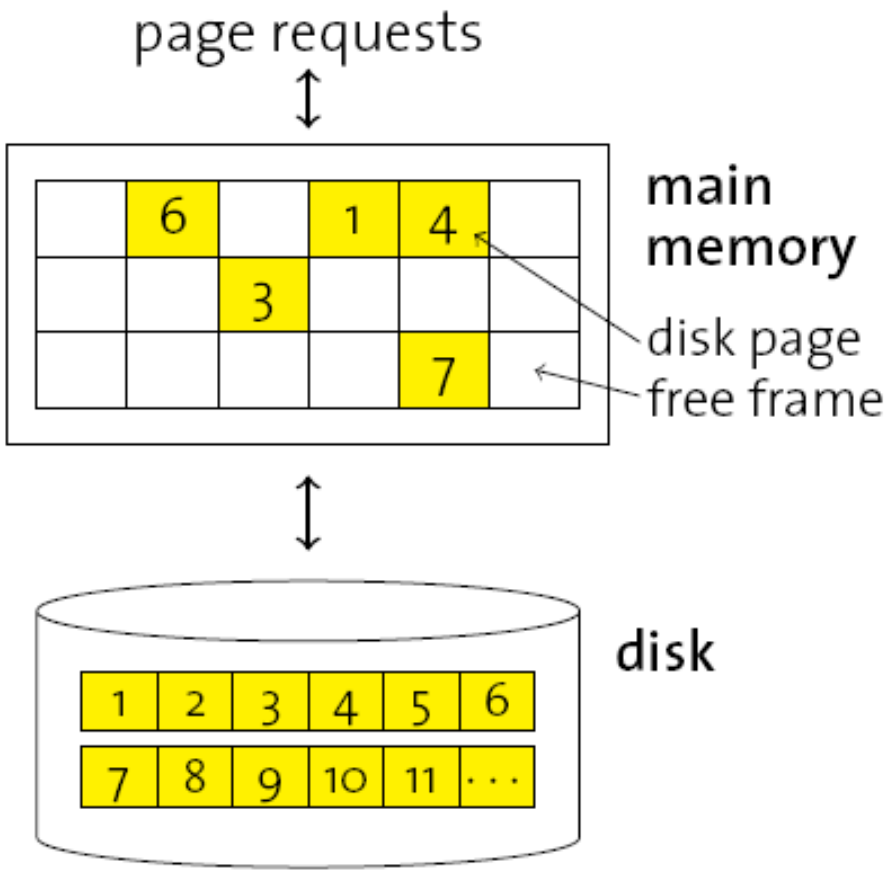
Empty Pages

- The disk space manager also keeps track of used/free blocks.
    1. Maintain a linked list of free pages
        - When a page is no longer needed, add it to the list.
    2. Maintain a bitmap with one bit for each page
        - Toggle bit n when page n is (de-)allocated.

Buffer Manager



Buffer Manager



- The **buffer manager**
  - mediates between external storage and main memory
  - manages a designated main memory area, the **buffer pool** for this task.
- Disk pages are brought into memory as needed and loaded into memory **frames.**
- A **replacement policy** decides which page to evict when the buffer is full.

Interface to the Buffer Manager

- Higher-level code requests (“pins”) pages from the buffer manager and releases (“unpins”) pages after use.

`pin(pageno)`

Request page number `pageno` from the buffer manager, load it into memory if necessary. Returns a reference to the frame containing `pageno`.

`unpin(pageno,dirty)`

Release page number `pageno`, making it a candidate for eviction. Must set `dirty=true` if the page was modified.

Implementation of `pin( )`

```
1  Function: pin(pageno)
2  if buffer pool already contains pageno then
3      pinCount (pageno) ← pinCount (pageno) + 1;
4      return address of frame holding pageno;
5  else
6      select a victim frame v using the replacement policy;
7      if dirty (v) then
8          write v to disk;
9      read page pageno from disk into frame v;
10     pinCount (pageno) ← 1;
11     dirty (pageno) ← false;
12     return address of frame v;
```

Implementation of unpin( )

```
1 Function: unpin(pageno, dirty)
2 pinCount (pageno) ← pinCount (pageno) − 1;
3 if dirty then
4     dirty (pageno) ← dirty;
```

Page Replacement

- Only frames with `pinCount=0` can be chosen for replacement.
- If no such frames, the buffer manager has to wait until there is one.
- If many such frames, one is chosen based on the buffer manager's replacement policy.

Page Replacement Policies

- The effectiveness of the buffer manager's **caching functionality** can depend on the **replacement policy** it uses, e.g.,
- **L**east **R**ecently **U**sed (LRU)
  - Evict the page whose latest `unpin( )` is the longest ago.
- **M**ost **R**ecently **U**sed (MRU)
  - Evict the page that has been unpinned the most recently.
- Random
  - Pick a victim randomly.

Buffer Management in Reality

- Prefetching
  - Buffer managers try to anticipate page requests to overlap CPU and I/O operations.
    - **Speculative prefetching:** Assume sequential scan and automatically read ahead.
    - **Prefetch lists:** Some database algorithms can instruct the buffer manager with a list of pages to prefetch.
- Page fixing/hating
  - Higher-level code may request to **fix** a page if it may be useful in the near future (e.g., index pages).
  - Likewise, an operator that **hates** a page won't access it any time soon (e.g., table pages in a sequential scan).
- Partitioned buffer pools
  - E.g., separate pools for indices and tables.

Database Systems vs. Operating Systems

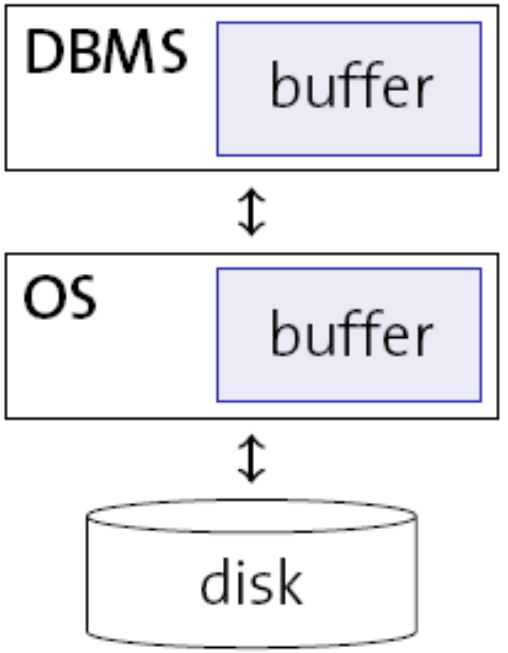
- Didn't we just re-invent the operating system?

- Yes,
  - disk space management and buffer management very much look like **file management** and **virtual memory** in OSs.

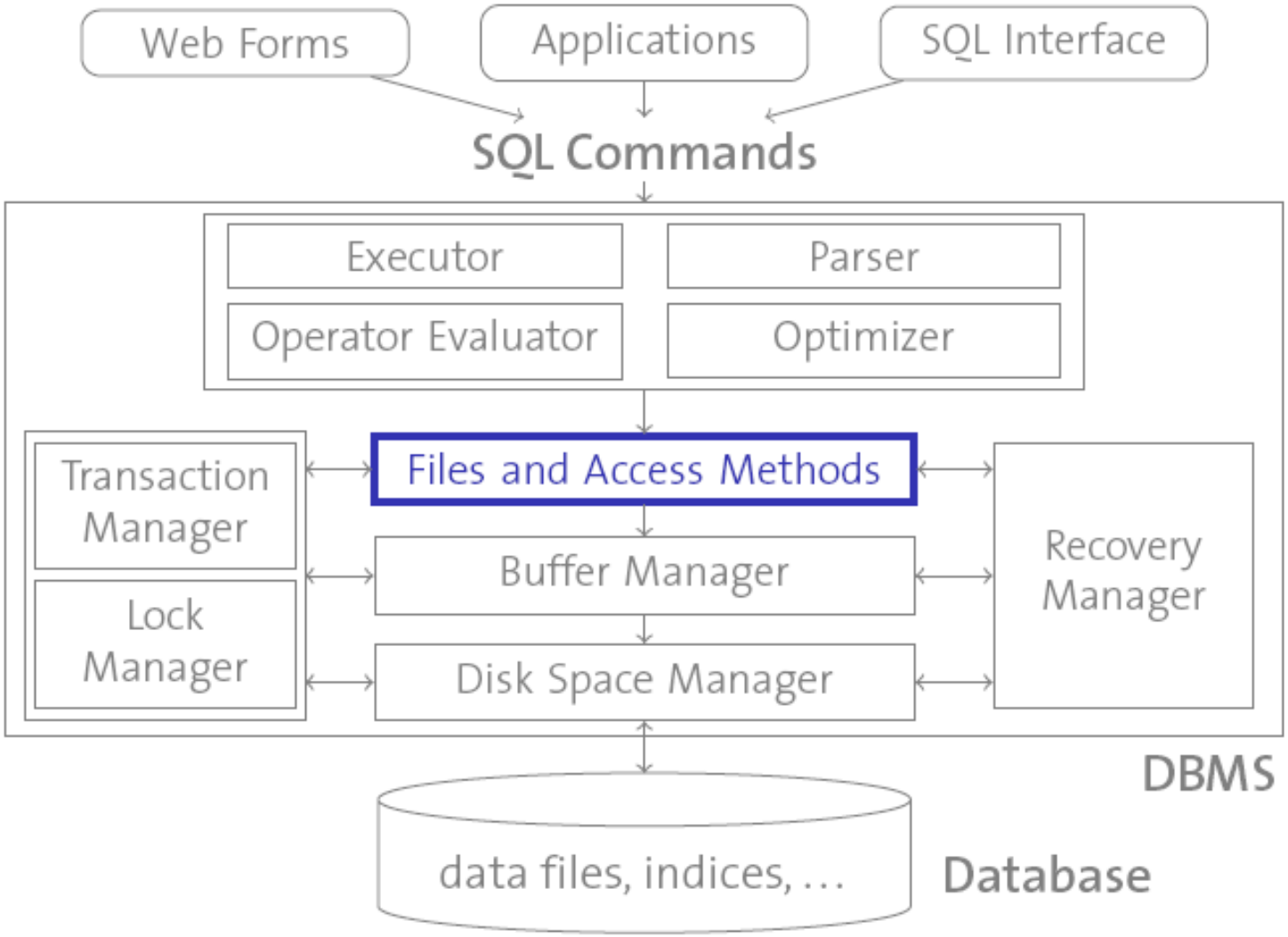
- But,
  - a DBMS may be much more aware of the **access patterns** of certain operators (prefetching, page fixing/hating),
  - concurrency control often calls for a **defined order** of write operations,
  - technical reasons may make OS tools unsuitable for a database (e.g., file size limitation, platform independence).

Database Systems vs. Operating Systems

- In fact, DBMS and OS systems sometimes interfere.
  - Operating system and buffer manager effectively buffer the same data twice.
  - Things get really bad if parts of the DBMS buffer get swapped out to disk by OS VM manager.
  - Similar problems: scheduling (Linux 3.6 vs. Postgres)
  - Classical approach: databases try to **turn off** OS functionality as much as possible.
  - Ongoing Research: New interfaces, cooperation, e.g. COD at CIDR 2013

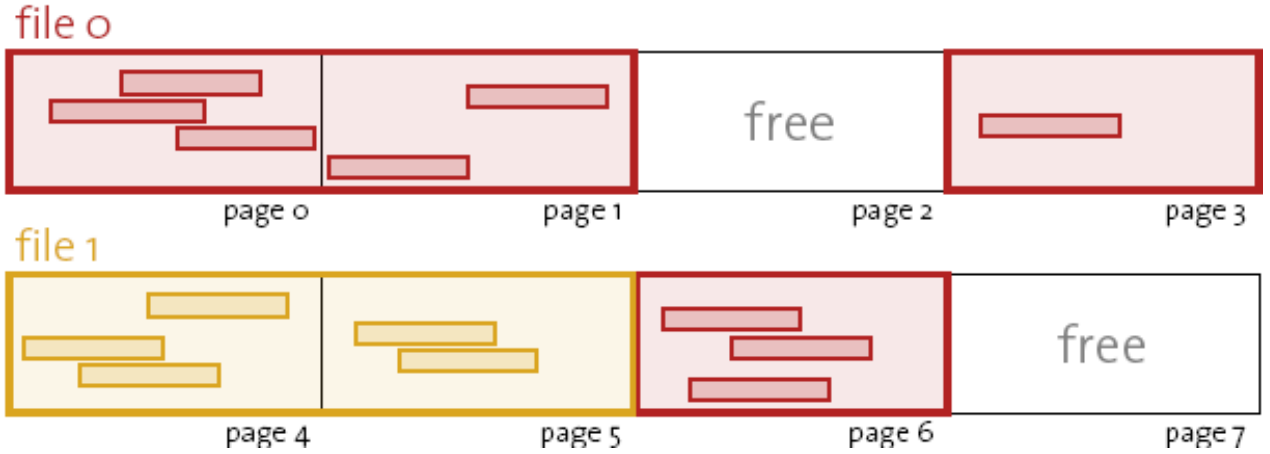


Files and Records



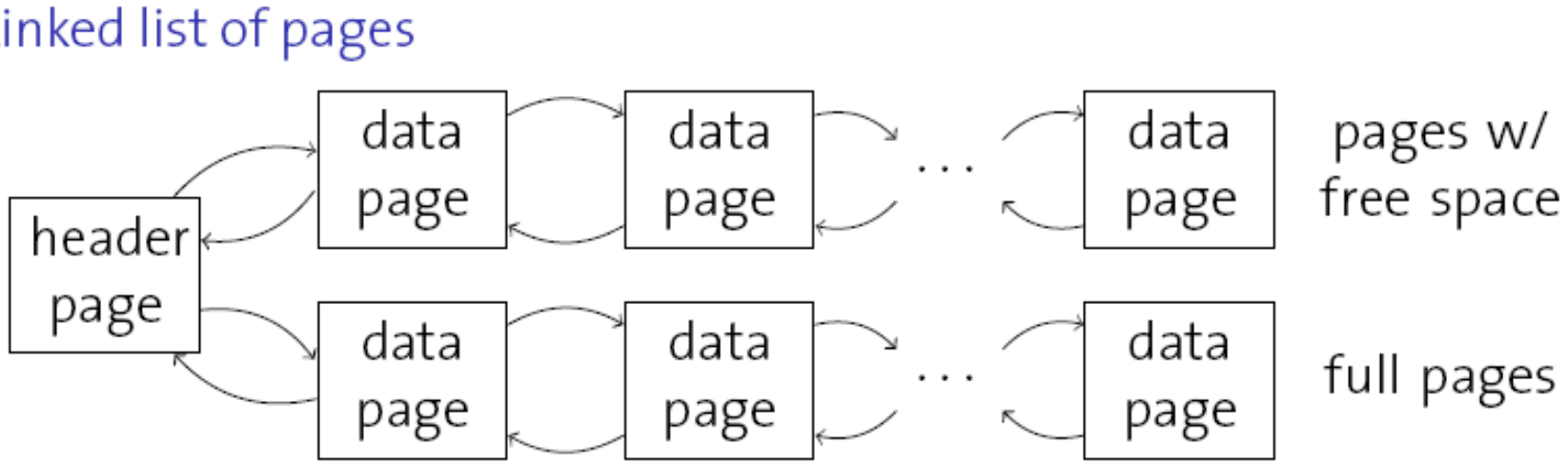
Database Files

- So far we have talked about **pages**. Their management is oblivious with respect to their actual content.
- On the conceptual level, a DBMS manages **tables of tuples** and **indices** (among others).
- Such tables are implemented as **files of records**:
  - A **file** consists of **one or more pages**.
  - Each **page** contains **one or more records**.
  - Each **record** corresponds to **one tuple**.



Heap Files

- The most important type of files in a database is the **heap file**. It stores records in **no particular order** (in line with, e.g., SQL).

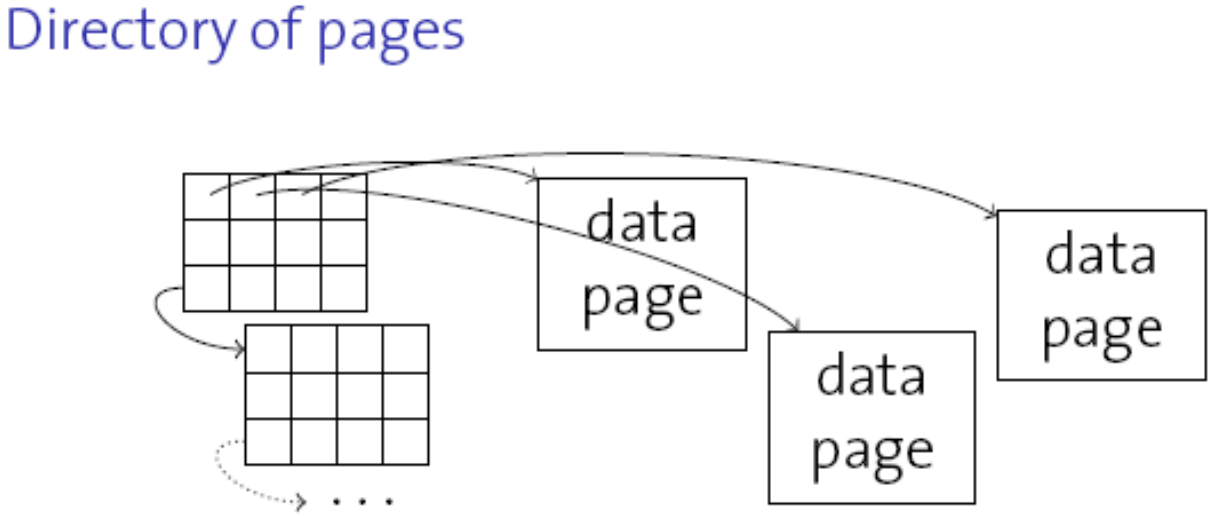


+ easy to implement

– most pages will end up in free page list

– might have to search many pages to place a (large) record

Heap Files



- Use as **space map** with information about free pages
  - granularity for trade-off between space and accuracy (ranges from open/closed bit to exact information)

+ free space search more efficient

– small memory overhead to host directory

Free Space Management

- Which page to pick for the insertion of a new record?

- Append Only
  - Always insert into the last page. Otherwise, create a new page.
- Best Fit
  - Reduces fragmentation, but requires searching the entire space map for each insert.
- First Fit
  - Search from the beginning, take first page with enough space.

    (These pages quickly fill up, and we waste a lot of search effort in first pages afterwards.)
- Next Fit
  - Maintain a **cursor** and continue searching where the search stopped last time.

Free Space Witnesses

- We can accelerate the search by remembering **witnesses**:
  - Classify pages into **buckets**, e.g., “75 % – 100% full”, “50 % – 75% full”, “25 % – 50% full”, and “0 % – 25% full”.
  - For each bucket, remember some **witness pages**.
  - Do a regular best/first/next fit search, only if no witness is recorded for the specific bucket.
  - Populate witness information, e.g., as a side effect when searching for a best/first/next fit page.

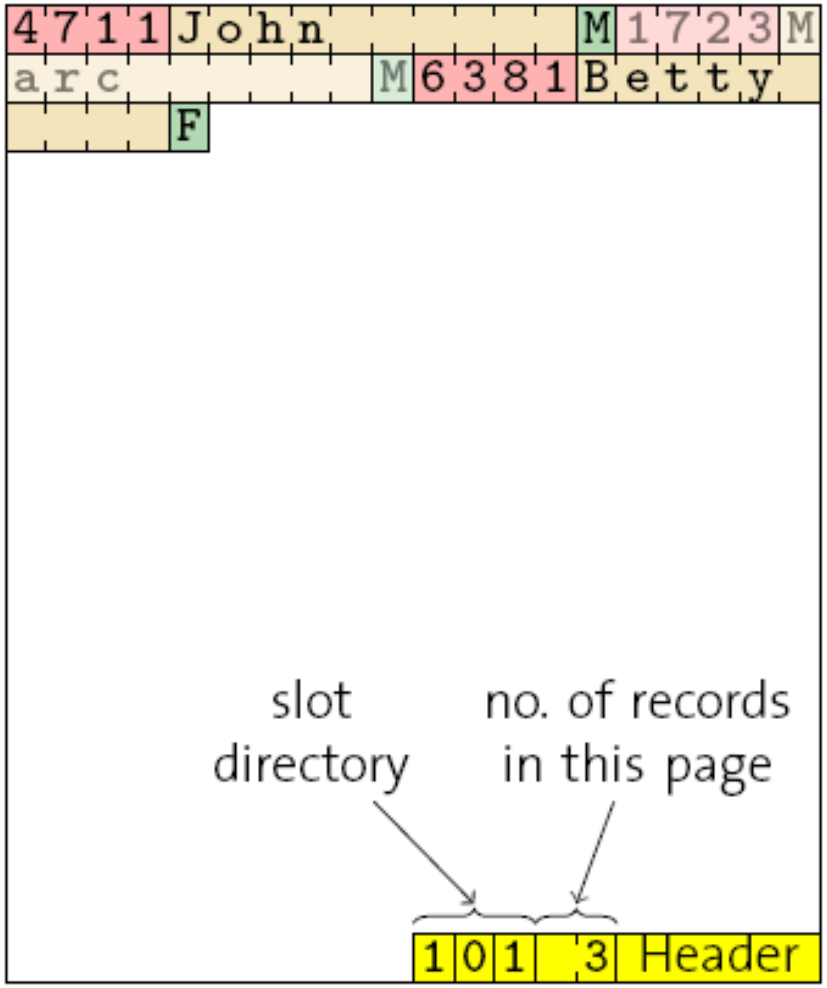
Inside a Page

ID	NAME	SEX
4711	John	M
~~1723~~	~~Marc~~	~~M~~
6381	Betty	F

- **record identifier (rid):**

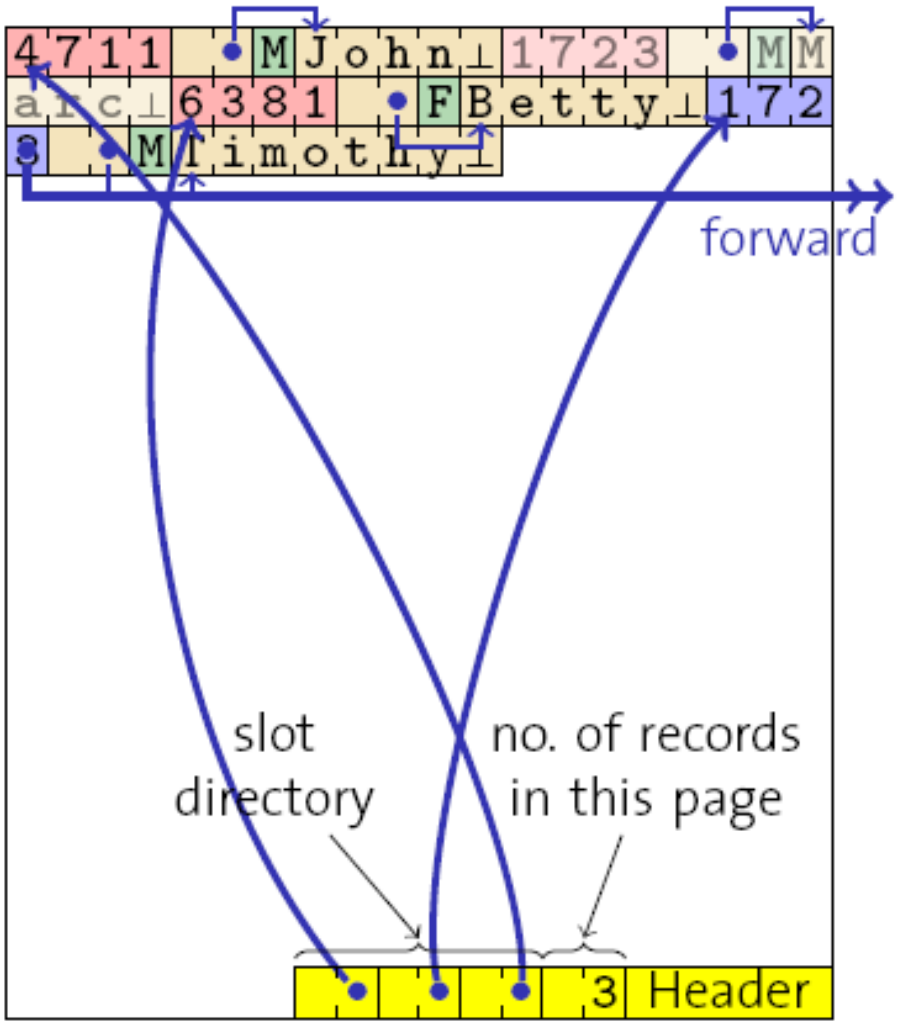
  <pageno, slotno>
- record position (within page):

  slotno x bytes per slot
- Tuple **deletion**?
  - record id shouldn't change
  - slot directory (bitmap)



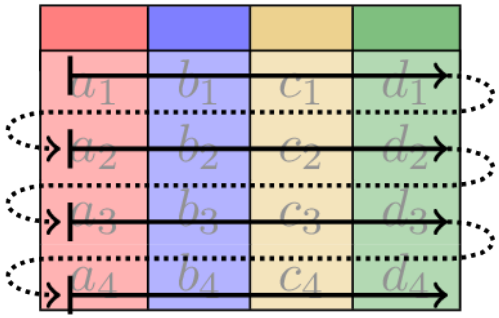
Inside a Page: Variable-sized Fields

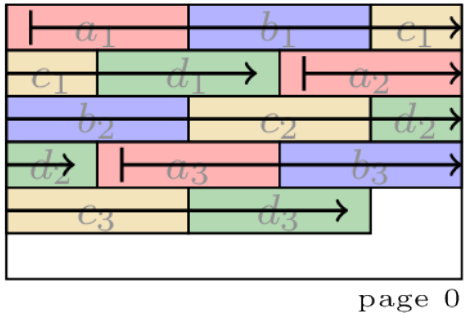
- Variable-sized fields moved to **end** of each record.
  - Placeholder points to location.
- Slot directory points to start of each record.
- Records **can move** on page.
  - E.g., if field size changes.
- Create "**forward address**" if record won't fit on page.

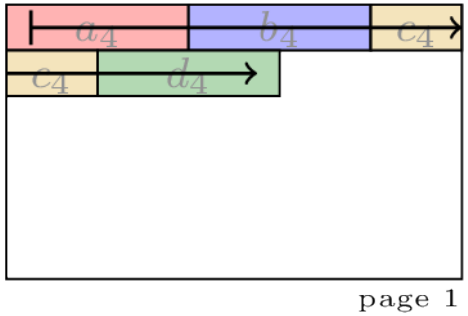


Variants of page layout

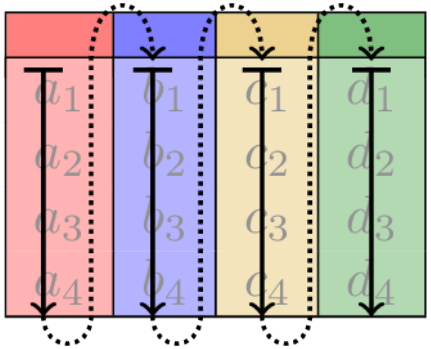
- Row-wise

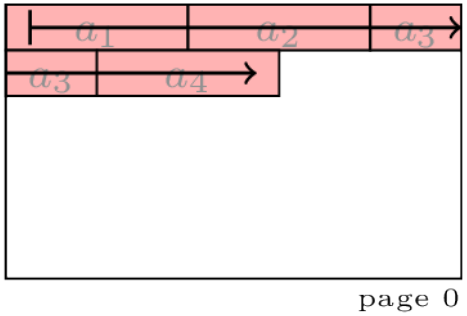


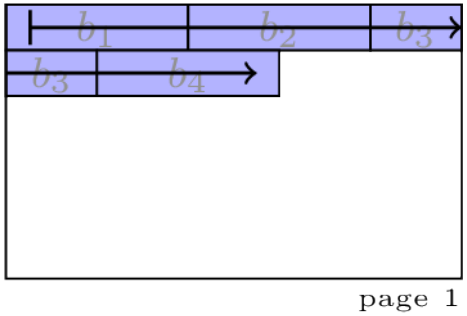




- Column-wise







(Figures by Jens Teubner, ETH)

Row Stores vs. Column Stores

- Which one is better?
- For what?
- Some ideas for evaluation:
  - How many attributes to tuples have? How many of them are read in a typical query
  - How would they deal with different levels of the storage hierarchy?
  - What happens on an update?
  - Which one would compress better?

Summary

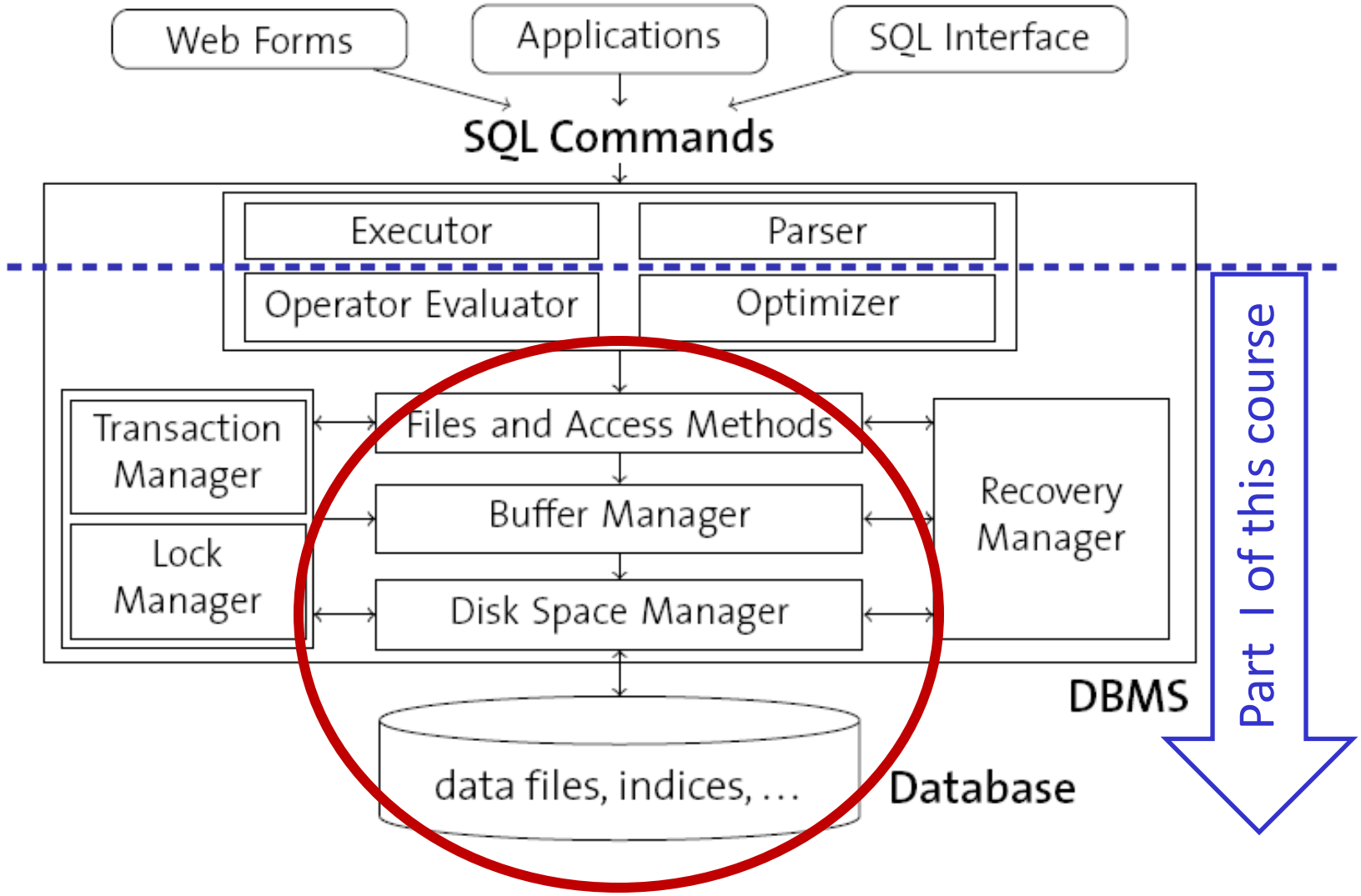


Figure inspired by Ramakrishnan/Gehrke: "Database Management Systems", McGraw-Hill 2003.