Systems Infrastructure for Data Science

Web Science Group
Uni Freiburg
WS 2014/15

Lecture I: Storage

Storage

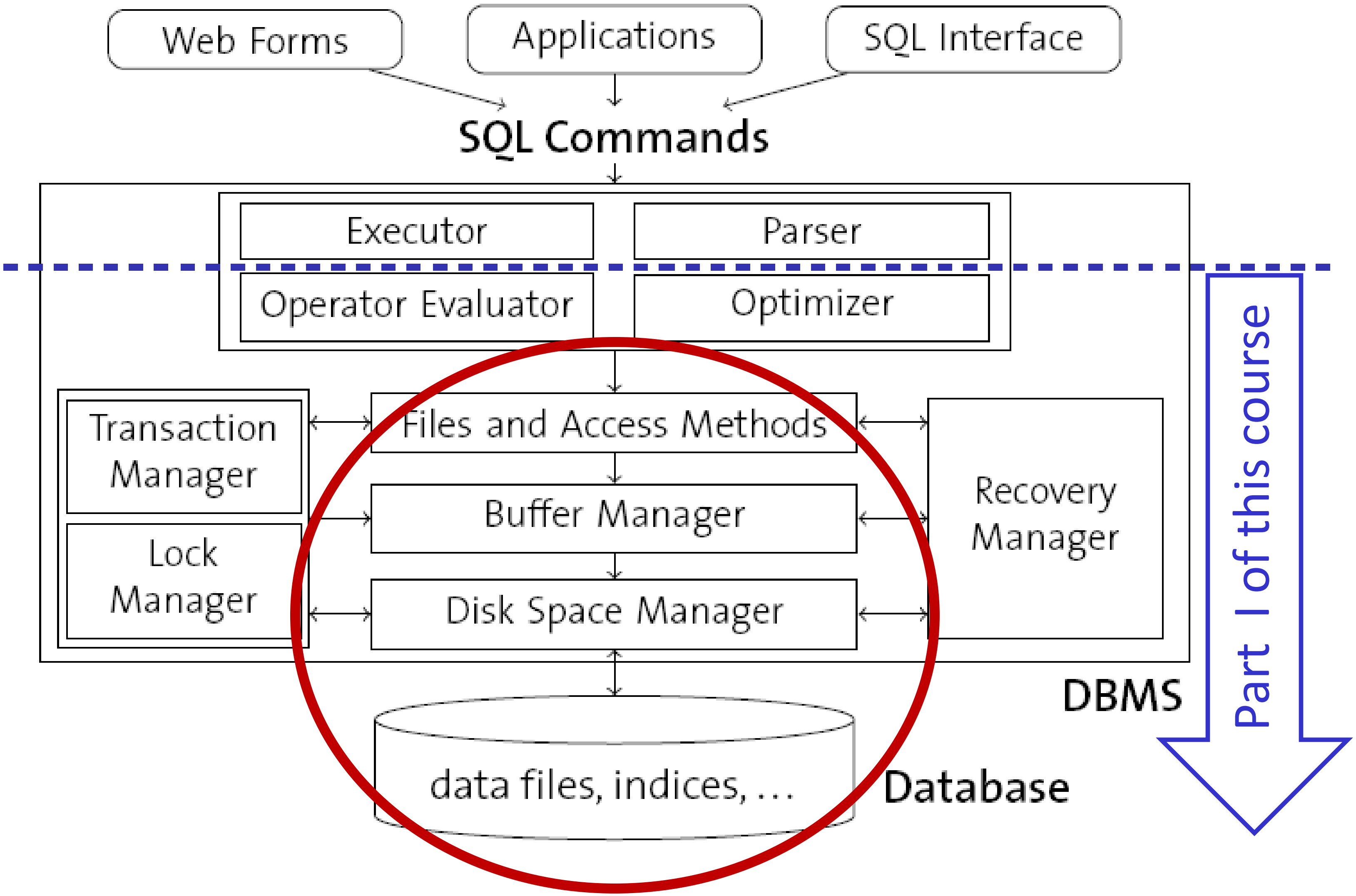
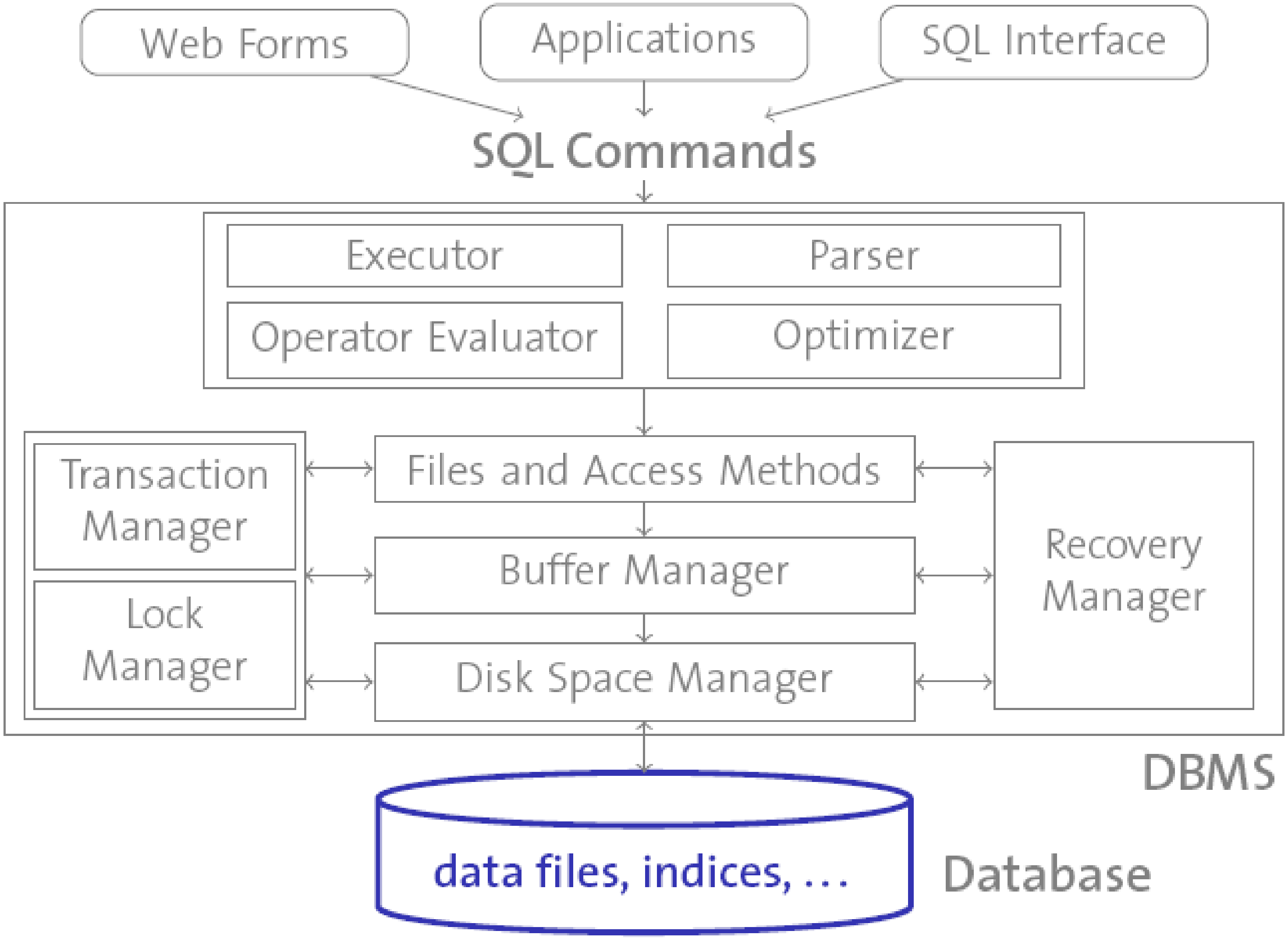
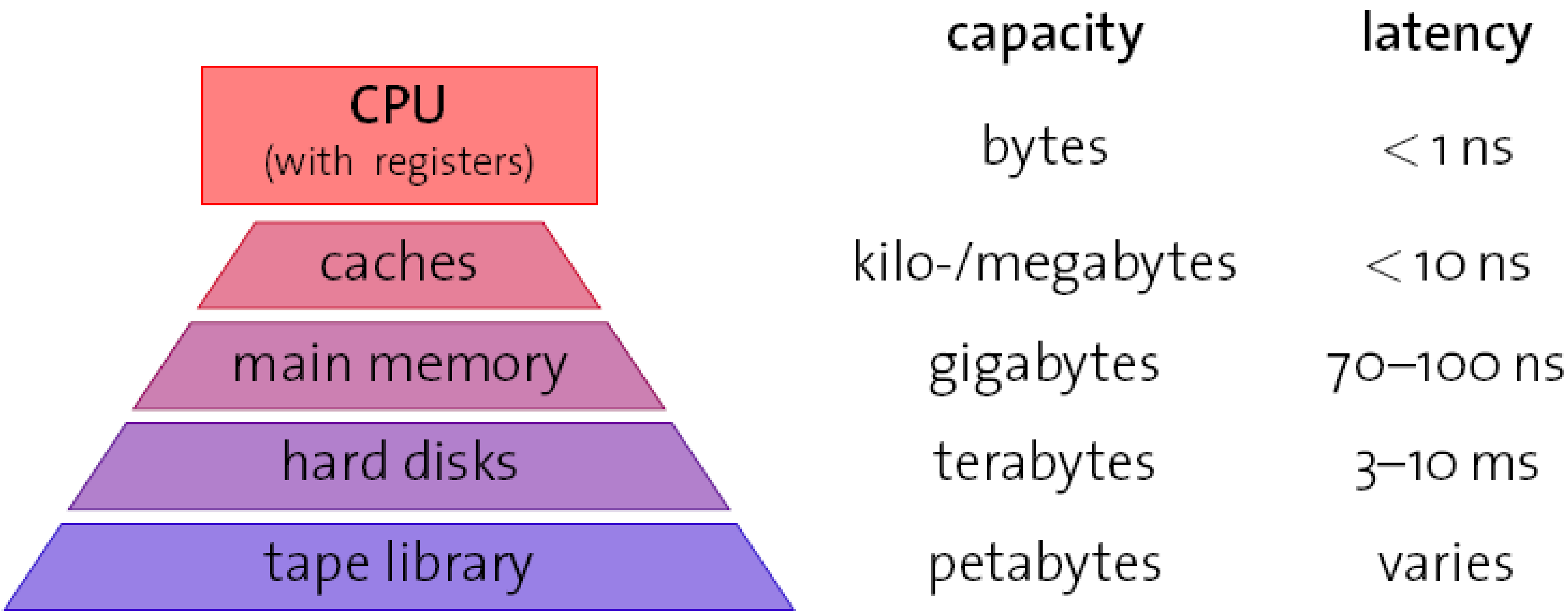


Figure inspired by Ramakrishnan/Gehrke: "Database Management Systems", McGraw-Hill 2003.

The Physical Layer



The Memory Hierarchy



- 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**.

A different take on latencies

Table 2.2 Example Time Scale of System Latencies

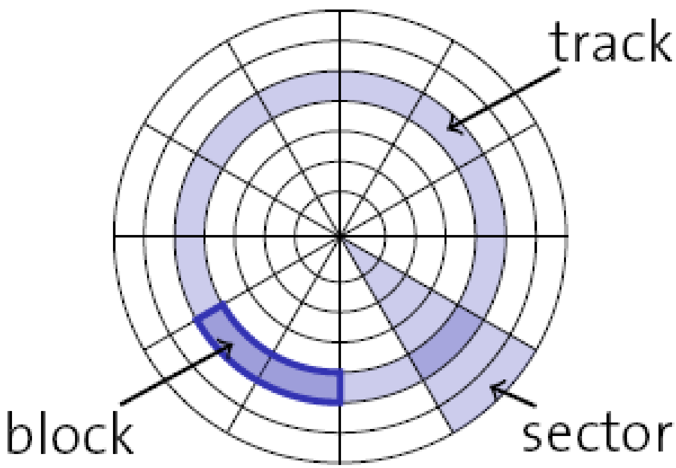
Event	Latency	Scaled
1 CPU cycle	0.3 ns	1 s
Level 1 cache access	0.9 ns	3 s
Level 2 cache access	2.8 ns	9 s
Level 3 cache access	12.9 ns	43 s
Main memory access (DRAM, from CPU)	120 ns	6 min
Solid-state disk I/O (flash memory)	50–150 μs	2–6 days
Rotational disk I/O	1–10 ms	1–12 months
Internet: San Francisco to New York	40 ms	4 years
Internet: San Francisco to United Kingdom	81 ms	8 years
Internet: San Francisco to Australia	183 ms	19 years
TCP packet retransmit	1–3 s	105–317 years
OS virtualization system reboot	4 s	423 years
SCSI command time-out	30 s	3 millennia
Hardware (HW) virtualization system reboot	40 s	4 millennia
Physical system reboot	5 m	32 millennia

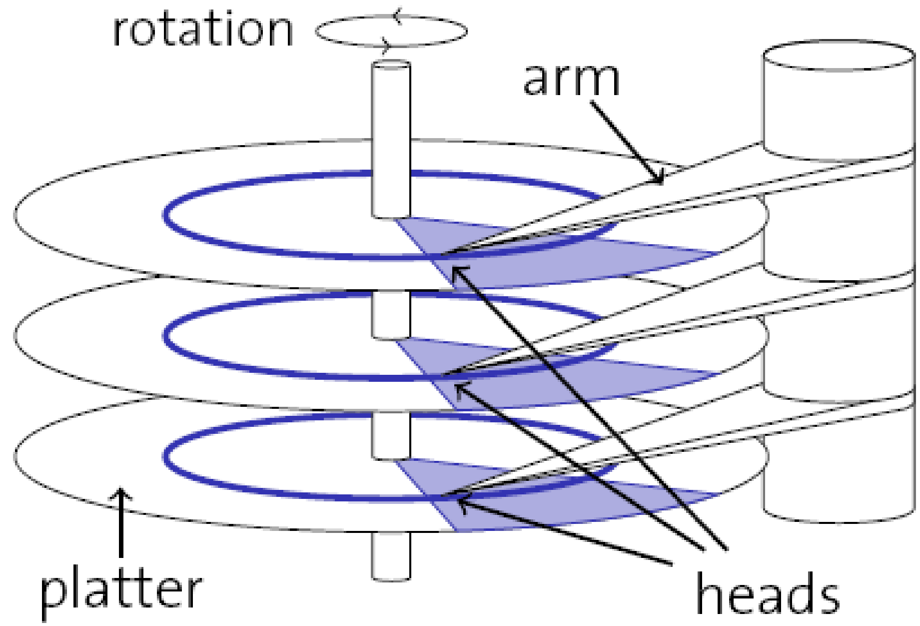
From Brendan Gregg - Systems Performance: Enterprise and the Cloud

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 levels
  - 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 = $\approx$ **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

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

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

max = 60,000/7200 ms

avg = max/2

Sequential vs. Random Access

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

- Random access:

$$t_{rnd} = 1000 * t$$
$$= 1000 * (t_s + t_r + t_{tr})$$
$$= 1000 * (10 + 4.17 + 0.16) = 1000 * 14.33 = \mathbf{14330\ ms}$$

- Sequential access:

$$t_{seq} = t_s + t_r + 1000 * t_{tr} + N * t_{\text{track-to-track seek time}}$$
$$= t_s + t_r + 1000 * 0.16\ ms + (16 * 1000)/63 * 1\ ms$$
$$= 10\ ms + 4.17\ ms + 160\ ms + 254\ ms \approx \mathbf{428\ ms}$$

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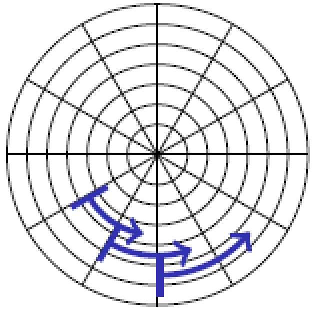
➢ Sequential I/O is **much** faster than random I/O.

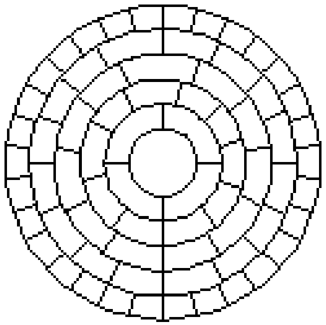
➢ Avoid **random I/O** whenever possible.

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.

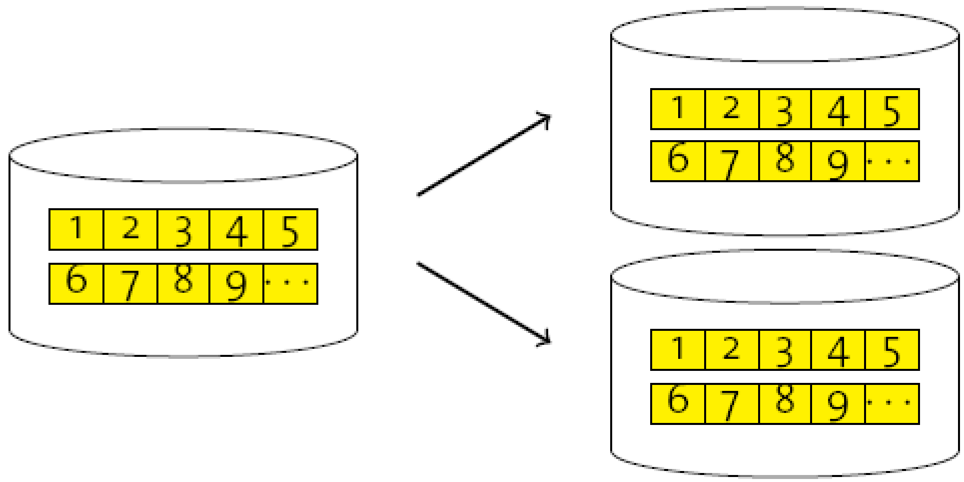
Ways to Improve I/O Performance

- 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

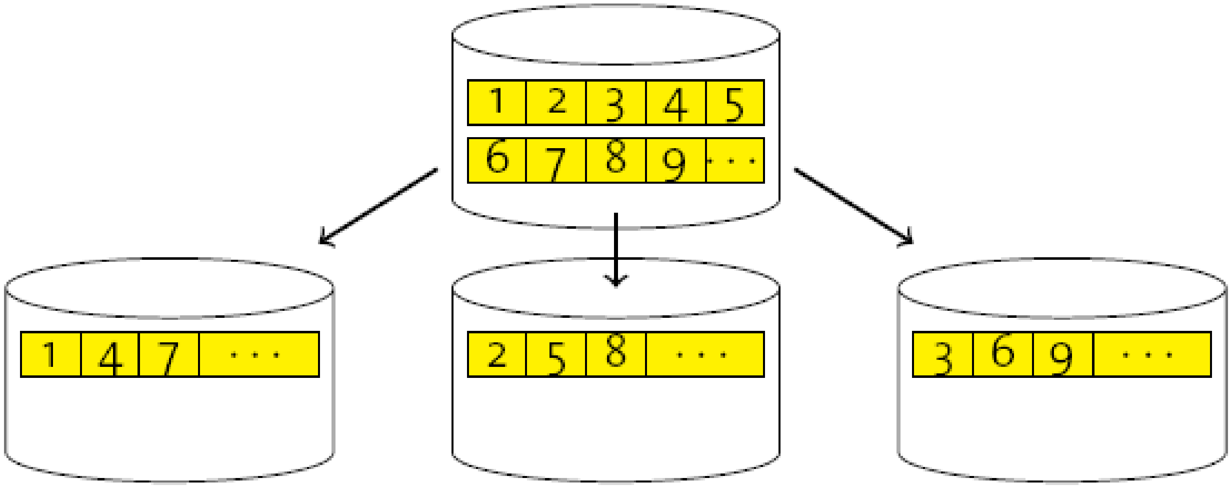
- Replicate data onto multiple disks:



- 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

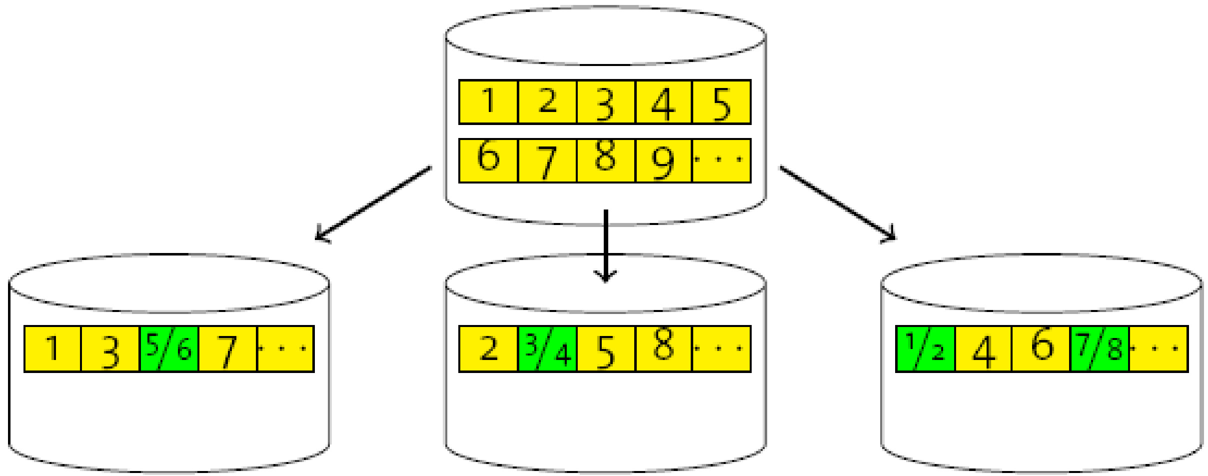
- Distribute data into equal-size partitions over multiple disks:



- ➢ 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

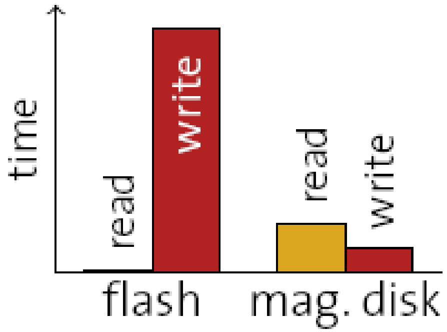
- **RAID 0**: block-level **striping** without parity or mirroring
- **RAID 1**: **mirroring** without parity or striping
- RAID 2: bit-level striping with dedicated parity
- RAID 3: byte-level striping with dedicated parity
- RAID 4: block-level striping with dedicated parity
- **RAID 5**: block-level 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.
  - Client-style SSDs typically have a caching layer to hide this



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)

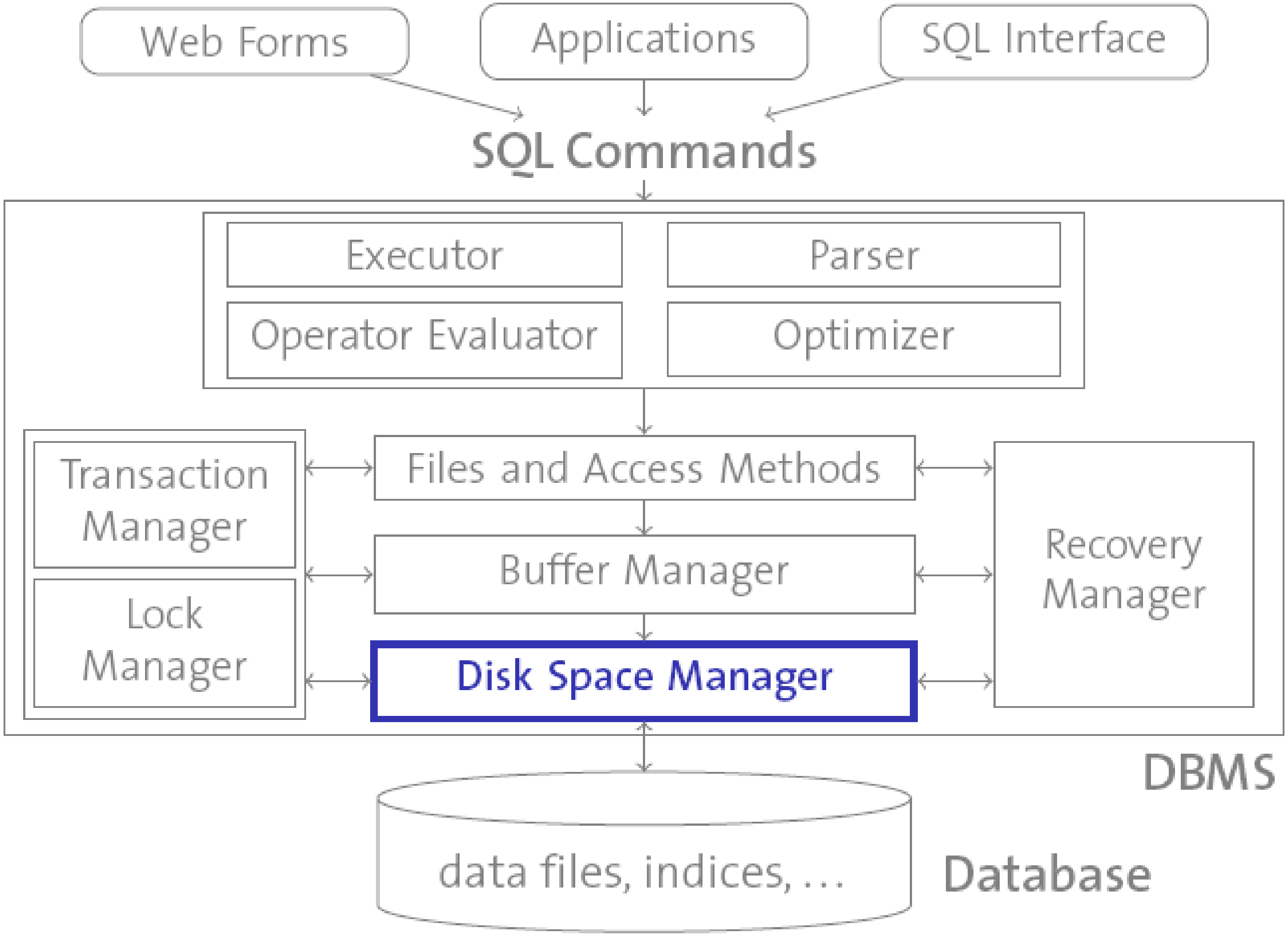
- **Block-based** network access to storage
  - Seen as logical disks ("Give me block 4711 from disk 42.")
  - Unlike network file systems (e.g., NFS)
- SAN storage devices typically abstract from RAID or physical disks, and present logical drives to the DBMS.
  - Hardware acceleration and simplified 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** ↔ **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 → 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

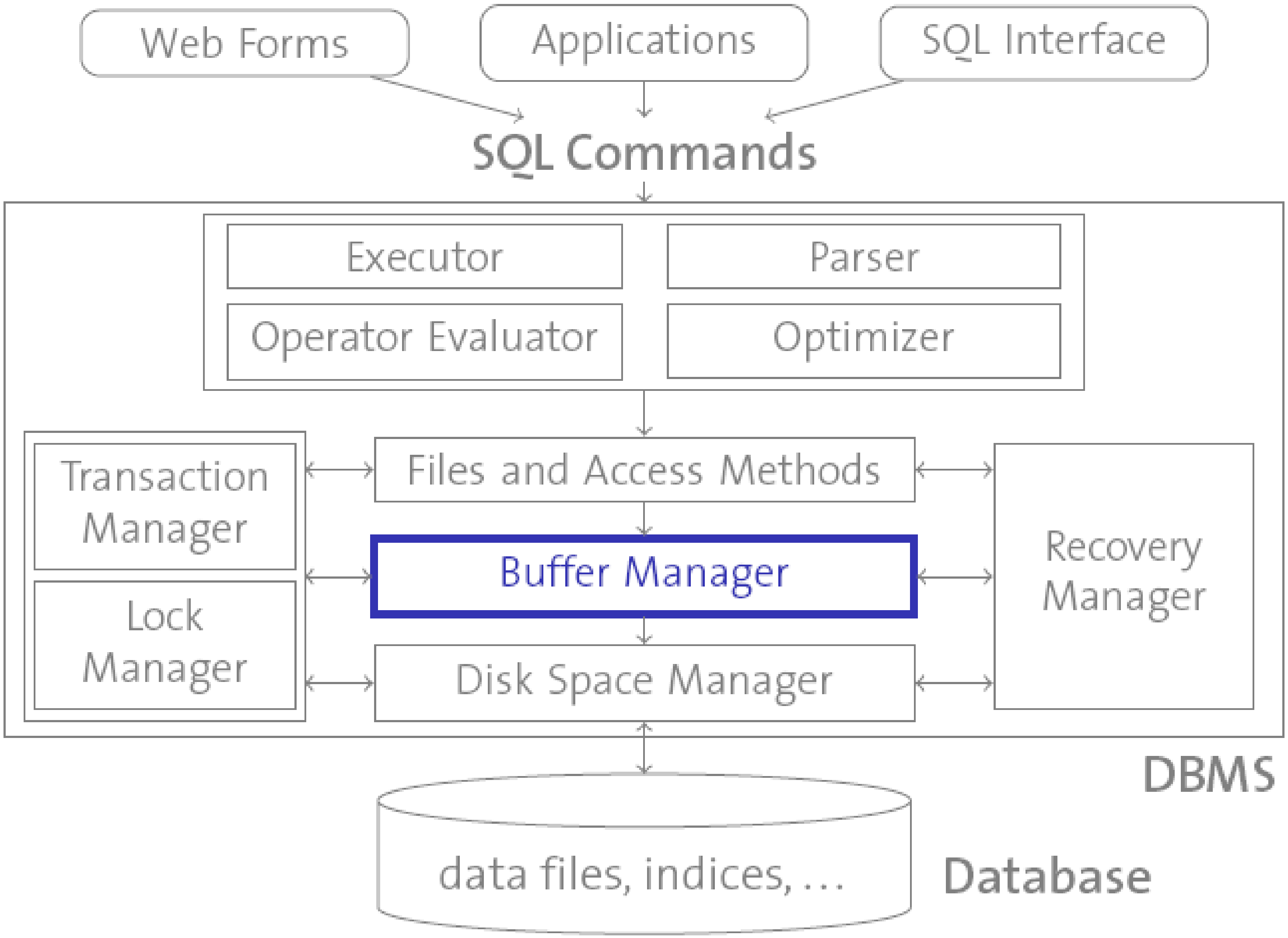
    page number $\rightarrow$ physical location

    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.

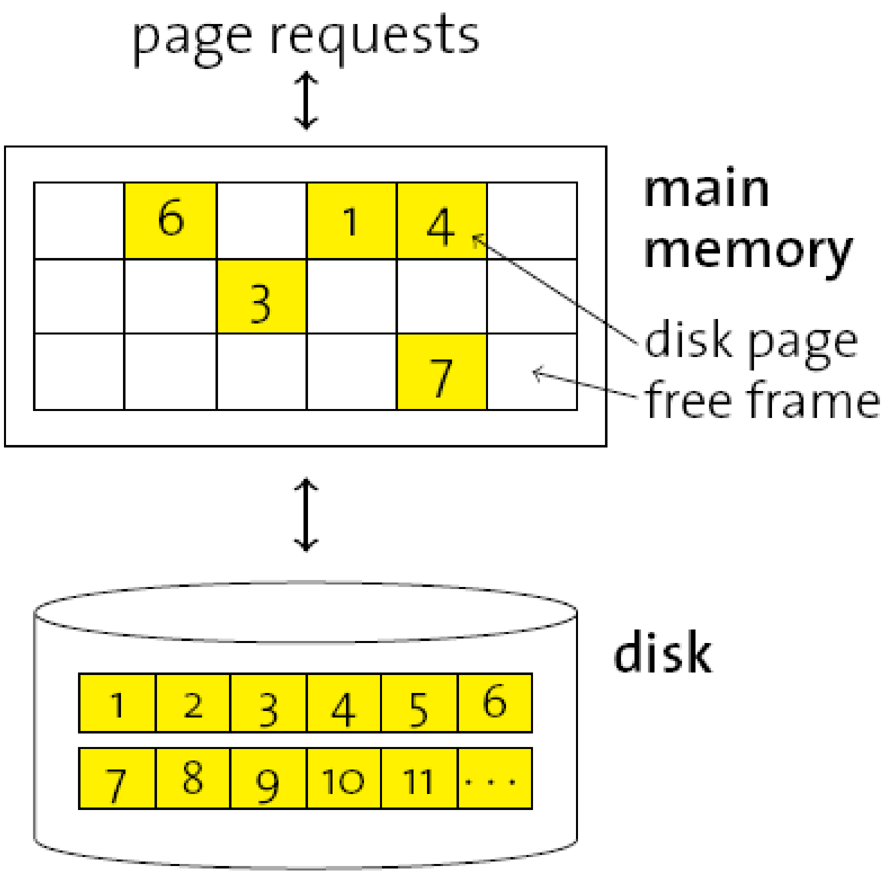
Empty Pages

- 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()`

```
Function: pin(pageno)
if buffer pool already contains pageno then
    pinCount (pageno) ← pinCount (pageno) + 1 ;
    return address of frame holding pageno ;
else
    select a victim frame v using the replacement policy ;
    if dirty (v) then
        write v to disk ;
    read page pageno from disk into frame v ;
    pinCount (pageno) ← 1 ;
    dirty (pageno) ← false ;
    return address of frame v ;
```

Implementation of `unpin()`

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

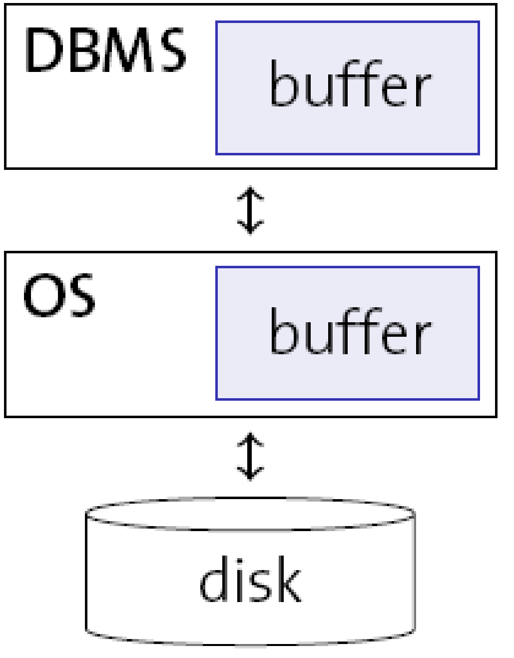
- Didn’t we just re-invent the operating system?

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

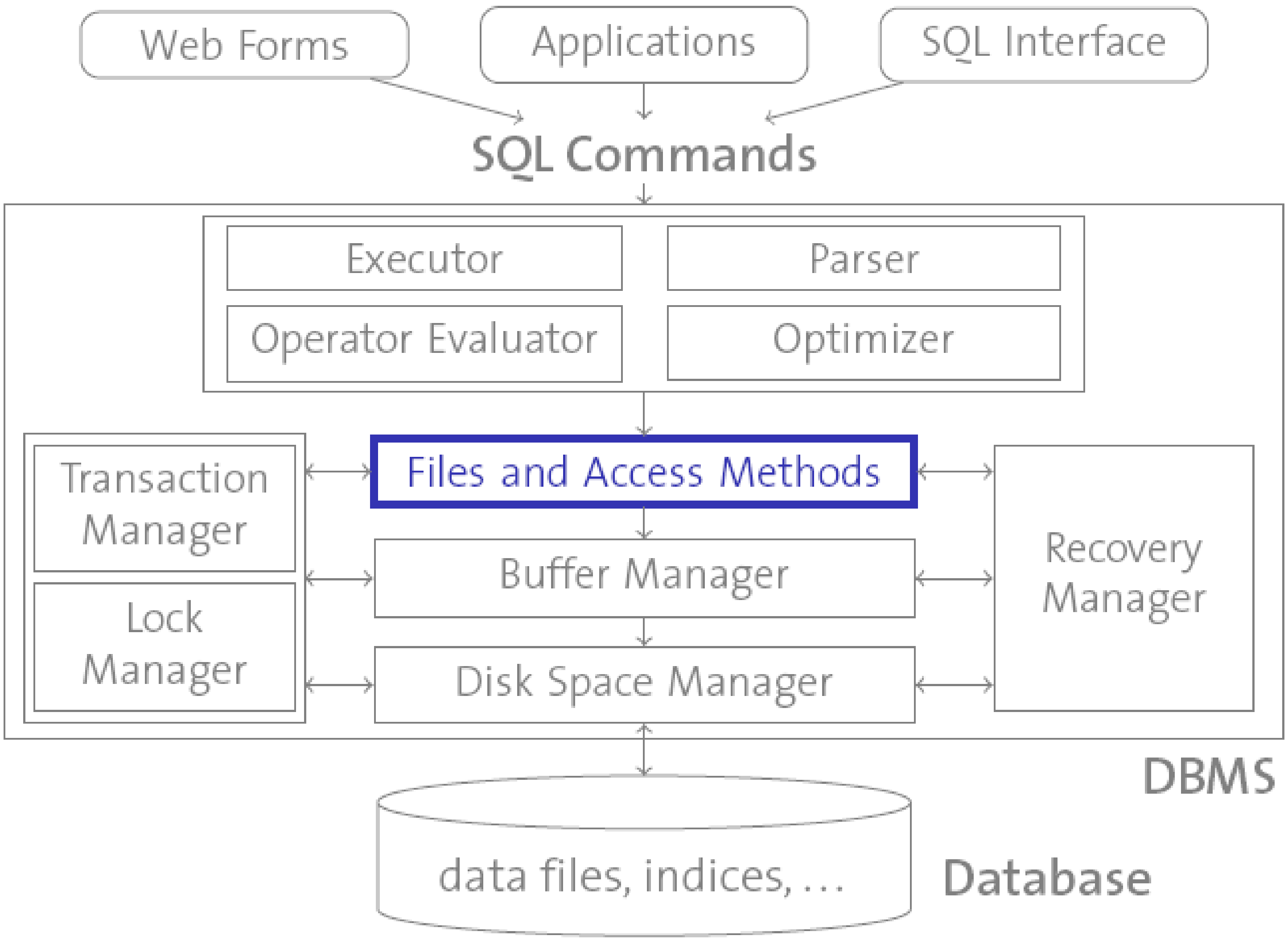
- But,
  - a DBMS may be much more aware of the **access patterns** of certain operators (prefetching, page fixing/hating),
  - concurrency control often calls for a **defined order** of write operations,
  - technical reasons may make OS tools unsuitable for a database (e.g., file size limitation, platform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

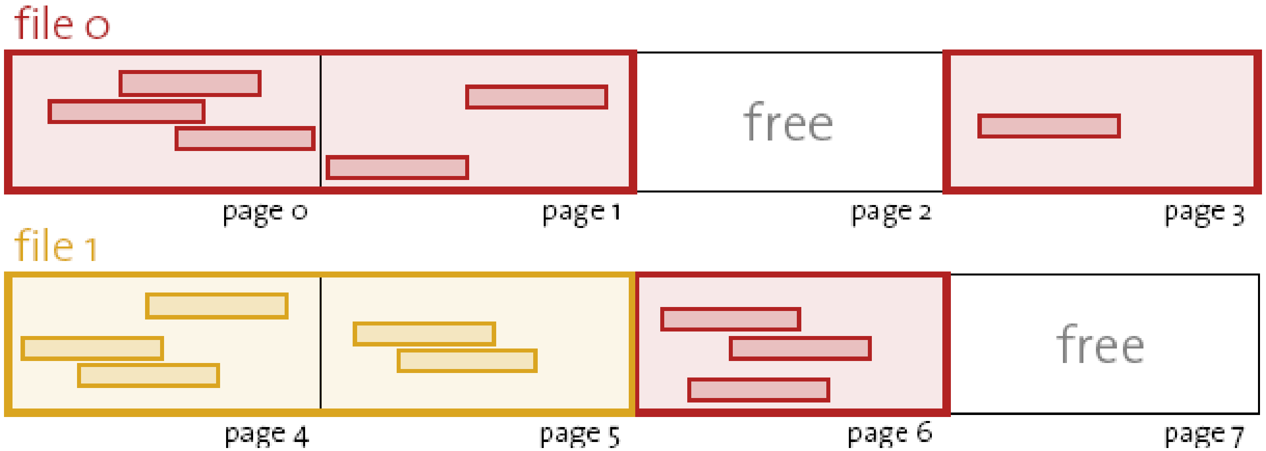


Files and Records



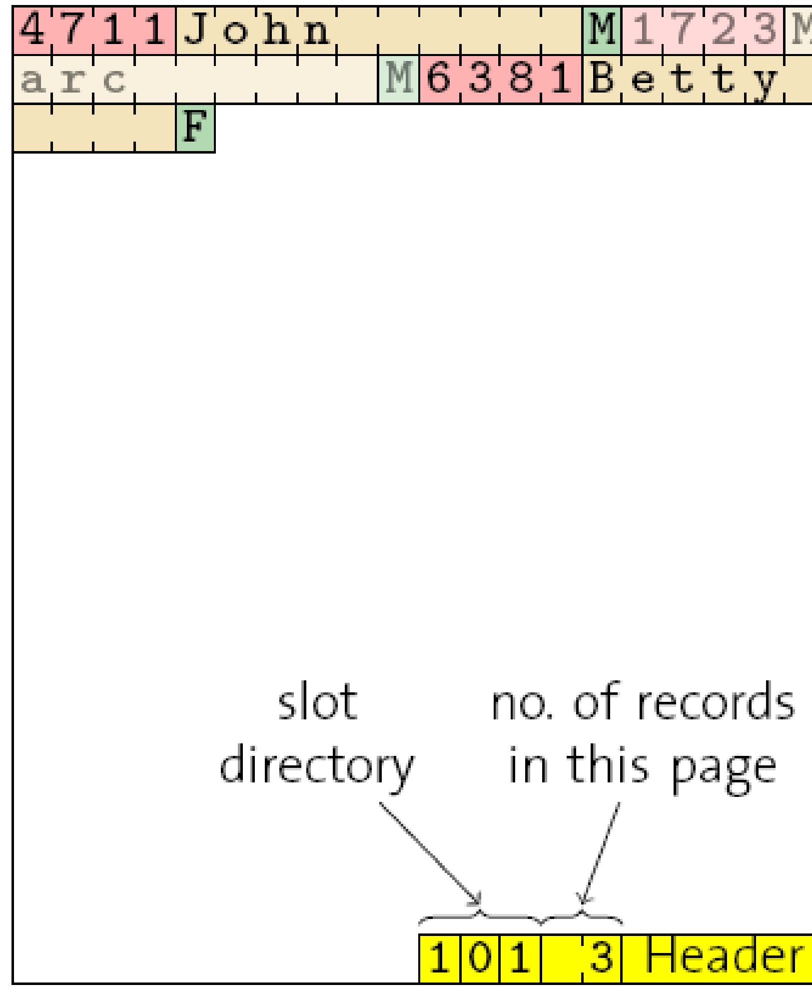
Database Files

- 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**.



Inside a Page

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



- **record identifier (rid):**

  <pageno, slotno>

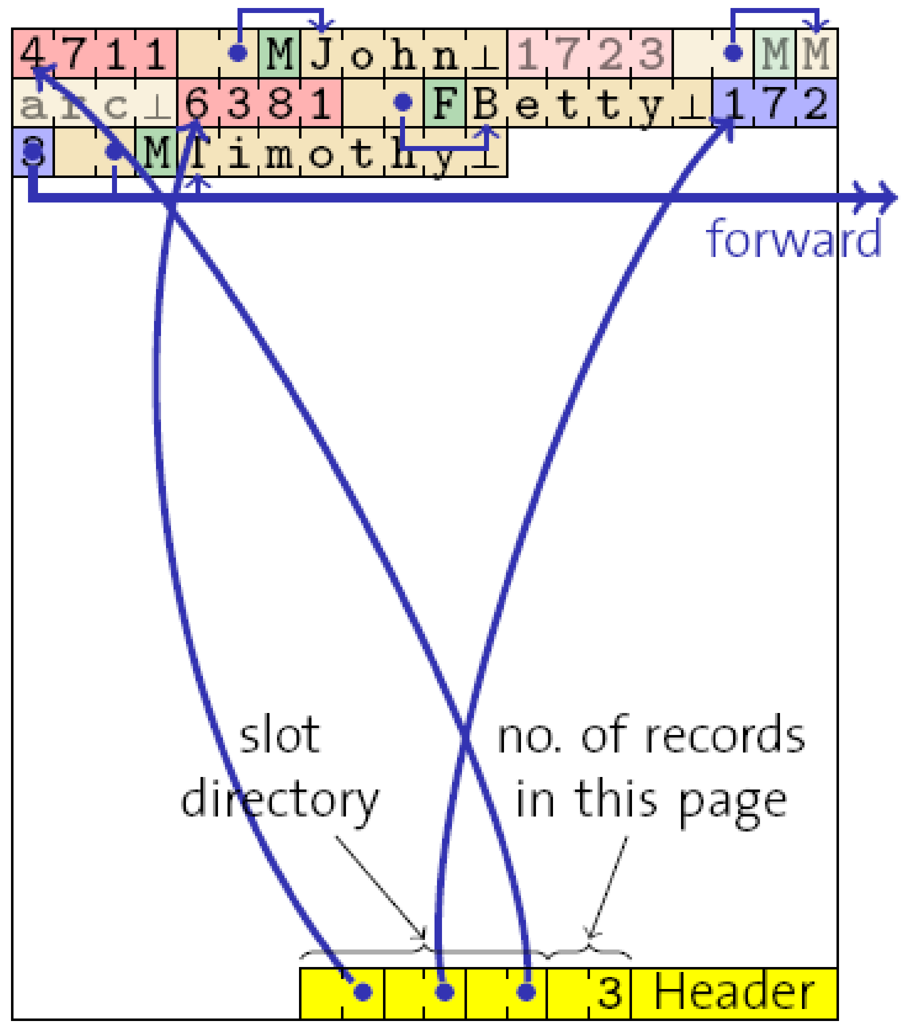
- record position (within page):

  slotno x bytes per slot

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

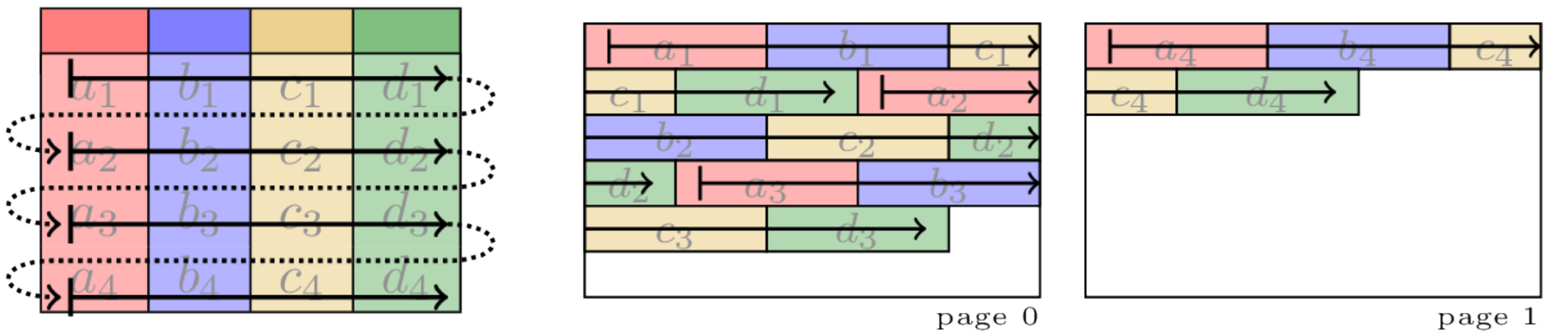
Inside a Page: Variable-sized Fields

- 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.

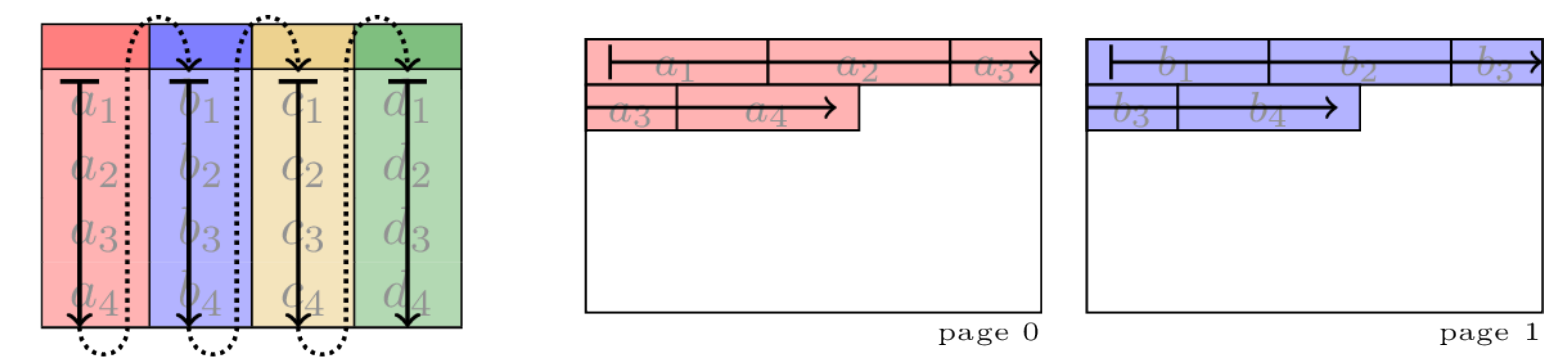


Variants of page layout

- Row-wise



- Column-wise

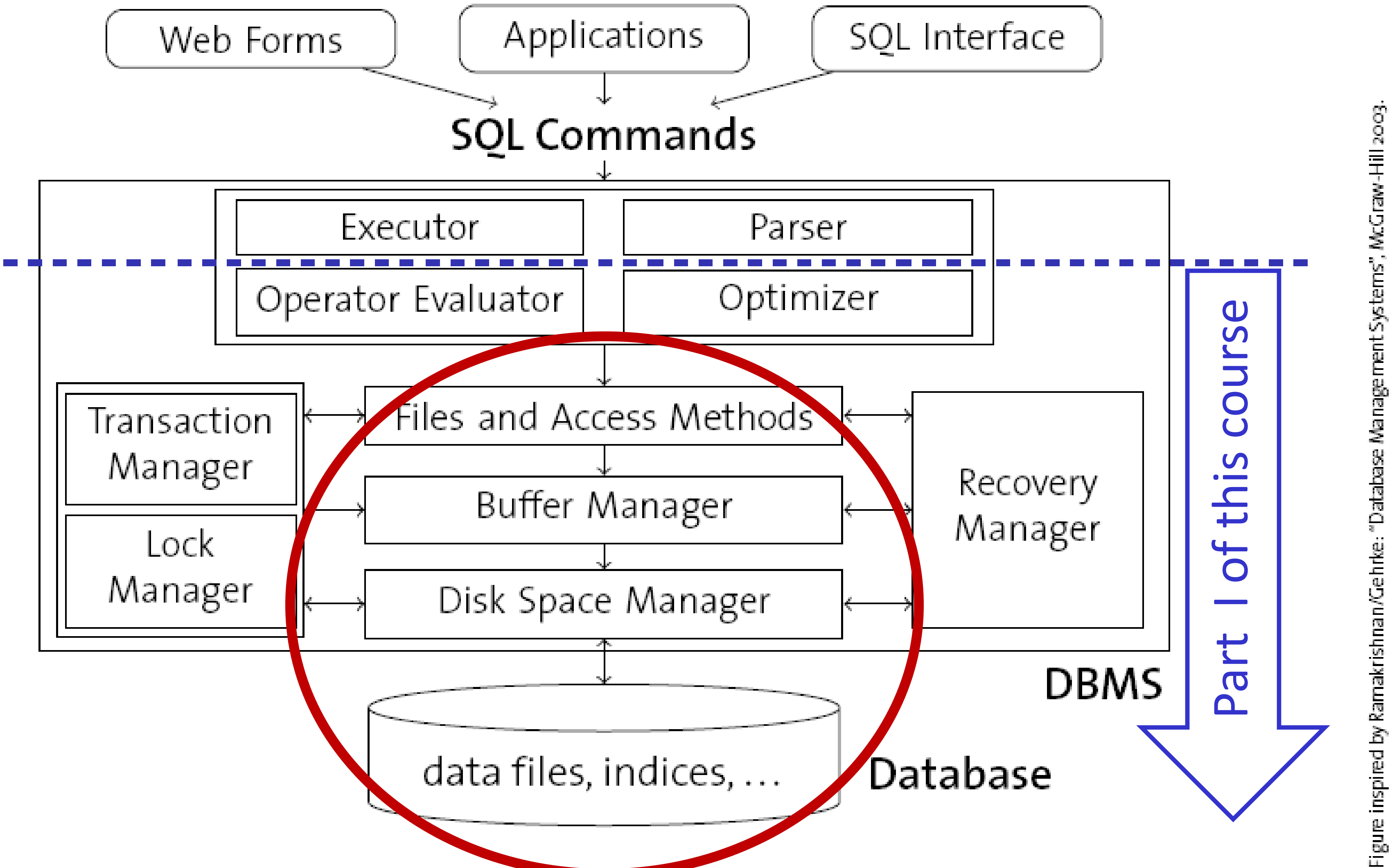


(Figures by Jens Teubner, ETH)

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



Web Forms
Applications
SQL Interface
SQL Commands
Executor
Parser
Operator Evaluator
Optimizer
Transaction Manager
Lock Manager
Files and Access Methods
Buffer Manager
Disk Space Manager
Recovery Manager
DBMS
data files, indices, …
Database
Part I of this course
Figure inspired by Ramakrishnan/Gehrke: "Database Management Systems", McGraw-Hill 2003.