

Chapter 2

Storage

Disks, Buffer Manager, Files...

Architecture and Implementation of Database Systems

Winter 2008/09

Torsten Grust
Wilhelm-Schickard-Institut für Informatik
Universität Tübingen



Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

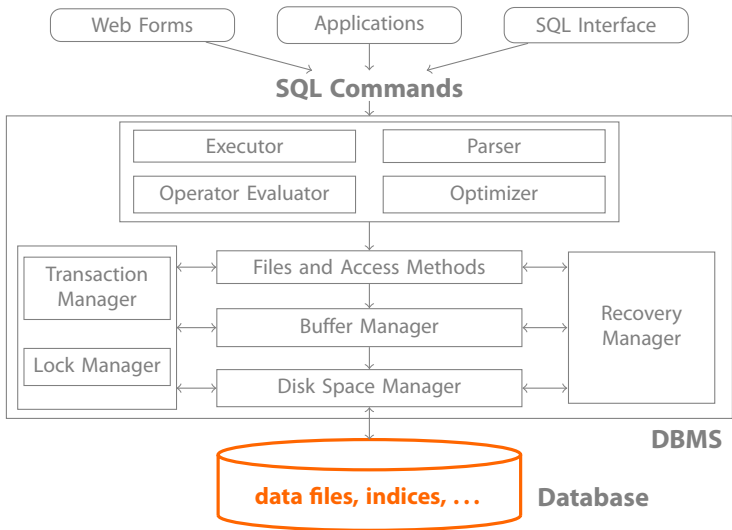
Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Database Architecture



Storage

Torsten Grust



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

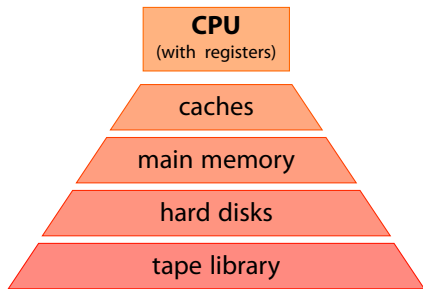
Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

The Memory Hierarchy



capacity

bytes

kilo-/megabytes

gigabytes

terabytes

petabytes

latency

< 1 ns

< 10 ns

70–100 ns

3–10 ms

varies

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

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

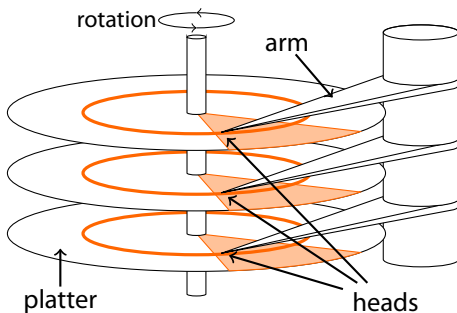
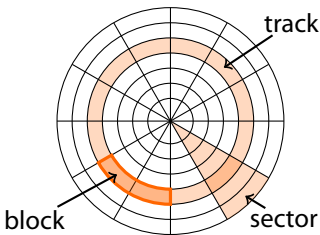
Free Space Management

Inside a Page

Alternative Page Layouts

Recap

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



Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Access Time

Data blocks can only be read and written if disk heads and platters are positioned accordingly.

- This design has implications on the **access time** to read/write a given block:

Definition (Access Time)

- 1 Move disk arms to desired track (**seek time** t_s)
- 2 Disk controller waits for desired block to rotate under disk head (**rotational delay** t_r)
- 3 Read/write data (**transfer time** t_{tr})

$$\Rightarrow \text{access time: } t = t_s + t_r + t_{tr}$$

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

Example: Seagate Barracuda 7200.7 (80 GB, server-class drive)

- Seagate Barracuda 7200.7 performance characteristics:
 - 2 heads, 512 bytes/sector, 80 GB capacity
 - rotational speed: 7200 rpm (revolutions per minute)
 - average seek time: 8.5 ms
 - transfer rate \approx 58 MB/s

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

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

Sequential vs. Random Access

Example (Read 1,000 blocks of size 8 KB)

- **random access:**

$$t_{\text{rnd}} = 1,000 \cdot 12.80 \text{ ms} = 12.80 \text{ s}$$

- **sequential read of adjacent blocks:**

$$\begin{aligned} t_{\text{seq}} &= t_s + t_r + 1,000 \cdot t_{tr} + \frac{16 \cdot 1,000}{63} \cdot t_{s, \text{track-to-track}} \\ &= 8.5 \text{ ms} + 4.17 \text{ ms} + 130 \text{ ms} + 254 \text{ ms} \approx 397 \text{ ms} \end{aligned}$$

The Seagate Barracuda 7200.7 has 63 sectors per track, with a 1 ms track-to-track seek time; one 8 KB block occupies 16 512-byte sectors

- ⇒ Sequential I/O is **much** faster than random I/O
- ⇒ **Avoid random I/O** whenever possible
- ⇒ As soon as we need at least $\frac{397 \text{ ms}}{12,800 \text{ ms}} = 3.1 \%$ of a file, we better read the **entire** file sequentially



Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

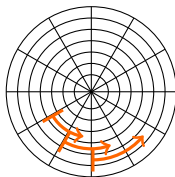
Recap

Performance Tricks

- Disk manufacturers play a number of tricks to improve performance:

track skewing

Align sector 0 of each track to avoid rotational delay during longer sequential scans



request scheduling

If **multiple requests** have to be served, choose the one that requires the smallest arm movement (SPTF: shortest positioning time first, elevator algorithms)

zoning

Outer tracks are longer than the inner ones. Therefore, divide outer tracks into more sectors than inner tracks

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Evolution of Hard Disk Technology

Disk latencies have only marginally improved over the last years ($\approx 10\%$ per year)

But:

- Throughput (i.e., transfer rates) improve by $\approx 50\%$ per year
- Hard disk capacity grows by $\approx 50\%$ every year

Therefore:

- Random access cost hurts even more as time progresses

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

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, try to hide latency

DB2. TPC-C: An industry benchmark for OLTP

The current #1 system (IBM DB2 9.5 on AIX) uses

- 10,992 disk drives (73.4 GB each, 15,000 rpm) (!)
plus 8 146.8 GB internal SCSI drives,
- connected with 68 4 Gbit fibre channel adapters,
- yielding 6 mio transactions per minute

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

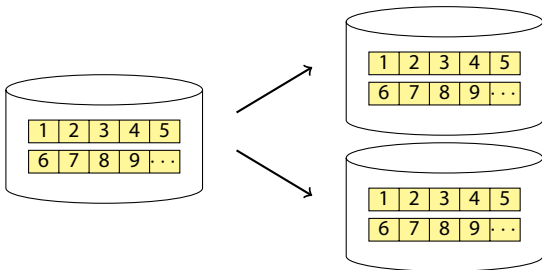
Inside a Page

Alternative Page Layouts

Recap

Disk Mirroring

- **Replicate** data onto multiple disks:



- Achieves I/O parallelism only for **reads**
- Improved failure tolerance—can survive one disk failure
- This is also known as **RAID 1** (mirroring without parity) (**RAID**: Redundant Array of Inexpensive Disks)



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

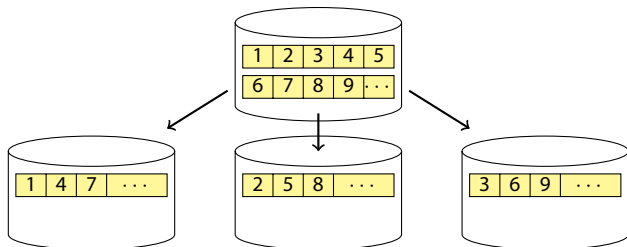
Inside a Page

Alternative Page Layouts

Recap

Disk Striping

- **Distribute** data over disks:



- Full I/O parallelism for **read and write** operations
- High failure risk (here: 3 times risk of single disk failure)!
- Also known as **RAID 0** (striping without parity)



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

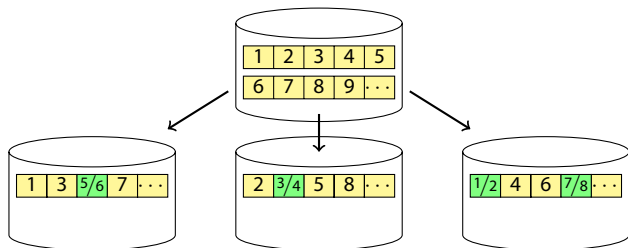
Inside a Page

Alternative Page Layouts

Recap

Disk Striping with Parity

- **Distribute** data and **parity** information over ≥ 3 disks:



- High I/O parallelism
- Fault tolerance: any **one disk may fail** without data loss (with dual parity/RAID 6: two disks may fail)
- Storage capacity of disk array reduced by one disk
- Also known as **RAID 5** (striping with distributed parity)



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

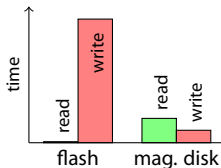
Alternative Page Layouts

Recap

Solid-State Disks

Solid state disks (SSDs) have emerged as an alternative to conventional hard disks

- SSDs provide **very low-latency random read access** (< 0.01 ms)
- 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 database technology to these characteristics is a current research topic



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Network-Based Storage

Today the network is **not** a bottleneck any more:

Storage media/interface	Transfer rate
Hard disk	50–100 MB/s
Serial ATA	375 MB/s
Ultra-640 SCSI	640 MB/s
10-Gbit Ethernet	1,250 MB/s
Infiniband QDR	12,000 MB/s
For comparison (RAM):	
PC2–5300 DDR2–SDRAM	10.6 GB/s
PC3–12800 DDR3–SDRAM	25.6 GB/s

⇒ Why not use the network for database storage?

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Storage Area Network (SAN)

- **Block-based** network access to storage:
 - SAN emulate interface of block-structured disks (*"read block #42 of disk 10"*)
 - This is unlike network file systems (*e.g., NFS, CIFS*)
- SAN storage devices typically abstract from RAID or physical disks and present logical drives to the DBMS
 - Hardware acceleration and simplified maintainability
- Typical setup: local area network with multiple participating servers and storage resources
 - Failure tolerance and increased flexibility

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Grid or Cloud Storage

Internet-scale enterprises employ clusters with 1000s commodity PCs (e.g., Amazon, Google, Yahoo!):

- **system cost** \leftrightarrow **reliability** and **performance**,
- use **massive replication** for data storage

Spare CPU cycles and disk space are sold as a **service**:

Amazon's Elastic Computing Cloud (EC2)

Use Linux-based compute cluster by the hour (~ 10 ¢/h).

Amazon's Simple Storage System (S3)

"Infinite" store for objects between 1 B and 5 GB in size, organized in a map data structure (key \mapsto object)

- Latency: 100 ms to 1 s (not impacted by load)
- pricing \approx disk drives (but addl. cost for access)

\Rightarrow Building a database on S3?
(\nearrow Brantner *et al.*, SIGMOD 2008)

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

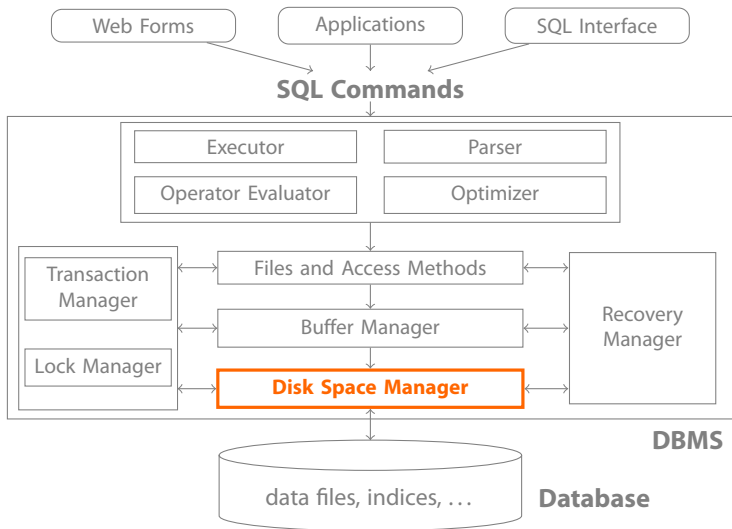
Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Managing Space



Storage

Torsten Grust



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

Definition (Disk Space Manager)

- Abstracts from the gory details of the underlying storage (disk space manager talks to I/O controller and initiates I/O)
- DBMS issues allocate/deallocate and read/write commands
- Provides the concept of a **page** (typically 4–64 KB) as a unit of storage to the remaining system components
- Maintains a locality-preserving mapping

page number \mapsto physical location ,

where a physical location could be, e.g.,

- an OS file name and an offset within that file,
- head, sector, and track of a hard drive, or
- tape number and offset for data stored in a tape library



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Empty Pages

The disk space manager also keeps track of **used/free blocks** (deallocation and subsequent allocation may create **holes**):

- 1 Maintain a **linked list** of free pages
 - When a page is no longer needed, add it to the list
- 2 Maintain a **bitmap** reserving one bit for each page
 - Toggle bit n when page n is (de-)allocated

Allocation of contiguous pages

To exploit **sequential access**, it is useful to allocate **contiguous** sequences of pages.

Which of the techniques (1 or 2) would you choose to support this?

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

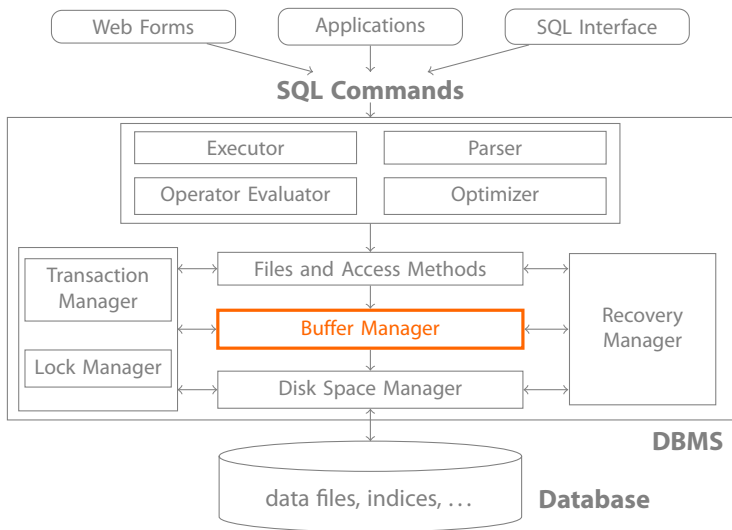
Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Buffer Manager



Storage

Torsten Grust



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

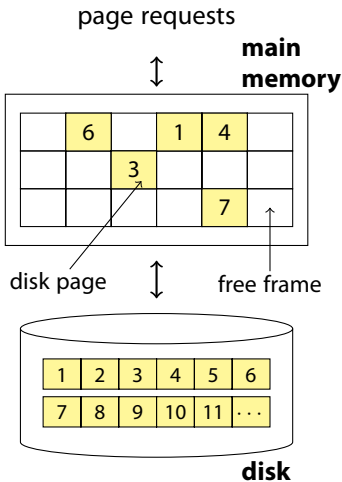
Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

Buffer Manager



Definition (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

Storage

Torsten Grust



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

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 and mark page as clean (\neg *dirty*). 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 page was modified.

Why do we need the *dirty* bit?

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Proper pin ()/unpin () Nesting

- Any database transaction is required to properly “bracket” any page operation using pin () and unpin () calls:

A read-only transaction

```
a ← pin (p);  
{  
  ∴  
  read data on page at memory address a;  
  ∴  
unpin (p, false);
```

- Proper bracketing enables the systems to keep a count of active users (*e.g.*, transactions) of a page

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Implementation of `pin()`

Function `pin(pageno)`

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

Storage

Torsten Grust



Magnetic Disks

- Access Time
- Sequential vs. Random Access

I/O Parallelism

- RAID Levels 1, 0, and 5

Alternative Storage Techniques

- Solid-State Disks
- Network-Based Storage

Managing Space

- Free Space Management

Buffer Manager

- Pinning and Unpinning
- Replacement Policies

Databases vs. Operating Systems

Files and Records

- Heap Files
- Free Space Management
- Inside a Page
- Alternative Page Layouts

Recap

Implementation of `unpin()`

Function `unpin(pageno, dirty)`

```
1 pinCount (pageno) ← pinCount (pageno) - 1 ;  
2 dirty (pageno) ← dirty (pageno) ∨ dirty ;
```

Why don't we write pages back to disk during `unpin()`?

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Concurrent Writes?

Conflicting changes to a block

Assume the following:

- 1 The same page p is requested by more than one transaction (i.e., $\text{pinCount}(p) > 1$), and
- 2 ...those transactions perform conflicting writes on p ?

Conflicts of this kind are resolved by the **concurrency control** (here: a lock manager) *before* the page is pinned (a topic of future lectures).

The buffer manager may assume that everything is in order whenever it receives an `unpin(p , true)` call.

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Replacement Policies

The effectiveness of the buffer manager's **caching** functionality can depend on the **replacement policy** it uses, e.g.,

Least Recently Used (LRU)

Evict the page whose latest `unpin()` is longest ago

LRU- k

Like LRU, but considers k -latest `unpin()`, not just latest

Most Recently Used (MRU)

Evict the page that has been unpinned most recently

Random

Pick a victim randomly

Rationales behind each of these policies?

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Example Policy: Clock (“Second Chance”)

- Simulate an LRU policy with less overhead (no LRU queue reorganization on every frame reference):

Clock (“Second Chance”)

- 1 Number the N frames in the buffer pool $0, \dots, N - 1$; initialize $\text{current} \leftarrow 0$, maintain a bit array $\text{referenced}[0, \dots, N - 1]$ initialized to all 0
- 2 In $\text{pin}(p)$, assign $\text{referenced}[p] \leftarrow 1$
- 3 To find the next victim, consider page current ; if $\text{referenced}[\text{current}] = 0$, current is the victim; otherwise, $\text{referenced}[\text{current}] \leftarrow 0$, $\text{current} \leftarrow \text{current} + 1 \bmod N$, repeat

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Heuristic Policies Can Fail

The mentioned policies, including LRU, are **heuristics** only and may fail miserably in certain scenarios.



Example (A Challenge for LRU)

A number of transactions want to scan the same sequence of pages (consider a repeated `SELECT * FROM R`).

Assume a buffer pool capacity of 10 pages.

- 1 Let the size of relation `R` be 10 or less pages.
How many I/O (actual disk page reads) do you expect?
- 2 Now grow `R` by one page.
How about the number of I/O operations in this case?

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

More Challenges for LRU

- 1 Transaction T_1 repeatedly accesses a fixed set of pages; transaction T_2 performs a sequential scan of the database pages.
- 2 Assume a B^+ -tree-indexed relation R . R occupies 10,000 data pages R_i , the B^+ -tree occupies one root node and 100 index leaf nodes I_k .
Transactions perform repeated random index key lookups on $R \Rightarrow$ **page access pattern** (ignores B^+ -tree root node):

$I_1, R_1, I_2, R_2, I_3, R_3, \dots$

 **How will LRU perform in this case?**

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Buffer Management in Practice

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.*, nested-loop join).

Likewise, an operator that **hates** a page will not access it any time soon (*e.g.*, table pages in a sequential scan).

Partitioned buffer pools

E.g., maintain separate pools for indexes and tables.

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Databases vs. Operating Systems

Wait! 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 **prescribed order** of write operations,
- technical reasons may make OS tools unsuitable for a database (e.g., file size limitation, platform independence).

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

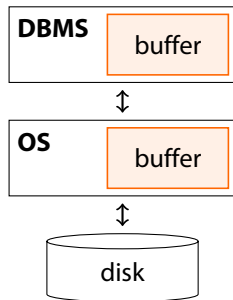
Alternative Page Layouts

Recap

Databases vs. Operating Systems

In fact, databases and operating 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.
 - Therefore, database systems try to **turn off** certain OS features or services.
- ⇒ **Raw disk** access instead of OS files.



Storage

Torsten Grust



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

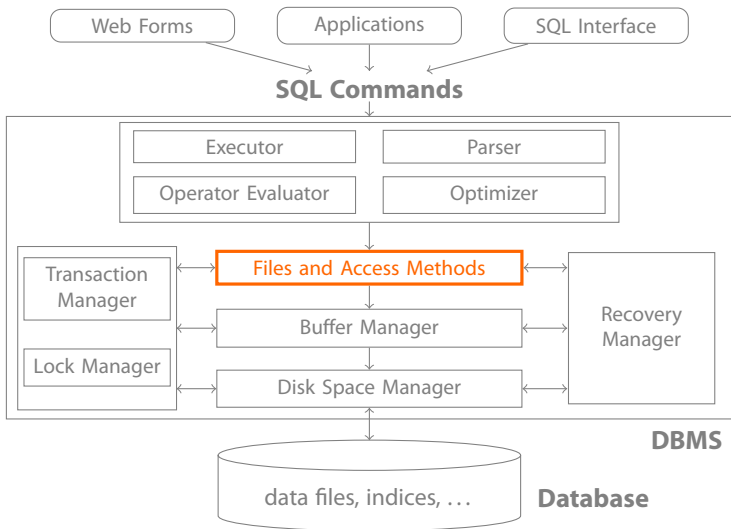
Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

Files and Records



Storage

Torsten Grust



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

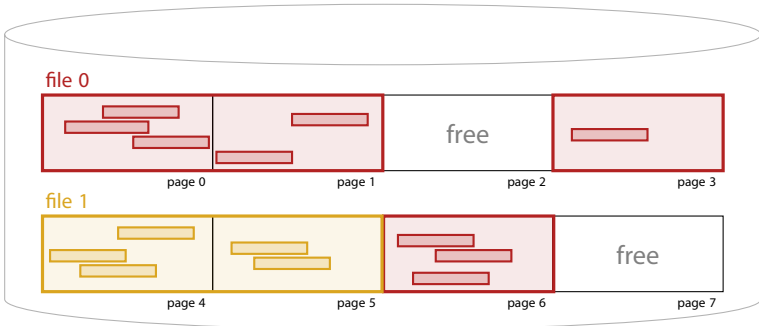
Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

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 primarily manages **tables of tuples** and **indexes**.
- 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**:



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Database 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.*, the SQL semantics):

Typical heap file interface

- **create/destroy** heap file f named n :
`createFile(n)`, `deleteFile(n)`
- **insert** record r and return its rid :
`insertRecord(f , r)`
- **delete** a record with a given rid :
`deleteRecord(f , rid)`
- **get** a record with a given rid :
`getRecord(f , rid)`
- initiate a **sequential scan** over the whole heap file:
`openScan(f)`

N.B. Record ids (rid) are used like **record addresses** (or pointers). The heap file structure maps a given rid to the page containing the record.



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

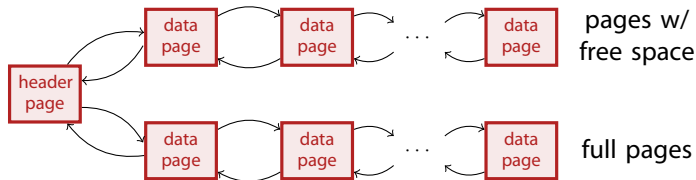
Alternative Page Layouts

Recap

Heap Files

(Doubly) Linked list of pages:

Header page allocated when `createFile(n)` is called—initially both page lists are empty:



- + easy to implement
- most pages will end up in free page list
- might have to search many pages to place a (large) record



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management
Inside a Page
Alternative Page Layouts

Recap

Heap Files

Operation `insertRecord(f,r)` for linked list of pages

- 1 Try to find a page p in the free list with free space $> |r|$; should this fail, ask the disk space manager to allocate a new page p
- 2 Write record r to page p
- 3 Since, generally, $|r| \ll |p|$, p will belong to the list of pages with free space
- 4 A unique *rid* for r is generated and returned to the caller

Generating sensible record ids (*rid*)

Given that *rids* are used like record addresses: what would be a feasible *rid* generation method?

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

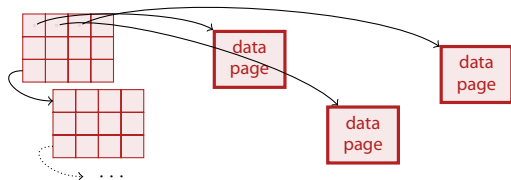
Inside a Page

Alternative Page Layouts

Recap

Heap Files

Directory of pages:



- Use as **space map** with information about free space on each page
 - granularity as trade-off space ↔ accuracy (may range from *open/closed* bit to exact information)
- + free space search more efficient
- memory overhead to host the page directory

Storage

Torsten Grust



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management
Inside a Page
Alternative Page Layouts

Recap

Free Space Management

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

Append Only

Always insert into last page. Otherwise, create a new page.

Best Fit

Reduces fragmentation, but requires searching the entire free list/space map for each insert.

First Fit

Search from beginning, take first page with sufficient space.
(\Rightarrow These pages quickly fill up, system may waste a lot of search effort in these first pages later on.)

Next Fit

Maintain **cursor** and continue searching where search stopped last time.

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

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.



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

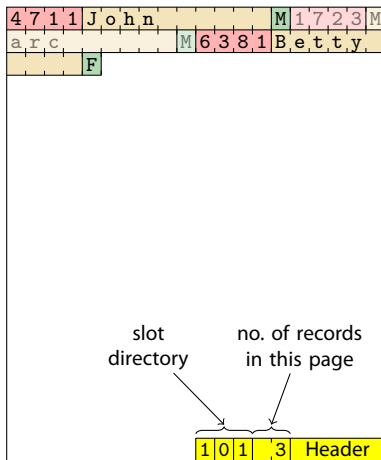
Recap

Inside a Page — Fixed-Length Records

Now turn to the **internal page structure**:

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

- **Record identifier** (*rid*):
 $\langle \text{pageno}, \text{slotno} \rangle$
- Record position (within page):
 $\text{slotno} \times \text{bytes per slot}$
- Record **deletion**?
 - record id should **not** change \Rightarrow **slot directory** (bitmap)



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records



Heap Files
Free Space Management

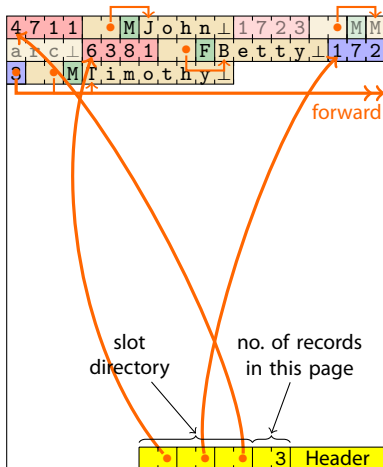
Inside a Page

Alternative Page Layouts

Recap

Inside a Page—Variable-Sized Fields

- Variable-sized fields moved to **end** of each record.
 - Placeholder points to location.
 -  **Why?**
- Slot directory points to start of each record.
- Records **can move** on page.
 - *E.g.*, if field size changes or page is compacted.
- Create **“forward address”** if record won't fit on page.
 -  **Future updates?**
- Related issue: space-efficient representation of NULL values.



Storage

Torsten Grust



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management


Inside a Page

Alternative Page Layouts

Recap



DB2. Data page and layout details

- Support for **4 K, 8 K, 16 K, 32 K data pages** in separate table spaces. Buffer manager pages match in size.
- 68 bytes of database manager overhead per page. On a 4 K page: maximum of 4,028 bytes of user data (maximum record size: 4,005 bytes). Records do *not* span pages.
- **Maximum table size:** 512 GB (with 32 K pages). Maximum number of columns: 1,012 (4 K page: 500), maximum number of rows/page: 255.  **IBM DB2 RID format?**
- Columns of type LONG VARCHAR, CLOB, etc. maintained outside regular data pages (pages contain descriptors only).
- **Free space management:** first-fit order. Free space map distributed on every 500th page in FSCR (free space control records). Records updated in-place if possible, otherwise uses forward records.

Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

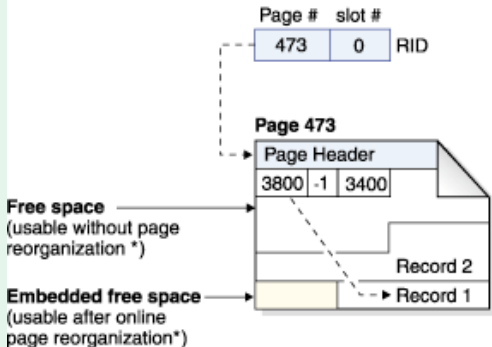
Inside a Page

Alternative Page Layouts

Recap

DB2. Taken directly from the DB2 V9.5 Information Center

Data page and RID format



Supported page sizes:
4KB, 8KB,
16KB, 32KB
Set on table space creation.
Each table space must be
assigned a buffer pool with
a matching page size.

* Exception: Any space reserved by an uncommitted DELETE is not usable.

<http://publib.boulder.ibm.com/infocenter/db2luw/v9r5/>



Magnetic Disks

Access Time
Sequential vs. Random
Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks
Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning
Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files
Free Space Management

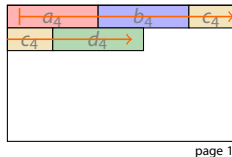
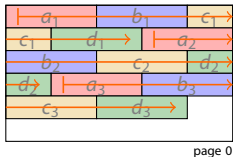
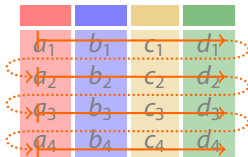
Inside a Page

Alternative Page Layouts

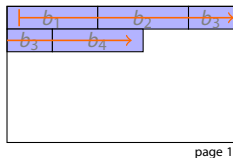
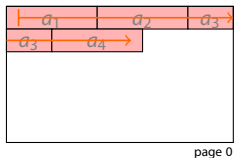
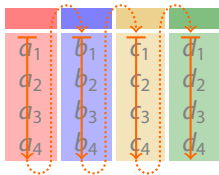
Recap

Alternative Page Layouts

We have just populated data pages in a **row-wise** fashion:



We could as well do that **column-wise**:



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

Alternative Page Layouts

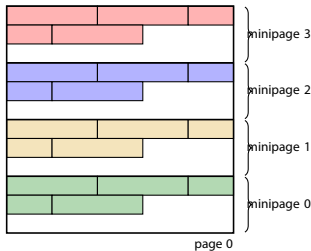
These two approaches are also known as **NSM (n-ary storage model)** and **DSM (decomposition storage model)**.¹

- Tuning knob for certain workload types (*e.g.*, OLAP)
- Suitable for narrow projections and in-memory database systems
(↗ Database Systems and Modern CPU Architecture)
- Different behavior with respect to **compression**.

A hybrid approach is the **PAX (Partition Attributes Across)** layout:

- Divide each page into **minipages**.
- Group attributes into them.

↗ Ailamaki *et al.* Weaving Relations for Cache Performance. *VLDB 2001*.



Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap

¹Recently, the terms **row-store** and **column-store** have become popular, too.

Recap

Magnetic Disks

Random access **orders of magnitude** slower than sequential.

Disk Space Manager

Abstracts from hardware details and maps page number \mapsto physical location.

Buffer Manager

Page **caching** in main memory; `pin ()/unpin ()` interface; **replacement policy** crucial for effectiveness.

File Organization

Stable **record identifiers (rids)**; maintenance with fixed-sized records and variable-sized fields; NSM vs. DSM.

Storage

Torsten Grust



Magnetic Disks

Access Time

Sequential vs. Random Access

I/O Parallelism

RAID Levels 1, 0, and 5

Alternative Storage Techniques

Solid-State Disks

Network-Based Storage

Managing Space

Free Space Management

Buffer Manager

Pinning and Unpinning

Replacement Policies

Databases vs. Operating Systems

Files and Records

Heap Files

Free Space Management

Inside a Page

Alternative Page Layouts

Recap