Chapter 2

Storage

Disks, Buffer Manager, Files…

Architecture and Implementation of Database Systems
Summer 2014

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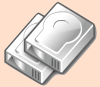

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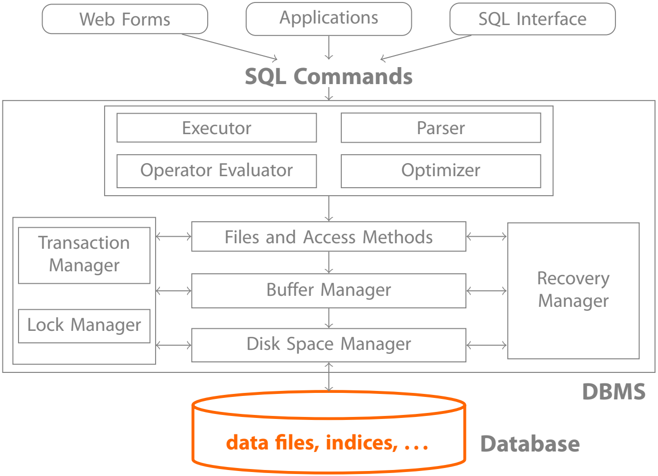
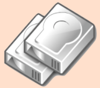
Database Architecture





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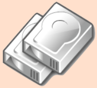
Recap

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
- DBMSs try to **hide latency** by using the fast memory as a **cache**.



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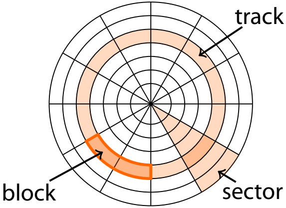

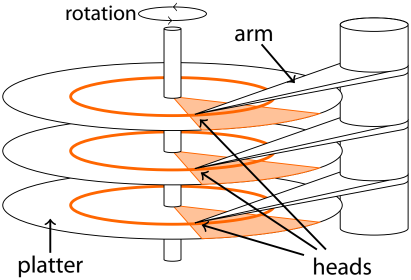

- A stepper motor positions an array of disk heads on the requested track
- Platters (disks) steadily rotate
- Disks are managed in blocks: the system reads/writes data one block at a time

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

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Access Time

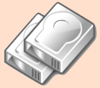
Data blocks can only be read and written if disk heads and platters are positioned accordingly.

- 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})

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



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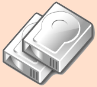
Example: Seagate Cheetah 15K.7 (600 GB, server-class drive)

- Seagate Cheetah 15K.7 performance characteristics:
  - 4 disks, 8 heads, avg. 512 kB/track, 600 GB capacity
  - rotational speed: 15 000 rpm (revolutions per minute)
  - average seek time: 3.4 ms
  - transfer rate ≈ 163 MB/s

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



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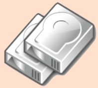
✎ What is the access time to read an 8 KB data block?

average seek time	$t_s =$	3.40 ms
average rotational delay: $\frac{1}{2} \cdot \frac{1}{15\,000\ \text{min}^{-1}}$	$t_r =$	2.00 ms
transfer time for 8 KB: $\frac{8\ \text{kB}}{163\ \text{MB/s}}$	$t_{tr} =$	0.05 ms
access time for an 8 kB data block	$t =$	5.45 ms



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Sequential vs. Random Access

Example (Read 1 000 blocks of size 8 kB)

- **random access:**

  $t_{\text{rnd}} = 1\,000 \cdot 5.45\,\text{ms} = 5.45\,\text{s}$

- **sequential read of adjacent blocks:**

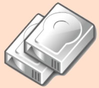
  $$\begin{aligned} t_{\text{seq}} &= t_s + t_r + 1\,000 \cdot t_{tr} + 16 \cdot t_{s,\text{track-to-track}} \\ &= 3.40\,\text{ms} + 2.00\,\text{ms} + 50\,\text{ms} + 3.2\,\text{ms} \approx 58.6\,\text{ms} \end{aligned}$$

  The Seagate Cheetah 15K.7 stores an average of 512 kB per track, with a 0.2 ms track-to-track seek time; our 8 kB blocks are spread across 16 tracks.

⇒ Sequential I/O is **much** faster than random I/O

⇒ **Avoid random I/O** whenever possible

⇒ As soon as we need at least $\frac{58.6\,\text{ms}}{5{,}450\,\text{ms}} = 1.07\,\%$ of a file, we better read the **entire** file sequentially

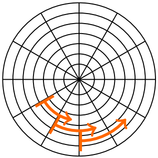


Performance Tricks

- 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

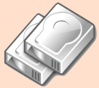


request scheduling

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



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Evolution of Hard Disk Technology

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

But:

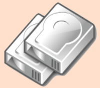
- Throughput (i.e., transfer rates) improve by $\approx$ 50 % per year
- Hard disk capacity grows by $\approx$ 50 % every year

Therefore:

- Random access cost hurts even more as time progresses

Example (5 Years Ago: Seagate Barracuda 7200.7)

Read 1K blocks of 8 kB sequentially/randomly: 397 ms / 12 800 ms



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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

TPC-C: An industry benchmark for OLTP

A recent #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

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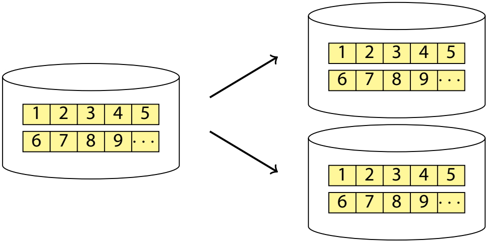
Disk Mirroring

- **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)

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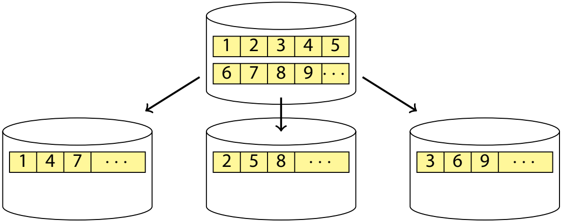
Disk Striping

- **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)

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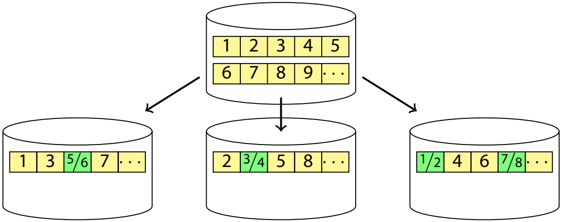
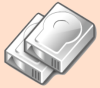
Disk Striping with Parity

- **Distribute** data and **parity** information over $\geqslant 3$ disks:



- High I/O parallelism
- Fault tolerance: any **one disk may fail** without data loss (with dual parity/RAID 6: two disks may fail)
- Distribute parity (*e.g.*, `XOR`) information over disks, separating data and associated parity
- Also known as **RAID 5** (striping with distributed parity)



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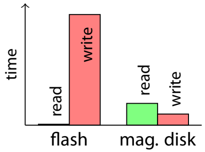
Solid-State Disks

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:
  1. (Blocks of) Pages have to be **erased** before they can be updated
  2. Once pages have been erased, sequentially writing them is almost as fast as reading



Storage

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SSDs: Page-Level Writes, Block-Level Deletes

- Typical **page size**: 128 kB
- SSDs erase **blocks of pages**: block $\approx$ 64 pages (8 MB)

Example (Perform block-level delete to accomodate new data pages)

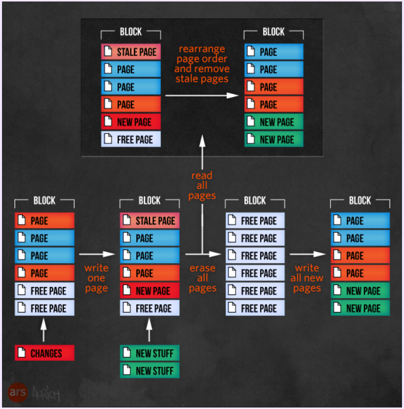

Illustration taken from arstechnica.com (The SSD Revolution)

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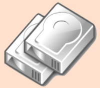
Example: Seagate Pulsar.2 (800 GB, server-class solid state drive)

- Seagate Pulsar.2 performance characteristics:
  - NAND flash memory, 800 GB capacity
  - standard 2.5″ enclosure, no moving/rotating parts
  - data read/written in pages of 128 kB size
  - transfer rate ≈ 370 MB/s

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



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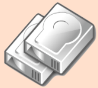
✎ What is the access time to read an 8 KB data block?

no seek time	$t_s =$	0.00 ms
no rotational delay:	$t_r =$	0.00 ms
transfer time for 8 KB: $\frac{128\text{ kB}}{370\text{ MB/s}}$	$t_{tr} =$	0.30 ms
access time for an 8 kB data block	$t =$	0.30 ms



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Sequential vs. Random Access with SSDs

Example (Read 1 000 blocks of size 8 kB)

- **random access:**

  $t_{\text{rnd}} = 1\,000 \cdot 0.30\,\text{ms} = 0.3\,\text{s}$

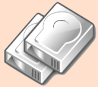
- **sequential read of adjacent pages:**

  $t_{\text{seq}} = \left\lceil \frac{1\,000 \cdot 8\,\text{kB}}{128\,\text{kB}} \right\rceil \cdot t_{tr} \approx 18.9\,\text{ms}$

  The Seagate Pulsar.2 (sequentially) reads data in 128 kB chunks.

$\Rightarrow$ Sequential I/O still beats random I/O (but random I/O is more feasible again)

- Adapting database technology to these characteristics is a current research topic



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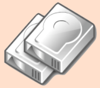
Network-Based Storage

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

Storage media/interface	Transfer rate
Hard disk	100–200 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?



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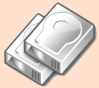
Storage Area Network (SAN)

- **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



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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)

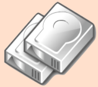
Use Linux-based compute cluster by the hour ($\sim$ 10 ¢/h).

Amazon's Simple Storage System (S3)

"Infinite" store for objects between 1 B and 5 TB 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)



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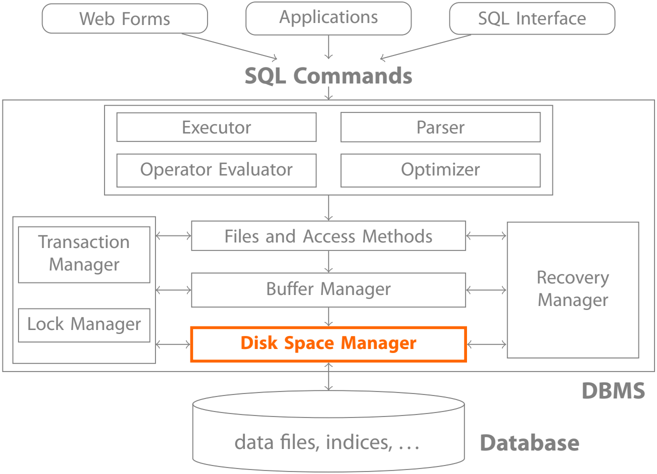
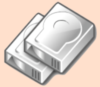
Managing Space





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Managing Space

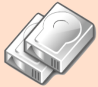
Definition (Disk Space Manager)

- 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

$$\text{page number} \mapsto \text{physical location} \quad ,$$

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



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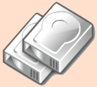
Empty Pages

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?



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✎ 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?

This is a lot easier to do with a free page bitmap (option 2).

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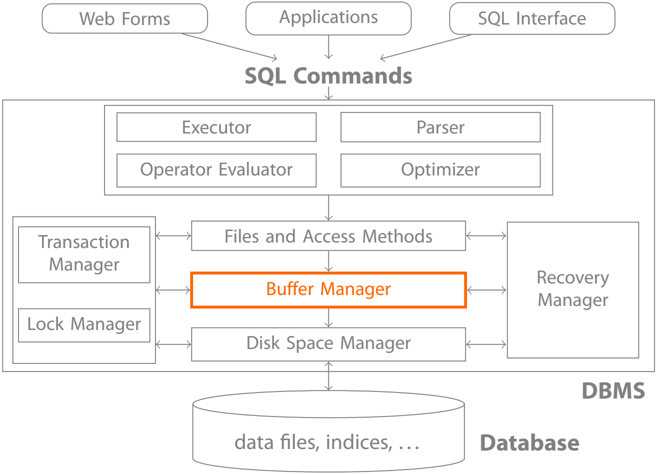

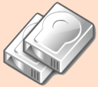

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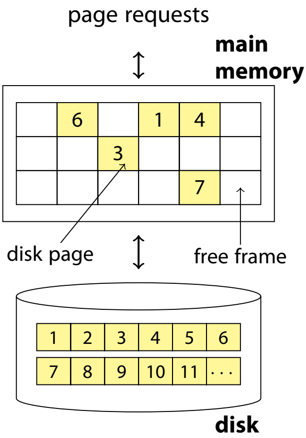

Definition (Buffer Manager)

- 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

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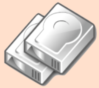
Interface to the Buffer Manager

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?**



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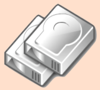
: Release page number *pageno*, making it a candidate for eviction. Must set *dirty* = true if page was modified.

✎ Why do we need the *dirty* bit?

Only **modified** pages need to be written back to disk upon eviction.



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Proper `pin ()`/`unpin ()` Nesting

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

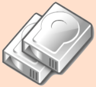
A read-only transaction

$a \leftarrow$ `pin` (p);

$\left\{ \begin{array}{l} \vdots \\ \text{read data on page at memory address } a; \\ \vdots \end{array} \right.$

`unpin` $(p,$ false$)$;

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



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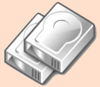
Implementation of `pin ()`

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 (page in v) then
        write page in v to disk ;
    read page pageno from disk into frame v ;
    pinCount (pageno) ← 1 ;
    dirty (pageno) ← false ;
    return address of frame v ;
```

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Implementation of `unpin ()`

Function `unpin`(*pageno*, *dirty*)

$\texttt{pinCount}\ (\mathit{pageno}) \leftarrow \texttt{pinCount}\ (\mathit{pageno}) - 1\ ;$
$\texttt{dirty}\ (\mathit{pageno}) \leftarrow \texttt{dirty}\ (\mathit{pageno}) \vee \mathit{dirty}\ ;$

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

Implementation of `unpin ()`

Function `unpin`(*pageno*, *dirty*)

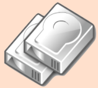
```
pinCount (pageno) ← pinCount (pageno) − 1 ;
dirty (pageno) ← dirty (pageno) ∨ dirty ;
```

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

Well, we could …

- \+ recovery from failure would be a lot simpler
- – higher I/O cost (every page write implies a write to disk)
- – bad response time for writing transactions

This discussion is also known as **force** (or **write-through**) vs. **write-back**. Actual database systems typically implement write-back.



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Concurrent Writes?

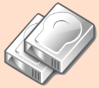
Conflicting changes to a block

Assume the following:

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

Conflicts of this kind are resolved by the system's **concurrency control**, a layer on top of the buffer manager (see "Introduction to Database Systems", transaction management, locks).

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



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Replacement Policies

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

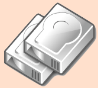
Least Recently Used (LRU)
: Evict the page whose latest `unpin()` is longest ago

LRU-*k*
: Like LRU, but considers the *k* latest `unpin()` calls, not just the 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?



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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 $0, \ldots, N-1$; initialize $\texttt{current} \leftarrow 0$, maintain a bit array $\texttt{referenced}[0, \ldots, N-1]$ initialized to all 0
2. In $\texttt{pin}(p)$: load p into buffer pool (if needed), assign $\texttt{referenced}[\texttt{frame-of}(p)] \leftarrow 1$
3. In $\texttt{pin}(p)$: if we need to find a victim, consider page $\texttt{current}$; if $\texttt{referenced}[\texttt{current}] = 0$, $\texttt{current}$ is the victim; otherwise, $\texttt{referenced}[\texttt{current}] \leftarrow 0$, $\texttt{current} \leftarrow \texttt{current} + 1 \bmod N$, repeat 3

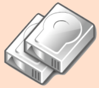
Heuristic Policies Can Fail

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?



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 $\mathtt{R}$. $\mathtt{R}$ occupies 10,000 data pages $\mathtt{R}_i$, the B$^+$-tree occupies one root node and 100 index leaf nodes $\mathtt{I}_k$.
   Transactions perform repeated random index key lookups on $\mathtt{R}$ $\Rightarrow$ **page access pattern** (ignores B$^+$-tree root node):

$$\mathtt{I}_1, \mathtt{R}_1, \mathtt{I}_2, \mathtt{R}_2, \mathtt{I}_3, \mathtt{R}_3, \ldots$$

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

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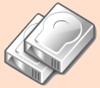
$$\mathtt{I}_1, \mathtt{R}_1, \mathtt{I}_2, \mathtt{R}_2, \mathtt{I}_3, \mathtt{R}_3, \ldots$$

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

With LRU, 50 % of the buffered pages will be pages of $\mathtt{R}$. However, the probability of re-accessing page $\mathtt{R}_i$ only is $^1/_{10,000}$.



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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.

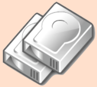
Page fixing/hating

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.



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Databases vs. Operating Systems

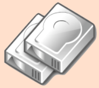
Wait! Didn't we just re-invent the operating system?

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).



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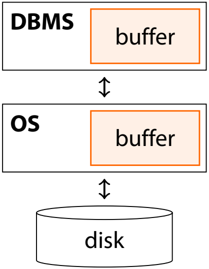
In fact, databases and operating systems sometimes interfere:

- 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.

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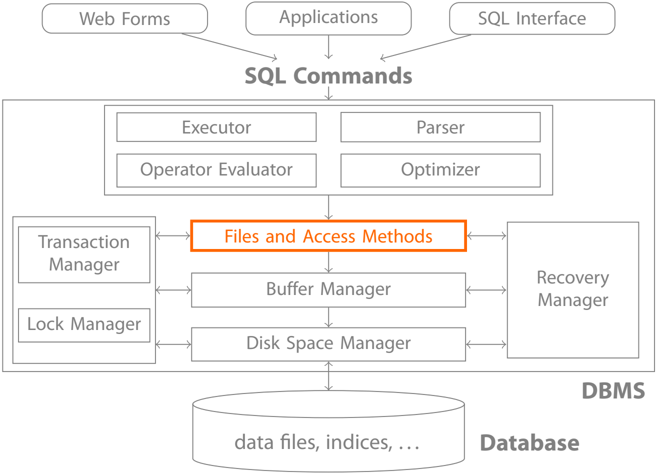

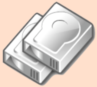

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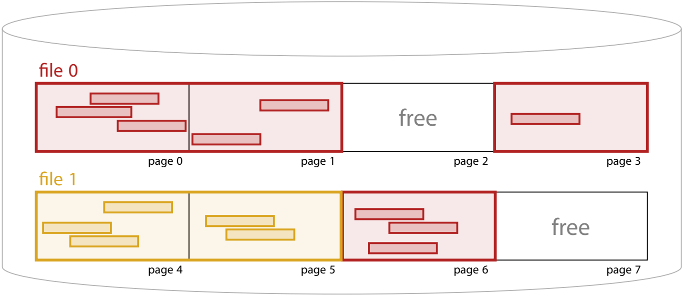
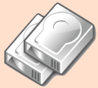
Database Files

- 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:**





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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*:
  f = `createFile`(*n*), `deleteFile`(*n*)
- **insert** record *r* and return its *rid*:
  rid = `insertRecord`(*f*,*r*)
- **delete** a record with a given *rid*:
  `deleteRecord`(*f*,*rid*)
- **get** a record with a given *rid*:
  r = `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.

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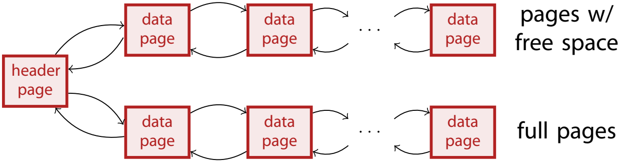
Heap Files

(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

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

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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*
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4. A unique *rid* for *r* is generated and returned to the caller

✎ Generating sensible record ids (*rid*)

Given that *rid*s are used like record addresses: what would be a feasible *rid* generation method?
Generate a **composite** *rid* consisting of the address of page *p* and the placement (offset/slot) of *r* inside *p*:

$$\langle \textit{pageno}\ p, \textit{slotno}\ r \rangle$$

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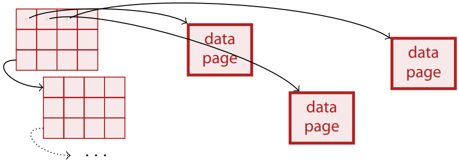
Heap Files

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

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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

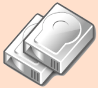
Reduces fragmentation, but requires searching the entire free list/space map for each insert.

First Fit

Search from beginning, take first page with sufficient space. (⇒ 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.



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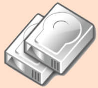
Free Space Witnesses

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.



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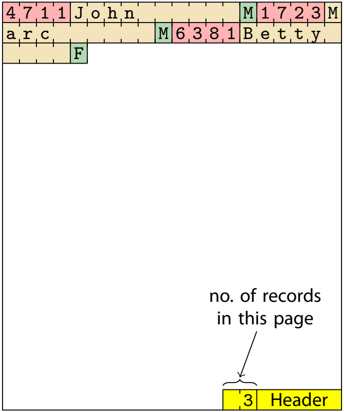
Inside a Page — Fixed-Length Records

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

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



- **Record identifier** (*rid*):

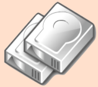
  $\langle pageno, slotno \rangle$

- Record position (within page):

  $slotno \times bytes\ per\ slot$

- Record **deletion**?
  - record id should **not** change

  ⇒ **slot directory** (bitmap)



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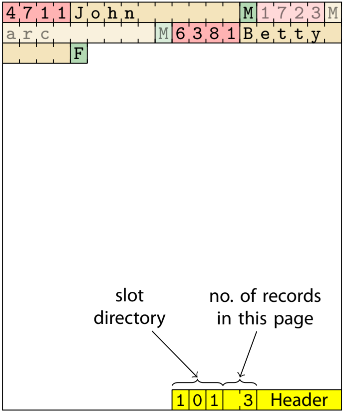

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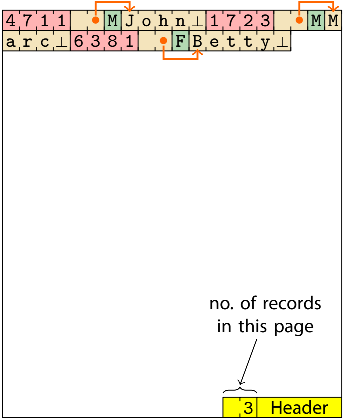
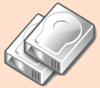
Inside a Page—Variable-Sized Fields

- Variable-sized fields moved to **end** of each record.
  - Placeholder points to location.
  - ✎ **Why?**





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Inside a Page—Variable-Sized Fields

- Variable-sized fields moved to **end** of each record.
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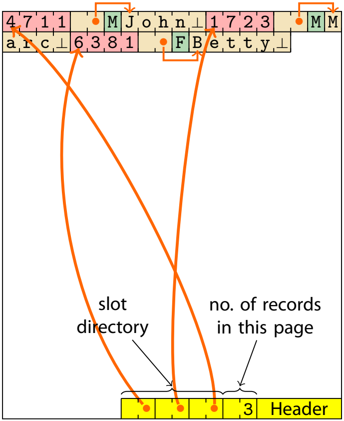
- Slot directory points to start of each record.



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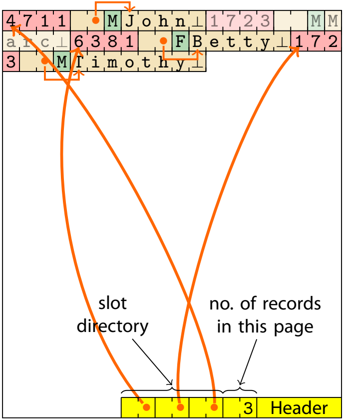
- Records **can move** on page.
  - *E.g.*, if field size changes or page is compacted.



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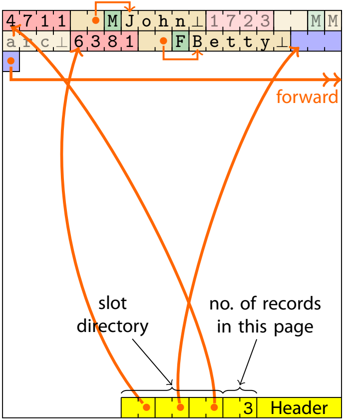
  - *E.g.*, if field size changes or page is compacted.
- Create **“forward address”** if record won’t fit on page.
  - ✎ **Future updates?**



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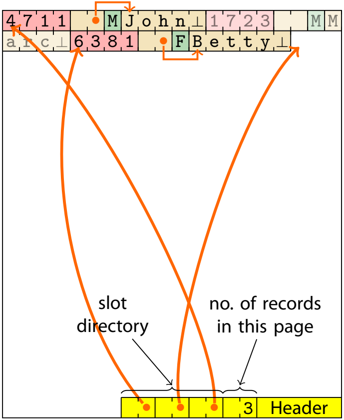
  - *E.g.*, if field size changes or page is compacted.
- Create **“forward address”** if record won’t fit on page.
  - ✎ **Future updates?**
- Related issue: space-efficient representation of `NULL` values.



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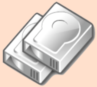
IBM DB2 Data Pages

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, otherwises uses forward records.



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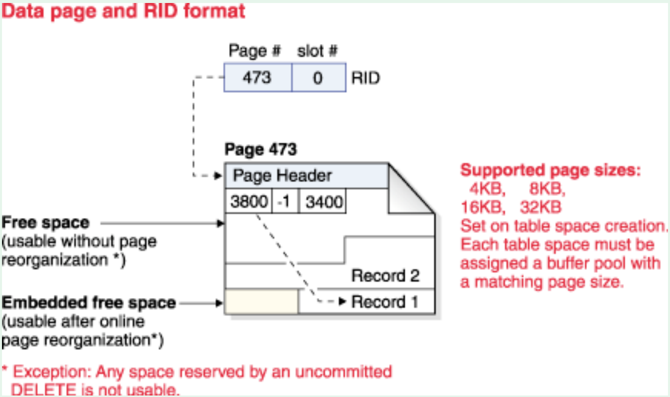
IBM DB2 Data Pages

DB2 Taken directly from the DB2 V9.5 Information Center



`http://publib.boulder.ibm.com/infocenter/db2luw/v9r5/`

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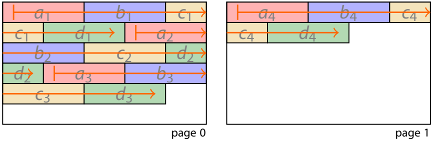
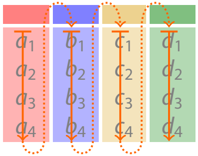
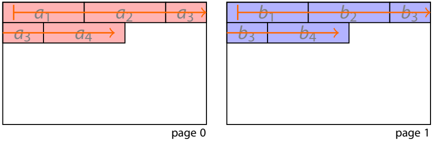
Alternative Page Layouts

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



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





Alternative Page Layouts

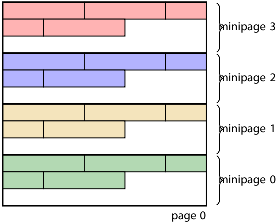
These two approaches are also known as **NSM (n-ary storage model)** and **DSM (decomposition storage model)**.[1]

- 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**.

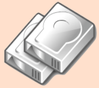
A hybrid approach is the **PAX (Partition Attributes Across)** layout:

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

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



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



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Magnetic Disks

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

Disk Space Manager

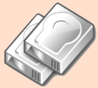
Abstracts from hardware details and maps page number $\mapsto$ physical location.

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.



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