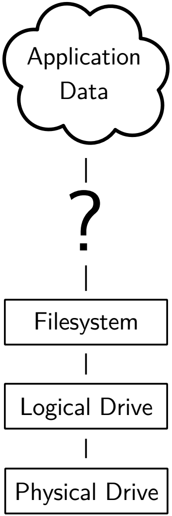
Storage

The Problem


Application
Data
?
Filesystem
Logical Drive
Physical Drive

Requirements

There are different classes of requirements:

- Data Independence
  - application is shielded from physical storage
  - physical storage can be reorganized
  - hardware can be changed
- Scalability
  - must scale to (nearly) arbitrary data sizes
  - fast retrieval
  - efficient access to individual data items
  - updating arbitrary data
- Reliability
  - data must never be lost
  - must cope with hardware and software failures
- ...

Layer Architecture

- implementing all these requirements on the “bare metal” is hard
- and not desirable
- a DBMS must be maintainable and extensible

Instead: use a **layer** architecture

- the DBMS logic is split into levels of functionality
- each level is implemented by a specific layer
- each layer interacts only with the next lower layer
- simplifies and modularizes the code

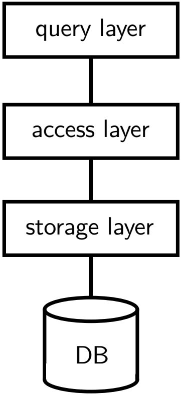
A Simple Layer Architecture

Purpose

query translation
and optimization

managing records
and access paths

DB buffer and
hardware interface



Access Granularity

declarative queries
sets of records

records

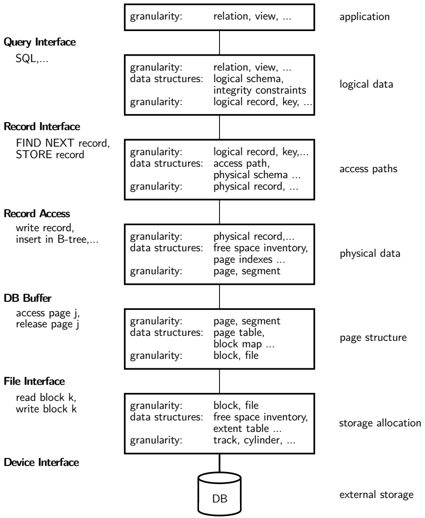
page

A Simple Layer Architecture (2)

- layers can be characterized by the data items they manipulate
- lower layer offers functionality for the next higher level
- keeps the complexity of individual layers reasonable
- rough structure: physical $\rightarrow$ low level $\rightarrow$ high level

This is a reasonable architecture, but simplified.
A more detailed architecture is needed for a complete DBMS.

A More Detailed Architecture



A More Detailed Architecture (2)

A few pieces are still missing:

- transaction isolation
- recovery

but otherwise it is a reasonable architecture.

Some system deviate slightly from this classical architecture

- most DBMSs nowadays delegate drive access to the OS
- some DBMSs delegate buffer management to the OS (tricky, though)
- a few DBMSs allow for direct logical record access
- ...

Influence of Hardware

Must take hardware into account when designing a storage system.

For a long time dominated by **Moore's Law**:

The number of transistors on a chip doubles every 18 month.

Indirectly drove a number of other parameters:

- main memory size
- CPU speed
  - no longer true!
- HD capacity
  - start getting problematic, too. density is very high
  - only capacity, not access time

Later we will look at these again.

Memory Hierarchy

capacity
latency

bytes
1ns

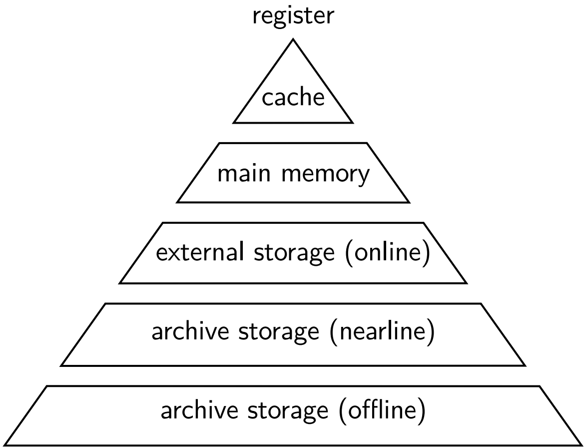
K-M bytes
<10ns

G bytes
<100ns

T bytes
ms

T bytes
sec

T-P bytes
sec-min



Memory Hierarchy (2)

There are huge gaps between hierarchy levels

- traditionally, main memory vs. disk is most important
- but memory vs. cache etc. also relevant

The DBMS must aim to maximize locality.

Hard Disk Access

Hard Disks are still the dominant external storage:

- rotating platters, mechanical effects
- transfer rate: ca. 150MB/s
- seek time ca. 3ms
- huge imbalance in random vs. sequential I/O!

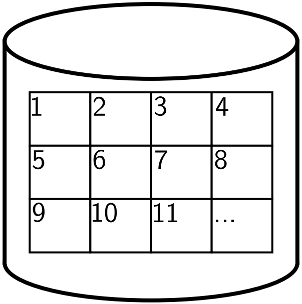
The DBMS must take these effects into account

- sequential access is much more efficient
- gap is growing instead of shrinking
- even SSDs are slightly asymmetric (and have other problems)

Hard Disk Access (2)

Techniques to speed up disk access:

- do not move the head for every single tuple
- instead, load larger chunks
- typical granularity: one **page**
- page size varies. traditionally 4KB, nowadays often 16K and more
- page size is a trade-off



Hard Disk Access (3)

The page structure is very prominent within the DBMS

- granularity of I/O
- granularity of buffering/memory management
- granularity of recovery

Page is still too small to hide random I/O though

- sequential page access is important
- DBMSs use read-ahead techniques
- asynchronous write-back

Buffer Management

Some pages are accessed very frequently

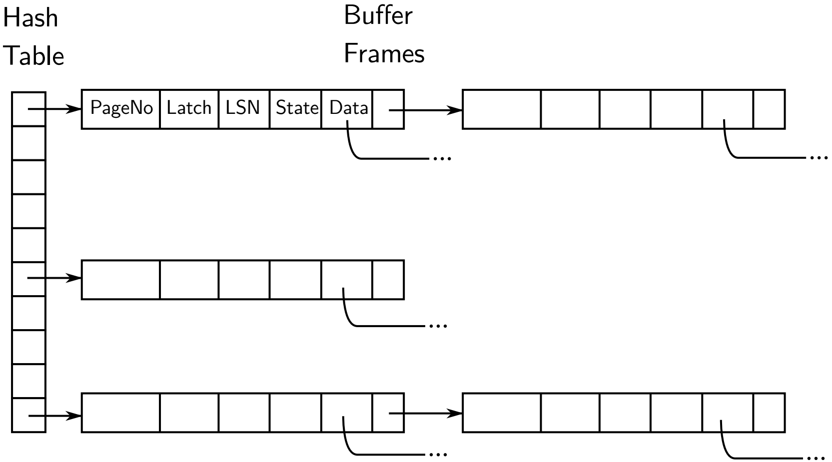
- reduce I/O by buffering/caching
- buffer manager keeps active pages in memory
- limited size, discards/write back when needed
- coupled with recovery, in particular logging

Basic interface:

1. FIX(pageNo,shared)
2. UNFIX(pageNo,dirty)

Pages can only be accessed (or modified) when they are **fixed**.

Buffer Managment



The buffer manager itself is protected by one or more latches.

Buffer Frame

Maintains the state of a certain page within the buffer

pageNo	the page number
latch	a read/writer lock to protect the page (note: must not block unrelated pages!)
LSN	LSN of the last change, for recovery (buffer manager must force the log before writing)
state	clean/dirty/newly created etc.
data	the actual data contained on the page

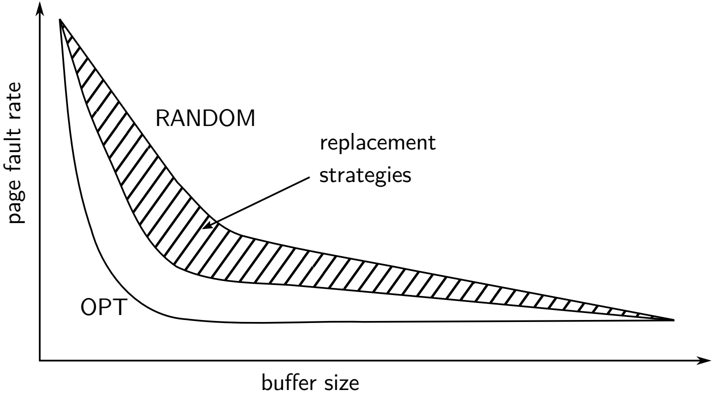
(will usually contain extra information for buffer replacement)

Usually kept in a hash table.

Buffer Replacement

When memory is full, some buffer pages have to be replaced

- clean pages can be simply discarded
- dirty pages have to be written back first
- discarded pages are replaced with new pages



Buffer Replacement - FIFO

First In - First Out

- simple replacement strategy
- buffer frames are kept in a linked list
- inserted at the end, remove from the head
- “old” pages are removed first

Does not take locality into account.

Buffer Replacement - LRU

Least Recently Used

- similar to FIFO, buffer frames are kept in a double-linked list
- remove from the head
- when a frame is unfixed, move it to the end of the list
- “hot” pages are kept in the buffer

A very popular strategy. Latching requires some care.

Buffer Replacement - LFU

Least Frequently Used

- remembers the number of access per page
- in-frequently used pages are remove first
- maintains a priority queue of pages

Sounds plausible, but too expensive in practice.

Buffer Replacement - Second Chance

LRU is nice, but the LRU list is a hot spot.

Idea: use a simpler mechanism to simulate LRU

- one bit per page
- bit is set when page is unfixed
- when replacing, replace pages with unset bit
- set bits are cleared during the process
- strategy is called “second chance” or “clock”

Easy to implement, but a bit crude.

Buffer Replacement - 2Q

Maintain not one queue but two

- many pages are referenced only once
- some pages are hot and reference frequently
- maintain a separate list for those

1. maintain all pages in FIFO queue
2. when a page is references again that is currently in FIFO, move it into an LRU queue
3. prefer evicting from FIFO

Hot pages are in LRU, read-once pages in FIFO. Good strategy for common DBMS operations.

Buffer Replacement - Hints

Application knowledge can help buffer replacement

- 2Q tries to recognize read-once pages
- these occur when scanning over data
- but the DBMS knows this anyway!
- it could therefore give **hints** when unfixing
- e.g., *will-need*, or *will-not-need* (changes placement in queue)

Segments

While page granularity is fine for I/O, it is somewhat unwieldy

- most structures within a DBMS span multiple pages
- relations, indexes, free space management, etc.
- convenient to treat these as one entity
- all DBMS pages are partitioned into sets of pages

Such a set of pages is called a **segment**.

Conceptually similar to a file or virtual memory.

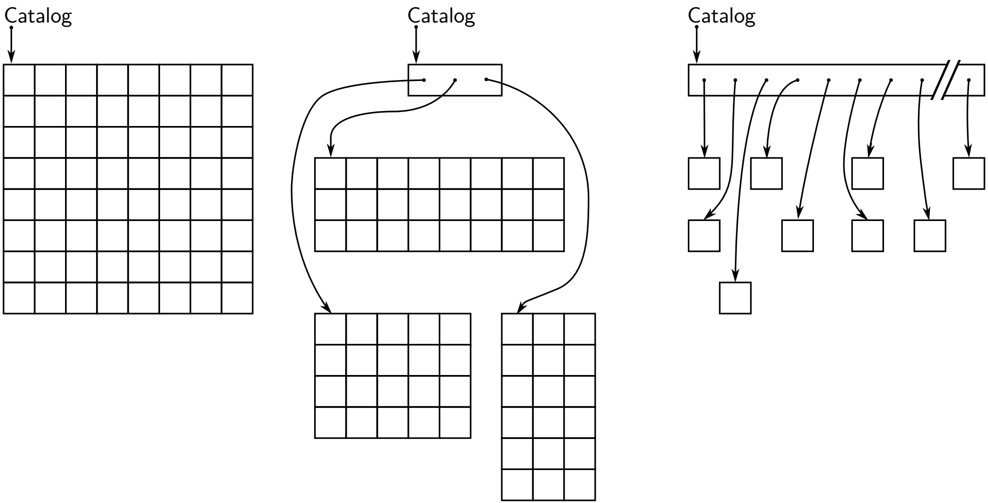
Segments (2)

A segment offers a virtual address space within the DBMS

- can allocate and release new pages
- can iterate over all pages
- can drop the whole segment
- optionally offers a linear address space

Greatly simplifies the logic of higher layers.

Block Allocation



static file-mapping | dynamic extent-mapping | dynamic block-mapping

Block Allocation

All approaches have pros and cons:

- static file-mapping
  - very simple, low overhead
  - resizing is difficult
- dynamic block-mapping
  - maximum flexibility
  - administrative overhead, additional indirection
- dynamic extent-mapping
  - can handle growth
  - slight overhead

In most cases extent-based mapping is preferable.

Block Allocation (5)

Dynamic extent-mapping:

- grows by adding a new extent
- should grow exponentially (e.g., factor 1.25)
- bounds the number of extents
- reduces both complexity and space consumption
- and helps with sequential I/O!

Segment Types

Segments can be classified into types

- private vs. public
- permanent vs. temporary
- automatic vs. manual
- with recovery vs. without recovery

Differ in complexity and required effort.

Standard Segments

Most DBMS will need at least two low-level segments:

- segment inventory
  - keeps track of all pages allocated to segments
  - keeps extent lists or page tables or ...
- free space inventory
  - keeps track of free pages
  - maintains bitmaps or free extents or ...

High-level segments built upon these.

Common high-level segments:

- schema
- relations
- temp segments (created and discard on demand)
- ...

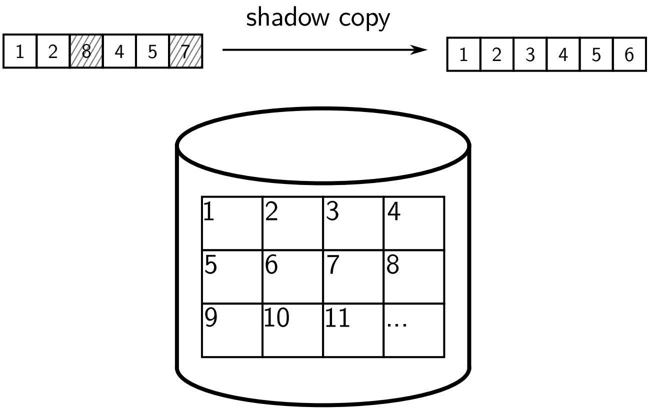
Update Strategies

DBMSs have different update behavior

	steal	$\neg$ steal
force		
$\neg$ force		

- usually one prefers steal, $\neg$ force
- but then pages contain dirty data
- when using *update-in-place*, dirty data is on on disk
- complicates recovery
- transactions could see dirty data

Shadow Paging



uses a page table, dirty pages are stored in a shadow copy.

Shadow Paging (2)

Advantages:

- the clean data is always available on disk
- greatly simplified recovery
- can be used for transaction isolation, too

Disadvantages:

- complicates the page access logic
- destroys data locality

Nowadays rarely used in disk-based systems.

Delta Files

Similar idea to shadow paging:

- on change pages are copied to a separate file
- a copied page can be changed in-place
- on commit discard the file, on abort copy back

Can be implemented in two flavors:

- store a clean copy in the delta
- store the dirty data in the delta

Both have pros and cons.

Delta Files (2)

Delta files have some advantages over shadow paging:

- preserve data locality
- no mixture of clean and dirty pages

Disadvantages:

- cause more I/O
- abort (or commit) becomes expensive
- keeping track of delta pages is non-trivial

Still, often preferable over shadow paging.