Storing Data: Disks and Files

Storing and Retrieving Data

- Database Management Systems need to:
  - Store large volumes of data
  - Store data reliably (so that data is not lost!)
  - Retrieve data efficiently
- Alternatives for storage
  - Main memory
  - Disks
  - Tape

Why Not Store Everything in Main Memory?

- *Costs too much.* $100 will buy you either 2GB of RAM (similar for flash memory) or 400GB of disk today.
- *Main memory is volatile.* We want data to be saved between runs. (Obviously!)
  - Flash memory is non-volatile

Why Not Store Everything in Tapes?

- *No random access.* Data has to be accessed sequentially
  - Not a great idea when accessing a small portion of a terabyte of data
- *Slow!* Data access times are larger than for disks

Disks

- Secondary storage device of choice
  - Cheap
  - Stable storage medium
  - Random access to data

- Main problem
  - Data read/write times much larger than for main memory
  - Positioning time in order of milliseconds
    - How many instructions could a 3 GHz CPU process during that time…

Solution 1: Techniques for making disks faster

- Intelligent data layout on disk
  - Put related data items together
- Redundant Array of Inexpensive Disks (RAID)
  - Achieve parallelism by using many disks

Solution 2: Buffer Management

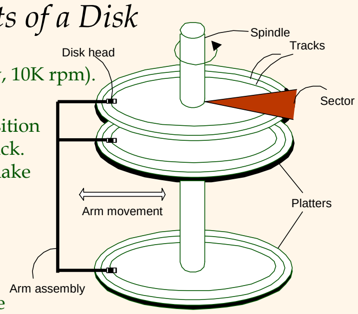
- Keep "currently used" data in main memory
  - How do we do this efficiently?
- Typical (simplified) storage hierarchy:
  - Main memory (RAM) for currently used data
  - Disks for the main database (secondary storage)
  - Tapes for archiving older versions of the data (tertiary storage)

Outline

- Disk technology and how to make disk read/writes faster
- Buffer management
- Storing "database files" on disk

Components of a Disk

- The platters spin (say, 10K rpm).
- The arm assembly is moved in or out to position a head on a desired track. Tracks under heads make a *cylinder* (imaginary!).
- Only one head reads/writes at any one time.
- *Block size* is a multiple of *sector size* (which is fixed).



Accessing a Disk Page

- Time to access (read/write) a disk block:
  - *seek time* (moving arms to position disk head on track)
  - *rotational delay* (waiting for block to rotate under head)
  - *transfer time* (actually moving data to/from disk surface)
- Seek time and rotational delay dominate.
  - Seek time varies from about 1 to 20msec
  - Rotational delay varies from 0 to 10msec
  - Transfer rate is about 0.1-0.5msec per 4KB page
- Key to lower I/O cost: reduce seek/rotation delays! Hardware vs. software solutions?

Arranging Pages on Disk

- \`*Next*' block concept:
  - blocks on same track, followed by
  - blocks on same cylinder, followed by
  - blocks on adjacent cylinder
- Blocks in a file should be arranged sequentially on disk (by \`next'), to minimize seek and rotational delay.
- For a sequential scan, *pre-fetching* several pages at a time is a big win!

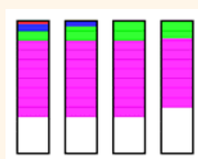
RAID

- Redundant Array of Inexpensive Disks
  - A.k.a. Redundant Array of Independent Disks
- Disk Array: Arrangement of several disks that gives abstraction of a single, large disk.
- Goals: Increase performance and reliability.
- Two main techniques:
  - Data striping: Data is partitioned; size of a partition is called the striping unit. Partitions are distributed over several disks.
  - Redundancy: More disks -> more failures. Redundant information allows reconstruction of data if a disk fails. Two main approaches: parity and mirroring.

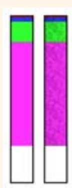
Parity

- Add 1 redundant block for every n blocks of data
  - XOR of the n blocks
- Example: D1, D2, D3, D4 are data blocks
  - Compute DP as D1 XOR D2 XOR D3 XOR D4
  - Store D1, D2, D3, D4, DP on different disks
  - Can recover any *one* of them from the other four by XORing them

RAID Levels

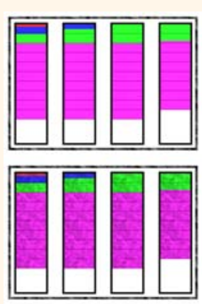


- Level 0: No redundancy
  - Striping without parity
- Level 1: Mirrored (two identical copies)



  - Each disk has a mirror image (check disk)
  - Parallel access: reduces positioning time, but transfer only from one disk.
    - Maximum transfer rate = transfer rate of one disk
  - Write involves two disks.

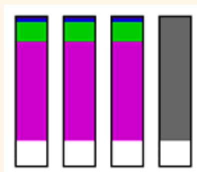
RAID Levels (Contd.)



- Level 0+1: Striping and Mirroring
  - Parallel reads.
  - Write involves two disks.
  - Maximum transfer rate = aggregate bandwidth
  - Combines performance of RAID 0 with redundancy of RAID 1.
- Example: 8 disks
  - Divide into two sets of 4 disks
  - Each set is a RAID 0 array
  - One set mirrors the other

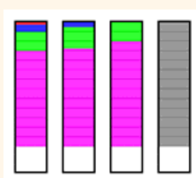
RAID Levels (Contd.)

- Level 3: Bit-Interleaved Parity
  - Striping Unit: One bit. One check disk.
  - Each read and write request involves all disks; disk array can process one request at a time.



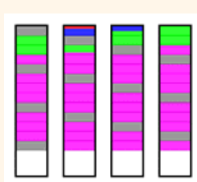
RAID Levels (Contd.)

- Level 4: Block-Interleaved Parity
  - Striping Unit: One disk block. One check disk.
  - Parallel reads possible for small requests, large requests can utilize full bandwidth
  - Writes involve modified block and check disk



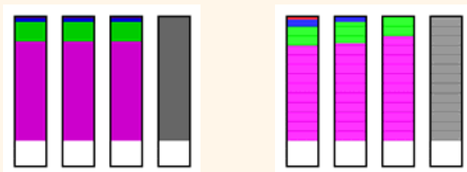
RAID Levels (Contd.)

- Level 5: Block-Interleaved Distributed Parity
  - Similar to RAID Level 4, but parity blocks are distributed over all disks
  - Eliminates check disk bottleneck, one more disk for higher read parallelism



In-Class Exercise

- How does the striping granularity (size of a stripe) affect performance, e.g., RAID 3 vs. RAID 4?



In-Class Exercise

- How does the striping granularity (size of a stripe) affect performance, e.g., RAID 3 vs. RAID 4?
- Smaller stripe -> file is broken into more and smaller pieces -> small files are distributed over more disks -> faster transfer when reading that file (parallel I/O)
- Disadvantage: when reading multiple files, each disk has more requests, leading to worse positioning time (seek + rotational delay)
- Write performance: need not (!) read whole stripe to re-compute parity
  - NewParity = (OldData XOR NewData) XOR OldParity

Which RAID to Choose?

- RAID 0: great performance at low cost, limited reliability
- RAID 0+1 (better than 1): small storage subsytems (cost of mirroring limited), or when write performance matters
- RAID 3 (better than 2): large transfer requests of contiguous blocks, bad for small requests of single blocks
- RAID 5 (better than 4): good general-purpose solution

Which RAID to Choose? Corrected.

- RAID 0: great performance at low cost, limited reliability
- RAID 0+1 (better than 1): small storage subsytems (cost of mirroring limited), or when write performance matters
- RAID 5 (better than 3, 4): good general-purpose solution

RAID Comparison (www.storagereview.com)

RAID Level	Number of Disks	Capacity	Storage Efficiency	Fault Tolerance	Availability	Random Read Perf	Random Write Perf	Sequential Read Perf	Sequential Write Perf	Cost
0	2,3,4,...	S*N	100%	none	*	****	****	****½	****	$
1	2	S*N/2	50%	****	****	***	***	**	***	$$
2	many	varies, large	~ 70-80%	**	****	**	*	****	**½	$$$$$
3	3,4,5,...	S*(N-1)	(N-1)/N	***	****	***	*	****	**½	$$
4	3,4,5,...	S*(N-1)	(N-1)/N	***	****	****	*½	***	**	$$
5	3,4,5,...	S*(N-1)	(N-1)/N	***	****	****½	**	***½	**½	$$
6	4,5,6,...	S*(N-2)	(N-2)/N	****½	*****	****½	*	***½	**	$$$
7	varies	varies	varies	***	****	****½	****	****½	****	$$$$$
01/10	4,6,8,...	S*N/2	50%	****	****½	****½	***½	****½	***½	$$$
03/30	6,8,9,10,...	S*N0*(N3-1)	(N3-1)/N3	***½	****	****	**	****½	***	$$$$
05/50	6,8,9,10,...	S*N0*(N5-1)	(N5-1)/N5	***½	****	****½	***	****	***	$$$$
15/51	6,8,10,...	S*((N/2)-1)	((N/2)-1)/N	*****	*****	****	***	****	***	$$$$$

This is just a rule-of-thumb comparison: don't worry about half a star difference, RAID 3 is overrated etc.

Disk Space Management

- Lowest layer of DBMS software manages space on disk.
- Higher levels call upon this layer to:
  - allocate/de-allocate a page
  - read/write a page
- Request for a *sequence* of pages must be satisfied by allocating the pages sequentially on disk! Higher levels don't need to know how this is done, or how free space is managed.

Outline

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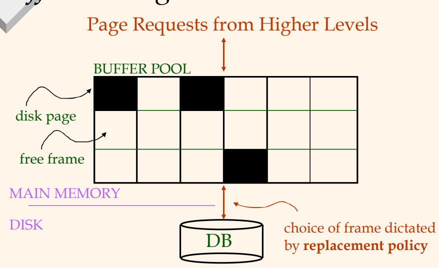
- Buffer management
- Storing "database files" on disk

Buffer Management in a DBMS



- *Data must be in RAM for DBMS to operate on it!*
- *Table of <frame#, pageid> pairs is maintained.*

When a Page is Requested ...

- If requested page is not in pool:
  - Choose a frame for *replacement*
  - If frame is dirty, write it to disk
  - Read requested page into chosen frame
- *Pin* the page and return its address.

* *If requests can be predicted (e.g., sequential scans) pages can be pre-fetched several pages at a time!*

More on Buffer Management

- Requestor of page must unpin it, and indicate whether page has been modified:
  - *dirty* bit is used for this.
- Page in pool may be requested many times,
  - a *pin count* is used. A page is a candidate for replacement iff *pin count* = 0.
- CC & recovery may entail additional I/O when a frame is chosen for replacement. (*Write-Ahead Log* protocol; more later.)

In Class Exercise

- What happens if the buffer is full and all frames have pin count > 0?
- What happens if multiple transactions (users) want to access the same page?

Buffer Replacement Policy

- Frame is chosen for replacement by a *replacement policy:*
  - Least-recently-used (LRU): priority queue based on last access to frame (time when pin count goes to 0)
  - Clock: round-robin replacement with *referenced* bit
  - Many others
    - First-in-first-out (FIFO), Most-recently-used (MRU), Random

Buffer Replacement Policy (Contd.)

- Policy can have big impact on # of I/O's; depends on the *access pattern*.
- *Sequential flooding*: Nasty situation caused by LRU + repeated sequential scans.
  - # buffer frames < # pages in file means each page request causes an I/O.
  - Which replacement policy is better?

DBMS vs. OS File System

OS does disk space & buffer mgmt: why not let OS manage these tasks?

- Differences in OS support: portability issues
- Some limitations, e.g., files can't span disks.
- Buffer management in DBMS requires ability to:
  - pin a page in buffer pool, force a page to disk (important for implementing CC & recovery),
  - adjust *replacement policy,* and pre-fetch pages based on access patterns in typical DB operations.

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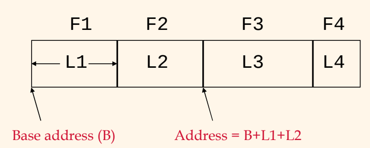
Files of Records

- Page or block is OK when doing I/O, but higher levels of DBMS operate on *records*, and *files of records*.
- FILE: A collection of pages, each containing a collection of records. Must support:
  - insert/delete/modify record
  - read a particular record (specified using *record id*)
  - scan all records (possibly with some conditions on the records to be retrieved)

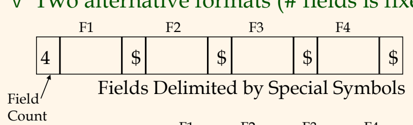
Record Formats: Fixed Length



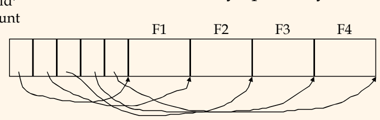
- Information about field types same for all records in a file; stored in *system catalogs.*
- Finding *i'th* field requires scan of record.

Record Formats: Variable Length

- Two alternative formats (# fields is fixed):



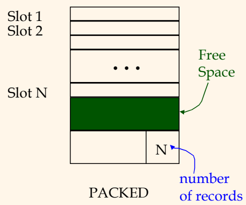
Fields Delimited by Special Symbols



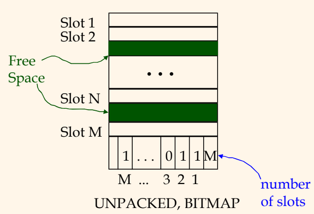
Array of Field Offsets

* Second offers direct access to i'th field, efficient storage of *nulls* (special *don't know* value); small directory overhead.

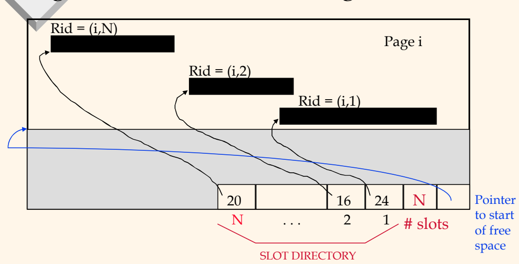
Page Formats: Fixed Length Records



Page Formats: Fixed Length Records



Page Formats: Variable Length Records

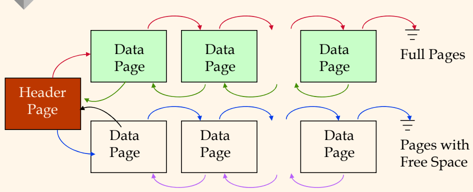


* *Can move records on page without changing rid; so, attractive for fixed-length records too.*

Unordered (Heap) Files

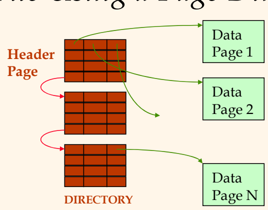
- Simplest file structure contains records in no particular order.
- As file grows and shrinks, disk pages are allocated and de-allocated.
- To support record level operations, we must:
  - keep track of the *pages* in a file
  - keep track of *free space* on pages
  - keep track of the *records* on a page
- There are many alternatives for keeping track of this.

Heap File Implemented as a List



- The header page id and Heap file name must be stored someplace.
- Each page contains 2 `pointers' plus data.

Heap File Using a Page Directory



- The entry for a page can include the number of free bytes on the page.
- The directory is a collection of pages; linked list implementation is just one alternative.
  - *Much smaller than linked list of all HF pages*!

Indexes

- A Heap file allows us to retrieve records:
  - by specifying the *rid*
    - *Usually <page id, slot number>, or some integer (need lookup table for corresponding page id and slot number)*
  - by scanning all records sequentially
- Sometimes, we want to retrieve records by specifying the *values in one or more fields*, e.g.,
  - Find all CS students with a gpa > 3
- Indexes are file structures that enable us to answer such value-based queries efficiently.

System Catalogs

- For each index:
  - structure (e.g., B+ tree) and search key fields
- For each relation:
  - name, file name, file structure (e.g., Heap file)
  - attribute name and type, for each attribute
  - index name, for each index
  - integrity constraints
- For each view:
  - view name and definition
- Plus statistics, authorization, buffer pool size, etc.
  - * *Catalogs are themselves stored as relations*!

Attr_Cat(attr_name, rel_name, type, position)

attr_name	rel_name	type	position
attr_name	Attribute_Cat	string	1
rel_name	Attribute_Cat	string	2
type	Attribute_Cat	string	3
position	Attribute_Cat	integer	4
sid	Students	string	1
name	Students	string	2
login	Students	string	3
age	Students	integer	4
gpa	Students	real	5
fid	Faculty	string	1
fname	Faculty	string	2
sal	Faculty	real	3

Summary

- Disks provide cheap, non-volatile storage
- Buffer manager brings pages into RAM
- DBMS vs. OS File Support
- Fixed and Variable length records
- Slotted page organization