CS 2451

DBMS System Design: A brief Introduction

http://www.seas.gwu.edu/~bhagiweb/cs2541

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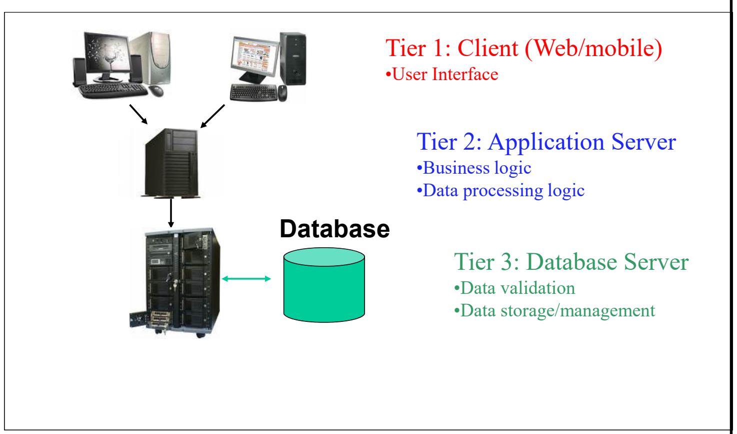
Building Database Applications: Steps

1. Start with a conceptual model
   - "On paper" using certain techniques (E-R Model)
   - ignore low-level details – focus on logical representation
   - "step-wise refinement" of design with client input
2. Design & implement schema
   - Design and codify (in SQL) the relations/tables
   - Refine the schema – *normalization*
   - Do physical layout – indexes, etc.
3. Import the data
4. Write applications using DBMS and other tools

   Many of the hard problems are taken care of by other people (DBMS, API writers, library authors, web server, etc.)

DBMS takes care of Query Optimization, Efficiency, etc.

Three-Tier Client-Server Architecture



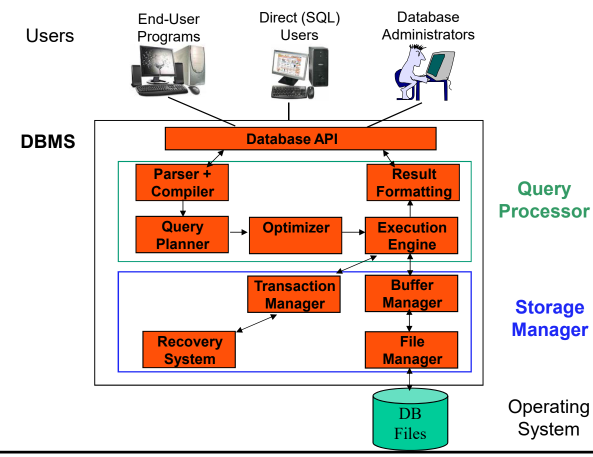
DBMS

- A database management system provides *efficient*, *convenient*, and *safe multi-user* storage and access to *massive* amounts of *persistent* data.
- ***Efficient*** - Able to handle large data sets and complex queries without searching all files and data items.
- ***Convenient*** - Easy to write queries to retrieve data.
- ***Safe*** - Protects data from system failures and hackers.
- ***Massive*** - Database sizes in gigabytes/terabytes/petabytes.
- ***Persistent*** - Data exists after program execution completes.
- ***Multi-user*** - More than one user can access and update data at the same time while preserving consistency….concept of **transactions**

Components of a DBMS

- A DBMS is a complicated software system containing many components:
  - ***Query processor*** - translates user/application queries into low-level data manipulation actions.
    Sub-components: query parser, query optimizer
  - ***Storage manager*** - maintains storage information including memory allocation, buffer management, and file storage.
    Sub-components: buffer manager, file manager
  - ***Transaction manager*** - performs scheduling of operations and implements concurrency control algorithms.

DBMS Architecture



Next: Look inside a DBMS

- Storage Manager: File organization
  - How is data organized/stored in secondary memory
  - Concept of indexing
  - Memory management…..more in operating systems
- (if time permits) Query processor
  - Very brief look at how queries are executed by the machine
  - Translation of SQL code to C code
- (if time permits) Transaction manager
  - Dealing with concurrency – abstract definition of scheduling primitives
    In operating systems you will work with implementation

Storage and Organization: Overview

- A database system relies on the operating system to store data on storage devices.
- Database performance depends on:
  - Properties of storage devices
  - How devices are used and accessed via the operating system
- Quick look into techniques for storing and representing data
  - Important Note: These apply for SQL as well as NoSQL systems
  - Key in efficient storage and retrieval systems
    Including search engines

Review from architecture (?): Memory Definitions

- ***Temporary memory*** retains data only while the power is on.
  - Also referred to as ***volatile storage***.
  - e.g. dynamic random-access memory (DRAM) (main memory)
- ***Permanent memory*** stores data even after the power is off.
  - Also referred to as ***non-volatile storage*** or **secondary storage**
  - e.g. flash memory, SSD, hard drive, DVD, tape drives
- ***Cache*** is faster memory used to store a subset of a larger, slower memory for performance.
  - processor cache (Level 1 & 2), disk cache, network cache

Physical Storage: Memory Hierarchy

- Primary Storage: cache & main memory
  - Can be directly accessed by CPU
  - Currently used data
- Secondary Storage: flash, SSD, magnetic disks, optical disks, tapes
  - Larger capacity, low cost, slow access
  - Cannot be directly processed by CPU
- DB stores large amount, persist over time
  - Data is stored in secondary storage
  - Contrast with run-time data structures
- Time taken to fetch data depends on how data is organized on disk/file

Why Not Store Everything in Main Memory?

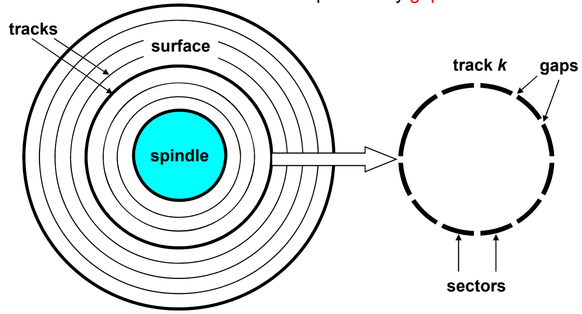
- *Costs too much.*
- *Main memory is volatile.*
  - We want data to be saved between runs. (Obviously!)
  - Situations that cause permanent loss of data occur less frequently in disks than primary memory
  - Disk/Flash storage is non-volatile

Recall: Disks

- Secondary storage device of choice.
- Main advantage over tapes: *random access* vs. *sequential*.
- Data is stored and retrieved in units called *disk blocks* or *pages.*
- Unlike RAM, time to retrieve a disk page varies depending upon location on disk.
  - Therefore, relative placement of pages on disk has major impact on DBMS performance!

Disk Geometry

- Disks consist of platters, each with two surfaces.
- Each surface consists of concentric rings called tracks.
- Each track consists of sectors separated by gaps.

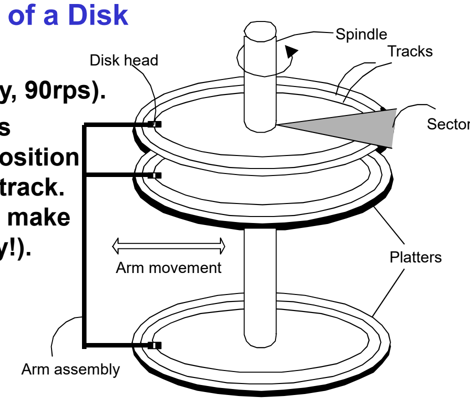


Components of a Disk

The platters spin (say, 90rps).

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).**

Disk Structure

- For READ/WRITE operations
  - H/W address of block and address of buffer is supplied to disk IO hardware via disk controller
  - Buffer is contiguous reserved area in main memory that holds block (page)
- Actual H/W that reads blocks is disk head, part of disk drive
- Disk drives rotate disk pack
- Disk arm positions disk head over block read
  - When block passes under disk head, data transferred to buffer

Logical Disk Blocks

- Modern disks present a simpler abstract view of the complex sector geometry:
  - The set of available sectors is modeled as a sequence of b-sized logical blocks (0, 1, 2, ...)
- Mapping between logical blocks and actual (physical) sectors
  - Maintained by hardware/firmware device called disk controller.
  - Converts requests for logical blocks into (surface,track,sector) triples.
  - Block *200* mapped to disk location *(x,y,z)*

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.
- Key to lower I/O cost: reduce seek/rotation delays! Hardware vs. software solutions?

Disk Access Time

- H/W address of disk block: (surface #, track #, sector #)
- Average time to access a target sector approximated by :
  - Taccess = T_{avg} seek + T_{avg} rotation + T_{avg} transfer
- Seek time (T_{avg} seek)
  - Time to position heads over cylinder containing target sector.
  - Typical Tavg seek = 9 ms
- Rotational latency (T_{avg} rotation)
  - Time waiting for first bit of target sector to pass under r/w head.
  - Tavg rotation = 1/2 x 1/RPMs x 60 sec/1 min
- Transfer time (T_{avg} transfer)
  - Time to read the bits in the target sector.
  - Tavg transfer = 1/RPM x 1/(avg # sectors/track) x 60 secs/1 min.

Summary: 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.
- Key to lower I/O cost: reduce seek/rotation delays! Hardware vs. software solutions?

Example

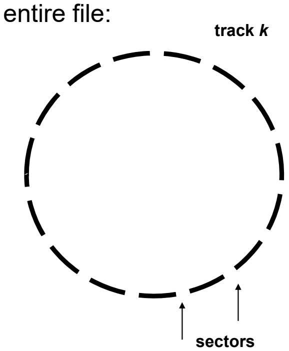
- SELECT * FROM EMP;
- Need to scan entire file
  - Read all records
- Access all blocks/pages of the file on the disk
  - Assume N pages
- How long does this take ?
- Simple approach: N* T_{access}
  - Taccess = T_{avg} seek + T_{avg} rotation + T_{avg} transfer

Example: 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!

Disk Geometry and File Layout

File = { block 1, b2, ….}
Need to read/scan entire file:



Example: time using next block approach

- Need to scan entire file
  - Read all records
- Time to read first block: T_seek + T_rotation + T_transfer
- Time to read next block: T_transfer
- ….
- Time to read all N blocks: First block and then one block every T_transfer cycles
  - (T_seek + T_rotation + T_transfer) + (N-1) T_transfer
- About (N-1)*(T_seek + T_rotate) less than naive approach
  - ~ O(N) faster since T_seek >> T_transfer

So what does this tell us ?

- Time to process a query can be reduced by careful mapping of the pages to the physical disk blocks
- Page and File organization on disk affects Query performance
  - Database performance linked to physical organization of data

File Interfaces

- Besides the physical characteristics of the media and device, how the data is allocated on the media affects performance…***file organization***.
- The physical device is controlled by the operating system. The operating system provides one or more interfaces to accessing the device.

Block-Level Interface

- A ***block-level interface*** allows a program to read and write a chunk of memory called a ***block*** (or ***page***) from the device.
- The page size is determined by the operating system. A page may be a multiple of the physical device's block size.
- The OS maintains a mapping from logical page numbers (starting at 0) to physical blocks on the device.

File and Data Organization

- How is data stored on disk?
  - Records
  - file of records
- how to organize the files to enable fast processing of queries
  - how to measure speed - computation or I/O time ?
- Study file/data organization techniques that lead to more efficient processing of queries

File and Record Organizations

- DB applications typically need small portion of database
  - when specific data needed:
    - located on disk
    - copied into main memory
    - rewritten into disk if data changed
- data stored on disk is organized as file of records
  - File is a sequence of records
    - Records mapped to disk blocks

Files of Records

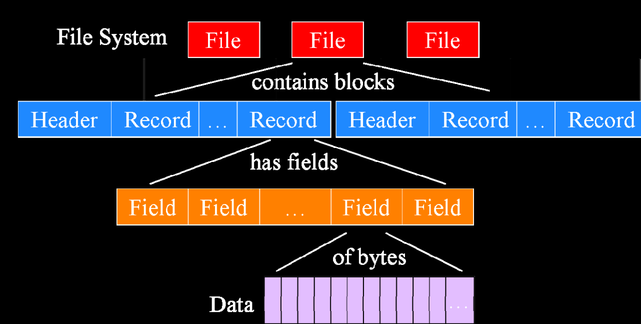
- Page or block is OK when doing I/O, but higher levels of DBMS operate on *records*, and *files of records*.
- FILE: A collection of pages, each containing a collection of records. Must support:
  - insert/delete/modify record
  - read a particular record (specified using *rid: record id*)
  - scan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

Mapping Relations to Files

- Most DBMS store each relation in separate file
  - records correspond to rows
  - record fields correspond to columns
  - joins require accessing multiple files

Recap: Representing Data in Databases

- A ***database*** is made up of one or more files.
  - Each ***file*** contains one or more blocks.
  - Each ***block*** has a header and contains one or more records.
  - Each ***record*** contains one or more fields.
  - Each ***field*** is a representation of a data item in a record.



File = Relation; Record = row/tuple; Field = column/attribute

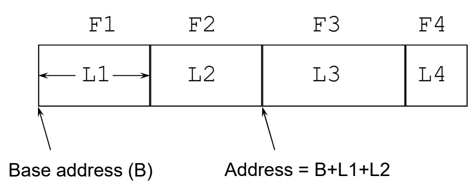
Organization of Records

- Record is collection of related information
  - Each tuple/row is a record
  - each value is one or more bytes, corresponds to a particular field of record
  - each field specifies some attribute
  - collection of field definitions and their types constitutes record type or format
    data type associated with each field
  - blocks are fixed size, but record sizes vary
- Two main types of records:
  - Variable length: size of record varies
  - Fixed length: all records have fixed length

Record Types

- Fixed length vs Variable length records
  - fixed is easier to implement
  - fixed wastes space when block size not multiple of record size
- spanned vs unspanned
  - when parts of a record can be placed onto a block, need pointers to next block where remainder of record is placed

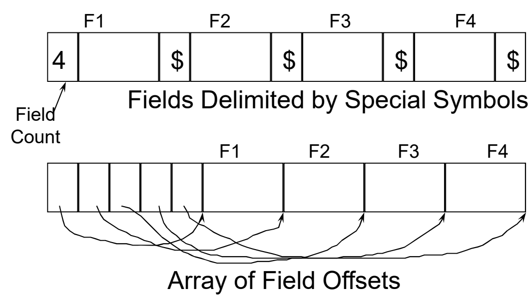
Record Formats: Fixed Length



- 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):



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

File Management

- Support search, scan, and insert/delete
- When records deleted or inserted, need to move records to occupy space or mark empty space
- maintain file header
  - point to next record that is deleted
  - first record point to next empty record etc.
  - can have dangling pointer problem on delete
    - pinned records: avoid moving or deleting records that are pointed to by other records

Link between file organization and DBMS efficiency ?

File Organizations

- File organization determines how records are physically placed on disk
  - heap file: no particular order
  - Sorted file
  - indexed file
    - hash index
    - tree indices
- Efficiency of file organization typically measured in terms of number of disk/SSD accesses to fetch data
  - Why ?

Evaluation of File Organizations

- Time always measured in # disk accesses
- Access time or lookup time
  - time to find particular data item
- Insertion time
  - time to insert new record
    - time to find correct location and time to insert
- Deletion time
- Modification time
- Space overhead
  - additional space occupied by index structure

Evaluation of File Organizations

- Relation of size *n* records – *n* rows/tuples
- disk block size *b* bytes – page size
- record size *r* bytes
  - average size
- "blocking factor" *p*, number of records/block
  - $p = b/r$
- *number of disk blocks to store relation*
  - $\lceil n/p \rceil$

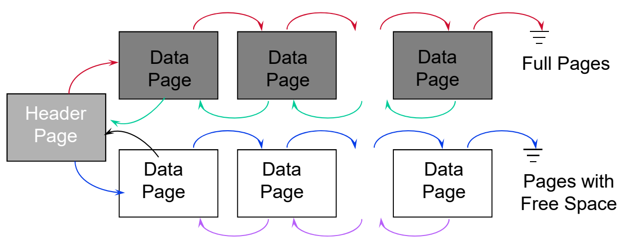
Example

- File of 1,000,000 records
- record size 200 bytes
- blocks are 4096 bytes
  - n = 1,000,000
  - r = 200
  - b = 4096
  - Blocking factor, $p = b/r$ = 4096/200 = 20
  - file size = $N = n/p$ = 1,000,000/20 = 50,000 blocks

Evaluation of File Organizations

- Baseline we use Heap File
  - The do nothing approach!
- Derive performance for each type of file organization
  - note that query type plays a large role in determining efficiency

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.

Evaluation of Heap Files

- Lookup time: on average retrieve ½(n/p) I/Os
  - worst case = $n/p = N$
- insertion time: retrieve last record on heap, if no empty space then start new block
  - 2 disk I/O
- deletion: find record and then delete
  - ½(n/p)+1 average, n/p+1 worst case
- modification: same as deletion

Example

- File of 1,000,000 records
- record size 200 bytes
- blocks are 4096 bytes
  - n = 1,000,000
  - r = 200
  - b = 4096
  - Blocking factor, $p = b/r$ = 4096/200 = 20
  - file size = $N = n/p$ = 1,000,000/20 = 50,000 blocks

Heap File Example

- Successful lookup ?
- Insertion time ?
- Deletion time ?
- Modification ?

Heap File: Example

- Successful lookup: average ½(n/p)= 25,000
  - worst case is n/p= 50,000 disk accesses
  - At 10ms disk access time, this is 500 seconds ~ 8 minutes!
- insertion = 2
- deletion = ½(n/p)+1 = 25,001
  - worst case = 50,001
- header page of pointers can get large
- Heap file summary: not a smart solution!

Lesson 1: better organize the records on the file

- Heap file will not cut it!
- Need to organize physical records on the file in some “smart” manner
  - Sorted file
  - Hash file

But….

- Sorted File
  - Search time: Log (Number of disk blocks)
- What if you are searching by another field….
  - Sorted by Number, search by name

Lesson 2: do we really need to access the entire file to answer a query ?

- Many queries reference small portion records
  - system should be able to locate these without having to search all records
  - Without having to search through the physical file of records ?
- Concept of Indexing