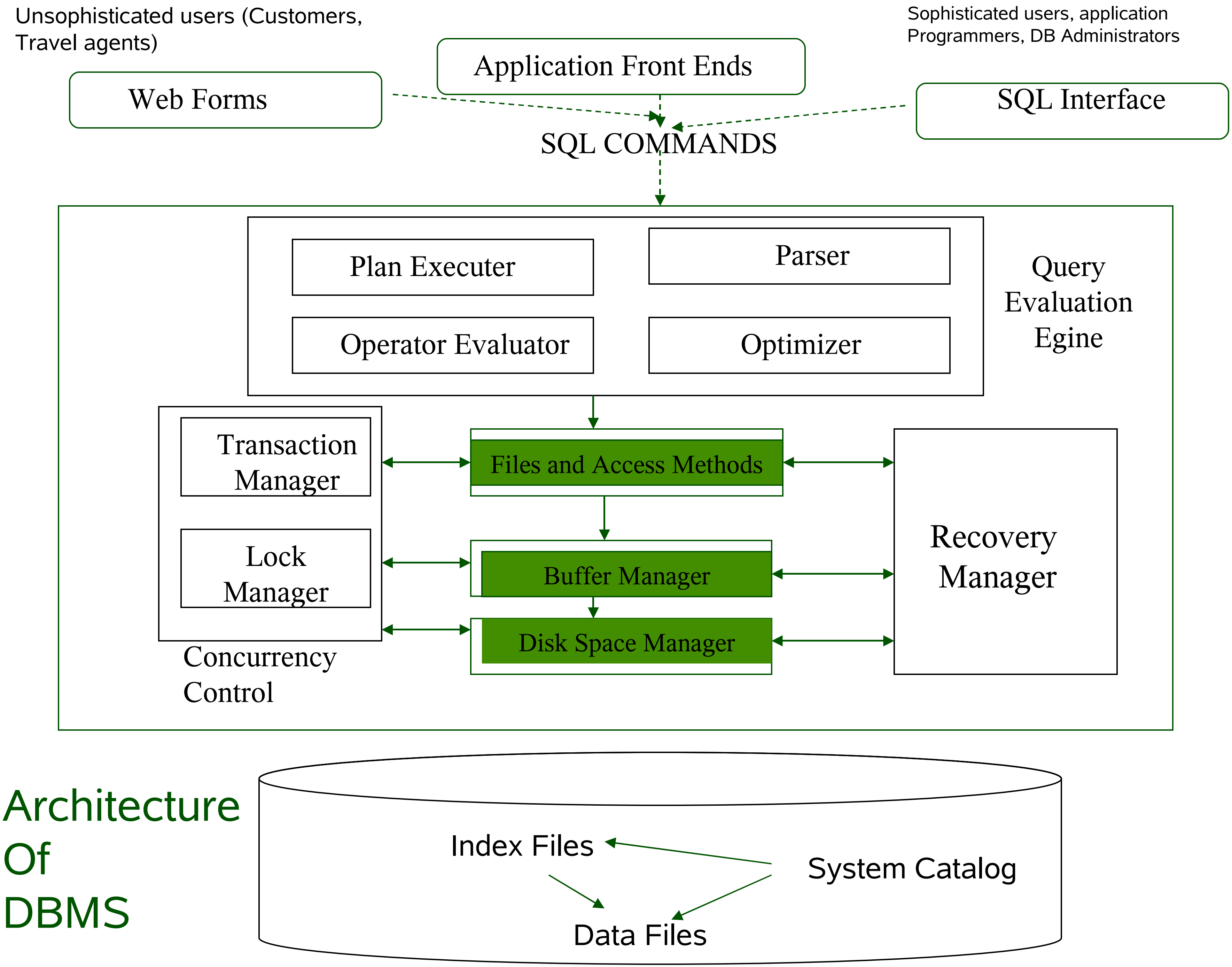
Storing Data: Disks and Files

Chapter 7



Architecture Of DBMS

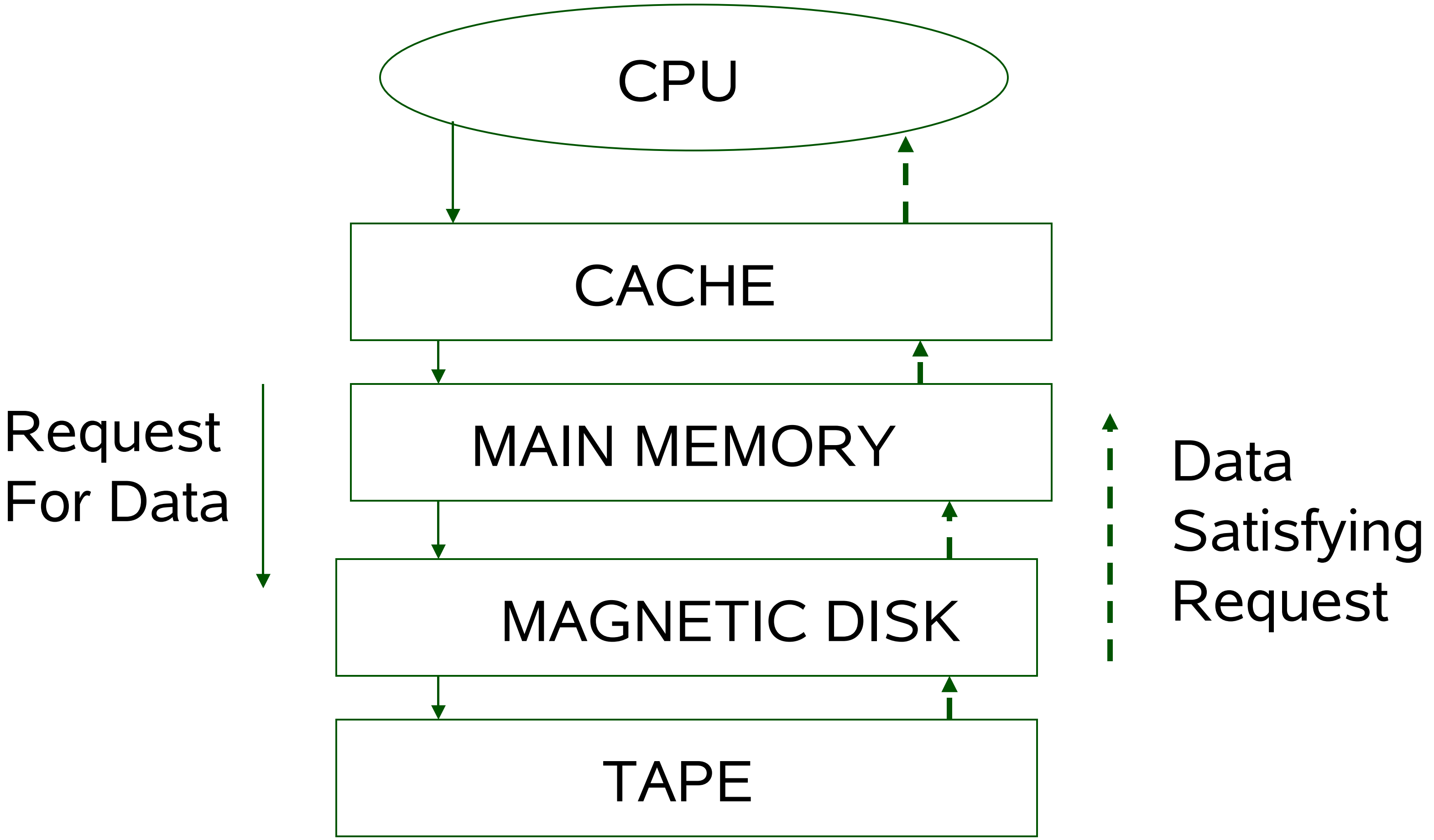
DBMS components covered

- We will cover
  - disc space manager
  - the buffer manager
  - Implementation oriented aspects of the files and access methods layer

Outline

- The memory hierarchy
- RAID
- Disk space management
- Buffer Manager
- Files of records
- Page formats
- Record formats

The Memory Hierarchy



The Memory Hierarchy

- Primary Storage
  - Cache and main memory
  - Provides fast access to data
- Secondary storage
  - Disk
- Tertiary storage
  - Slow
  - Tapes and optical disks
- Cost of main memory is 100 times of main memory
- Tapes play a major role as data size is huge.
- We have to build Database systems to retrieve data from lower levels of memory hierarchy into main memory.

Disks and Files

- DBMS stores information on (“hard”) disks.
- This has major implications for DBMS design!
  - READ: transfer data from disk to main memory (RAM).
  - WRITE: transfer data from RAM to disk.
  - Both are high-cost operations, relative to in-memory operations, so must be planned carefully!

Why Not Store Everything in Main Memory?

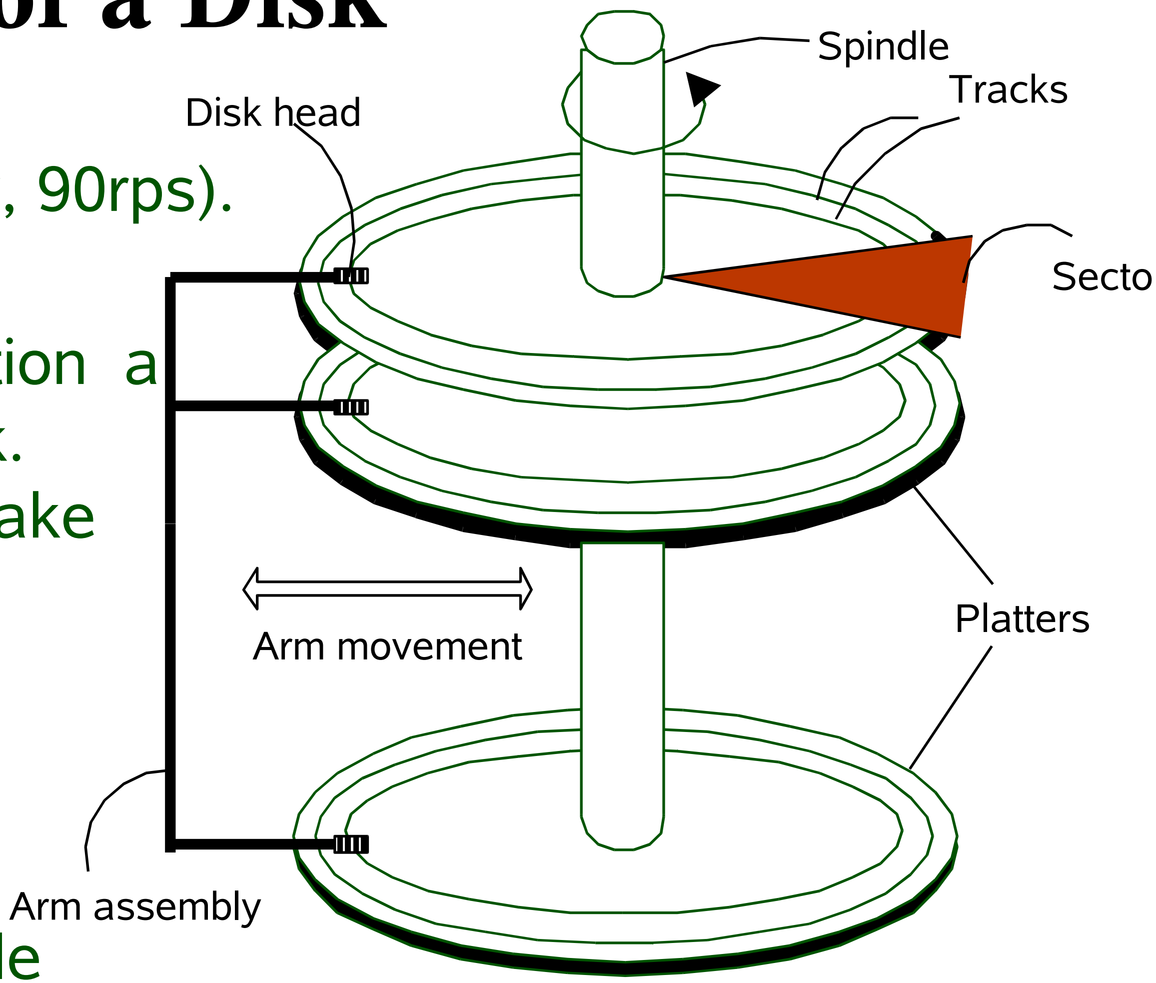
- *Costs too much.* $1000 will buy you either 128MB of RAM or 7.5GB of disk today.
- *Main memory is volatile.* We want data to be saved between runs. (Obviously!)
- Typical storage hierarchy:
  - Main memory (RAM) for currently used data.
  - Disk for the main database (secondary storage).
  - Tapes for archiving older versions of the data (tertiary storage).

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!

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).



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 1msec 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!

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RAID

- 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.

RAID Levels

- Level 0: No redundancy
- Level 1: Mirrored (two identical copies)
  - Each disk has a mirror image (check disk)
  - Parallel reads, a write involves two disks.
  - Maximum transfer rate = transfer rate of one disk
- Level 0+1: Striping and Mirroring
  - Parallel reads, a write involves two disks.
  - Maximum transfer rate = aggregate bandwidth

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.
- 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
- Level 5: Block-Interleaved Distributed Parity
  - Similar to RAID Level 4, but parity blocks are distributed over all disks

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Disk Space Management

- Lowest layer of DBMS software manages space on disk.
- Supports the concept of a page as a unit of data.
- Higher-levels issue commnads
  - 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.
- The disk space manager hides details of the underlying hardware.
- Higher levels of the software think of the data as a collection of pages.

Keeping the track of Free Blocks

- Although blocks are allocated sequentially on disk, allocations and de-allocations could in general create `holes'
- Methods
  - Linked-list approach: Keep the list of free blocks and occupied blocks.
  - Maintain a bit-map with one bit for each disk block.
    - Bit-map method allows very fast identification and allocation of contiguous areas on disk.

Using OS File Systems to Manage Disk Space

- OS
  - supports the abstraction of a file as a sequence of bytes.
  - Manages space on disk and translates requests, such as “Read byte ***i*** of file ***f***, into corresponding low level instructions: “Read block ***m*** of track ***t*** of cylinder ***c*** of disk ***d***”.
- DB disk manager can be build using OS files
  - Entire DB can be managed with one or more OD files.
  - The disk space manager is responsible for managing the space in these OS files.
- Many DB systems do not rely on the OS file system
  - They have separate disk management
  - Reason: DBMS can not be specific to any OS file system
  - DBMS may want to access bigger files than the file sizes OS supports
  - OS file may not span more than one disk, but in DBMS it is necessary.

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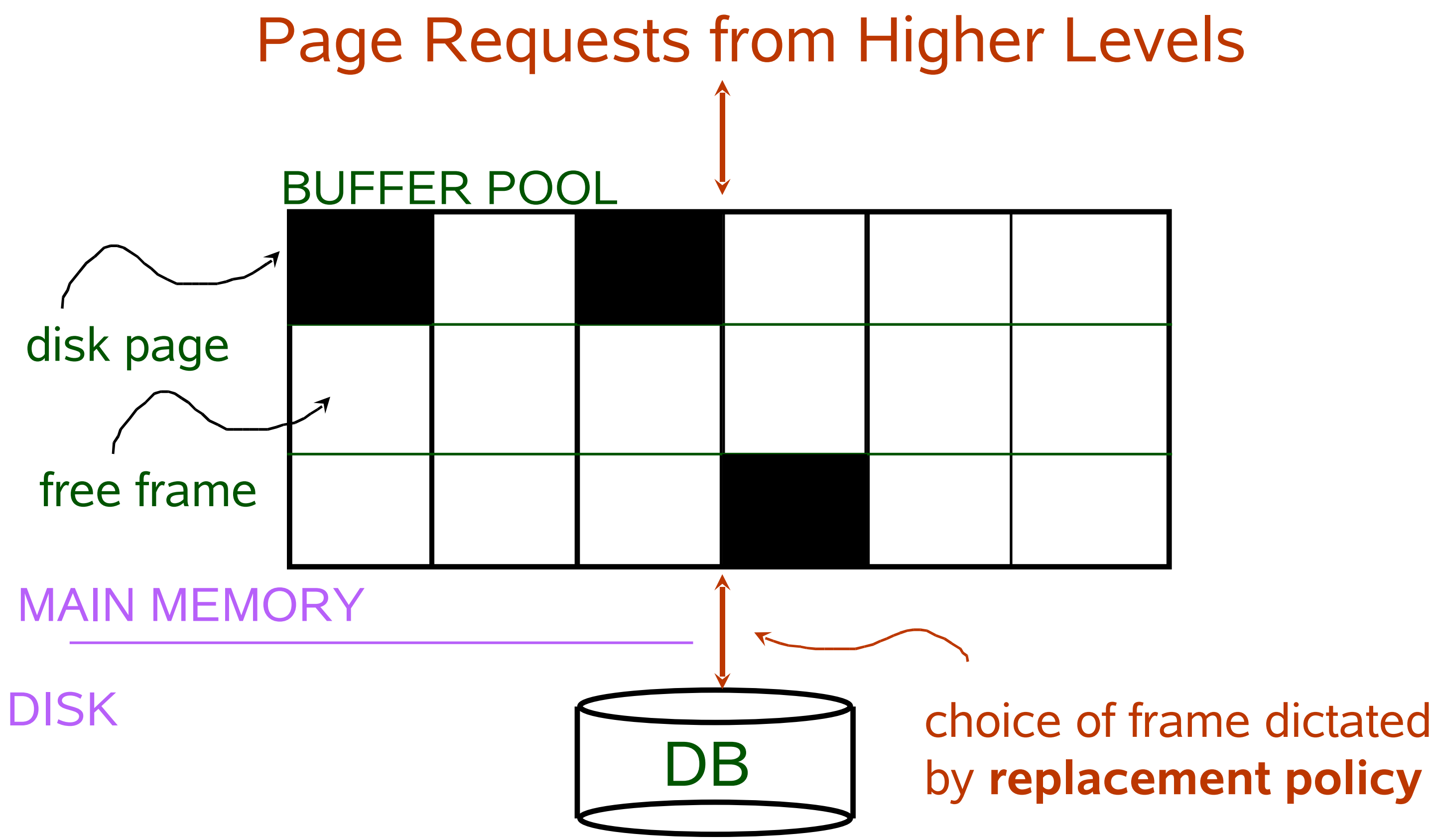
Buffer Manager

- Example:
  - DB contains 1 million pages
  - 100 pages can be held in main memory
  - Query: scan 1 million pages.
- Since all the data can not be brought to main memory, DBMS
  - brings pages to main memory when they are needed.
  - Decide existing page to replace when there is no space
- Buffer manager is a software layer responsible to bring the pages to main memory.
- Higher-level code can be written whether data pages are in memory or not.

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.)

Buffer Replacement Policy

- Frame is chosen for replacement by a *replacement policy:*
  - Least-recently-used (LRU), Clock, MRU etc.
- 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. MRU much better in this situation (but not in all situations, of course).

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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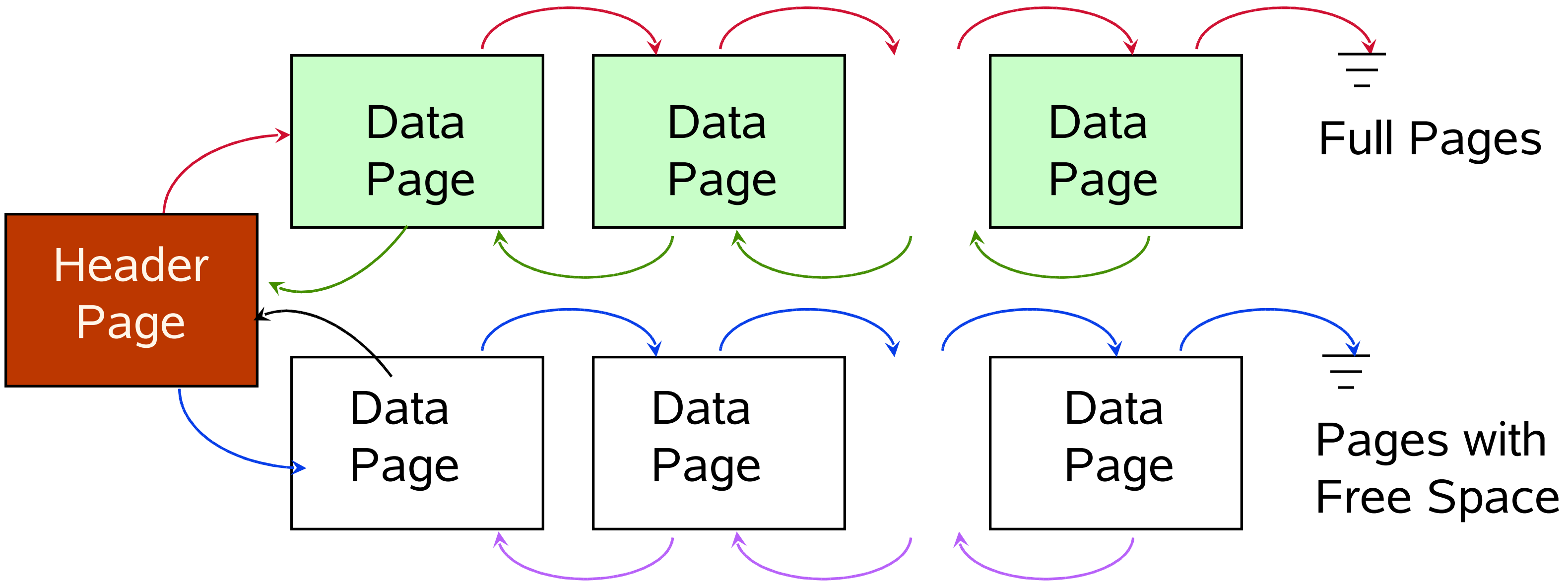
Files of Records

- 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)

Unordered (Heap) Files

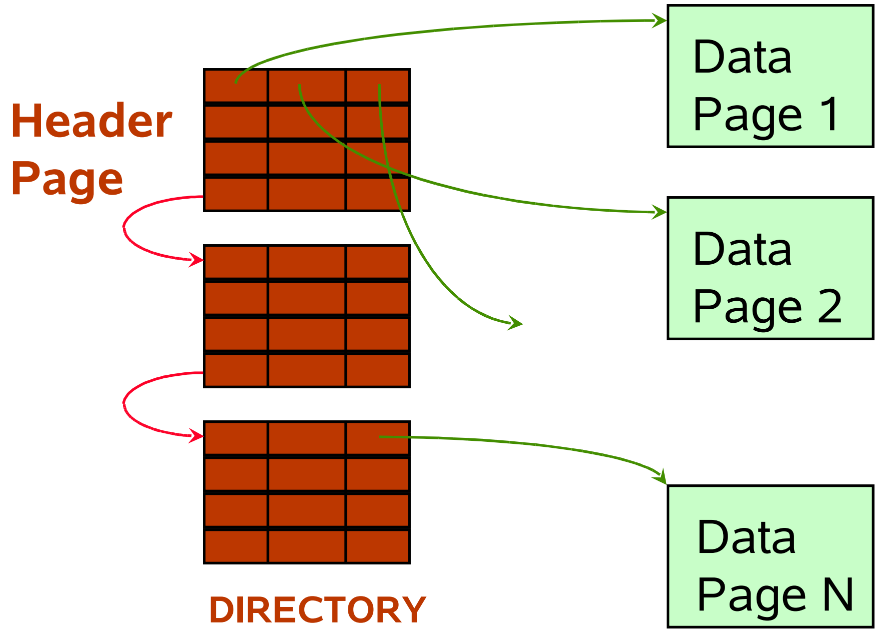
- Simplest file structure contains records in no particular order.
- As file grows and shrinks, disk pages are allocated and de-allocated.
- To support record level operations, we must:
  - keep track of the *pages* in a file
  - keep track of *free space* on pages
  - keep track of the *records* on 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.
- Disadvantage:
  - All pages in a file is in free list if records are of variable length.

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!*

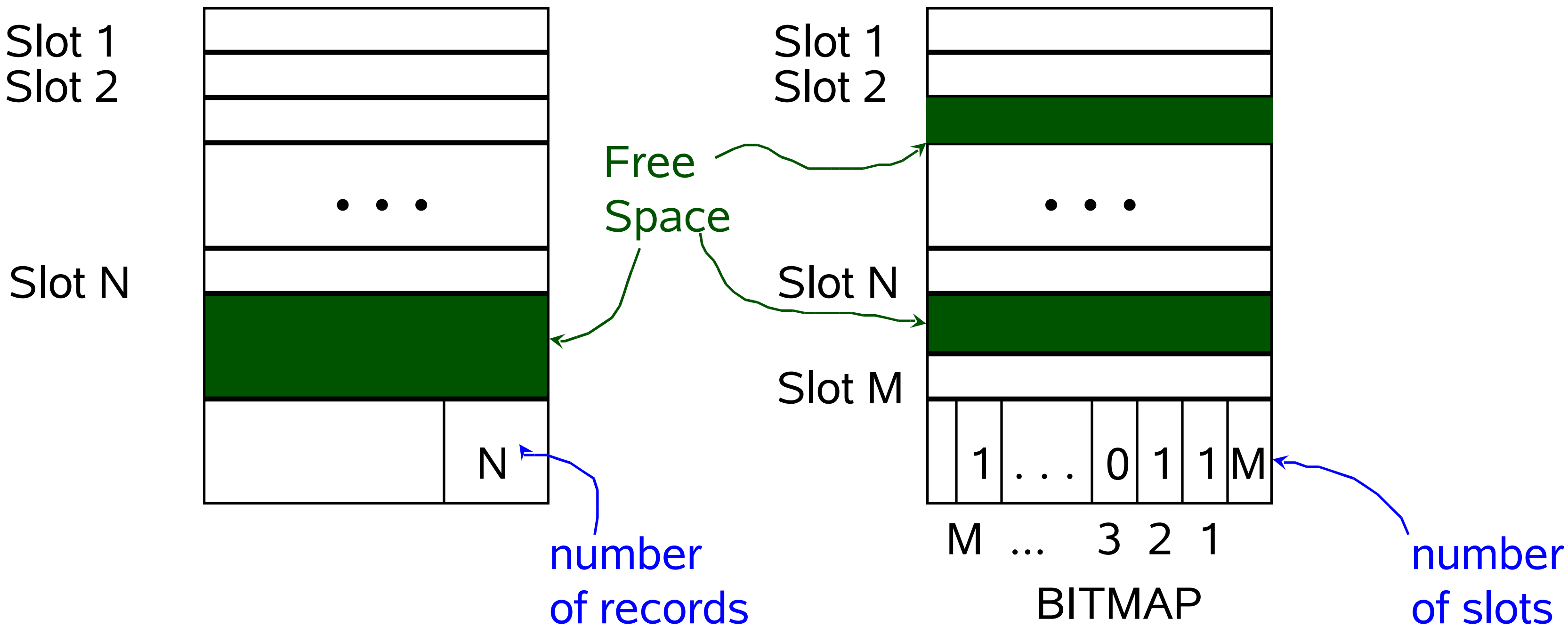
Page Formats

- Page abstraction is appropriate when dealing with I/O issues.
- Higher levels of DBMS see data as a collection of records.
- A page is a collection of slots, where each slot contains a record.
- It can be identified with <page-id, slot-id>, which is a record id.

Fixed length records

- If the records of a page are guaranteed to be of the same length, records can be arranged consecutively within the page.
- At any time, some slots are occupied and others are unoccupied.
- When a record is inserted, we must locate empty slot and place the record.
- Issue: How to keep track of empty slots and how to locate all records on the page ?
- Alternative 1: Store records in the first N slots, when the record is deleted, move the last record in the page to the vacated slot.
  - It will not work, if there is external reference.
- Alternative 2: Handle deletions using array of bits, one per slot, to keep track of free slot information.

Page Formats: Fixed Length Records

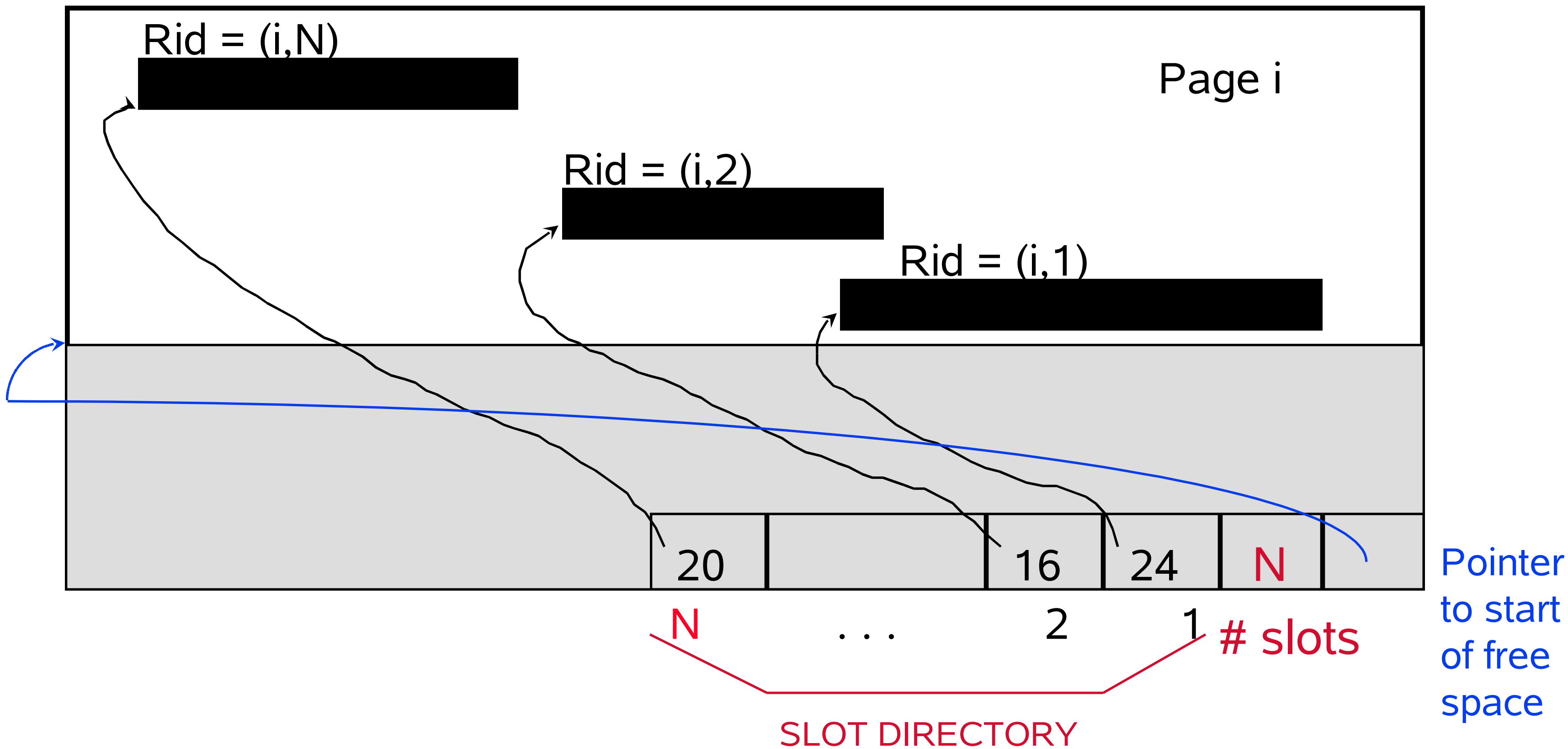


- *Record id = <page id, slot #>. In first alternative, moving records for free space management changes rid; may not be acceptable.*

Variable-length records

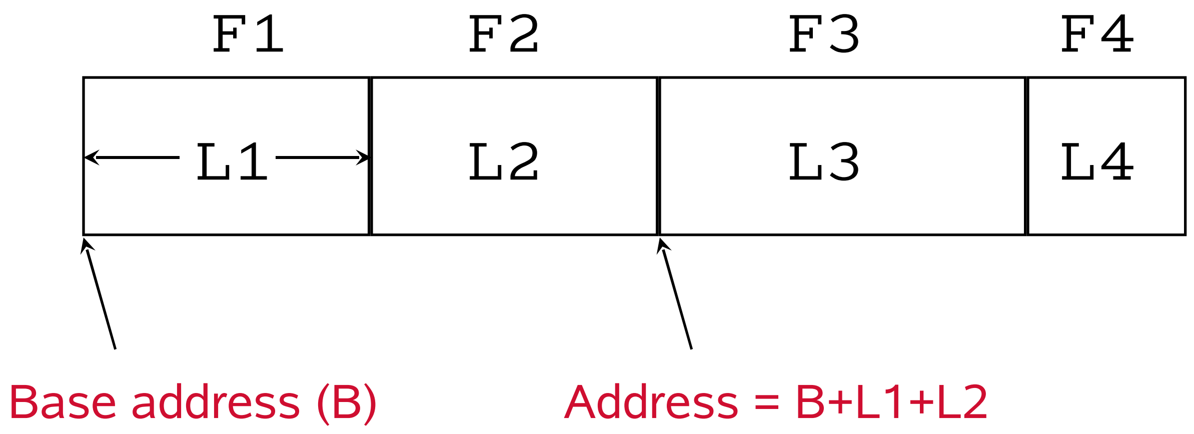
- If records are of variable length, we can not divide the page into a fixed collection of records.
  - Problem: finding the empty slot of right length
    - If he slot is too big, it waste space!
- Solution: Maintain a directory of slots
  - Record offset and record length for each record.
  - Record offset is the pointer to the record
- The free space available should be managed carefully, as the page is not preformatted into slots.

Page Formats: Variable Length Records



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

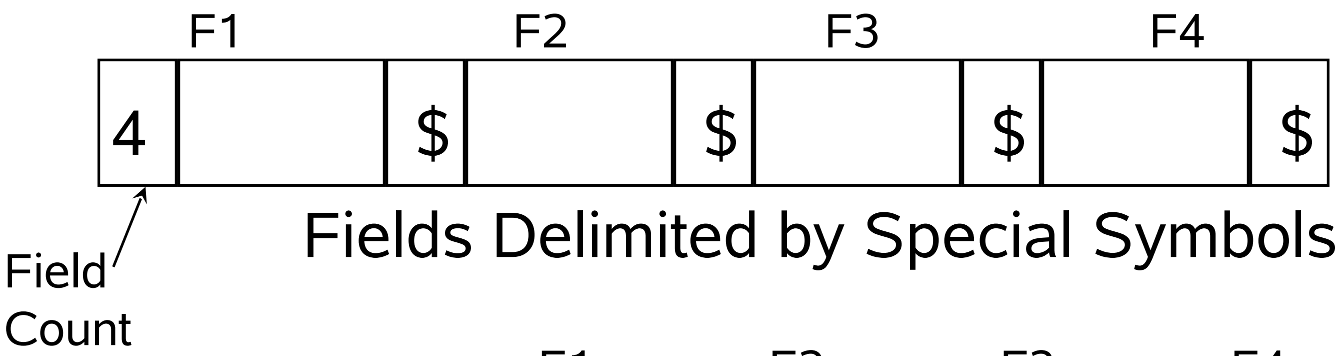
Record Formats: Fixed Length



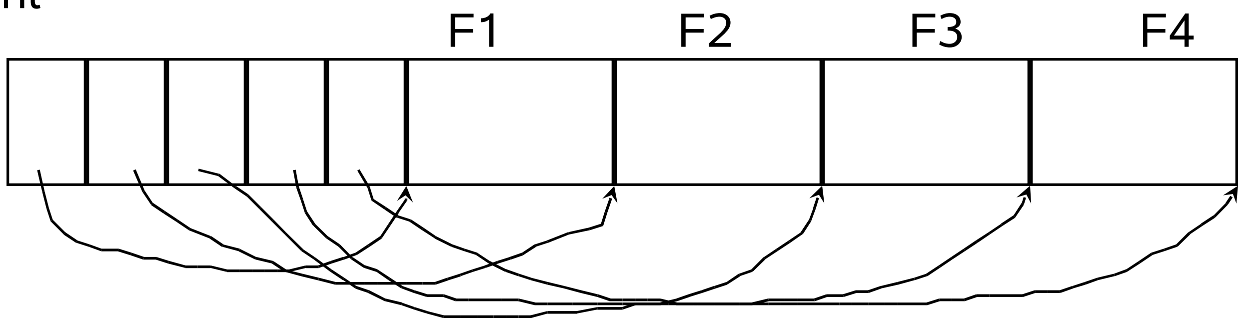
- Information about field types same for all records in a file; stored in *system catalogs.*
- Finding *i'th* field requires scan of record.

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.

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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.
  - Random access, but cost depends on location of page on disk; important to arrange data sequentially to minimize *seek* and *rotation* delays.
- Buffer manager brings pages into RAM.
  - Page stays in RAM until released by requestor.
  - Written to disk when frame chosen for replacement (which is sometime after requestor releases the page).
  - Choice of frame to replace based on *replacement policy*.
  - Tries to *pre-fetch* several pages at a time.

Summary (Contd.)

- DBMS vs. OS File Support
  - DBMS needs features not found in many OS's, e.g., forcing a page to disk, controlling the order of page writes to disk, files spanning disks, ability to control pre-fetching and page replacement policy based on predictable access patterns, etc.
- Variable length record format with field offset directory offers support for direct access to i'th field and null values.
- Slotted page format supports variable length records and allows records to move on page.

Summary (Contd.)

- File layer keeps track of pages in a file, and supports abstraction of a collection of records.
  - Pages with free space identified using linked list or directory structure (similar to how pages in file are kept track of).
- Indexes support efficient retrieval of records based on the values in some fields.
- Catalog relations store information about relations, indexes and views. (*Information that is common to all records in a given collection.*)