Storing and Buffering Data

Problem Set #2 is due before midnight tonight.
Problem Set #3 is online and due on 10/10.

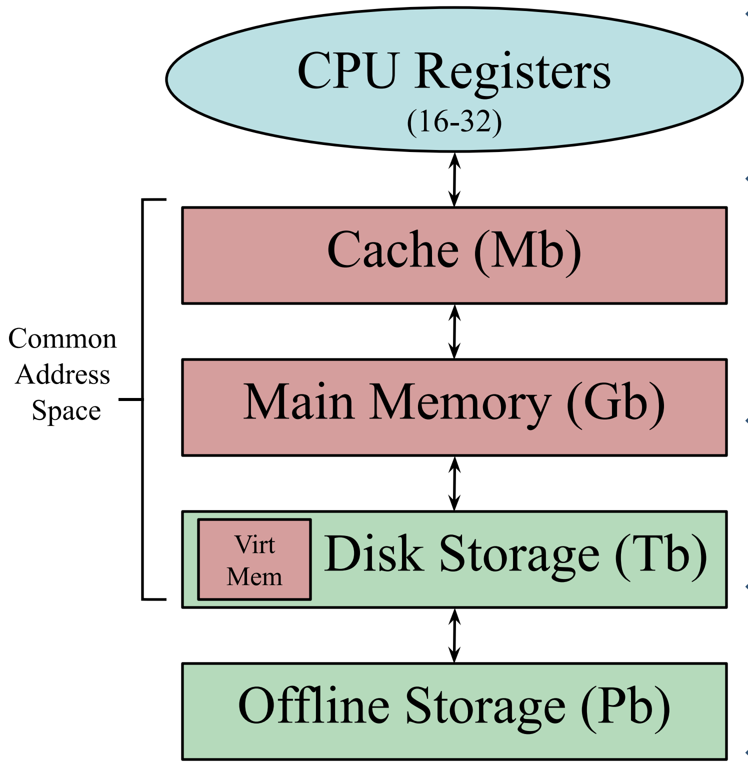
Disks and Files

- A DBMS stores information in non-volatile storage.
  - Magnetic Disks
  - Solid State Disks
  - Tapes
- This has major implications for DBMS design!
  - READ: transfers from disk to main memory (RAM).
  - WRITE: transfer from disk to RAM,
    change it, and then RAM to disk.
  - Disk transfers are costly (slow) operations, relative to in-memory operations, so they must be planned and managed carefully!

Why Not Store Everything in Memory?

- *Costs too much.* $100 will buy you either 32GB of RAM or 4TB of disk today (125x).
- *Main memory is volatile.* We want data to be saved between runs. (Obviously!)
- Data Size > Memory Size > *Address Space*
- Typical storage hierarchy:
  - CPU Registers – temporary variables
  - Cache – Fast copies of frequently accessed memory locations (Cache and memory should indistinguishable)
  - Main memory (RAM) for currently used “addressable” data.
  - Disk for the main “big data” (secondary storage).

Storage Hierarchy



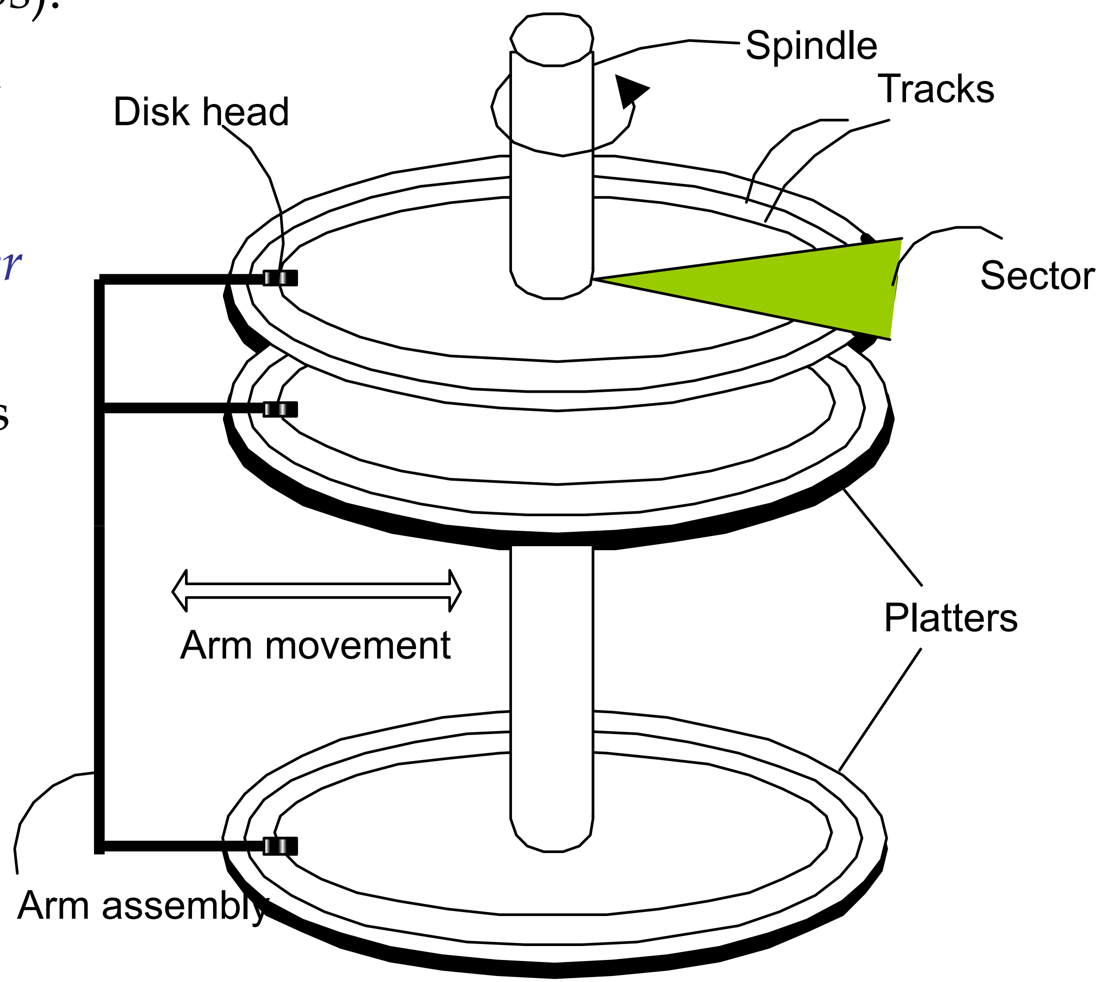
- CPU Registers – temporary program variables
- Cache – Fast copies of frequently accessed memory locations (Cache and memory are indistinguishable)
- Main memory (RAM) for currently "addressable" data.
- Disk for files and databases (*secondary* storage).
- Tapes for archiving older versions of the 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 can vary depending upon its location on disk.
  - Therefore, relative placement of pages on disk has major impact on DBMS performance!

Components of a Magnetic Disk

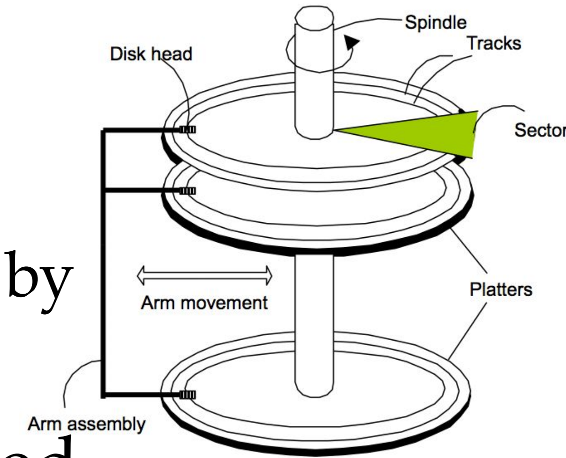
- The platters spin (say, 120rps).
- The arm assembly is moved in or out to position a head on a desired track. Tracks under heads make a *cylinder* (imaginary!).
- Only one head reads/writes at any one time.
- In the old days *blocks* corresponded to an angular region of the disk called a *sector*. These days there are more blocks along the outer tracks than the inner ones.



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 2 to 15mS
  - Rotational delay from 0 to 8.3mS (ave 4.2mS)
  - Transfer rate is about 3.5mS per 256KB page (75 MB/sec)
- Key to lower I/O cost: reduce seek/rotation delays! Hardware vs. software solutions?

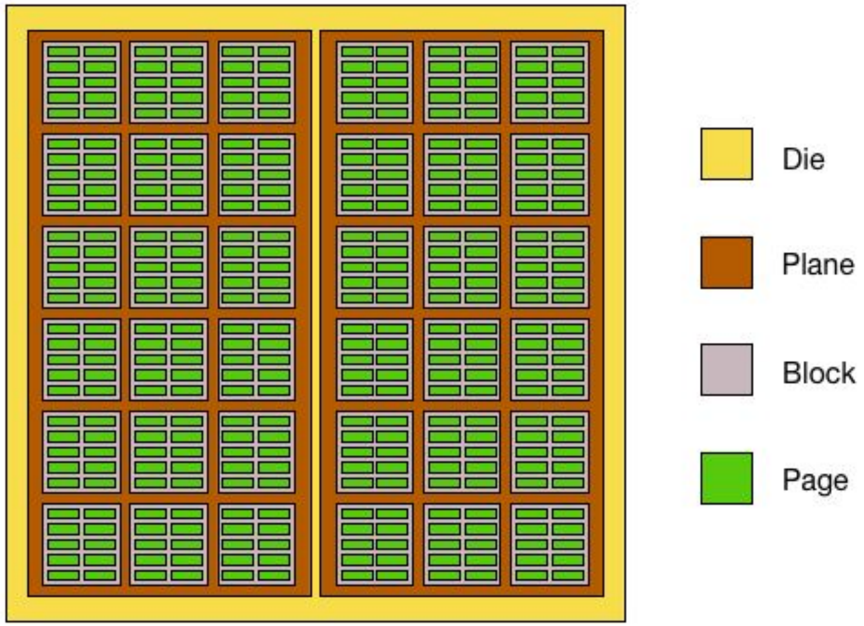
Arranging Pages on Disk



- *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 to minimize seek and rotational delays.
- For a sequential scan, *pre-fetching* several pages at a time is a big win!

Solid State Disk Drives

- A single transistor per 1-3 bits stored
- Data is read and written a page at a time, and erased a block at a time
- Typical block sizes:
  - 128 pages of 4,096+128 bytes each for a block size of 512 kB
- Timing:
  - Seek time: 0.08 to 0.16 mS
  - Rotational Delay: 0 mS
  - Transfer time: 0.5mS per 256Kb page (500 MB/S)
- ~$100 for 500 MB (8x more than a magnetic drive)

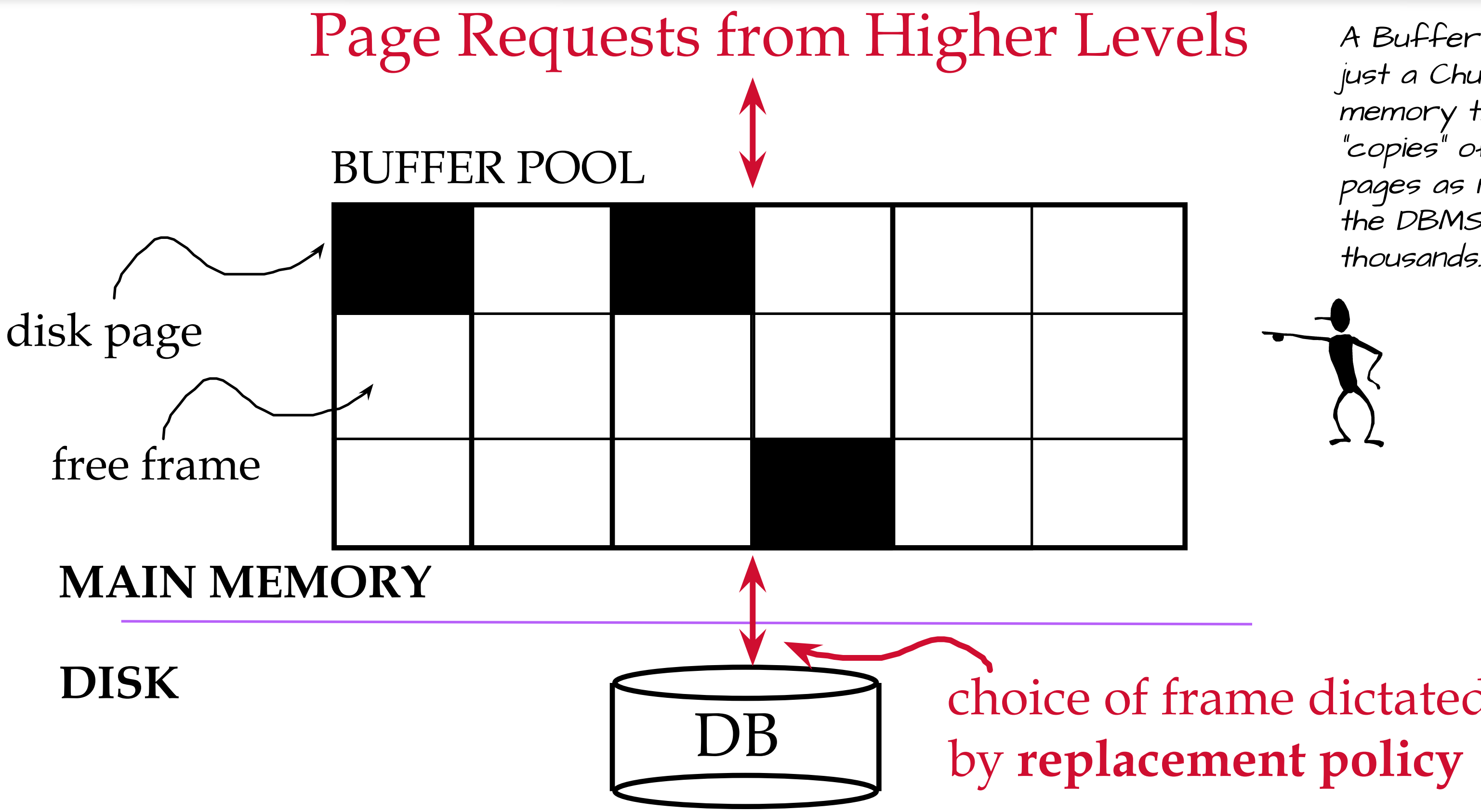


Operation	Area
Read	Page
Program (Write)	Page
Erase	**Block**

Disk Space Management

- Lowest layer of DBMS manages how space is used on disk. Abstraction unit is a "*page*"
- 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.
- O/S Disk management vs. DBMS

Buffer Management in a DBMS



A Buffer Pool is just a Chunk of memory that holds "copies" of disk pages as needed by the DBMS. Usually thousands.

- *Data must be in RAM for DBMS to operate on it!*
- *Table of <frame#, pageid> pairs is maintained. (i.e. which disk page is in which buffer pool frame)*

When a Page is Requested ...

- If requested page is not in pool:
  - Choose a frame for *replacement*
  - If frame is *dirty* (*its contents have been modified*), 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

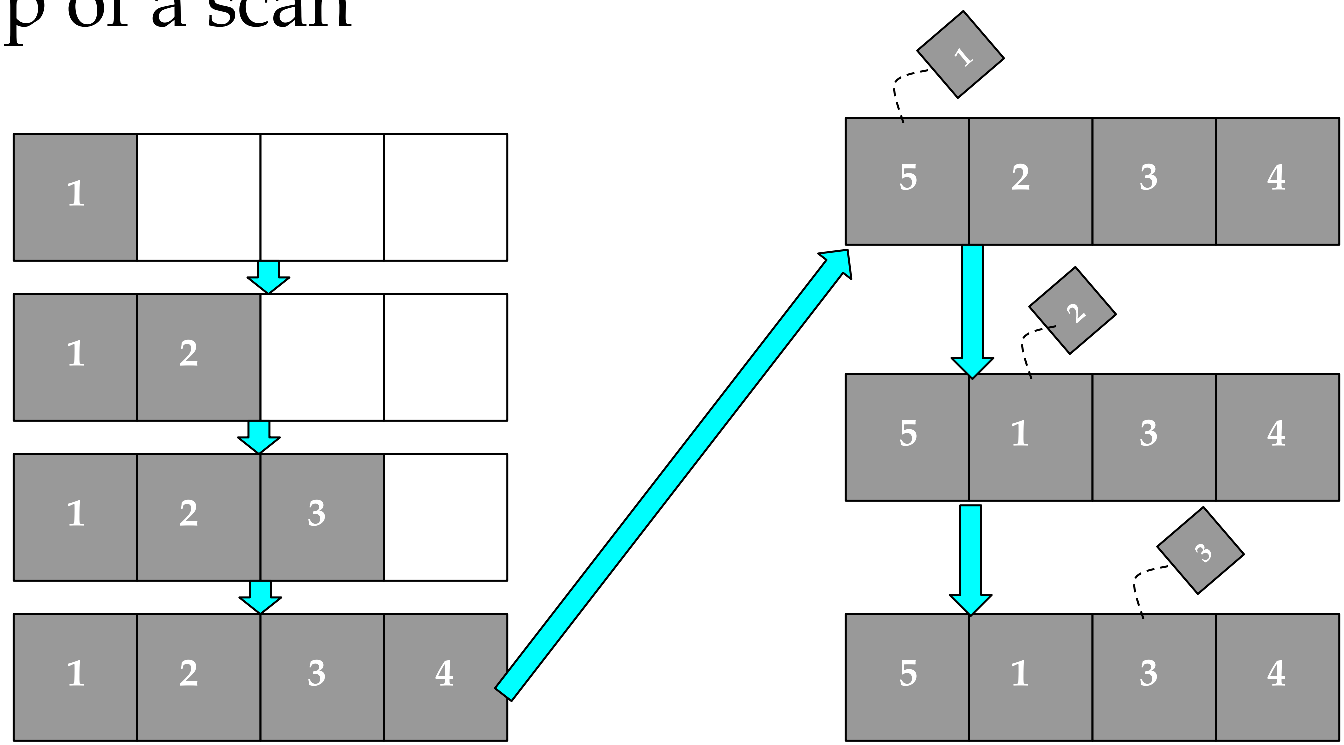
- Requestor of page must *unpin* a frame when it is done, and indicate whether page has been modified:
  - *dirty* bit is used for this.
- Some pages in the pool are be requested many times,
  - Thus, a *pin count* is used. A page is a candidate for replacement iff *pin count* = 0.
- Crash recovery protocols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

Buffer Replacement Policy

- Frame is chosen for replacement by a *replacement policy:*
  - Non-dirty, Least-recently-used LRU, FIFO, Clock, MRU etc.
- Policy can have big impact on # of I/O's; depends on the *access pattern*.
- *Sequential flooding*: Nasty collision 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).

Sequential Flooding

Imagine N frames are allocated for a table that occupies N+1 pages, and is accessed in an inner loop of a scan



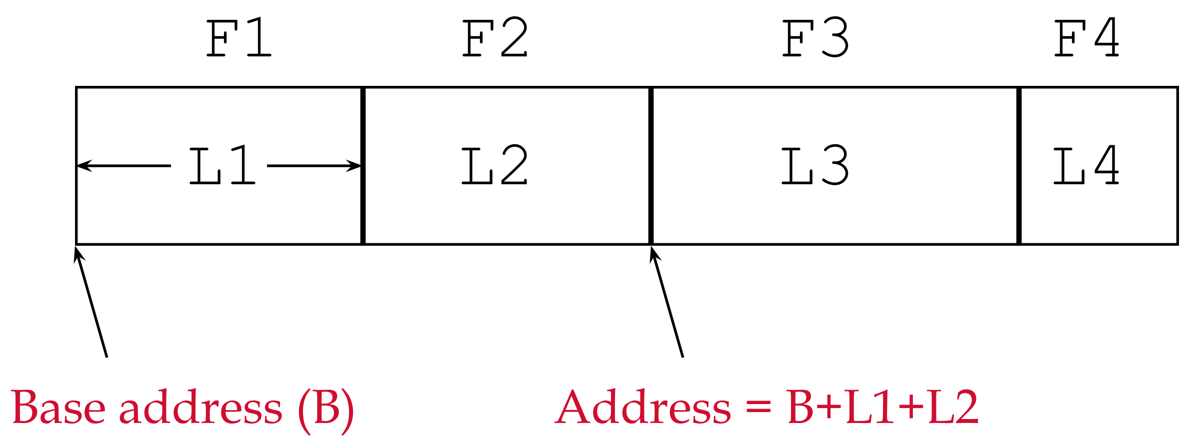
DBMS vs. OS File System

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

- Differences in OS support: portability issues
- Some limitations, e.g., files don'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.

Record Formats: Fixed Length

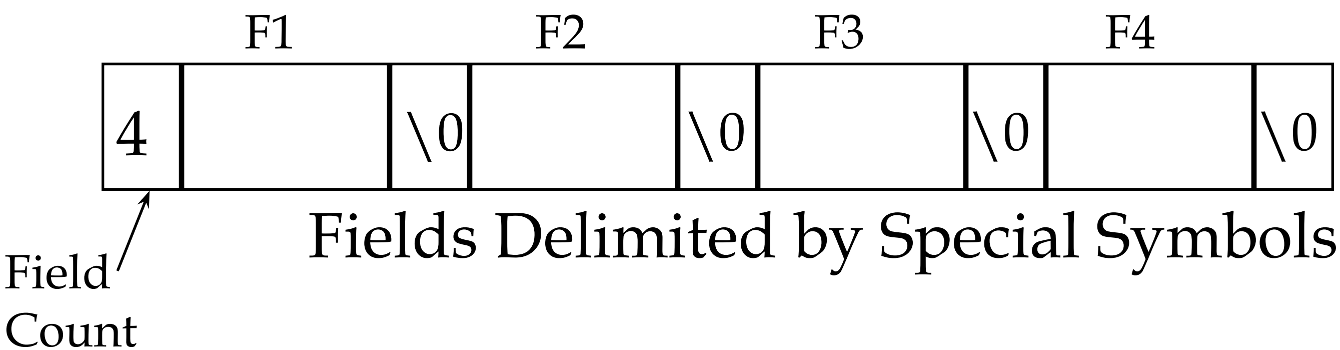
How is data laid out within a block?



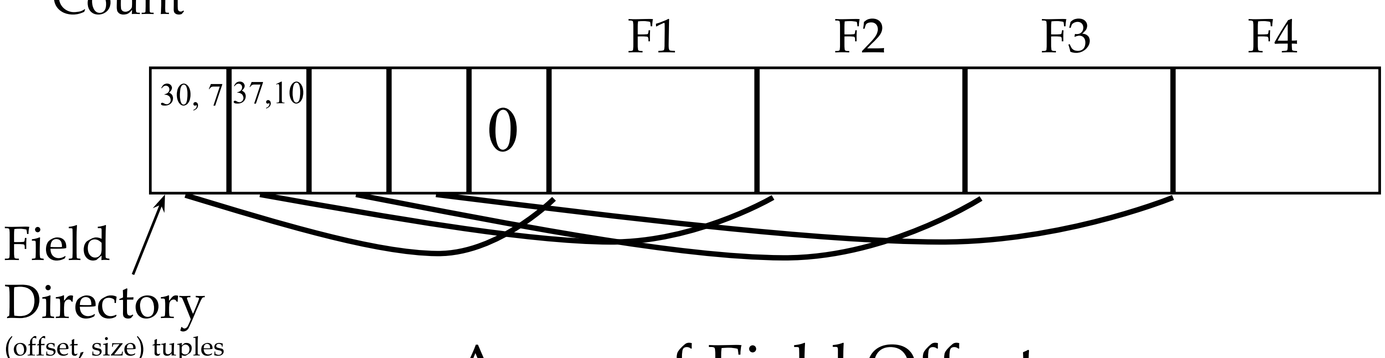
- Information about field types same for all records in a relation; stored in *system catalogs.*
- Finding *i'th* field does not require scan of record.

Record Formats: Variable Length

- Two alternative formats (# fields is fixed):



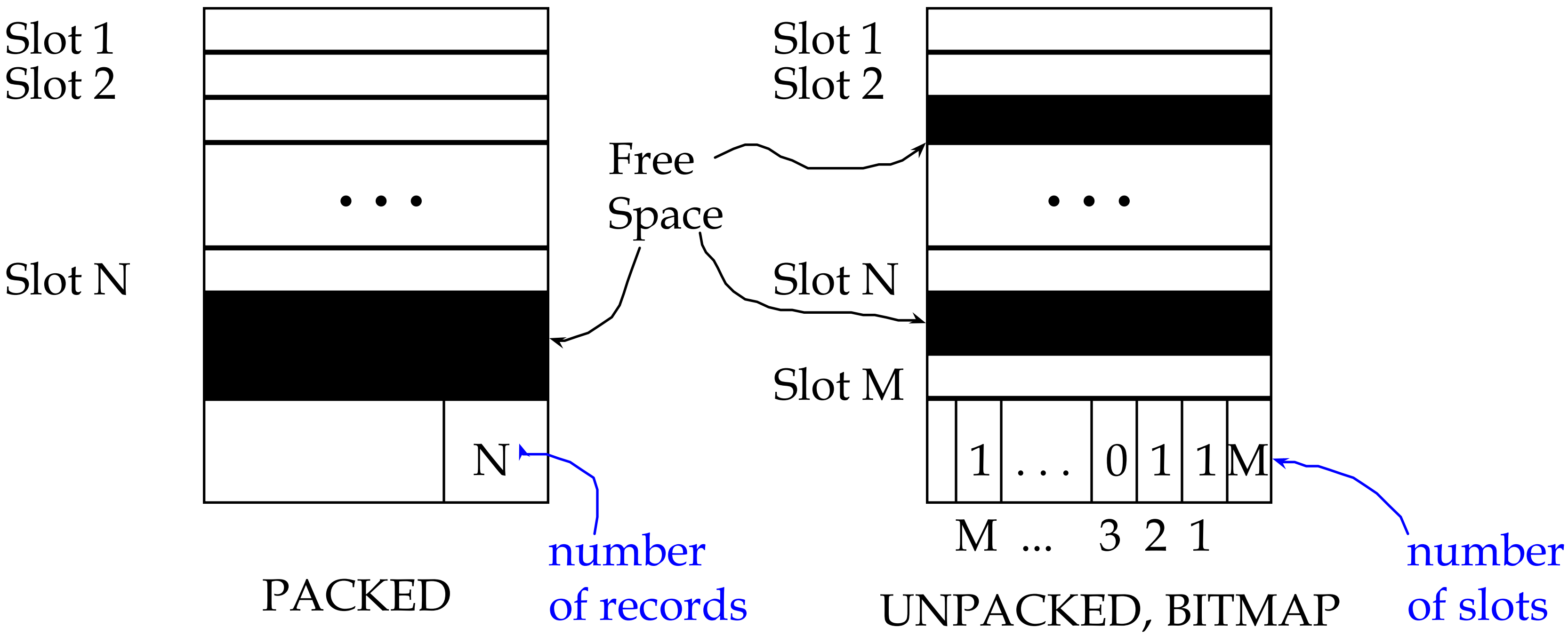
Fields Delimited by Special Symbols



Array of Field Offsets

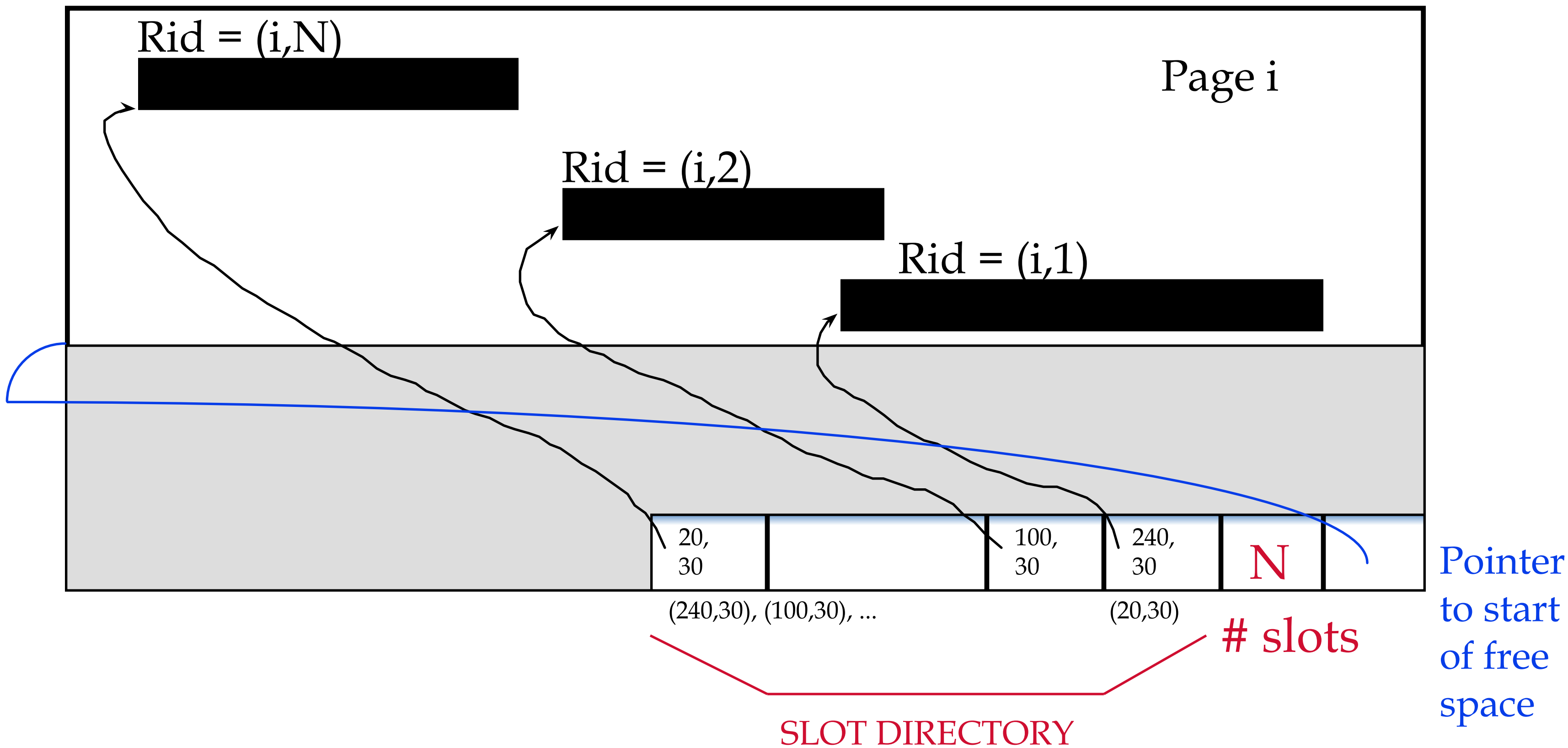
- Second offers direct access to i'th field, efficient storage of *nulls* (special *don't know* value); small directory overhead.

Page Formats: Fixed Length Records



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

Page Formats: Variable Length Records



- *With a field directory you can reorder records without moving them. (key when building indices)*
- *You can also track "free space"*

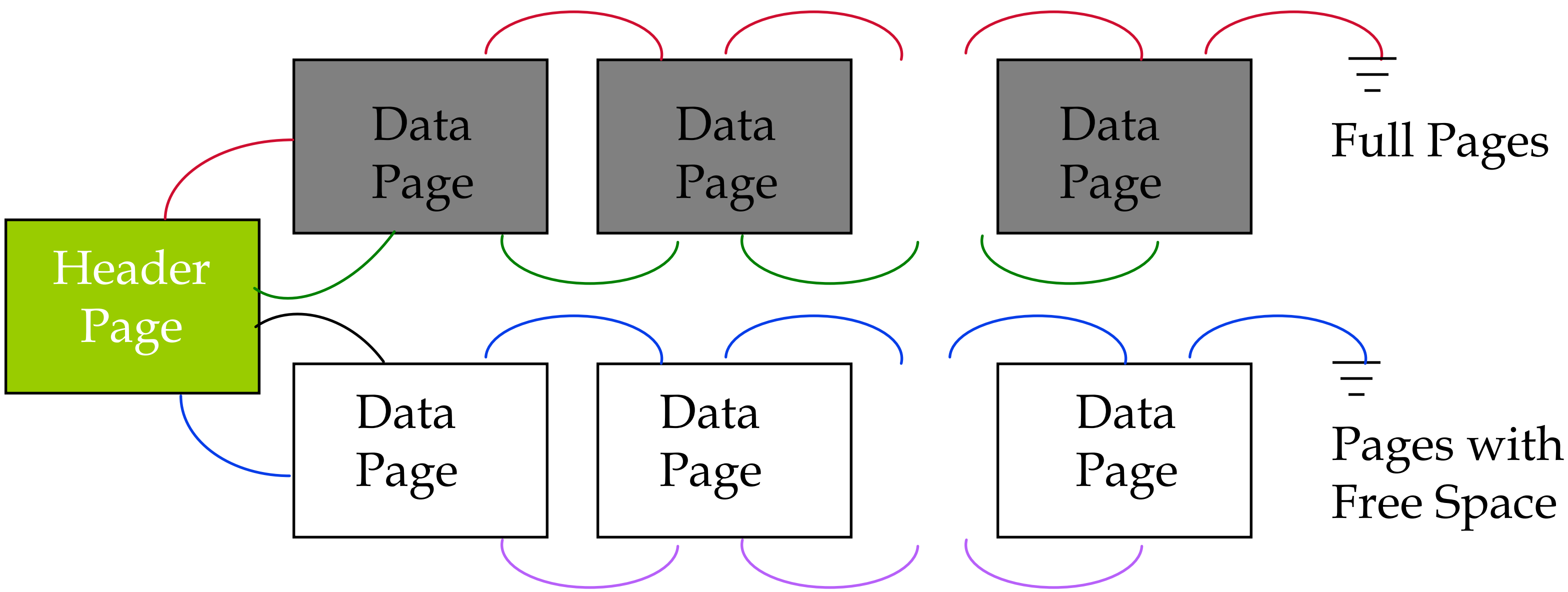
Files of Records

- 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

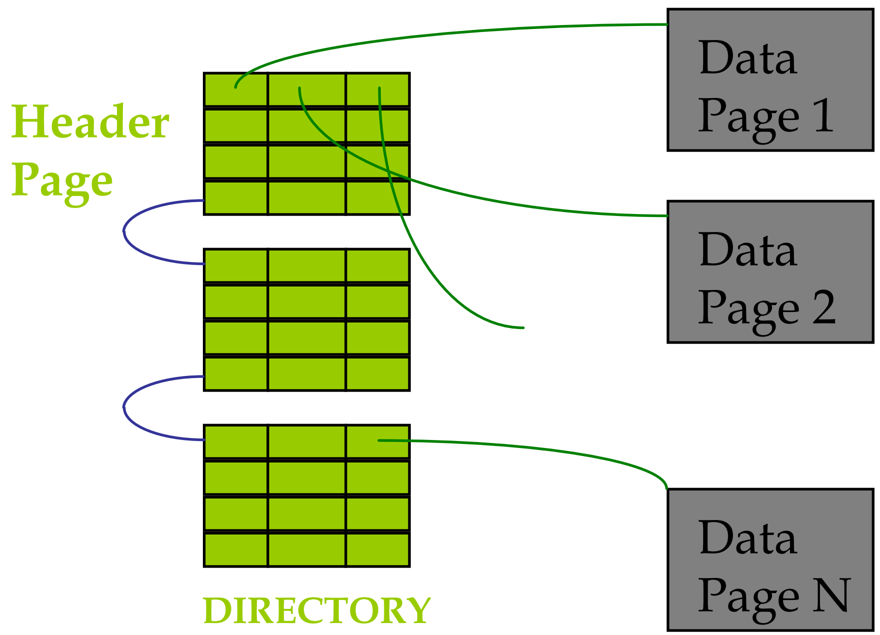
- Simplest file structure contains records in no particular order.
- As file grows and shrinks, disk pages are allocated and de-allocated.
- To support record level operations, we must:
  - keep track of the *pages* in a file
  - keep track of *free space* on pages
  - keep track of the *records* on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

Heap File Using a Page Directory



- The entry for a page might also include the number records and/or free bytes on the page.
- The directory is itself a collection of pages; linked list implementation is just one alternative.
  - *Typically smaller than linked list of all HF pages!*

System Catalogs

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

Sqlite_master

```
import sqlite3
db = sqlite3.connect("NFL.db")
cursor = db.cursor()
cursor.execute("SELECT * FROM sqlite_master")

for row in cursor:
    print([v for v in row])
```

Sqlite_master

['table', 'Team', 'Team', 2, "CREATE TABLE Team(\n   tid INTEGER PRIMARY KEY,\n   mascot TEXT DEFAULT ''\n)"]

['table', 'Player', 'Player', 3, 'CREATE TABLE Player(\n   pid INTEGER PRIMARY KEY,\n   name TEXT,\n   height TEXT,\n   weight INTEGER,\n   college TEXT,\n   dob DATE\n)']

['table', 'PlayedFor', 'PlayedFor', 4, 'CREATE TABLE PlayedFor(\n   pid INTEGER,\n   tid INTEGER,\n   year INTEGER,\n   position TEXT,\n   jersey TEXT,\n   games INTEGER,\n   starts INTEGER,\n   FOREIGN KEY(tid) REFERENCES Team(tid),\n   FOREIGN KEY(pid) REFERENCES Player(pid),\n   UNIQUE(pid,tid,year)\n)']

['index', 'sqlite_autoindex_PlayedFor_1', 'PlayedFor', 5, None]

['table', 'TeamLocation', 'TeamLocation', 6, "CREATE TABLE TeamLocation(\n   tid INTEGER,\n   year INTEGER,\n   place TEXT DEFAULT '',\n   headcoach TEXT DEFAULT '',\n   FOREIGN KEY(tid) REFERENCES Team(tid),\n   UNIQUE(tid,year)\n)"]

['index', 'sqlite_autoindex_TeamLocation_1', 'TeamLocation', 7, None]

['table', 'Draft', 'Draft', 8, 'CREATE TABLE Draft(\n   pid INTEGER PRIMARY KEY,\n   year INTEGER,\n   round INTEGER,\n   overall INTEGER,\n   tid INTEGER,\n   FOREIGN KEY(tid) REFERENCES Team(tid)\n)']

['table', 'Game', 'Game', 1452, 'CREATE TABLE Game(\n   season INTEGER,\n   week TEXT,\n   date DATE,\n   vtid INTEGER,\n   vscore INTEGER,\n   htid INTEGER,\n   hscore INTEGER,\n   notes TEXT,\n   FOREIGN KEY(vtid) REFERENCES Team(tid),\n   FOREIGN KEY(htid) REFERENCES Team(tid),\n   UNIQUE(season,week,htid)\n)']

['index', 'sqlite_autoindex_Game_1', 'Game', 1453, None]

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.*)