Database Systems

November 22/23, 2006

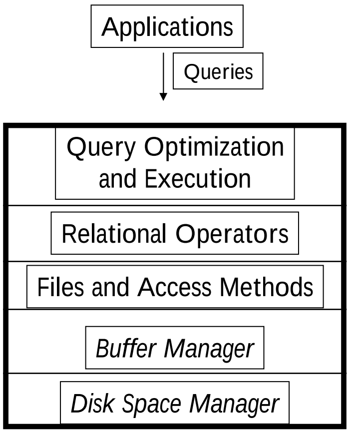
Lecture #7

Announcement

- Assignment #3 is due on Thur (12/7) outside TA's office in 336/338.
  - Do not accept late assignments.

Structure of DBMS

- Disk Space Manager
  - Manage space (pages) on disk.
- Buffer Manager
  - Manage traffic between disk and main memory. (bring in pages from disk to main memory).
- File and Access Methods
  - Organize records into pages and files.



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Storing Data: Disks and Files

Chapter 9

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Disks and Files

- DBMS stores information on ("hard") disks.
- This has major performance implications for DB system 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!

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Why Not Store Everything in Main Memory?

- *Costs too much.*
  - $100 for 1G of SDRAM
  - $100 for 250 GB of HD (cost *x250*)
  - $40 for 50 GB of tapes. (cost same as HD) -> "Is Tape for backup dead?"
- *Main memory is volatile.*
  - We want data to be saved between runs.
- 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 (backup storage) or just disk-to-disk backup.

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Disks

- Secondary storage device of choice.
  – Main advantage over tapes: *random access* vs. *sequential*.
- Tapes are for data backup, not for operational data.
  – Access the last byte in a tape requires winding through the entire tape.
- 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!

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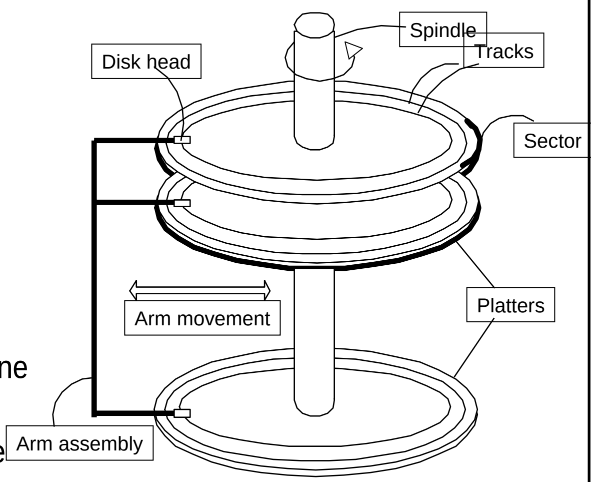
Components of a Disk

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



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Physical Specifications	
Formatted Capacity [1]	250,059 MB
Interface	40-pin EIDE
Actuator Type	Rotary Voice Coil
Number of Disks	3
Data Surfaces	6
Number of Heads	6
Bytes Per Sector	512
User Sectors Per Drive	488,397,168
Servo Type	Embedded
Recording Method EPR4	Rate 16/17 PRML
ECC	Reed Solomon
Head Park [2]	Automatic

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Accessing a Disk Page

- Time to access (read/write) a disk block is called *access time*.
- It is a sum of:
  - *seek time* (moving arm to position disk head on right track)
  - *rotational delay* (waiting for block to rotate under head)
  - *transfer time* (actually moving data to/from disk surface)
- Seek time and rotational delay (mechanical parts) dominate the access time
  - Seek time varies from about 1 to 20msec (avg 10msec)
  - Rotational delay varies from 0 to 8msec (avg. 4msec)
  - Transfer rate is about 100MBps (0.025msec per 4KB page)

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Performance Specifications	
Average Seek [1]	
- Read	8.9 ms average
- Write	10.9 ms average
Track-to-Track Seek	2.0 ms average
Full Stroke Seek	21 ms average
Index Pulse Period	8.3 ms (nominal)
Average Latency	4.2 ms (nominal)
Rotational Speed	7200 RPM (nominal)
Data Transfer Rate (maximum)	
- Buffer to Host	100 MB/s (Mode 5 Ultra ATA) 66.6 MB/s (Mode 4 Ultra ATA) 33.3 MB/s (Mode 2 Ultra ATA) 16.6 MB/s (Mode 4 PIO) 16.6 MB/s (Mode 2 multi-word DMA)
- Buffer to Disk	748 Mbits/s maximum
Interleave	1:1
Buffer Size	2 MB
Error Rate - Unrecoverable	<1 in 10^{14} bits read
Spindle Start Time	
- From Power-on to Drive Ready [2]	9.0 s average
- From Power-on to Rotational Speed [3]	7.0 s average
Spindle Stop Time	8.0 s average
Contact Start/Stop Cycles (CSS)	50,000 minimum

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How to reduce I/O cost?

- *access time = seek time + rotational latency + transfer time*

- How to lower I/O cost?
  - R*educe seek/rotation delays!*
- How to reduce seek/rotational delays for a large I/O requests of many pages?
  - If two pages of records are accessed together frequently, put them *close* together on disk.

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Arranging Pages on Disk

- *Next* block concept (measure the closeness of blocks)
  – (1) blocks on same track (no movement of arm), followed by
  – (2) blocks on same cylinder (switch head, but almost no movement of arm), followed by
  – (3) blocks on adjacent cylinder (little movement of arm)
- 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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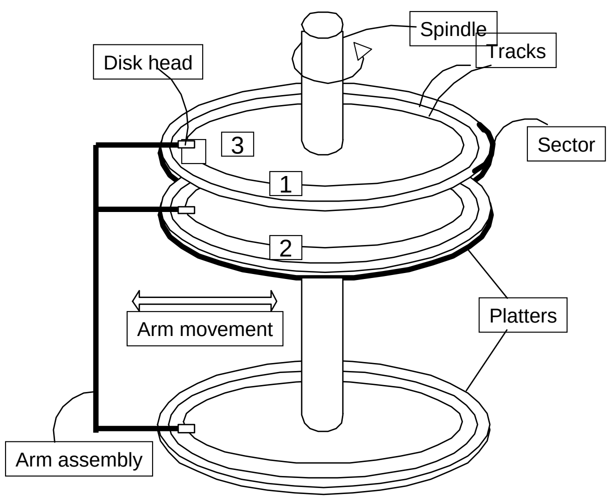
Next Block Concept



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RAID

- RAID = Redundant Arrays of Independent (Inexpensive) Disks
  - Disk Array: Arrangement of several disks that gives abstraction of a single, large disk.
- Goals: Increase *performance* and *reliability*.
  - Say you have *D* disks & each I/O request wants *D* blocks
    - How to improve the performance (*data transfer rate*)?
  - Say you have *D* disks & *D* number of I/O request each wanting one block
    - How to improve the performance (*request service rate*)?
  - Say you have *D* disks and at most one disk can fail at any time
    - How to improve reliability (in case of *disk failure*)?

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Two main techniques in RAID

- *Data striping* improves performance.
  - Data (e.g., in the same time file) is partitioned across multiple HDs; size of a partition is called the *striping unit*.
  - Performance gain is from reading/writing multiple HDs at the same time.
- *Redundancy* improves reliability.
  - Data striping lowers reliability: More disks → more failures.
  - Store *redundant* information on different disks. When a disk fails, you can reconstruct data from other disks.

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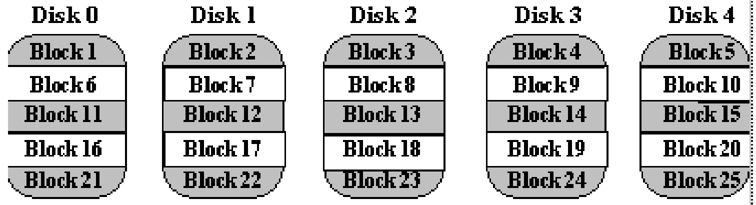
RAID Levels

- Level 0: No redundancy (only data striping)
- Level 1: Mirrored (two identical copies)
- Level 0+1: Striping and Mirroring
- *(Level 2: Error-Correcting Code)*
- Level 3: Bit-Interleaved Parity
- Level 4: Block-Interleaved Parity
- Level 5: Block-Interleaved Distributed Parity
- *(Level 6: Error-Correcting Code)*
- *More Levels (01-10, 03/30, …)*

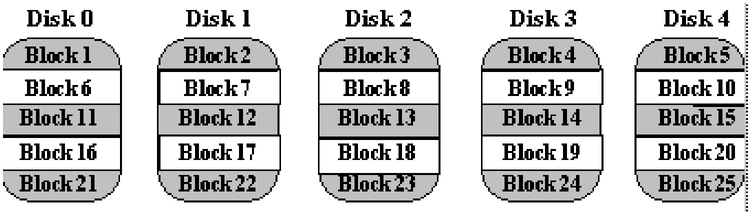
RAID Level 0

- Strip data across all drives (minimum 2 drives)
- Sequential blocks of data (in the same file) are written across multiple disks in stripes.
- Two performance criterions:
  - *Data transfer rate*: net transfer rate for a single (large) file
  - *Request service rate*: rate at which multiple requests (from different files) can be serviced



RAID Level 0

- Improve data transfer rate:
  - Read 10 blocks (1~10) takes o -block access time (worse of 5 disks).
  - Theoretical speedup over single disk = (number of disks)
- Improve request service rate:
  - File 1 occupies blocks 1 and file 2 occupies block 2. Service two requests (two files) at the same time.
  - Given N disks, theoretical speedup over single disk =



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RAID Level 0

- Poor reliability:
  - *Mean Time To Failure (MTTF)* of one disk = 50K hours (5.7 years).
  - MTTF of a disk array of 100 disks is
  - MTTF decreases linearly with the number of disks.
- Space redundancy overhead?
  -

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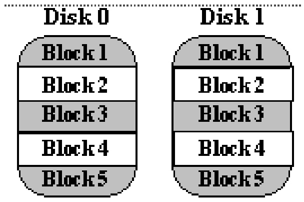
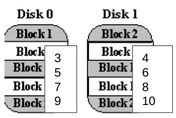
Mirrored (RAID Level 1)

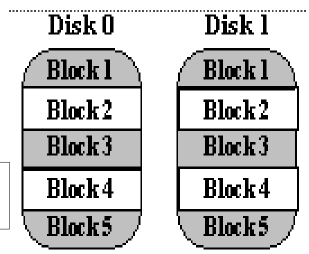
- Redundancy by duplicating data on different disks:
  - Mirror means copy each file to both disks
  - Simple but expensive.
- Fault-tolerant to a single disk failure
  - Recovery by copying data from the other disk to new disk.
  - The other copy can continue to service requests (*availability*) during recovery.



Mirrored (RAID Level 1)

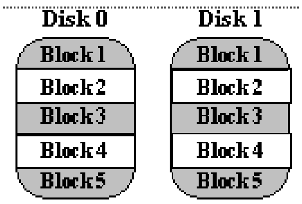
- Performance is not the objective, but *reliability*.
  - Mirroring frequently used when availability is more important than storage efficiency.
- Data transfer rate:
  - Write performance may be slower than single disk, why?
    - Worse of 2 disks
  - Read performance can be faster than single disk, why?
    - Consider reading block 1 from disk 0 and block 2 from disk 1 at the same time.
  - Compare read performance to RAID Level 0?
    - Better, but why?





Mirrored (RAID Level 1)

- Data reliability:
  - Assume Mean-Time-To-Repair (MTTR) is 1 hour.
    - Shorter with Hotswap HDs.
  - MTTF of Mirrored 2-disks = 1 / (probability that 2 disks will fail within the same hour) = $MTTR^2/2$ = $(50K)^2/2$ hours = many many years.
- Space redundancy overhead:
  - 50% overhead



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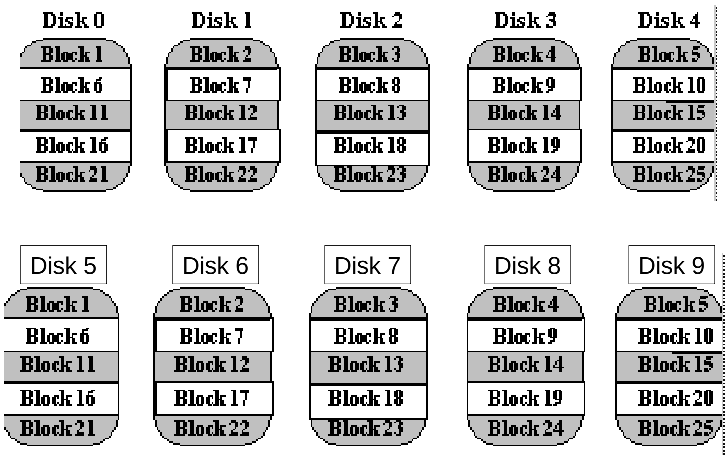
Striping and Mirrors (RAID 0+1)



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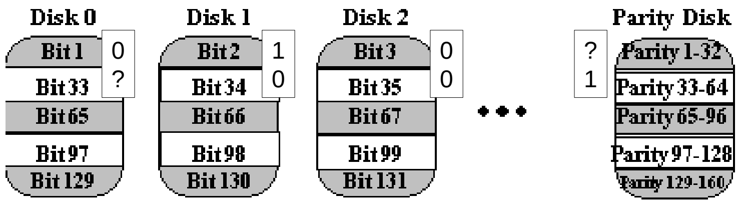
Bit-Interleaved Parity (RAID Level 3)

- Fine-grained striping at the bit level
- One parity disk:
  - Parity bit value = XOR across all data bit values
- If one disk fails, recover the lost data:
  - XOR across all good data bit values and parity bit value



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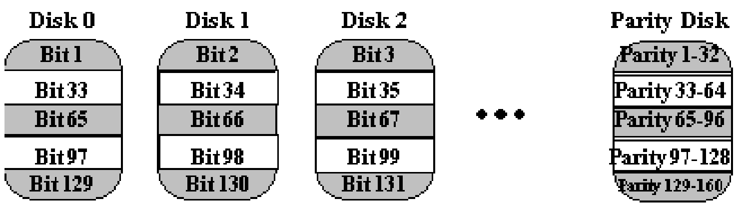
Bit-Interleaved Parity (RAID Level 3)

- Performance:
  - Transfer rate speedup?
    - *x*32 of single disk
  - Request service rate improvement?
    - Same as single disk (do one request at a time)
- Reliability:
  - Can tolerate 1 disk failure.
- Space overhead:
  - One parity disk (1/33 overhead)



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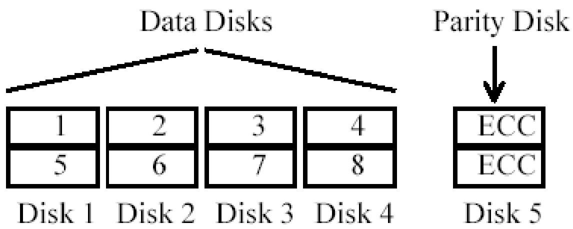
Block-Interleaved Parity (RAID Level 4)

- Coarse-grained striping at the block level
  - Otherwise, it is similar to RAID 3
- If one disk fails, recovery the lost block:
  - Read same block of all disks (including parity disk) to reconstruct the lost block.



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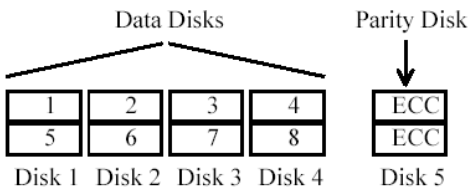
Block-Interleaved Parity (RAID Level 4)

- Performance:
  - If error, read/write of same block on all disks (worse-of-N on one block)
  - If no error, write also needs to update (read-n-write) the parity block. (no need to read other disks)
    - Can compute new parity based on old data, new data, and old parity
    - New parity = (old data XOR new data) XOR old parity
  - *Result in bottleneck on the parity disk!* (can do only one write at a time)
    - How to remove this bottleneck?



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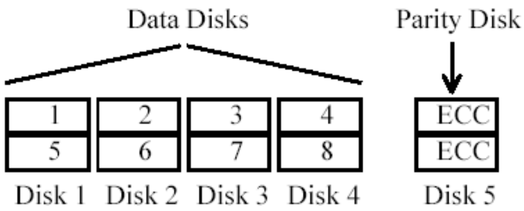
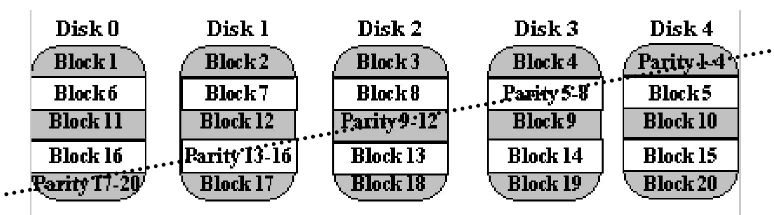
Block-Interleaved Parity (RAID Level 4)

- Reliability:
  - Can tolerate disk failure.
- Space redundancy overhead:
  - 1



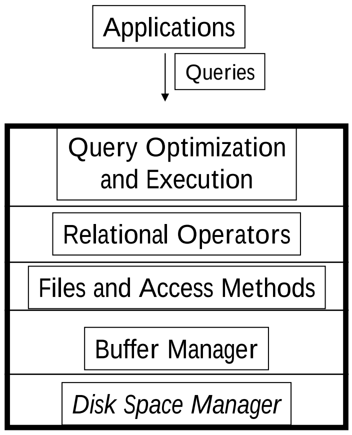
Block-Interleaved Distributed-Parity (RAID Level 5)

- Remove the parity disk bottleneck in RAID L4 by distributing the parity uniformly over all of the disks.
  - *No single parity disk as bottleneck*; otherwise, it is the same as RAID 4.
- Performance improvement in write.
  - You can write to multiple disks (in 2-disk pairs) in parallel.
- Reliability & space redundancy are the same as RAID L4.



Structure of DBMS

- Disk Space Manager
  - manage space (pages) on disk.
- Buffer Manager
  - manage traffic between disk and main memory. (bring in pages from disk to main memory).
- File and Access Methods
  - Organize records into pages and files.



Disk Space Manager

- 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 should be satisfied by *allocating the pages sequentially on disk!*
  - Support the “Next” block concept (reduce I/O cost when multiple sequential pages are requested at the same time).
  - Higher levels (buffer manager) don’t need to know how this is done, or how free space is managed.

More on Disk Space Manager

- Keep track of free (used) blocks:
  - List of free blocks + the pointer to the first free block
  - Bitmap with one bit for each disk block. Bit=1 (used), bit=0 (free)
  - Bitmap approach can be used to identify contiguous areas on disk.

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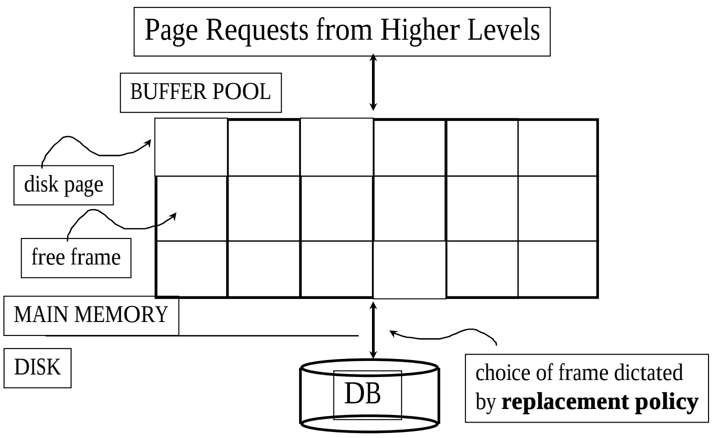
Buffer Manager



- Typically, DBMS has more data than main memory.
- Bring Data into main memory for DBMS to operate on it!
- Table of <frame#, pageid> pairs is maintained.

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When a Page is Requested ...

- If the requested page is not in pool (and no free frame):
  - Choose an occupied frame for *replacement*
    - *Page replacement policy (minimize page miss rate)*
  - If the replaced frame is dirty, write it to disk
  - Read requested page into chosen frame
  - Pin the page and return its address.
- For each frame, you maintain
  - *Pin_count*: number of outstanding requests
  - *Dirty*: modified and need to written back to disk
- If requests can be predicted (e.g., sequential scans) ..
  - pages can be *pre-fetched* several pages at a time.

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More on Buffer Manager

- Requestor of page must *unpin* it (no longer need it), and indicate whether the 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.

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Buffer Replacement Policy

- Frame is chosen for replacement by a *replacement policy:*
  - FIFO, MRU, Random, etc.
  - Least-recently-used (LRU): have LRU queue of frames with pin_count = 0
- What is the overhead of implementing LRU?
- Clock (approximate LRU with less overhead)
  - Use an additional *reference_bit* per page; set to 1 when the frame is accessed
  - *Clock hand* moving from frame 0 to frame n.
  - Reset reference_bit of recently accessed frames.
  - Replace frame(s) with reference_bit = 0 & pin_count = 0.
- Policy can have big impact on # of I/O's; depends on the *access pattern.*

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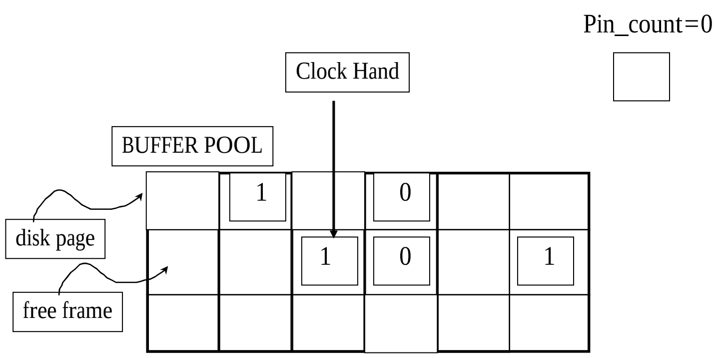
Clock Algorithm Example



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Sequential Flooding

- #buffer frames = 2
- #pages in a file = 3 (P1, P2, P3)
- Use LRU + repeated sequential scans
- What many page I/O replacements?
- Repeated scan of file
  - # buffer frames < # pages in file
  - Every scan of the file result in reading every page of the file.

Block read	*Frame #1*	*Frame #2*
P1	$\boxed{P1}$	
P2	*P1*	$\boxed{P2}$
P3	$\boxed{P3}$	*P2*
P1	*P3*	$\boxed{P1}$
P2	$\boxed{P2}$	*P1*
P3	*P2*	$\boxed{P3}$

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DBMS vs. OS File System

- OS also does disk space & buffer mgmt.
- Why not let OS manage these tasks?
  - Better predict the page reference patterns & pre-fetch pages.
    - Adjust replacement policy, and pre-fetch pages based on access patterns in typical DB operations.
  - Pin a page in memory and force a page to disk.
    - Differences in OS support: portability issues
  - Maintain a virtual file that spans multiple disks.

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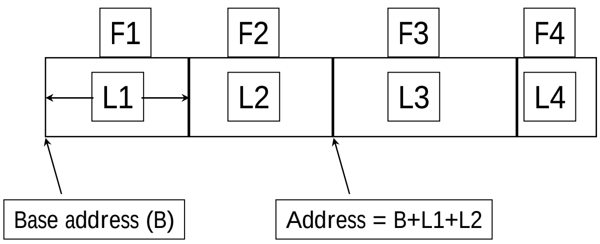
Files of Records

- 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(s)
  - Read a particular record (specified using *record id*)
  - Scan all records (possibly with some conditions on the records to be retrieved)
- To support record level operations, we must keep track of:
  - Fields in a record: *Record format*
  - Records on a page: *Page format*
  - Pages in a file: *File format*

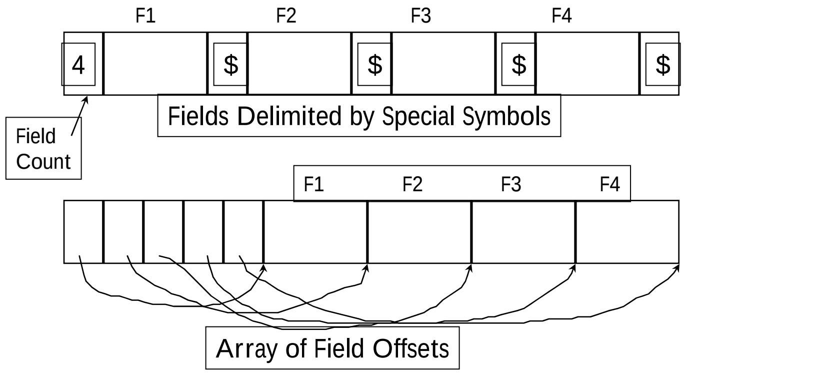
Record Formats (how to organize fields in a record): Fixed Length



- Information about field types and offset same for all records in a file; stored in *system catalogs*.
- Finding i-th field requires adding offsets to base address.

Record Formats: Variable Length

- Two alternative formats (# fields is fixed):



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

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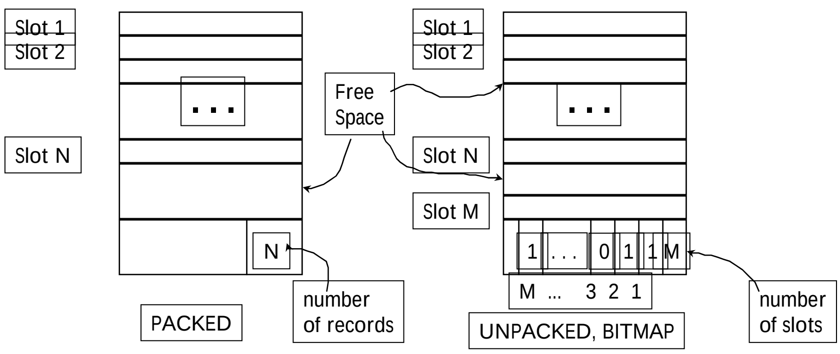
Page Formats (How to store records in a page): Fixed Length Records



- Record id = <page id, slot #>.
- They differ on how deletion (which creates a hole) is handled.
- In first alternative, shift remaining records to fill hole => changes rid; may not be acceptable given external reference.

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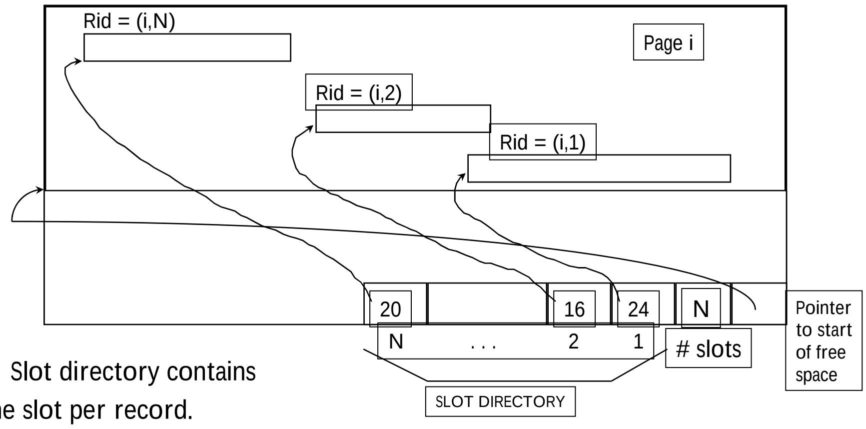
Page Formats: Variable Length Records



* Slot directory contains one slot per record.
* Each slot contains (record offset, record length)
* Deletion is by setting the record offset to -1.
* Can move records on page without changing rid (change the record offset, but same slot number); so, attractive for fixed-length records.

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Unordered (Heap) Files

- Simplest file structure contains records in no particular order.
- As file grows and shrinks, disk pages are allocated and de-allocated.
- How would you implement a heap file (data structure)?
  - Double-Linked lists
  - Page directory

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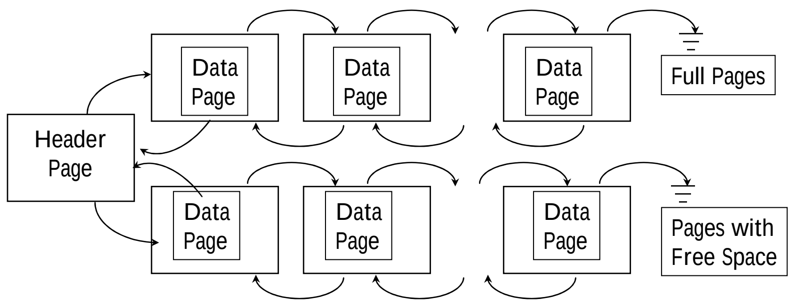
Heap File (Doubly Linked Lists)



- The header page id and Heap file name must be stored someplace.
- Each page contains 2 `pointers' plus data.
- The problem is that inserting a variable size record requires walking through free space list to find a page with enough space.

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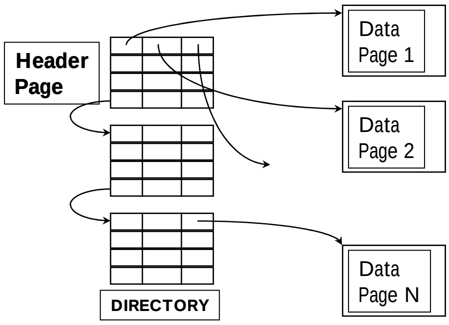
Heap File (Page Directory)



- The directory is a collection of pages.
  - Each directory page contains multiple directory entries – one per data page.
  - The directory entry contains <page id, free bytes on the page>
  - Eliminate the problem in the double-linked list approach.

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