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Carnegie Mellon Univ. Dept. of Computer Science 15-415/615 - DB Applications

C. Faloutsos & A. Pavlo

Lecture #8 (R&G ch9)

Storing Data: Disks and Files

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Overview

- Memory hierarchy
- RAID (briefly)
- Disk space management
- Buffer management
- Files of records
- Page Formats
- Record Formats

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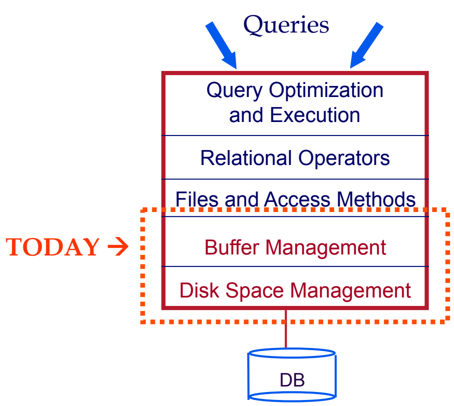
DBMS Layers:



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Leverage OS for disk/file management?

- Layers of abstraction are good … but:

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Leverage OS for disk/file management?

- Layers of abstraction are good … but:
  - Unfortunately, OS often gets in the way of DBMS

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Leverage OS for disk/file management?

- DBMS wants/needs to do things “its own way”
  - Specialized prefetching
  - Control over buffer replacement policy
    - LRU not always best (sometimes worst!!)
  - Control over thread/process scheduling
    - “Convoy problem”
      - Arises when OS scheduling conflicts with DBMS locking
  - Control over flushing data to disk
    - WAL protocol requires flushing log entries to disk

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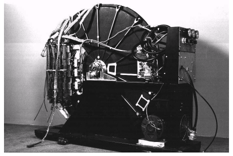
Disks and Files



- DBMS stores information on disks.
  - but: disks are (relatively) VERY slow!
- Major implications for DBMS design!

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Disks and Files

- Major implications for DBMS design:
  - READ: disk -> main memory (RAM).
  - WRITE: reverse
  - Both are high-cost operations, relative to in-memory operations, so must be planned carefully!

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Why Not Store It All in Main Memory?

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Why Not Store It All in Main Memory?

- *Costs too much.*
  - disk: ~$0.1/Gb; memory: ~$10/Gb
  - High-end Databases today in the 10-100 TB range.
  - Approx 60% of the cost of a production system is in the disks.
- *Main memory is volatile.*
- *Note*: some specialized systems do store entire database in main memory.

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The Storage Hierarchy

Smaller, Faster

Bigger, Slower

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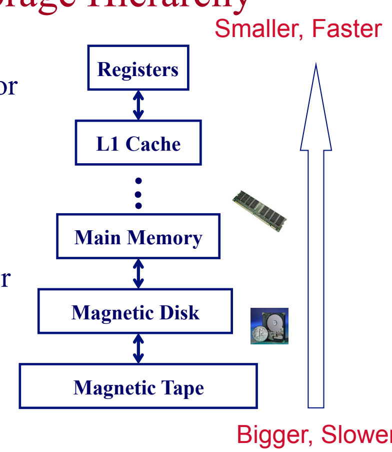
The Storage Hierarchy

–Main memory (RAM) for currently used data.

–Disk for the main database (secondary storage).

–Tapes for archiving older versions of the data (tertiary storage).



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The Storage Hierarchy

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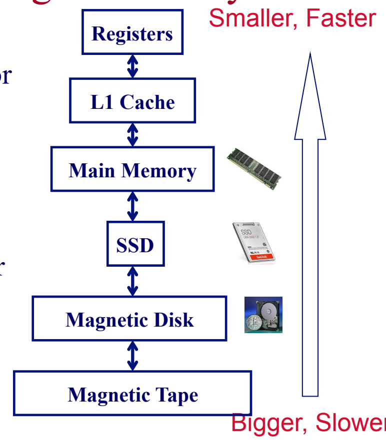

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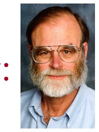
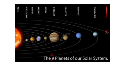
Jim Gray's Storage Latency Analogy: How Far Away is the Data?



10**9 tape	Andromeda		2,000yr
10**6 disk	Pluto		2yr
100 Memory	Pittsburgh		1.5h
10 On board cache	This building		10min
2 on chip cache	This room		1min
1 registers	In my head		

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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.
  – relative placement of pages on disk is important!

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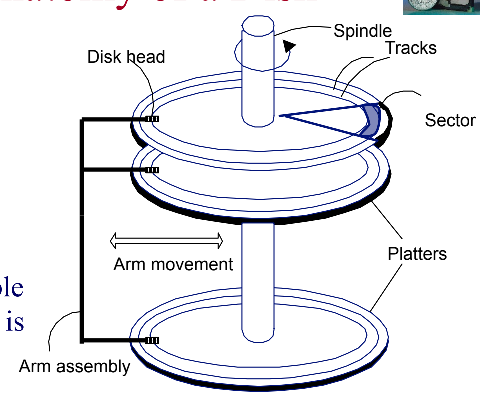
Anatomy of a Disk

- Sector
- Track
- Cylinder
- Platter
- Block size = multiple of sector size (which is fixed)



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Accessing a Disk Page

- Time to access (read/write) a disk block:
  - .
  - .
  - .

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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

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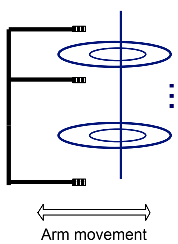
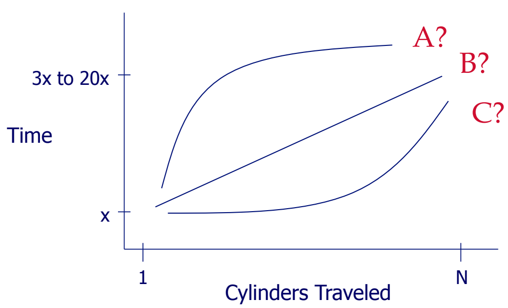
Seek Time





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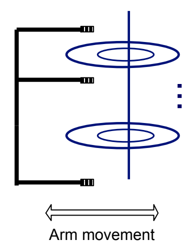
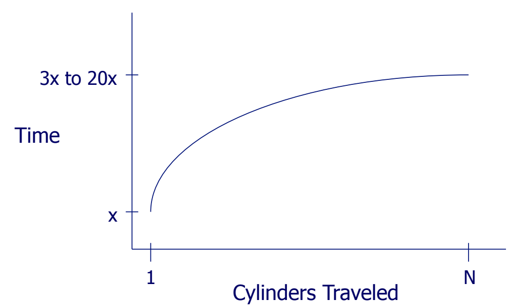
Seek Time





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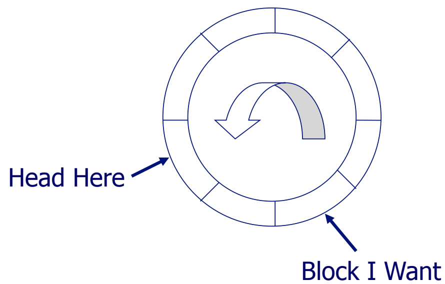
Rotational Delay



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Accessing a Disk Page

- Relative times?
  - *seek time:*
  - *rotational delay:*
  - *transfer time:*

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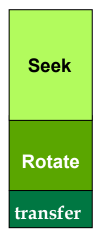
Accessing a Disk Page

- Relative times?
  - *seek time:* about 1 to 20msec
  - *rotational delay:* 0 to 10msec
  - *transfer time:* < 1msec per 4KB page



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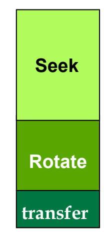
Seek time & rotational delay dominate

- Key to lower I/O cost:
  reduce seek/rotation delays!
- Also note: For shared disks, much time spent waiting in queue for access to arm/controller



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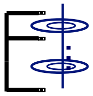
Arranging Pages on Disk



- "*Next*" block concept:
  - blocks on same track, followed by
  - blocks on same cylinder, followed by
  - blocks on adjacent cylinder

Q1: Why not equal?

Q2: Why?

- Accesing 'next' block is cheap
- An important optimization: <u>pre-fetching</u>
  - See R&G page 323

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Rules of thumb…

1. Memory access <u>much</u> faster than disk I/O (~ 1000x)

- "Sequential" I/O faster than "random" I/O (~ 10x)

write on blackboard

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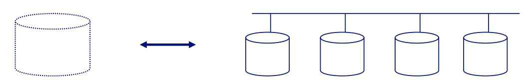
Disk Arrays: RAID

Prof. Garth Gibson



Logical Physical

- Benefits:
  - Higher throughput (via data "striping")
  - Longer MTTF

(Why?)

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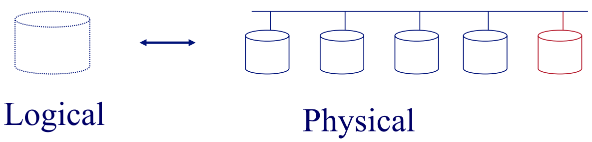
Disk Arrays: RAID



- Benefits:
  - Higher throughput (via data "striping")
  - Longer MTTF (via redundancy)

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Overview

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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
- Best if requested pages are stored sequentially on disk! Higher levels don't need to know if/how this is done, nor how free space is managed.

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Overview

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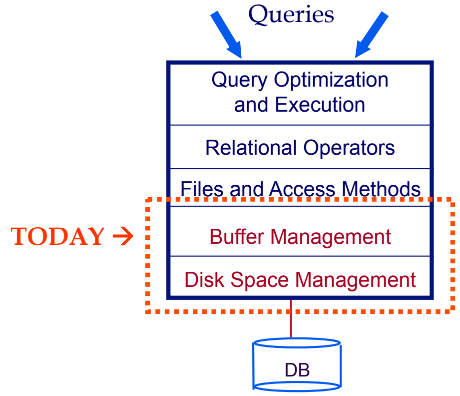
Recall: DBMS Layers



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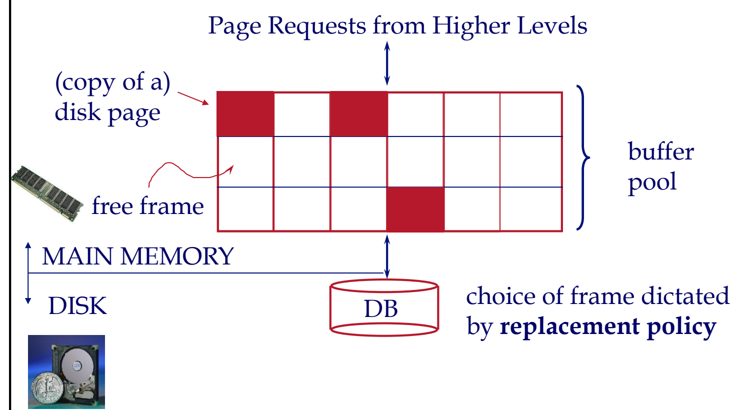
Buffer Management in a DBMS



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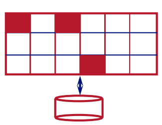
Buffer Management in a DBMS

- Data must be in RAM for DBMS to operate on it!
- Buffer Mgr hides the fact that not all data is in RAM



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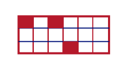
When a Page is Requested ...

Buffer pool information table contains:
<???>

- If requested page is not in pool:
  - Choose an (un-pinned) frame for *replacement*
    - If frame is "dirty", write it to disk
  - Read requested page into chosen frame
- *Pin* the page and return its address



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When a Page is Requested ...

Buffer pool information table contains:
<frame#, pageid, pin_count, dirty-bit>

- If requested page is not in pool:
  - Choose an (un-pinned) frame for *replacement*
    - If frame is "dirty", write it to disk
  - Read requested page into chosen frame
- *Pin* the page and return its address

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When a Page is Requested ...

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

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More on Buffer Management

- When done, requestor of page must
  - unpin it, and
  - indicate whether page has been modified: *dirty* bit
- Page in pool may be requested many times:
  - *pin count*
- if *pin count* = 0 (*"unpinned"*), page is candidate for replacement

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More on Buffer Management

- CC & recovery may entail additional I/O when a frame is chosen for replacement. (*Write-Ahead Log* protocol; more later.)

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Buffer Replacement Policy

- Frame is chosen for replacement by a *replacement policy:*
  - Least-recently-used (LRU), MRU, Clock, etc.
- Policy -> big impact on # of I/O ' s; depends on the *access pattern.*

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LRU Replacement Policy

- *Least Recently Used (LRU)*
  - for each page in buffer pool, keep track of time last *unpinned*
  - replace the frame which has the oldest (earliest) time
  - very common policy: intuitive and simple
- Problems?

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LRU Replacement Policy

- Problem: *Sequential flooding*
  - 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).

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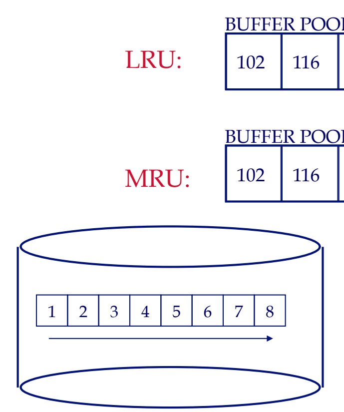
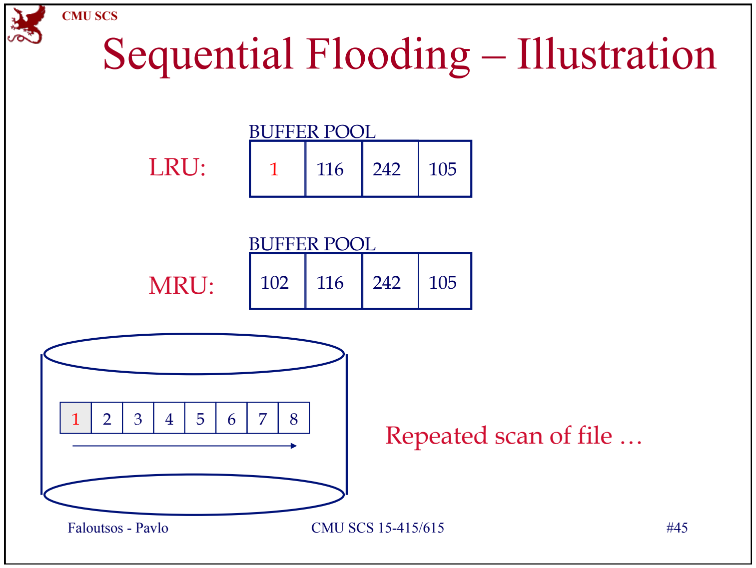
Sequential Flooding – Illustration



Repeated scan of file …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Sequential Flooding – Illustration
BUFFER POOL
LRU:
1 116 242 105
BUFFER POOL
MRU:
102 116 242 105
1 2 3 4 5 6 7 8
Repeated scan of file …
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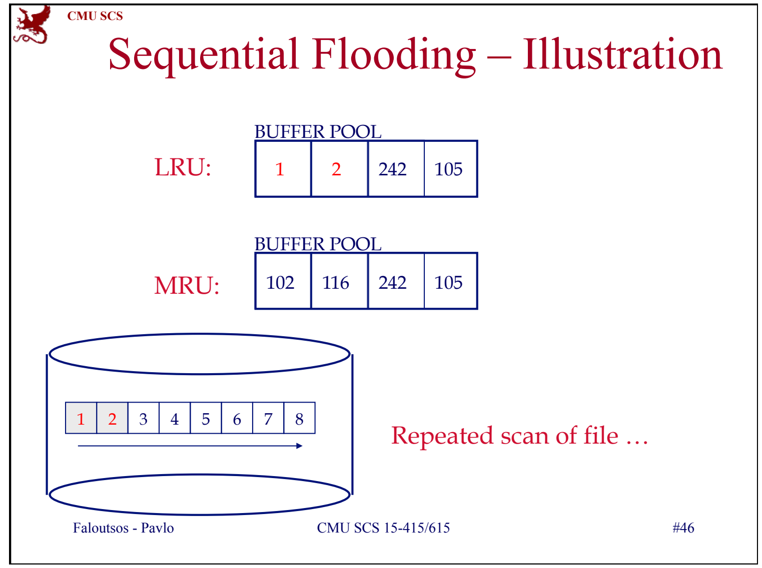
CMU SCS
Sequential Flooding – Illustration
BUFFER POOL
LRU:
1 2 242 105
BUFFER POOL
MRU:
102 116 242 105
1 2 3 4 5 6 7 8
Repeated scan of file …
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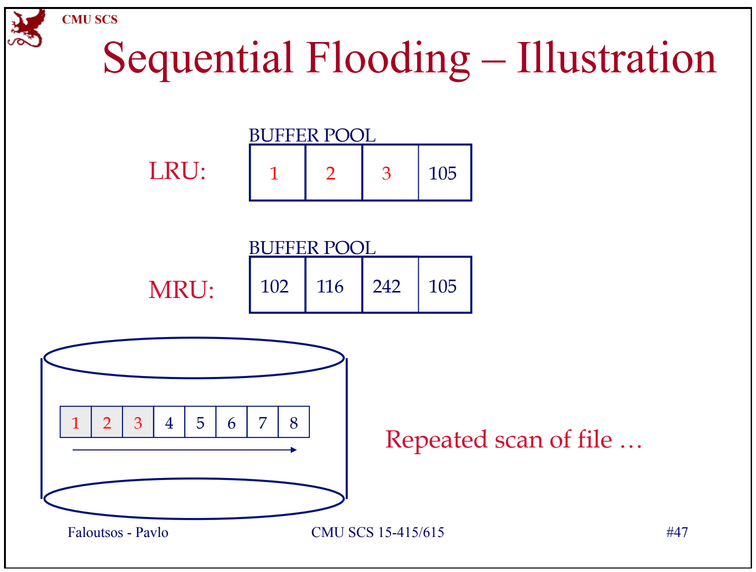
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Sequential Flooding – Illustration
BUFFER POOL
LRU:
1 2 3 105
BUFFER POOL
MRU:
102 116 242 105
1 2 3 4 5 6 7 8
Repeated scan of file …
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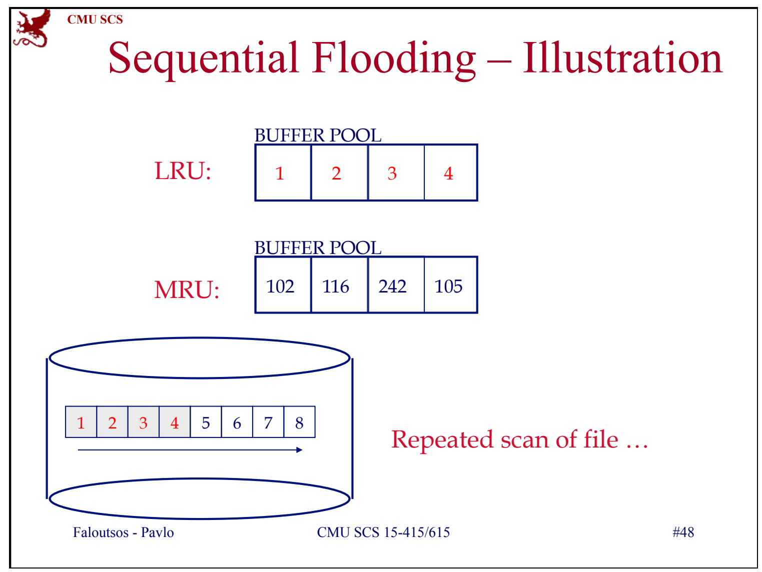
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Sequential Flooding – Illustration
BUFFER POOL
LRU:
1 2 3 4
BUFFER POOL
MRU:
102 116 242 105
1 2 3 4 5 6 7 8
Repeated scan of file …
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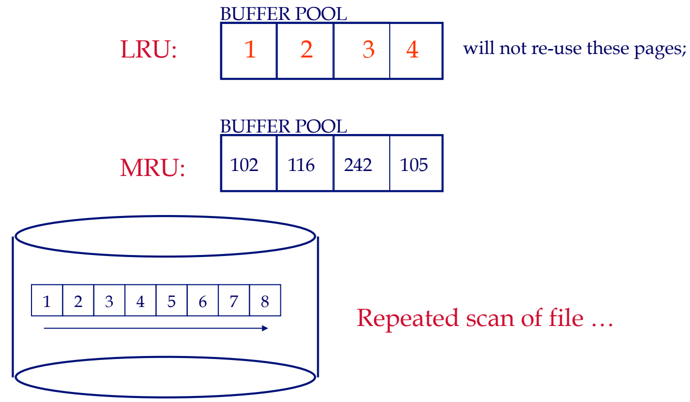
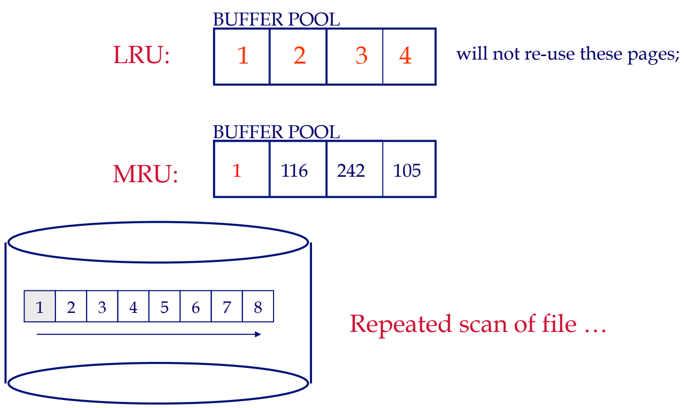
How will MRU work?

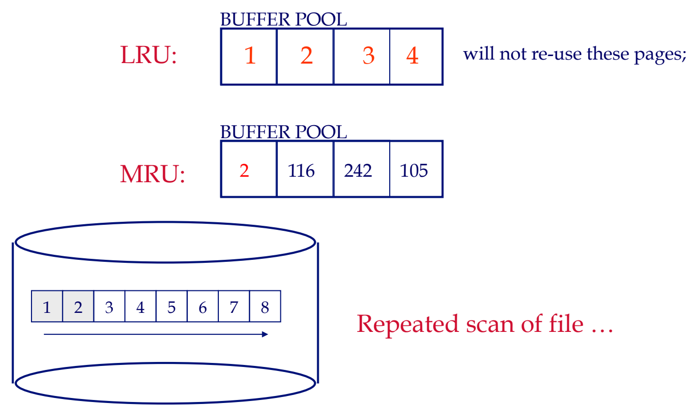
Sequential Flooding – Illustration



Sequential Flooding – Illustration



Sequential Flooding – Illustration



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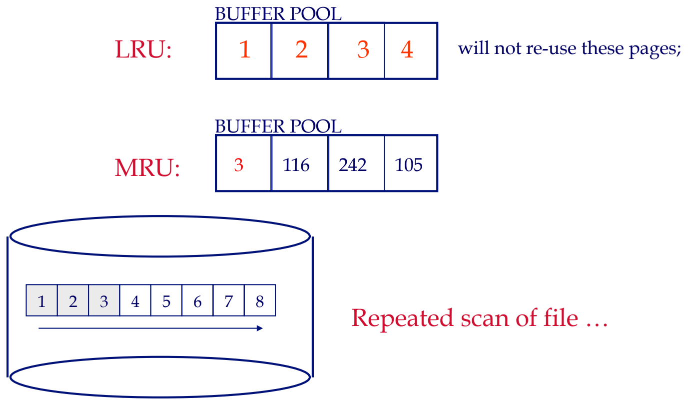
Sequential Flooding – Illustration



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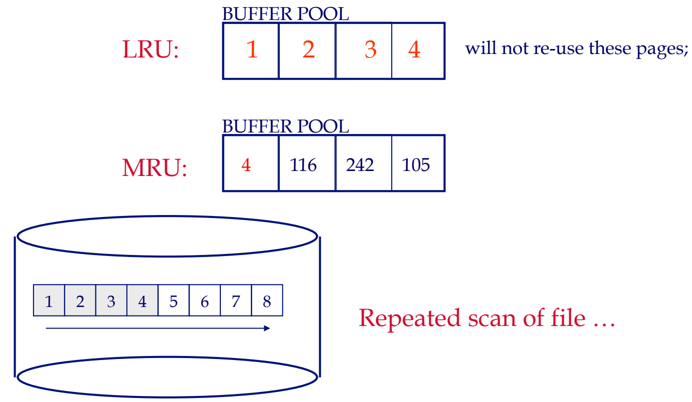
Sequential Flooding – Illustration



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Other policies?

- LRU is often good - but needs timestamps and sorting on them
- something easier to maintain?

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“Clock” Replacement Policy

Main ideas:

- Approximation of LRU.
- Instead of maintaining & sorting time-stamps, find a ‘reasonably old’ frame to evict.
- How? by round-robin, and marking each frame - frames are evicted the second time they are visited.
- Specifically:

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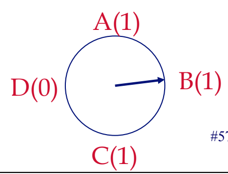
"Clock" Replacement Policy

- Arrange frames into a cycle, store one "reference bit" per frame
- When pin count goes to 0, reference bit set on (= 'one life left' - not ready for eviction yet)
- When replacement necessary, get the next frame that has reference-bit = 0



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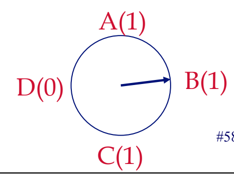
"Clock" Replacement Policy

```
do {
    if (pincount == 0 && ref bit is off)
        choose current page for replacement;
    else if (pincount == 0 && ref bit is on)
        turn off ref bit;
        advance current frame;
} until a page is chosen for replacement;
```



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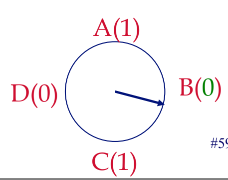
"Clock" Replacement Policy



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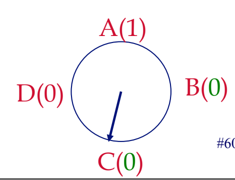
"Clock" Replacement Policy



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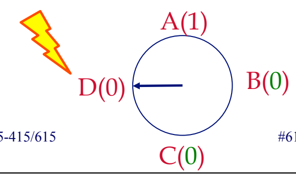
"Clock" Replacement Policy



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Summary

- Buffer manager brings pages into RAM.
- Very important for performance
  - 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.*
  - Good to *pre-fetch* several pages at a time.

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- <u>Files of records</u>
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Files

- <u>FILE</u>: 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)

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Alternative File Organizations

Several alternatives (w/ trade-offs):

- Heap files: Suitable when typical access is a file scan retrieving all records.
- Sorted Files: } later
- Index File Organizations: } later

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Files of records

- Heap of pages
  - as linked list or
  - directory of pages

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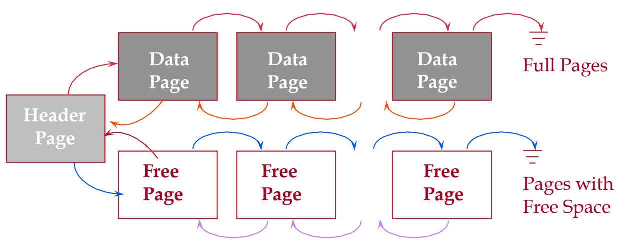
Heap File Using Lists



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

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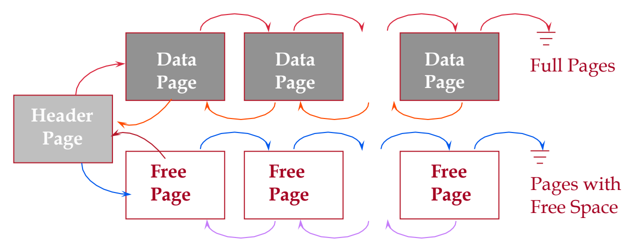
Heap File Using Lists



- Any problems?

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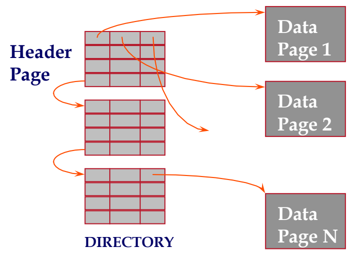
Heap File Using a Page Directory



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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*!

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Page Formats

- fixed length records
- variable length records

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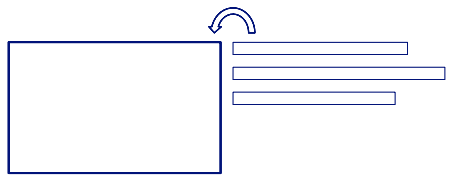
Problem definition

Q: How would you store records on a page/ file, such that

1. you can point to them
2. you can insert/delete records with few disk accesses

4kb page



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Page Formats

Important concept: *rid* == record id

Q0: why do we need it?

Q1: How to mark the location of a record?

Q2: Why not its byte offset in the file?

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Page Formats

Important concept: *rid* == record id

Q0: why do we need it?

A0: eg., for indexing

Q1: How to mark the location of a record?

A1:

⇨ Q2: Why not its byte offset in the file?

A2:

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Page Formats

Important concept: *rid* == record id

Q0: why do we need it?

A0: eg., for indexing

Q1: How to mark the location of a record?

A1:

Q2: Why not its byte offset in the file?

A2: too much re-organization on ins/del.

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Page Formats

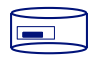
Important concept: *rid* == record id

Q0: why do we need it?

A0: eg., for indexing

Q1: How to mark the location of a record?

A1: <u>rid = record id = page-id & slot-id</u>



Q2: Why not its byte offset in the file?

A2: too much re-organization on ins/del.

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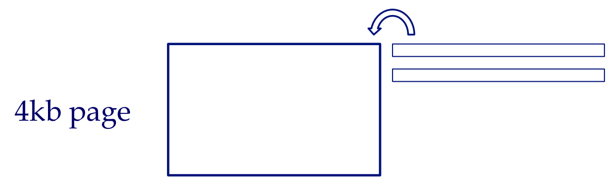
Fixed length records

- Q: How would you store them on a page/ file?



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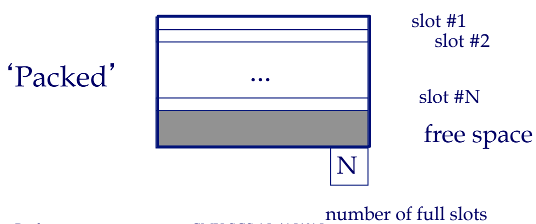
Fixed length records

- Q: How would you store them on a page/ file?
- A1: How about:



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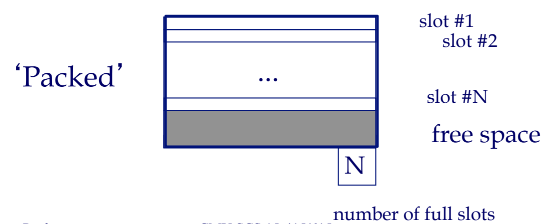
Fixed length records

- OK – how about insertion?



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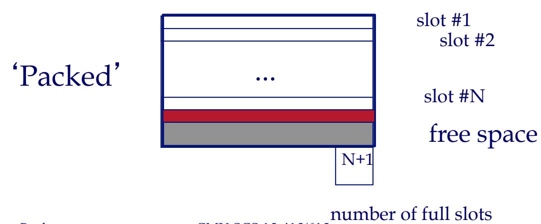
Fixed length records

- OK – how about insertion?



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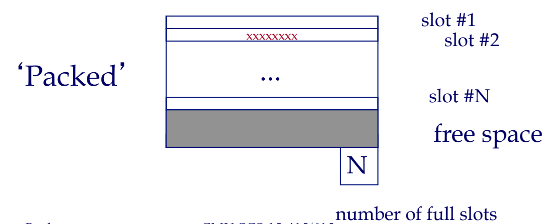
Fixed length records

- How about deletion?



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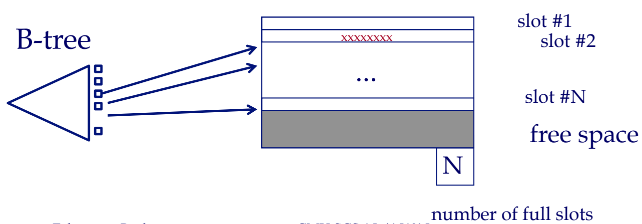
Fixed length records

- How about deletion?
- Bad - we have too much to reorganize/update



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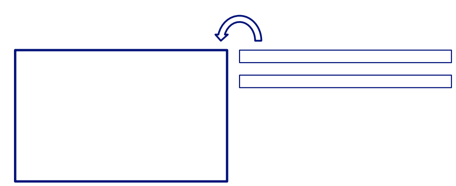
Fixed length records

- What would you do?



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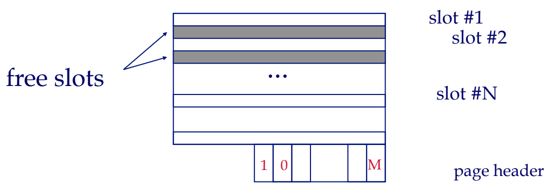
Fixed length records

- Q: How would you store them on a page/ file?
- A2: Bitmaps



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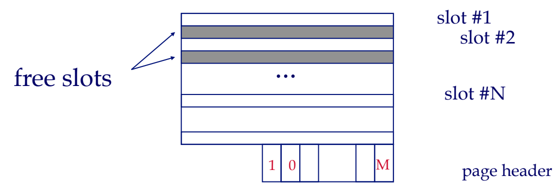
Fixed length records

- Q: How would you store them on a page/ file?
- A2: Bitmaps : ✔ insertions, ✔ deletions



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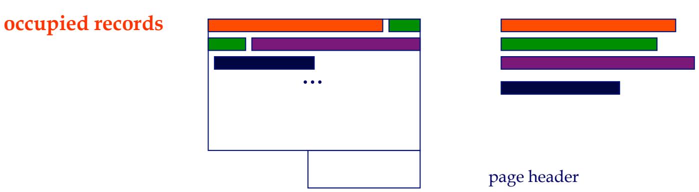
Variable length records

- Q: How would you store them on a page/ file?



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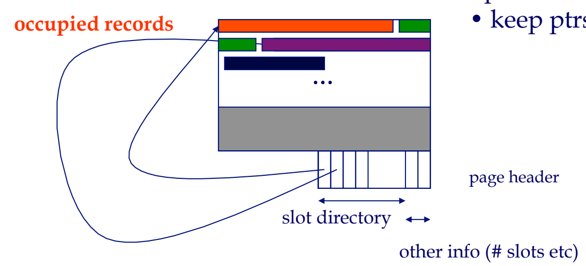
SLOTTED PAGE

Variable length records

- Q: How would you store them on a page/ file?
  - pack them
  - keep ptrs to them



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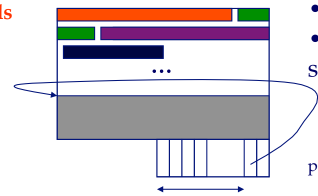
SLOTTED PAGE

Variable length records

- Q: How would you store them on a page/ file?

occupied records



- pack them
- keep ptrs to them
- mark start of free space

page header

slot directory

other info (# slots etc)

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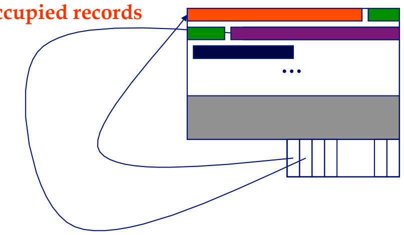
SLOTTED PAGE

Variable length records

- Q: How would you store them on a page/ file?

occupied records



- how many disk accesses to insert a record?
- to delete one?

page header

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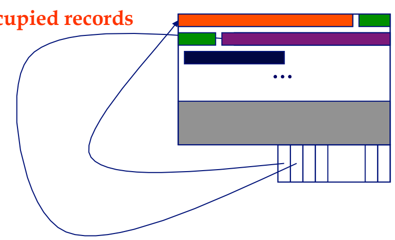
SLOTTED PAGE

Variable length records

- SLOTTED PAGE organization - popular.

occupied records



page header

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Overview

- Memory hierarchy
- RAID (briefly)
- Disk space management
- Buffer management
- Files of records
- Page Formats
- Record Formats

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Formats of records

- Fixed length records
  - How would you store them?
- Variable length records

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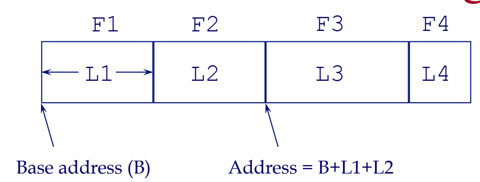
Record Formats: Fixed Length



- Information about field types same for all records in a file; stored in *system catalogs.*
- Finding *i'th* field done via arithmetic.

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Formats of records

- Fixed length records: straightforward - store info in catalog
- Variable length records: encode the length of each field
  - ?
  - ?

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Formats of records

- Fixed length records: straightforward - store info in catalog
- Variable length records: encode the length of each field
  - store its length or
  - use a field delimiter

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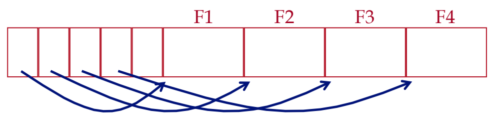
Variable Length records

- Two alternative formats (# fields is fixed):

Fields Delimited by Special Symbols



Array of Field Offsets

Pros and cons?

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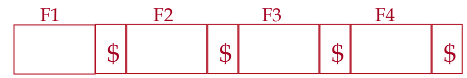
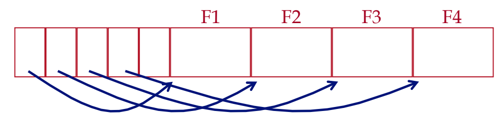
Variable Length records

- Two alternative formats (# fields is fixed):



Fields Delimited by Special Symbols



Array of Field Offsets

Offset approach: usually superior (direct access to i-th field)

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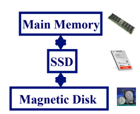
Conclusions



- Memory hierarchy
- Disks: (>1000x slower) - thus
  - pack info in blocks
  - try to fetch nearby blocks (sequentially)
- Buffer management: very important
  - LRU, MRU, Clock, etc
- Record organization: Slotted page