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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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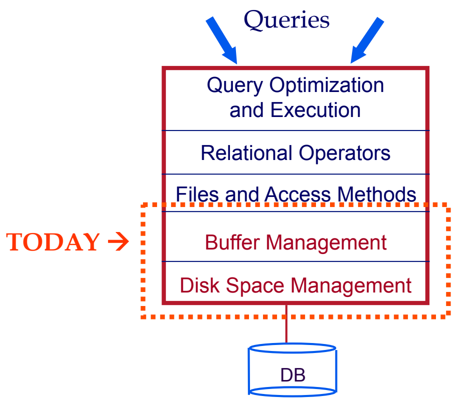
DBMS Layers:



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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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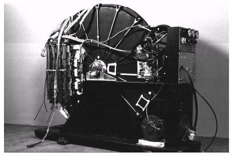
Disks and Files



- 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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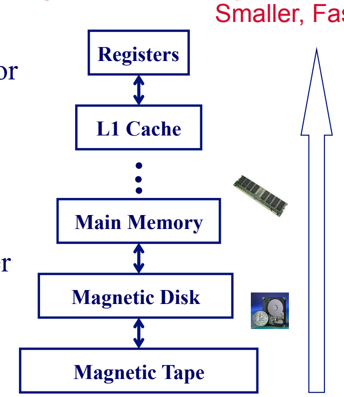
The Storage Hierarchy

Smaller, Faster

–Main memory (RAM) for currently used data.

–Disk for the main database (secondary storage).

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



Bigger, Slower

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The Storage Hierarchy

–Main memory (RAM) for currently used data.

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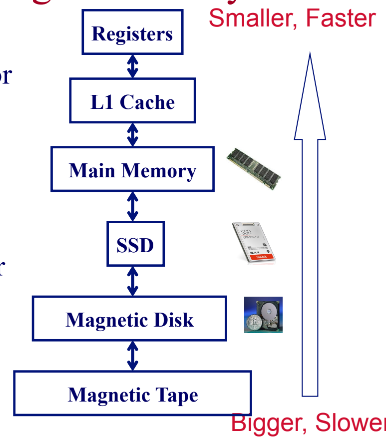

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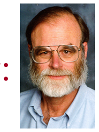
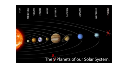
Jim Gray's Storage Latency Analogy: How Far Away is the Data?



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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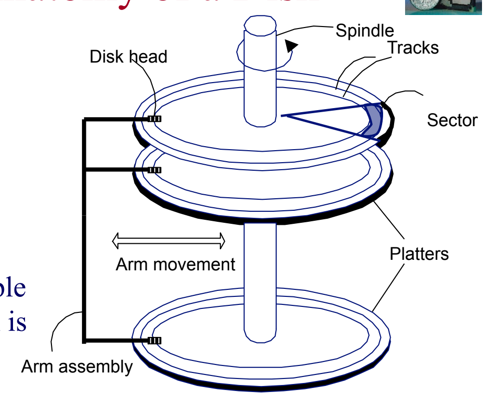
Anatomy of a Disk

- 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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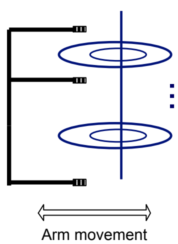
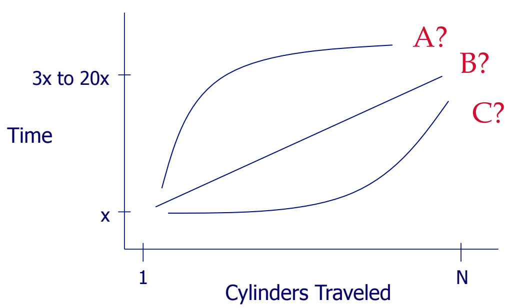
Seek Time





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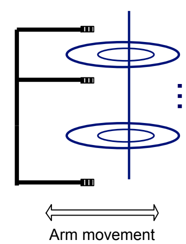
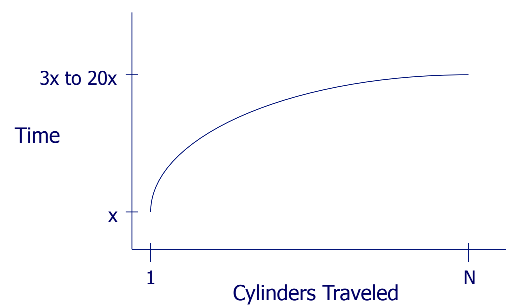
Seek Time





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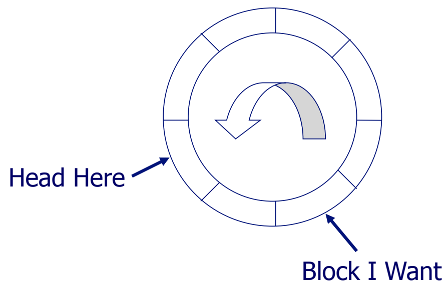
Rotational Delay



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Accessing a Disk Page

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

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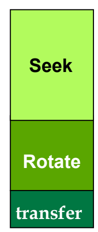
Accessing a Disk Page

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



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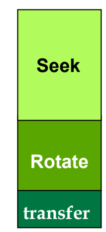
Seek time & rotational delay dominate

- 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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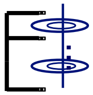
Arranging Pages on Disk



- "*Next*" block concept:
  - blocks on same track, followed by
  - blocks on same cylinder, followed by
  - blocks on adjacent cylinder
- Accesing 'next' block is cheap
- An important optimization: pre-fetching
  - See R&G page 323

Q1: Why not equal?

Q2: Why?

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Rules of thumb…

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

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

write on blackboard

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Overview

- Memory hierarchy
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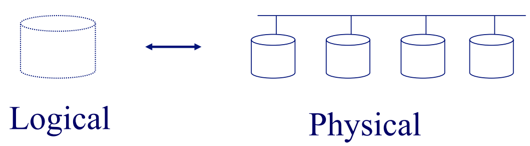
Disk Arrays: RAID

Prof. Garth Gibson



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

(Why?)

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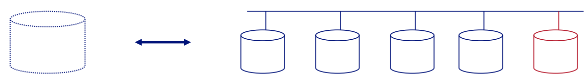
Disk Arrays: RAID



Logical Physical

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

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Overview

- Memory hierarchy
- RAID (briefly)
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- Page Formats
- Record Formats

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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

- Memory hierarchy
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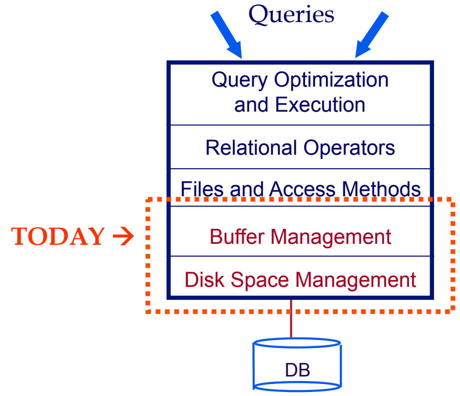
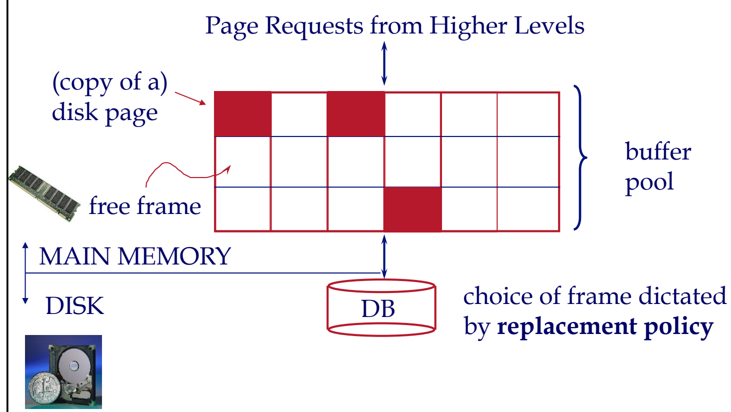
Recall: DBMS Layers

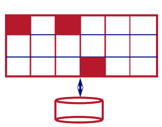


Buffer Management in a DBMS



Buffer Management in a DBMS

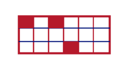
- Data must be in RAM for DBMS to operate on it!
- Buffer Mgr hides the fact that not all data is in RAM



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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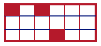
When a Page is Requested ...

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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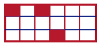
More on Buffer Management

- 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

BUFFER POOL

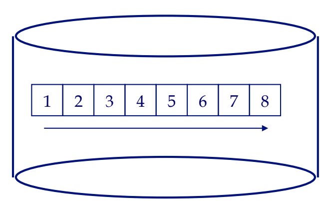
LRU:

102	116	242	105

BUFFER POOL

MRU:

102	116	242	105



Repeated scan of file …

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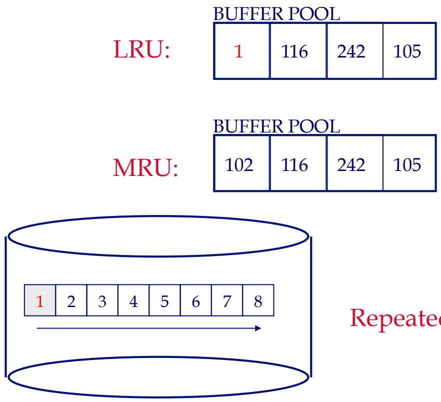
Sequential Flooding – Illustration



Repeated scan of file …

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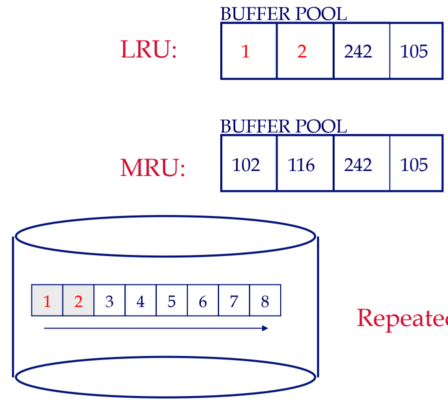
Sequential Flooding – Illustration



Repeated scan of file …

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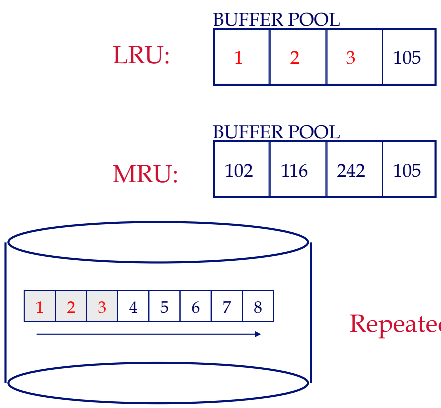
Sequential Flooding – Illustration



Repeated scan of file …

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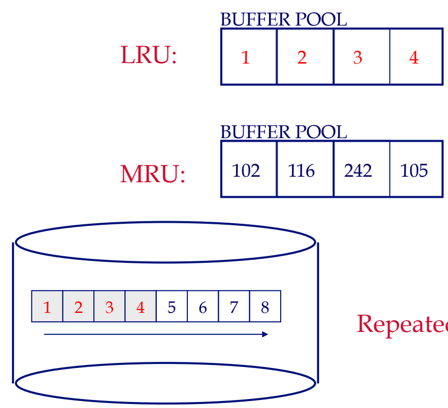
Sequential Flooding – Illustration



Repeated scan of file …

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How will MRU work?

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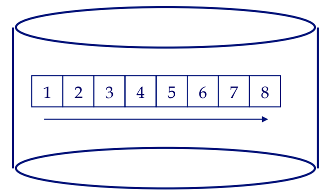
Sequential Flooding – Illustration

BUFFER POOL

LRU:	1	2	3	4	will not re-use these pages;

BUFFER POOL

MRU:	102	116	242	105



Repeated scan of file …

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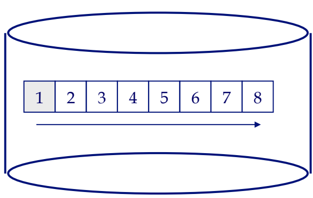
Sequential Flooding – Illustration

BUFFER POOL

LRU:	1	2	3	4	will not re-use these pages;

BUFFER POOL

MRU:	1	116	242	105



Repeated scan of file …

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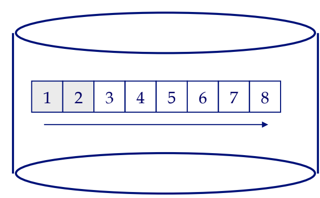
Sequential Flooding – Illustration

BUFFER POOL

LRU:	1	2	3	4	will not re-use these pages;

BUFFER POOL

MRU:	2	116	242	105



Repeated scan of file …

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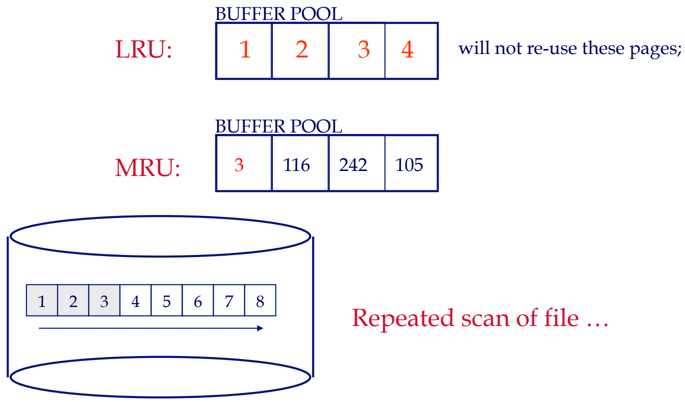
Sequential Flooding – Illustration



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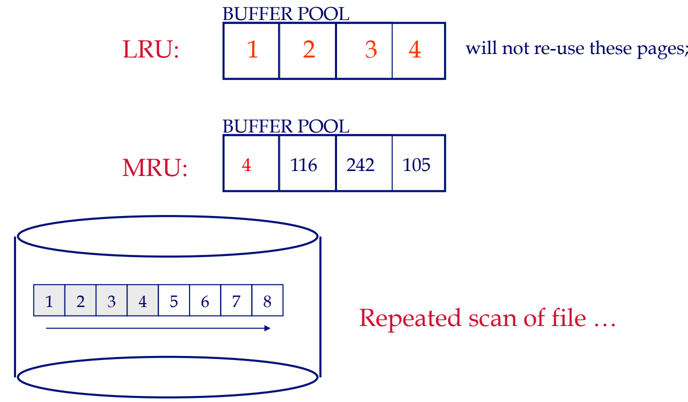
Sequential Flooding – Illustration



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SKIP

Other policies?

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

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SKIP

"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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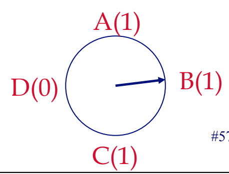
"Clock" Replacement Policy

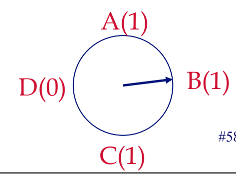
- Arrange frames into a cycle, store one "reference bit" per frame
- When pin count goes to 0, reference bit set on (= 'one life left' - not ready for eviction yet)
- When replacement necessary, get the next frame that has reference-bit = 0



SKIP

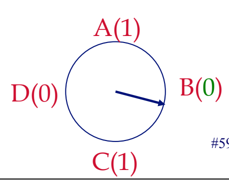
"Clock" Replacement Policy

```
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;
```



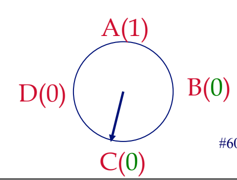
SKIP

"Clock" Replacement Policy



SKIP

"Clock" Replacement Policy



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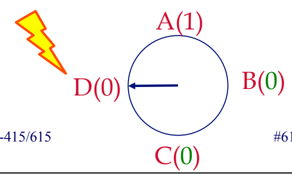
SKIP

"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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Files

- 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)

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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:
- 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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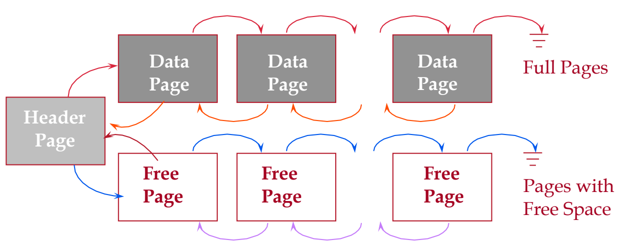
Heap File Using Lists



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

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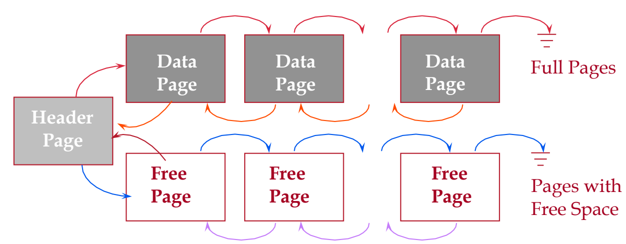
Heap File Using Lists



- Any problems?

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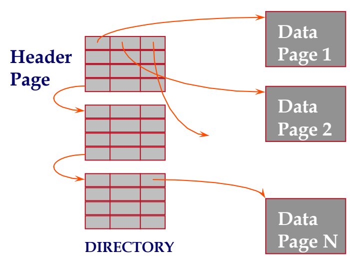
Heap File Using a Page Directory



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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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Overview

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

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Page Formats

- fixed length records
- variable length records

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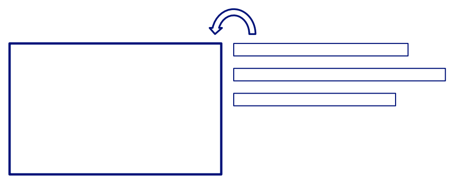
Problem definition

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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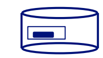
Page Formats

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

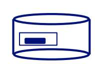
Q0: why do we need it?

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

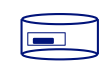
Q0: why do we need it?

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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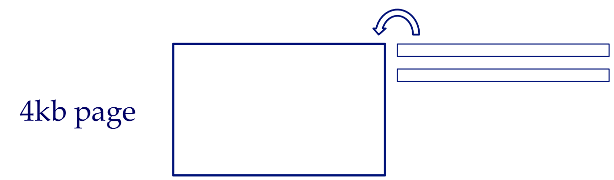
Fixed length records

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



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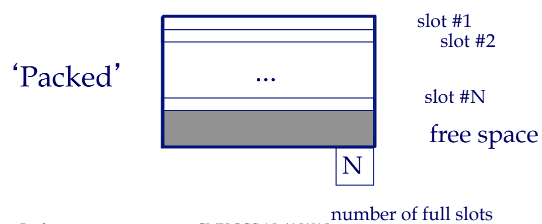
Fixed length records

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



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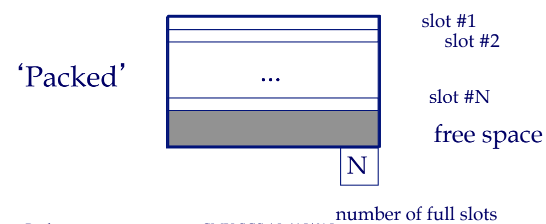
Fixed length records

- OK – how about insertion?



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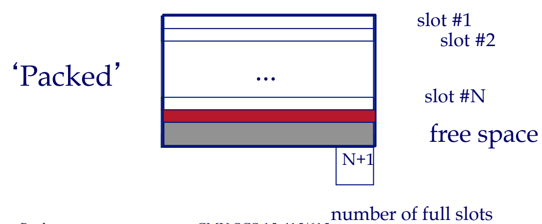
Fixed length records

- OK – how about insertion?



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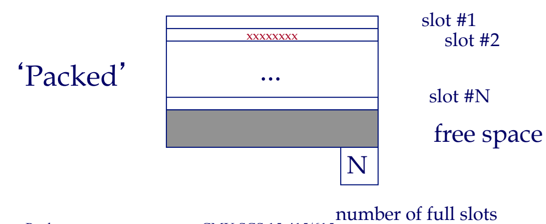
Fixed length records

- How about deletion?



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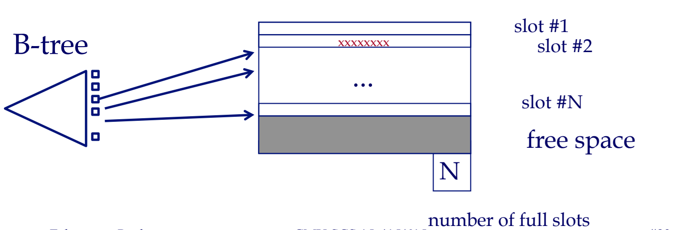
Fixed length records

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



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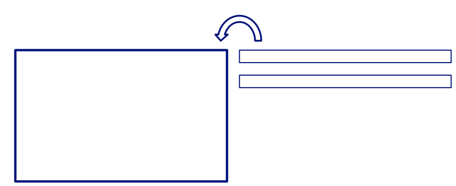
Fixed length records

- What would you do?



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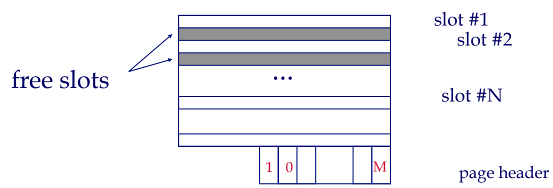
Fixed length records

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



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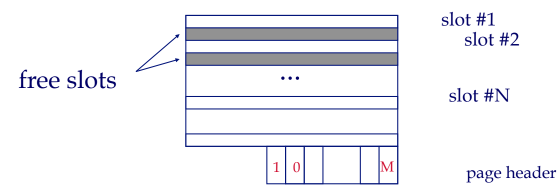
Fixed length records

- 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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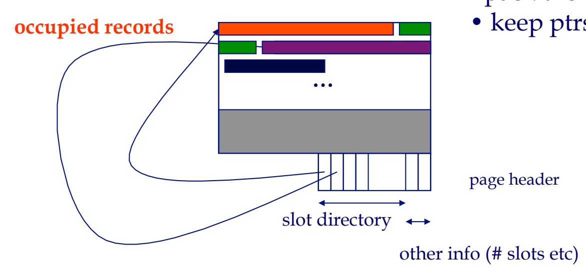
SLOTTED PAGE

Variable length records

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



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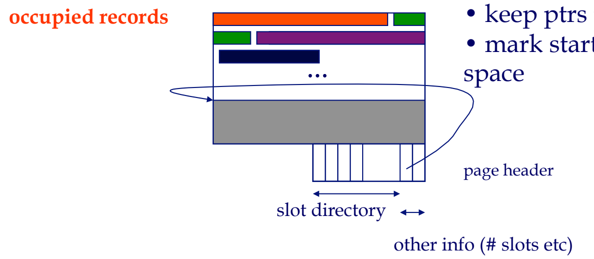
SLOTTED PAGE

Variable length records

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



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

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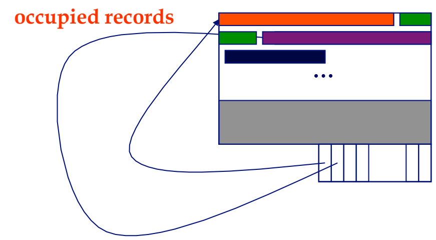
Variable length records

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



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

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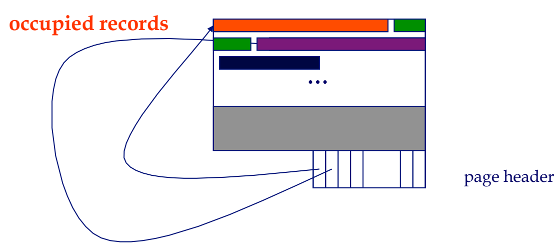
SLOTTED PAGE

Variable length records

- SLOTTED PAGE organization - popular.



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Overview

- Memory hierarchy
- RAID (briefly)
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- Record Formats

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Formats of records

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

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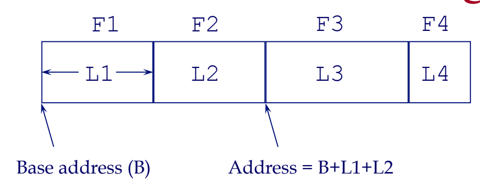
Record Formats: Fixed Length



- 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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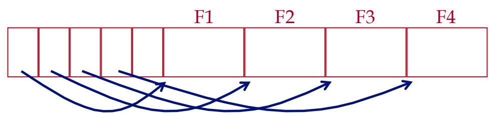
Variable Length records

- Two alternative formats (# fields is fixed):

Fields Delimited by Special Symbols



Array of Field Offsets

Pros and cons?

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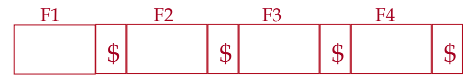
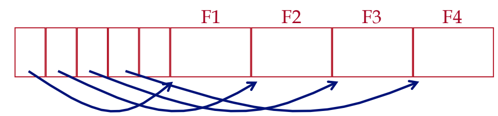
Variable Length records

- 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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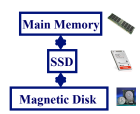
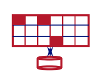
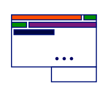
Conclusions



- 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





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