CMU SCS

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

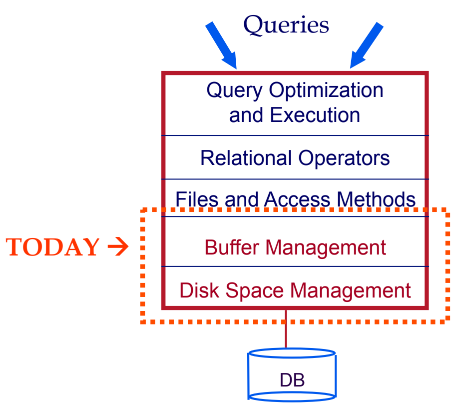
CMU SCS

Overview

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

CMU SCS

DBMS Layers:



CMU SCS

Leverage OS for disk/file management?

- Layers of abstraction are good … but:

CMU SCS

Leverage OS for disk/file management?

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

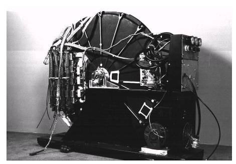
CMU SCS

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

CMU SCS

Disks and Files



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

CMU SCS

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!

CMU SCS

Why Not Store It All in Main Memory?

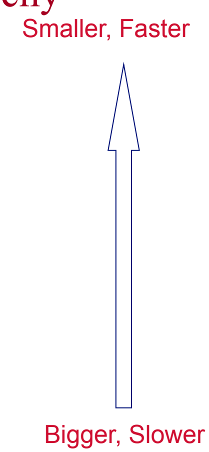
CMU SCS

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.

CMU SCS

The Storage Hierarchy



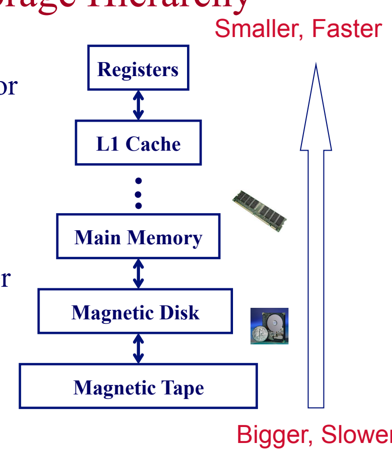
CMU SCS

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).



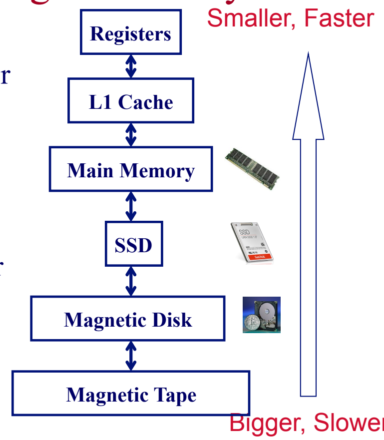
CMU SCS

The Storage Hierarchy

–Main memory (RAM) for currently used data.

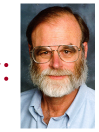
–Disk for the main database (secondary storage).

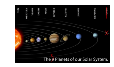
–Tapes for archiving older versions of the data (tertiary storage).



CMU SCS

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	

CMU SCS

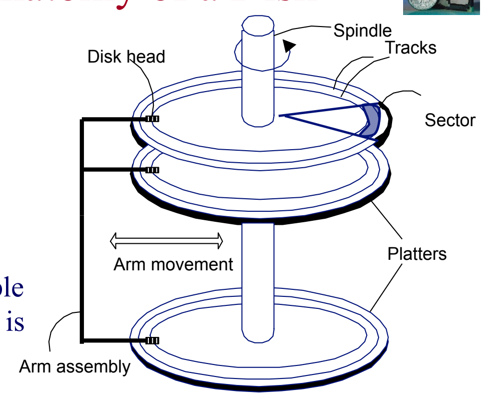
Disks

- 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!

CMU SCS

Anatomy of a Disk

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



CMU SCS

Accessing a Disk Page

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

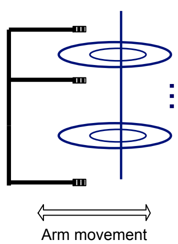
CMU SCS

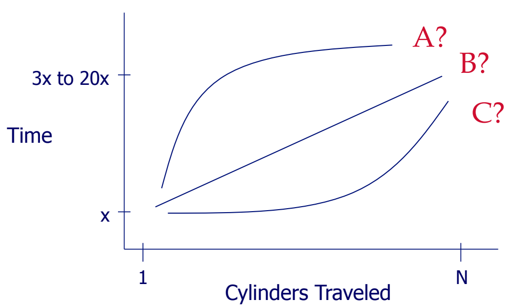
Accessing a Disk Page

- 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

CMU SCS

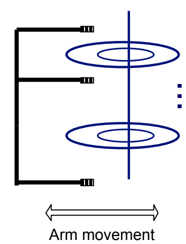
Seek Time

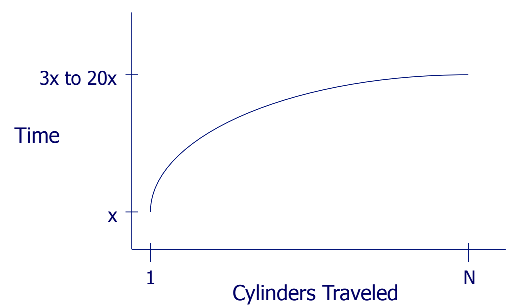




CMU SCS

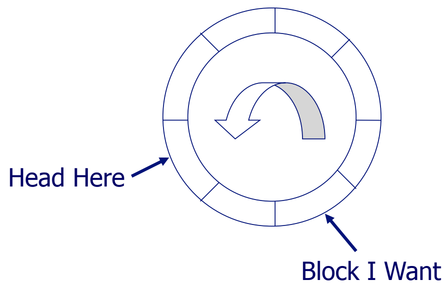
Seek Time





CMU SCS

Rotational Delay



CMU SCS

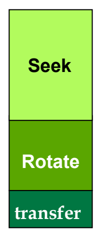
Accessing a Disk Page

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

CMU SCS

Accessing a Disk Page

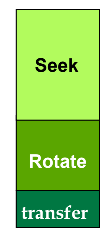
- Relative times?
  - *seek time:* about 1 to 20msec
  - *rotational delay:* 0 to 10msec
  - *transfer time:* < 1msec per 4KB page



CMU SCS

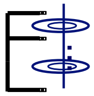
Seek time & rotational delay dominate

- 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



CMU SCS

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?

Faloutsos - Pavlo CMU SCS 15-415/615 #25

CMU SCS

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

Faloutsos - Pavlo CMU SCS 15-415/615 #26

CMU SCS

Overview

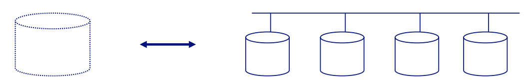
- Memory hierarchy
- RAID (briefly)
- Disk space management
- Buffer management
- Files of records
- Page Formats
- Record Formats

Faloutsos - Pavlo CMU SCS 15-415/615 #27

CMU SCS

Disk Arrays: RAID

Prof. Garth Gibson



Logical Physical

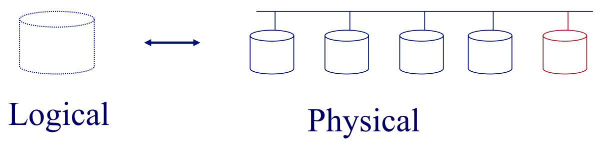
- Benefits:
  - Higher throughput (via data "striping")
  - Longer MTTF

(Why?)

Faloutsos - Pavlo CMU SCS 15-415/615 #28

CMU SCS

Disk Arrays: RAID



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

CMU SCS

Overview

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

CMU SCS

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.

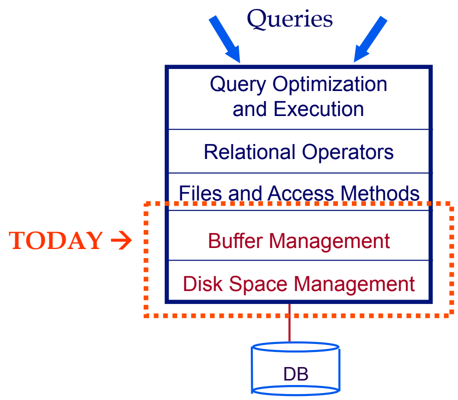
CMU SCS

Overview

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

CMU SCS

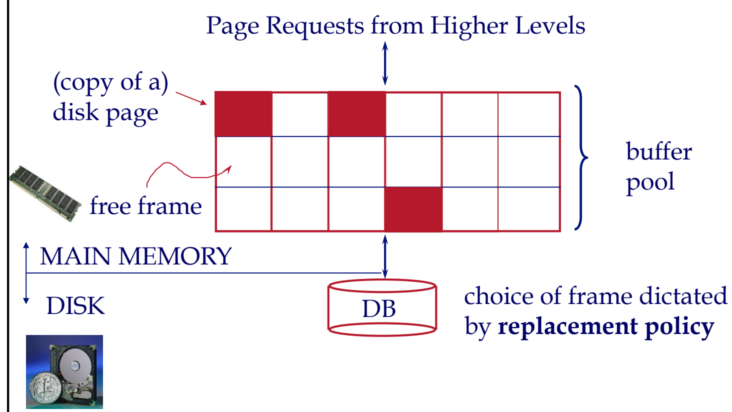
Recall: DBMS Layers



Faloutsos - Pavlo CMU SCS 15-415/615 #33

CMU SCS

Buffer Management in a DBMS

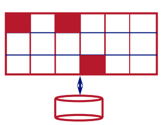


Faloutsos - Pavlo CMU SCS 15-415/615 #34

CMU SCS

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



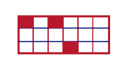
Faloutsos - Pavlo CMU SCS 15-415/615 #35

CMU SCS

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



Faloutsos - Pavlo CMU SCS 15-415/615 #36

CMU SCS

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

Faloutsos - Pavlo CMU SCS 15-415/615 #37

CMU SCS

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!

Faloutsos - Pavlo CMU SCS 15-415/615 #38

CMU SCS

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

Faloutsos - Pavlo CMU SCS 15-415/615 #39

CMU SCS

More on Buffer Management

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

Faloutsos - Pavlo CMU SCS 15-415/615 #40

CMU SCS

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.*

CMU SCS

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?

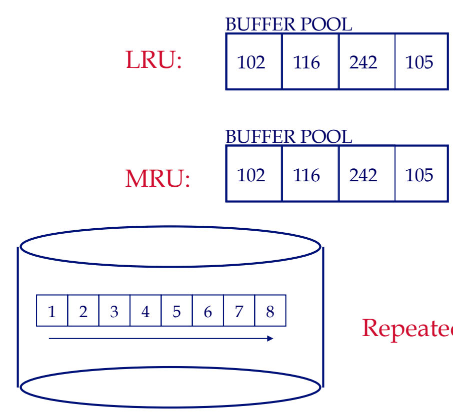
CMU SCS

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).

CMU SCS

Sequential Flooding – Illustration



Repeated scan of file …

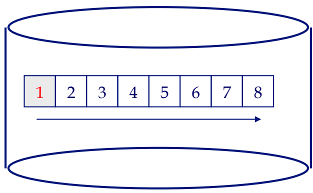
Sequential Flooding – Illustration

LRU: BUFFER POOL

1	116	242	105

MRU: BUFFER POOL

102	116	242	105



Repeated scan of file …

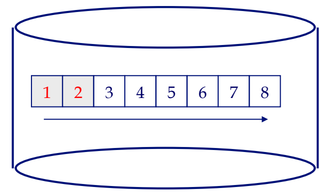
Sequential Flooding – Illustration

LRU: BUFFER POOL

1	2	242	105

MRU: BUFFER POOL

102	116	242	105



Repeated scan of file …

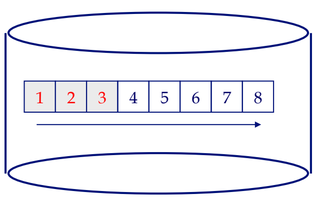
Sequential Flooding – Illustration

LRU: BUFFER POOL

1	2	3	105

MRU: BUFFER POOL

102	116	242	105



Repeated scan of file …

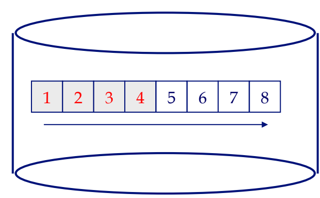
Sequential Flooding – Illustration

LRU: BUFFER POOL

1	2	3	4

MRU: BUFFER POOL

102	116	242	105



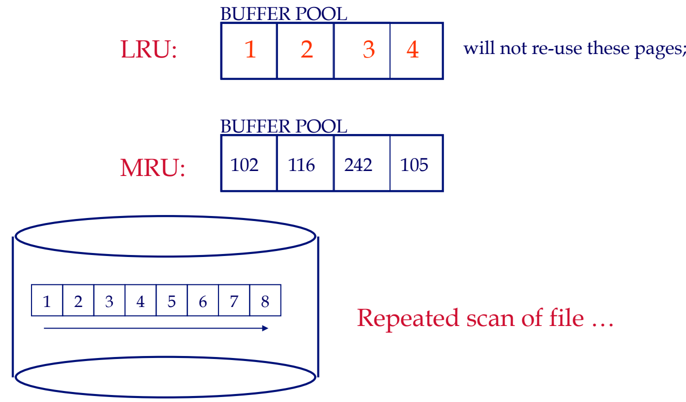
Repeated scan of file …

CMU SCS

How will MRU work?

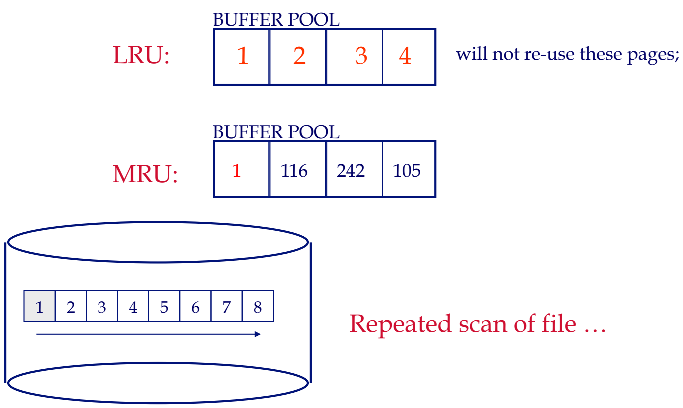
CMU SCS

Sequential Flooding – Illustration



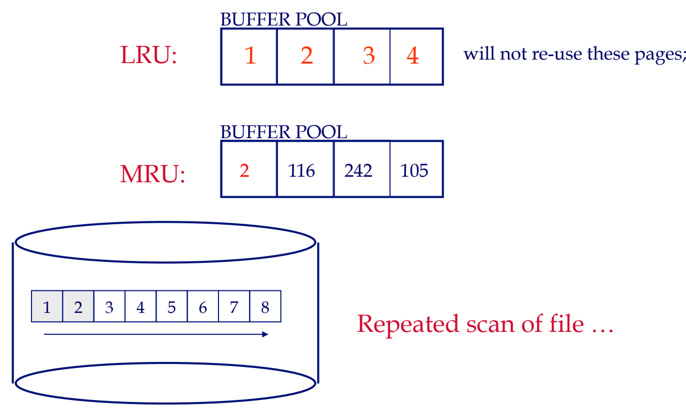
CMU SCS

Sequential Flooding – Illustration



CMU SCS

Sequential Flooding – Illustration



CMU SCS

Sequential Flooding – Illustration

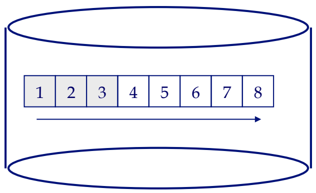
LRU: BUFFER POOL

1	2	3	4

will not re-use these pages;

MRU: BUFFER POOL

3	116	242	105



Repeated scan of file …

CMU SCS

Sequential Flooding – Illustration

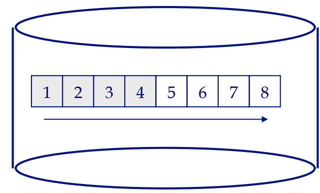
LRU: BUFFER POOL

1	2	3	4

will not re-use these pages;

MRU: BUFFER POOL

4	116	242	105



Repeated scan of file …

CMU SCS

Other policies?

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

CMU SCS

"Clock" Replacement Policy

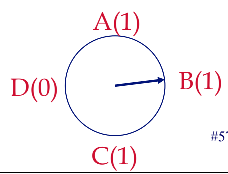
Main ideas:

- 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:

CMU SCS

"Clock" Replacement Policy

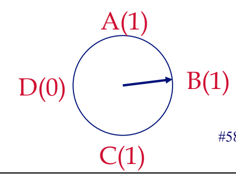
- Arrange frames into a cycle, store one "reference bit" per frame
- When pin count goes to 0, reference bit set on (= 'one life left' - not ready for eviction yet)
- When replacement necessary, get the next frame that has reference-bit = 0



CMU SCS

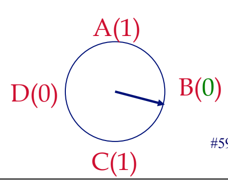
"Clock" Replacement Policy

```
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;
```



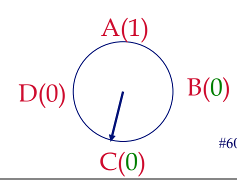
CMU SCS

"Clock" Replacement Policy



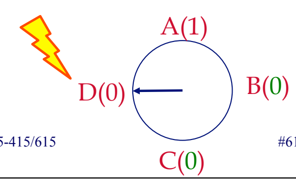
CMU SCS

"Clock" Replacement Policy



CMU SCS

"Clock" Replacement Policy



CMU SCS

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.

CMU SCS

Overview

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

CMU SCS

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)

CMU SCS

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

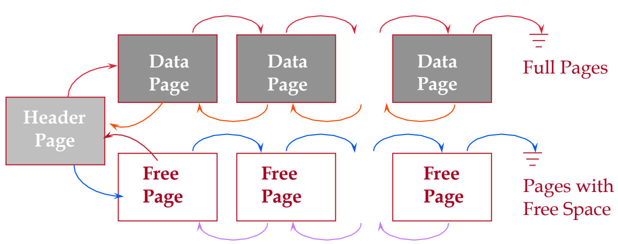
CMU SCS

Files of records

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

CMU SCS

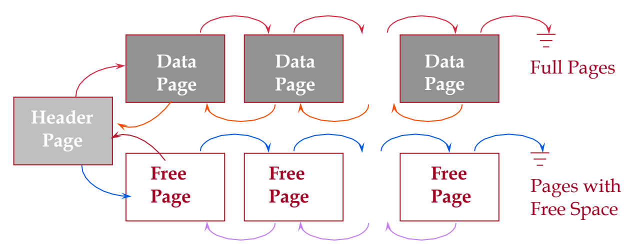
Heap File Using Lists



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

CMU SCS

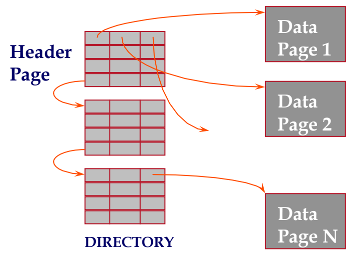
Heap File Using Lists



- Any problems?

CMU SCS

Heap File Using a Page Directory



Faloutsos - Pavlo CMU SCS 15-415/615 #69

CMU SCS

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*!

Faloutsos - Pavlo CMU SCS 15-415/615 #70

CMU SCS

Overview

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

Faloutsos - Pavlo CMU SCS 15-415/615 #71

CMU SCS

Page Formats

- fixed length records
- variable length records

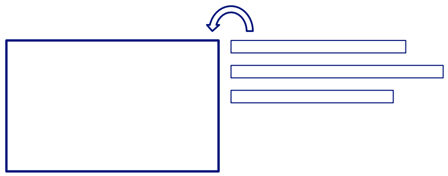
Faloutsos - Pavlo CMU SCS 15-415/615 #72

CMU SCS

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

Faloutsos - Pavlo CMU SCS 15-415/615 #73

CMU SCS

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?

Faloutsos - Pavlo CMU SCS 15-415/615 #74

CMU SCS

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:

Faloutsos - Pavlo CMU SCS 15-415/615 #75

CMU SCS

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.

Faloutsos - Pavlo CMU SCS 15-415/615 #76

CMU SCS

Page Formats

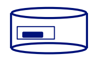
Important concept: *rid* == record id

Q0: why do we need it?

A0: eg., for indexing

Q1: How to mark the location of a record?

A1: rid = record id = page-id & slot-id



Q2: Why not its byte offset in the file?

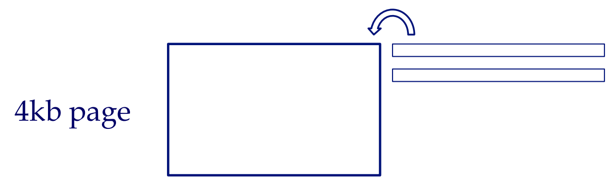
A2: too much re-organization on ins/del.

Faloutsos - Pavlo CMU SCS 15-415/615 #77

CMU SCS

Fixed length records

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

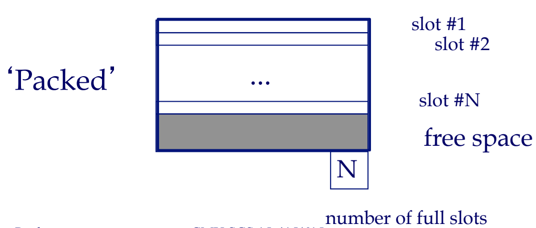


Faloutsos - Pavlo CMU SCS 15-415/615 #78

CMU SCS

Fixed length records

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

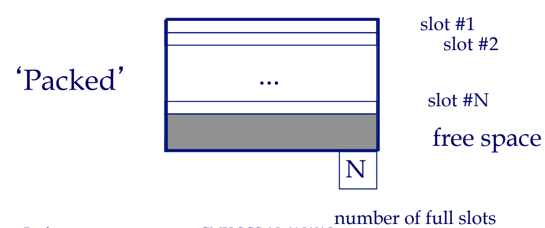


Faloutsos - Pavlo CMU SCS 15-415/615 #79

CMU SCS

Fixed length records

- OK – how about insertion?

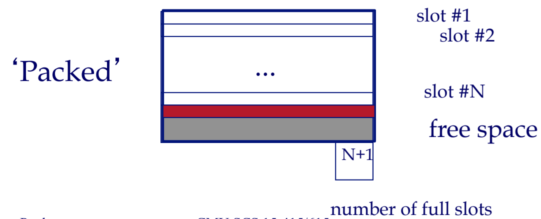


Faloutsos - Pavlo CMU SCS 15-415/615 #80

CMU SCS

Fixed length records

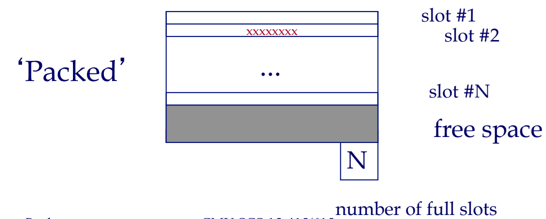
- OK – how about insertion?



CMU SCS

Fixed length records

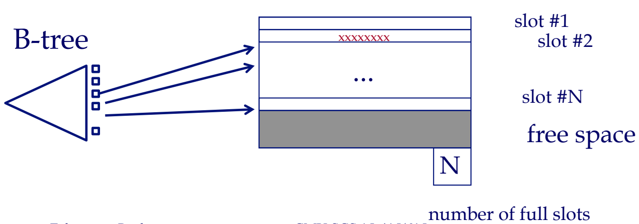
- How about deletion?



CMU SCS

Fixed length records

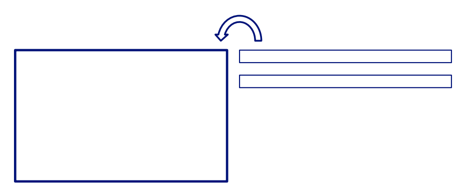
- How about deletion?
- Bad - we have too much to reorganize/update



CMU SCS

Fixed length records

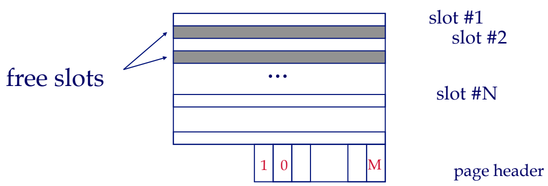
- What would you do?



CMU SCS

Fixed length records

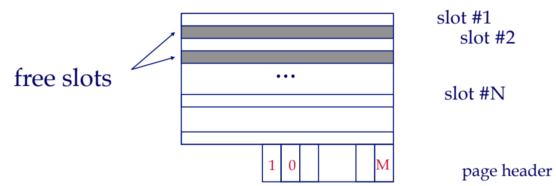
- Q: How would you store them on a page/ file?
- A2: Bitmaps



CMU SCS

Fixed length records

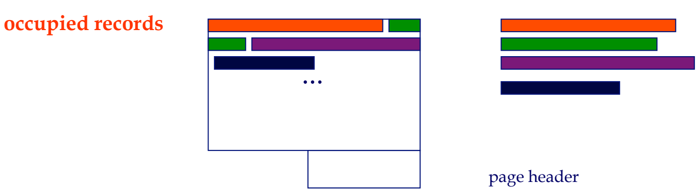
- Q: How would you store them on a page/ file?
- A2: Bitmaps : ✔ insertions, ✔ deletions



CMU SCS

Variable length records

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

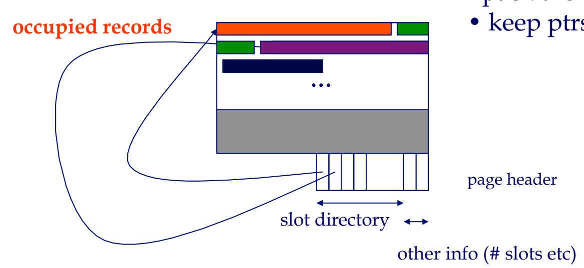


CMU SCS

SLOTTED PAGE

Variable length records

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



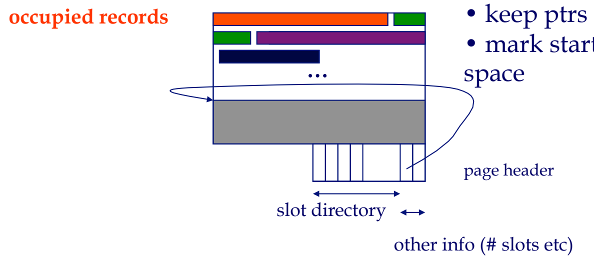
CMU SCS

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



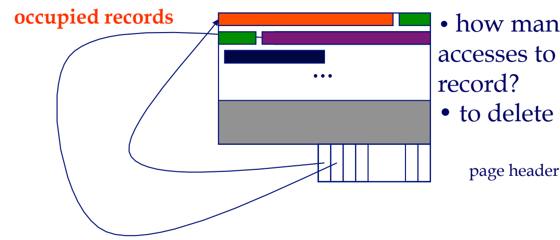
CMU SCS

SLOTTED PAGE

Variable length records

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

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

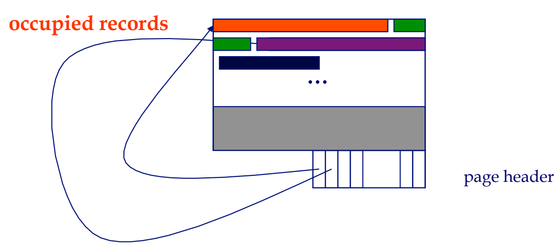


CMU SCS

SLOTTED PAGE

Variable length records

- SLOTTED PAGE organization - popular.



CMU SCS

Overview

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

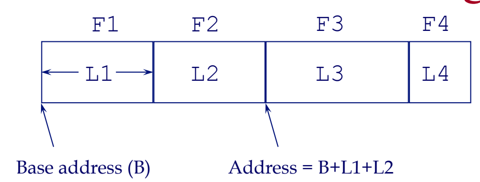
CMU SCS

Formats of records

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

CMU SCS

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.

CMU SCS

Formats of records

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

CMU SCS

Formats of records

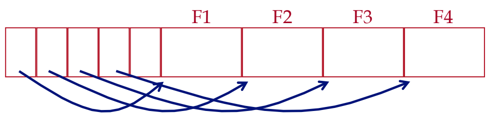
- Fixed length records: straightforward - store info in catalog
- Variable length records: encode the length of each field
  - store its length or
  - use a field delimiter

CMU SCS

Variable Length records

- Two alternative formats (# fields is fixed):

Fields Delimited by Special Symbols



Array of Field Offsets

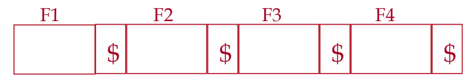
Pros and cons?

Faloutsos - Pavlo CMU SCS 15-415/615 #97

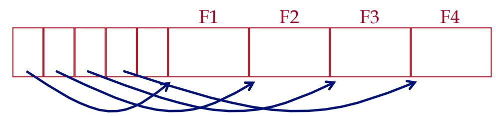
CMU SCS

Variable Length records

- Two alternative formats (# fields is fixed):



Fields Delimited by Special Symbols



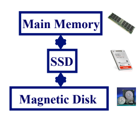
Array of Field Offsets

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

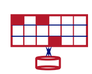
Faloutsos - Pavlo CMU SCS 15-415/615 #98

CMU SCS

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



Faloutsos - Pavlo CMU SCS 15-415/615 #99