Databases

Lecture 8

The Physical Structure of Databases

Files and Indexes

The Physical Structure of Databases

Secondary Storage – Magnetic Disks

- DBMSs operate on data when it is in memory
- block - unit for data transfer between disk and main memory
- time to access a desired location:
    - main memory - approximately the same
    - disk - depends on where the data is stored
- disk access time
    - seek time + rotational delay + transfer time
    - seek time
        - time to move the disk head to the desired track
    - rotational delay
        - time for the block to get under the head
    - transfer time
        - time to read / write the block, once the disk head is positioned over it

Secondary Storage – Magnetic Disks

- the time required for DB operations is usually significantly lower than the time taken to transfer blocks between disk and main memory
- goal
  - minimize access time
  - for this purpose, data should be carefully placed on disk
- records that are often used together should be close to each other:
  - same block
  - same track
  - same cylinder
  - adjacent cylinder
- accessing data in a sequential fashion reduces seek time and rotational delay

Secondary Storage – Magnetic Disks

characteristics, e.g.:

- storage capacity (e.g., GB)
- platters
  - number, *single-sided* or *double-sided*
- average / max seek time (ms)
- average rotational delay (ms)
- number of rotations / min
- data transfer rate (MB/s)
- ...

Gordon Moore

- "the improvement of integrated circuits is following an exponential curve that doubles every 18 months"
    - speed of processors, e.g., number of instructions executed / sec
    - no. of bits / chip
    - disks capacities
- parameters that do not follow Moore’s law
    - access speed of main memory
    - disk rotation speed

=> latency keeps increasing

- time to move data between memory hierarchy levels appears to take longer compared with computation time

Solid State Drives

- NAND flash components
- extremely low latency
- very fast read / write speeds
- no moving parts, completely silent
- cost per GB - higher than HDDs
- limited write cycles

Managing Space on the Disk

- the *disk space manager* (DSM) manages space on disk
- page
  - unit of data
  - size of a page = size of a disk block
  - R/W a page - one I/O operation
- upper layers in the DBMS can operate with data as a collection of pages; DSM hides details of the hardware
- DSM
  - commands to allocate / deallocate / read / write a page
  - knows which pages are on which disk blocks
  - monitors disk usage, keeping track of available disk blocks

Managing Space on the Disk

- free blocks can be identified:
  - by maintaining them as a linked list (on deallocation, a block is added to the list)
  - by maintaining a bitmap with one bit / block, indicating whether the corresponding block is used or not
    - allows for fast identification of contiguous available areas on disk

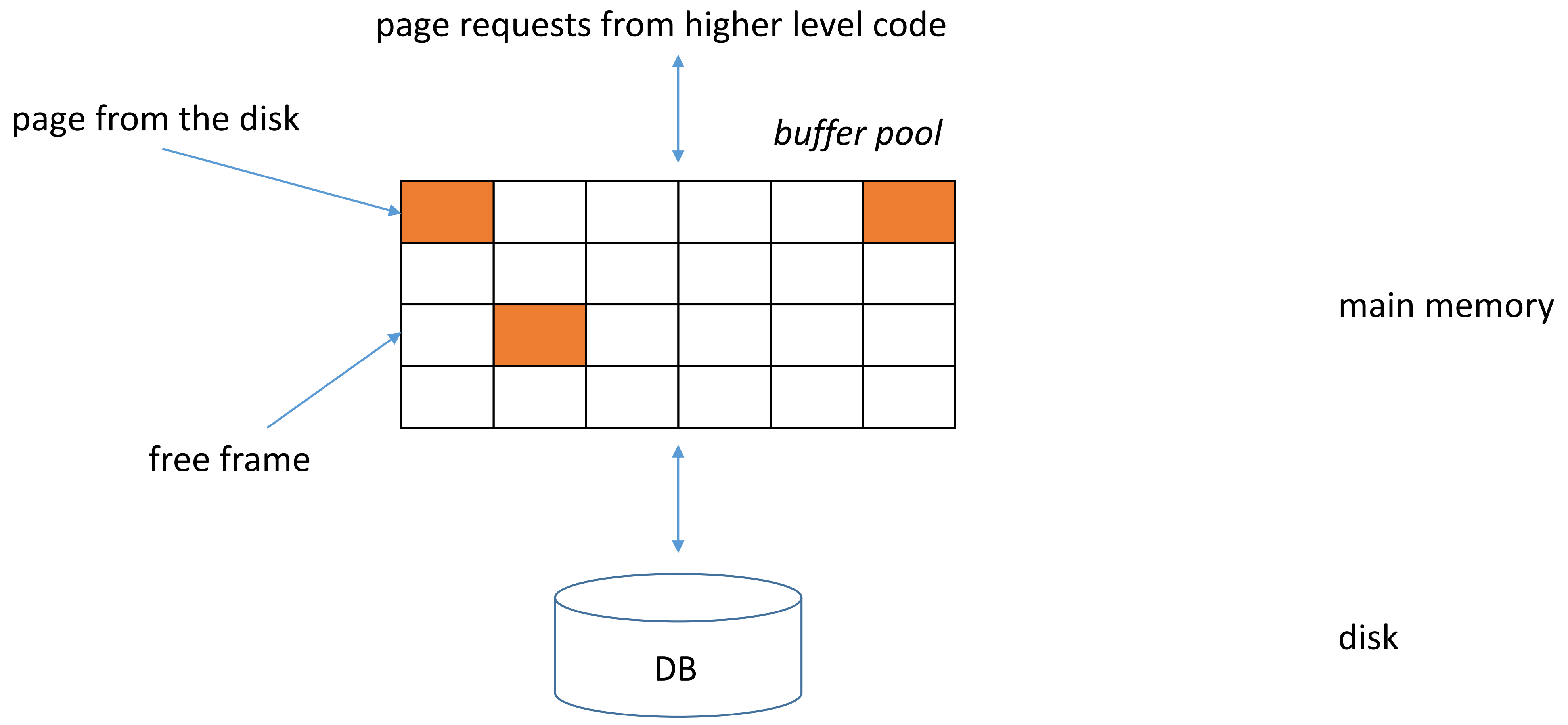
Buffer Manager

- e.g., DB = 500.000 pages, main memory - 1000 available pages, query that scans the entire data set
- *buffer manager* (BM)
    - brings new data pages from disk into main memory as they are required
    - decides what main memory pages can be replaced
    - manages the available main memory
        - collection of pages called the *buffer pool* (BP)
        - *frames*
            - pages in the BP
            - slots that can hold a page
- *replacement policy*
    - policy that dictates the choice of replacement frames in the BP

Buffer Manager

- higher level layer L in the DBMS:
    - asks the BM for page P
    - if P is not in the BP, the BM brings it into a frame F in the BP
    - when P is no longer needed:
        - L releases P
        - the BM is notified, so F can be reused
        - if P has been modified, the BM is notified and propagates the changes in the BP to the disk

Buffer Manager



Buffer Manager

- BM maintains 2 variables for every frame F
    - *pin_count*
        - number of current users (requested the page in F but haven't released it yet)
        - only frames with pin_count = 0 can be chosen as replacement frames
    - *dirty*
        - boolean value indicating whether the page in F has been changed since being brought into F
- incrementing pin_count
    - pinning a page P in a frame F
- decrementing pin_count
    - unpinning a page

Buffer Manager

- initially, pin_count = 0, dirty = off, ∀ F ∈ BP
- L asks for a page P; the BM:

1. checks whether page P is in a frame F in BP; if so, pin_count(F)++;

otherwise:

a. BM chooses a frame FR for replacement

- if the BP contains multiple frames with pin_count = 0, one frame is chosen according to the BM's replacement policy
- pin_count(FR)++;

b. if dirty(FR) = on, BM writes the page in FR to disk

c. BM reads page P in frame FR

2. the BM returns L the address of the BP frame that contains P

Buffer Manager

- obs. if no BP frame has pin_count = 0 and page P is not in BP, BM has to wait / the transaction may be aborted
- page requested by several transactions; no conflicting updates

- crash recovery, Write-Ahead Log (WAL) protocol - additional restrictions when a frame is chosen for replacement

Buffer Manager

- replacement policies
  - *Least Recently Used (LRU)*
    - queue of pointers to frames with pin_count = 0
    - a frame is added to the queue when its pin_count becomes 0
    - the frame at the head of the queue is chosen for replacement
  - *Most Recently Used (MRU)*
  - *random*
  - *...*

Buffer Manager

- replacement policies
    - *clock replacement*
        - LRU variant
        - *n* – number of frames in BP
        - frame - *referenced* bit; set to *on* when *pin_count* becomes 0
        - *crt* variable - frames 1 through *n*, circular order
        - if the current frame is not chosen, then *crt*++, examine next frame

        - if *pin_count* > 0
            - current frame not a candidate, *crt*++
        - if *referenced = on*
            - *referenced* := *off*, *crt*++
        - if *pin_count* = 0 AND *referenced = off*
            - choose current frame for replacement

Buffer Manager

- replacement policies
    - can have a significant impact on performance
- e.g.:
    - BM uses LRU
    - repeated scans of file *f*
    - BP: 5 frames, *f*: <= 5 pages
        - first scan of *f* brings all the pages in the BP
        - subsequent scans find all the pages in the BP
    - BP: 5 frames, *f*: 6 pages
        - *sequential flooding*: every scan of *f* reads all the pages
        - MRU – better in this case (but not in all cases)

Disk Space Manager & Buffer Manager

- DSM
  - portability - different OSs
  - specialized disk management, i.e., Disk Space Manager
- BM
  - DBMS can anticipate the next several page requests (operations with a known page access pattern, e.g., sequential scans)
  - *prefetching* - BM brings pages in the BP before they are requested
  - prefetched pages
    - contiguous: faster reading (than reading the same pages at different times)
    - not contiguous: determine an access order that minimizes seek times / rotational delays

Disk Space Manager & Buffer Manager

- BM
  - DBMS needs
    - ability to explicitly force a page to disk
    - ability to write some pages to disk before other pages are written
      - WAL protocol - first write log records describing page changes, then write modified page
  - specialized main memory management, i.e., Buffer Manager

Files and Indexes

Files

- higher level layers in the DBMS treat pages as collections of records
- file of records
    - collection of records; one or more pages
- different ways to organize a file's collection of pages
- every record has an identifier, i.e., the rid
- given the rid of a record, one can obtain the page that contains the record

Heap Files

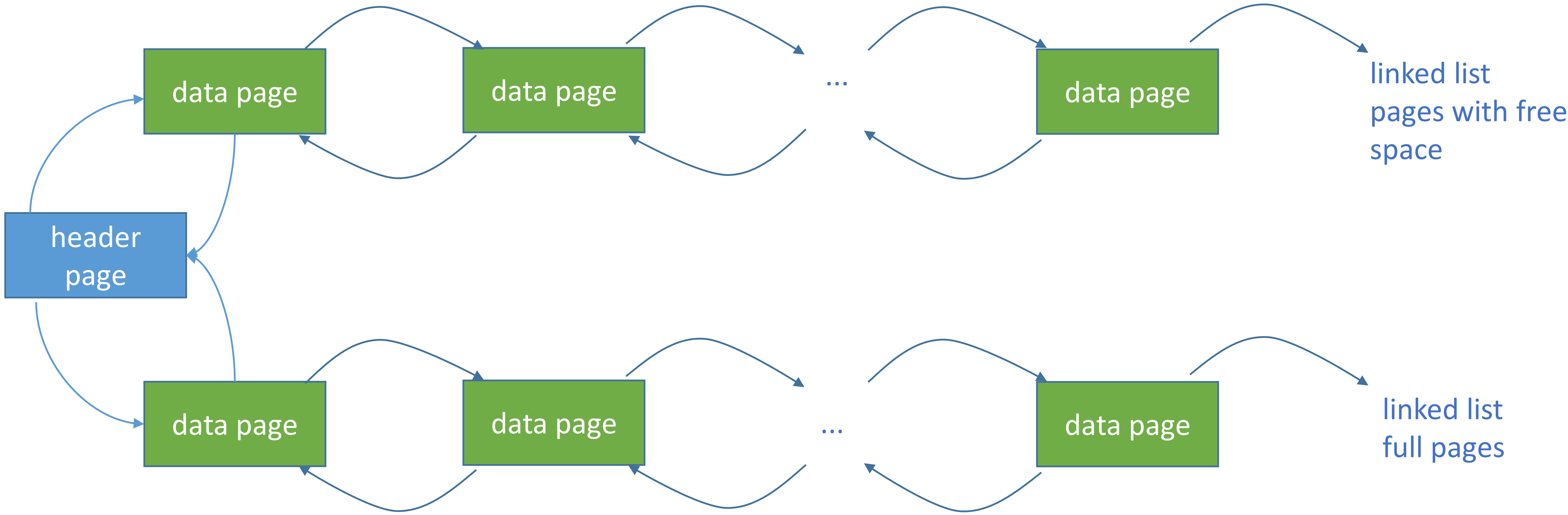
- the simplest file structure
- records are not ordered
- supported operations
  - create file
  - destroy file
  - insert a record
    - need to monitor pages with free space
  - retrieve a record given its rid
  - delete a record given its rid
  - scan all records
    - need to keep track of all the pages in the file

Heap Files

- appropriate when the expected pattern of use includes frequent scans to obtain all the records

Heap Files - Linked List

- doubly linked list of pages
- DBMS stores the address of the first page (*header page*) of each file, i.e., table holding pairs of the form <*heap_file_name*, *page1_address*>
- 2 lists – pages with free space and full pages

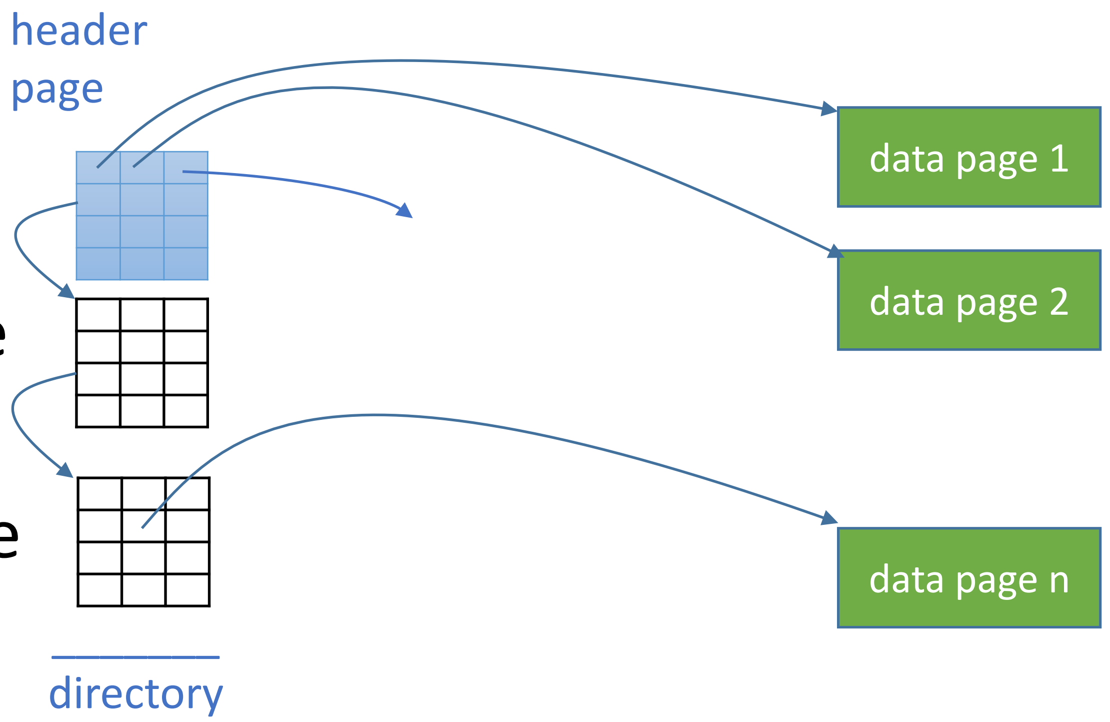


Heap Files - Linked List

- drawback
  - variable-length records => most of the pages will be in the list of pages with free space
  - when adding a record, multiple pages have to be checked until one is found that has enough free space

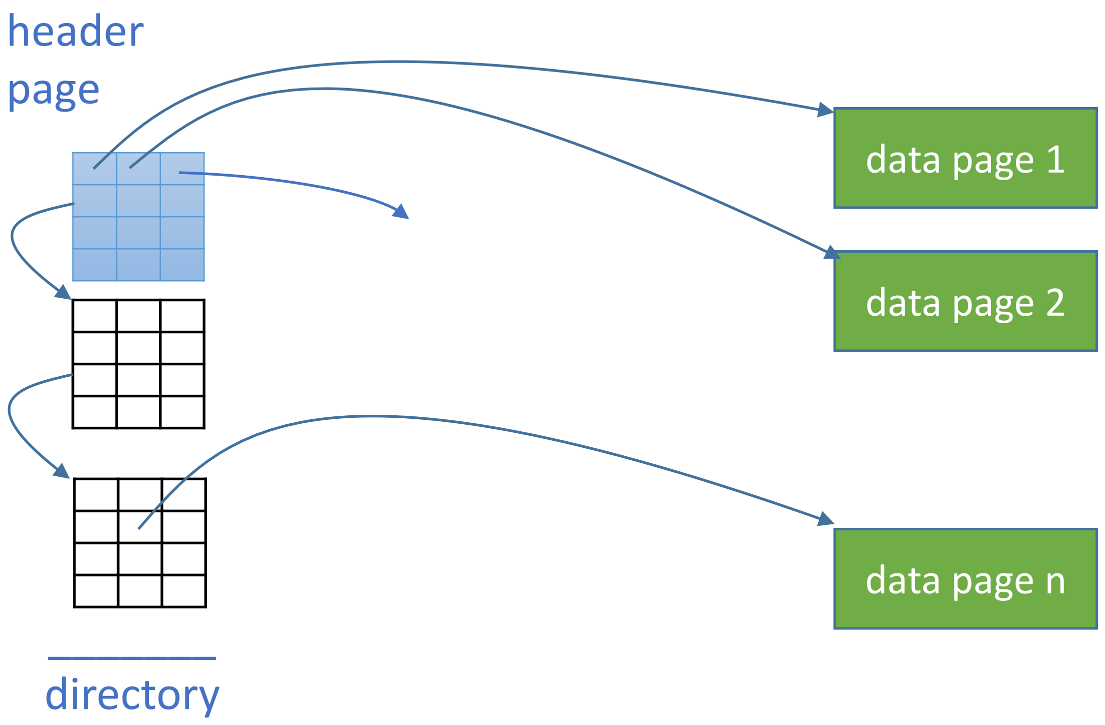
Heap Files - Directory of Pages

- DBMS stores the location of the header page for each heap file directory
- directory
  - collection of pages (e.g., linked list)
- directory entry
  - identifies a page in the file
- directory entry size
  - much smaller than the size of a page
- directory size
  - much smaller than the size of the file



Heap Files - Directory of Pages

- free space management
  - 1 bit / directory entry
    - corresponding page has / doesn't have free space
  - count / entry
    - available space on the corresponding page => efficient search of pages with enough free space when adding a variable-length record

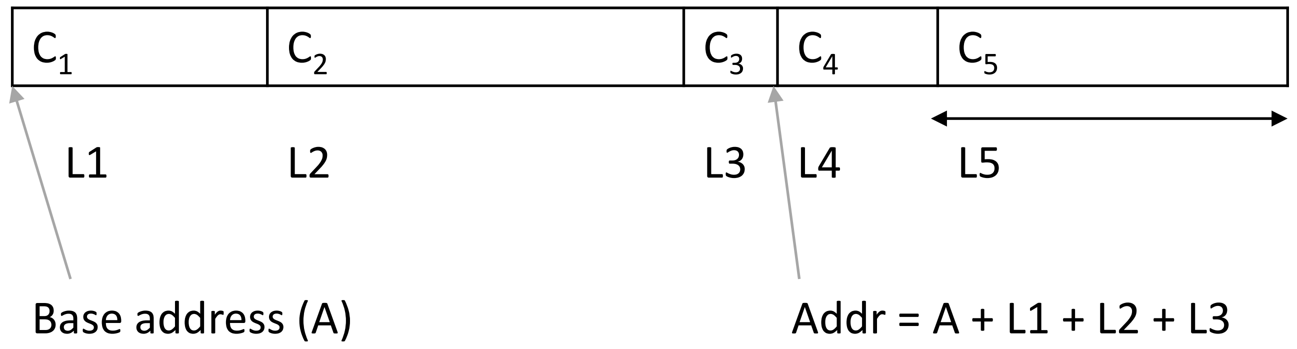


Files - Other File Organizations

- ordered files
  - suitable when data must be sorted, when doing range selections
- files hashed on some fields
  - records are stored according to a hash function

Record Formats

- fixed-length records

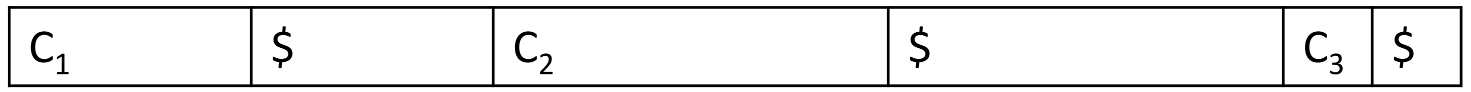


  - each field has a fixed length
  - fixed number of fields
  - fields - stored consecutively
  - computing a field's address
    - record address, length of preceding fields (from the system catalog)

Record Formats

- variable-length records
    - variable-length fields

v1

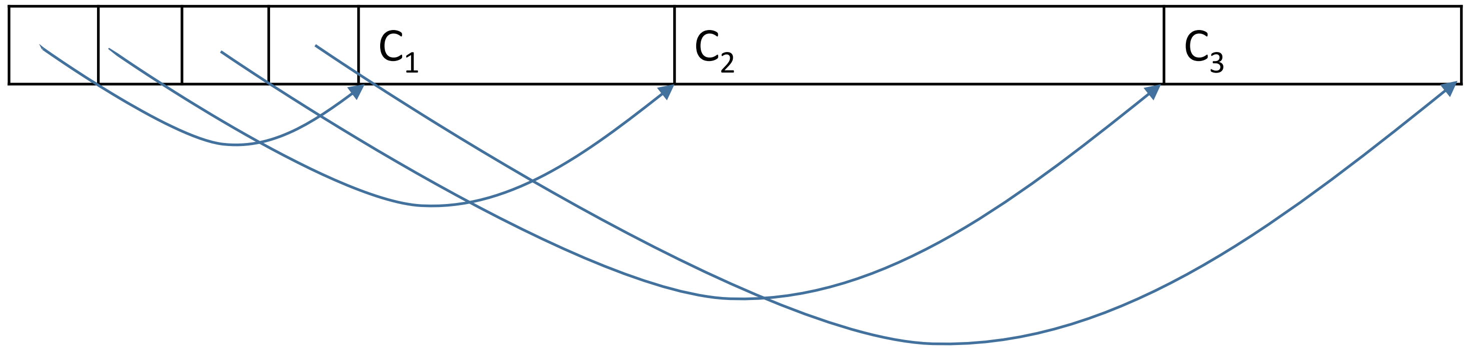


- fields
    - stored consecutively, separated by delimiters
- finding a field
    - a record scan

Record Formats

- variable-length records

v2



- reserve space at the beginning of the record
  - array of fields offsets, offset to the end of the record
- array overhead, but direct access to every field

Page Formats

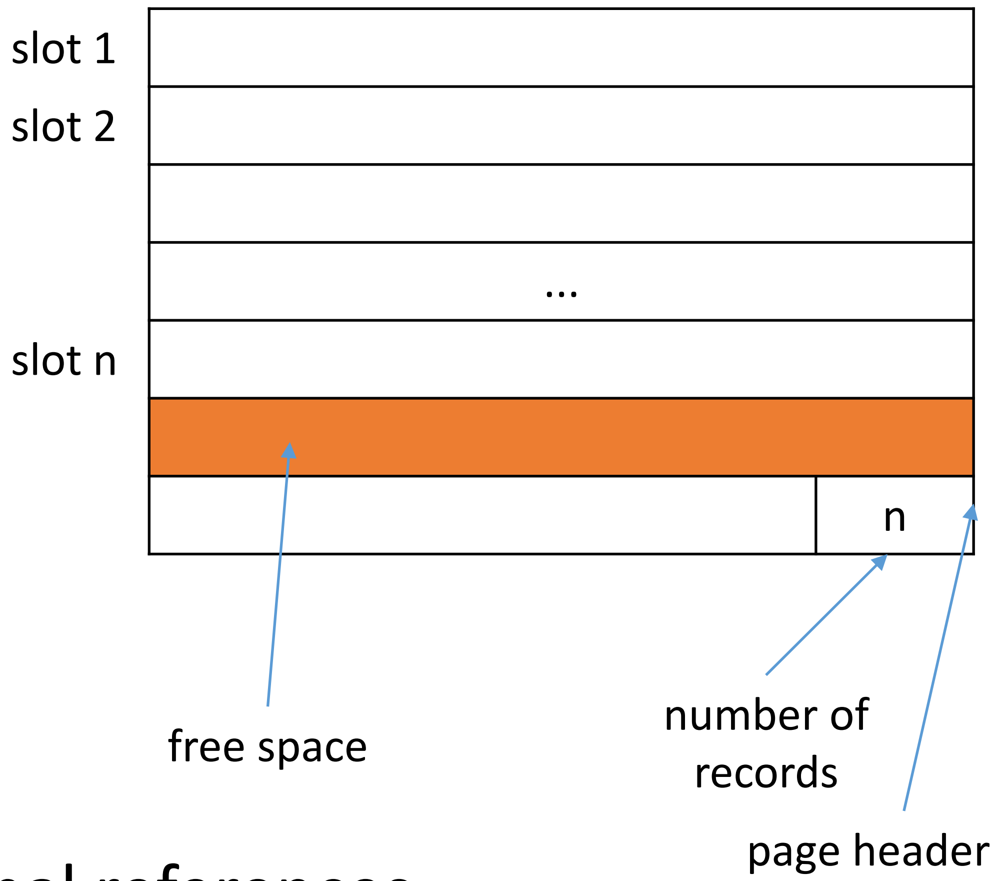
- page
    - collection of slots
    - 1 record / slot
- identifying a record
    - record id (rid): <page id, slot number>
- how to arrange records on pages
- how to manage slots

Page Formats

- fixed-length records
    - records have the same size
    - uniform, consecutive slots
    - adding a record
        - finding an available slot
    - problems
        - keeping track of available slots
        - locating records

Page Formats

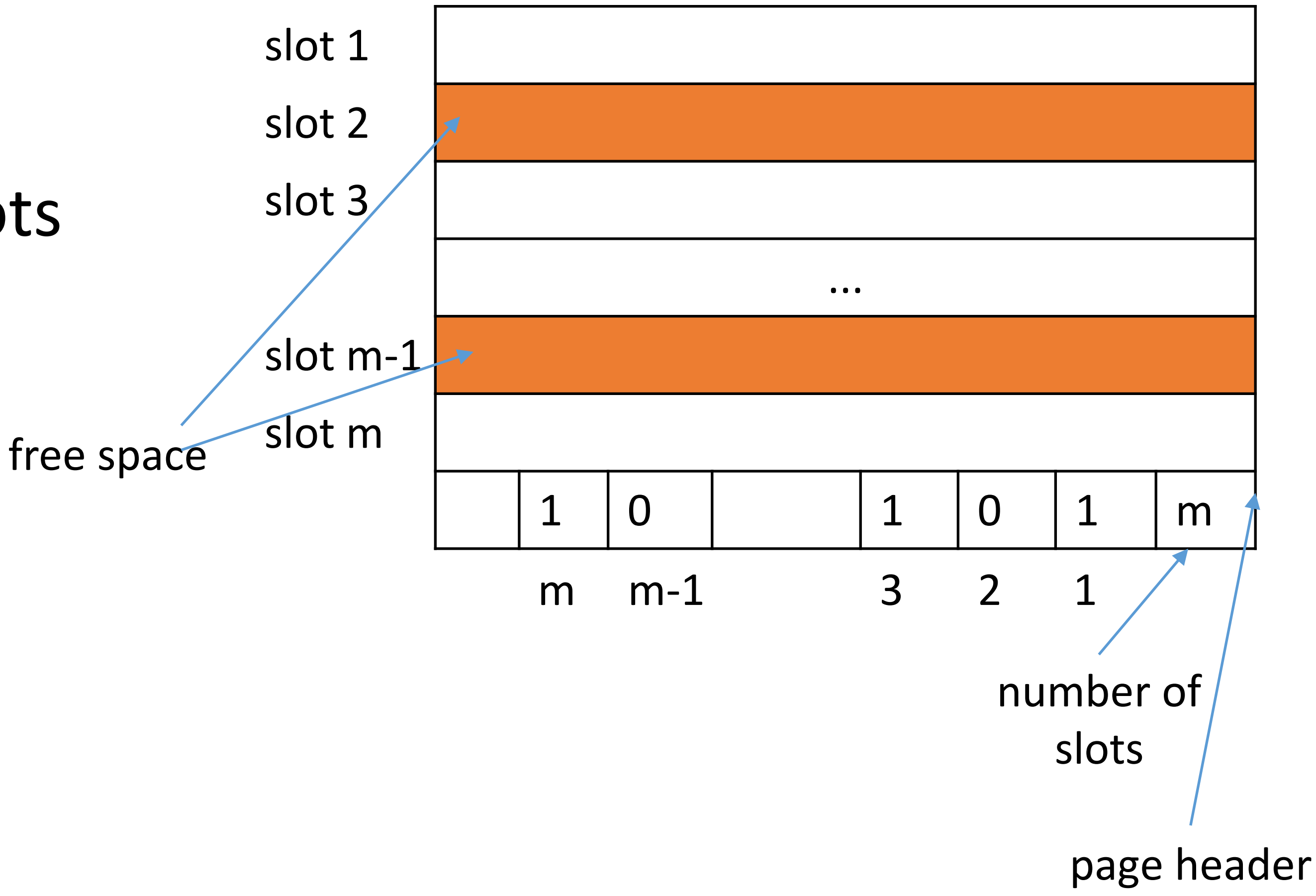
- fixed-length records - v1
  - *n* – number of records on the page
  - records are stored in the first *n* slots
  - locating record *i* - compute corresponding offset
  - deleting a record - the last record on the page is moved into the empty slot
  - empty slots - at the end of the page



- problems when a moved record has external references
  - the record's slot number would change, but the rid contains the slot number!

Page Formats

- fixed-length records - v2
- array of bits to monitor available slots
- 1 bit / slot
- deleting a record - turning off the corresponding bit

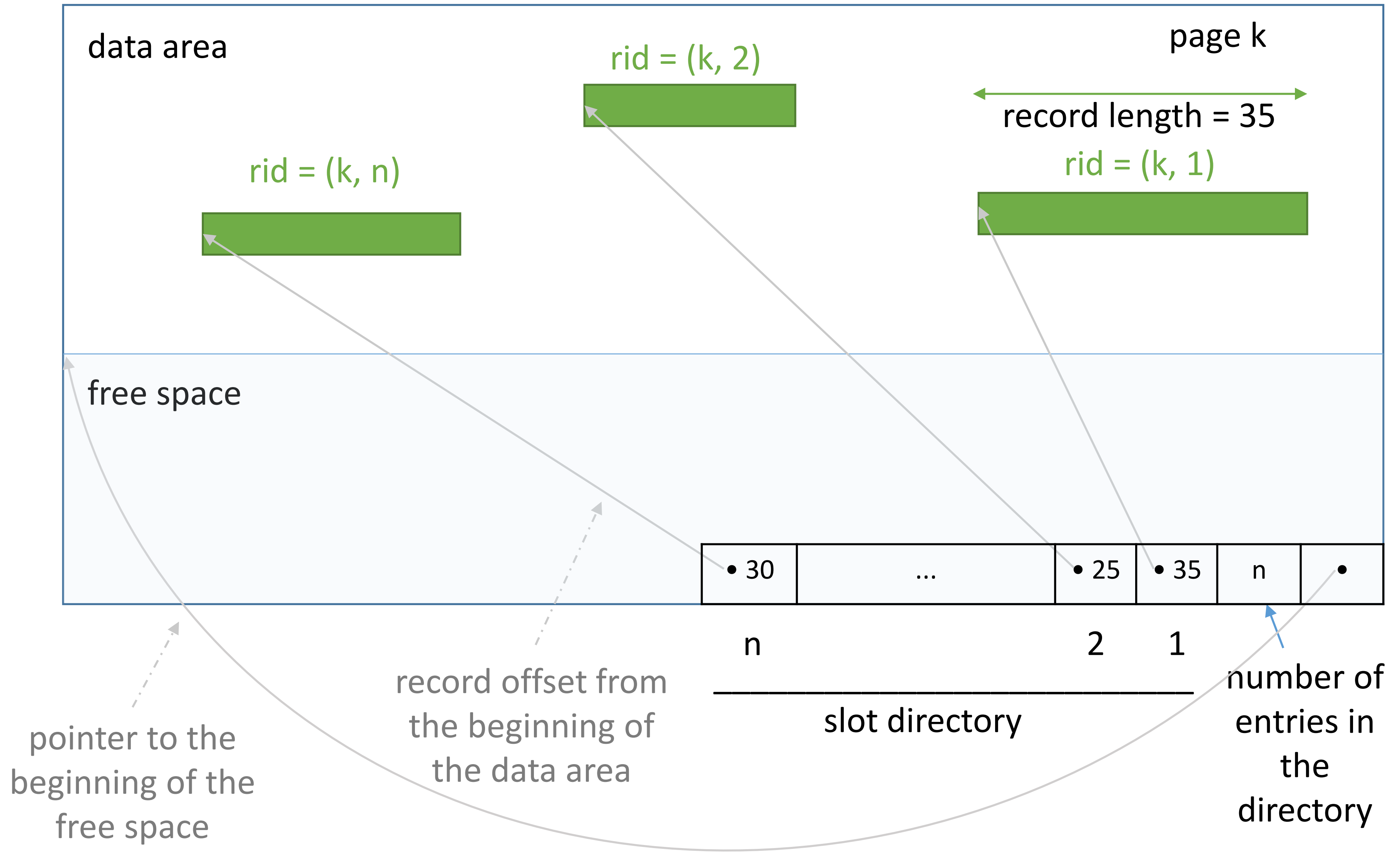


Page Formats

- variable-length records
  - adding a record
    - finding an empty slot of the right size
  - deleting a record
    - contiguous free space
  - a directory of slots / page
  - a pair <record offset , record length> / slot
  - a pointer to the beginning of the free space area on the page
  - moving a record on the page
    - only the record's offset changes
    - its slot remains unmodified
  - can also be used for fixed-length records (e.g., when records need to be kept sorted)

Page Formats

- variable-length records


data area
page k
rid = (k, 2)
record length = 35
rid = (k, 1)
rid = (k, n)
free space
• 30
...
• 25
• 35
n
•
n
2
1
slot directory
number of entries in the directory
record offset from the beginning of the data area
pointer to the beginning of the free space

Indexes

- motivating example
  - file of students records sorted by name
  - the following operation can be efficiently carried out, given the organization of the file
    - *retrieve all the students in alphabetical order*
  - but the file organization doesn't support the efficient execution of the following operations, both of which would require a scan of the file
    - *retrieve all the students whose age is in a given range*
    - *retrieve all the students who live in Timișoara*

Indexes

- index
  - auxiliary data structure that speeds up operations which can't be efficiently carried out given the file's organization
  - enables the retrieval of the rids of records that meet a selection condition (e.g., the rids of records describing students who live in Timișoara)

Indexes

- *search key*
  - set of one or more attributes of the indexed file (different from the *key* that identifies records)
- an index speeds up queries with equality / range selection conditions on the search key
- *entries*
  - records in the index
  - enable the retrieval of the records with a given search key value, e.g., <search key, rid>

Indexes

- example
  - files with students records
  - index built on attribute *city*
  - entries: <city, rid>, where rid identifies a student record
  - such an index would speed up queries about students living in a given city:
    - find entries in the index with city *= 'Timisoara'*
    - follow rids from obtained entries to retrieve records storing data about students who live in Timișoara

Indexes

- an index can improve the efficiency of certain types of queries, not of all queries, e.g., when searching for a book at the library, index cards sorted on author name cannot be used to efficiently locate a book given its title
- organization techniques (access methods) - examples
  - B+ trees
  - structures based on hash functions

Indexes

- changing the data in the file => update the indexes associated with the file (e.g., inserting records, updating search key columns, updating columns that are not part of the key, but are included in the index)
- index size
  - as small as possible, as indexes are brought into main memory for searches

References

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