Chapter 7: Storage Management

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Outline[1]

1. Storage Media
2. Representation of Databases on Disks
   - Value Representation
   - Tuple Layout
   - Page Layout
     - Tuple-Oriented Page Layout
     - Log-Structured Page Layout
   - File Organization
3. System Catalogs
4. Buffer Management

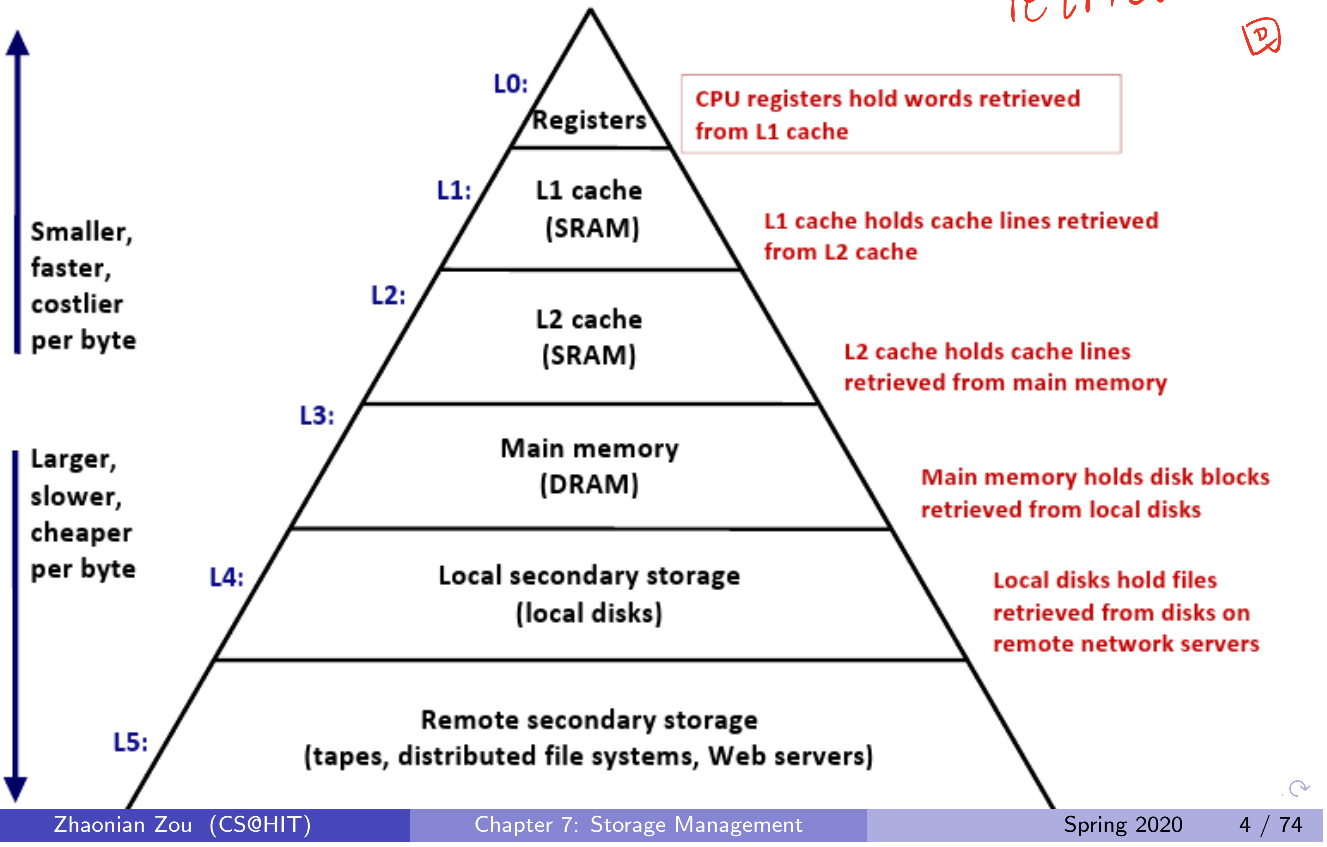
[1] Updated on March 24, 2020

Storage Media

The Memory Hierarchy (存储层级)

Memory in a computer system is arranged in a *hierarchy*

retrieve 恢复、取回



Smaller, faster, costlier per byte

Larger, slower, cheaper per byte

L0: Registers

L1: L1 cache (SRAM)

L2: L2 cache (SRAM)

L3: Main memory (DRAM)

L4: Local secondary storage (local disks)

L5: Remote secondary storage (tapes, distributed file systems, Web servers)

CPU registers hold words retrieved from L1 cache

L1 cache holds cache lines retrieved from L2 cache

L2 cache holds cache lines retrieved from main memory

Main memory holds disk blocks retrieved from local disks

Local disks hold files retrieved from disks on remote network servers

Primary Storage (主存储器)

Data in primary storage can be operated on directly by CPUs using `load/store`

- Registers (寄存器)
- Cache (高速缓存)
- Main memory (内存)

Primary storage is byte-addressable (按字节寻址)

Secondary Storage (二级存储器)

Data in secondary storage cannot be processed directly by CPUs; It must first be copied into primary storage using `read/write`

- Magnetic disks (磁盘)/Hard disk drives (HDD, 机械硬盘)
- Flash memory (闪存)/Solid state drives (SSD, 固态硬盘)

Secondary storage is block-addressable (按块寻址) and online (联机)

Tertiary Storage (三级存储器)

Data in tertiary storage must first be copied into secondary storage

- Magnetic tape (磁带)
- Optical disks (光盘)
- Network Storage (网络存储)

Tertiary storage is block-addressable and offline (脱机)

Access Time (访存时间)

Access time (ns)	Storage media
0.5	L1 cache
7	L2 cache
100	DRAM
150,000	SSD
10,000,000	HDD
30,000,000	Network storage
1,000,000,000	Tape

Data Transfer Between Levels

- Cache

  ↕ Unit: cache lines (缓存行), size: 64B
- Main memory

  ↕ Unit: blocks (块)/pages (页), size: 512B–16KB
- Secondary storage

  ↕ Unit: blocks/pages, size: 512B–16KB
- Tertiary storage

Categories of Storage Media

Volatile Storage

Volatile Storage (易失存储器)
Data in volatile storage is lost when the computer is restarted (after a shutdown or a crash)

- Primary storage

Non-volatile Storage (非易失存储器)
Data in non-volatile storage is retained when the computer is restarted

- Secondary storage
- Tertiary storage

Non-volatile main memory is emerging!

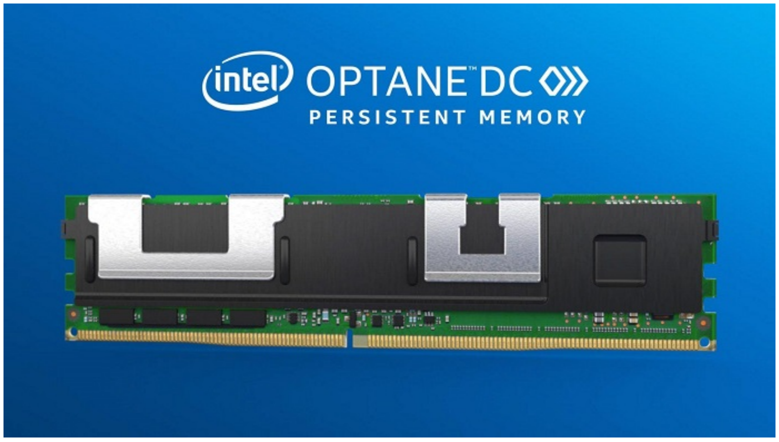
Non-volatile Main Memory (NVM, 非易失主存)

NVM is also known as persistent memory or storage-class memory (SCM)

持续的

- Byte-addressable
- Non-volatile (persistent)

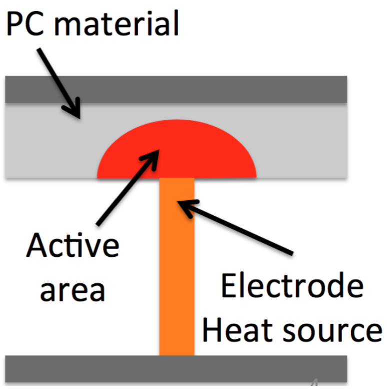
Intel Optane (傲腾) DC Persistent Memory



Persistent Memory Developing Toolkit (PMDK) (`http://pmem.io`)

Phase-Change Memory (PCM, 相变存储器)

- PCM stores data using phase-change material (相变材料)
  - Amorphous phase (非晶态): high resistivity ⟶ 0
  - Crystalline phase (晶态): low resistivity ⟶ 1
- Set phase via current pulse
  - Fast cooling → Amorphous
  - Slow cooling → Crystalline



Characteristics of NVM

Characteristics	DRAM	PCM	Memristor	MRAM	SSD	HDD
Volatility	Yes	No	No	No	No	No
Addressability	Byte	Byte	Byte	Byte	Block	Block
Volume	GB	TB	TB	TB	TB	TB
Read latency	60ns	50ns	100ns	20ns	25μs	10ms
Write latency	60ns	150ns	100ns	20ns	300μs	10ms
Energy per bit	2pJ	2pJ	100pJ	0.02pJ	10nJ	0.1J
Endurance	10^{16}	10^{10}	10^{8}	10^{15}	10^{5}	10^{16}

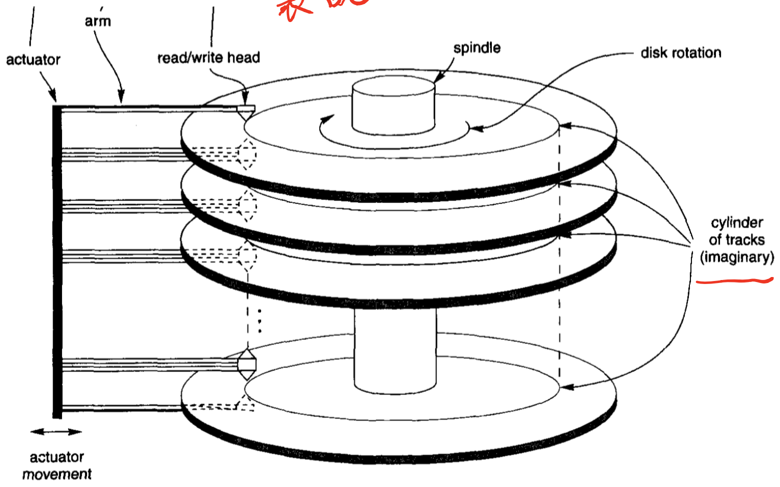
NVM will become a critical level in the memory hierarchy and plays important roles in computer systems and DBMS

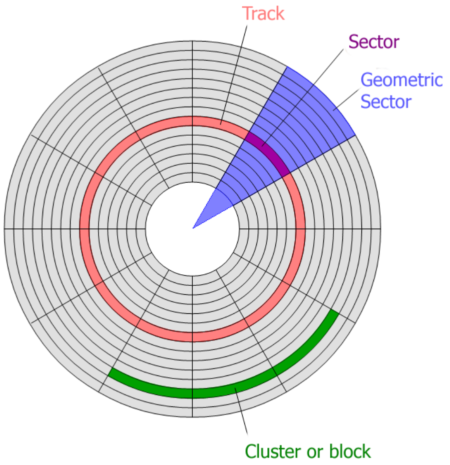
Magnetic Disks (磁盘)

A magnetic disk is composed by two components:

- Disk assembly: sectors (扇区) ⊂ tracks (磁道) ⊂ cylinders (柱面)
- Head assembly: disk heads (磁头) and disk arms (磁臂)

装配





Sectors (扇区)

Every track on disks is divided into smaller sectors

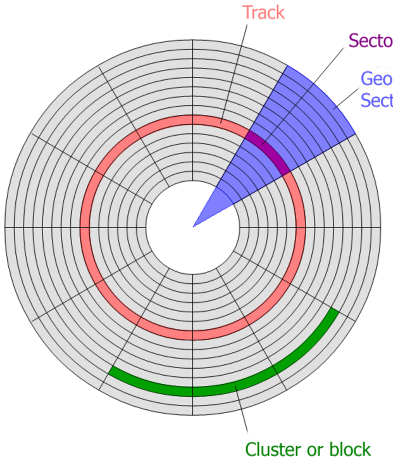
- The division of a track into sectors is hard-coded on the disk surface and cannot be changed

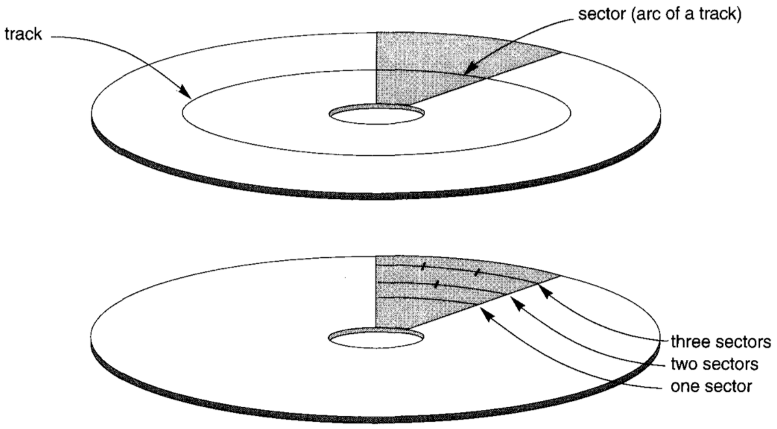
Sector organizations

朝向

Approach

- Approach #1: Sectors subtend a fixed angle
- Approach #2: Sectors maintain a uniform recording density





Disk Blocks (磁盘块)/Pages (页)

磁道

The OS divides a track into equal-sized disk blocks (or pages) during disk formatting

- The size of a disk block can be set as a multiple of the sector size
- Block size is fixed during disk formatting and cannot be changed dynamically
- Typical disk block size is 512B–4KB

Logical Block Address (LBA, 逻辑块地址)

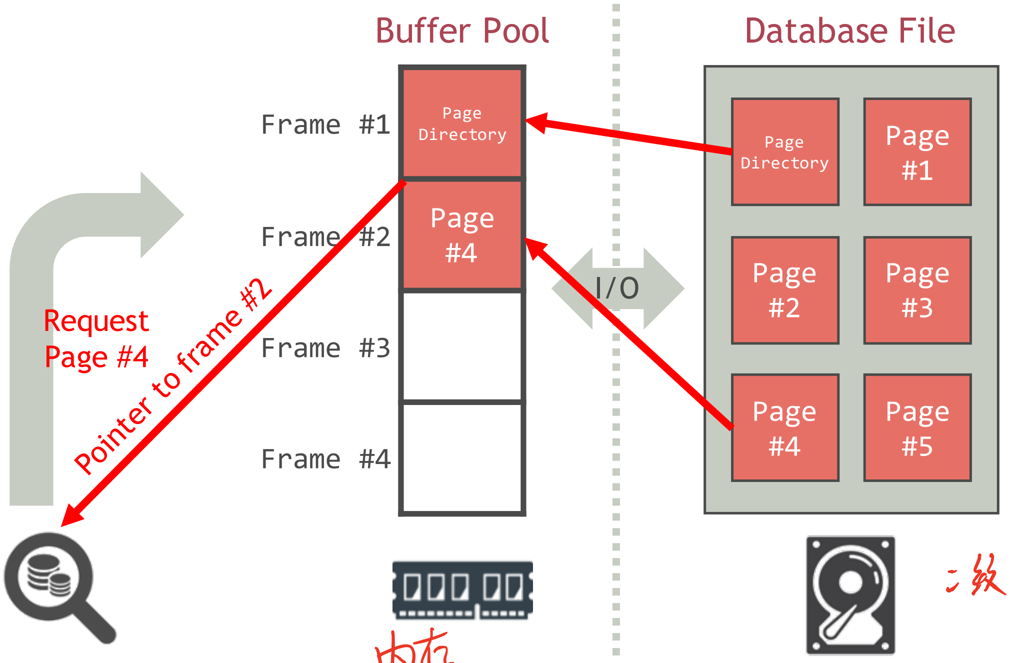
The LBA of a disk block is a number between 0 and $n-1$ (assuming the total capacity of the disk is n blocks)

容量

面向磁盘

Disk-Oriented Database Storage

- Data is persistently stored on secondary storage
- Data is loaded into main memory when it is going to be read or modified (but not yet found in main memory)



Buffer Pool

Database File

Frame #1

Frame #2

Frame #3

Frame #4

Page Directory

Page #4

Page #1

Page #2

Page #3

Page #5

I/O

Request Page #4

Pointer to frame #2

持续化存储

二级 storage

内存

Disk-Oriented Database Storage (Cont'd)

Design Goals

超过

- Allow the DBMS to manage databases that exceed the amount of memory available
- Reading/writing to disk is expensive, so it must be managed carefully to avoid large stalls and performance degradation 退化

Spatial Control (空间方面的控制)

- Where to write pages on disk
- The goal is to keep pages that are used together often as physically close together as possible on disk (data locality)

Temporal Control (时间方面的控制)

- When to read pages into memory, and when to write them to disk
- The goal is minimize the number of stalls from having to read data from disk

拖延

Representation of Databases on Disks

Representation of Databases on Disks

Value Representation

Representation of Numbers

INT/INTEGER/BIGINT/SMALLINT/TINYINT （整数）

- C/C++ representation

FLOAT/DOUBLE/REAL （浮点数）

- IEEE-754 standard
- Typically faster than arbitrary precision numbers, but can have rounding errors

精度

NUMERIC/DECIMAL （定点数）

- Arbitrary precision and scale
- Used when rounding errors are unacceptable
- Typically stored in an exact, variable-length binary representation with additional meta-data (like a `VARCHAR` but not stored as a string)

Representation of Strings

CHAR(n)/BINARY(n) （定长字符串/字节串）

- an array of *n* bytes
- If the length of a string is shorter than *n*, the array is padded with a special null character
- Example: 'cat' is represented as | 'c' | 'a' | 't' | 0 | 0 | in CHAR(5)

VARCHAR/VARBINARY/TEXT/BLOB （变长字符串/字节串）

- Header with length, followed by data bytes
- Example: 'cat' is represented as | 3 | 'c' | 'a' | 't' | in VARCHAR(5)
- C/C++ null-terminated string representation is not used

BIT(n) （定长位串）

- an array of $\lceil n/8 \rceil$ bytes 12位
- Example: BIT(12), 010111110011 → | 01011111 | | 00110000 |

补0

Representation of Other Types of Values

TIME/DATE/DATETIME/TIMESTAMP（时间/日期）

- 32/64-bit integer of (micro)seconds since Unix epoch

ENUM（枚举型值）

- An enumerated type with n items is represented as BIT($\lceil \log_2 n \rceil$)
- Example: ENUM(RED, GREEN, BLUE, YELLOW), RED → 00, GREEN → 01, BLUE → 10, YELLOW → 11

Representation of Databases on Disks
Tuple Layout

Tuple Layout

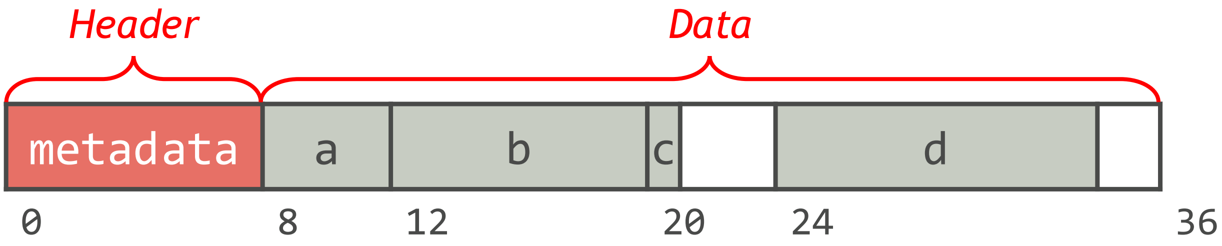
本质上

A tuple (元组) is essentially a sequence of bytes

- It is the job of the DBMS to interpret those bytes into attribute types and values

翻译

- The DBMS's catalogs (目录) contain the schema information about tables that the DBMS uses to figure out the tuple's layout



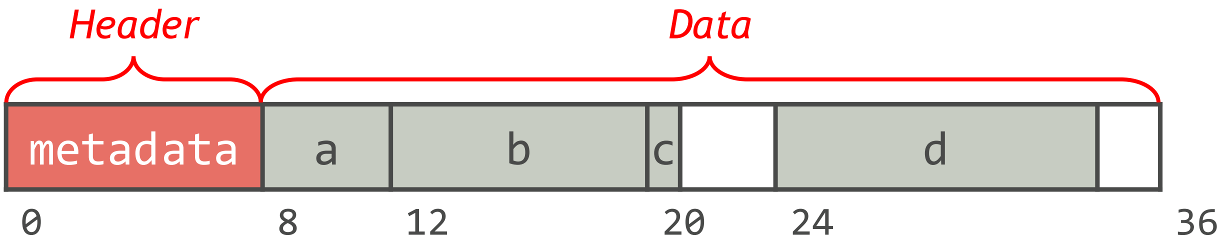
Tuple Header (头部)

Each tuple is prefixed with a header that contains meta-data about it

- A pointer to where the DBMS stores the schema for this type of tuple
- The length of the tuple
- Visibility info (concurrency control)

并发控制

- A bitmap for `NULL` values



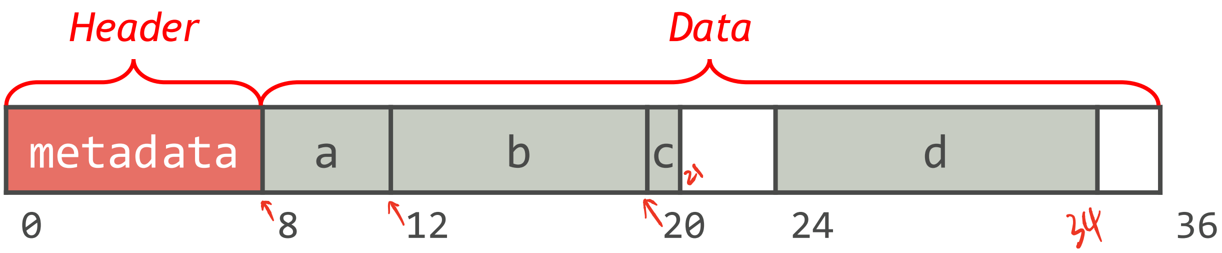
Tuple Data

连接

The tuple data part concatenates all attribute values of the tuple

- Attributes are typically stored in the order that you specify when you create the table
- 排列 Each attribute value aligns at an offset from the beginning of the tuple by a multiple of 4 bytes/8 bytes

```
CREATE TABLE Foo (
  a INT NOT NULL,          4
  b BIGINT NOT NULL,  8
  c CHAR NOT NULL,       1
  d VARCHAR(10) NOT NULL);
                        10
```



Representation of Databases on Disks
Page Layout

Database Pages (数据库页面)

A page is a fixed-size block of data (512B–16KB)

- It can contain tuples, meta-data, indexes, log records . . .
- Most DBMSs do not mix page types
- Some DBMSs require a page to be self-contained 独立的

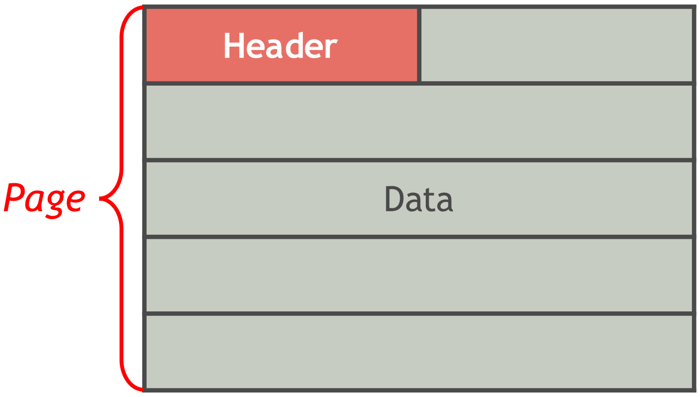
Each page is given a unique identifier as its page ID (页号)

- The DBMS uses an indirection layer to map page IDs to physical locations

间接层

Page Layout (页面布局)

A page is comprised of the page header and the page data

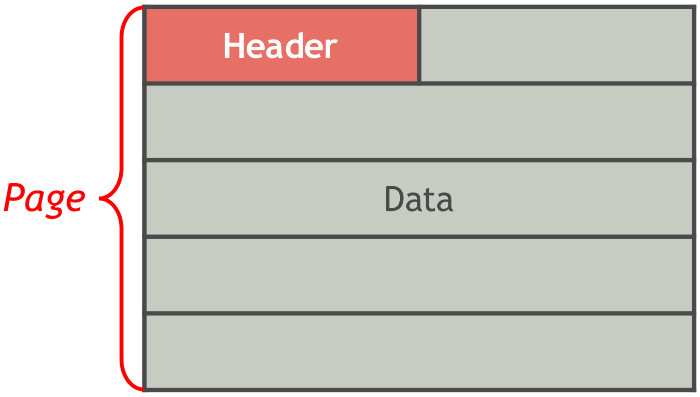


Page Header

Every page contains a header of metadata about the page's contents

- Page size
- Checksum (校验码)
- DBMS version
- Transaction visibility 事务. 交易
- Compression information

压缩

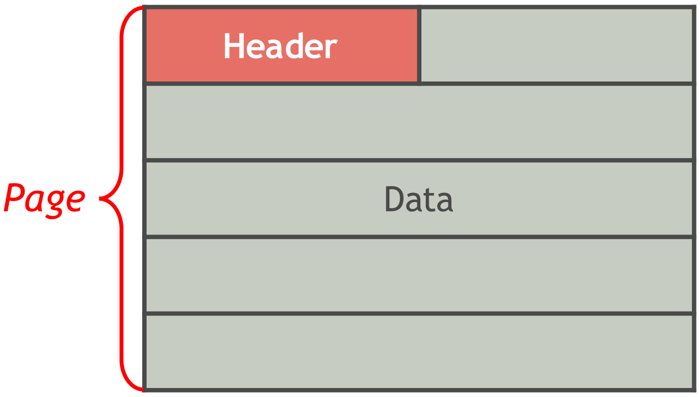


Page Data

Here we only consider pages storing a number of tuples

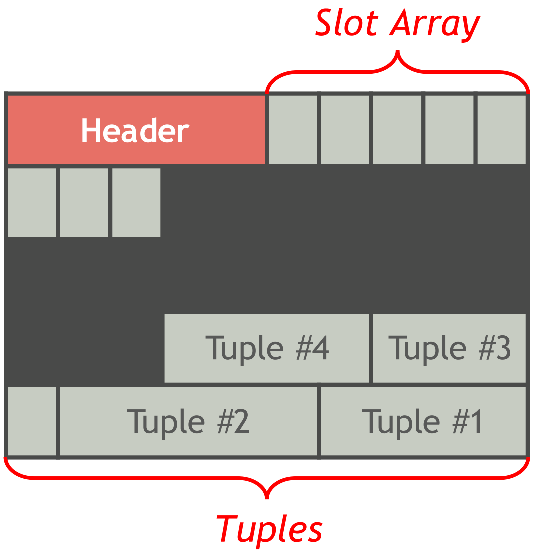
How to organize the data stored inside of a page?

- Approach #1: Tuple-oriented 面向 Tuple
- Approach #2: Log-structured



Tuple-Oriented Page Layout

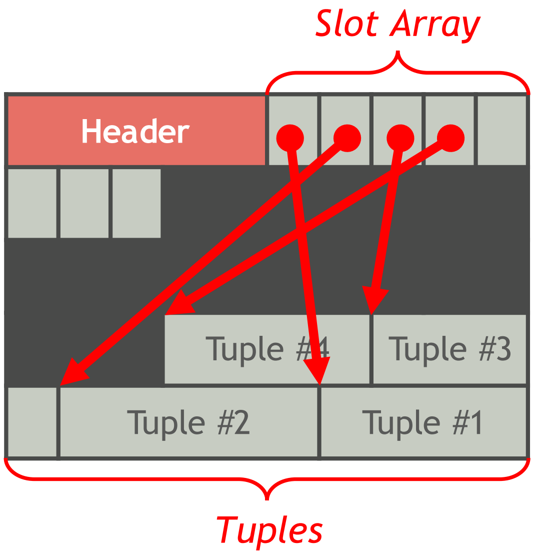
The most common page layout scheme is called slotted pages (分槽页面)



Slot Pages (分槽页面)

狭槽

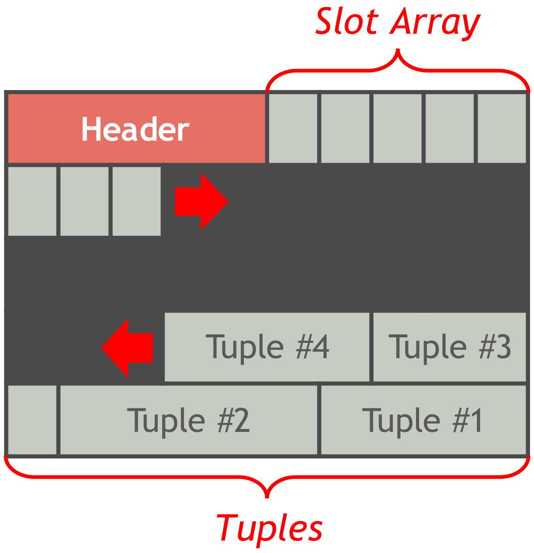
The slot array maps the used “slots” to the tuples’ starting position offsets



Slotted Pages (Cont'd)

The header of a slotted page keeps track of

- The # of used slots
- The offset of the starting location of the last slot used

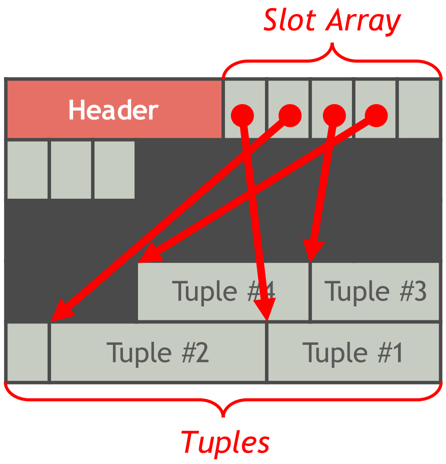


Record ID (记录号)

To keep track of individual tuples, the DBMS assigns each tuple with a unique record identifier

The most common record ID is (PageID, Slot#)

- PageID: the ID of the page containing the tuple
- Slot#: the # of the slot where the tuple is stored in the page



Large Values

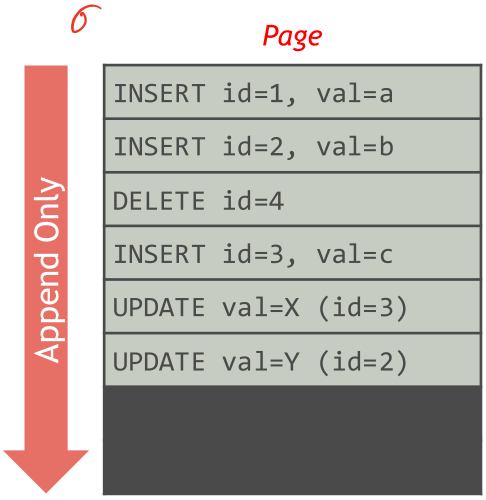
- Most DBMSs don't allow a tuple to exceed the size of a single page
- To store values that are larger than a page, the DBMS uses separate overflow storage pages

Log-Structured Page Layout

Instead of storing tuples in pages, the DBMS only appends log records (日志记录) to the file of how the database was modified

- Inserts store the entire tuple
- Deletes mark the tuple as deleted
- Updates contain the delta of just the attributes that were modified

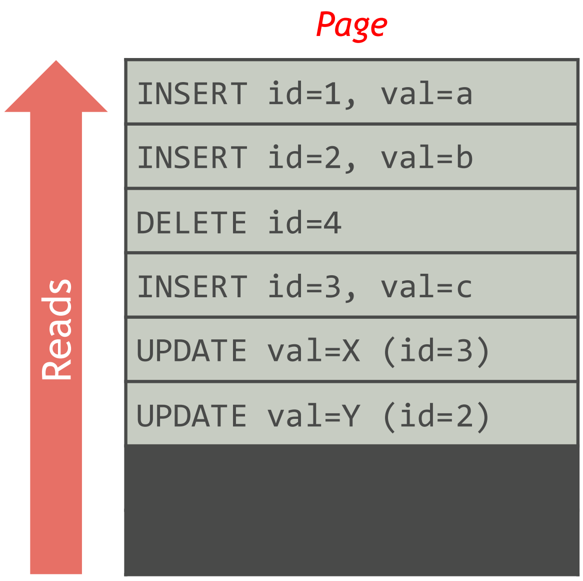
δ



INSERT id=1, val=a
INSERT id=2, val=b
DELETE id=4
INSERT id=3, val=c
UPDATE val=X (id=3)
UPDATE val=Y (id=2)

Log-Structured Page Layout (Cont'd)

To read a tuple, the DBMS scans the log backwards and "recreates" the tuple to find what it needs

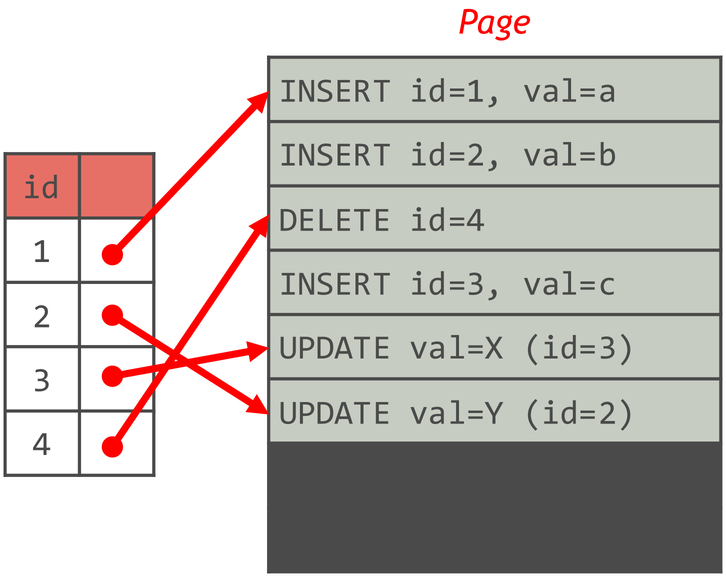


```
INSERT id=1, val=a
INSERT id=2, val=b
DELETE id=4
INSERT id=3, val=c
UPDATE val=X (id=3)
UPDATE val=Y (id=2)
```

(id=1, val=a); (id=2, val=Y); (id=3, val=X); id=4 deleted;

Log-Structured Page Layout (Cont'd)

Build indexes to allow the DBMS to jump to locations in the log



id	
1	
2	
3	
4	

```
INSERT id=1, val=a
INSERT id=2, val=b
DELETE id=4
INSERT id=3, val=c
UPDATE val=X (id=3)
UPDATE val=Y (id=2)
```

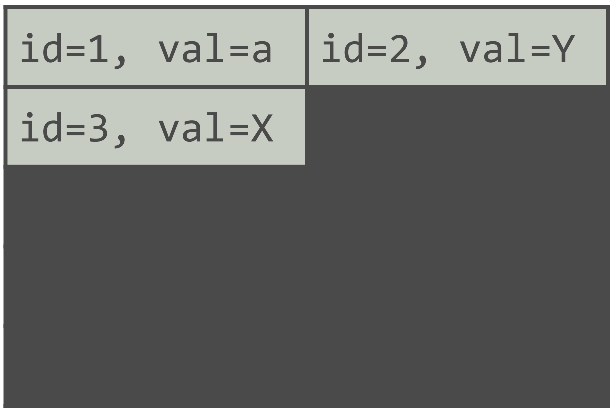
Log-Structured Page Layout (Cont'd)

压缩.

Periodically compact the log

定期地

Compacted Page



id=1, val=a

id=2, val=Y

id=3, val=X

Representation of Databases on Disks

File Organization

File Storage

The DBMS stores a database as one or more files on disk

- The OS doesn't know anything about the contents of these files

The storage manager is responsible for maintaining a database's files. It organizes the files as a collection of pages.

- It tracks data read/written to pages
- It tracks the available space

Page Storage Architecture

Different DBMSs manage pages in files on disk in different ways

- Approach #1: Heap File Organization
- Approach #2: Sequential/Sorted File Organization
- Approach #3: Hashing File Organization (Chapter 8)

Heap File Organization (堆文件组织)

A heap file (堆文件) is an unordered collection of pages where tuples that are stored in random order

- Create/get/write/delete pages
- Must also support iterating over all pages

Need meta-data to keep track of what pages exist and which ones have free space

Two ways to represent a heap file

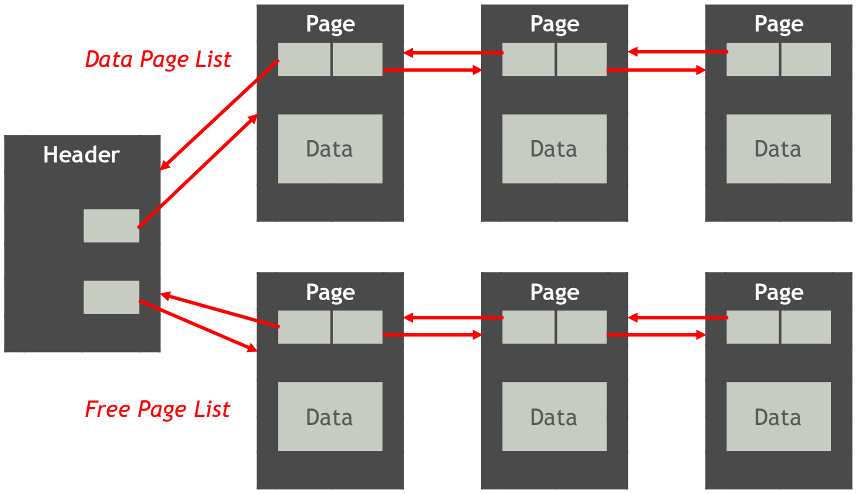
- Approach #1: Linked lists
- Approach #2: Page directory

Heap Files: Linked Lists (链表法)

Maintain a header page at the beginning of the file that stores two pointers

- The head of the free page list
- The head of the data page list

Each page keeps track of the number of free slots in itself



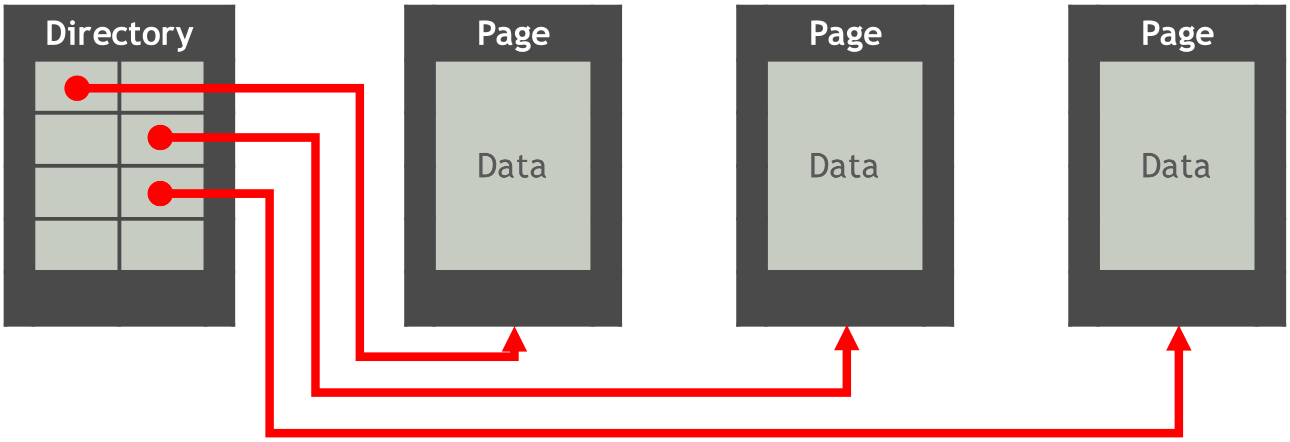
free

data

Heap Files: Page Directory (页目录法)

- The DBMS maintains special pages that tracks the location of data pages in the database files
- The directory also records the number of free slots per page
- The DBMS has to make sure that the directory pages are in sync with the data pages

同步



Sequential/Sorted File Organization (顺序/有序文件组织)

A sequential/sorted file is an ordered collection of pages where tuples that are stored in sorted key order

- Ordered files are rarely used unless a primary index is used

System Catalogs

System Catalogs (系统目录)

A DBMS stores meta-data about databases in its internal catalogs

- Tables, columns, indexes, views
- Users, permissions
- Internal statistics

Almost every DBMS stores their a database's catalog in itself

System Catalogs (系统目录)

You can query the DBMS's internal INFORMATION_SCHEMA catalog to get info about the database

- ANSI standard set of read-only views that provide info about all of the tables, views, columns, and procedures in a database

DBMSs also have non-standard shortcuts to retrieve this information

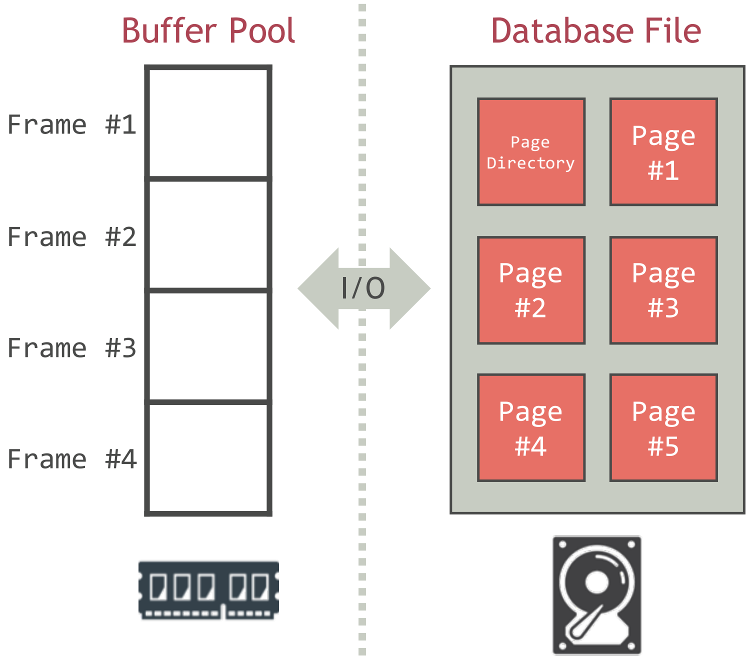
Example (MySQL System Catalogs)

- List all the tables in the current database: `show tables;`
- List the schema of a table: `describe student;`

Buffer Management

Buffer Pool (缓冲池)

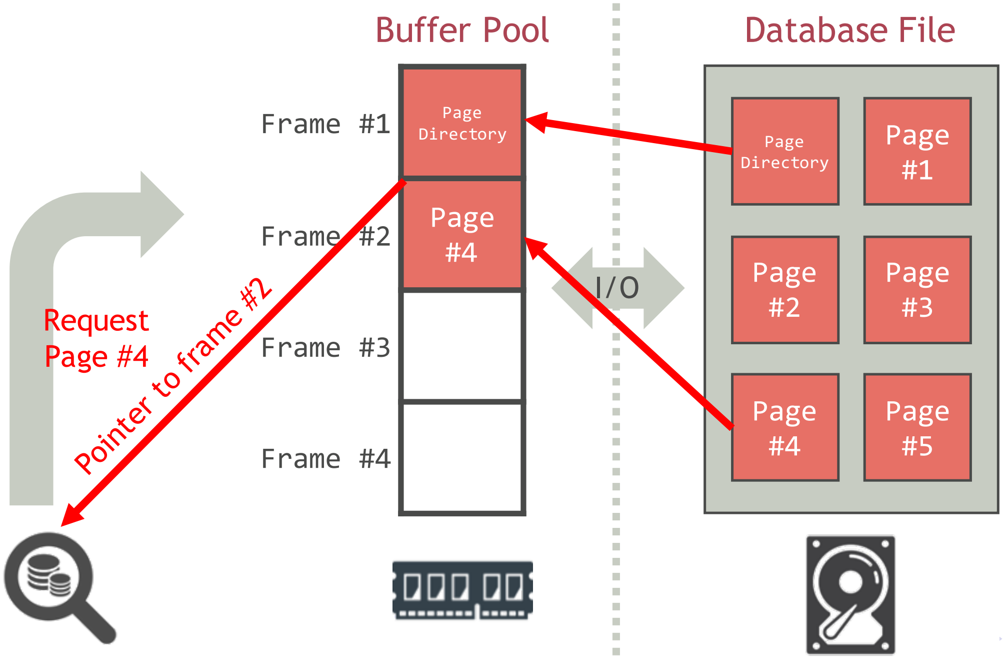
- The available memory region is partitioned into an array of fixed-size pages, which are collectively called the buffer pool (缓冲池)
- The pages in the buffer pool are called frames (页框)



Buffer Manager (缓冲区管理器)

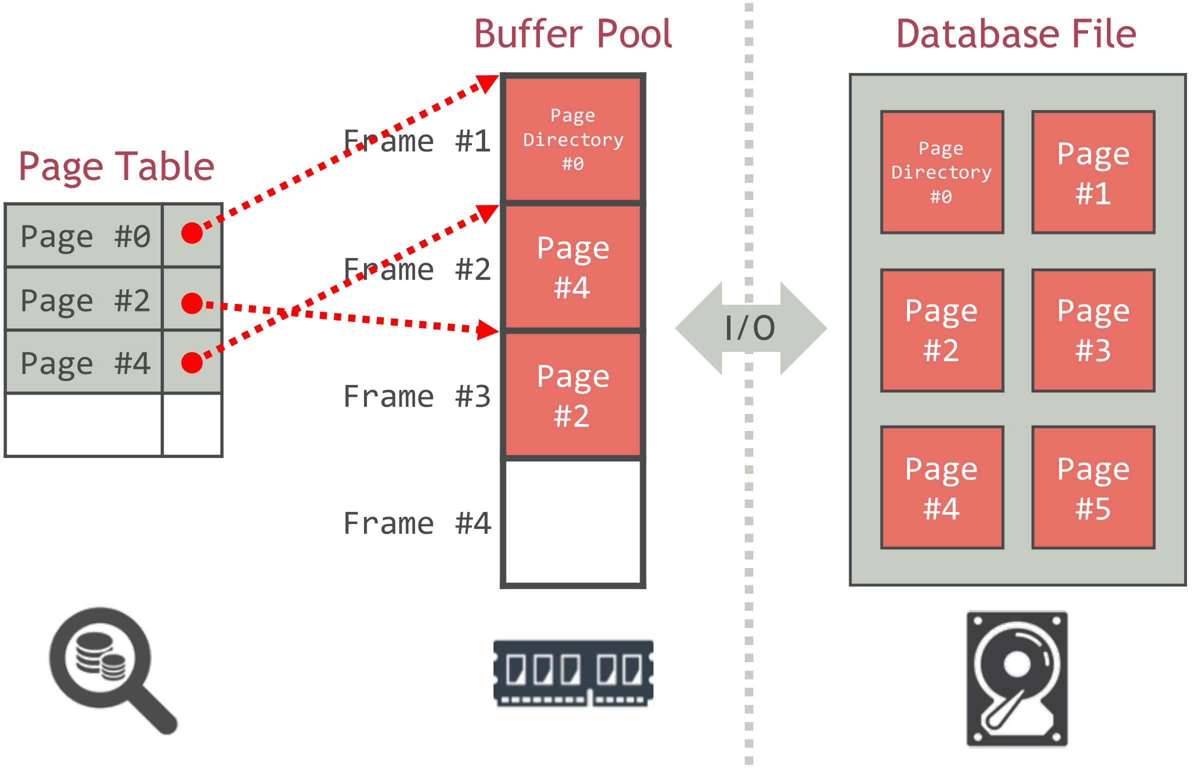
The buffer manager is responsible for bringing pages into the buffer pool as needed

- The buffer manager decides what existing page in the buffer pool to replace to make space for the new page (if the buffer pool is full)



Buffer Pool Internals: Page Table (页表)

The page table keeps track of pages that are currently in the buffer pool



Page Table vs. Page Directory

在二级 storage 中

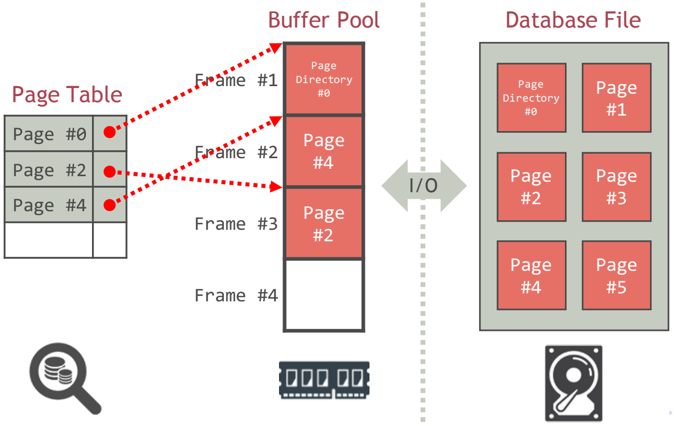
The page directory is the mapping from page IDs to page locations in the database files

- All changes must be recorded on disk to allow the DBMS to find on restart

The page table is the mapping from page IDs to a copy of the page in buffer pool frames

- This is an in-memory data structure that does not need to be stored on disk

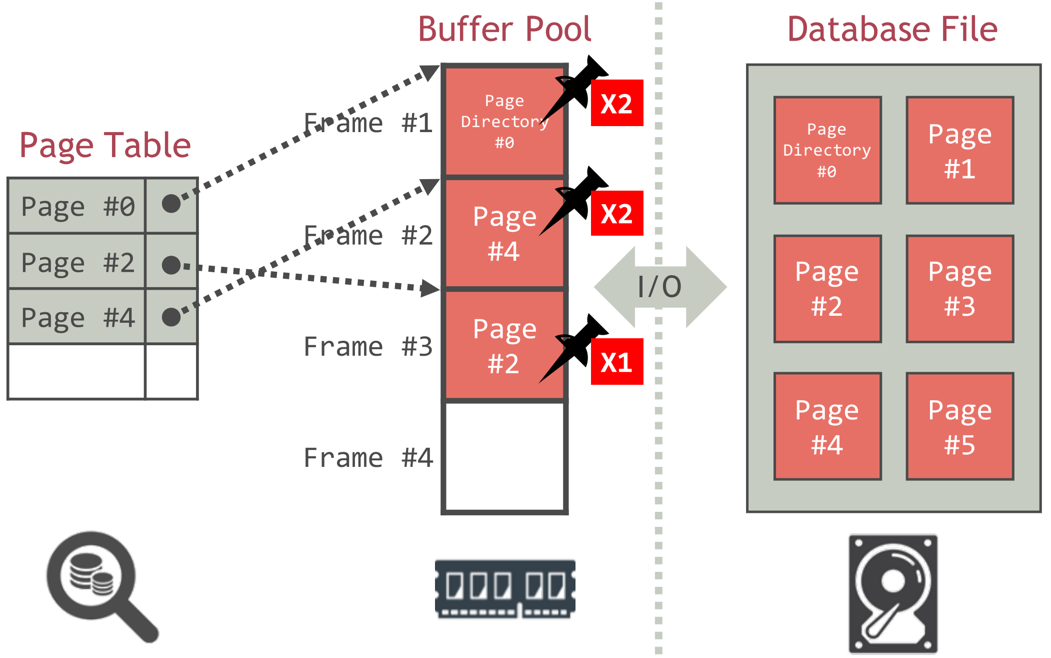
Page Table



Buffer Pool Internals: Frame's Meta-Data

The buffer manager maintains two variables for each frame

- pin_count: the number of times that the page currently in the frame has been requested but not released, i.e., the number of current users of the page

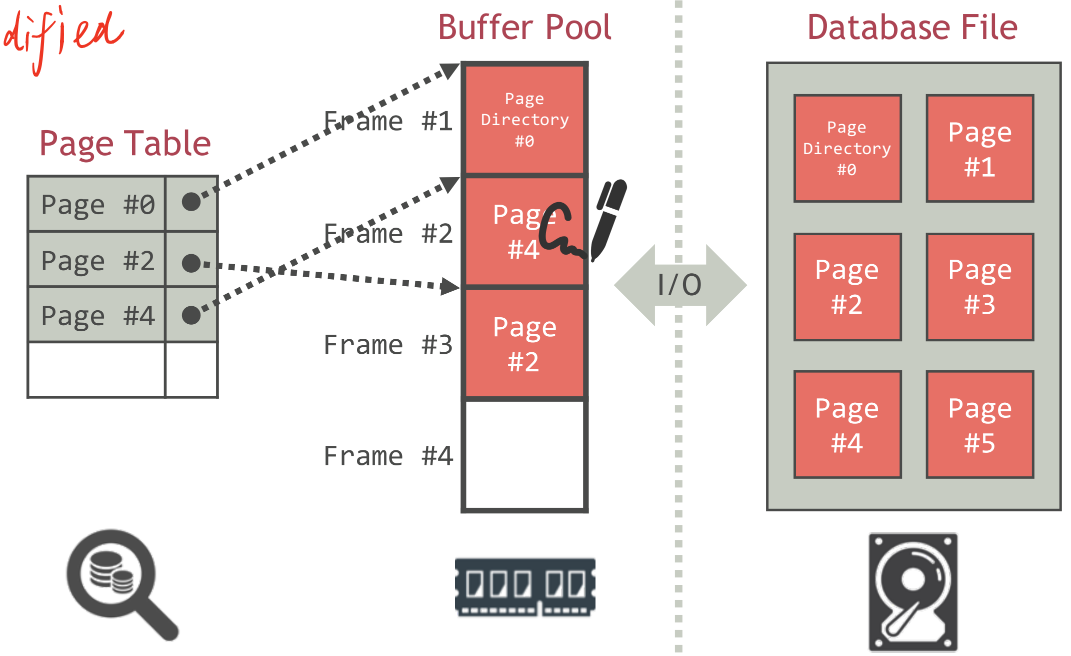


Buffer Pool Internals: Frame's Meta-Data

The buffer manager maintains two variables for each frame

- dirty: the status whether the page in the frame has been modified since it was brought into the buffer pool

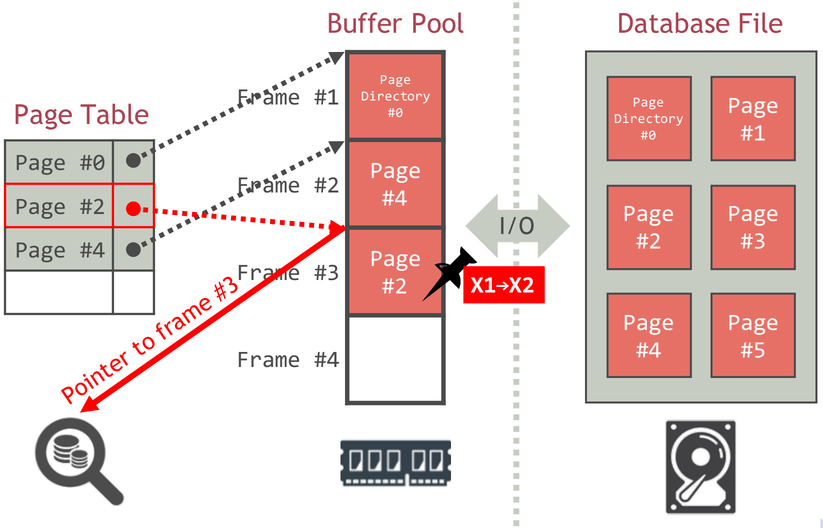
若被 modified
则
dirty



Page Requests (请求页) —动作

1. Check the page table to see if some frame contains the requested page P
2. If P is in the buffer pool, pin page P, i.e., increment the pin_count of the frame containing P
3. Return the pointer of the frame containing P

Example: Request page #2



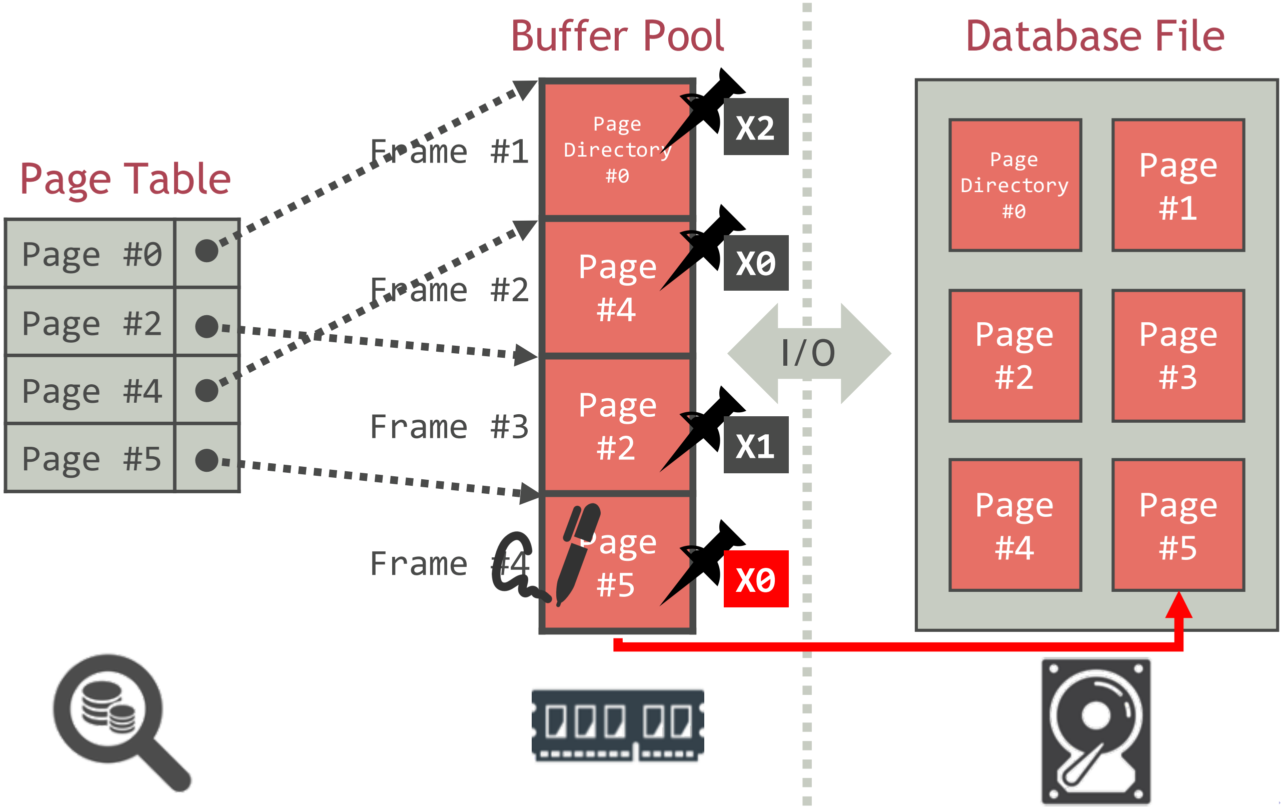
Page Requests (Cont'd)

If the requested page is not in the buffer pool,

1. (选替换页) Chooses a frame with pin_count = 0 for replacement, using the replacement policy, and increments its pin_count
2. (写回脏页) If the dirty bit for the replacement frame is on, writes the page it contains to disk
3. (读请求页) Reads the requested page into the replacement frame

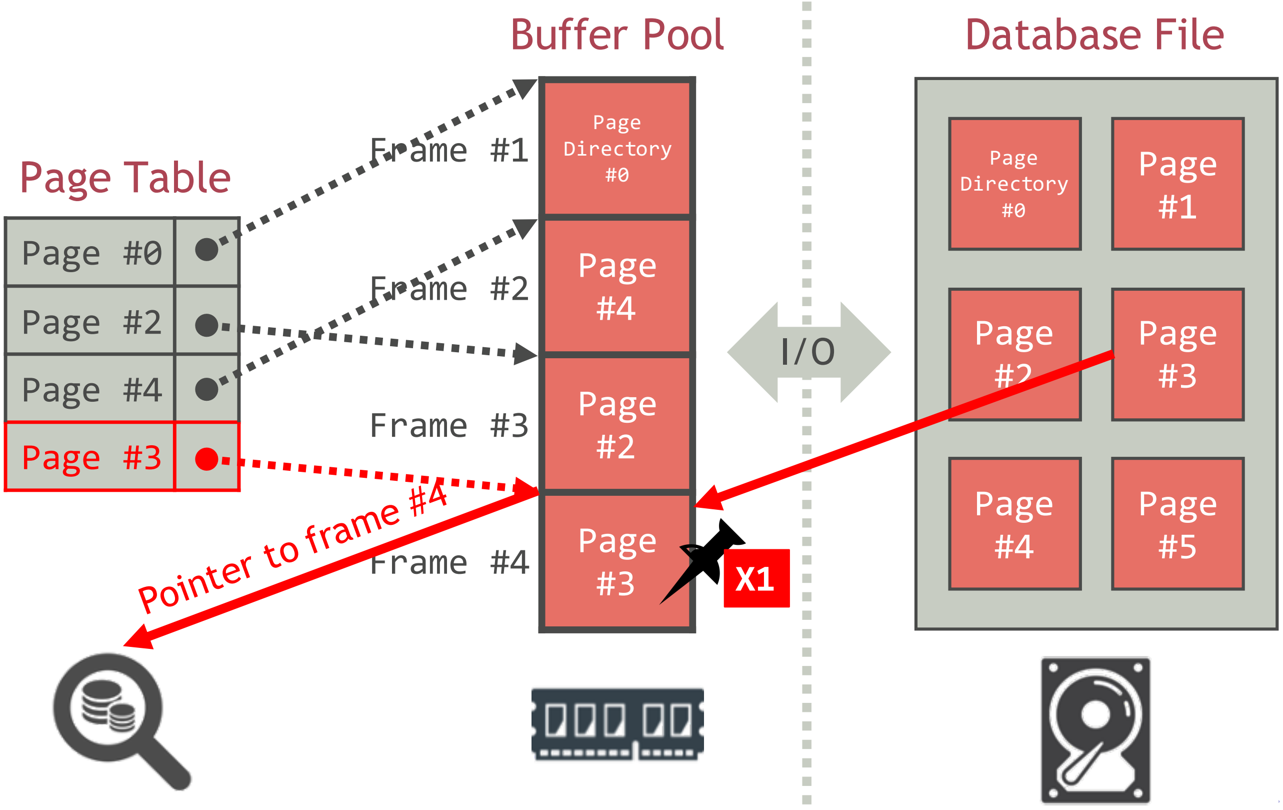
Page Requests (Cont'd)

Example: Request page #3



Page Requests (Cont'd)

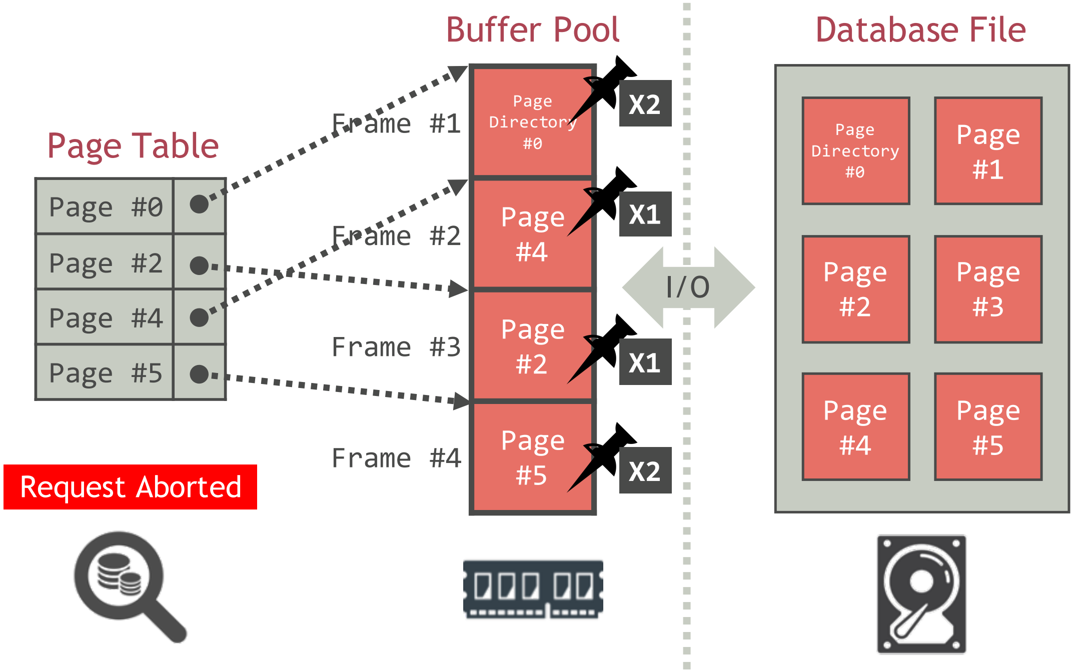
Example: Request page #3



Page Requests (Cont'd)

If no page in the buffer pool has pin_count = 0, the buffer manager must wait until some page is released before responding to the page request

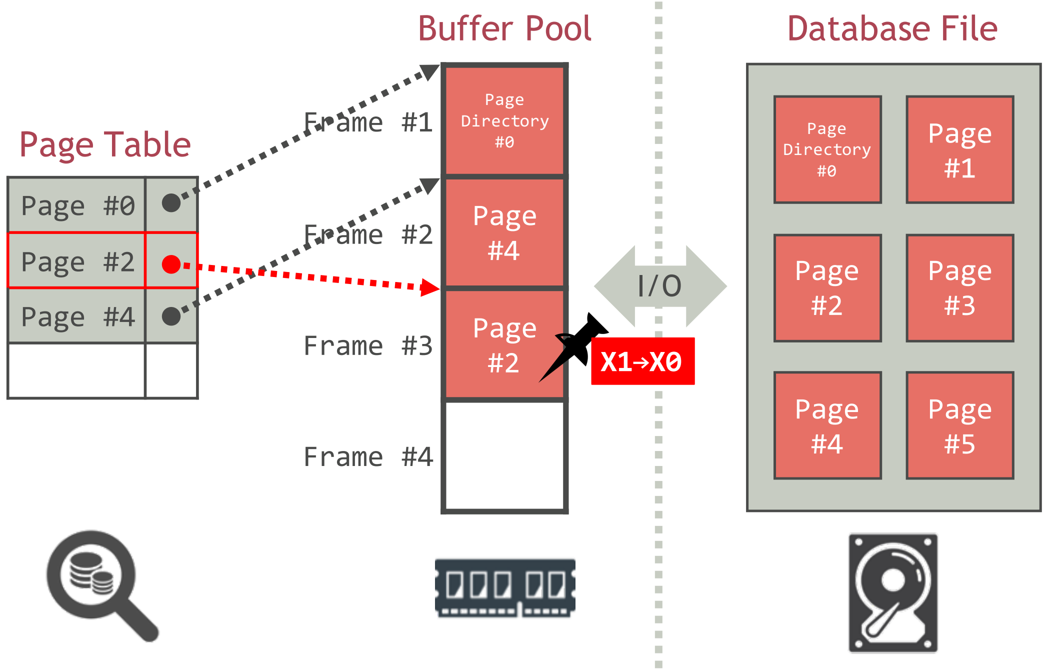
In practice, the transaction requesting the page may simply be aborted 失败 退出



Page Releases (页释放)

Unpin the released page, i.e., decrement the pin_count of the frame containing the page

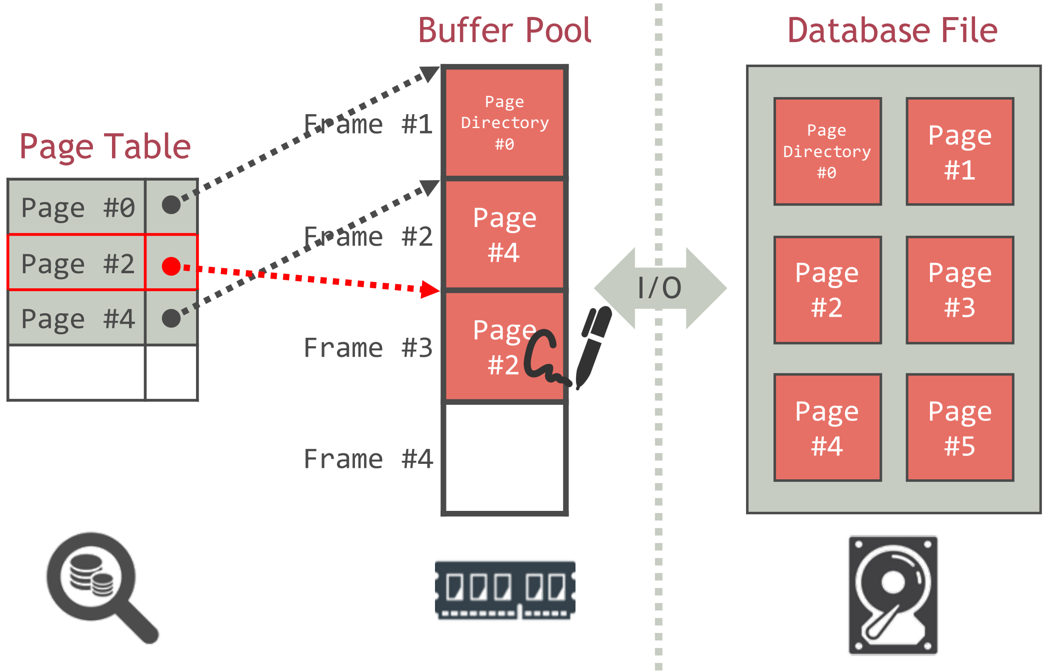
Example: Request page #2



Page Modifications (页修改)

Set the dirty bit for the frame containing the modified page

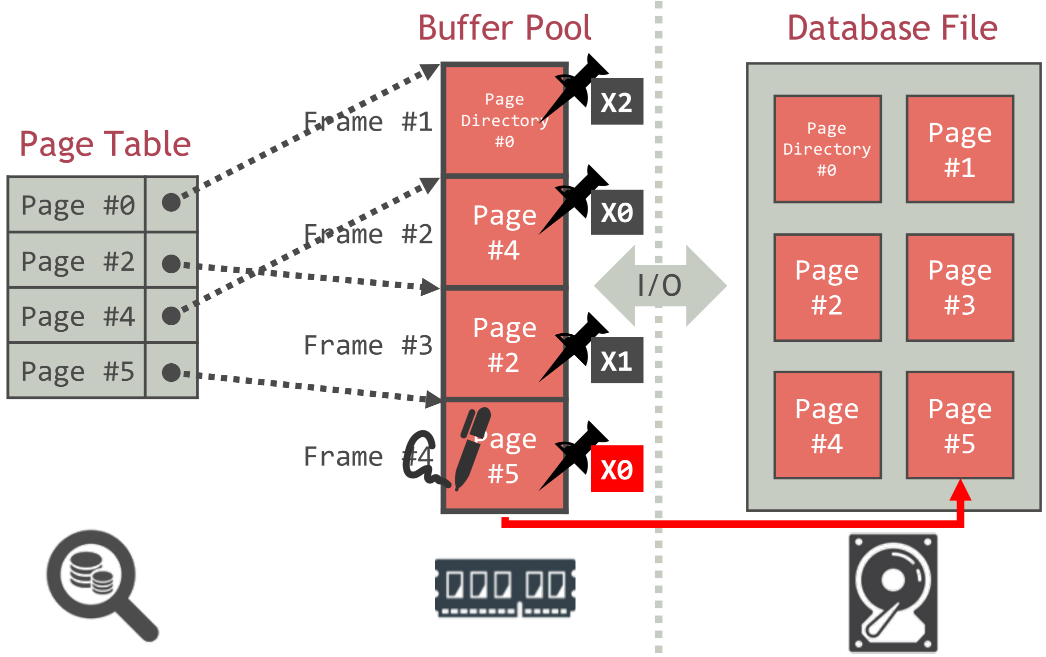
Example: Modify page #2



Page Replacement Policies (页替换策略)

When the buffer manager needs to free up a frame to make room for a new page, it must decide which page to evict from the buffer pool 驱逐

- The page replacement policy can affect the time taken for database operations considerably



Least Recently Used (LRU) Relpacement Policy

上次被访问的时间

Maintain a timestamp of when each page was last accessed

When the DBMS needs to evict a page, select the one with the oldest timestamp

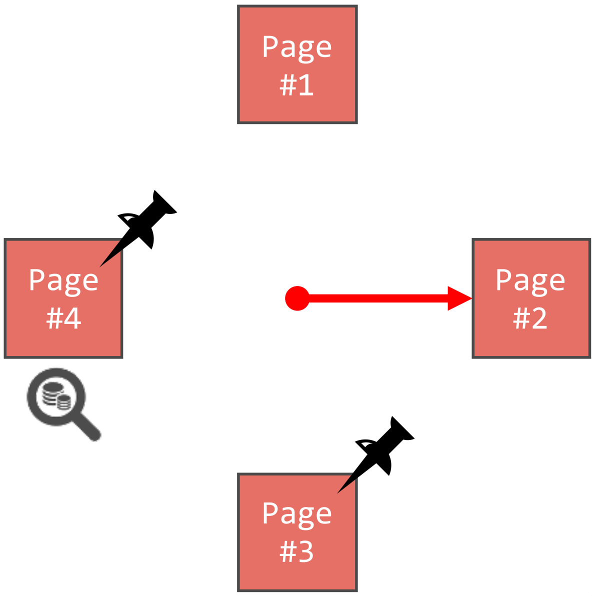
- Keep the pages in sorted order to reduce the search time on eviction

Clock Replacement Policy (时钟替换策略)

The clock replacement policy is an approximation of LRU without needing a separate timestamp per page

近似

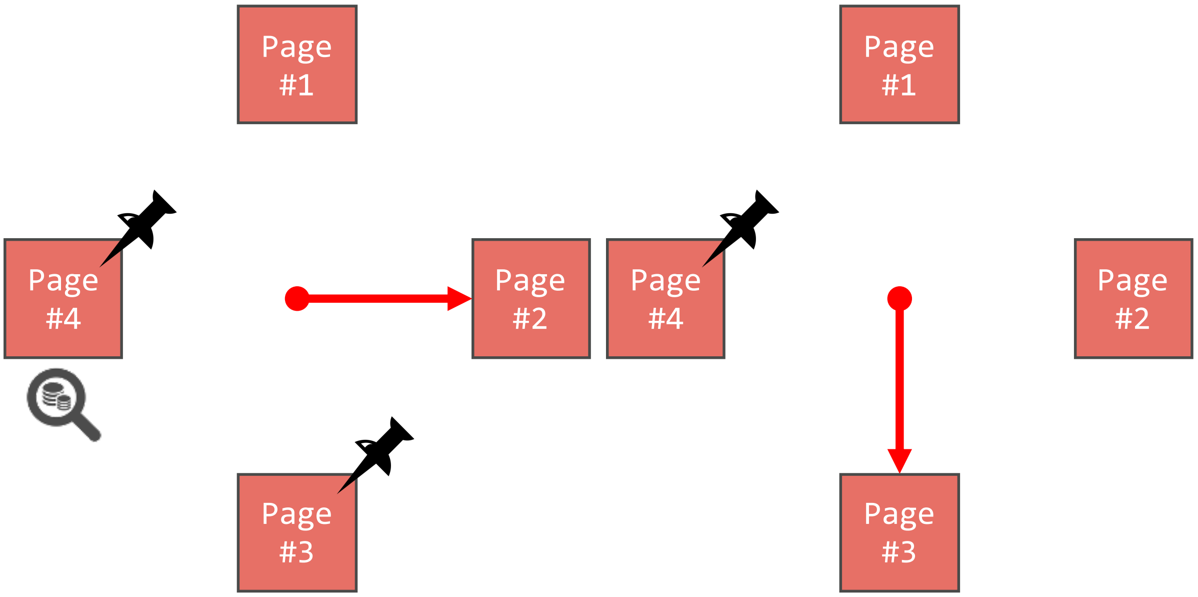
- Each frame has a reference bit, which is either 0 or 1
- When a page is read into a frame or when the page in a frame is accessed, its reference bit is set to 1



Clock Replacement Policy (Cont'd)

The frames are organized in a circular buffer with a "clock hand"

- The clock hand rotates clockwise
- Upon sweeping, check if a page's reference bit is set to 1
- If yes, set the reference bit to 0

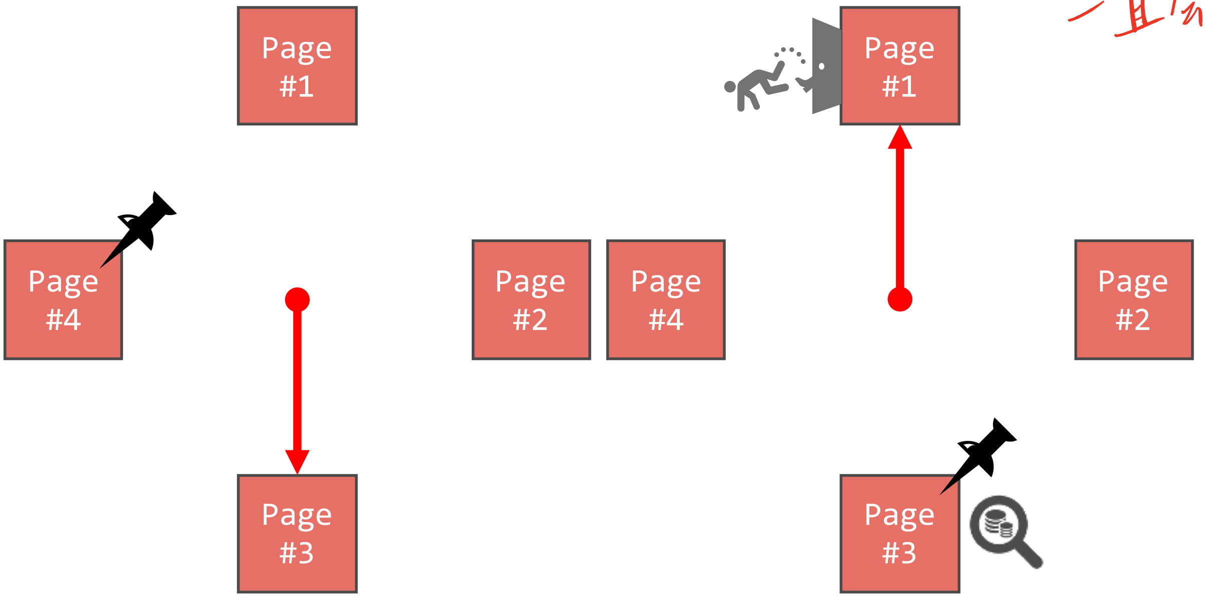


Clock Replacement Policy (Cont'd)

When the buffer manager needs a frame for a new page,

- Look for the first frame with reference bit 0
- Evict the page in the frame

clockwise
一直会转



Buffer Pool VS Virtual Memory

Similarities

- Similar goal: Both provide access to more data that cannot fit in main memory
- Similar operations: Both bring in pages from disk to main memory as needed, replacing pages no longer needed in main memory

Why can't we build a DBMS using the virtual memory capability of an OS?

容量、

Buffer Management VS Virtual Memory (Cont'd)

Why can't we build a DBMS using the virtual memory capability of an OS?

Reason 1 (Page reference pattern prediction)

A DBMS can often predict the order in which pages will be accessed, or page reference patterns, much more accurately than is typical in an OS environment

Implication

- Page Replacement: The ability to predict page reference patterns allows for a better choice of pages to replace
- Page Prefetching: Being able to predict page reference patterns enables the buffer manager to anticipate the next several page requests and fetch the corresponding pages into memory before the pages are requested

Buffer Management VS Virtual Memory (Cont'd)

Why can't we build a DBMS using the virtual memory capability of an OS?

Reason 2 (Forcing page write)

- A DBMS requires the ability to explicitly force a page to disk, that is, to ensure that the copy of the page on disk is updated with the copy in memory
- The OS command to write a page to disk may be implemented by 本质上 essentially recording the write request and deferring 推迟 the actual modification of the disk copy. If the system crashes in the interim, the effects can be catastrophic for a DBMS 过渡时期

Implication

A DBMS must be able to ensure that certain pages in the buffer pool are written to disk before certain other pages to implement the Write Ahead Logging (WAL) protocol for crash recovery

Summary

1. Storage Media
2. Representation of Databases on Disks
   - Value Representation
   - Tuple Layout
   - Page Layout
     - Tuple-Oriented Page Layout
     - Log-Structured Page Layout
   - File Organization
3. System Catalogs
4. Buffer Management