Georgia Tech

Lecture 4: Disk Space Management

CREATING THE NEXT®

Administrivia

- Assignment 1 is due on September 7th @ 11:59pm
- Introduction Sheet is due on September 7th @ 11:59pm

Today's Agenda

Recap

List of SQL Features

- Aggregations + Group By
- String / Date / Time Operations
- Output Control + Redirection
- Nested Queries
- Join
- Common Table Expressions
- Window Functions

Window Functions

- **Task:** Get the name of the students with the second highest grade for each course.

```
SELECT cid, sid, grade, rank FROM (
  SELECT *, RANK()
    OVER (PARTITION BY cid ORDER BY grade ASC) AS rank
    FROM enrolled
  ) AS ranking
  WHERE ranking.rank = 2  --- Update rank
```

cid	sid	grade	rank
2	4	C	2

Common Table Expressions

- **Task:** Find students record with the highest id that is enrolled in at least one course.

```
WITH cteSource (maxId) AS (
  SELECT MAX(sid) FROM enrolled
)
SELECT name FROM students, cteSource
  WHERE students.sid = cteSource.maxId
```

Types of Join: Lateral Join

- **Task:** List the names of students **with** hobbies (get student name once for each occurence of their hobby).

```
SELECT name
  FROM students, LATERAL (SELECT id FROM hobbies
                          WHERE students.id = hobbies.id) ss;
```

name
Maria
Maria
Rahul
Peter

Layered Architecture

Overview

- We now understand what a database looks like at a **logical** level and how to write queries to read/write data from it (*i.e.*, **physical** level).
- We will next learn how to build software that manages a database.

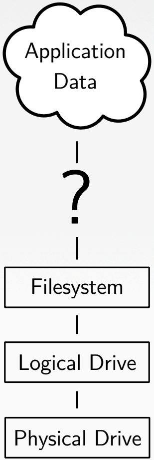
Anatomy of a Database System [Monologue]

- Process Manager
  - Manages client connections
- Query Processor
  - Parse, plan and execute queries on top of storage manager
- Transactional Storage Manager
  - Knits together buffer management, concurrency control, logging and recovery
- Shared Utilities
  - Manage hardware resources across threads

Anatomy of a Database System [Monologue] (2)

- Process Manager
  - Connection Manager + Admission Control
- Query Processor
  - Query Parser
  - Query Optimizer (*a.k.a.*, Query Planner)
  - Query Executor
- Transactional Storage Manager
  - Lock Manager
  - Access Methods (*a.k.a.*, Indexes)
  - Buffer Pool Manager
  - Log Manager
- Shared Utilities
  - Memory, Disk, and Networking Manager

The Problem



Georgia Tech

Requirements

There are different classes of requirements:

- Data Independence
  - application logic must be shielded from physical storage implementation details
  - physical storage can be reorganized
  - hardware can be changed
- Scalability
  - must scale to (nearly) arbitrary data size
  - efficiently access to individual tuples
  - efficiently update an arbitrary subset of tuples
- Reliability
  - data must never be lost
  - must cope with hardware and software failures
- ...

Layered Architecture

- implementing all these requirements on “bare metal” is hard
- and not desirable
- a DBMS must be maintainable and extensible

Instead: use a **layered architecture**

- the DBMS logic is split into levels of functionality
- each level is implemented by a specific layer
- each layer interacts only with the next lower layer
- simplifies and modularizes the code

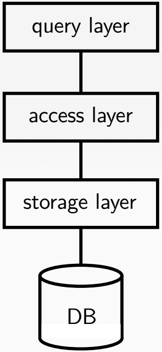
A Simple Layered Architecture

Purpose

query translation and optimization

managing records and access paths

DB buffer and hardware interface



Access Granularity

declarative queries
sets of records

records

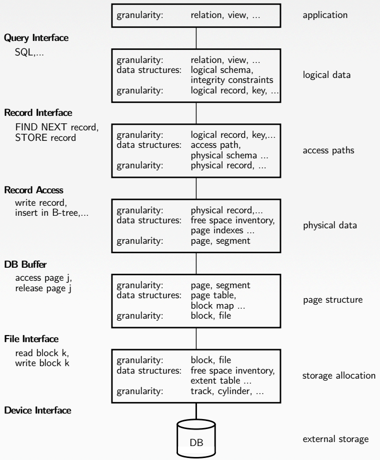
page

A Simple Layered Architecture (2)

- layers can be characterized by the data items they manipulate
- lower layer offers functionality for the next higher level
- keeps the complexity of individual layers reasonable
- rough structure: physical → low level → high level

This is a reasonable architecture, but simplified.
A more detailed architecture is needed for a complete DBMS.

A More Detailed Architecture



A More Detailed Architecture (2)

A few pieces are still missing:

- transaction isolation
- recovery

but otherwise it is a reasonable architecture.

Some system deviate slightly from this classical architecture

- many DBMSs nowadays delegate disk access to the OS
- some DBMSs delegate **buffer management** to the OS (tricky, though)
- a few DBMSs allow for direct logical record access
- ...

Hints for Computer System Design

Presented in 1983 by Butler Lampson (Xerox Palo Alto Research Center).
Designing a computer system is very different from designing an algorithm. Paper Link

- Functionality
- Speed
- Fault-Tolerance

Hardware Properties

Impact of Hardware

Must take hardware properties into account when designing a storage system.

For a long time dominated by **Moore's Law**:

The number of transistors on a chip doubles every 18 month.

Indirectly drove a number of other parameters:

- main memory size
- CPU speed
  - no longer true!
- HDD capacity
  - start getting problematic, too. density is very high
  - only capacity, not access time

Memory Hierarchy

capacity
latency

bytes
1ns

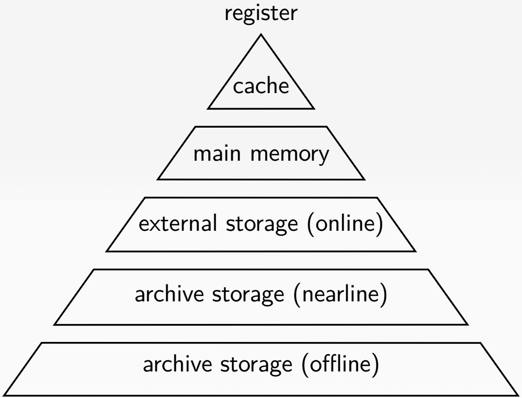
K-M bytes
$<$10ns

G bytes
$<$100ns

T bytes
ms

T bytes
sec

T-P bytes
sec-min



Memory Hierarchy (2)

There are huge gaps between hierarchy levels

- traditionally, main memory vs. disk is most important
- but memory vs. cache etc. also relevant

The DBMS must aim to maximize locality.

Hard Disk Access

Hard Disks are still the dominant external storage:

- rotating platters, mechanical effects
- transfer rate: ca. 150MB/s
- seek time ca. 3ms
- huge imbalance in random vs. sequential I/O!

Hard Disk Access (2)

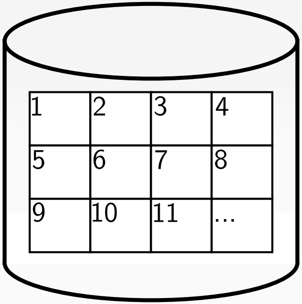
The DBMS must take these effects into account

- sequential access is much more efficient
- traditional DBMSs are designed to maximize sequential access
- gap is growing instead of shrinking
- even SSDs are slightly asymmetric (and have other problems)
- DBMSs try to reduce number of writes to random pages by organizing data in **contiguous blocks**.
- Allocating multiple pages at the same time is called a **segment**

Hard Disk Access (3)

Techniques to speed up disk access:

- do not move the head for every single tuple
- instead, load larger chunks. typical granularity: one **page**
- page size varies. traditionally 4KB, nowadays often 16K and more (**trade-off**)



Georgia Tech

Hard Disk Access (4)

The page structure is very prominent within the DBMS

- granularity of I/O
- granularity of buffering/memory management
- granularity of recovery

Page is still too small to hide random I/O though

- sequential page access is important
- DBMSs use read-ahead techniques
- asynchronous write-back

Database System Architectures

Storage Management

Disk-Centric Database System

- The DBMS assumes that the primary storage location of the database is HDD.

Memory-Centric Database System (**MMDB**)

- The DBMS assumes that the primary storage location of the database is DRAM.

Buffer Management

The DBMS's components manage the movement of data between non-volatile and volatile storage.

Access Times

Access Time	Hardware	Scaled Time
0.5 ns	L1 Cache	0.5 sec
7 ns	L2 Cache	7 sec
100 ns	DRAM	100 sec
350 ns	NVM	6 min
150 us	SSD	1.7 days
10 ms	HDD	16.5 weeks
30 ms	Network Storage	11.4 months
1 s	Tape Archives	31.7 years

Source: Latency numbers every programmer should know

Disk-Oriented DBMS

Design Goals

- 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.

Disk-Oriented DBMS

Query execution engine ⟶ Storage Manager: Get Page 2

Memory | Buffer Pool

Page Directory	-	-	-

Disk | Database File

Page Directory	8	5	1	4	7	3	2	9	6

Disk-Oriented DBMS

- Each page has a **header** with the page's metadata (*e.g.*, page number, free space bitmap)
- Query execution engine gets pointer to page 2
  - Interprets the contents of page 2 using the header
- **Page directory** is typically implemented as a hash table
  - page number $\longrightarrow$ buffer pool slot
  - page number $\longrightarrow$ file block
- Page migration between disk and memory is known as buffer management

Why not use the OS?

- One can use **memory mapping (mmap)** to store the contents of a file into a process' address space.
- The OS is responsible for moving data for moving the files' pages in and out of memory.

Problems

- What if we allow multiple threads to access the mmap files to hide page fault stalls?
- This works good enough for read-only access.
- It is complicated when there are multiple writers.

Why not use the OS?

- There are some solutions to this problem:
  - **madvise:** Tell the OS how you expect to read certain pages.
  - **mlock:** Tell the OS that memory ranges cannot be paged out.
  - **msync:** Tell the OS to flush memory ranges out to disk.
- Database systems using mmap
  - Full Usage: MonetDB, LMDB, *e.t.c.*
  - Partial Usage: mongoDB, MemSQL, *e.t.c.*

Why not use the OS?

- DBMS (almost) always wants to control things itself and can do a better job at it.
  - Flushing dirty pages to disk in the correct order.
  - Specialized prefetching.
  - Buffer replacement policy.
  - Thread/process scheduling.

Storage Management

- File Storage
- Page Layout
- Tuple Layout

File Storage

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.
- Early systems in the 1980s used custom filesystems on raw storage.
  - Some "enterprise" DBMSs still support this.
  - Most newer DBMSs do not roll their own filesystem

Storage Manager

- The **storage manager** is responsible for maintaining a database's files.
  - Some do their own **scheduling** of I/O operations to improve spatial and temporal locality of pages.
- It organizes the files as a collection of pages.
  - Tracks data being read from and written to pages.
  - Tracks the available free space.

Database Pages

- A **page** is a fixed-size block of data.
  - It can contain tuples, meta-data, indexes, log records...
  - Most systems do not mix page types.
  - Some systems require a page to be self-contained. Why?
- Each page is given a unique identifier.
  - The DBMS uses an **indirection layer** to map page ids to physical locations.
  - This is implemented as a page directory table.

Database Pages

- There are three different notions of ”pages” in a DBMS:
  - Hardware Page (usually 4 KB)
  - OS Page (usually 4 KB)
  - Database Page (512 B – 16 KB)
- By hardware page, we mean at what level the device can guarantee a ”failsafe write”.

Page Storage Architectures

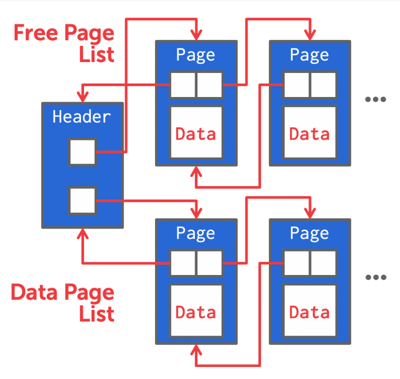
- Different DBMSs manage pages in files on disk in different ways.
  - **Heap File Organization**
  - Sequential / Sorted File Organization
  - Hashing File Organization
- At this point in the hierarchy we don't need to know anything about what is inside of the pages.

Database Heap

- A **heap file** is an unordered collection of pages where tuples are stored in random order.
  - Create / Get / Write / Delete Page
  - 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:
  - Linked List
  - Page Directory

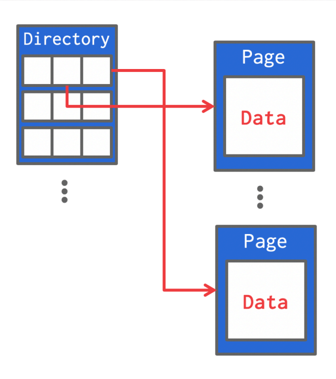
Heap File Organization: Linked List

- Maintain a **header page** at the beginning of the file that stores two pointers:
  - HEAD of the **free page list**.
  - HEAD of the **data page list**.
- Each page keeps track of the number of free slots in itself.



Heap File Organization: Page Directory

- 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.



Page Layout

Page Header

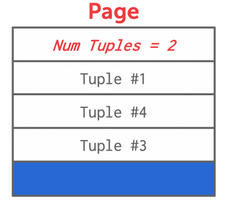
- Every page contains a header of meta-data about the page's contents.
  - Page Size
  - Checksum
  - DBMS Version
  - Transaction Visibility
  - Compression Information
- Some systems require pages to be **self-contained** (*e.g.*, Oracle).

Page Layout

- For any page storage architecture, we now need to understand how to organize the data stored inside of the page.
  - We are still assuming that we are only storing tuples.
- Two approaches:
  - Tuple-oriented
  - Log-structured

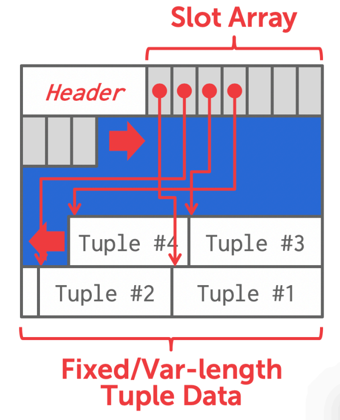
Tuple Storage

- How to store tuples in a page?
- Strawman Idea: Keep track of the number of tuples in a page and then just append a new tuple to the end.
  - What happens if we delete a tuple?
  - What happens if we have a variable-length attribute?



Slotted Pages

- The most common page layout scheme is called slotted pages.
- The **slot array** maps "slots" to the tuples' starting position offsets.
- The header keeps track of:
  - The number of used slots
  - The offset of the starting location of the last slot used.



Georgia Tech

Tuple Layout

Tuple Layout

- A tuple is essentially a sequence of bytes.
- It's the job of the DBMS to interpret those bytes into attribute types and values.

Tuple Header

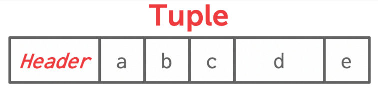
- Each tuple is prefixed with a header that contains meta-data about it.
  - Visibility info (concurrency control)
  - Bit map for keeping track of NULL values.
- We do not need to store meta-data about the schema. Why?

Georgia Tech

Tuple Data

- Attributes are typically stored in the order that you specify them when you create the table.
- This is done for software engineering reasons.

```
CREATE TABLE foo (
~~Ia INT PRIMARY KEY,
~~Ib INT NOT NULL,
~~Ic INT,
~~Id DOUBLE,
~~Ie FLOAT
);
```



Tuple IDs

- The DBMS needs a way to keep track of individual tuples.
- Each tuple is assigned a unique record identifier.
  - Most common: page_id + offset/slot
  - Can also contain file location info.
- An application **cannot** rely on these ids to mean anything.
- Examples
  - PostgreSQL: CTID (6-bytes)
  - SQLite: ROWID (10-bytes)
  - Oracle: ROWID (8-bytes)

BuzzDB

BuzzDB

- BuzzDB – version 4

C++: Tuple (version 1)

```
#include <iostream>
#include <map>
#include <vector>

// A "class" in C++ is a user-defined data type.
// It is a blueprint for creating objects of a particular type,
// providing initial values for state (member variables or fields),
// and implementations of behavior (member functions or methods)
class Tuple {
public:
    int key;
    int value;
};
```

C++: Field

```cpp
enum FieldType { INT, FLOAT };

// Define a basic Field variant class that can hold different types
class Field {
public:
    FieldType type;

    union {
        int i;
        float f;
    } data;

public:
    Field(int i) : type(INT) { data.i = i; }
    Field(float f) : type(FLOAT) { data.f = f; }
};
```

C++: Field

```
enum FieldType { INT, FLOAT };

class Field {
    FieldType getType() const { return type; }
    int asInt() const { return data.i; }
    float asFloat() const { return data.f; }

    void print() const{
        switch(getType()){
            case INT: std::cout << data.i; break;
            case FLOAT: std::cout << data.f; break;
        }
    }
};
```

C++: Tuple

```
class Tuple {
    std::vector<Field> fields;

public:
    void addField(const Field& field) {
        fields.push_back(field);
    }

    void print() const {
        for (const auto& field : fields) {
            field.print();
        }
        std::cout << "\n";
    }
};
```

Conclusion

- Database systems have a layered architecture.
- Design of database system components affected by hardware properties.
- Database is physically organized as a collection of pages on disk.
- Different ways to manage pages and tuples.

Next Class

- Memory Management