Relational Database System Implementation

CS122 – Lecture 1

Winter Term, 2017-2018

Welcome!

- **How do relational databases work?**
  - Provide a *hands-on* opportunity to explore this topic
- This is a project course:
  - A sequence of programming assignments focusing on various areas of database system implementation
  - Also some reading and problem-solving, but not a lot
- No midterm, no final exam ☺

Prerequisites

- You should be familiar with:
  - The SQL query language (DDL and DML)
  - The relational model and relational algebra
  - I will post a link to the CS121 slides
- Also, familiarity with:
  - Algorithms (e.g. sorting, searching), trees, graphs, etc.
  - Basic time and space complexity
- All programming is in Java SE 8+

Software Development

- Secondary focus of course is on software development
  - Automated build system: Ant
  - Documentation generation: Javadoc
  - Automated testing: TestNG (JaCoCo for test coverage)
  - Code linting / static analysis: FindBugs
  - Version control: Git
  - Integrated development environments (e.g. IntelliJ IDEA, Eclipse, etc.)
- You will work with all of these tools during the term

Software Development (2)

- Databases must be correct
  - A portion of each assignment's grade will depend on the correctness of your work
- All work must be clean and well-documented
  - Follow standard Java coding conventions
  - Use Javadoc to document the code you write
  - Clearly and concisely comment your code as well
  - Commit-logs must also include clear documentation of your changes
  - Failure to do these things will result in point deductions

Teams and Collaboration

- You must work in teams of 2-3 people
  - Need to decide team composition relatively quickly
  - First assignment hopefully out by Wednesday this week
- Each team's submission must be entirely its own work
- Feel free to help debug each other's programs, get tools or the debugger working, etc.
  - Follow the "50-foot rule" for helping other teams debug: help others with your brain, not your code.

Course Website

- Lectures, assignments, and other course details are available on the Caltech Moodle
  - https://courses.caltech.edu/course/view.php?id=2900
  - Enrollment key: writeahead
  - **Please enroll ASAP!** All course announcements are made through Moodle.

- Course policies, collaboration policy, contact info, etc. will all be posted there – make sure to review it all!

Late Policy

- Late penalties will be applied to assignments:
  - Up to 24 hours late: -10%
  - Up to 48 hours late: -30%
  - Up to 72 hours late: -60%
  - After 72 hours: don’t bother ☹
- Extensions are available for extenuating circumstances
  - Health center notes, extensions from Dean’s office, or talk to me if these aren’t appropriate
- Teams also have 4 tokens to use throughout the term
  - Each token worth a 24-hour extension, “no questions asked”
  - State in your submission how many tokens you are using

Course Overview

- This class focuses on the implementation of *relational databases*
- Tables (relations) populated with rows (tuples), manipulated with SQL queries
- Lots of other kinds of databases too, but (sadly) we won't discuss them this term
  - CS123 is a great venue to explore other data models, e.g. XML databases, graph databases, NoSQL, etc.

Relational DB Requirements (1)

- Need generalized query support
  - Use the SQL query language
- How to represent query plans internally?
- How to optimize query plans?
  - What plan transformations are allowed?
  - What data statistics do we need to guide this phase?
- How to execute query plans?
  - General issues: subqueries, correlated subqueries, inserts/updates/deletes, etc.
  - Advanced techniques (e.g. parallel execution)

Relational DB Requirements (2)

- Typically needs persistent storage of data
  - Some databases are in-memory only
  - (Makes things *much* simpler!)
- Problem: disks are slow
- How to improve data access performance?
  - Storage formats, data layouts, data access patterns
  - Alternate *access paths* (i.e. indexes)
  - Better hardware? (e.g. RAID, SSD)
- How do these improvements affect query planning and execution?

Relational DB Requirements (3)

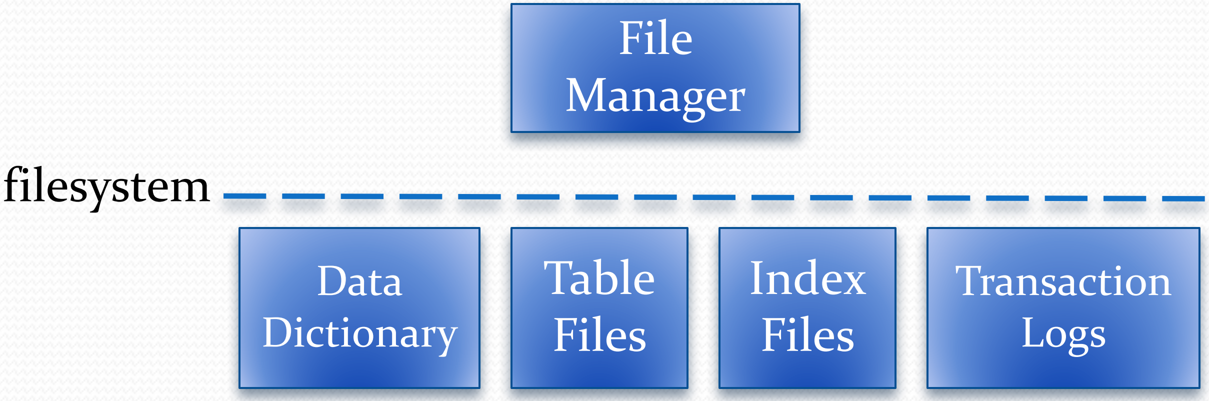
- Generally, databases should provide transacted operations
  - Satisfy specific properties (ACID)
- Example: Durability
  - I complete some critical piece of work
    - i.e. the database reports the transaction as committed
  - Then the power fails!
  - At restart, database should ensure my work is still there…
- Example: Consistency and Atomicity
  - I am performing a multiple-step transaction…
  - Along the way, I violate a database constraint!
    - DB must roll back all other changes in the transaction

Relational DB Requirements (4)

- Databases often need to support concurrent access from multiple clients
- How to ensure that client operations are isolated from each other?
  - *(And what do we mean by "isolated" anyway?)*
  - How to govern access to shared tables/records
  - What techniques can make this fast and efficient?
- How does concurrent access affect query planning, optimization, and execution?

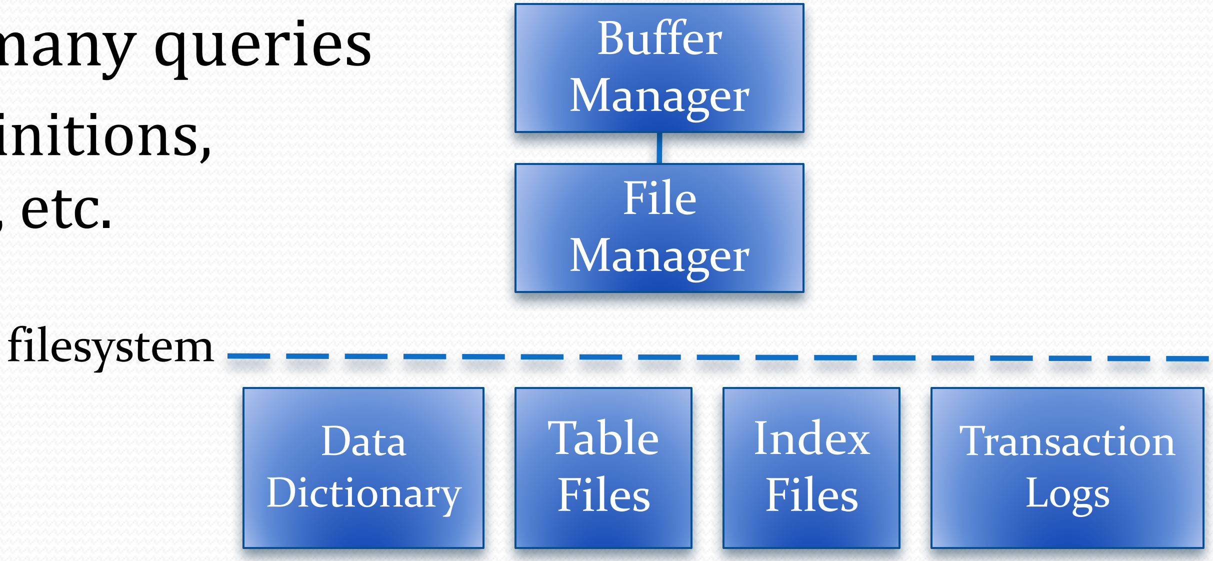
DB Architecture (1)

- Database data is stored in files on disks
  - Files are read and written in blocks to improve performance and simplify transaction processing
- The *file manager* exposes raw disk data to the DB
  - e.g. allows blocks or pages of data to be read from a file
  - e.g. allows files to be created or deleted as well



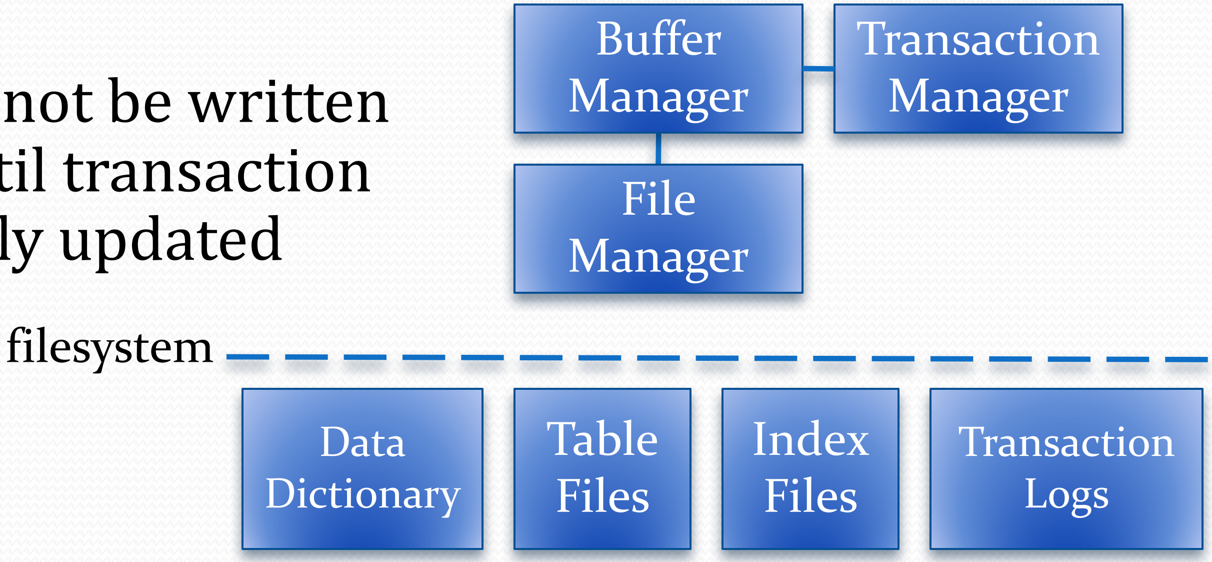
DB Architecture (2)

- The *buffer manager* caches disk pages in memory
  - Ensures that disk is only accessed when necessary
  - Allows very large data files to be managed by database
- Frequently, most widely used data pages remain cached in memory across many queries
  - e.g. schema definitions, critical indexes, etc.



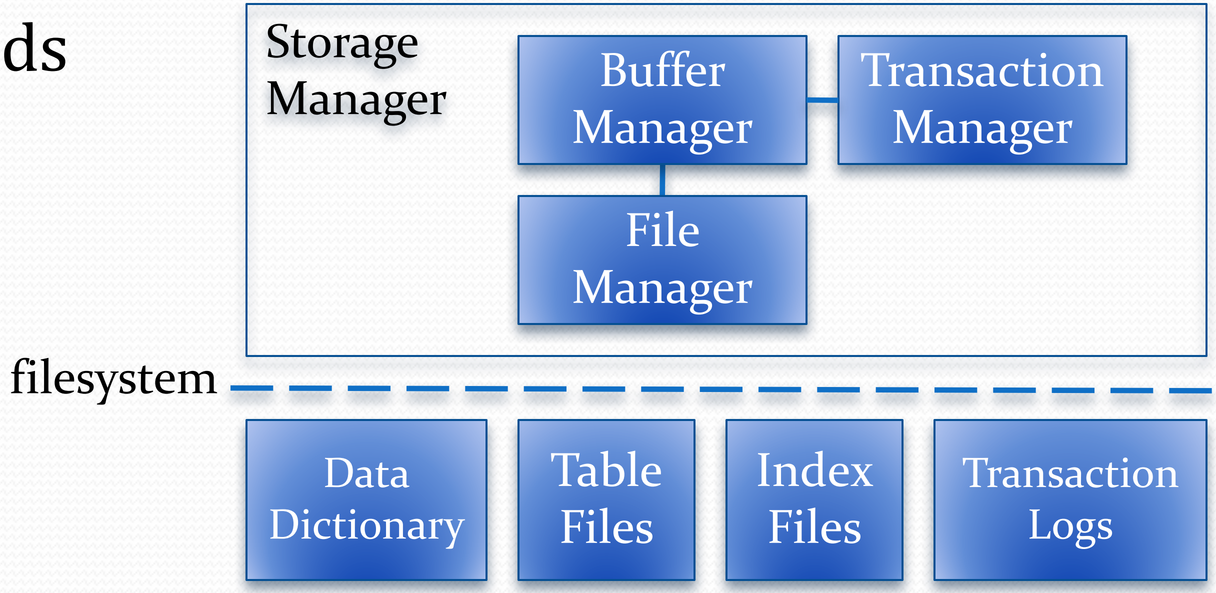
DB Architecture (3)

- The *transaction manager* provides transaction processing in the system
  - Must work closely with the buffer manager
  - Ensure pages are written back to disk in a way that also satisfies transaction properties
- Example:
  - Dirty pages cannot be written back to disk until transaction logs are properly updated



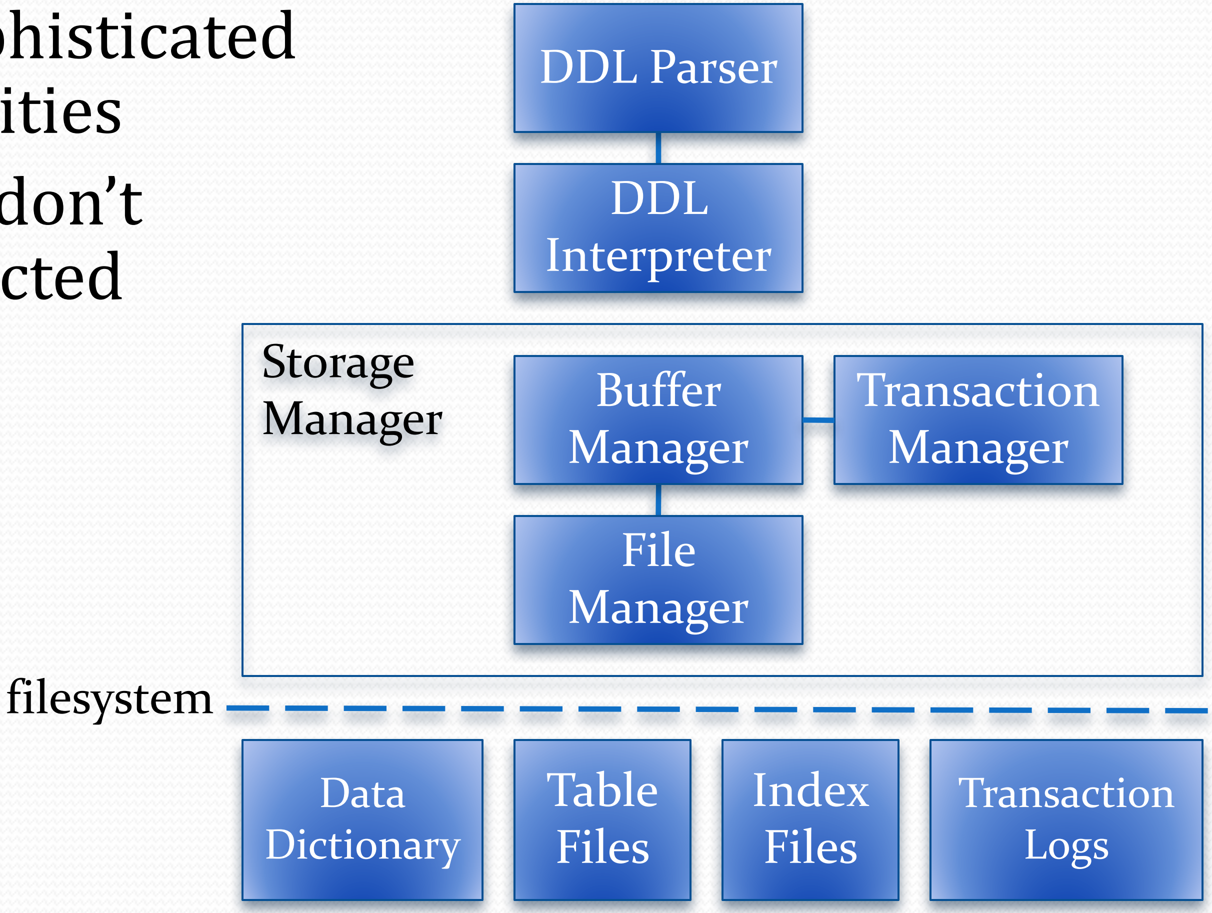
DB Architecture (4)

- These components collectively comprise the *storage manager*
- Provides access to schema information, table data, indexes, and statistics about table data
- Can also manipulate each of these kinds of data



DB Architecture (5)

- Data definition operations don't require sophisticated querying capabilities
- Many databases don't even have transacted DDL

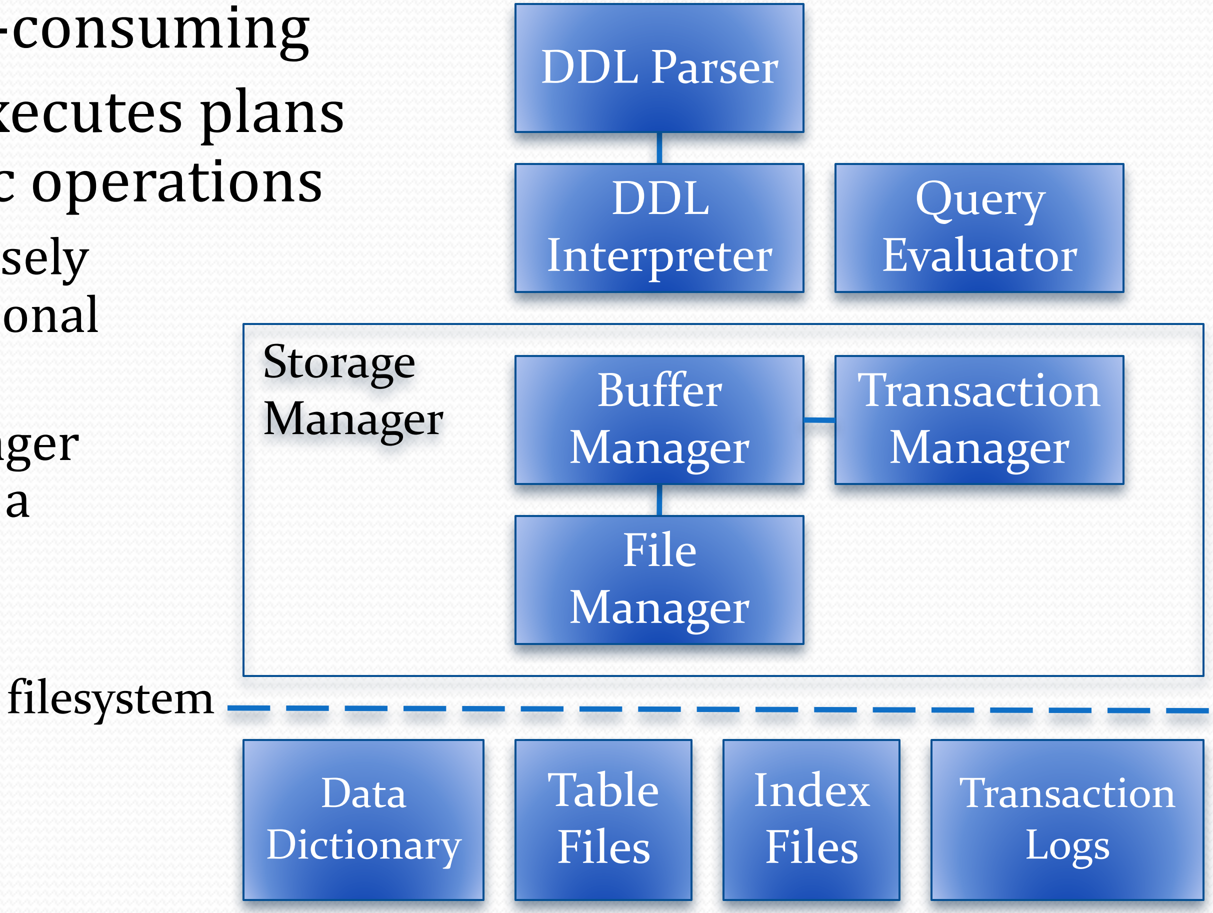


Data Definition

- Data definition operations require manipulation of data dictionary, table files, and index files
  - Create/alter/drop a table
  - Create/alter/drop an index
- The *data dictionary* holds all DB schema information
  - Most databases use another set of tables to store the data dictionary
    - Use same machinery to read/write tuples in data dictionary
    - Makes it easier to transact DDL operations too
    - Manipulation of these tables is performed more directly, without using query processing system

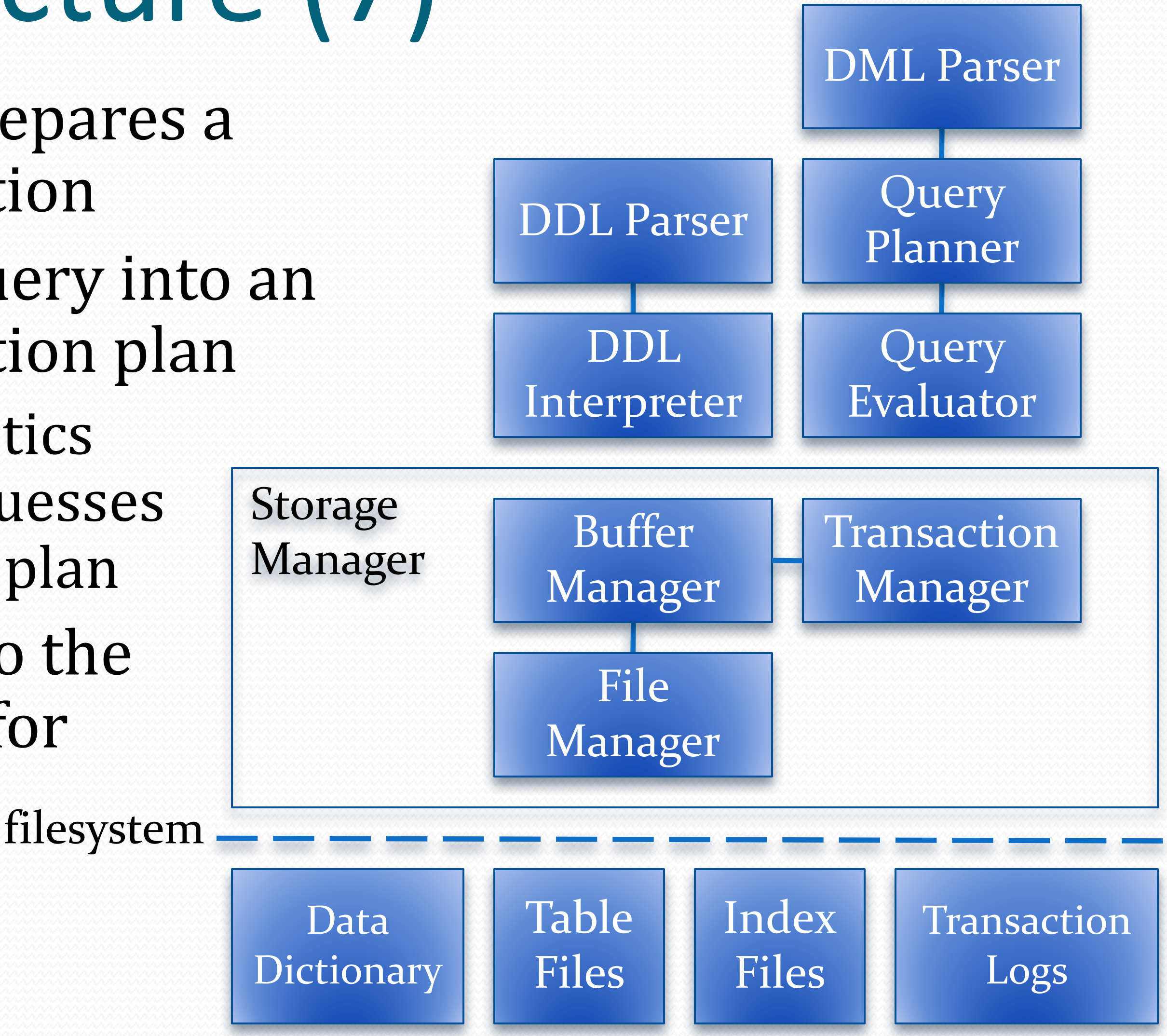
DB Architecture (6)

- Database queries can be very complex and time-consuming
- *Query evaluator* executes plans comprised of basic operations
  - Operations are loosely based on the relational algebra operators
  - Uses storage manager to access tables as a sequence of tuples



DB Architecture (7)

- *Query planner* prepares a query for evaluation
- Translates the query into an optimized execution plan
  - Uses data statistics and educated guesses to optimize the plan
- Passes the plan to the query evaluator for execution



Introducing NanoDB

- Assignments and projects will be based on the NanoDB codebase
  - A simple Java database implementation
- Primary goal is to be understandable and extensible
  - When deciding between performance and clarity, NanoDB generally chooses clarity
  - (Most open-source database projects go the other way.)
- Definitely still a work in progress!
  - Plenty of opportunity to make a lasting contribution to this project, and to future iterations of this class

Database Files

- The database stores data in files, and manipulates data in memory…
  - …this data is stored on physical devices in the computer
- Need to understand the characteristics of these devices to understand how to implement databases properly

Storage Hierarchy

- Wide variety of storage media available for use
- Can classify storage media based on:
  - Access speed
  - Cost per unit storage
  - Reliability
- Different media support different access patterns
  - Affects their usefulness for various tasks
- Examples:
  - Magnetic tapes are best suited to sequential access; random access is prohibitively slow
  - DRAM/flash memory are very good for random access

Storage Hierarchy (2)

- Primary storage:
  - Cache memory is usually very small, very fast
  - Main memory is much larger than cache, but usually still too small to hold an entire database
  - Supports random access (a.k.a. direct access)
  - Storage is *volatile*: data doesn't survive a power loss
- Secondary storage, a.k.a. online storage:
  - Much larger, cheaper, and slower than primary storage
  - Storage is *persistent*: data lasts through a power loss
  - Magnetic disks are most common form of secondary storage
  - Flash memory devices (Solid State Drives or SSD) are increasingly common, but are still smaller/more expensive

Storage Hierarchy (3)

- Tertiary storage, a.k.a. offline storage:
  - Optical storage (CDs, DVDs, etc.), tape storage
  - Primarily used for backup and archival storage
  - Access rates are *very* slow compared to primary and secondary storage
  - Tapes only support sequential access, not direct access
- Tapes/optical disks can be managed in a library
  - Robotic system to load specific tapes/disks into a drive
  - Called near-line storage
- Primary difference between offline & near-line storage:
  - A computer can access near-line storage and load it into online storage all by itself
  - A human being must make offline storage available

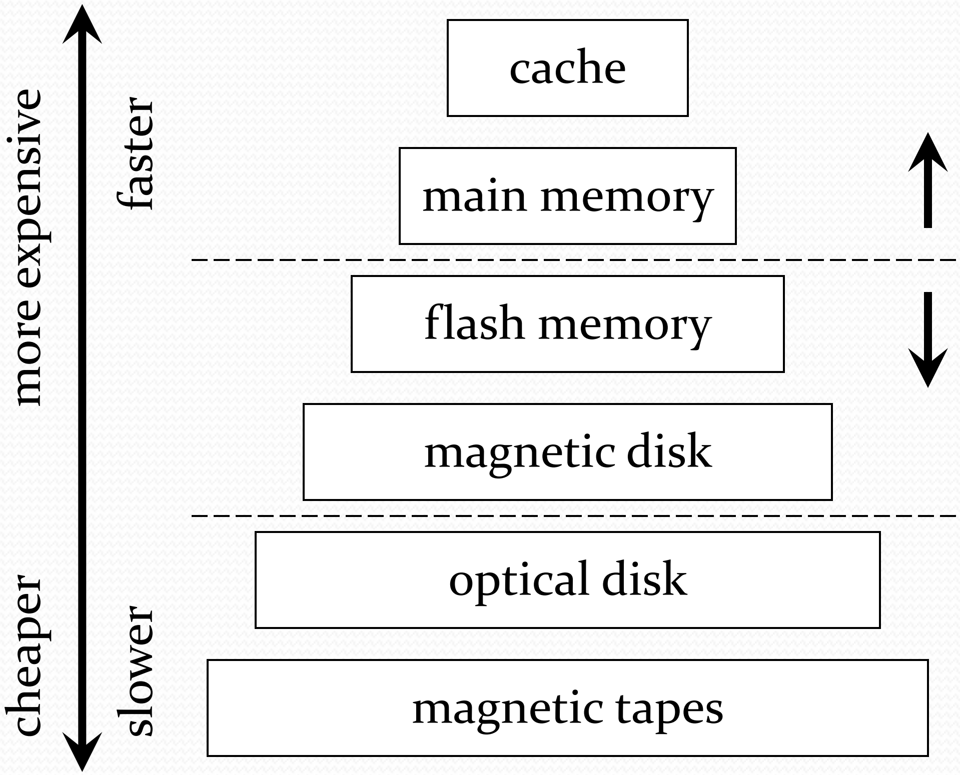
Internal vs. External Memory

- In database systems, primary storage is also often called *internal memory*
  - Memory the CPU can access quickly and efficiently
- Similarly, secondary storage (flash memory, magnetic disks) are called *external memory*
- Algorithms designed to work with data sets much larger than primary storage are called *external memory algorithms*
  - Must repeatedly load portions of data into internal memory, process them, then store them back to disk

Internal vs. External Memory (2)

- Data structures for organizing data on disk are called external memory structures
  - e.g. hash file organization also called *external hashing*
- Frequently encounter "external-memory (*whatever*)" in database literature
  - Simply means the algorithm/structure is designed to work with data stored on disk, not just in memory

Storage Hierarchy (4)



more expensive

faster

cheaper

slower

cache

main memory

flash memory

magnetic disk

optical disk

magnetic tapes

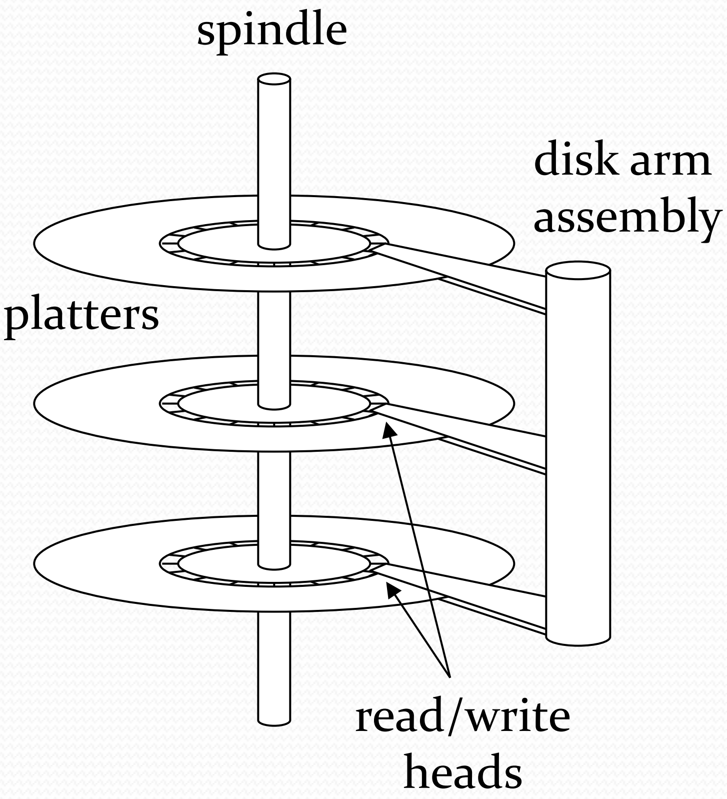
primary storage
(aka “internal memory”)
CPU can access directly
volatile storage

secondary (on-line) storage
(aka “external memory”)
OS must facilitate access
nonvolatile storage

tertiary (off-line) storage
Usually, a person must
facilitate access

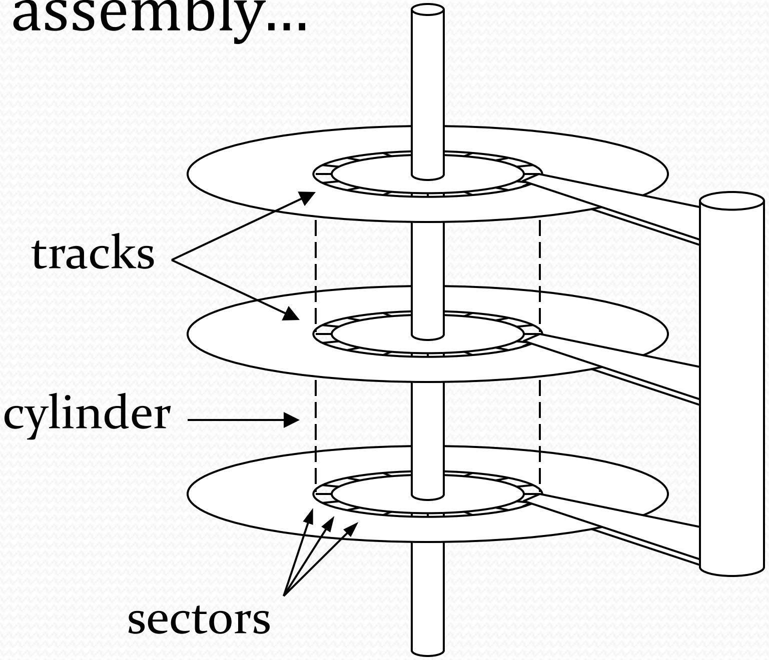
Magnetic Disks

- Magnetic disks are most widely used online storage medium in computers
    - Hard disk drives (HDD)
- Drive contains some number of *platters* mounted on a *spindle*
    - Platters spin at a constant rate of speed
    - 5400 RPM, up to 15000 RPM
- Read/write heads are suspended above platters on a *disk arm*
    - All heads move together as a unit



Magnetic Disks (2)

- Platters are divided into *tracks*
- Tracks are divided into *sectors*
  - Modern drives have more sectors towards edge of disk
- All heads are positioned by one assembly…
  - A *cylinder* is made up of the tracks on all platters at the same position
- To read a sector from disk:
  - Assembly *seeks* to the appropriate cylinder
  - Sector is read when it rotates under the disk head



Disk Performance Measures

- *Access time* is the time between a read/write request being issued, and the data being returned
  - Read/write heads must be moved to appropriate track
  - Sectors must rotate past the read/write heads
- First operation is called a *seek*
  - Average seek time of a disk is measured from a series of random seeks (uniform distribution)
  - Generally ranges from 3-15ms
  - Typical consumer drives are in the range of 9-12ms
- Seeking nearby tracks will obviously be faster
  - Track-to-track seek times in range of 0.2-0.8ms
- (SSDs have “seek times” in the 0.08-0.16ms range)

Disk Performance Measures (2)

- *Rotational latency time* is amount of time for sector to pass under read/write heads
  - Average rotational latency is ½ the time for a full rotation
  - 5,400 RPM: 5.6ms
  - 7,200 RPM: 4.2ms
  - 15,000 RPM: 2ms
- Disks can only read/write information so quickly
  - *Data transfer rate* specifies how fast data is read from/written to the disk
  - Current interfaces can support up to 600+ MB/sec
  - Actual transfer rate depends on several things:
    - The disk and its controller, motherboard chipset, etc.
    - The section of the disk being accessed

Disk-Access Optimizations

- Wide range of techniques used to improve hard disk performance
  - Implemented in the HDD itself, and/or in operating system
- Buffering
  - When data is read, store it in a memory buffer
  - If same data is requested again, provide it from the buffer
- Read-ahead
  - When a sector is read, read other sectors in the same track
  - If a program is scanning through a file, subsequent accesses can be satisfied immediately from cache

Disk-Access Optimizations (2)

- I/O Scheduling
  - The hard disk can queue up batches of read and write requests, then schedule them in a reasonable way
  - Goal: reduce the average seek time of accesses
  - Writes can be buffered in volatile memory to facilitate this (can cause problems if power fails before write is performed)
- Nonvolatile write buffers
  - Disk provides NV-RAM to cache disk writes
  - Data is saved in NV-RAM before being saved to disk
  - Data isn’t written to disk until the disk is idle, or the NV-RAM buffer is full
  - If power fails, contents of NV-RAM are still intact!