CS 6400 A

Database Systems Concepts and Design

Lecture 25

11/24/25

Announcements

- Assignment 3 due today
- Project final report and code due next Monday
- Schedule this week:
  - No lecture on Wednesday; no office hour
- Final exam (take home):
  - Released Dec 4 (Thursday) at 3PM; due Dec 5 (Friday) at 9PM.
  - Practice exam on canvas
  - Review lecture next Monday

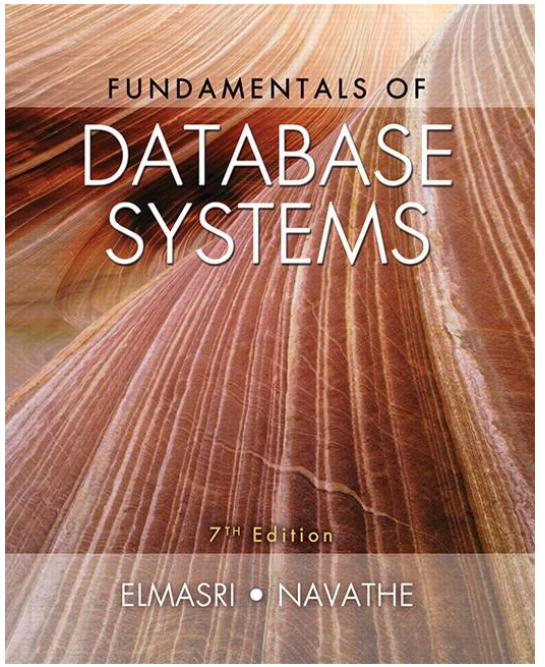
Agenda

1. NoSQL
2. Course Summary

Reading Materials

Fundamental of Database Systems (7th Edition)

- Chapter 24: NOSQL Databases and Big Data Storage Systems



Research Papers:

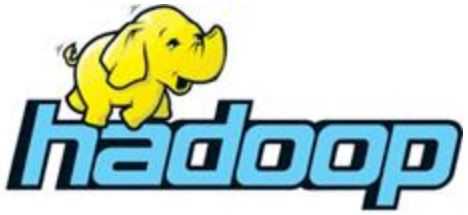
- The LSM Tree Paper

Review: SQL history and motivation

Initially developed in the early 1970's

By 1986, ANSI and ISO standard groups standardize SQL

- New versions of standard published in 1989, 1992, and more up to 2016



"Dark times" in 2000s

- NoSQL for Web 2.0
- Google's BigTable, Amazon's Dynamo
- Are relational databases dead?

NewSQL systems in 2010s

- Bring back ACID

1. NoSQL

NoSQL

NoSQL stands for “Not Only SQL” or “Not Relational”

- relax on consistency requirements to gain efficiency and scalability

Designed to scale simple “OLTP”-style application loads

- to provide good horizontal scalability for simple read/write database operations distributed over many servers

Originally motivated by Web 2.0 applications

- these systems are designed to scale to thousands or millions of users

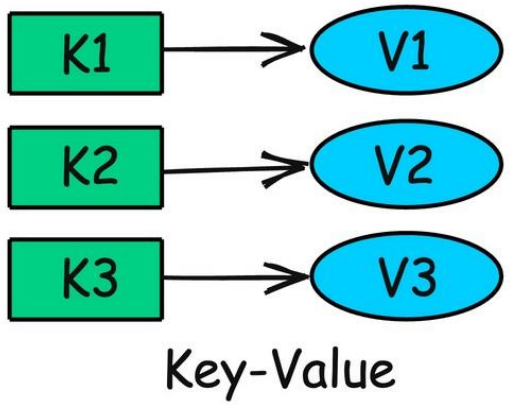
Example NoSQL systems

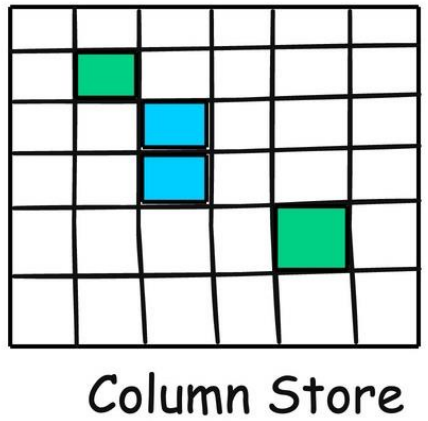
Key-value store:
DynamoDB, Redis

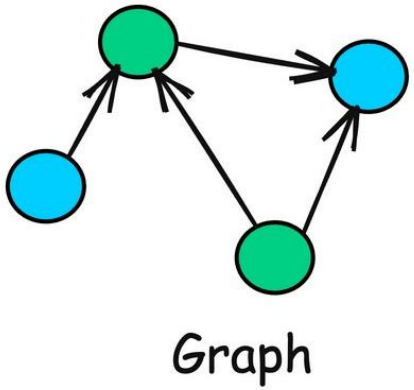
Document store:
MongoDB, CouchDB

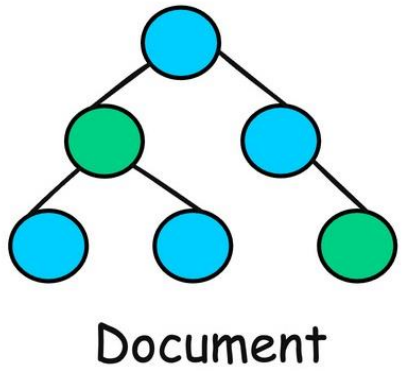
Wide-column stores:
Cassandra, BigTable

Graph database:
Neo4j, AWS Neptune









NoSQL vs RDBMS

Two important distinctions:

Consistency Model:

- ACID (Strong Consistency) vs BASE (Eventual Consistency)

Data structure:

- B+ tree vs LSM Tree

Problem with ACID

Recall ACID for RDBMS desired properties of transactions

Challenge: maintaining ACID across multiple servers requires coordination

- Coordination = latency + reduced availability

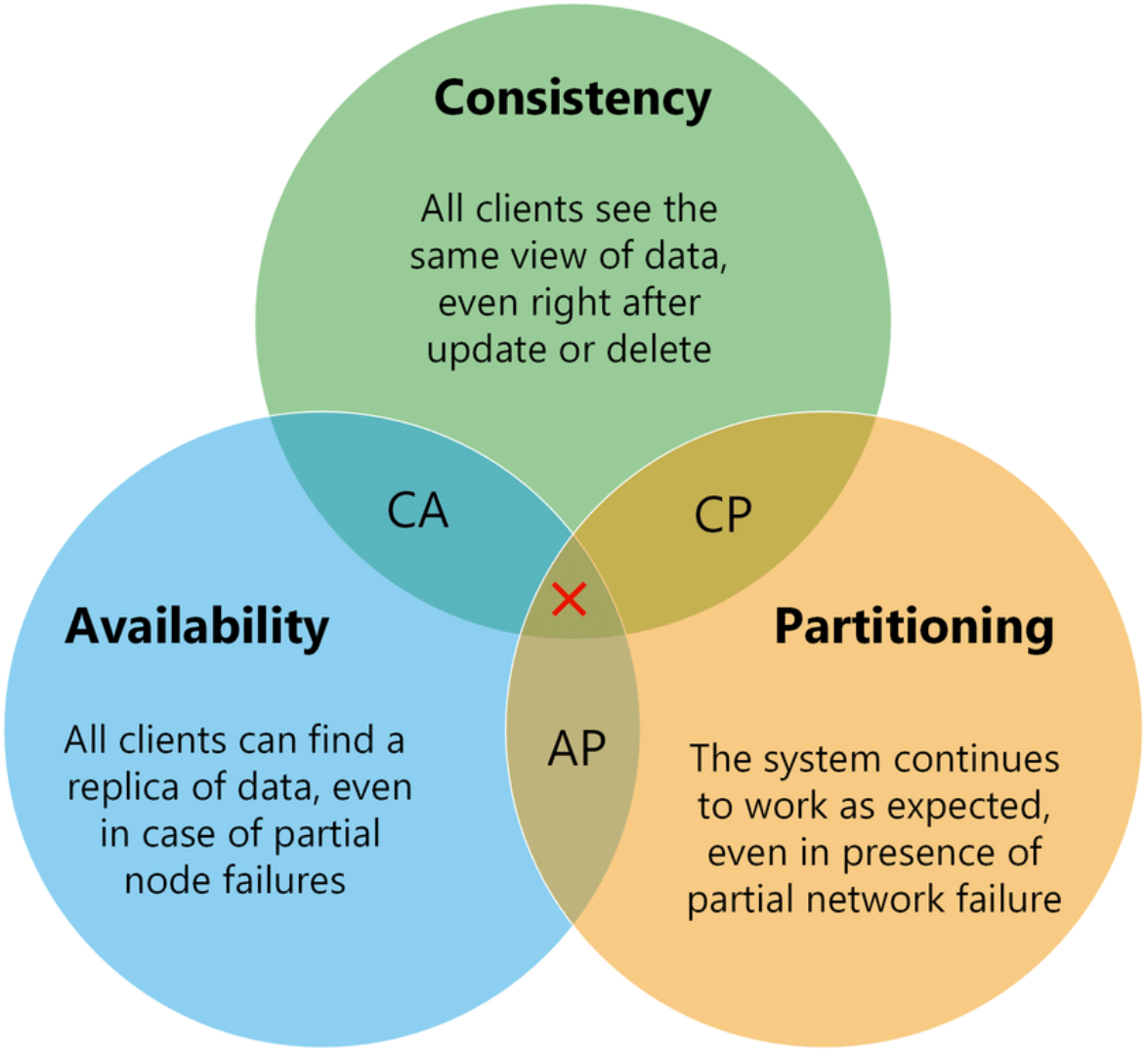
Example: adding an item to shopping cart

- Option 1: System says "I can't guarantee your cart is consistent across all servers, so I'm refusing your request"
- Option 2: System says "I'll accept your cart addition on this datacenter, we'll sync up later"

CAP Theorem

Any distributed data store can provide only two of the following three guarantees: **C**onsistency, **A**vailability, and **P**artition-tolerance.

AP: eventual consistency
CP: strong consistency



NoSQL systems generally give up consistency (AP system)

Image source: https://medium.com/nerd-for-tech/understand-cap-theorem-751f0672890e

ACID vs BASE

NOSQL systems typically do not provide ACID: they sacrifice strong consistency for availability/performance

- Basically Available
- Soft state
- Eventually consistent

The systems differ in how much they give up

- e.g., most of the systems call themselves “eventually consistent”, meaning that updates are eventually propagated to all nodes
- Many modern NoSQL systems offer tunable consistency - you can choose between strong consistency (more ACID-like) and eventual consistency (BASE) depending on your need

Problem with B+-Trees

Optimized for reads, not for writes (insert, update, delete)

Write amplification:

- ratio of the amount of data written to the storage device versus the amount of data written to the database
- Inserting and deleting a record could require updating multiple pages on disk (many random disk I/Os)

NoSQL systems face extreme *write workloads*:

- High write throughput: social media posts, IoT sensors, logs
- Distributed writes across many nodes
- Append-heavy workloads

Log-structured Merge Tree (LSM Tree)

Proposed by O'Neil, Cheng, and Gawlick in 1996

Uses write-optimized techniques to significantly speed up inserts

Used by many NoSQL systems:

- e.g., Bigtable, Cassandra, Dynamo, HBase, RocksDB, InfluxDB

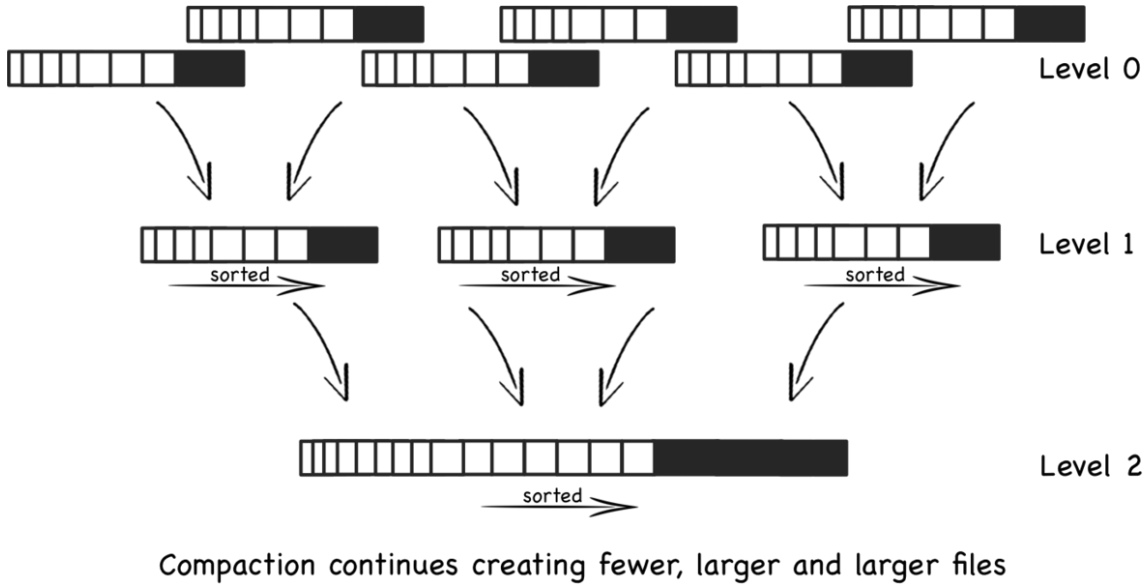


Image source: https://en.wikipedia.org/wiki/Log-structured_merge-tree

LSM Tree: Overview

Log-structured · Merge · Tree

Log-structured

Data is written sequentially in append-only fashion, like writing to a log file

Merge

As data evolves, sequentially written runs of key-value pairs are merged

- Runs of data are indexed for efficient lookup
- Merges happen only after much new data is accumulated

Tree

The hierarchy of key-value pair runs form a tree

- Searches start at the root, progress downwards

LSM Tree: Overview [O'Neil, Cheng, Gawlick '96]

An LSM-tree comprises a hierarchy of levels of increasing size

- All data inserted into in-memory tree (C_0); no I/O cost at this step
- Larger on disk levels ($C_{i>0}$) hold data that does not fit into memory

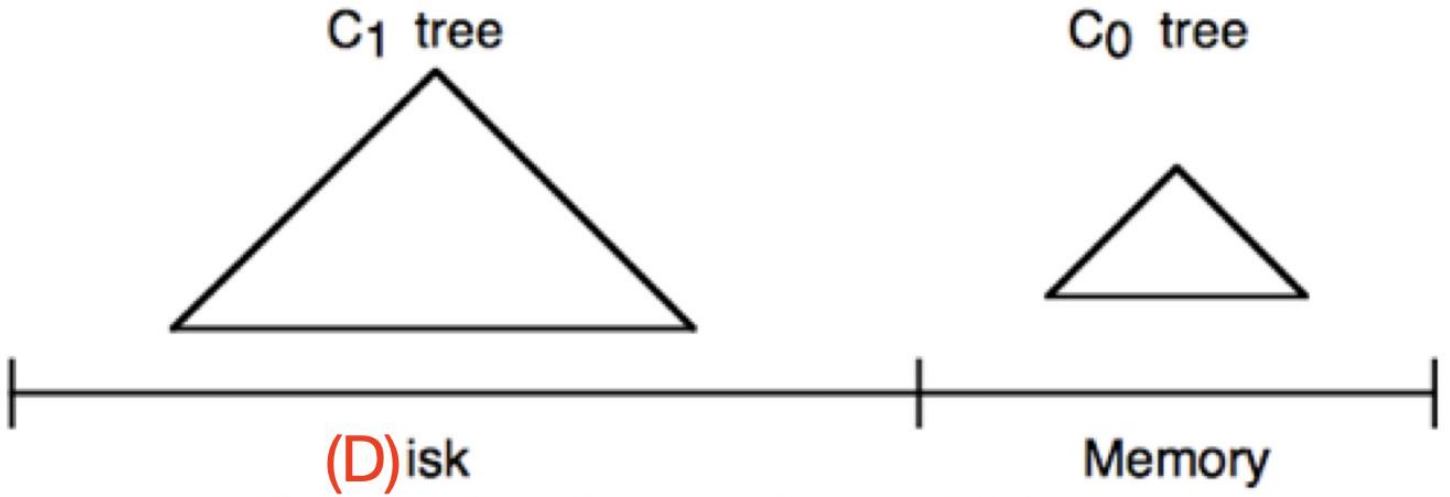


Figure 2.1. Schematic picture of an LSM-tree of two components

LSM Tree: Overview [O'Neil, Cheng, Gawlick '96]

When a level exceeds its size limit, its data is merged and rewritten

- Also called "compaction"
- Higher level is always merged into next lower level (C_i merged with C_{i+1})
- Merging always proceeds top down

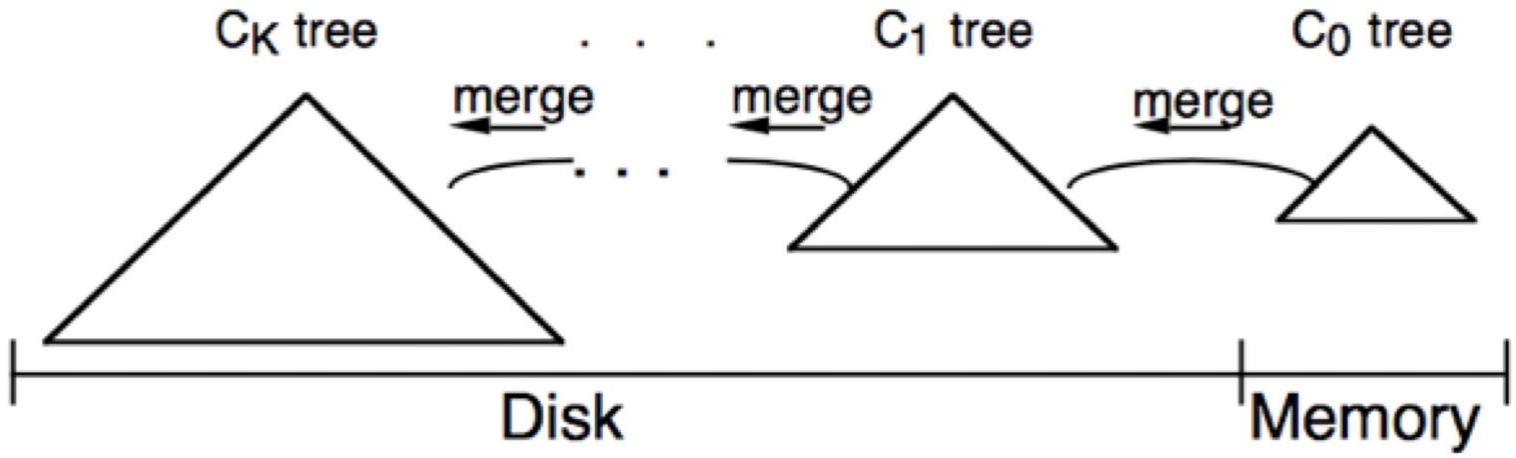


Figure 3.1. An LSM-tree of K+1 components

LSM Tree: Inserts

New data is written to an in-memory buffer (MemTable)

- typically organized as a balanced tree (like a Red-Black tree) to maintain sorted order
- Append-only log

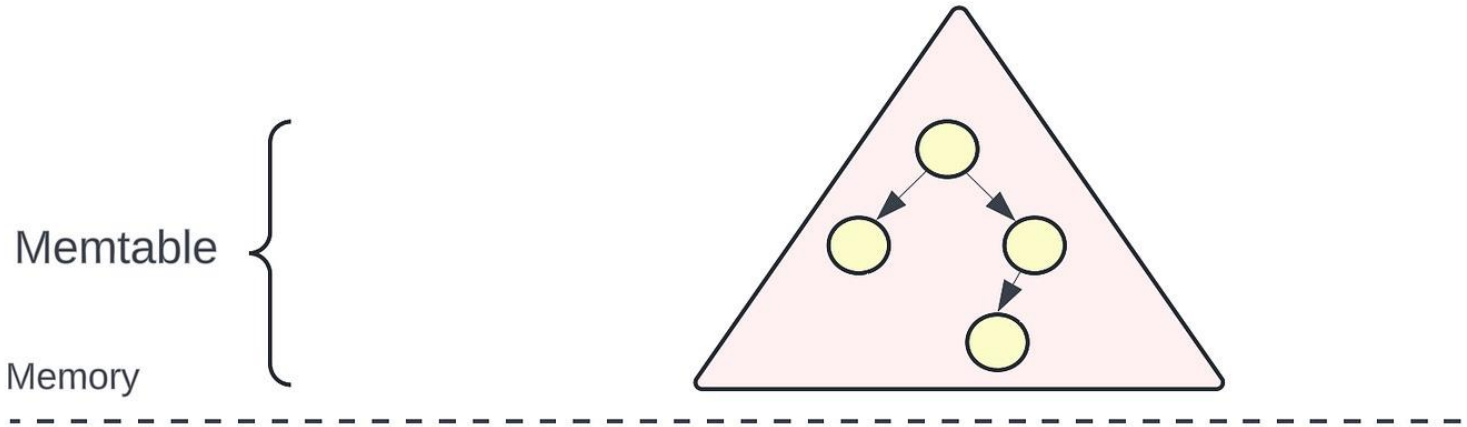


Image source: https://vivekbansal.substack.com/p/what-is-lsm-tree

LSM Tree: Inserts

New data is written to an in-memory buffer (MemTable)

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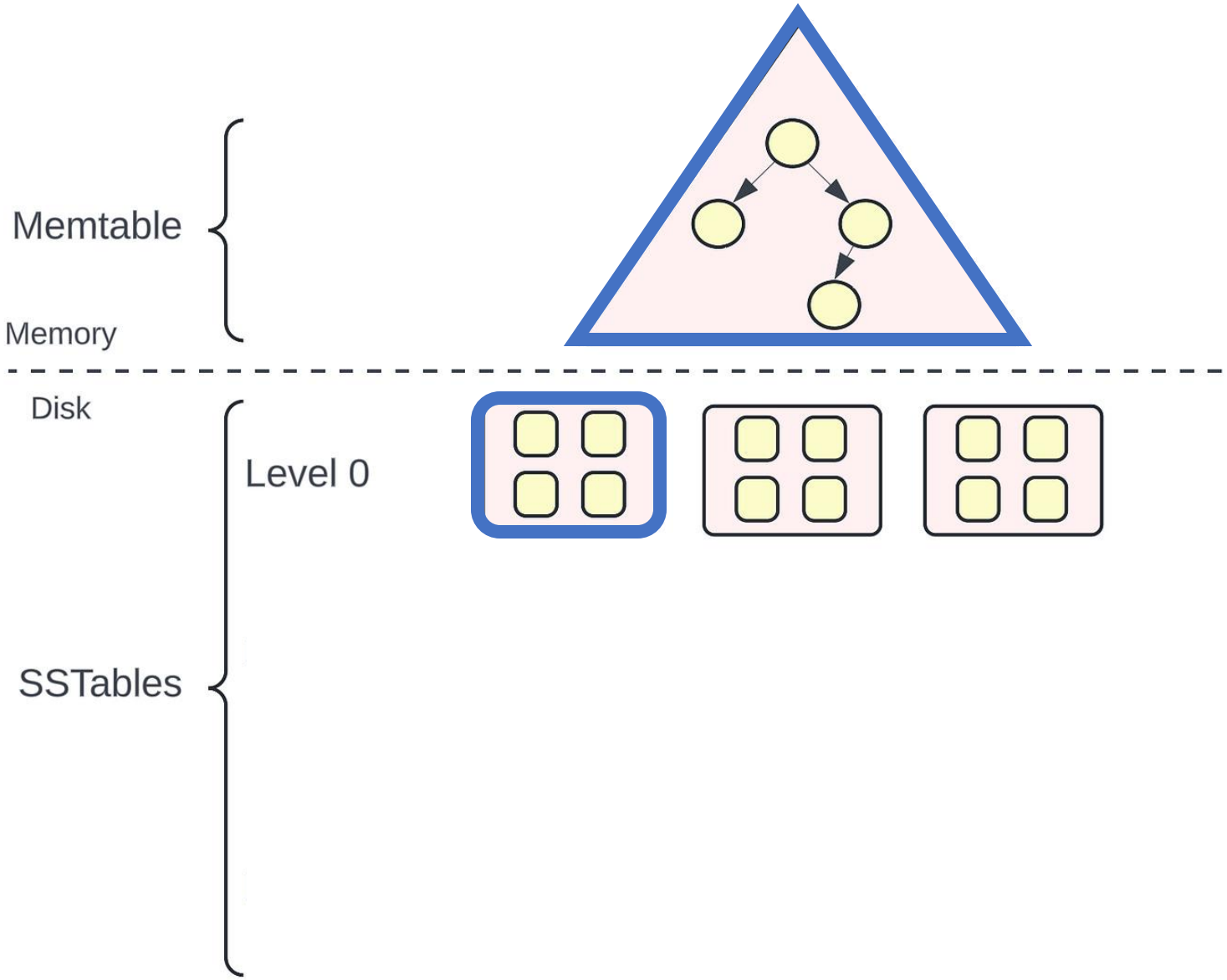
When the MemTable fills up, it's flushed to disk as a new SSTable file (the “run”) in Level 0



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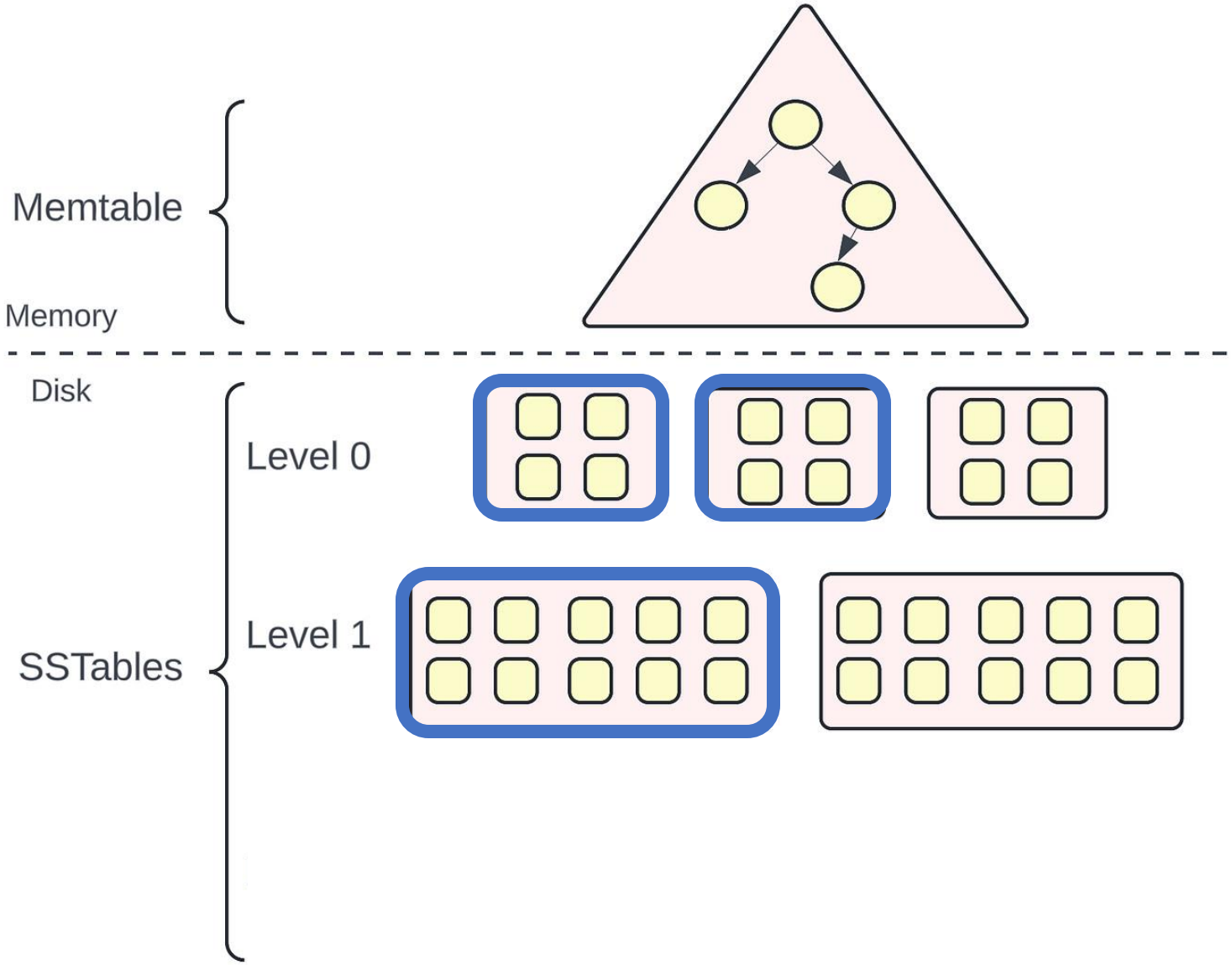
LSM Tree: Inserts

Once too many L0 files exist, compaction merges them into L1

- k-way merge sort
- Input: L0 files + L1 files with overlapping key ranges
- Output: new L1 files with non-overlapping ranges



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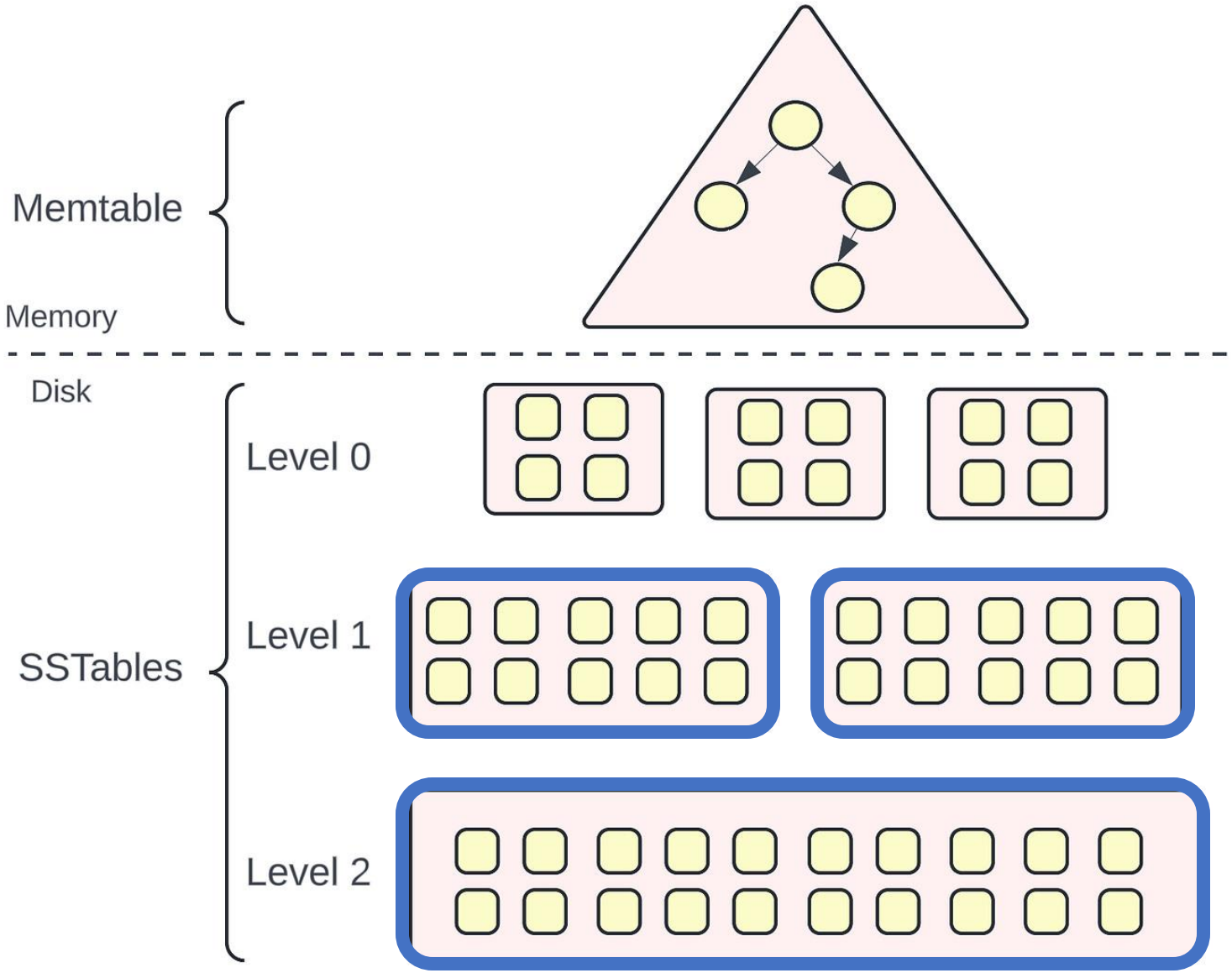
LSM Tree: Inserts

Once too many L0 files exist, compaction merges them into L1

Similarly, when there are too many L1 files, compaction merges them into L2



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LSM Tree: Inserts

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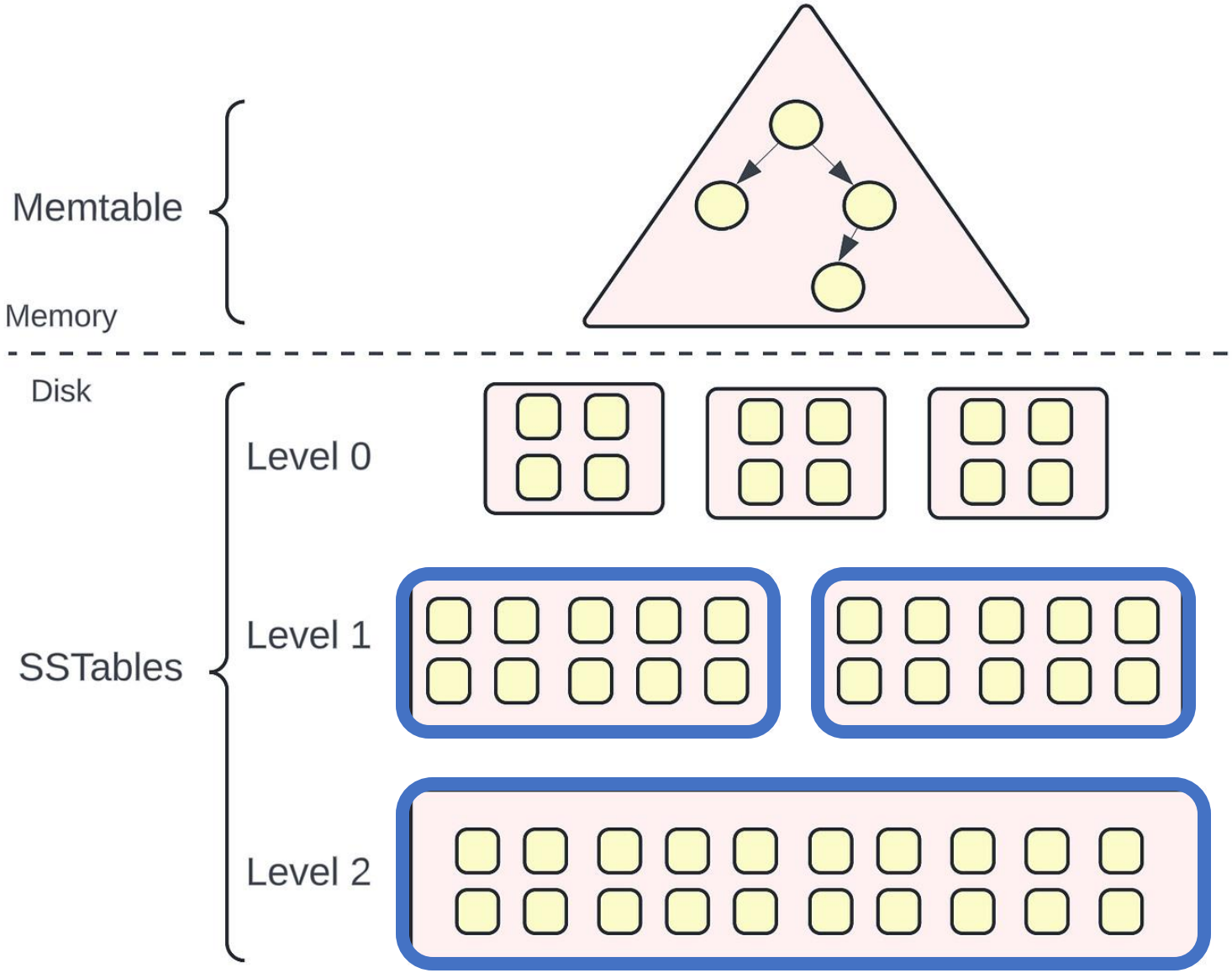
Different compaction strategies:

- Size tiered compaction strategy (bigger files in deeper levels)
- Leveled compaction strategy (more files per level)



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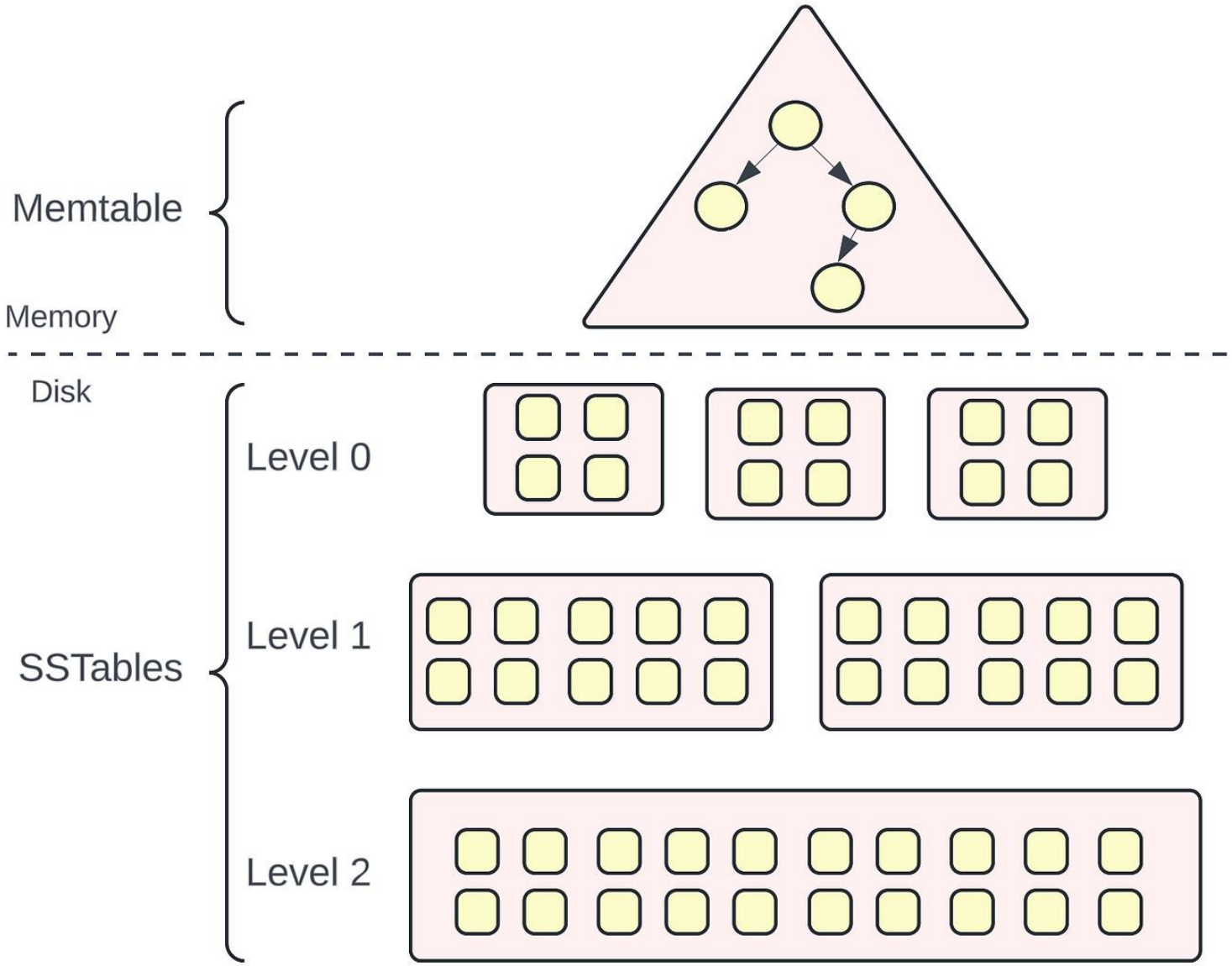
LSM Tree: Lookups

Check Memtables

Check SSTables:

- Bloom Filter:
  - check existence of key
- Summary Tables:
  - e.g., store the range of keys in each SSTable
  - Skip irrelevant files



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Summary: B+ Tree vs LSM Tree

	B+ Tree	LSM Tree
Structure	Balanced tree with internal nodes and leaves	Multiple levels, memtable, and SSTables

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Typical Use Cases	Relational databases, read-heavy workloads	NoSQL databases, log-structured systems, write-heavy workloads

2. Course Summary

Course Summary

We learned…

1. How to query a database

1. Intro

2-3. SQL

4. ER Diagrams

5. Relational Algebra

6-7. DB Design

8-13. Index, Storage

14-17. QO

18-21. TXNs

22-25. Beyond RDBMS

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1. How to query a database
2. How to design a database
3. How records is stored and indexed
4. How to optimize the performance of a database
5. How to handle concurrent user requests and crashes/aborts
6. How RDBMS relates to OLAP, Distributed Query Processing, Parallel and Distributed DBMS, NoSQL etc.

1. Intro

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Relational databases => Data-intensive systems

Most important computer applications must manage, update and query datasets

- Bank, store, search app…

Data quality, quantity & timeliness becoming even more important with AI

- Machine learning = algorithms that generalize from data

Relational databases => Data-intensive systems

Relational databases are the most popular type of data-intensive system (MySQL, Oracle, etc)

Many other systems facing similar concerns: key-value stores, streaming systems, ML frameworks, your custom app?

Reliability in the face of crashes, bugs, bad user input, etc
Concurrency: access by multiple users
Performance: throughput, latency, etc
Access interface from many, changing apps
Security and data privacy (not covered in this course)

Beyond this class

Classes:

- CS 4420/6422: Database System Implementation
- CS 4423/6423: Advanced Database System Implementation
- CS 6220: Big Data Systems and Analytics
- CS 8803-LRV: Large Scale & Real-Time Visual Analysis
- CS 8803-DML: Data-Centric Machine Learning

DB research at GT:

- Data Systems and Analytics Group