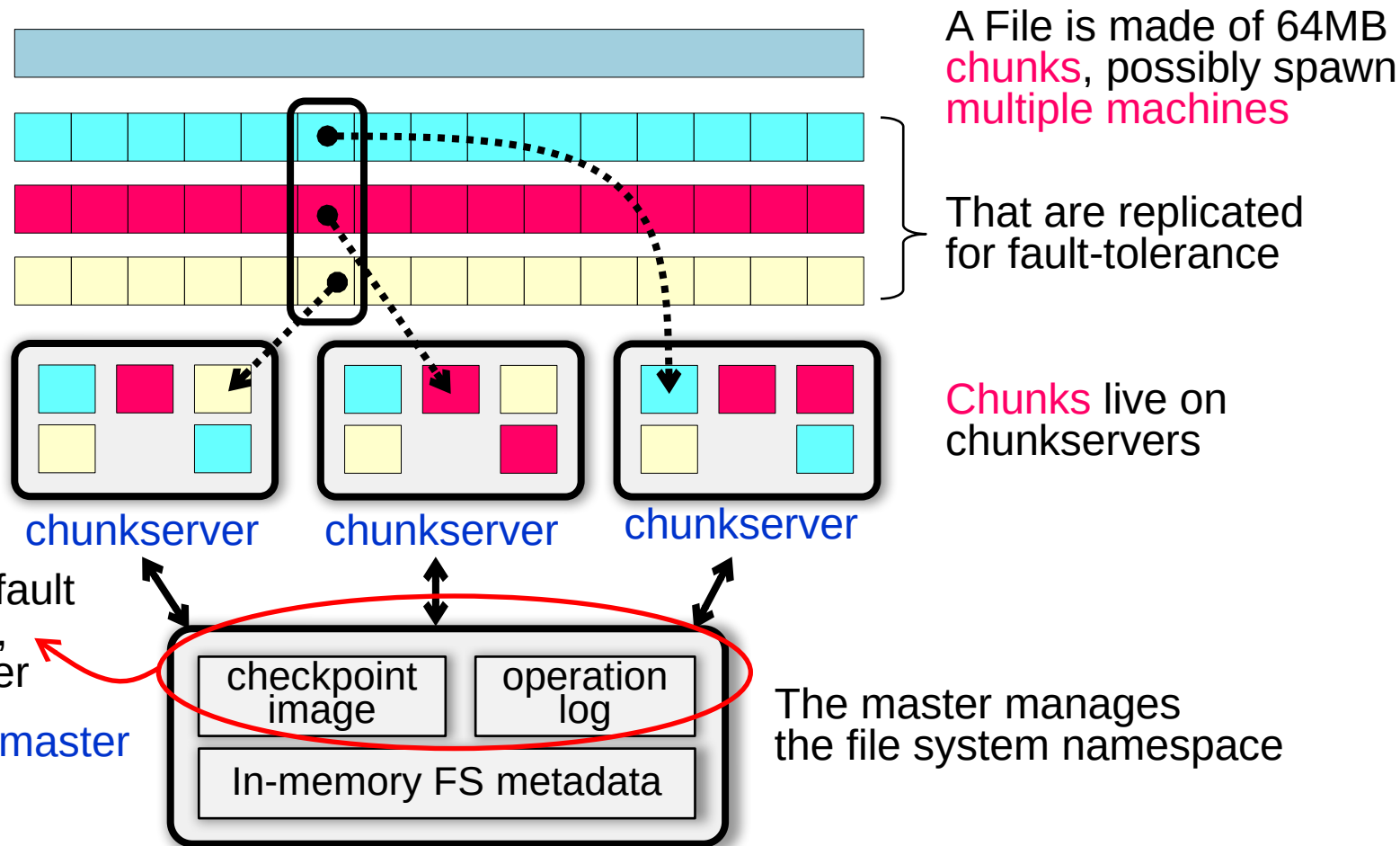


Designing efficient key-value store/storage (KVS) on a single node

IPADS, Shanghai Jiao Tong University

<https://www.sjtu.edu.cn>

Review: GFS



Reading a file in GFS (very similar to the naïve DFS)

Reading a file is simple in GFS

1. Contact the **master**
2. Get file's **metadata**: chunk handles
3. Get the **location** of each of the chunk handles
 - Multiple replicated chunkservers per chunk
4. Contact any **available** chunkserver for chunk

Writing a File in GFS (More complicated due to replication)

Less frequent than reading

- But is more complex, because we need to deal with the consistency issues
- GFS adopts a **relaxed consistency model (see later lectures)**
- E.g, may have inconsistency state, but work well for their apps
- Benefits: simple & efficient to implement

Master grants a **chunk lease** to one of the replicas

- This replica will be the **primary** chunkserver
 - The only one that can modify the chunk
- Primary can request extensions (of lease), if needed
 - Master increases the chunk version number and informs replicas

Naming in GFS: simple flat naming

No **per-directory** data structure like most file systems

- E.g., directory file contains names of all files in the directory

No aliases (i.e., no hard or symbolic links)

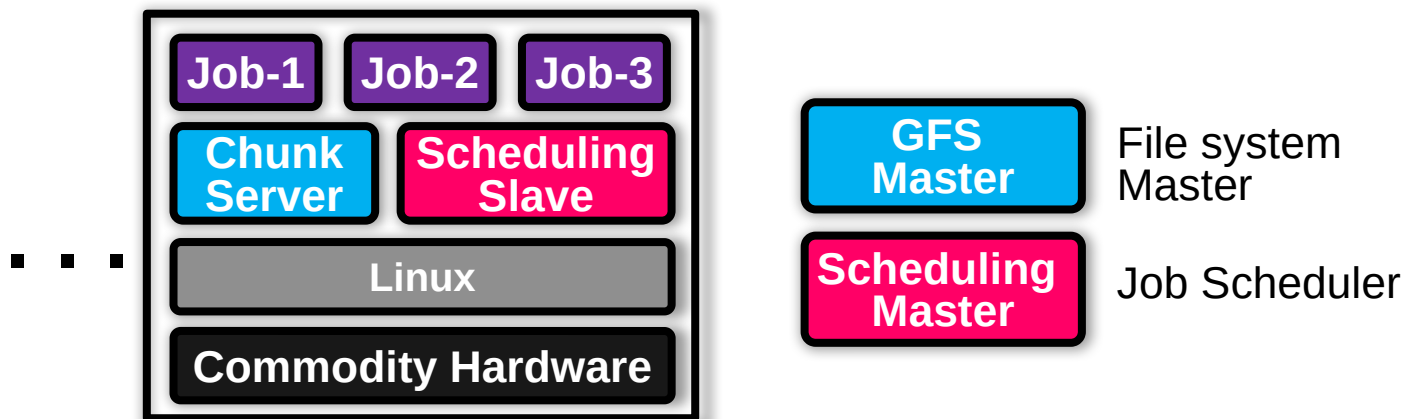
Namespace is **a single lookup table**

- Maps pathnames to metadata

Review: GFS in Google cluster

Google cluster environment

- Core services: GFS + cluster scheduling system
- Typically, 100s to 1000s of active jobs
- 200+ clusters, many with 1000s of machines
- Pools of 1000s of clients
- 4+ PB filesystems, 40GB/s read/write loads



HDFS: another popular (open-source) DFS

Hadoop Distributed FS

Primary storage system for Hadoop apps



A framework that allows for the distributed processing of large data sets across clusters of computers



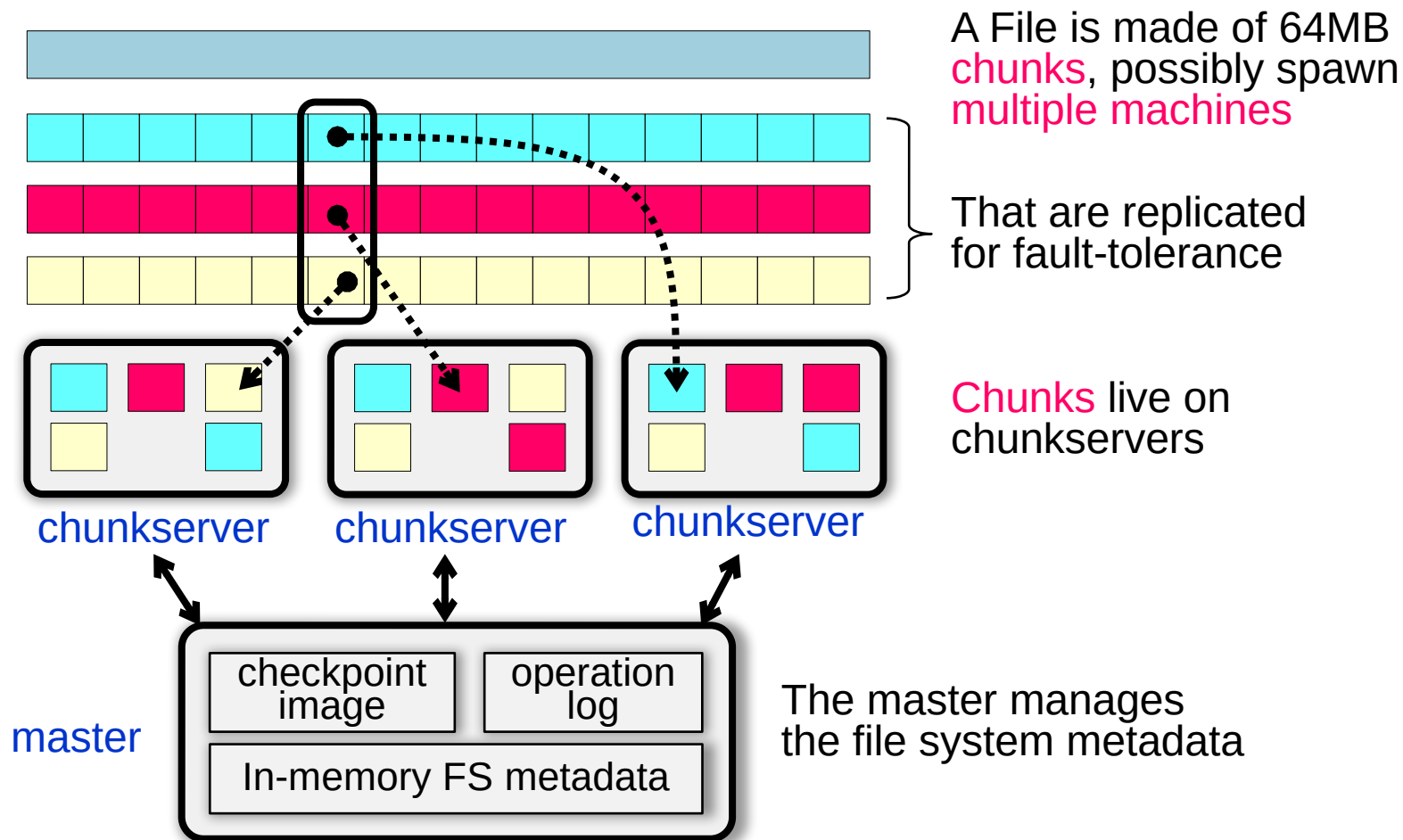
Design Goals & Assumptions of HDFS

HDFS is an **open source** (Apache) implementation **inspired by GFS** design

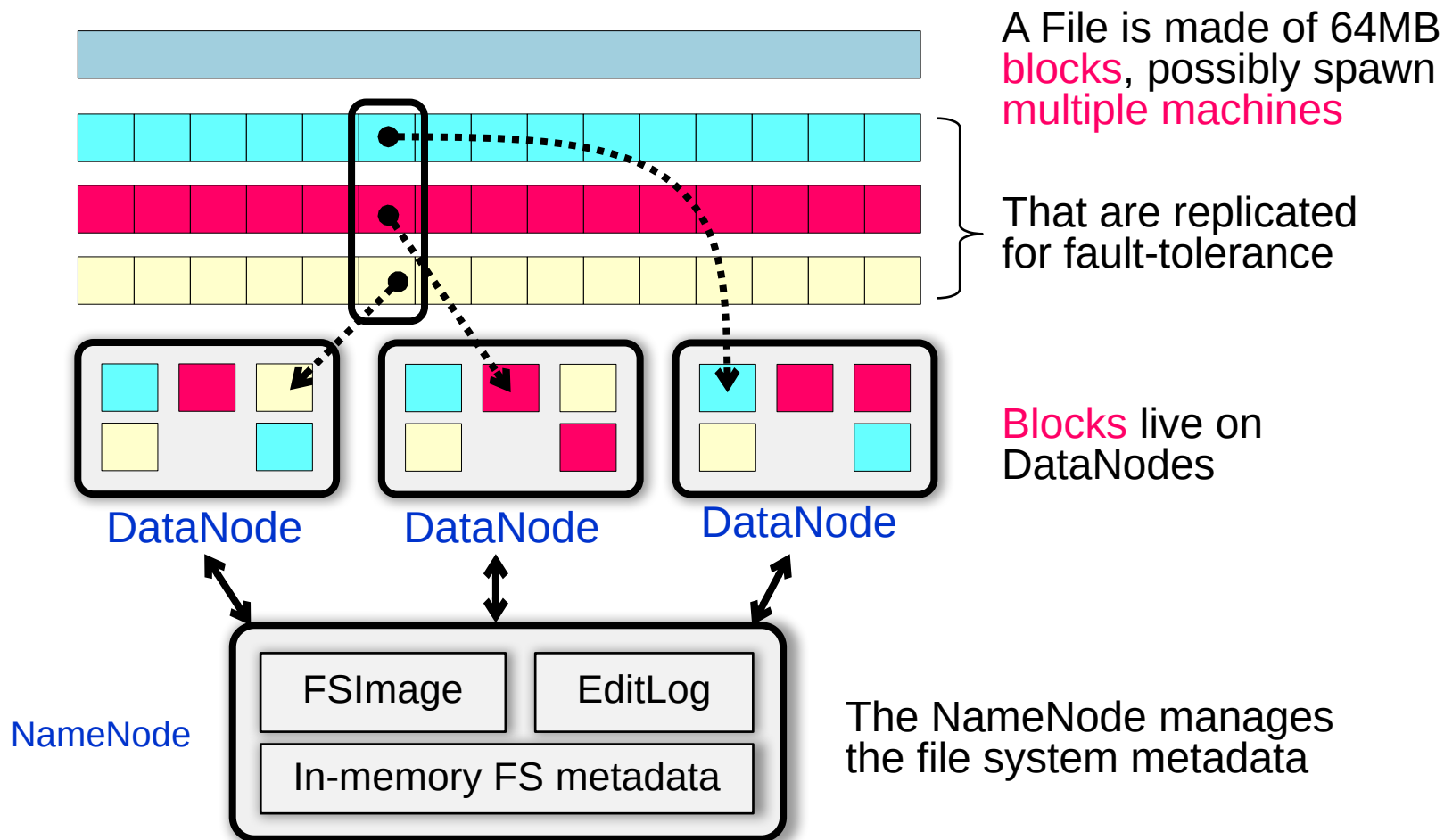
Similar goals as GFS

- Run on commodity hardware
- Highly fault tolerant
- High throughput & large-scale deployments
- ...

Recall GFS files



HDFS files



Summary

Designing distributed file system (DFS) is not simply

- Single-node file system + RPC

Many design choices for performance, consistency model & failure handling

- Interface
- Caching
- Access model

Two case studies

- **NFS**: transparent access files on a remote server
- **GFS**: highly-scalable & fault-tolerant DFS optimized for Google's workload

GFS or NFS are not Perfect

NFS

- Can **not scale**
- Is **not fault-tolerant**
- But is well-enough for many workloads, e.g., sharing the data for experiments in our lab ◀◀

GFS

- **Relaxed consistency model**: the results of concurrent mutations are undefined
- Single-node master: single point of failures (though next-generation of GFS refines this, with more advanced techniques developed later)
- Work well in Google's datacenter workloads

GFS or NFS are not Perfect

NFS

- Can **not scale**
- Is **not fault-tolerant**
- But is well-enough for many workloads, e.g., sharing the data for experiments in the lab

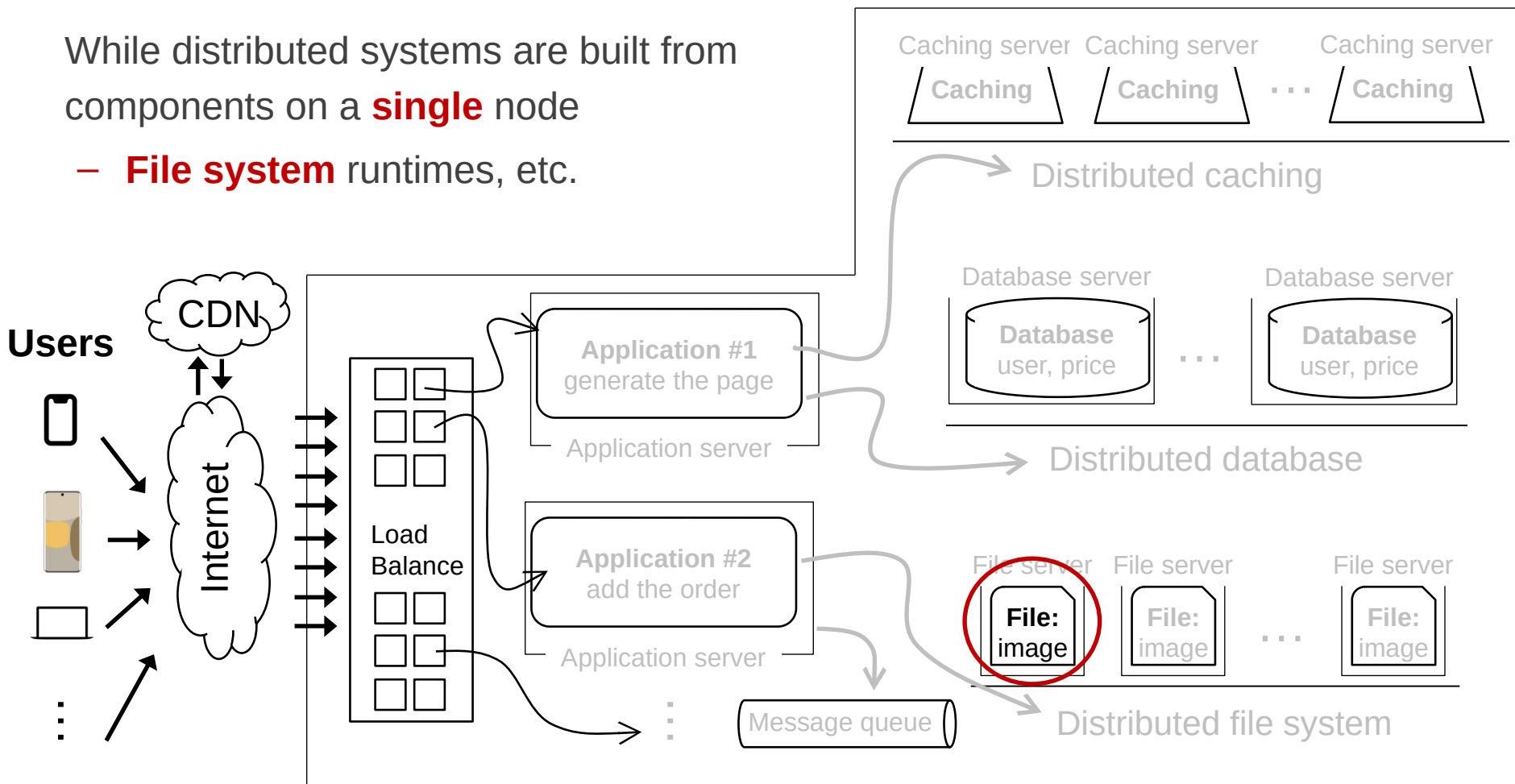
GFS

- **Relaxed consistency model**: the results of concurrent mutations are undefined **We will see system principles to cope with them in future lectures.**
- Single-node master: single point of failures (though next-generation of GFS refines this)
- Work well in Google's datacenter workloads
For other workloads (e.g., Database) may not sufficient.

Review: Large-scale websites on distributed systems

While distributed systems are built from components on a **single** node

- **File system** runtimes, etc.



Review: The filesystem API

API

- CHDIR, MKDIR
- CREAT, LINK, UNLINK, RENAME
- SYMLINK
- MOUNT, UNMOUNT
- OPEN, READ, WRITE, APPEND, CLOSE
- SYNC

Implemented as **system calls** to user applications

- Kernel has many sets of function pointers implementing the API
- Each set is specific to a FS (chose at mount point)

Does filesystem API sufficient?

Recall: Different storage systems to support different type of data

File system

Database

Key-value store

The screenshot shows the Apple Store website for the 10.5-inch iPad Air. The page layout includes a navigation bar at the top with links to Mac, iPhone, Watch, iPad, Music, Education, and Accessories. The main content area displays the product name, price (¥3896.00-6039.00), shipping information, and various configuration options like color, network type, and storage capacity. The bottom of the page features a share button, a popularity indicator (10883 popularity), and buttons for '立即购买' (Buy Now) and '加入购物车' (Add to Cart). Annotations with lines point to specific parts of the page: 'File system' points to the product image, 'Database' points to the price range, and 'Key-value store' points to the share button.

Apple Store 官方旗舰店 Mac iPhone Watch iPad Music 教育专区 选购配件

Apple/苹果 10.5 英寸 iPad Air

价格 ¥3896.00-6039.00

运费 上海 至 上海 黄浦区 快递: 0.00

累计评价 1749 送天猫积分 389起

颜色分类

网络类型 无线局域网机型 无线局域网 + 蜂窝网络机型

存储容量 64GB 256GB

数量 1

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立即购买 加入购物车

Key-value storage (KVS): system w/ a simpler API

Storage abstraction:

- Each data (**Value**) is opaque to the underlying storage/database
 - The K and V can be arbitrary byte-sequence (e.g., JSON, int, string)
- Indexed by a key (**K**), which itself is also a data
- Stored on disk (tolerate failure & support a large capacity)

Application-level Interface (API)

- Get(K) -> V, Scan(K,N)
- Update(K,V), Insert(K,V), Delete(K,V)



LEVELDB



RocksDB



redis

Why key-value storage instead of filesystem?

1. Filesystem is designed for bulk storage

- E.g., images, videos KV

For small data, we need a way to store them in one file to improve storage efficiency

- But question remains: how can we find data in a file efficiently?

2. Developers need a way to map abstract name to the concrete data

- E.g., "item name" -> number of views
- They don't need to take care of directory, etc.



Key-value store

Naïve solution to implement a KVS atop of filesystem

Storage abstraction remapping:

- Key 📧 The file name
 - Assume the key is not so long
- Value 📧 The file content
- So we can store each K,V as a file ◀◀

Application-level Interface (API)

- Get(K) -> V is similar to OPEN(...) + READ(...)
- Insert(K,V) -> is similar to CREATE(...) + WRITE(...)
- Etc.

Naïve implement a KVS on the filesystem is inefficient

Redundant system call caused by mismatched interface

- Example
 - E.g., Get(K,V) needs OPEN(...) + READ(...)
 - Ideally, we want to query the data in one system call, better **0**

Space amplification

- File data are stored in fixed-sized blocks (e.g., 512B – 4096B)
 - Why? To match the underlying device block size
- On the other hand, the value in key-value store can be small (e.g., 64B)

Naïve implement a KVS on the filesystem is inefficient

Redundant system call caused by mismatched interface

- Example
 - E.g., Get(K,V) needs OPEN(...) + READ(...)
 - Ideally, we want to query the data in one system call, better **0**

Space amplification

- File data are stored in fixed-sized blocks (e.g., 512B – 4096B)
- The value in key-value store can be small (e.g., 8B)

Idea: using one or few file to store key-value store data

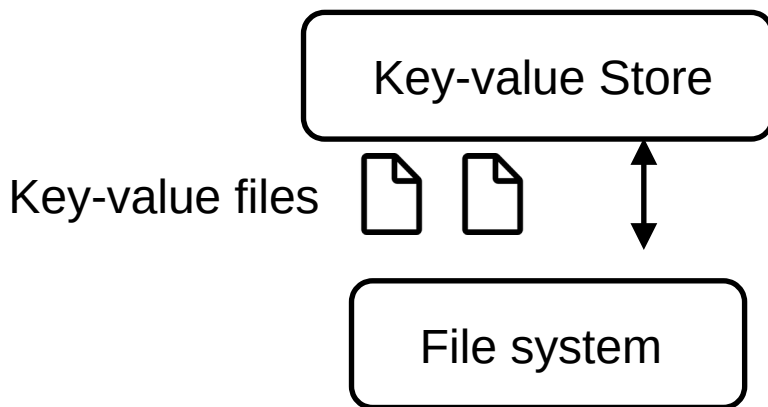
- Different key-values can pack into the same disk block
- Reduce system call overhead: open file once, serve all the requests then

Building Key-value Storage on File System

Why builds upon the file system?

- We still need a system to interact with the disk hardware!
- Though modern KVS may also bypass the file system, but is uncommon

“All problems in computer science can be solved by another level of indirection” -- often attributed to Butler Lampson, who attributes it to David Wheeler



A naïve Key-Value Storage (KVS)

Suppose we store all the KV **in a single file** in the following format:

Key

Value

```
123456 , '{ "name": "London", "attractions": ["Big Ben", "London  
Eye"] }'  
42 , '{ "name": "San Francisco", "attractions": ["Golden Gate  
Bridge"] }'  
...
```


Update(K,V) in the naïve KVS

Suppose we store all the KV **in a single file** in the following format:

Key Value

```
123456 , '{"name":"London","attractions":["Big Ben","London  
Eye"]}'  
42 , '{"name":"San Francisco","attractions":["Golden Gate  
Bridge"]}'  
...
```

How to implement the update? It is simple:

- Directly **append** update to the **end of the file**

```
procedure UPDATE(integer fd, character[] &key, character[] &value)
```

Update(K,V) in the naïve KVS

Suppose we store all the KV **in a single file** in the following format:

Key

Value

```
123456 , ' {"name": "London", "attractions": ["Big Ben", "London  
Eye"]} '
```

```
42 , ' {"name": "San Francisco", "attractions": ["Golden Gate  
Bridge"]} '
```

```
...
```

How to implement the update? It is simple:

- Directly **append** update to the **end of the file**
- **Benefits:** update the file is efficient, if there are **many updates**, because disks are good at **sequential writes**
- **Overwrite the original content** introduce **slow random accesses**

Insert(K,V) in the naïve KVS

Suppose we store all the KV **in a single file** in the following format:

Key

Value

```
123456 , ' {"name": "London", "attractions": ["Big Ben", "London  
Eye"]} } '  
42 , ' {"name": "San Francisco", "attractions": ["Golden Gate  
Bridge"]} } '  
...
```

How about the insertion? The same as the update

- Question: what about deletion?
 - Append a NULL entry and later garbage collected (will talk later)

BTW: File format of naïve KVS & log file

The file format is some kind of log file

- We called **Log-structured file**: an **append-only** sequence of records

Widely used in computer systems in various scenarios

- Suits the performance of underlying hardware (e.g., disk)
- E.g., ensure consistency under failure, etc.
- We will see more examples in later lectures

Hardware speed matters!
In our case: disk.

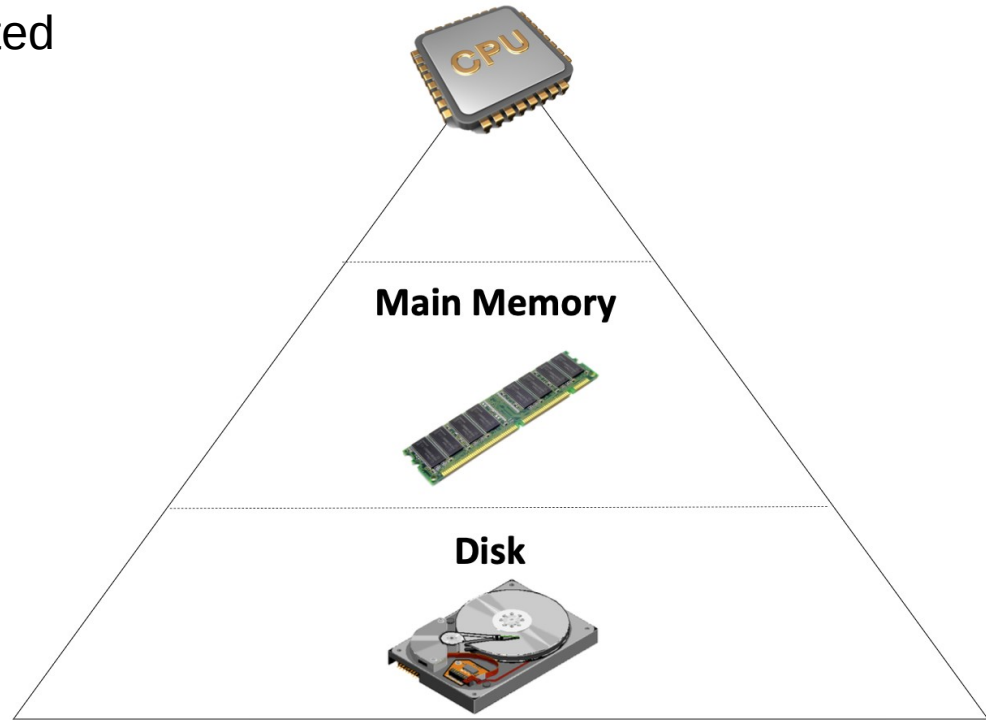
Storage Hierarchy

Fast device (e.g., Main Memory)

- Fast, but capacity is limited
- Expensive
- Volatile

Disk has huge capacity

- Cheap & slow
- Non-volatile



Storage Hierarchy: asymmetric performance of disk

CPU <-> Memory

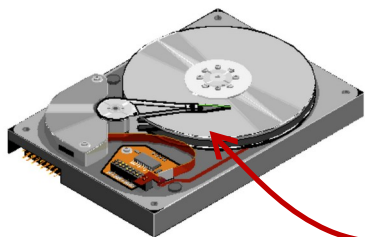
- $\sim 100\text{ns}$

Memory <-> Disk

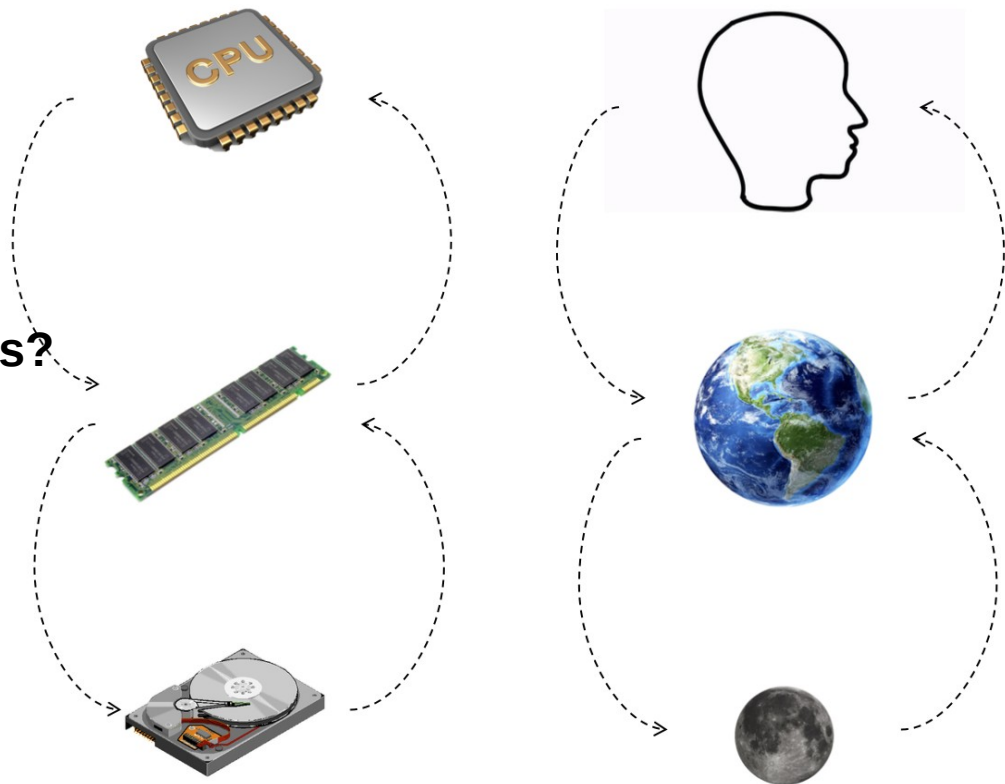
- $\sim 10\text{ms}$

Why disk is slow at random access?

- **Random**: move disk header
- **Sequential**: disk just spins




Disk Header



Updates work Well, What about Get(K,V)?

Suppose we store all the KV **in a single file** in the following format:

Key Value



```
123456  '{"name":"London","attractions":["Big Ben","London  
Eye"]}'  
42  '{"name":"San Francisco","attractions":["Golden Gate  
Bridge"]}'  
...
```

Get is much tricky to implement

- We need to iterate the file line by line **starting at the end of file**, and then finds the first line whose key matches K
- **Terrible performance!** Complexity: $O(n)$

Principle: Accelerate Get with index

Index

- An **additional structure** that is derived from the primary data (e.g., log file)
- Can be added/removed without affecting the primary data
 - Only affects the **performance** instead of correctness

Example of index data structure:

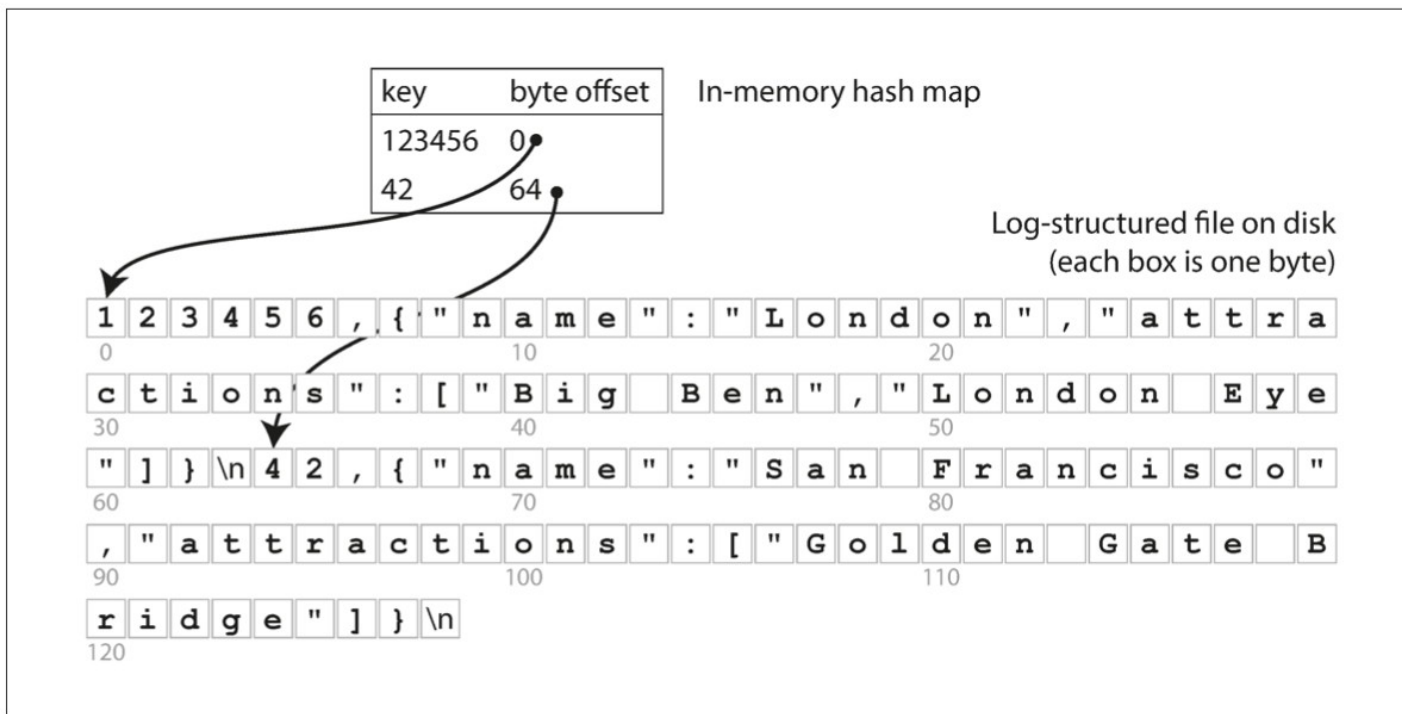
- B+Tree, HashTable, etc
- The inode table in Lab1 is essentially an index; but is extremely simple.

What are the trade-offs of an inode table?

First try of index: an In-memory Hash Index

The simplest possible indexing strategy

- Keep an in-memory hash map that map key -> byte offset in the log file



Hash index & log-structured data file

The simplest possible indexing strategy

- Keep an in-memory hash map that map key -> byte offset in the log file

A viable solution

- Adopted by commercial systems , e.g., Bitcask in [riakKV](#)



Benefits

- High-performance of reads/writes

Restrictions?

Hash index & log-structured data file

The simplest possible indexing strategy

- Keep an in-memory hash map that map key -> byte offset in the log file

A viable solution

- Adopted by commercial systems , e.g., Bitcask in [riakKV](#)



Benefits

- High-performance of reads/writes

Restrictions

- Index must **fit into the RAM**
- Only good at: when workloads have many updates but not insertions
 - Too many insertions will exhaust the RAM

Hash Index++: Put it onto the disk

Question: how to choose the appropriate hash index data structure?

Many hash data structures exist

- Their performance differences are not so different in an in-memory setting for KVS
- But on disk, the things are different, because accessing the disk is orders of magnitude slower than the memory

Different hash indexes have different **trade-offs when stored on disk**

- For a specific index, we need make some optimization to make it suit for the disk

Linked-list based hash index

The simplest data structures

Pros:

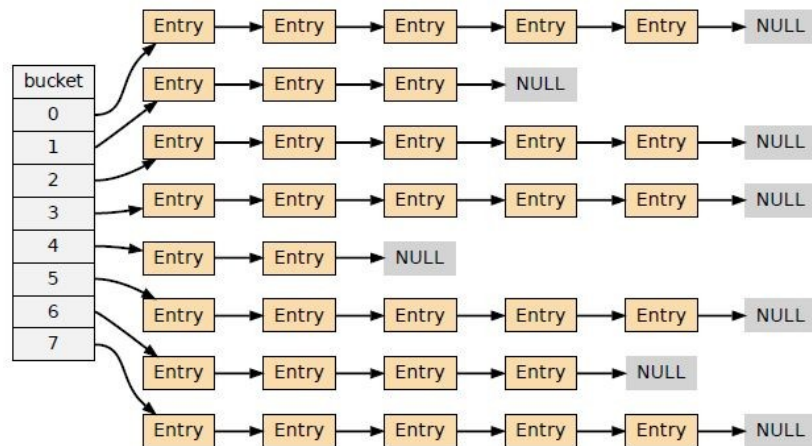
- Easy for implementation

Cons (of the easiest implementation):

- Bad **read** performance under hash collision
 - Requires traverse the linked buckets in random I/O
- Bad **insert** performance under hash collision
 - Similar problem as the read

Question: can you make it better?

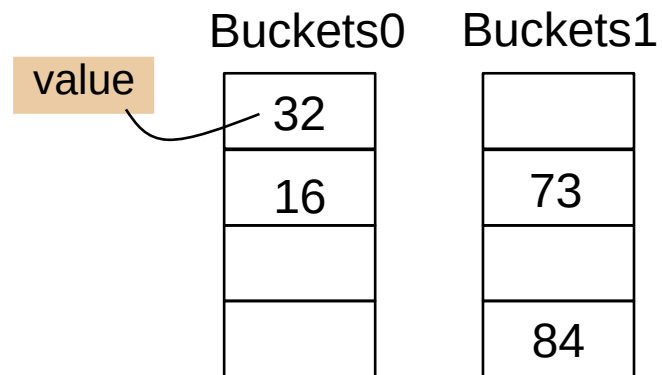
- Simple idea: put the entries in the same file block to reduce the chain length



Cuckoo hashing

Cuckoo hashing

- Maintain two hash buckets



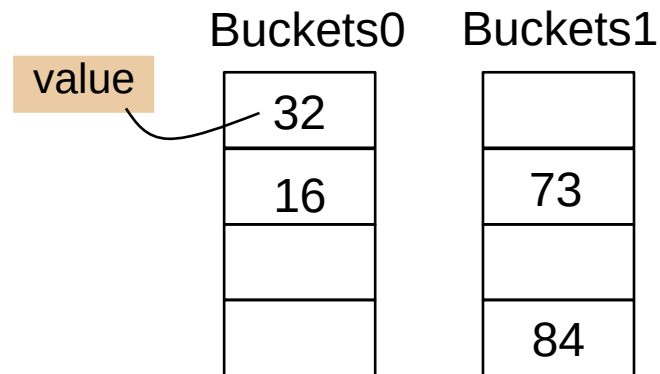
Cuckoo hashing

Cuckoo hashing

- Maintain two hash buckets

Get()

- Using two hash functions H_0 & H_1
- The **key** must be in **Buckets0**[$H_0(\text{key})$] or **Buckets1**[$H_1(\text{key})$]



Cuckoo hashing

Cuckoo hashing

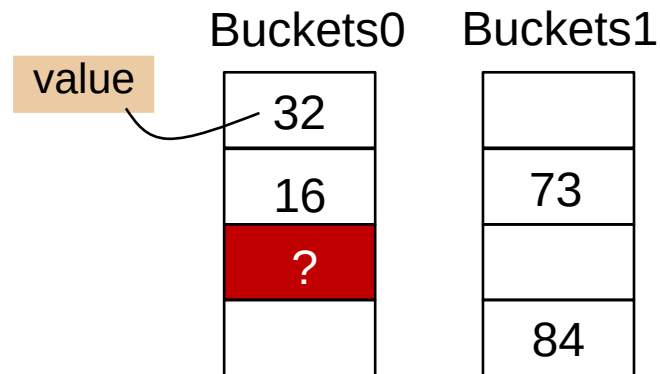
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- The **key** must be in **Buckets0**[$H_0(\text{key})$] or **Buckets1**[$H_1(\text{key})$]

Example: Get(73)

- **Buckets0**[$H_0(73)$] = 2



Cuckoo hashing

Cuckoo hashing

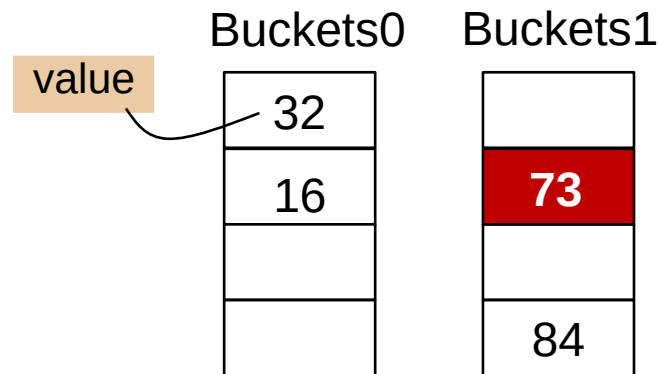
- Maintain two hash buckets

Get()

- Using two hash functions H_0 & H_1
- The **key** must be in **Buckets0**[$H_0(\text{key})$] or **Buckets1**[$H_1(\text{key})$]

Example: Get(73)

- **Buckets0**[$H_0(73)$] = 2 & **Buckets1**[$H_1(73)$] = 1



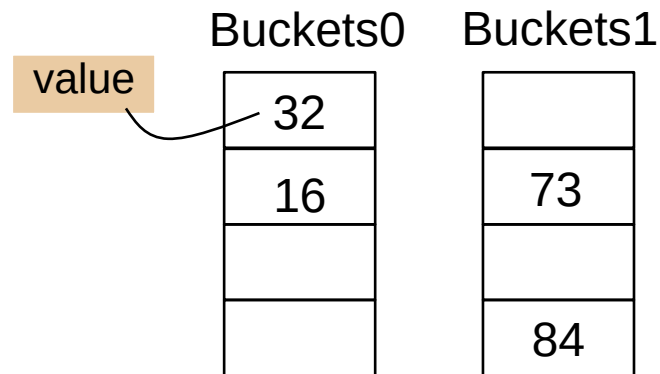
Cuckoo hashing

Cuckoo hashing

- Maintain two hash buckets

Update()

- Similar as Get ()
 - 1. find the bucket
 - 2. update the value



What about insert?

Cuckoo hashing

Cuckoo hashing

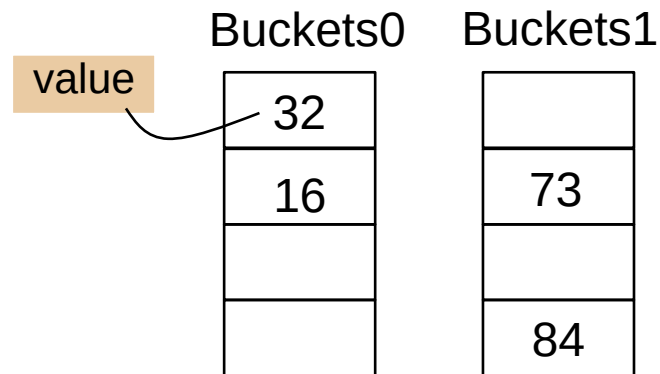
- Maintain two hash buckets

Insert()

- Much complicated: should insert to

Buckets0[H0(key)] or **Buckets1[H1(key)]**

- Question: what if no available space?



Cuckoo hashing

Cuckoo hashing

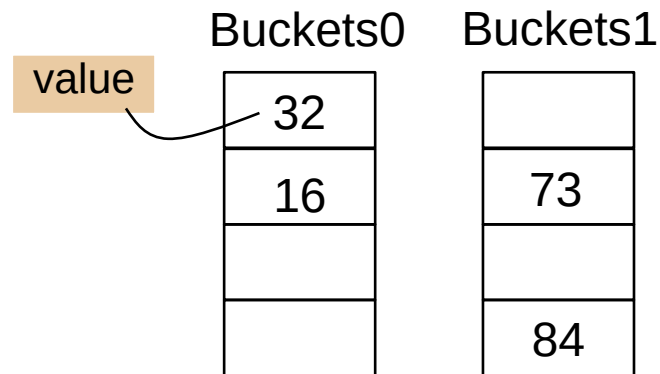
- Maintain two hash buckets

Insert()

- Much complicated: should insert to
 $\text{Buckets0}[\text{H0}(\text{key})]$ or $\text{Buckets1}[\text{H1}(\text{key})]$

Example: Insert(2)

- **$\text{Buckets0}[\text{H0}(2)] = 0$ & $\text{Buckets1}[\text{H1}(2)] = 0$**



Cuckoo hashing

Cuckoo hashing

- Maintain two hash buckets

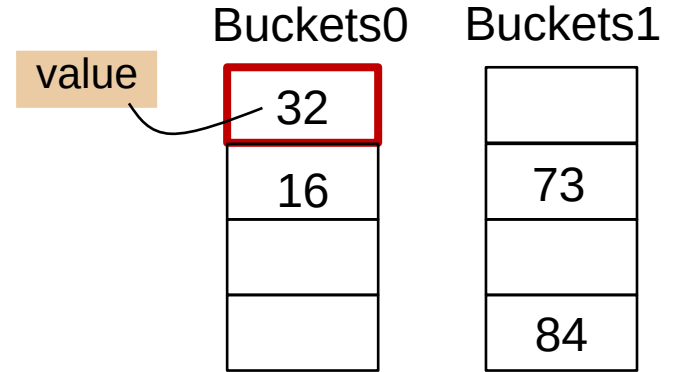
Insert()

- Much complicated: should insert to
Buckets0[H0(key)] or **Buckets1[H1(key)]**

Example: Insert(2)

- **Buckets0[H0(2)] = 0** & Buckets1[H1(2)] =
0

Can we insert here?



Cuckoo hashing

Cuckoo hashing

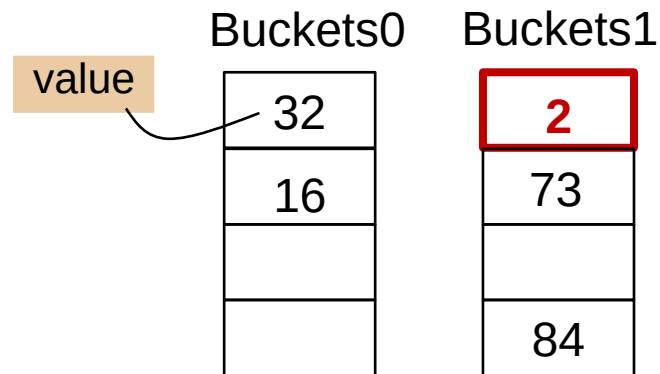
- Maintain two hash buckets

Insert()

- Much complicated: should insert to
 $\text{Buckets0}[\text{H0}(\text{key})]$ or $\text{Buckets1}[\text{H1}(\text{key})]$

Example: Insert(2)

- $\text{Buckets0}[\text{H0}(2)] = 0$ & **$\text{Buckets1}[\text{H1}(2)] = 0$**
- Insert here!



Cuckoo hashing

Cuckoo hashing

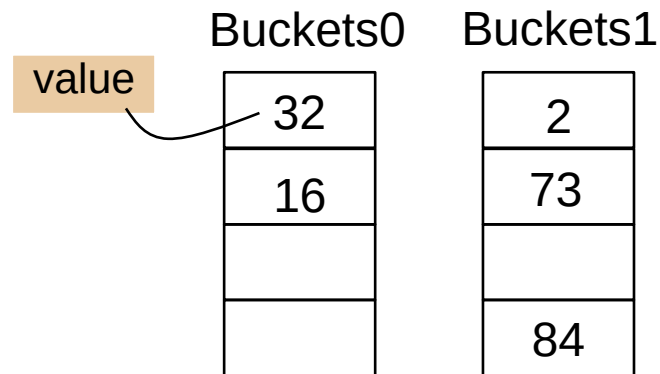
- Maintain two hash buckets

Insert()

- Much complicated: should insert to
Buckets0[H0(key)] or **Buckets1[H1(key)]**

Example: Insert(9)

- $\text{Buckets0}[\text{H0}(9)] = 0$ & $\text{Buckets1}[\text{H1}(9)] = 0$



Cuckoo hashing

Cuckoo hashing

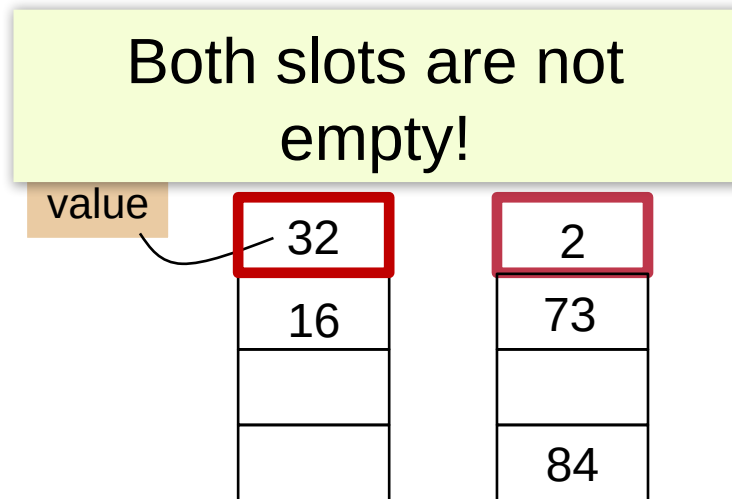
- Maintain two hash buckets

Insert()

- Much complicated: should insert to **$\text{Buckets0}[\text{H0}(\text{key})]$** or **$\text{Buckets1}[\text{H1}(\text{key})]$**

Example: Insert(9)

- $\text{Buckets0}[\text{H0}(9)] = 0$ & $\text{Buckets1}[\text{H1}(9)] = 0$



Cuckoo hashing

Cuckoo hashing

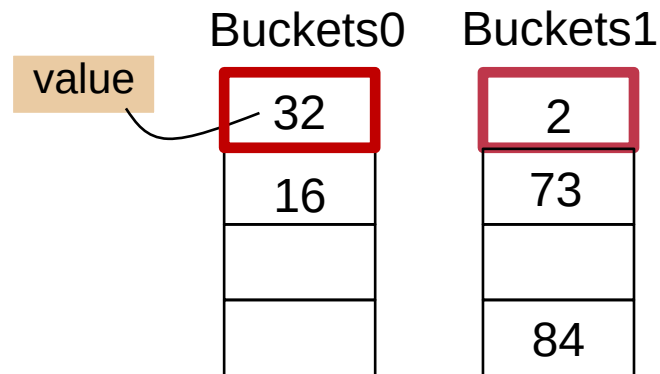
- Maintain two hash buckets

Insert()

- Much complicated: should insert to
 $\text{Buckets0}[\text{H0}(\text{key})]$ or **$\text{Buckets1}[\text{H1}(\text{key})]$**

Example: Insert(9)

- $\text{Buckets0}[\text{H0}(9)] = 0$ & $\text{Buckets1}[\text{H1}(9)] = 0$
- Cuckoo hashing will kick others to different place to create space for the new insertions



Cuckoo hashing

Cuckoo hashing

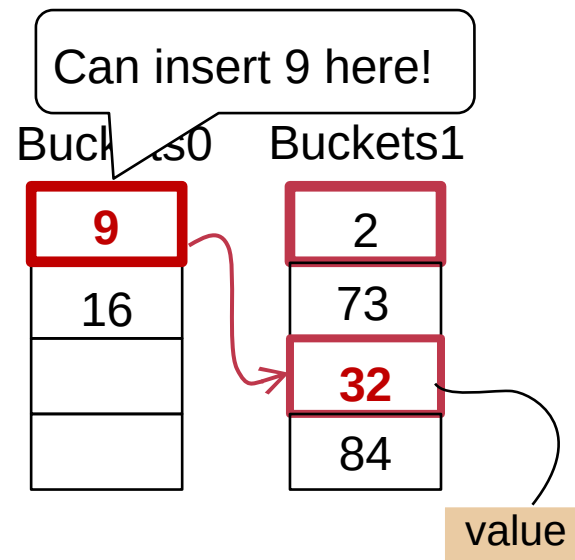
- Maintain two hash buckets

Insert()

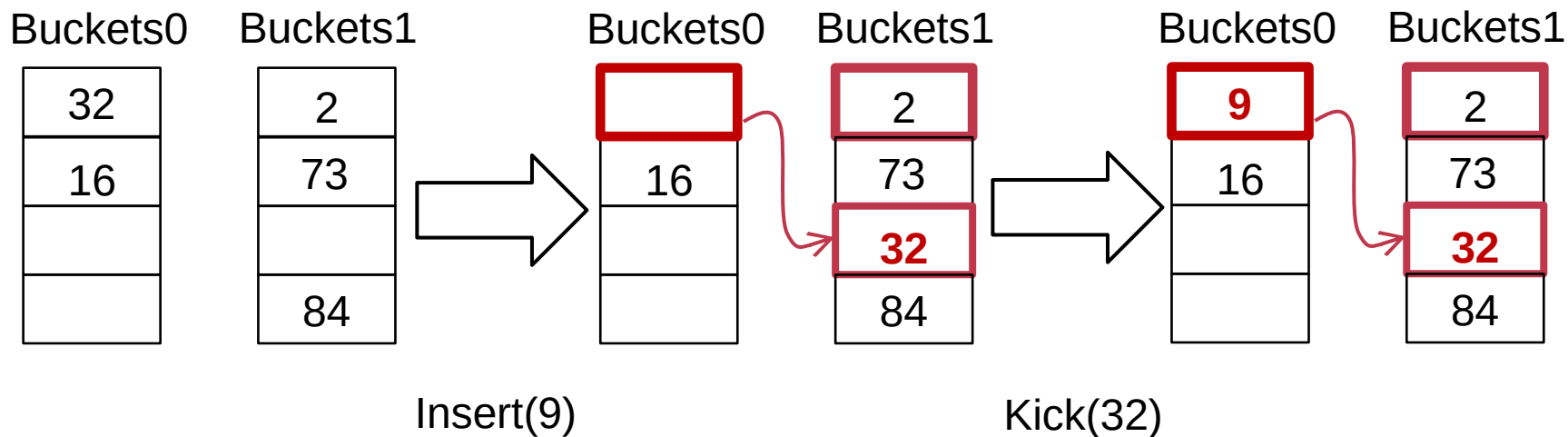
- Much complicated: should insert to **$\text{Buckets0}[\text{H0}(\text{key})]$** or **$\text{Buckets1}[\text{H1}(\text{key})]$**

Example: Insert(9)

- $\text{Buckets0}[\text{H0}(9)] = 0$ & $\text{Buckets1}[\text{H1}(9)] = 0$
- Cuckoo hashing will kick others to different place to create space for the new insertions
 - Kick 32 ($\text{Buckets0}[0]$) to another place
 - Assume: $\text{H1}(32) = 2$



Cuckoo hashing



$\text{Buckets0}[\text{H0}(9)] = 0$
& $\text{Buckets1}[\text{H1}(9)] = 0$

$\text{H1}(32) = 2$

Question: what if $\text{H1}(32) = 3$? (which is taken by 84)

Cuckoo hashing

Cuckoo hashing

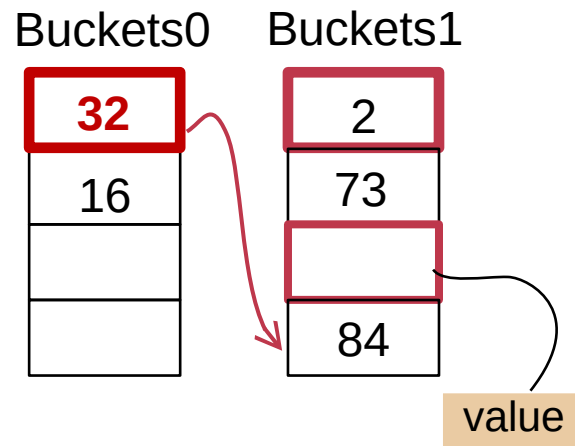
- Maintain two hash buckets

Insert()

- Much complicated: should insert to **Buckets0[H0(key)]** or **Buckets1[H1(key)]**

Example: Insert(9)

- $\text{Buckets0}[\text{H0}(9)] = 0$ & $\text{Buckets1}[\text{H1}(9)] = 0$
- Cuckoo hashing will kick others to different place to empty
 - Kick 32 (Buckets0[0]) to another place
 - **Question: what if $\text{H1}(32) = -2 = 3$?**



Cuckoo hashing

Cuckoo hashing

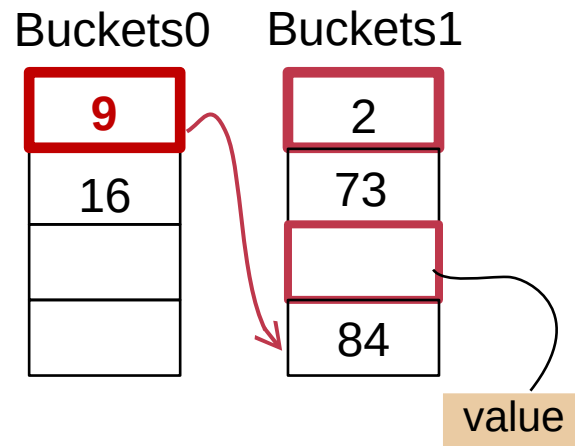
- Maintain two hash buckets

Insert()

- Much complicated: should insert to **Buckets0[H0(key)]** or **Buckets1[H1(key)]**

Example: Insert(9)

- $\text{Buckets0}[H0(9)] = 0$ & $\text{Buckets1}[H1(9)] = 0$
- Cuckoo hashing will kick others to different place to empty
 - Kick 32 (Buckets0[0]) to another place
 - Kick 2 (Buckets1[0]) to another place



Cuckoo hashing

Cuckoo hashing

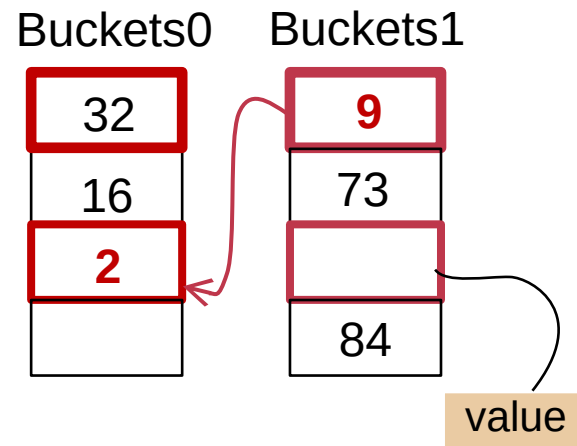
- Maintain two hash buckets

Insert()

- Much complicated: should insert to **$\text{Buckets0}[\text{H0}(\text{key})]$** or **$\text{Buckets1}[\text{H1}(\text{key})]$**

Example: Insert(9)

- $\text{Buckets0}[\text{H0}(9)] = 0$ & $\text{Buckets1}[\text{H1}(9)] = 0$
- Cuckoo hashing will kick others to different place to empty
 - Kick 2 ($\text{Buckets1}[0]$) to another place
 - Assume: $\text{H0}(2) = 2$



Cuckoo hashing

Cuckoo hashing

- Maintain two hash buckets

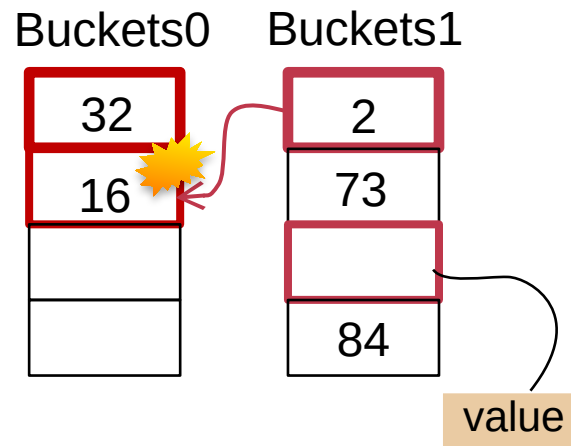
Insert()

- Much complicated: should insert to **Buckets0[H0(key)]** or **Buckets1[H1(key)]**

Example: Insert(9)

- $\text{Buckets0}[\text{H0}(9)] = 0$ & $\text{Buckets1}[\text{H1}(9)] = 0$
- Cuckoo hashing will kick others to different place to empty
 - Kick 2 (Buckets1[0]) to another place
 - Assume: $\text{H0}(2) = 2$ **1** What if that happens?

No available slots!



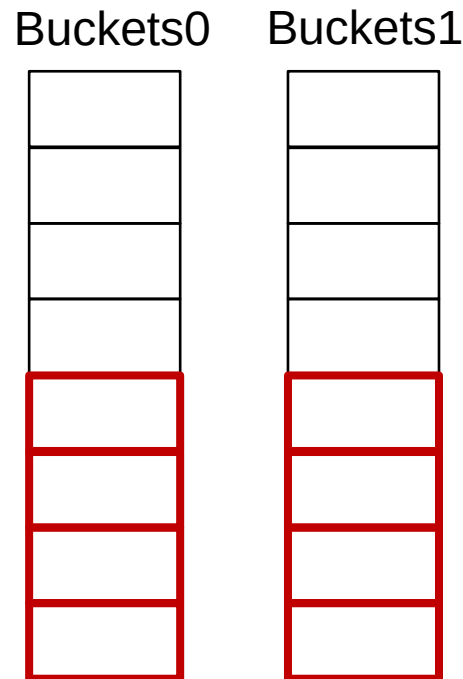
Cuckoo hashing

Cuckoo hashing

- Maintain two hash buckets

Insert()

- Much complicated: should insert to **Buckets0[H0(key)]** or **Buckets1[H1(key)]**
- If no available slots, **rehashing** & repeat the above insert process
- Rehashing: enlarge the buckets (typically **X2**)



Cuckoo hashing

Cuckoo hashing

- Two tables & Two hash functions (H_1, H_2)
- The key can only at $T_1[H_2(\text{key})]$ or $T_2[H_2(\text{key})]$

Pros

- Good for read: at most two 2 random I/O for get

Cons

- Insertion is complex and can issue many random disk I/O
- **Rehashing** is required if there are many insertions, which is extremely **slow**
 - Expanding the table, and re-insert all the keys in the new table (!)

	97
32	
	26
84	
59	41
93	23
58	
	53

T_1 T_2

Selecting a proper index for KV store is non-trivial

Not just choosing a data structure

Trade-offs of selecting indexes (The RUM Conjecture[1])

- **Read** performance vs. **update** performance
 - An index needs to be updated upon inserts/deletions
- Whether index **is friendly to** the storage?
 - E.g., random vs. sequential
- Others (e.g., storage overhead)

Issues of using hash index & log file

Naïve in-memory hash index has a limited capacity

- Can put it on the disk, but needs to carefully redesign the hash scheme or carefully select an appropriate hash scheme

Log file is growing forever -> running out of disk space

Lack range query support

- E.g., scan over all keys between kitty00000 & kitty99999

Issues of using hash index & log file

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Log file is growing forever -> running out of disk space

Lack range query support

- E.g., scan over all keys between kitty00000 & kitty99999

How to prevent a file from growing forever?

Log-structured design makes updates fast

- Only append to the file

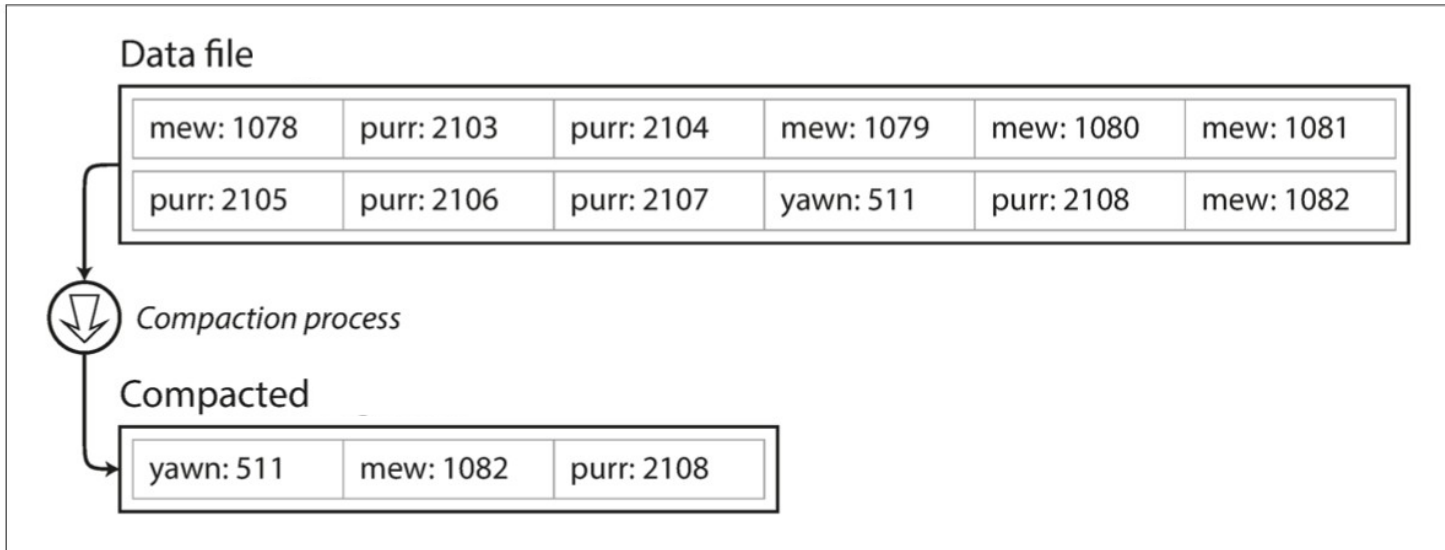
However, we will eventually run out of disk space

- Since many **duplicate records** in the log file, we should have space to store more records
- A deleted value is also left on the file

How to prevent a file from growing forever?

Solution: compaction

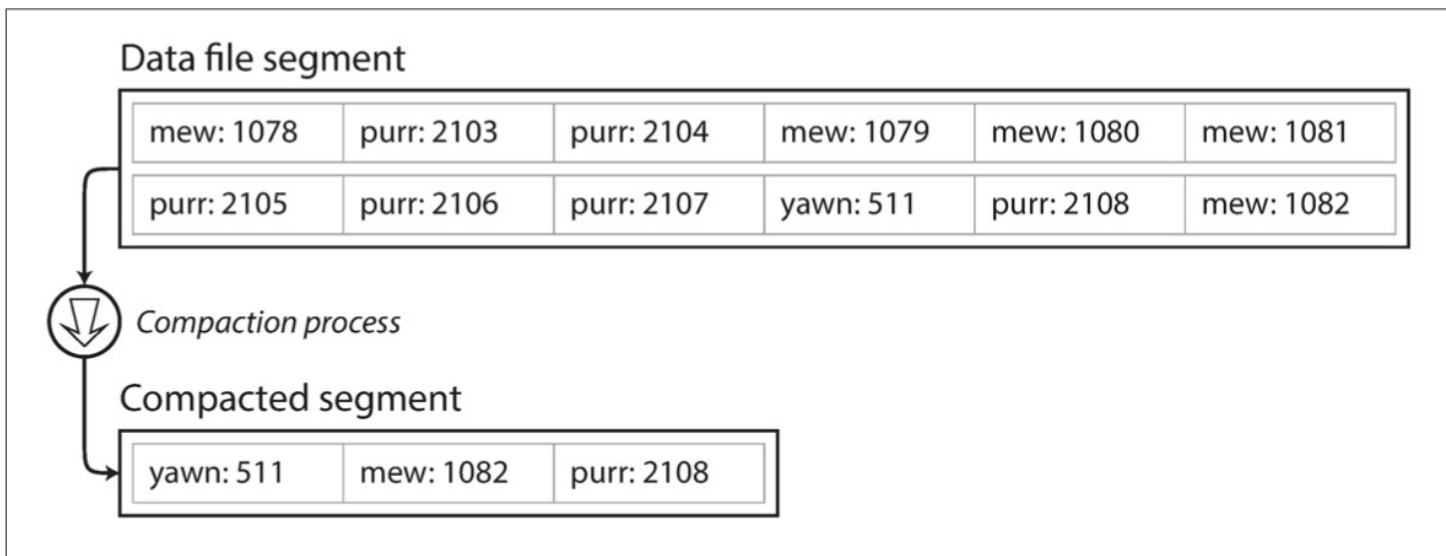
- Scan the whole file, delete duplicate records and write to a new file
- **Question:** what if the file is too large?



How to prevent a file from growing forever?

Solution: compaction with **segmentation**

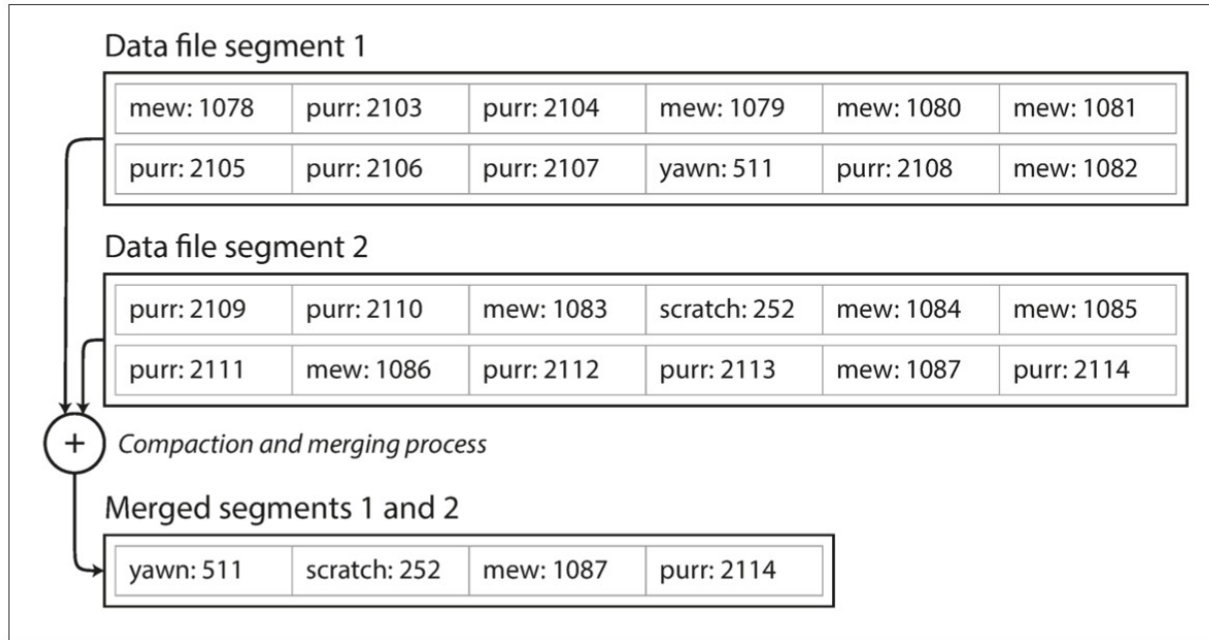
- Break a file into **fixed-sized** segments
- If a segment is full, then create a new file for insertions
- Can control the compaction **granularity** with the segment size



How to prevent a file from growing forever?

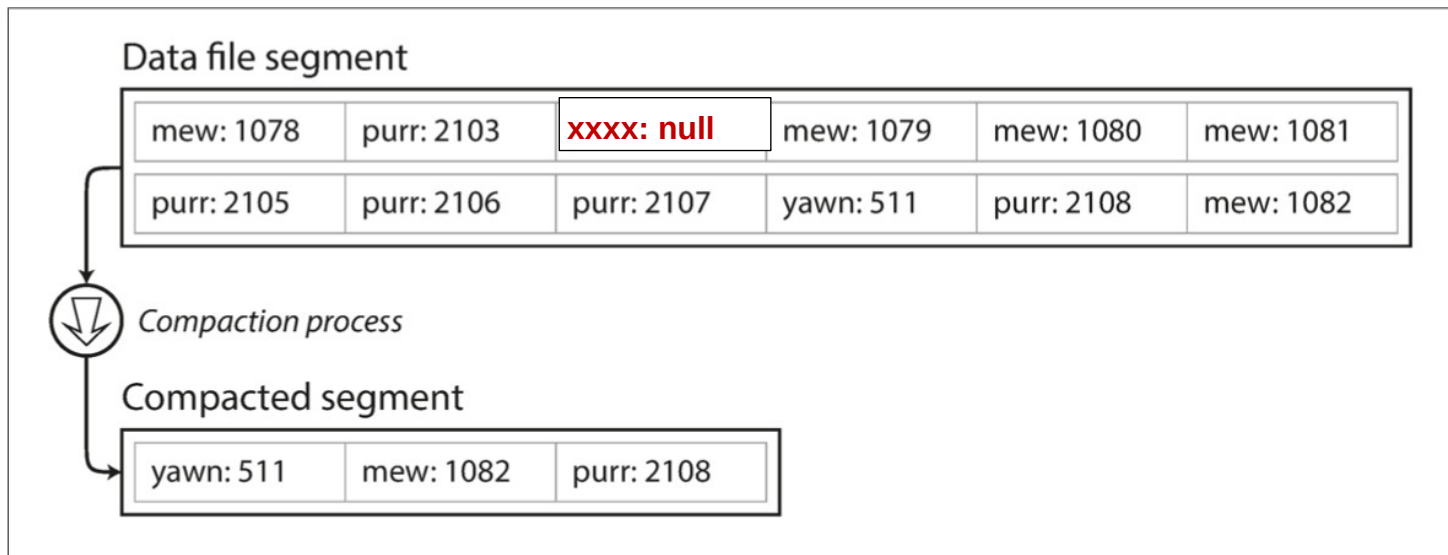
Solution: compaction with **segmentation + Merge**

- **Compact:** remove duplicated records in a segmented file
- **Merge:** merge two compacted segments into a new one
 - Why? Because compaction makes the segment smaller



Recall: how to handle delete() for log-structured file?

1. Append a NULL entry
2. Garbage-collected during compaction!



Issues of using hash index & segmented log file

Naïve in-memory hash index has a limited capacity

- Can put it on the disk, but needs to carefully redesign the hash scheme or carefully select an appropriate hash scheme

Log file is growing forever -> running out of disk space

Lack range query support

- E.g., scan over all keys between kitty00000 & kitty99999

B-Tree (B+Tree) indexes: a form of ordered index

Introduced in 1970, the “ubiquitous” index 10 years later for disk data

- Standard data structures of many databases and key-value stores

“It could be said that the world’s information is at our fingertips because of B-trees”



Goetz Graefe Microsoft, HP Fellow, now Google
ACM Software System Award

B+Tree indexes

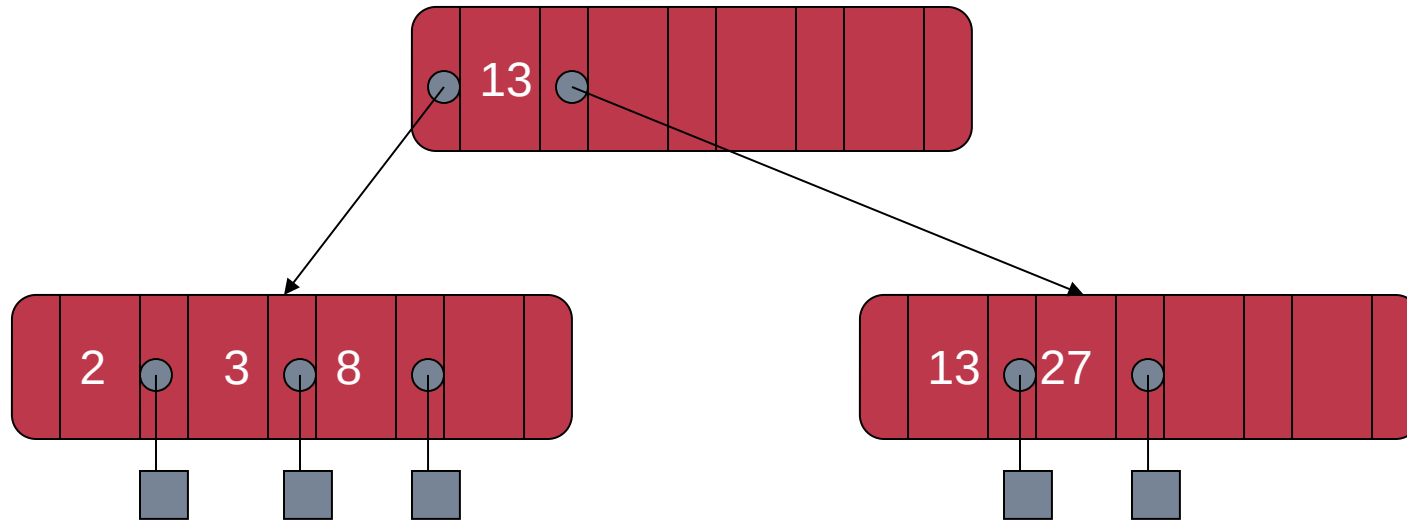
A B-tree is a tree-like data structure (one or a few files)

- Each node is **fixed-sized**, can store multiple keys, and keys are **sorted**
- Support **efficient range** operations (e.g., Scan)
- Optimized for **large** read/write blocks of data

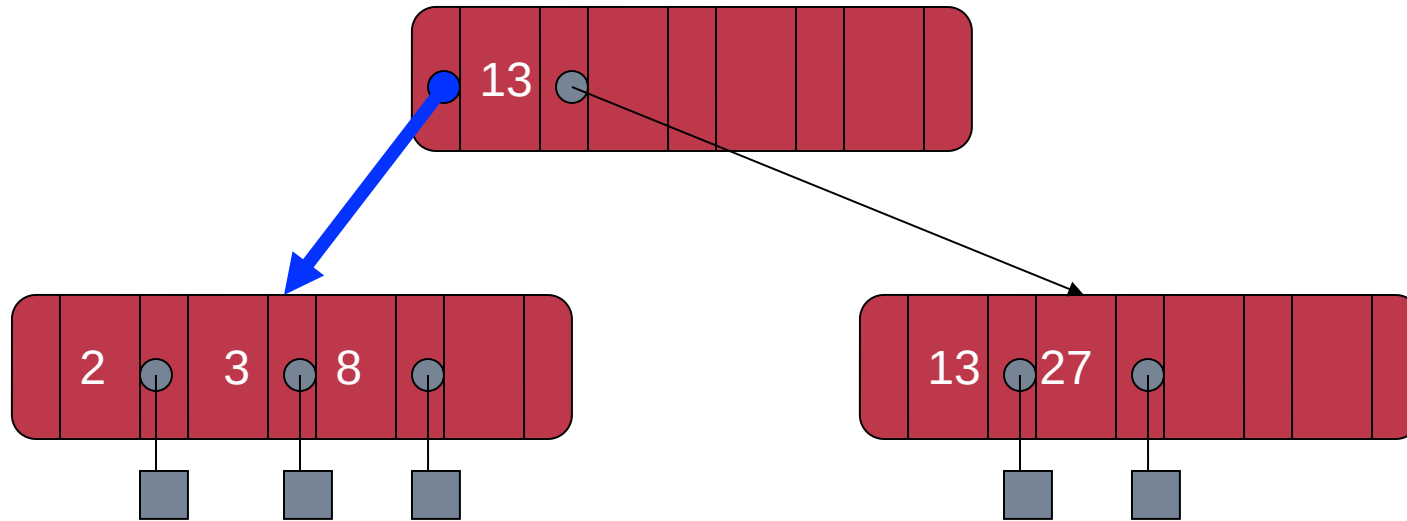
Many variants exist, e.g., B+Tree

- All the leaf nodes of the B-tree must be at the same level
 - Simpler to link leaf nodes to support range queries

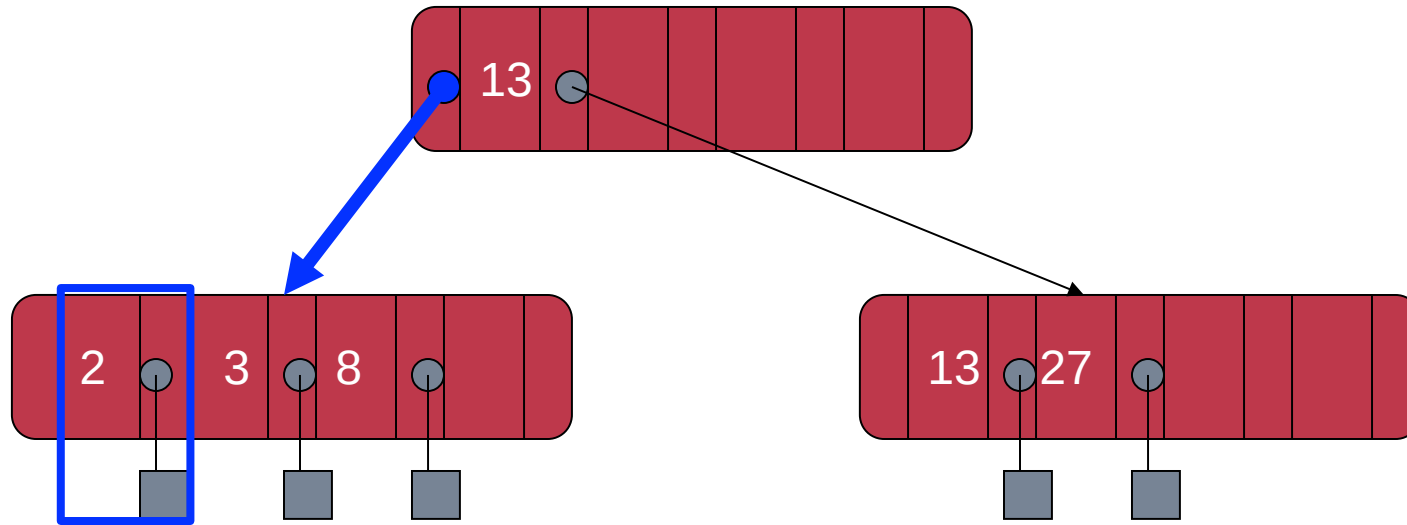
B+Tree indexes example (fanout = 5)



B+Tree indexes example: Get(2)



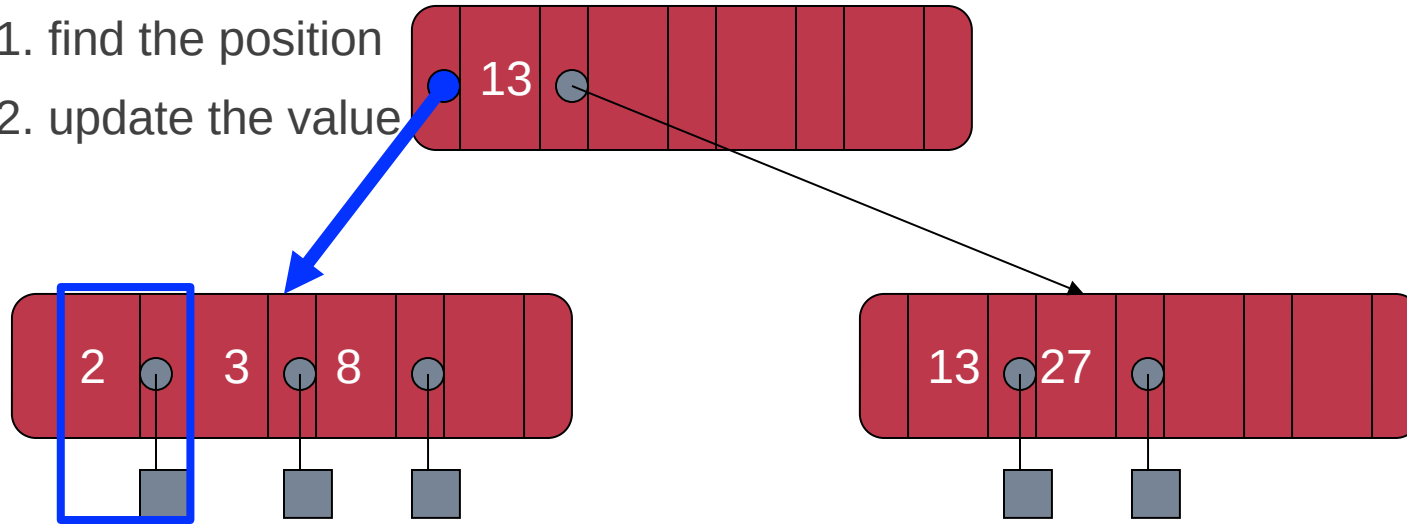
B+Tree indexes example: Get(2)



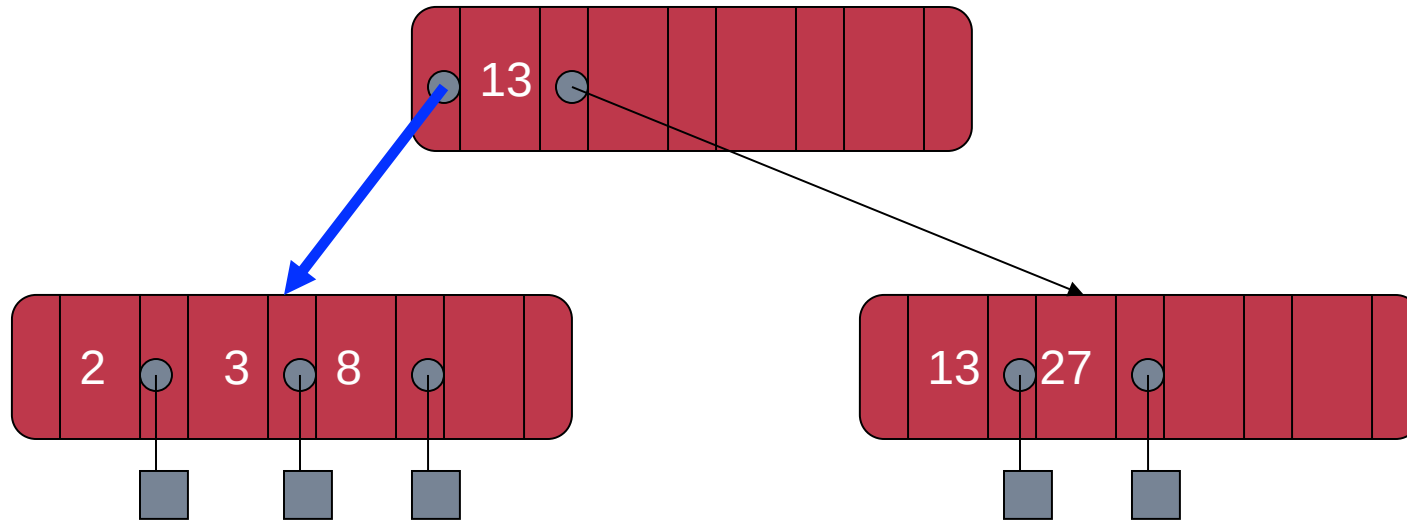
B+Tree indexes example: Update(2)

Similar to Get()

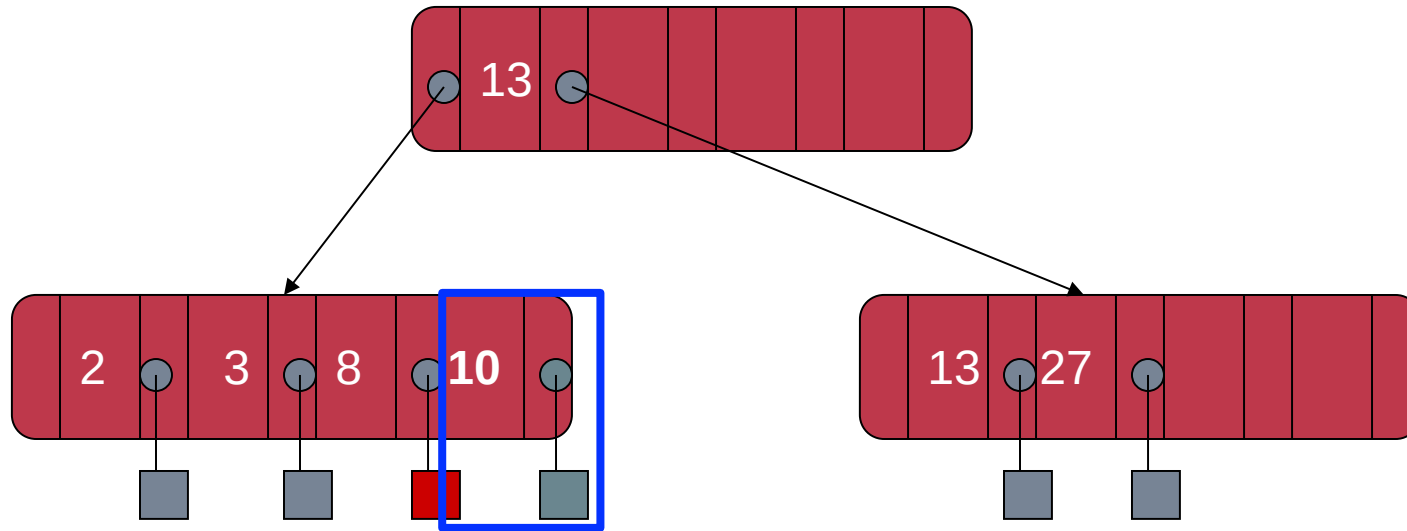
- 1. find the position
- 2. update the value



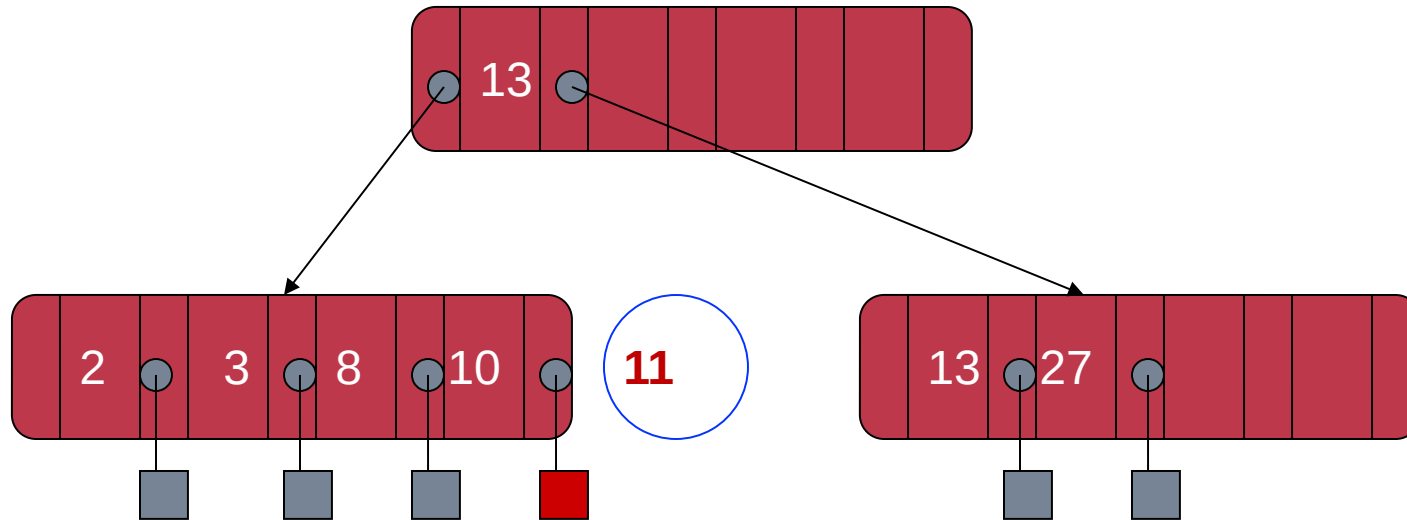
B+Tree indexes example: insert(10)



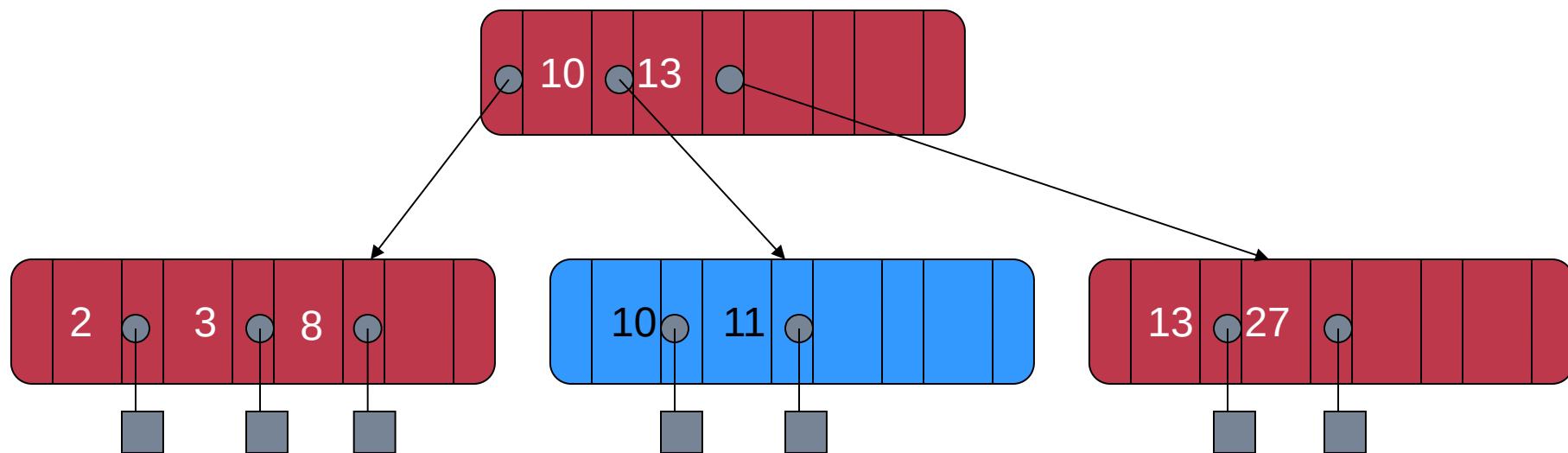
B+Tree indexes example: insert(10)



B+Tree indexes example: insert(11)



B+Tree indexes example: insert(11)

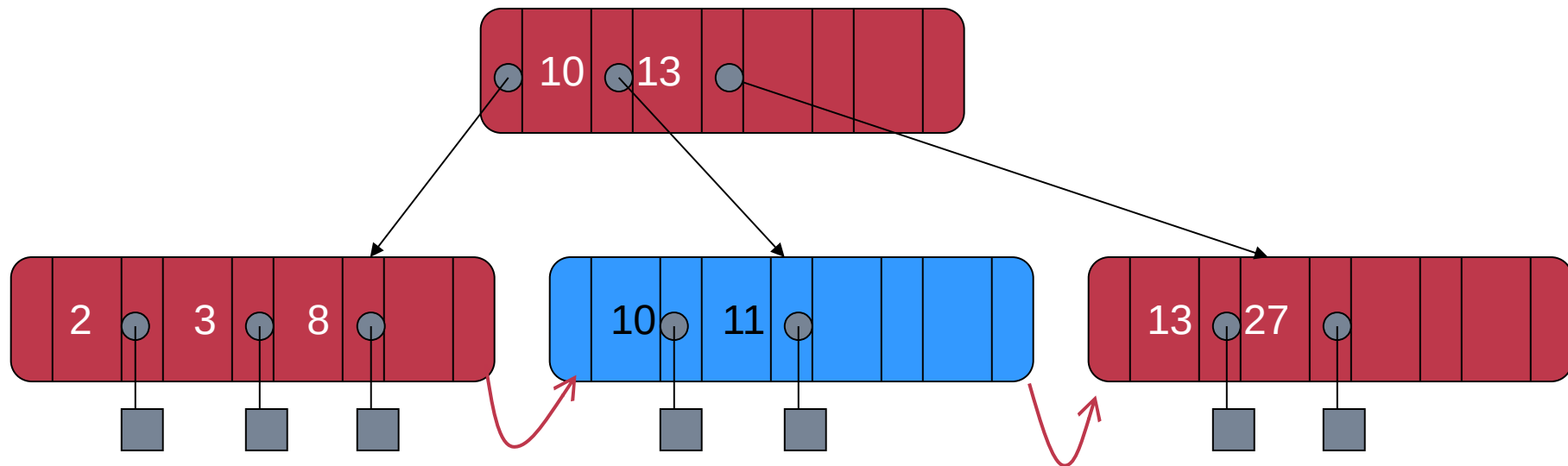


Split the nodes!

B+Tree can support efficient range operations

Add a sibling link between the leaves

e.g., SCAN(3,5)

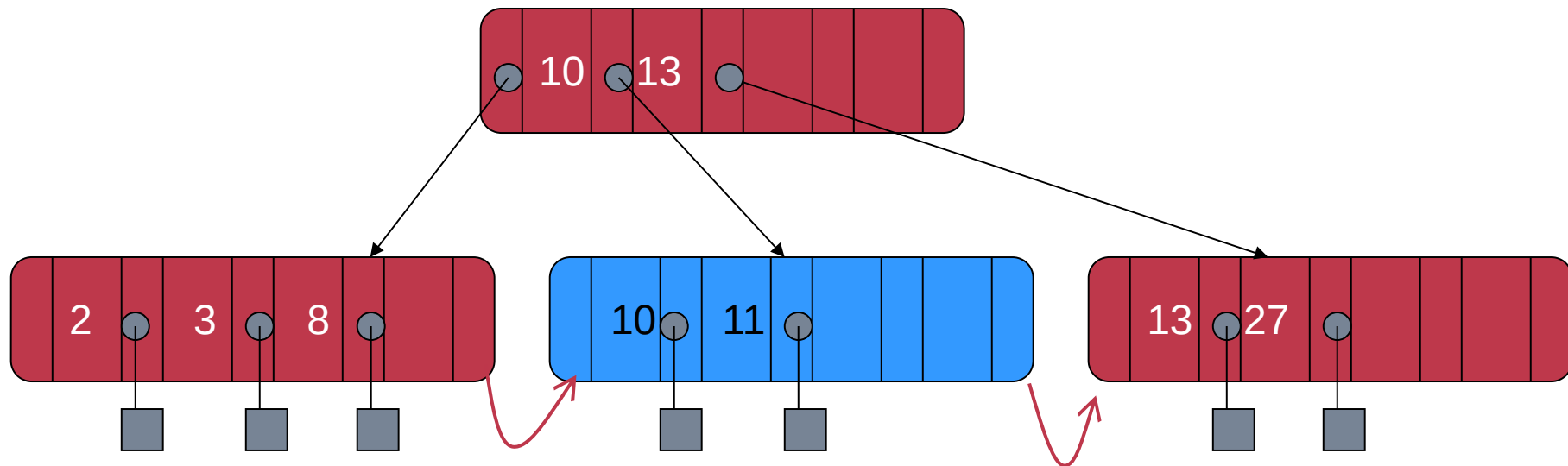


Question: need a B+Tree to index the values in the log?

No. It can store the values in its leaf node

- Which does not need compaction & merge

But, what are the costs?



B-Tree indexes on the disk?

Get(K), Insert(K,V) and Update(K,V) are slow

- $O(\log(n))$ random disk accesses
- Typically, is small, since B-Tree indexes uses large node size. But is still a killer for performance

B+Tree indexes are not good enough for insertion-intensive workloads

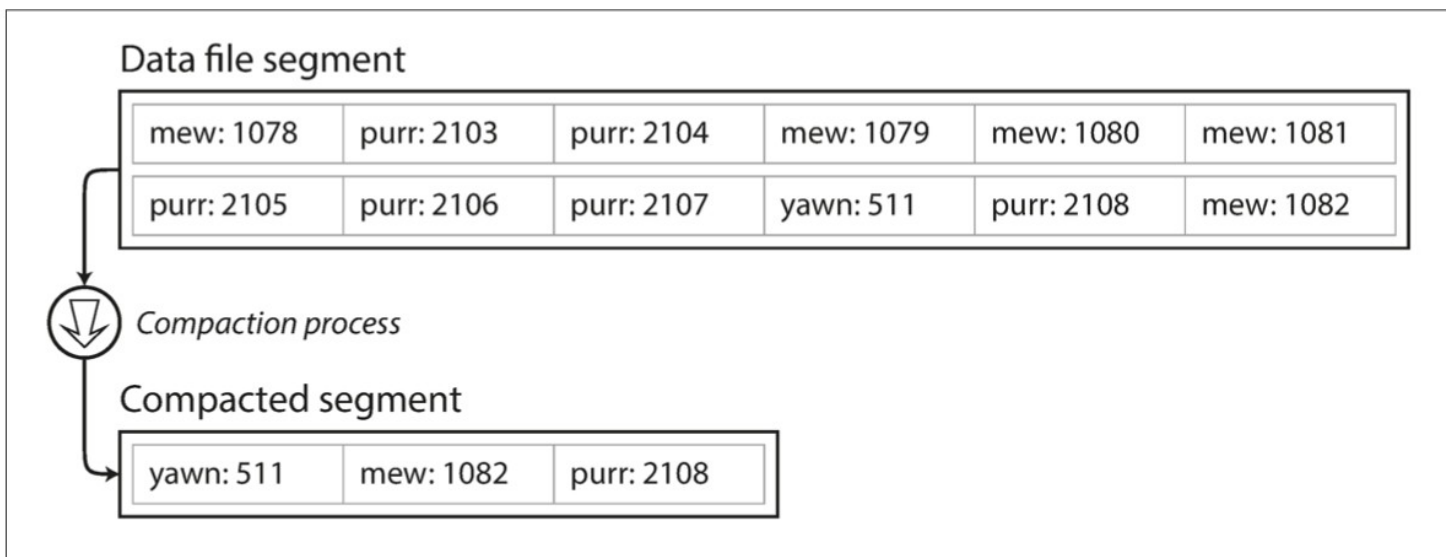
- Still **many random disk I/O** involved
- Insertions are common for on-disk storages, because reads are served by other system components, e.g., a cache system like Memached
 - E.g., check lecture 02, step#2 for scaling a website

Can we avoid random access for
index updates and insertions ?

Recall: segmented log file

Compaction & **segmentation**

- Break a file into **fixed-sized** segments
- If a segment is full, then create a new file for insertions
- Can control the compaction **granularity** with the segment size



LSM Trees: SSTables (Sorted String Table)

SSTable is based on the **segmented log file** described in the hash index

- Break a file into **fixed-sized** segments
- If a segment is full, then create a new file for insertion

LSM Trees: SSTables (Sorted String Table)

SSTable is based on the **segmented log file** described in the hash index

- Break a file into **fixed-sized** segments
- If a segment is full, then create a new file for insertion

With two extensions

- Key-values in a segment are **sorted** by the key
- Old segment files are **immutable** and can be **compacted** to save spaces

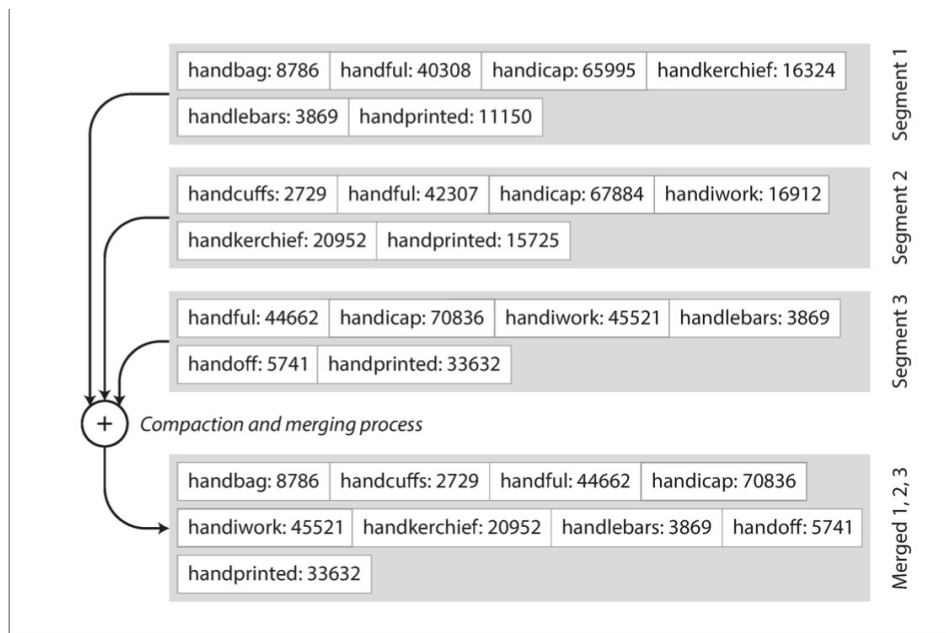
Why immutable? Inserting in a SSTable is **not
append-only**

We will come back to this topic later

Benefits of SSTable (compared to original log file)

#1. Merging two SSTables is efficient

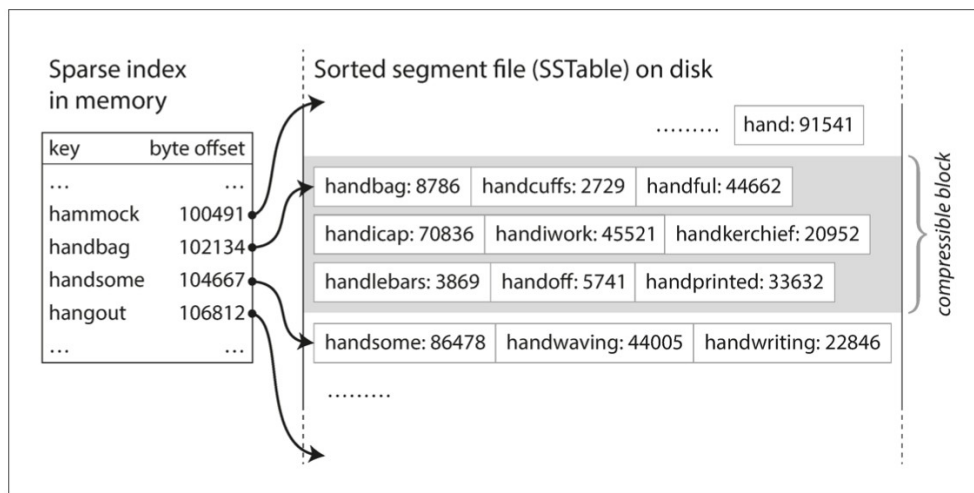
- Even if the two tables are much larger than the available memory
- Similar to the mergesort



Benefits of SSTable (compared to original log file)

#2. Searching a given key in a SSTable is efficient

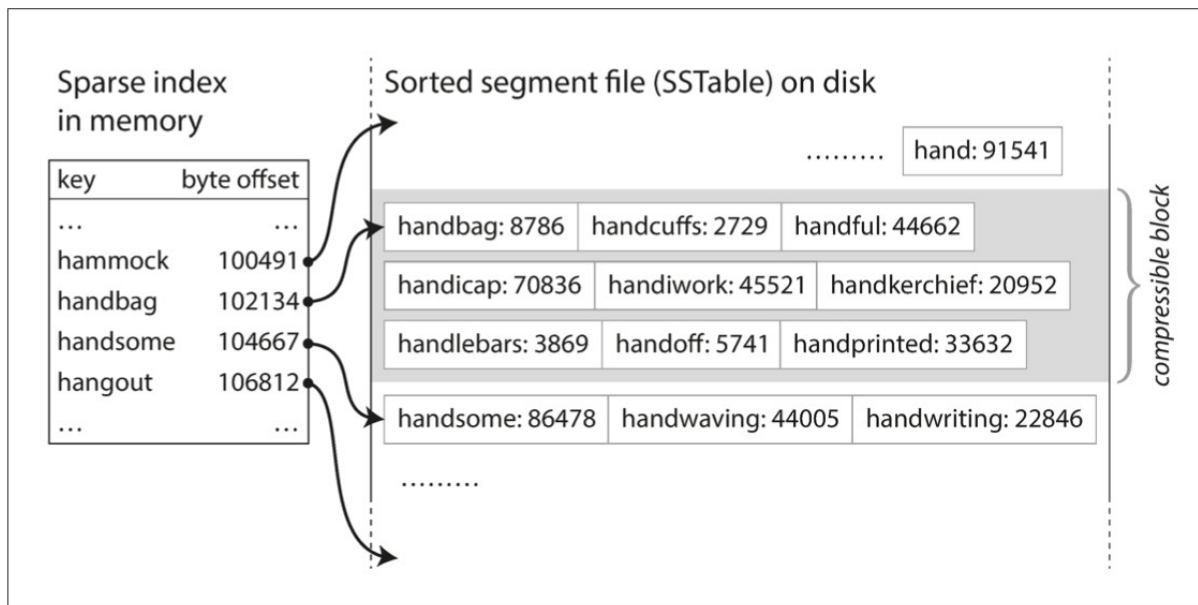
- We can use binary search to lookup a given key
- Or we only need some **sparse index** for the acceleration, one for each SSTable
- E.g., one key in index for every few KB of SSTable is sufficient, since scanning them is quick



Benefits of SSTable (compared to original log file)

#3. Support range operations

- Since the KVS are sorted in the file



How to maintain SSTable with sequential writes?

Use a MemTable: an in-memory data structure (e.g., a red-black Tree)

- Simple quiz: why not using hash table?



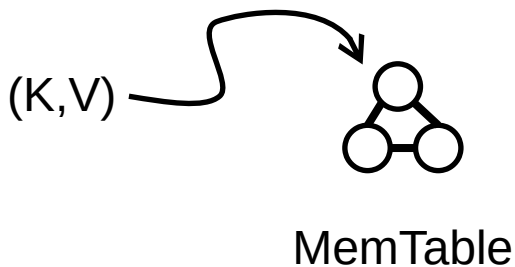
MemTable

How to maintain SSTable with sequential writes?

Use a MemTable: an in-memory data structure (e.g., a red-black Tree)

Example: insert a (K, V) into SSTable

- ① Insert the (K, V) into the MemTable

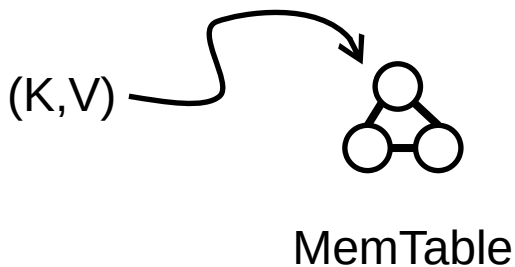


How to maintain SSTable with sequential writes?

Use a MemTable: an in-memory data structure (e.g., a red-black Tree)

Example: insert a (K, V) into SSTable

- ① Insert the (K, V) into the MemTable



Question: does writing to SSTable sequential?

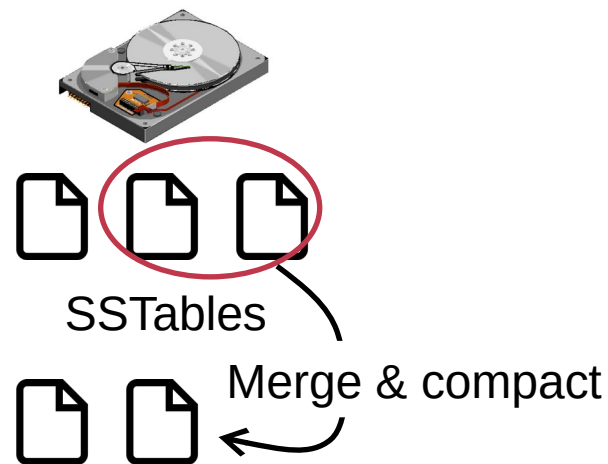
- ② check whether MemTable exceeds some threshold, If so, flush it to a new SSTable

How to maintain SSTable with sequential writes?

Use a MemTable: an in-memory sorted data structure (e.g., red-black Tree)

Example: insert a (K, V) into SSTable

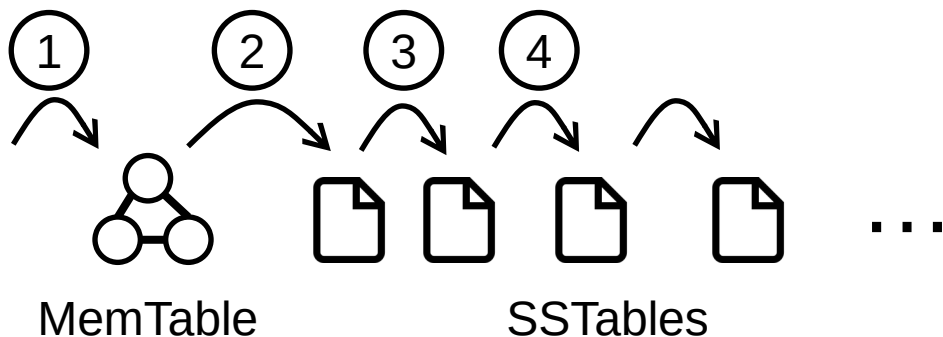
- ③ What if there are too many SSTables?
We can **merge & compact** them as we have done before with segmented log files



Reads with MemTable + SSTable

1. Checks the MemTable
2. If misses, checks the latest SSTable
3. If still misses, checks the next older SSTable
4. ...

Optimization: keep a sparse index on each SSTable to accelerate the lookup

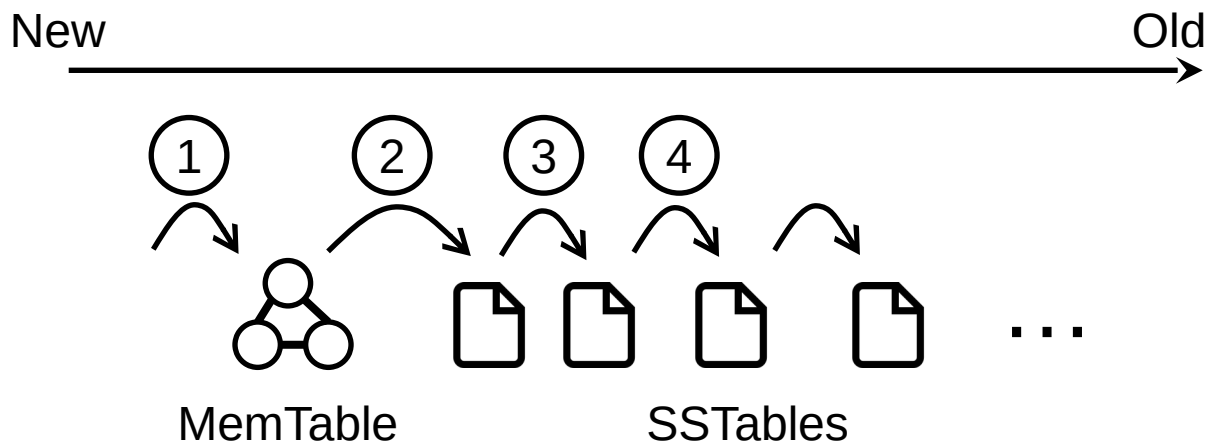


Question: what are the drawbacks of
such a design?

Organizing data sequentially has several drawbacks

#1. Finding the old value is slow

#2. Cannot support efficient scan

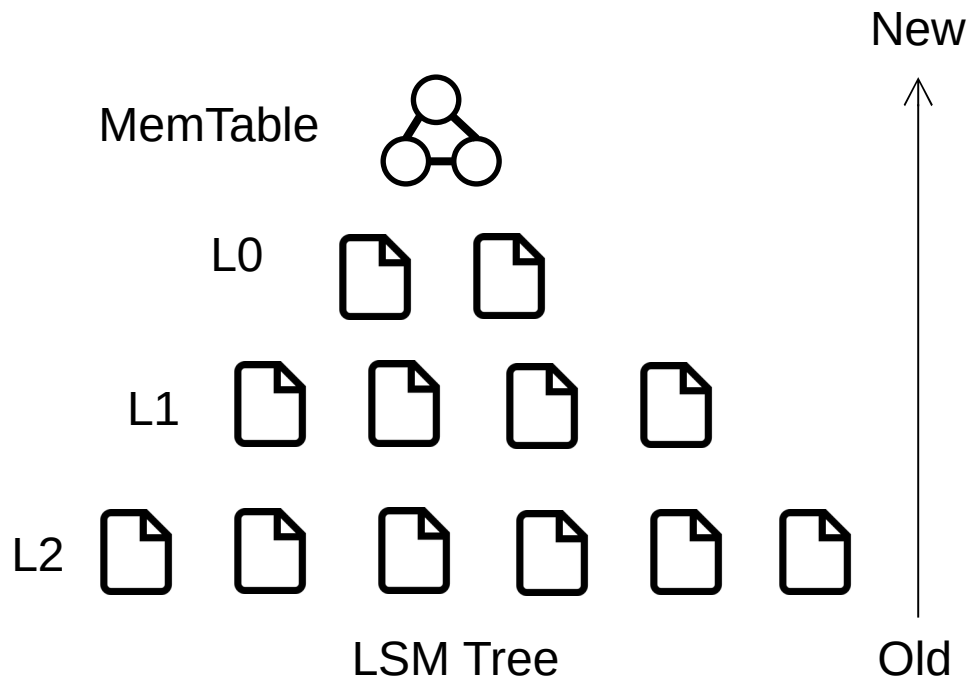


LSM Tree organizes SSTables in a hierarchy

The famous **Log**-structured **merge** tree

Each layer has the entire KVS data of some time

- Each layer has maximum size
- Except L0, all files in layers are **sorted, and does not have duplicated keys**



Hierarchy can speed up old value lookup

Each layer has only one file that store the key (except L0)

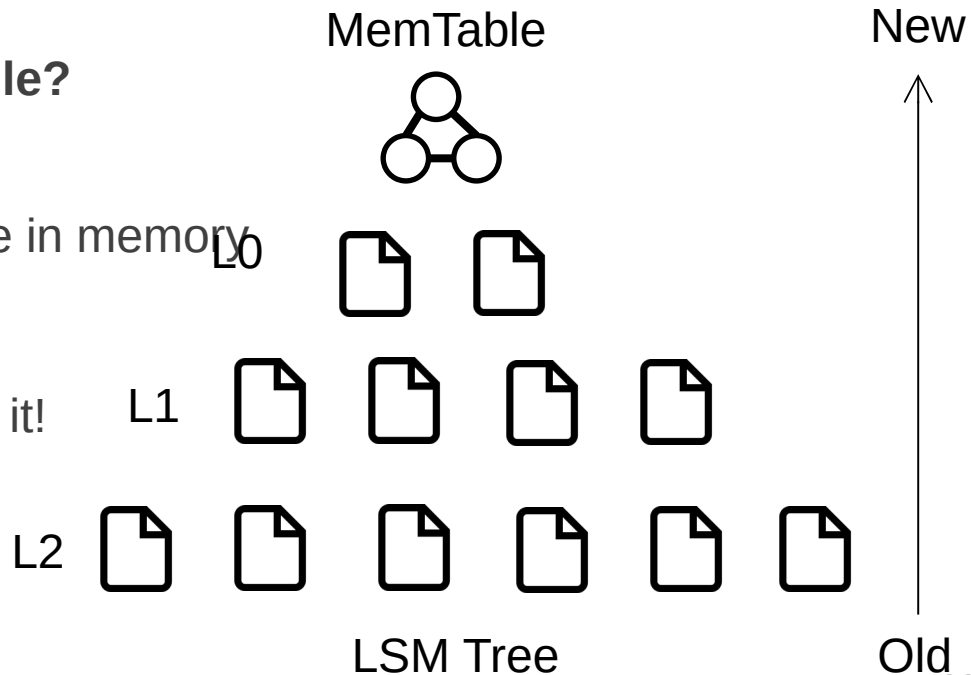
- So we can search only one file per-layer (not per-file search)

Question: how to find the key file?

- Many methods exist
- E.g., store a [min, max] per file in memory

Read upon lower layers

- First identify the file, then look it!
- $O(1)$ access per layer

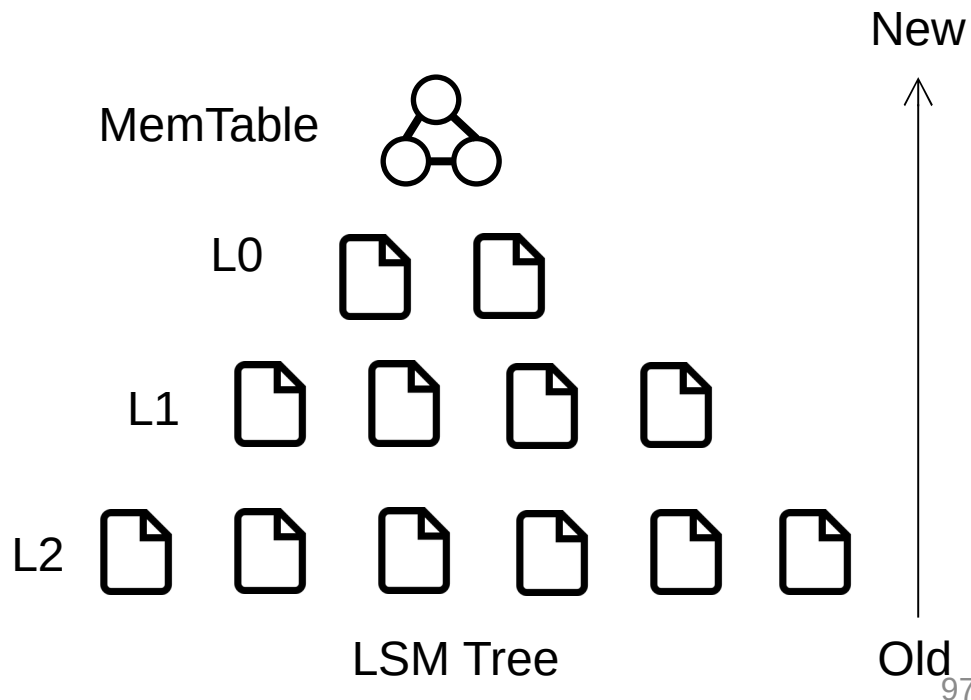


Hierarchy can speed up range query

Store a [min, max] per file

Range query

- Query layer-by-layer
- Then merge the results



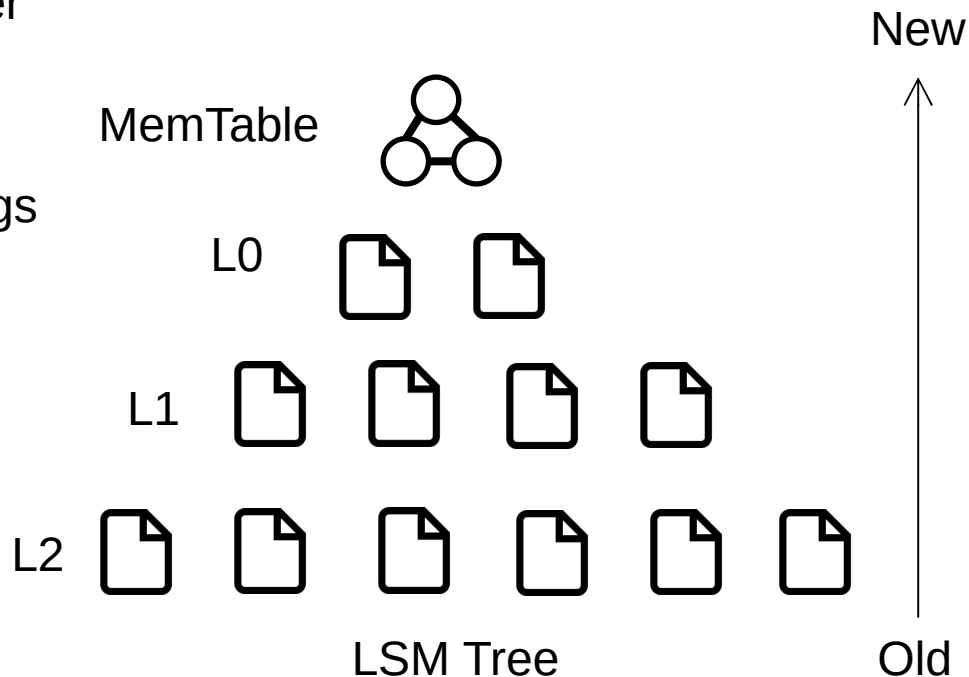
Range Query in LSM Tree

1. Search each layer using **binary search**

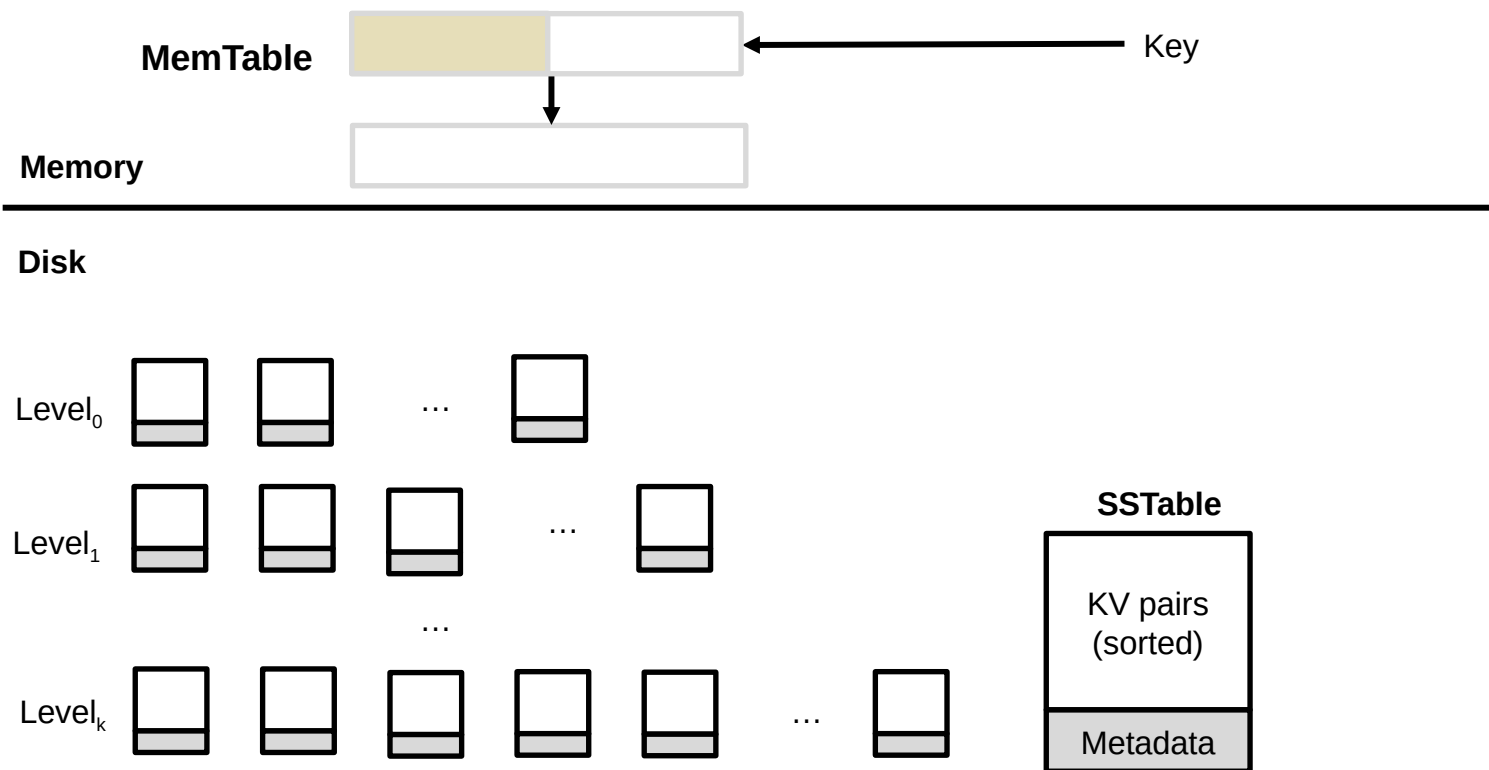
2. **Merge** the results of each layer

Not as good as B+Tree,

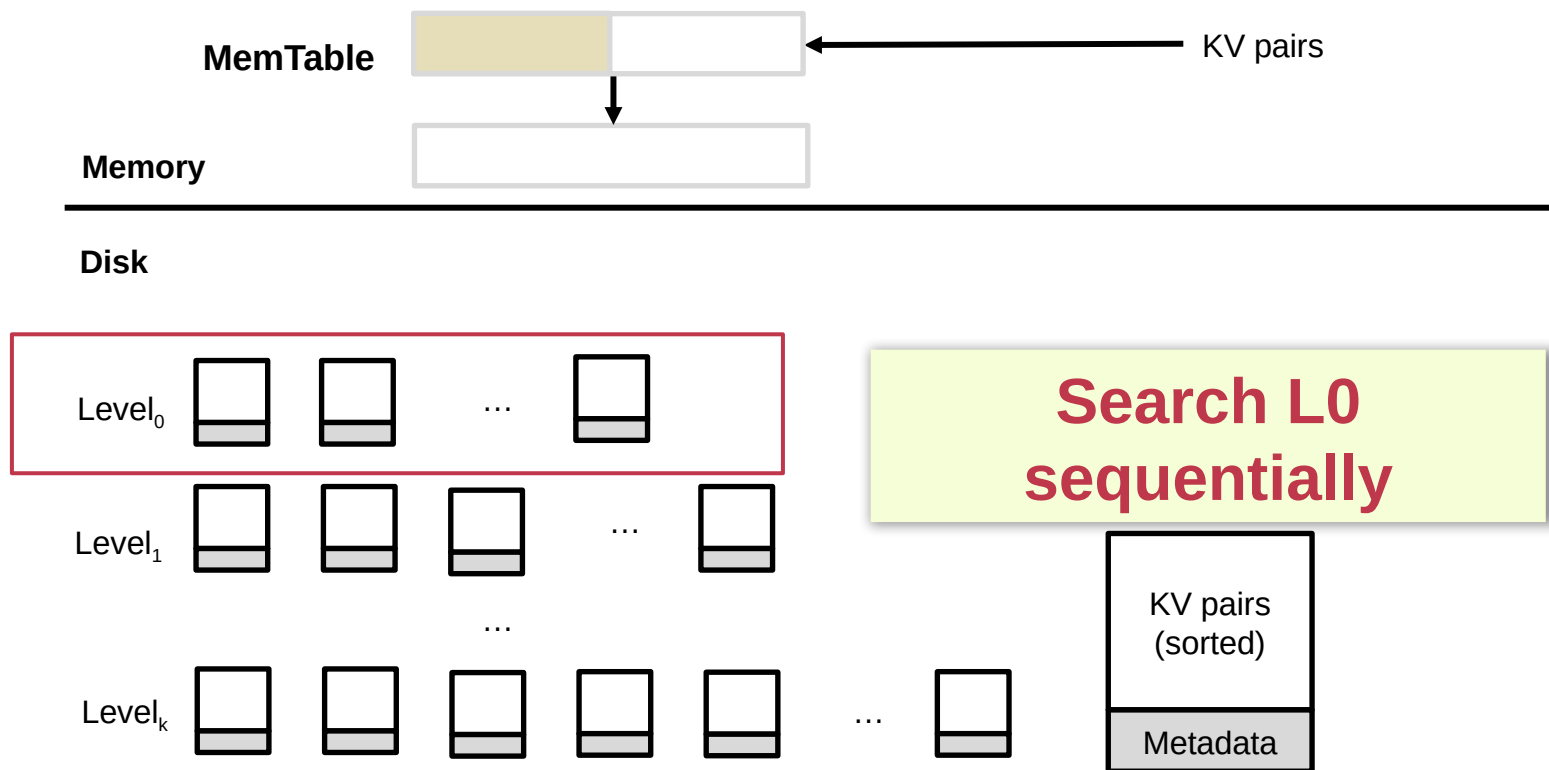
but is much better than hash & logs
without hierarchy! !



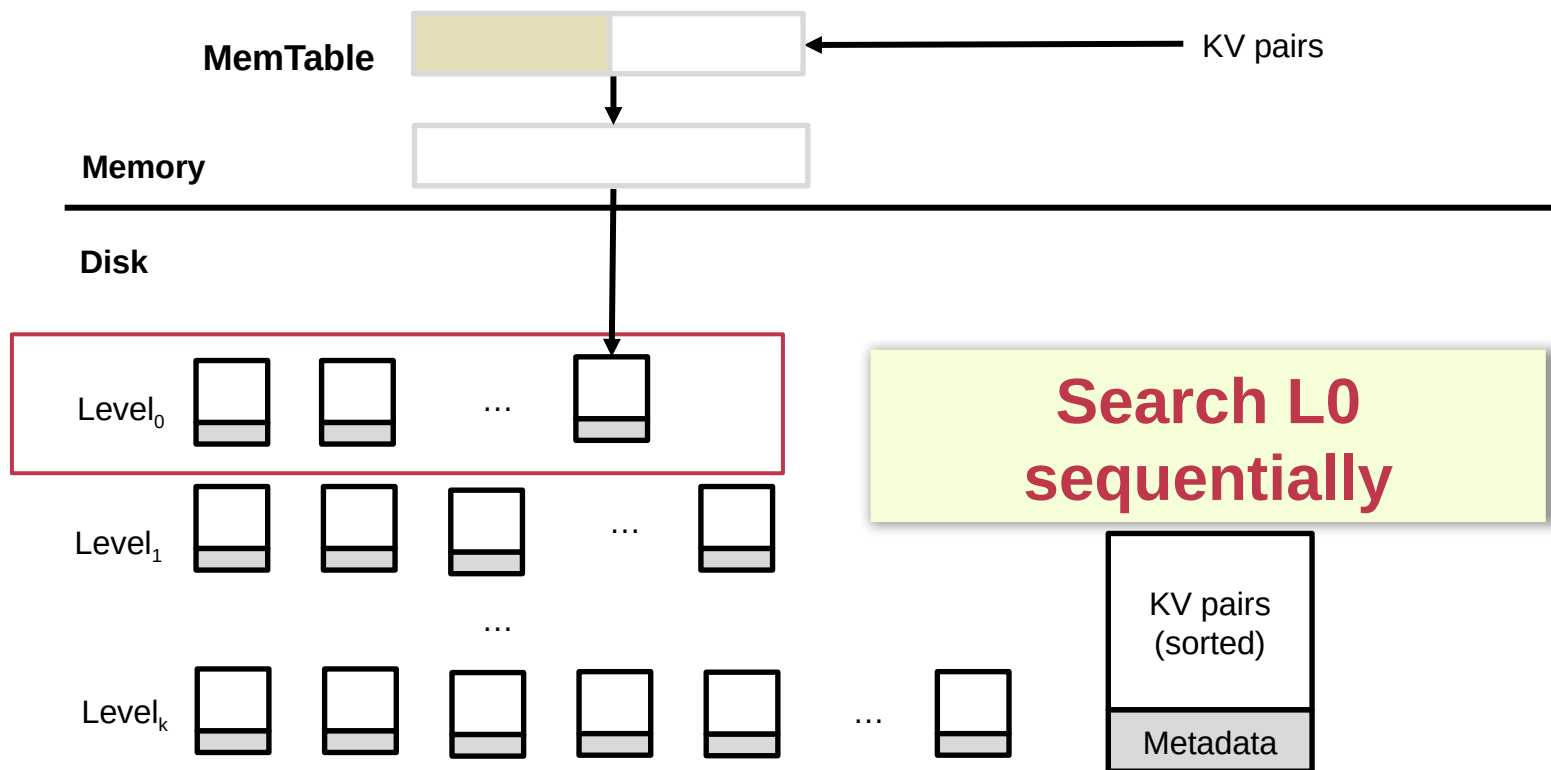
Example: Read in LSM-Tree (Similar to SSTables)



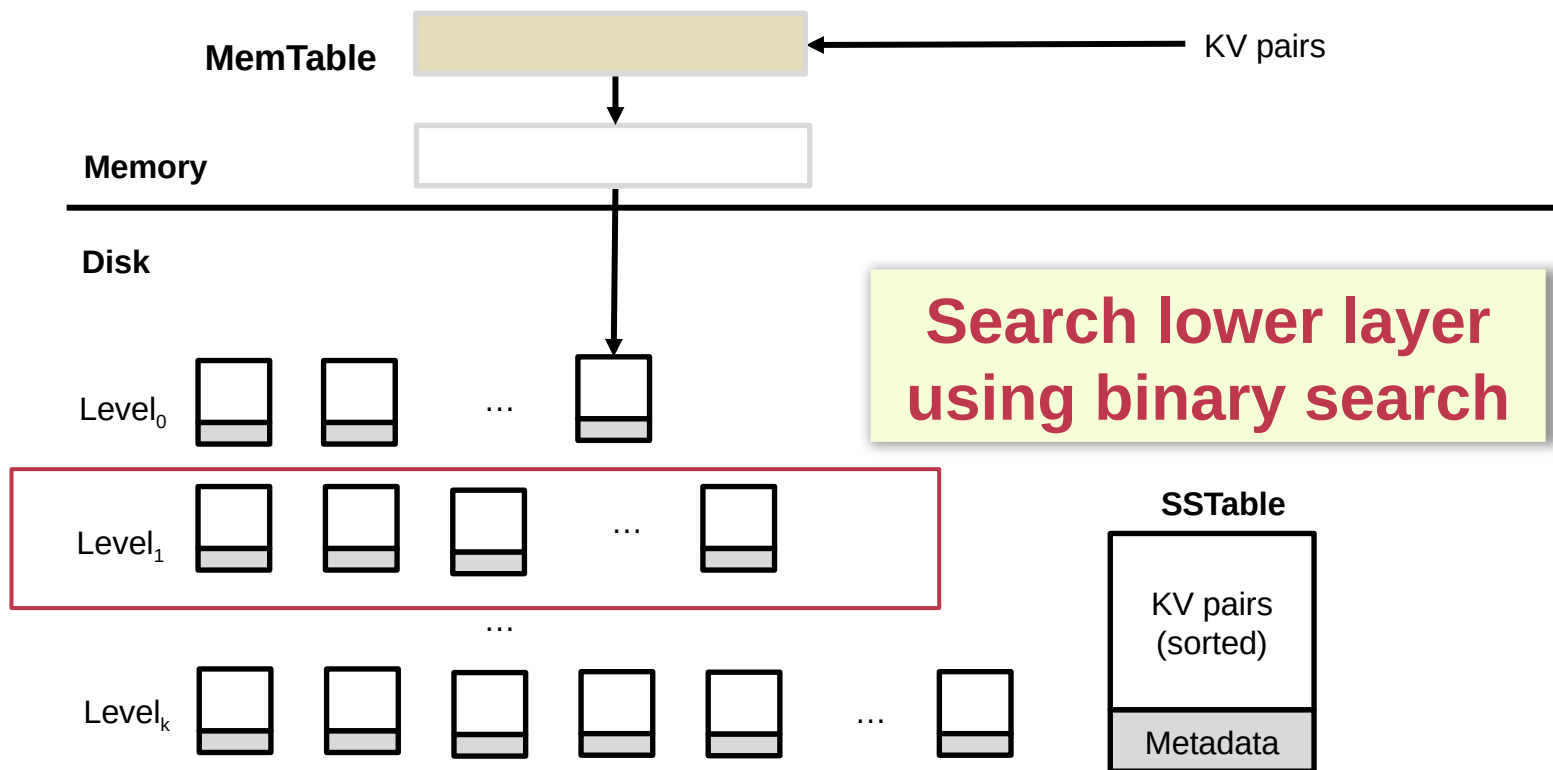
Example: Read in LSM-Tree



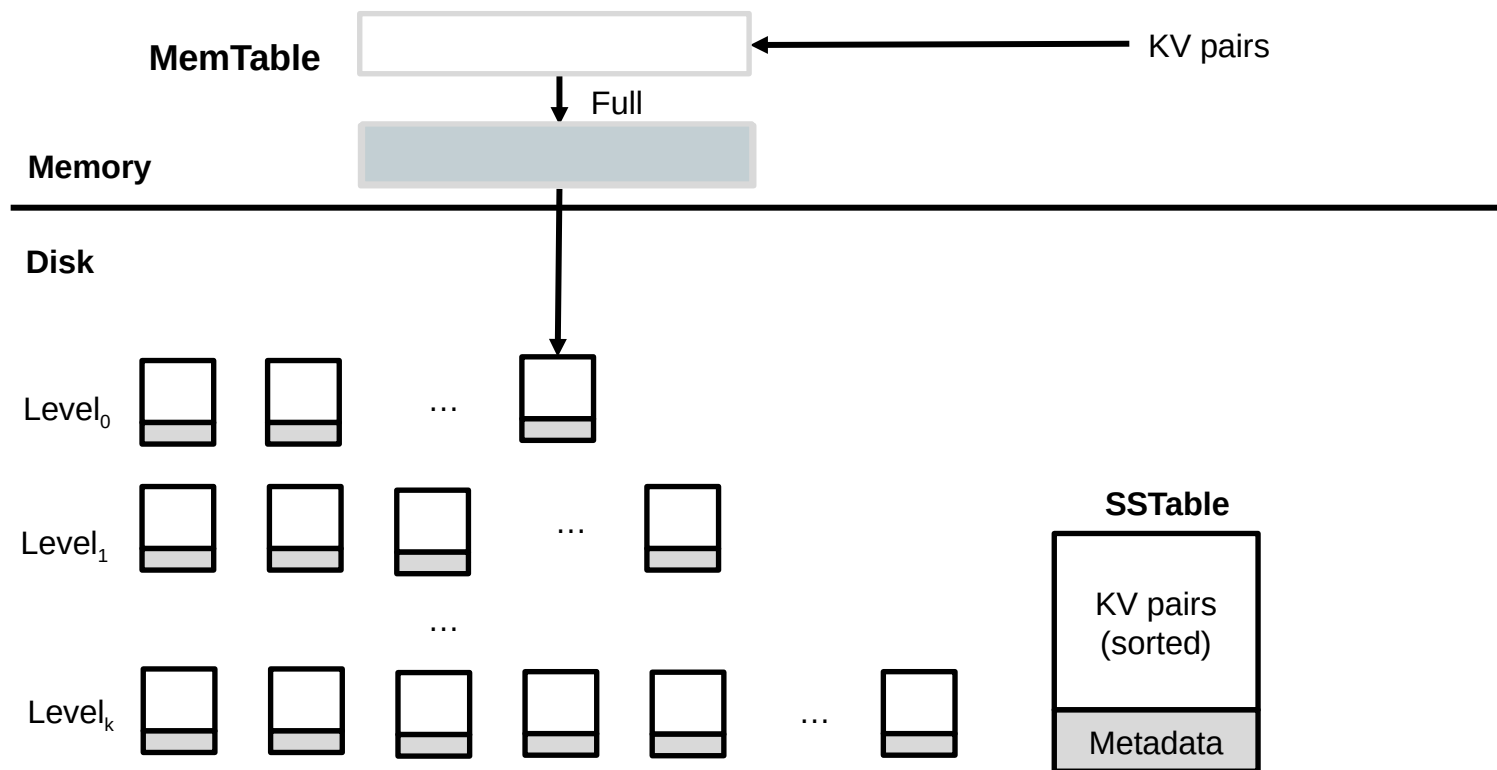
Example: Read in LSM-Tree



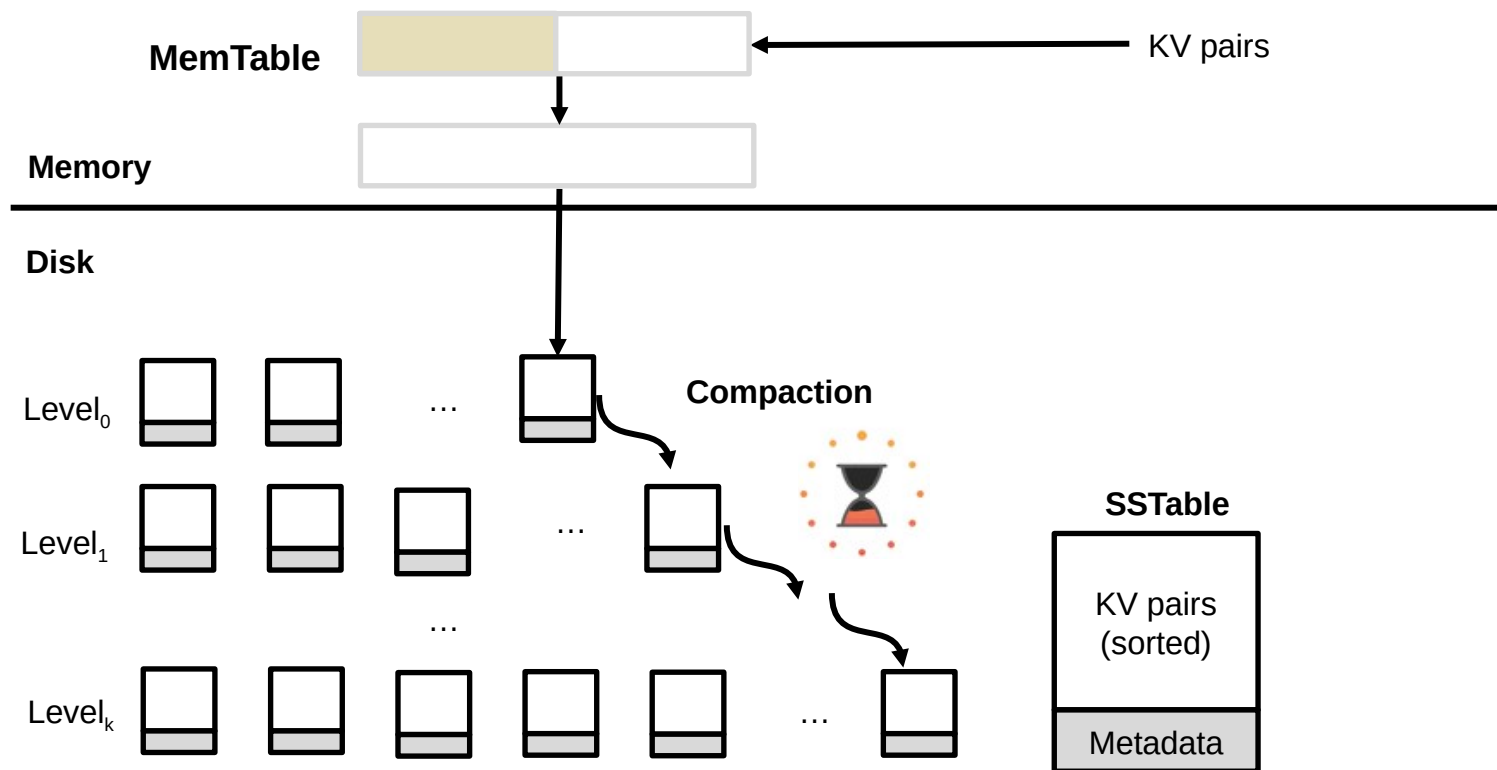
Example: Read in LSM-Tree



Example: insert/update in LSM-Tree



Example: insert/update in LSM-Tree



What about crash?

MemTable is an in-memory data structure

- So it is vulnerable to machine failure

Goal: a successful insertion will store the data durably

Solution:

- Keep a separate log file the MemTable (may not be sorted)
- Before inserting to the MemTable, adding the KV to the log first (also a sequential write); reply if the log is successful
- If the machine crashed, reboot it, and reconstruct the MemTable from the log

LSM Tree Summary

Good when

- Massive dataset
- Rapid updates/insertions
- Fast single-point lookup for recently updated data

Widely adopted in modern single-node key-value stores



LEVELDB

Google Cloud Bigtable



RocksDB



LSM Tree Summary

Good when

- Massive dataset
- Rapid updates/insertions
- Fast single-point lookup for recently updated data

Compared with B-Tree

- **Pros:** good write performance due to sequential writes
- **Cons:** additional compaction process, possible slow range queries, write stall caused by the compaction, slow lookup for non-existent key

LSM Tree Summary

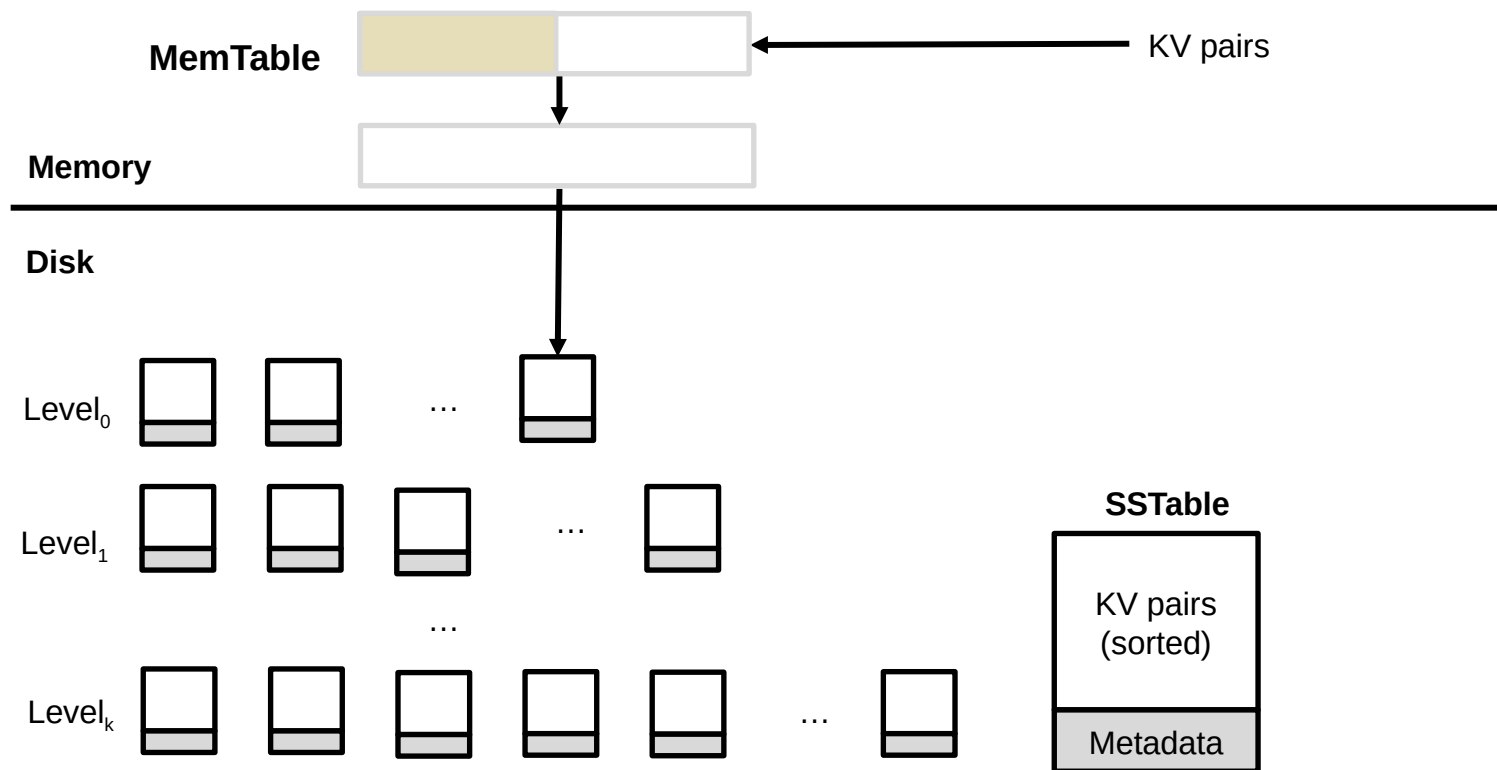
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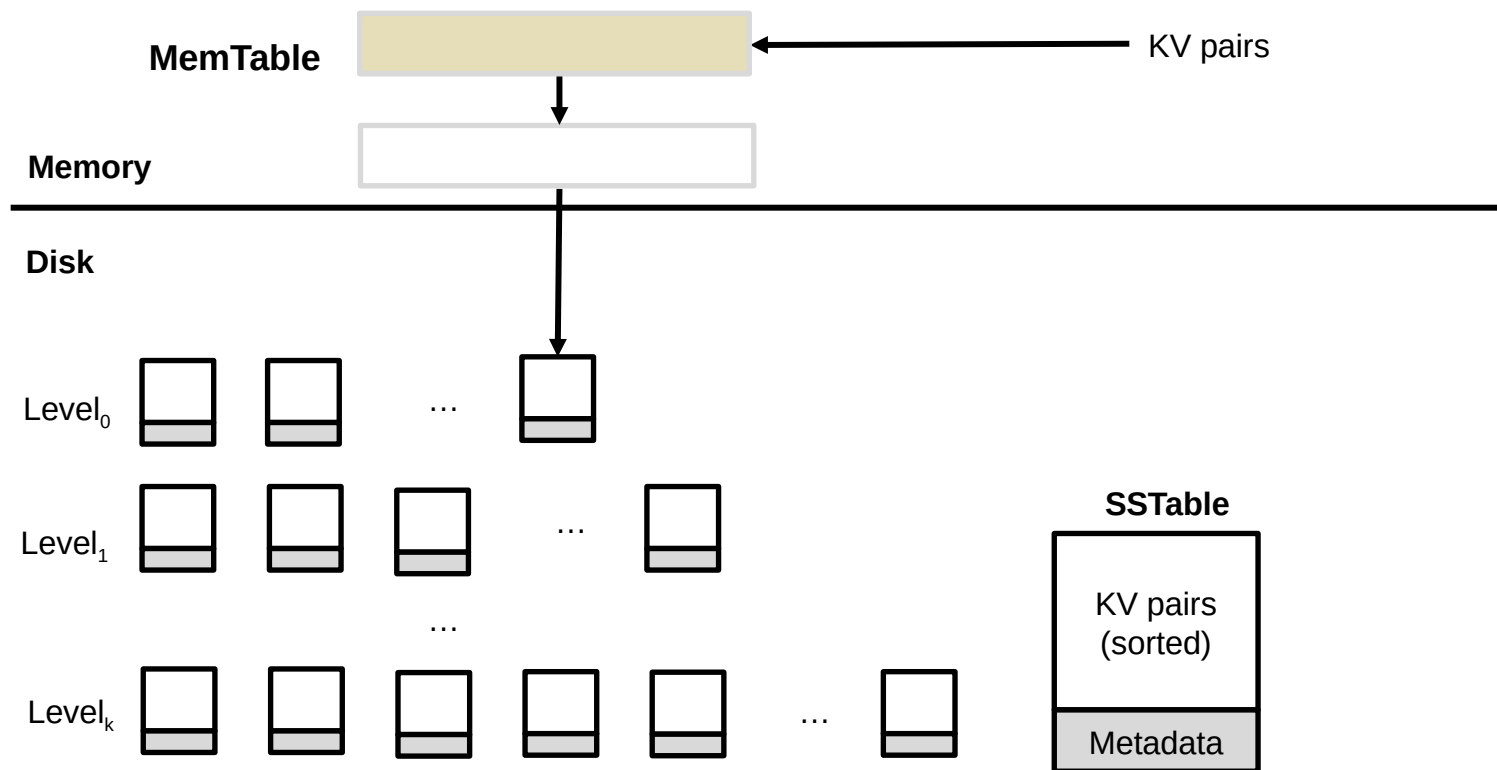
Compared with B-Tree

- **Pros:** good write performance due to sequential writes
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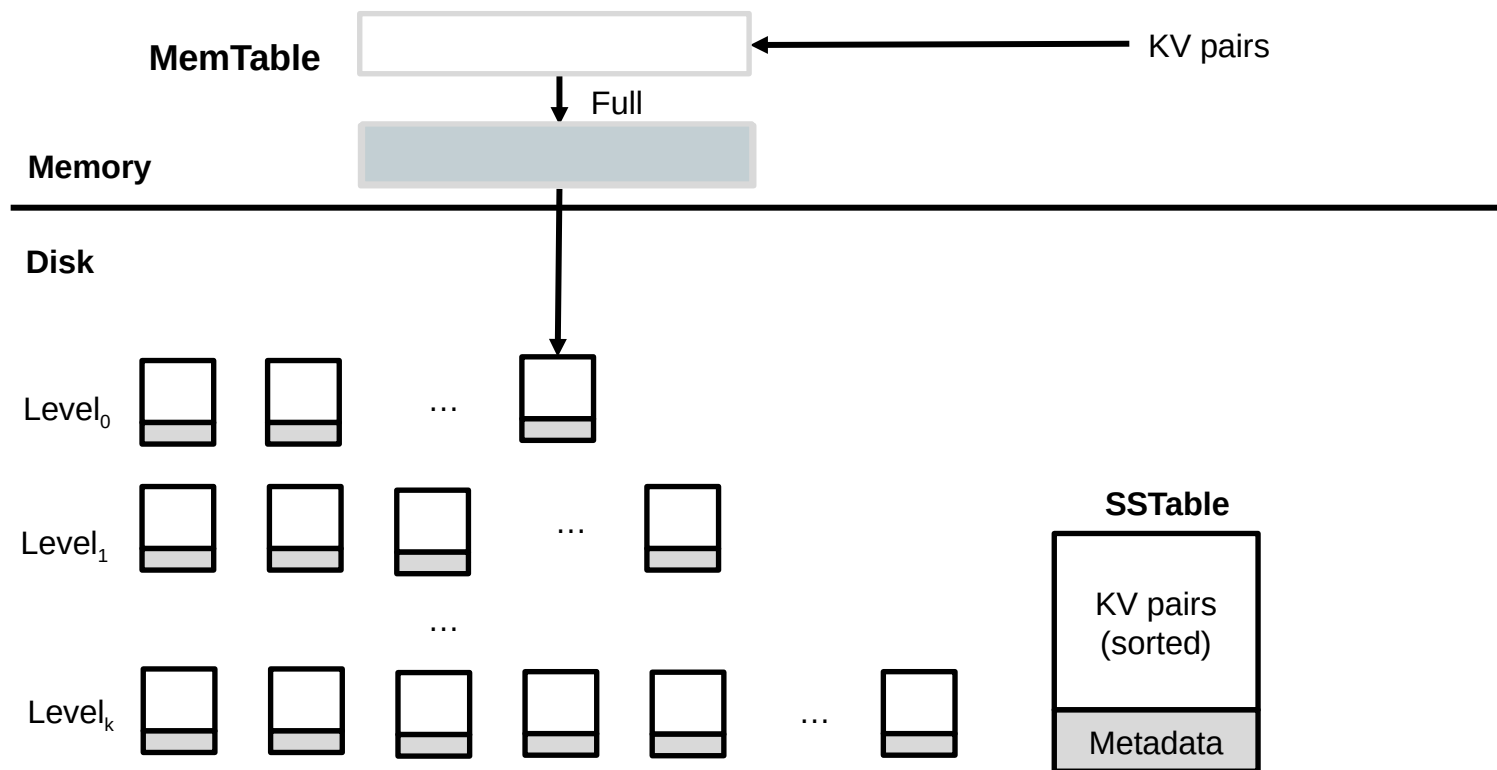
Write stall caused by compaction in LSM Tree



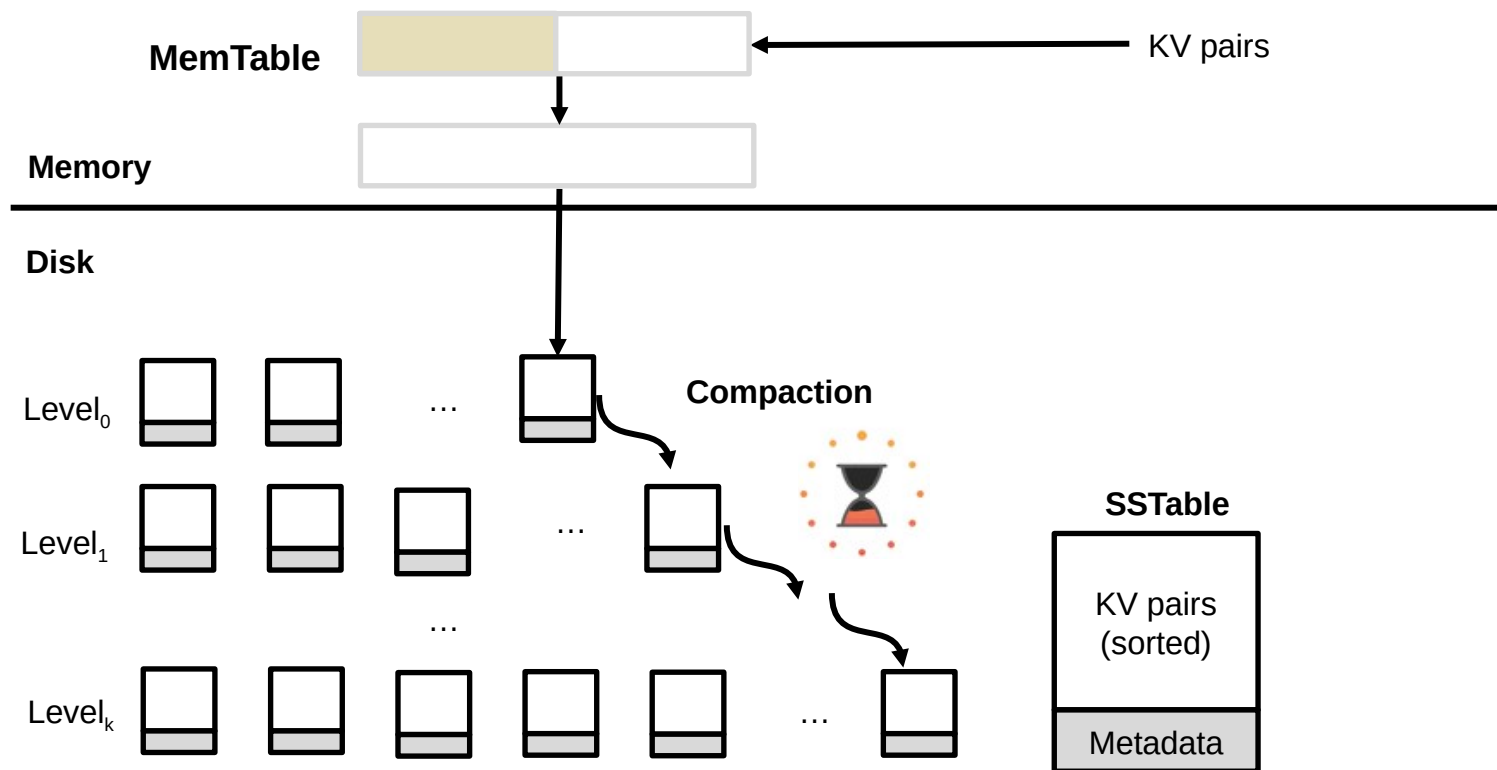
Write stall caused by compaction in LSM Tree



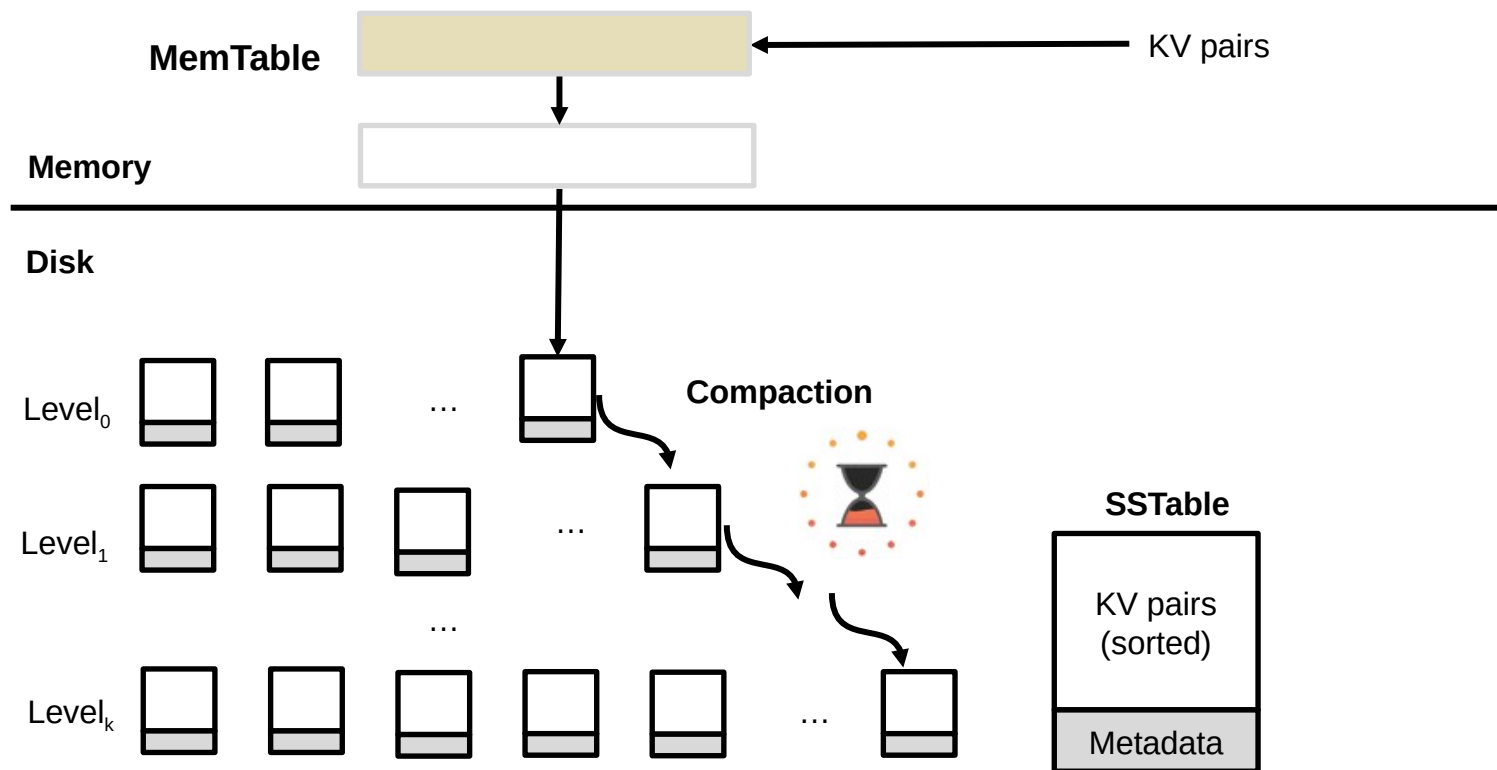
Write stall caused by compaction in LSM Tree



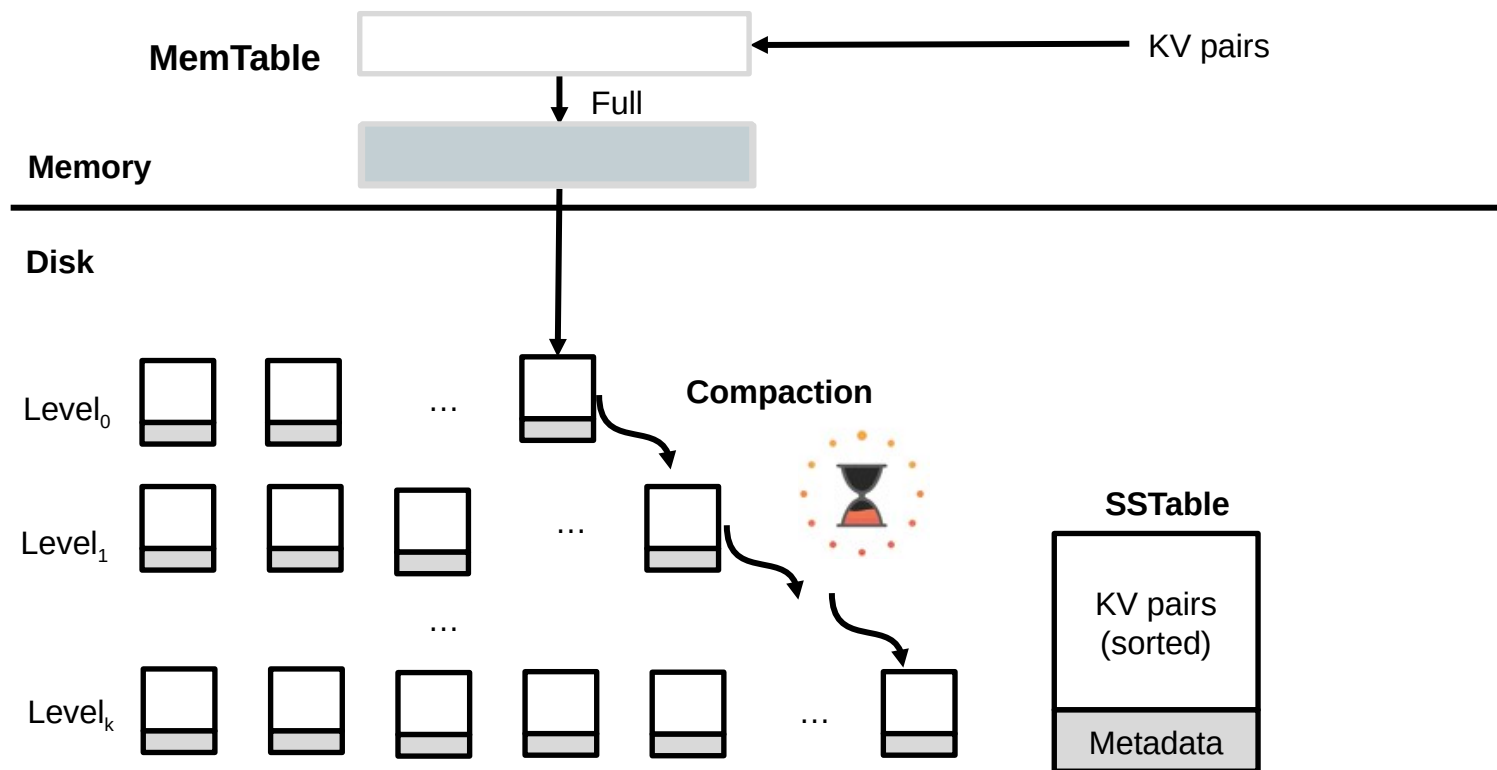
Write stall caused by compaction in LSM Tree



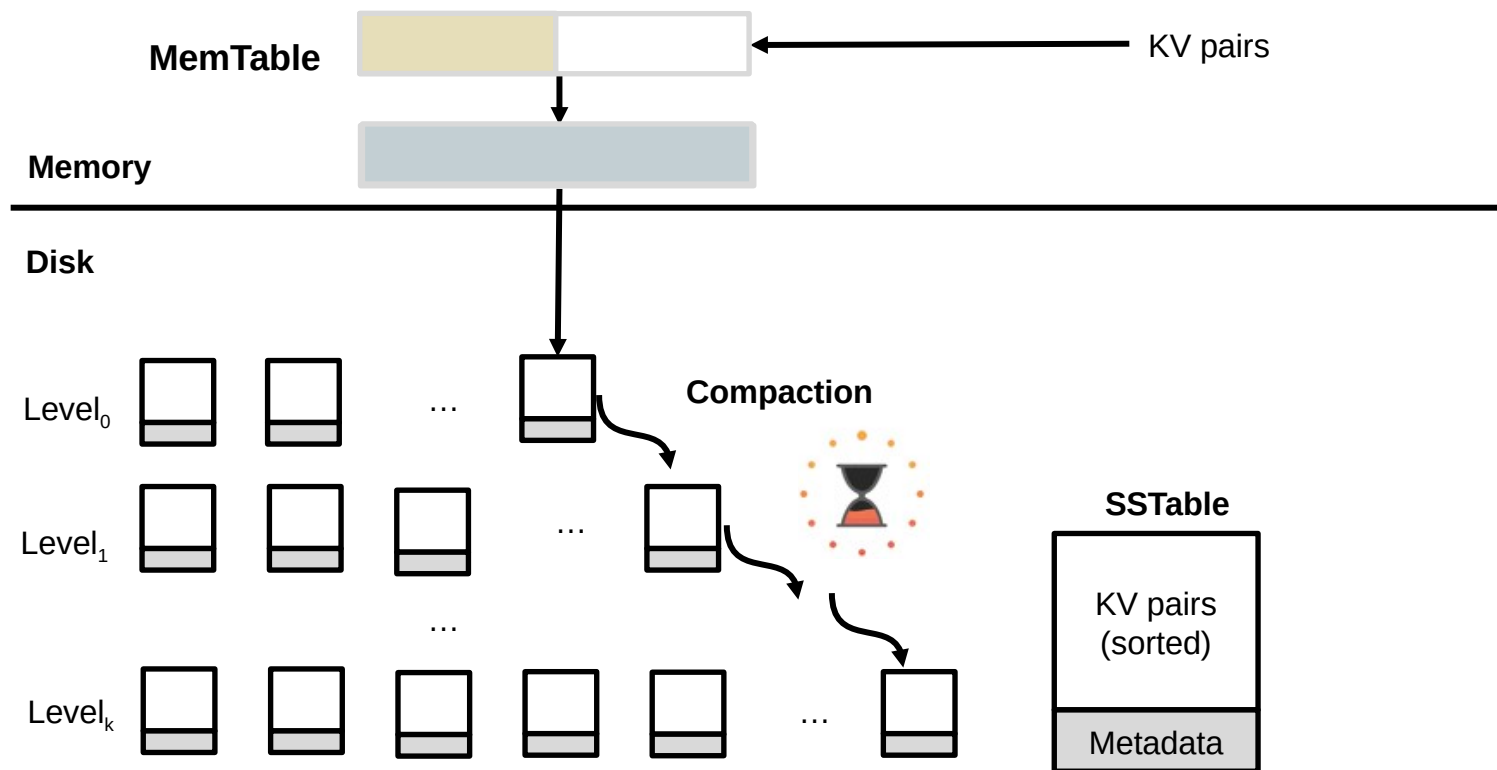
Write stall caused by compaction in LSM Tree



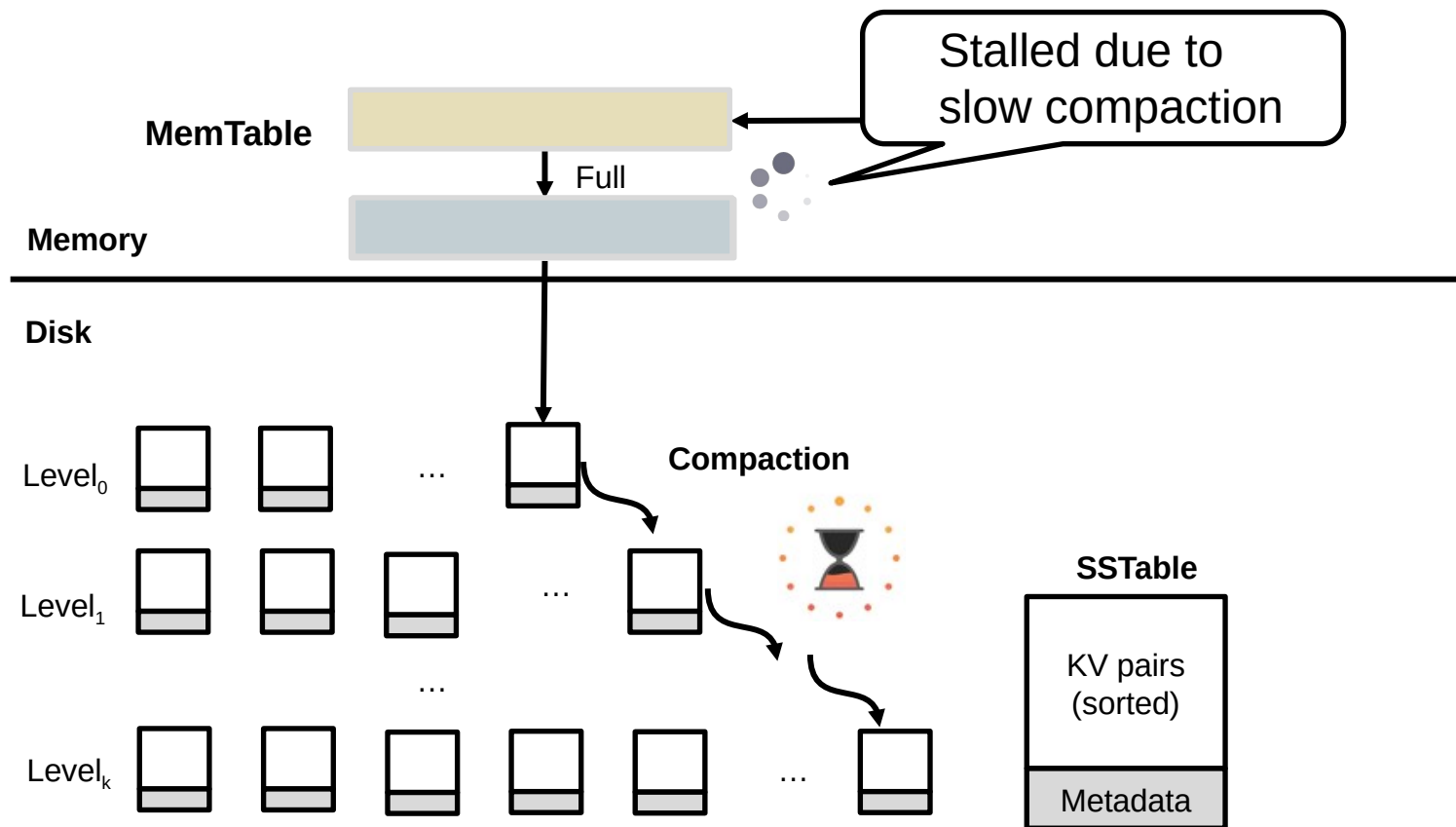
Write stall caused by compaction in LSM Tree



Write stall caused by compaction in LSM Tree



Write stall caused by compaction in LSM Tree



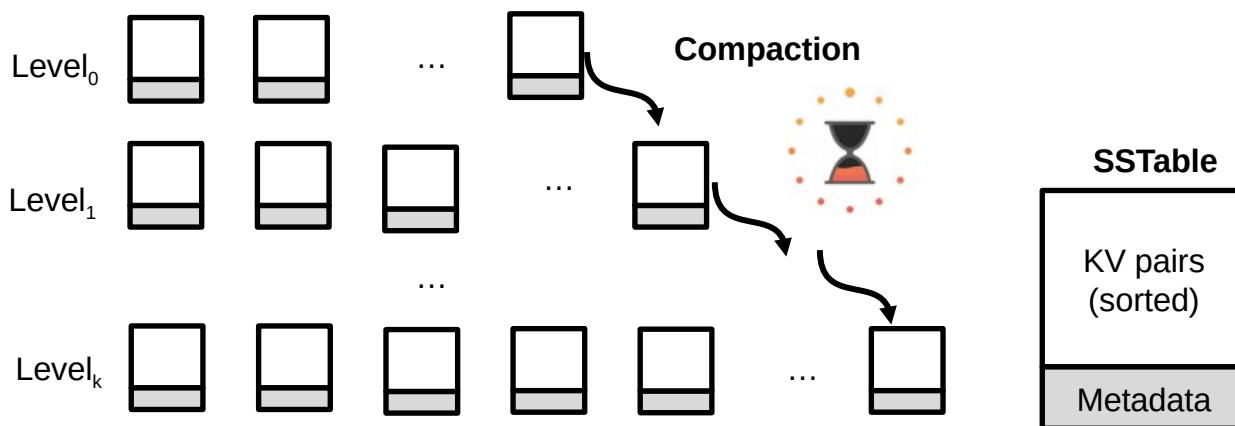
How to avoid write stall?

In principle, hard to prevent

Can only alleviate

- E.g., speed up compaction & merge process with advanced hardware

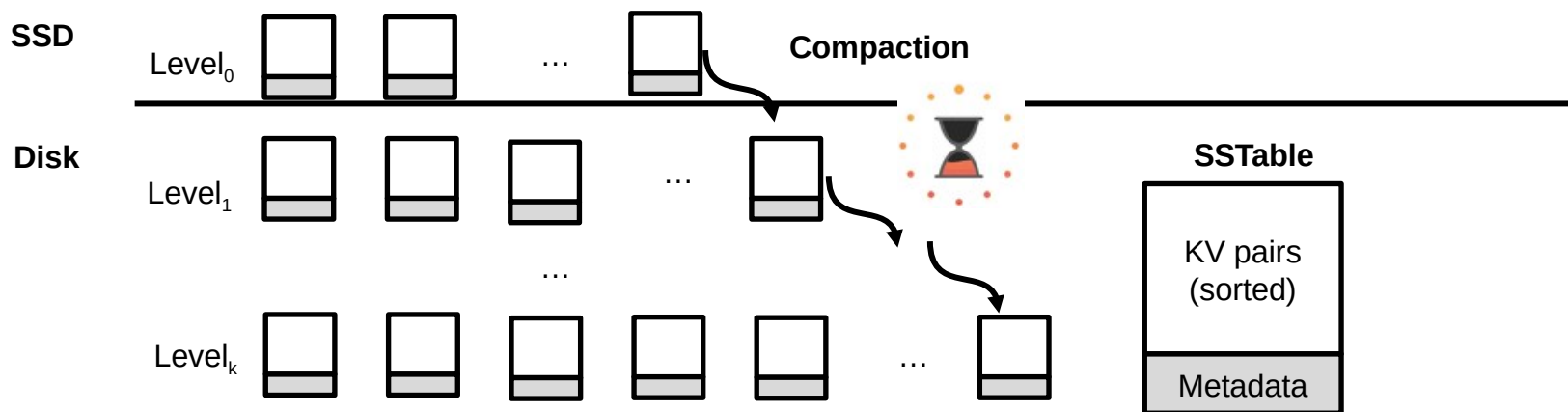
Disk



In principle, hard to prevent

Can only alleviate

- E.g., speed up compaction & merge process with **advanced hardware**
- **Observation:** SSD is much faster than disk on storage
 - Using it to store up-layer SSTables



LSM Tree Summary

Good when

- Massive dataset
- Rapid updates/insertions
- Fast lookups

Compared with B-Tree

- **Pros:** good write performance due to sequential writes
- **Cons:** additional compaction process, possible slow range queries, write stall caused by the compaction, **slow lookup for non-existent key**

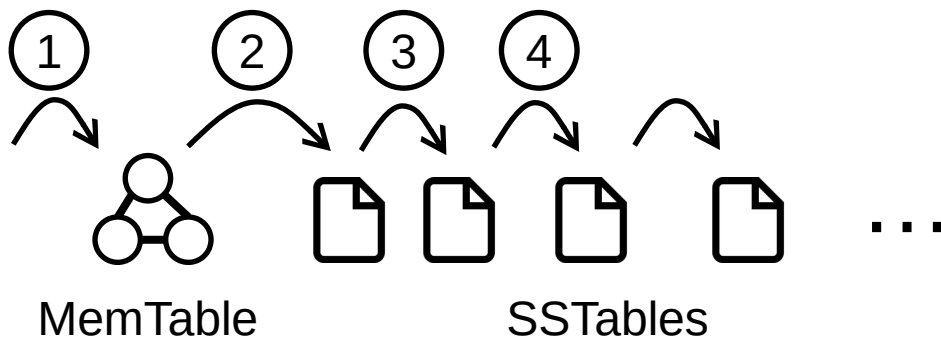
Slow lookup for non-existent key

Recall: how LSM Tree lookup keys

1. Checks the MemTable
2. If misses, checks the latest SSTable
3. If still misses, checks the next older SSTable
4. ...

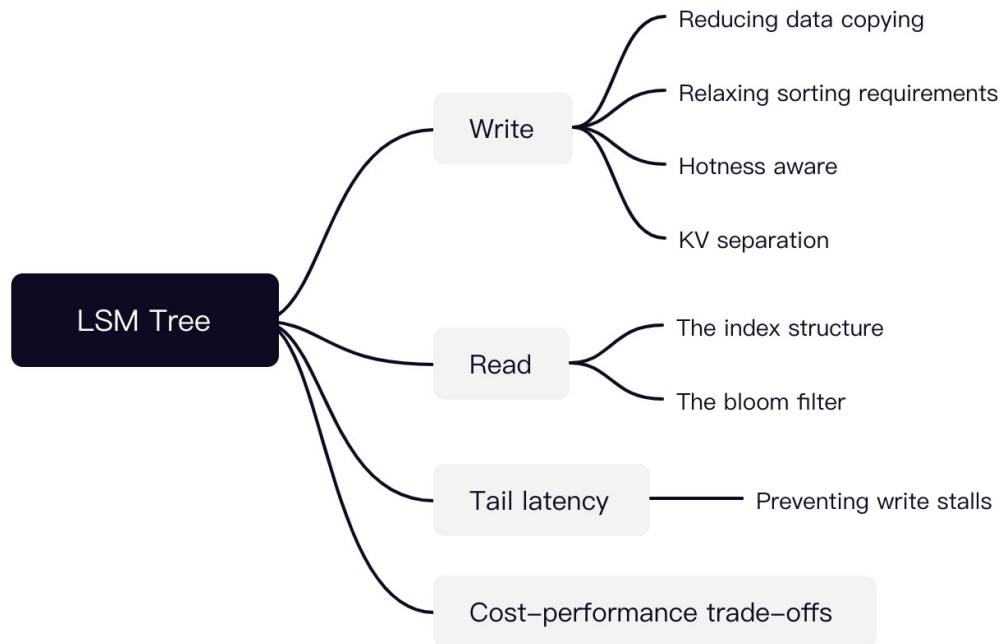
Question: what if the key non-exist?

Will lookup all the files!



LSM Tree is a hot research topic today

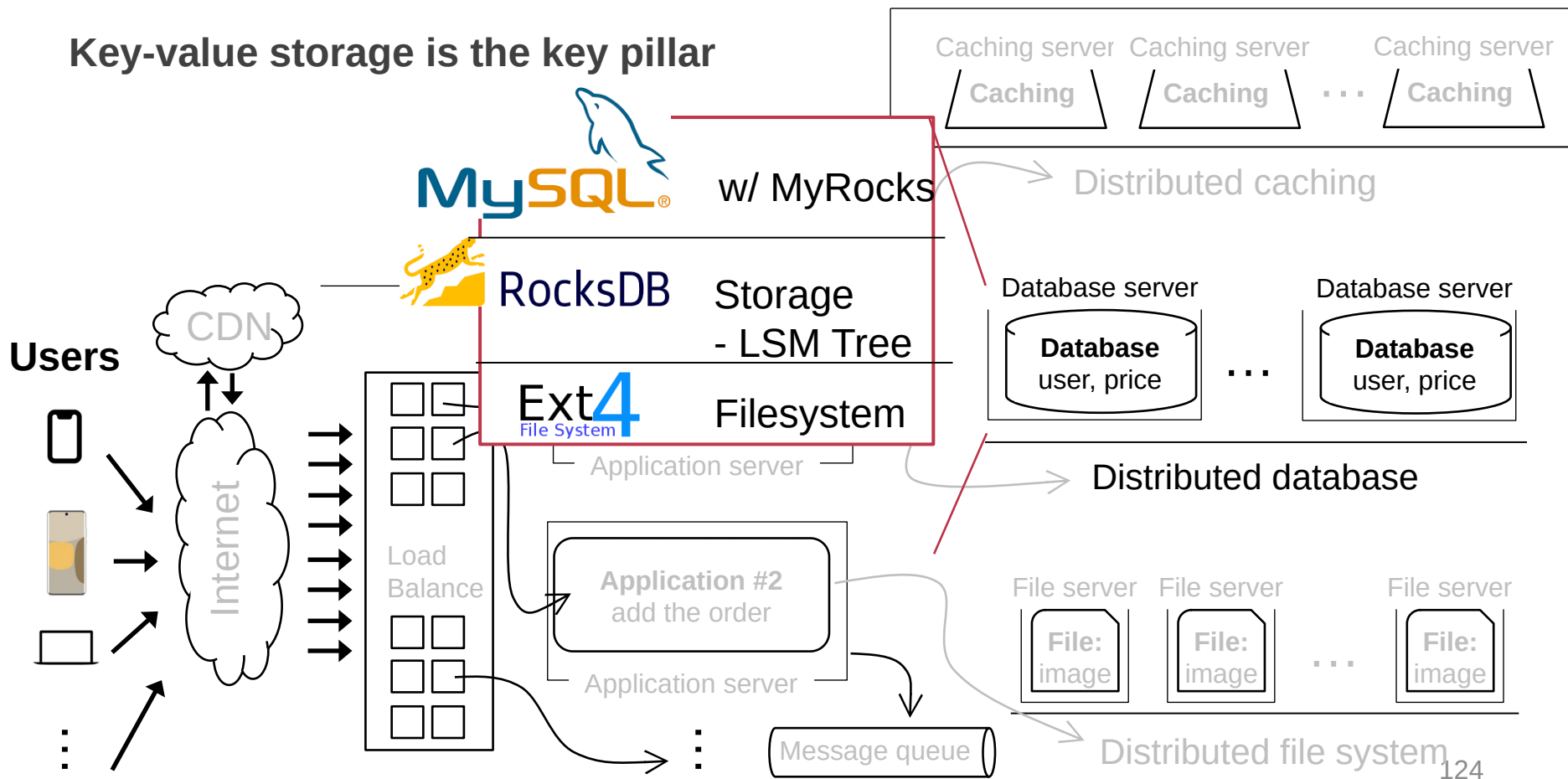
Many possible directions



Key-value storage is a key component in
large-scale website

Review: large-scale websites

Key-value storage is the key pillar



Distributed key-value storage

Distributed key-value storage

Make KV store distributed (see later lectures)

- RPC + key-value storage = distributed key-value storage!
 - See the next lecture
- We can also shard the data across multiple nodes
 - i.e., high scalability

Key challenge:

- How to find the data?
 - E.g., consistent hashing

Other problems:

- Fault tolerance (see later lectures)
- Availability, replication & consistency (see later lectures)

Summary of this lecture

Key-value store is an important component in computer systems

- Typically built upon a filesystem to simplify disk hardware management

We show how KVS is evolved from log-structured file to the LSM tree

- Log-structured file
- Indexing
- LSM Tree

