

Write-Optimized Indexing

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31 January, 2023

We will begin at 2:10 pm



We are trying to optimize the following kinds of queries

A B C

```
select * from table where A = "..."
```

```
select * from table where B > "..." and B < "..."
```

Let's reconsider four baselines

Append-Only Table

Sorted Table

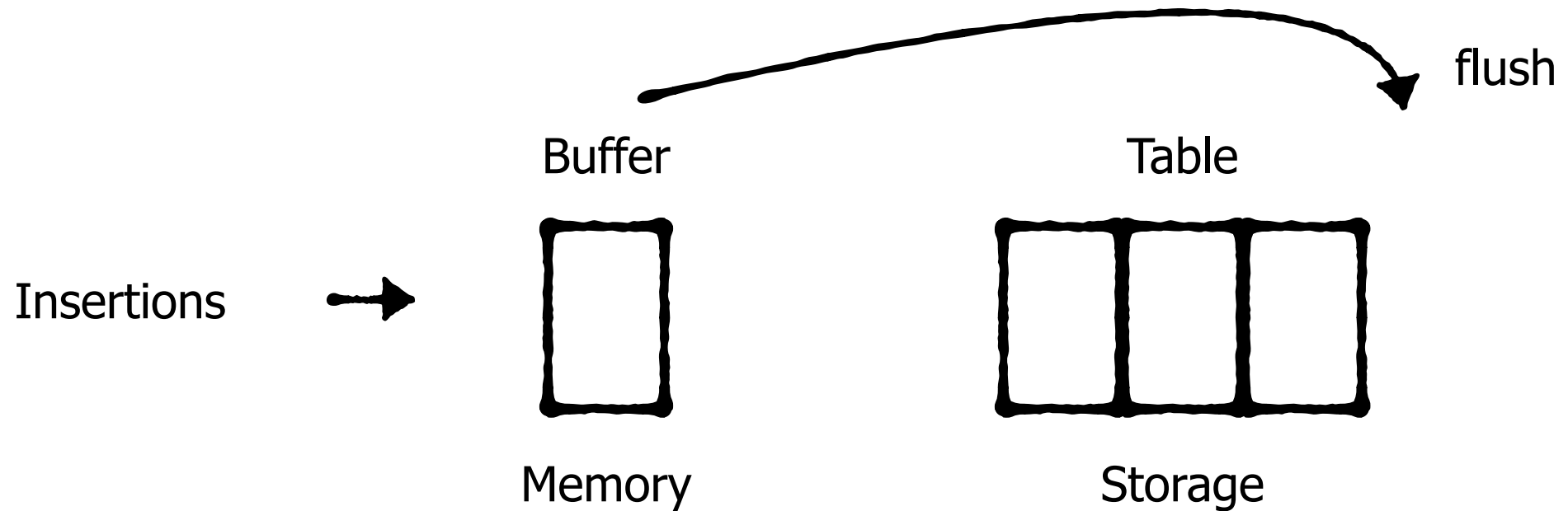
Extendible Hashing

B-tree

Append-Only Table

$O(N/B)$ for any selection query

$O(1/B)$ for insertions



Let's reconsider four baselines

Append-Only Table

Sorted Table

Extendible Hashing

B-tree

Sorted Table

A	...
2	...
7	...
22	...
32	...
32	...
61	...
74	...
90	...
97	...

Binary search: $O(\log_2 N/B)$ I/O

Update/insert/delete: $O(N/B)$ read & write I/O

Let's reconsider four baselines

Append-Only Table

Sorted Table

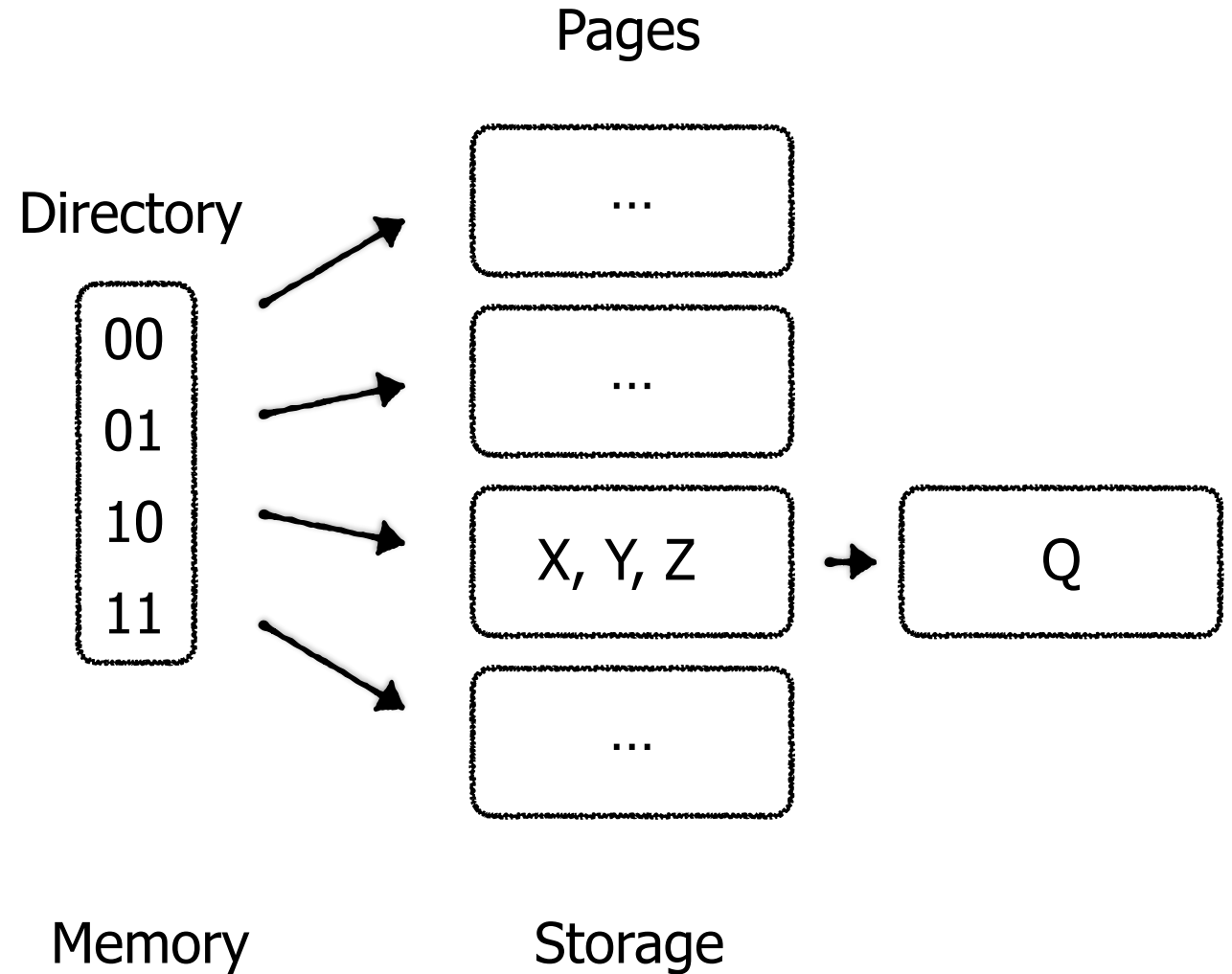
Extendible Hashing

B-tree

Extendible Hashing

A directory maps pages in storage with a given hash prefix

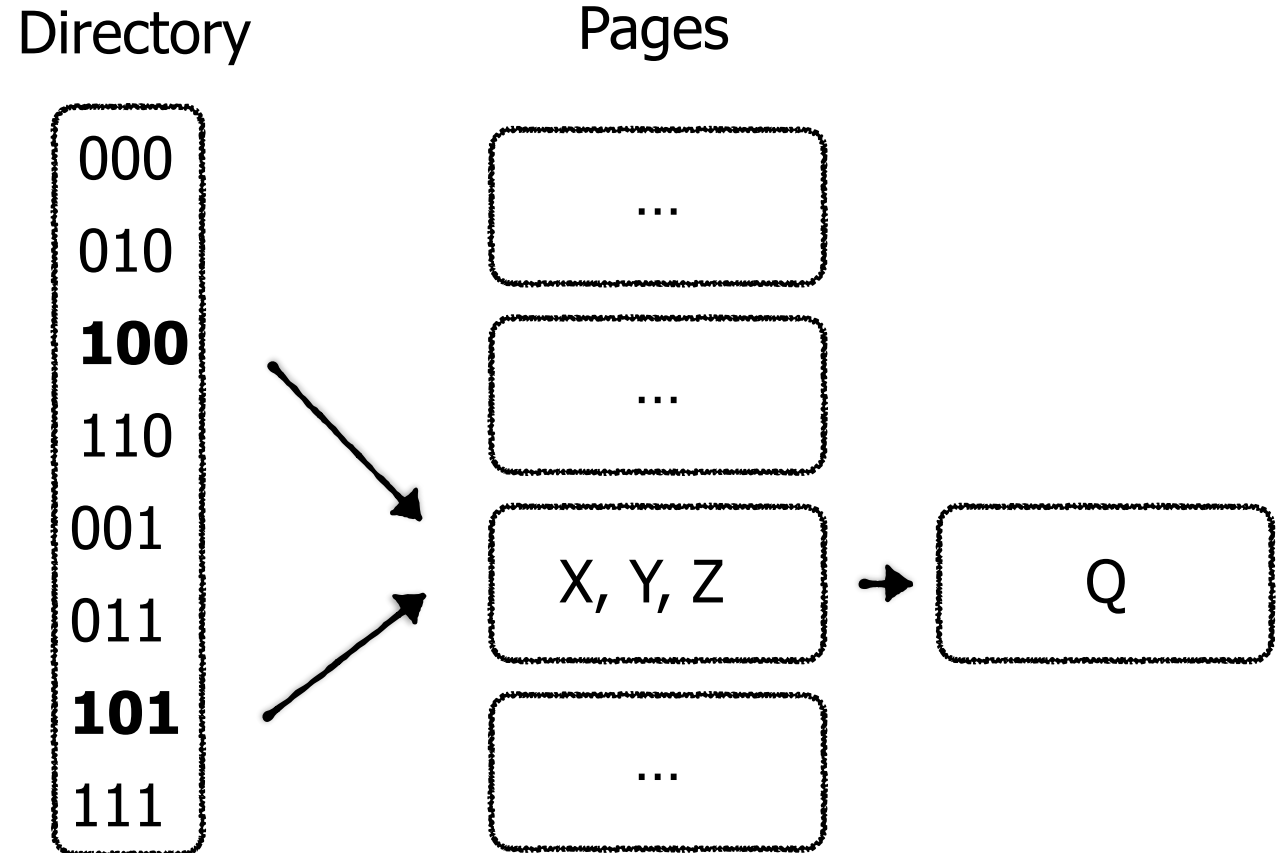
Handle overflows via chaining



Extendible Hashing

When we reach capacity, double directory size.

New directory slots still point to previous pages



Extendible Hashing

Split one overflowing bucket at a time by rehashing entries.

Directory

000
010
100
110
001
011
101
111

Pages

...

...

X, Z

Q, Y

...



Extendible Hashing

Query cost: $O(1)$ read I/O

Insertion cost:

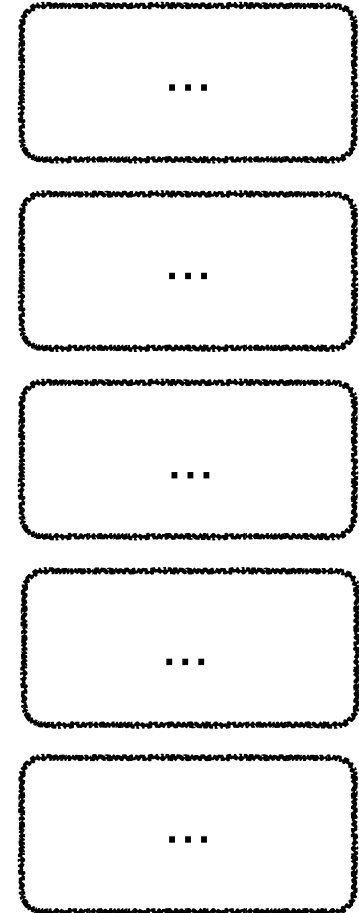
$O(1)$ read I/O

$O(1)$ write I/O

Directory

000
010
100
110
001
011
101
111

Pages



Extendible Hashing

Query cost: $O(1)$ read I/O

Insertion cost:

$O(1)$ read I/O

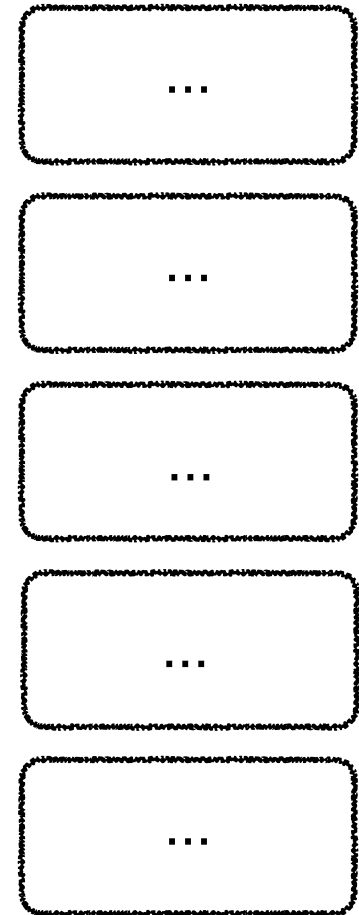
$O(1) * \mathbf{GC}$ write I/O

Random writes to storage entail SSD
garbage-collection

Directory

000
010
100
110
001
011
101
111

Pages



Let's reconsider four baselines

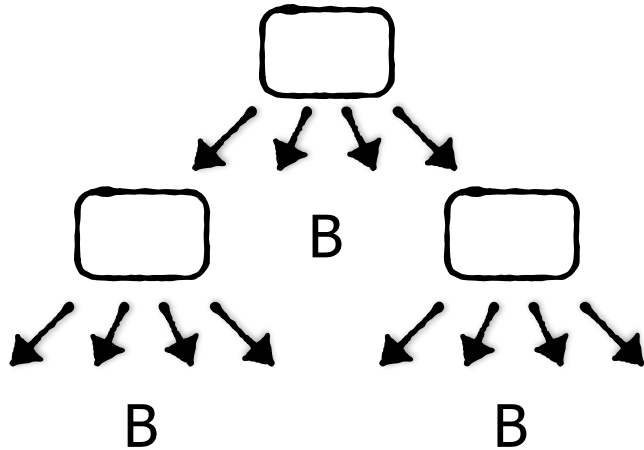
Append-Only Table

Sorted Table

Extendible Hashing

B-Tree

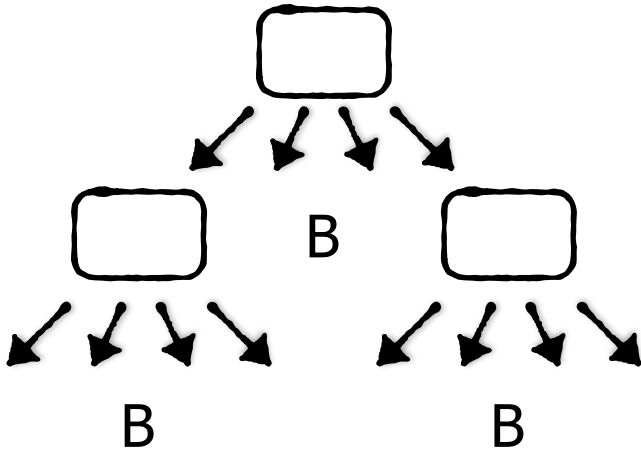
B-Tree



Each node has B children. This allows pruning by a factor of B in each level

Can issue random writes to storage leading to SSD garbage-collection

B-Tree



Each node has B children. This allows pruning by a factor of B in each level

Can issue random writes to storage leading to SSD garbage-collection

Query: $O(\log_B N)$ read I/O

Update/insert/query: $O(\log_B N)$ read I/O
& $O(1) * \text{GC write I/O}$

Operation	I/O	append-only table	Sorted File	Extendible Hashing	B-Tree
Query	Reads	$O(N/B)$	$O(\log_2 N/B)$	$O(1)$	$O(\log_B N)$
Insert	Reads	0	$O(N/B)$	$O(1)$	$O(\log_B N)$
	Writes	$O(1/B)$	$O(N/B)$	$O(1)$ & GC	$O(1)$ & GC

Operation	I/O	append-only table	B-Tree
Query	Reads	$O(N/B)$	$O(\log_B N)$
Insert	Reads	0	$O(\log_B N)$
	Writes	$O(1/B)$	$O(1)$ & GC

Can we somehow
combine these?



The Log-Structured Merge-Tree





B-tree
is invented
1970

LSM-tree is
invented
1996

Google's BigTable
adopts LSM-tree
2005

LSM-tree is
widely used
Today



B-tree
is invented
1970

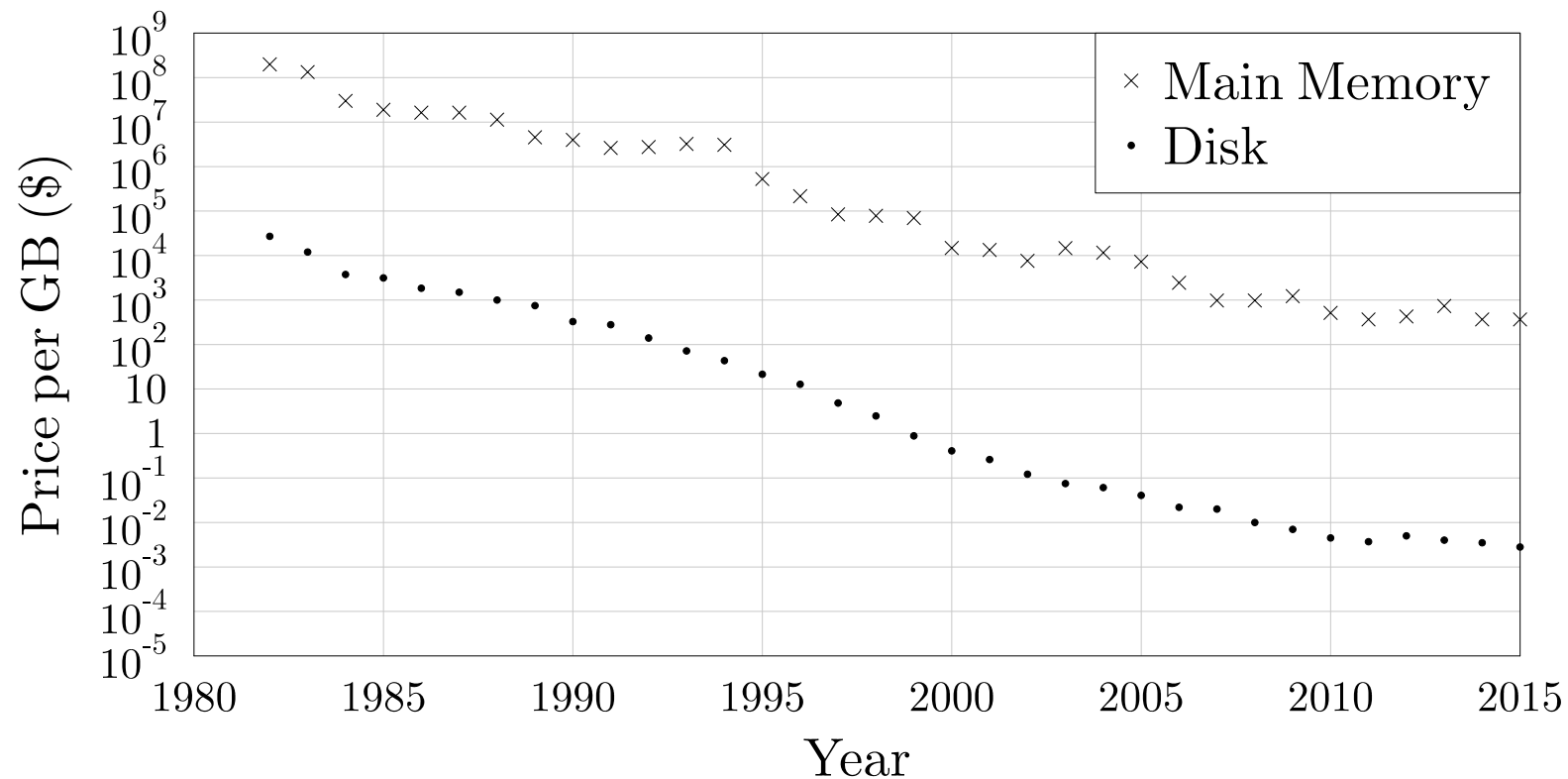
LSM-tree is
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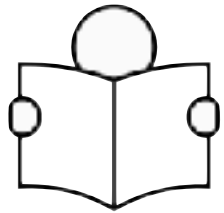
LSM-tree is
widely used
Today

Why was it not invented and used sooner?

The declining costs of storage allow us to store more data cheaply.
Hence, application workloads are becoming more write-intensive.
This drives a need to optimize for data ingestion.



Leveled LSM-tree

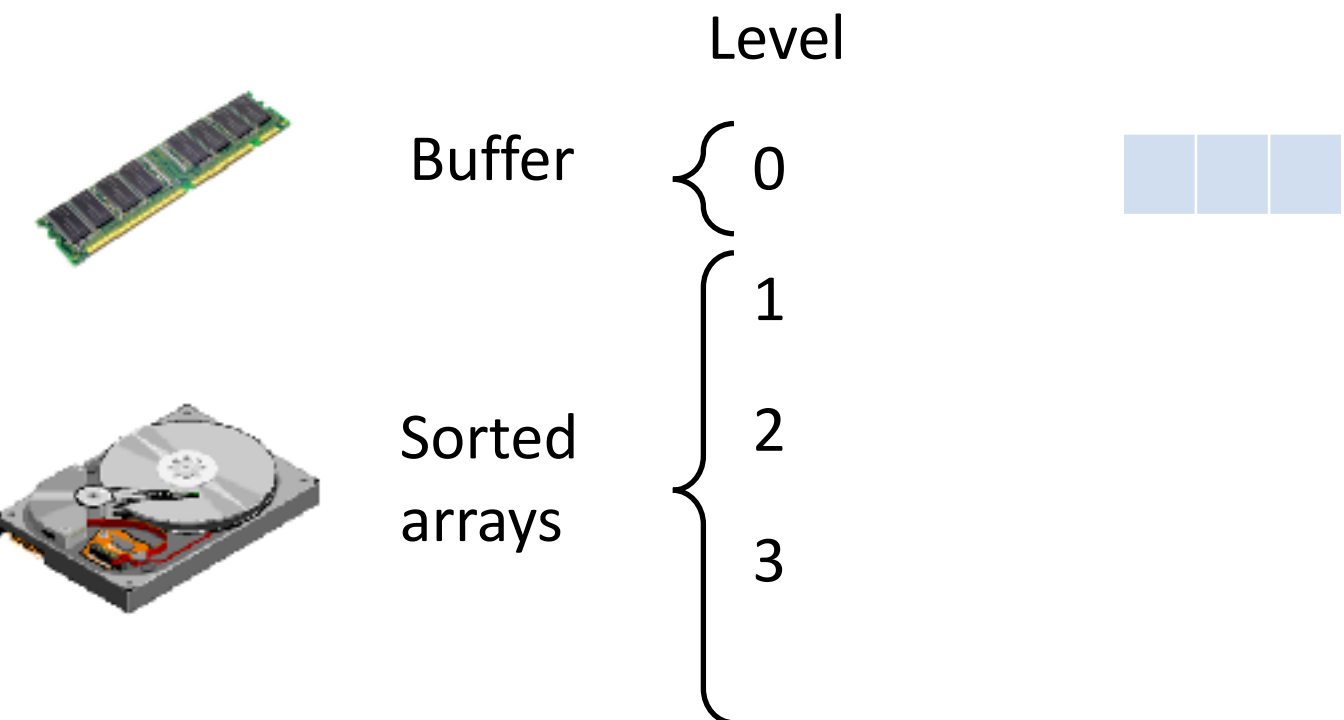


Basic LSM-tree

Tiered LSM-tree



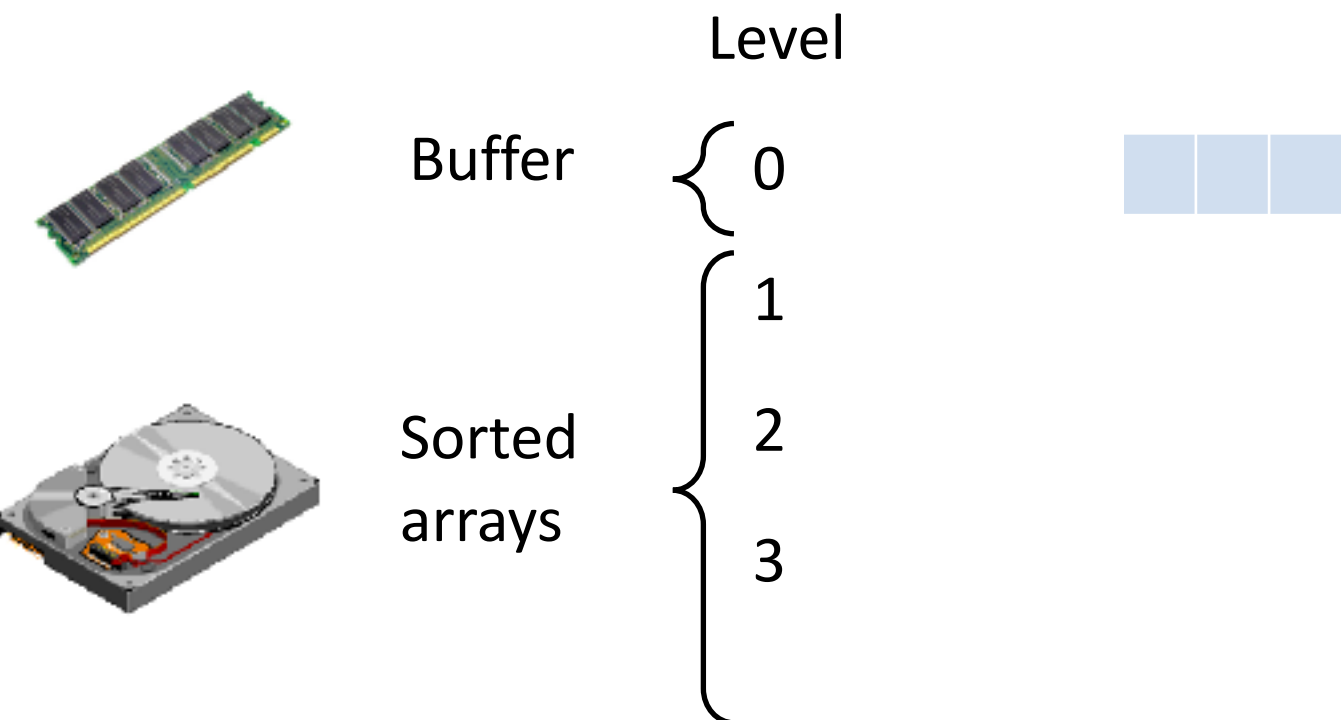
Basic LSM-tree



Basic LSM-tree

Design principle #1:

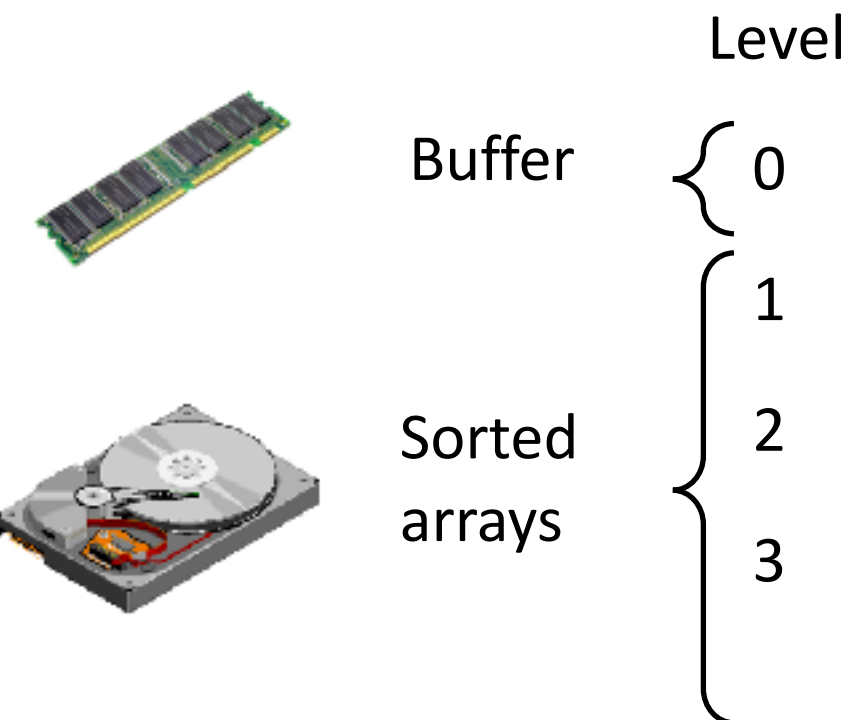
optimize for insertions by buffering



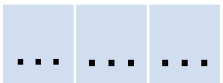
Basic LSM-tree

Design principle #1:

optimize for insertions by buffering



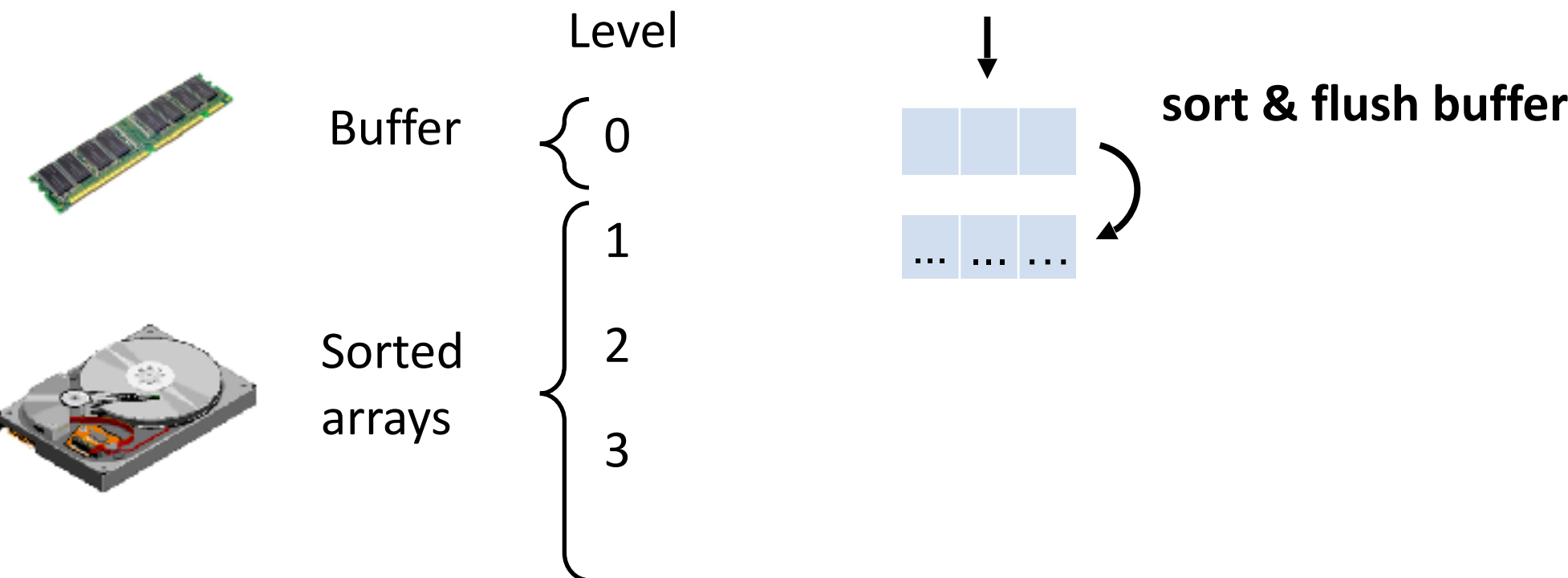
Inserts



Basic LSM-tree

Design principle #1:

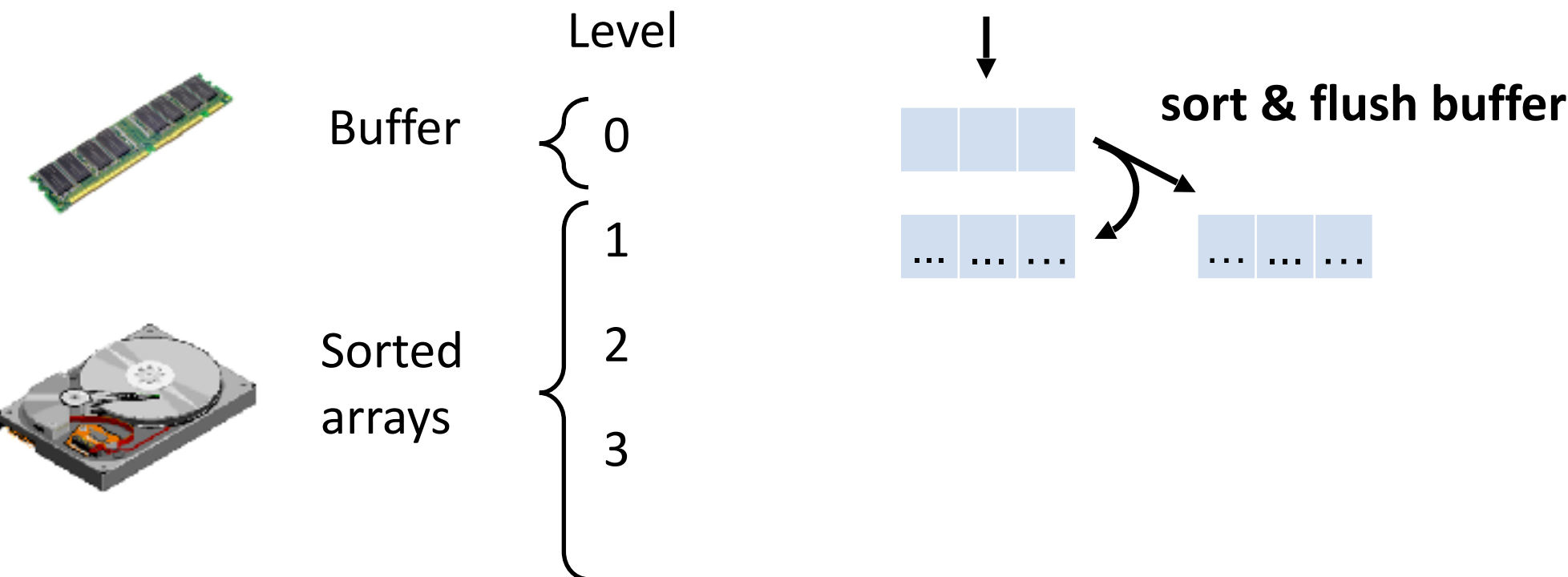
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Basic LSM-tree

Design principle #1:

optimize for insertions by buffering



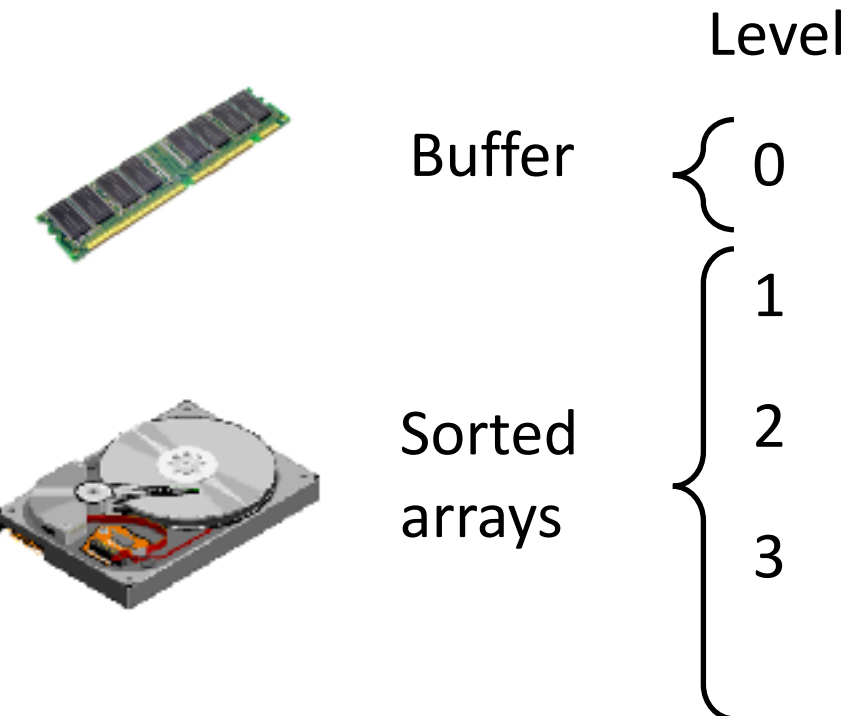
Basic LSM-tree

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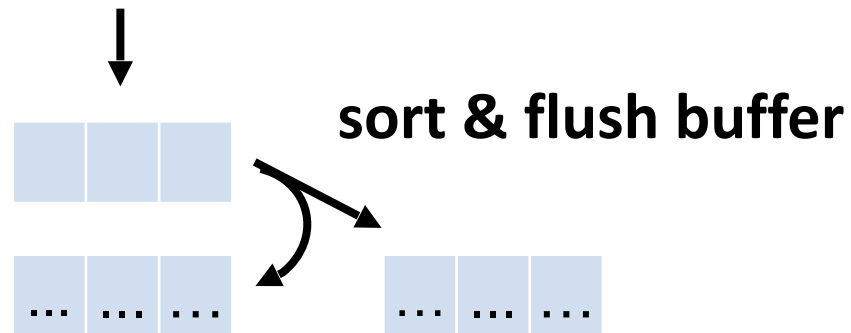
optimize for insertions by buffering

Design principle #2:

optimize for lookups by sort-merging SSTs



Inserts



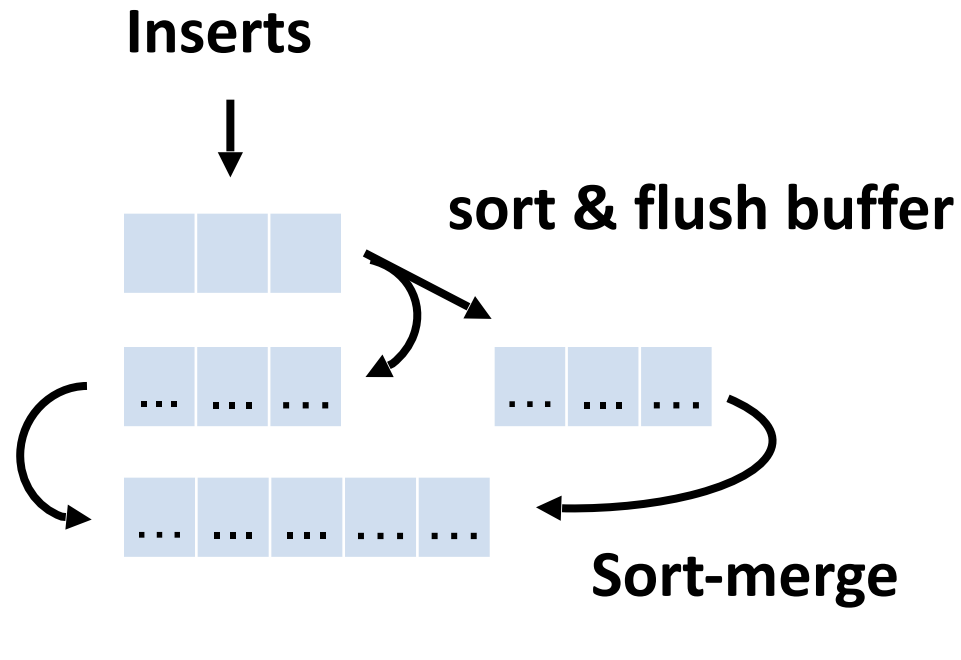
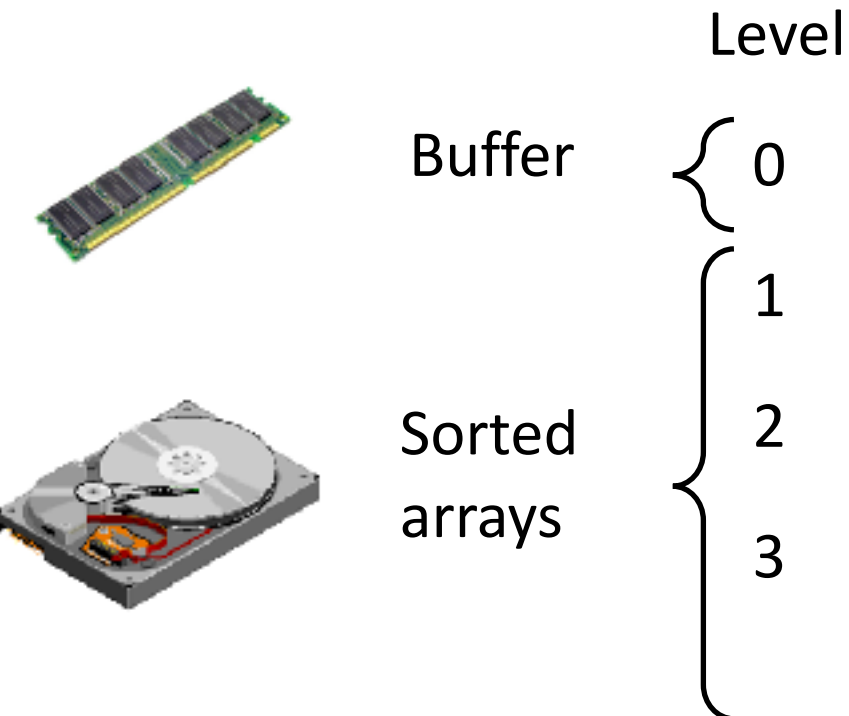
Basic LSM-tree

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Design principle #2:

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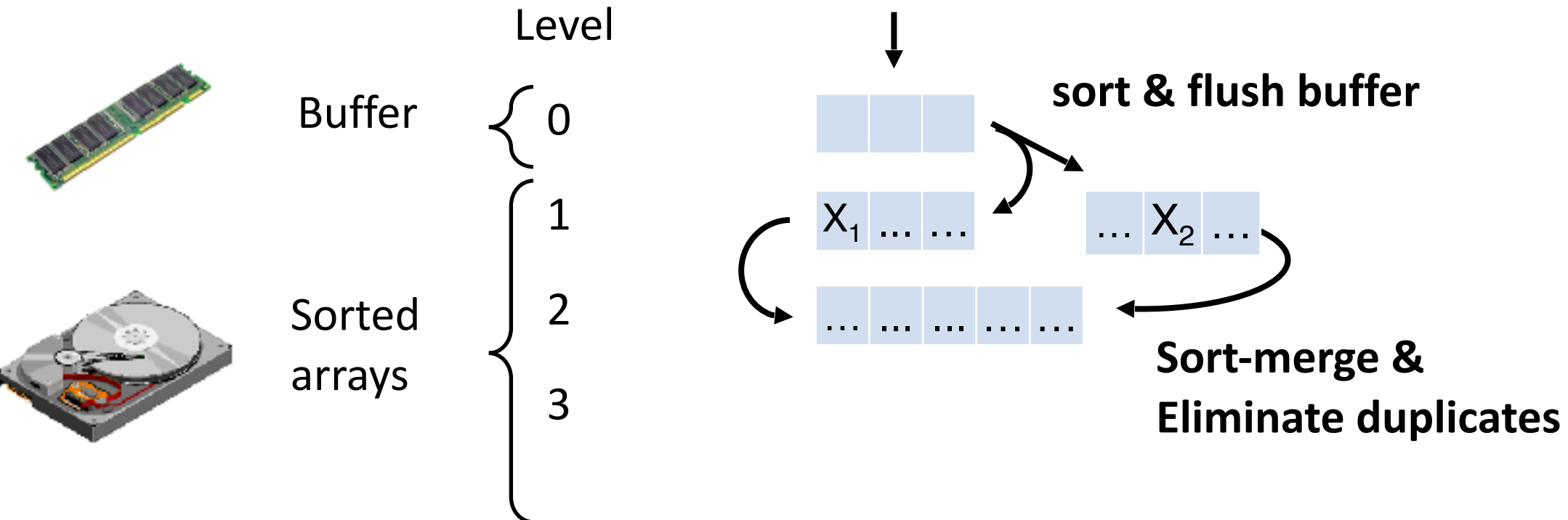
Basic LSM-tree

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Design principle #2:

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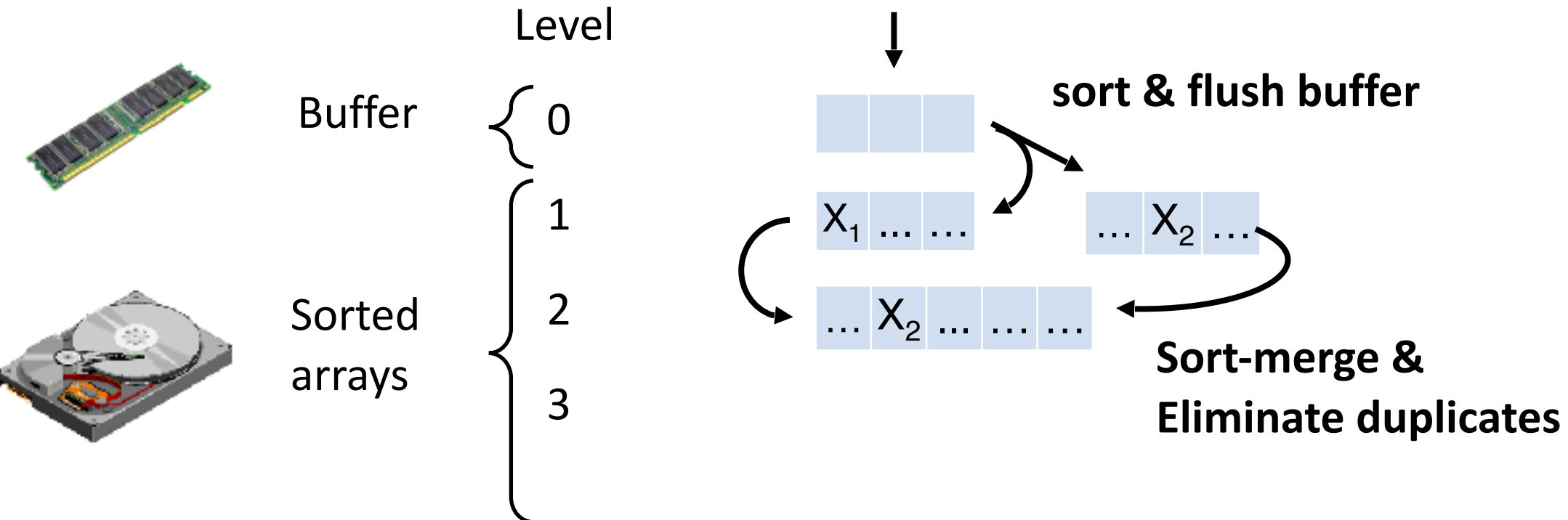
Basic LSM-tree

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Design principle #2:

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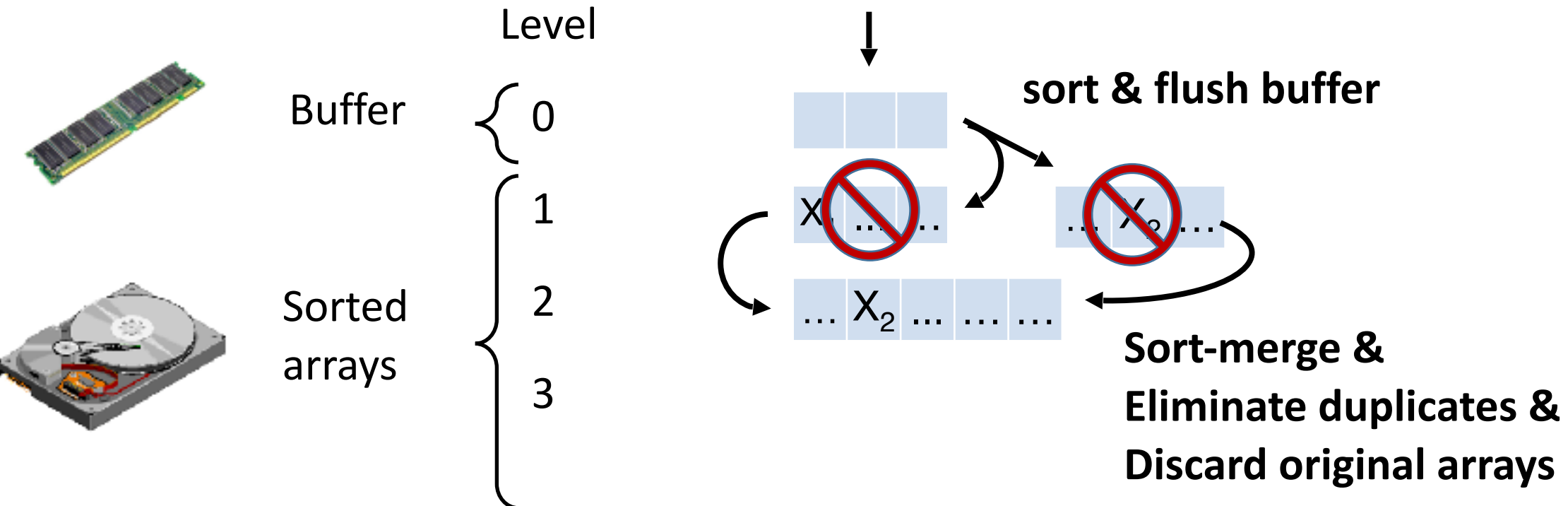
Basic LSM-tree

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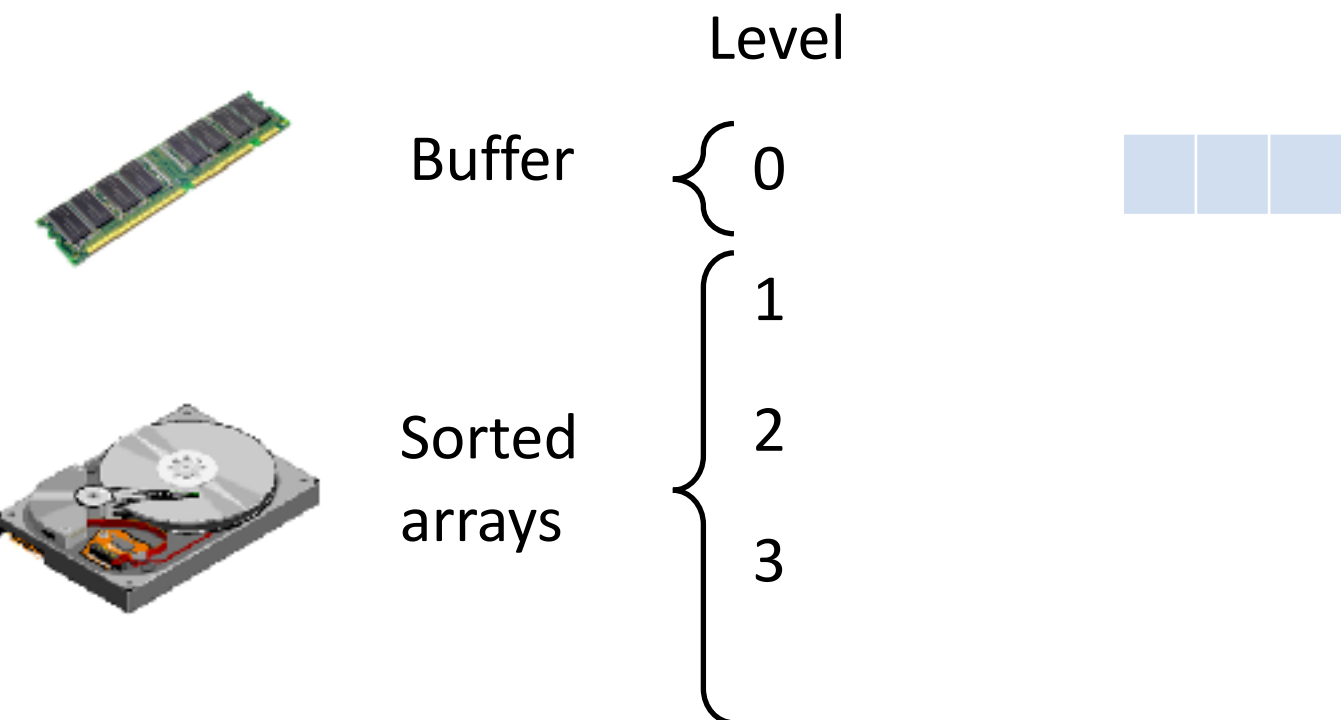
optimize for insertions by buffering

Design principle #2:

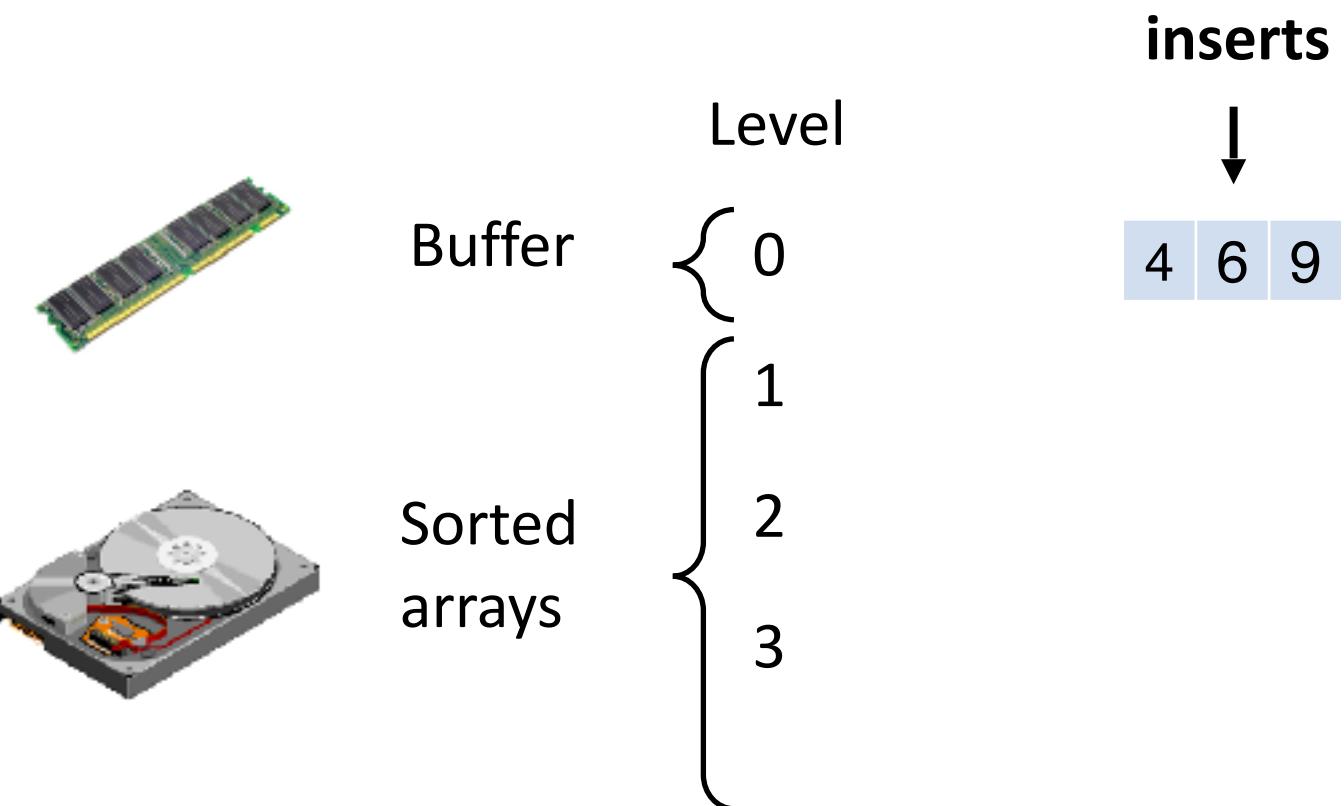
optimize for lookups by sort-merging SSTs



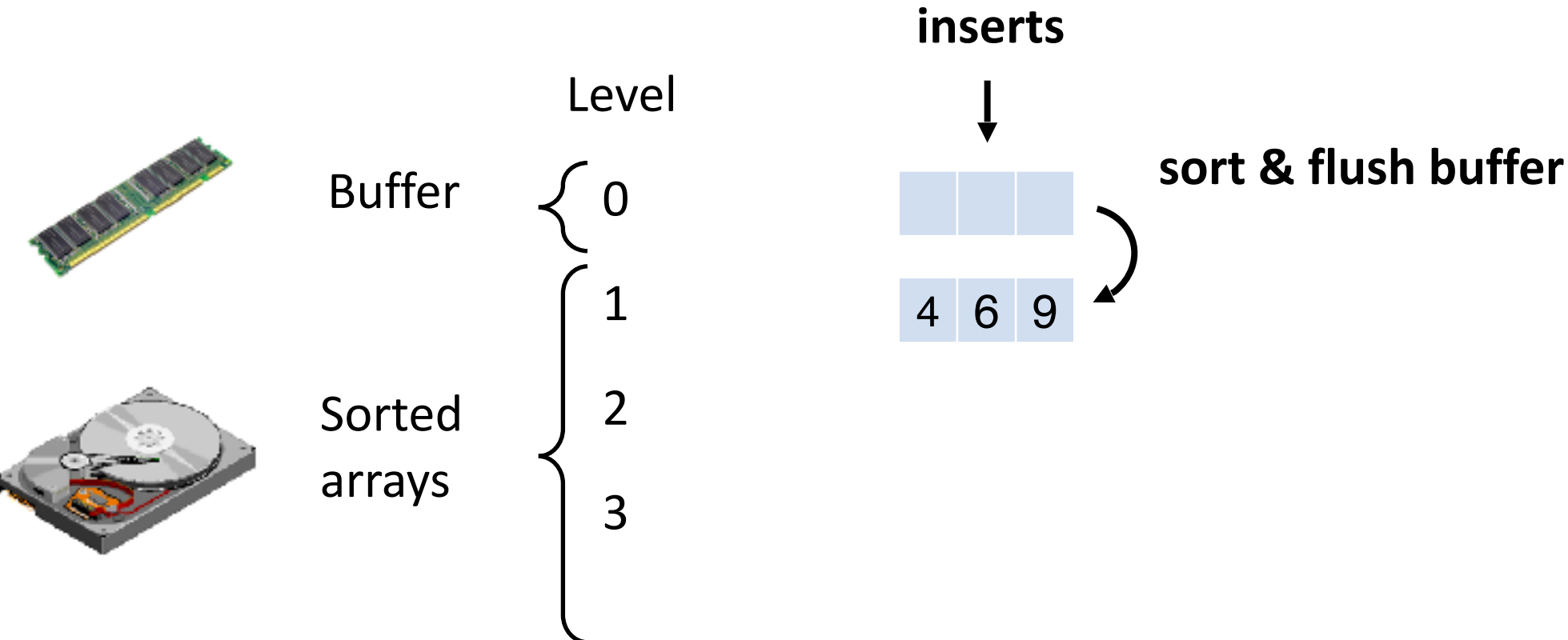
Basic LSM-tree – Example



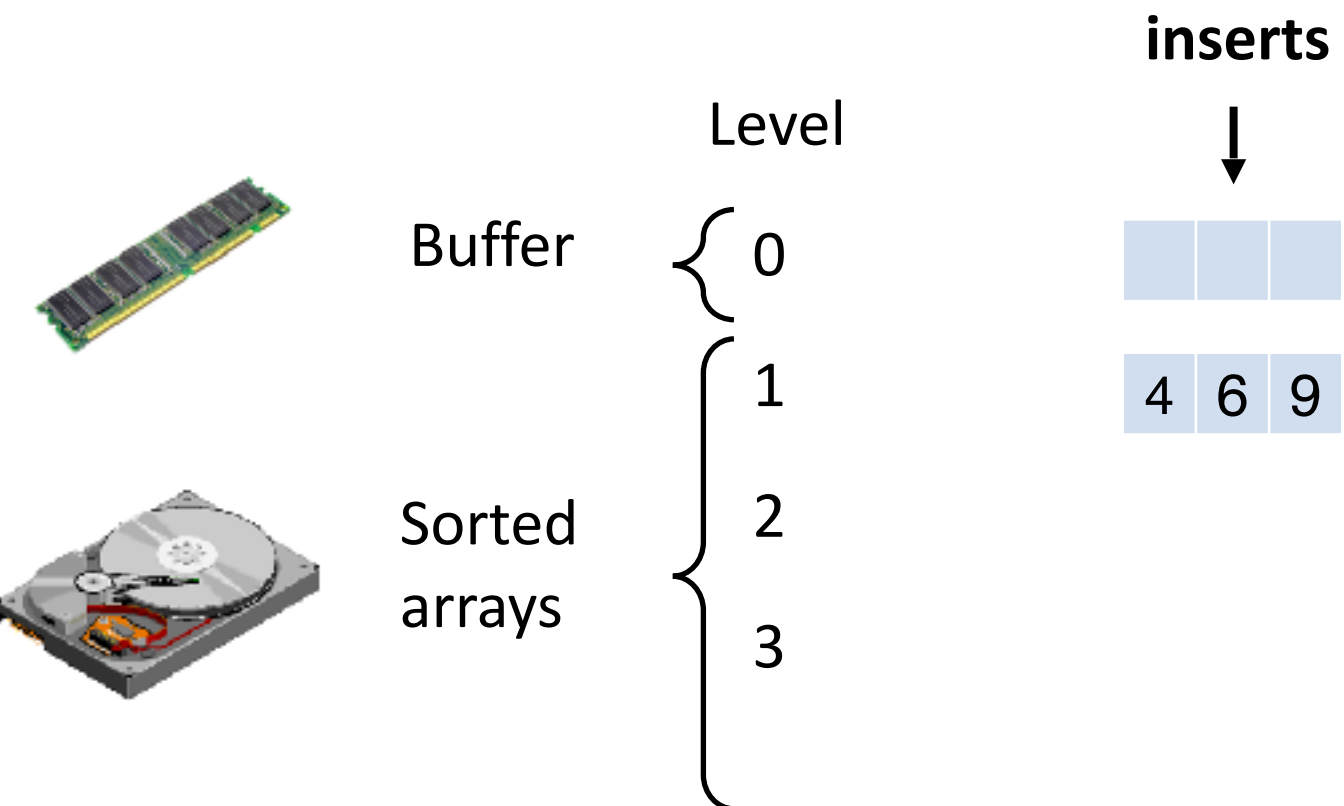
Basic LSM-tree – Example



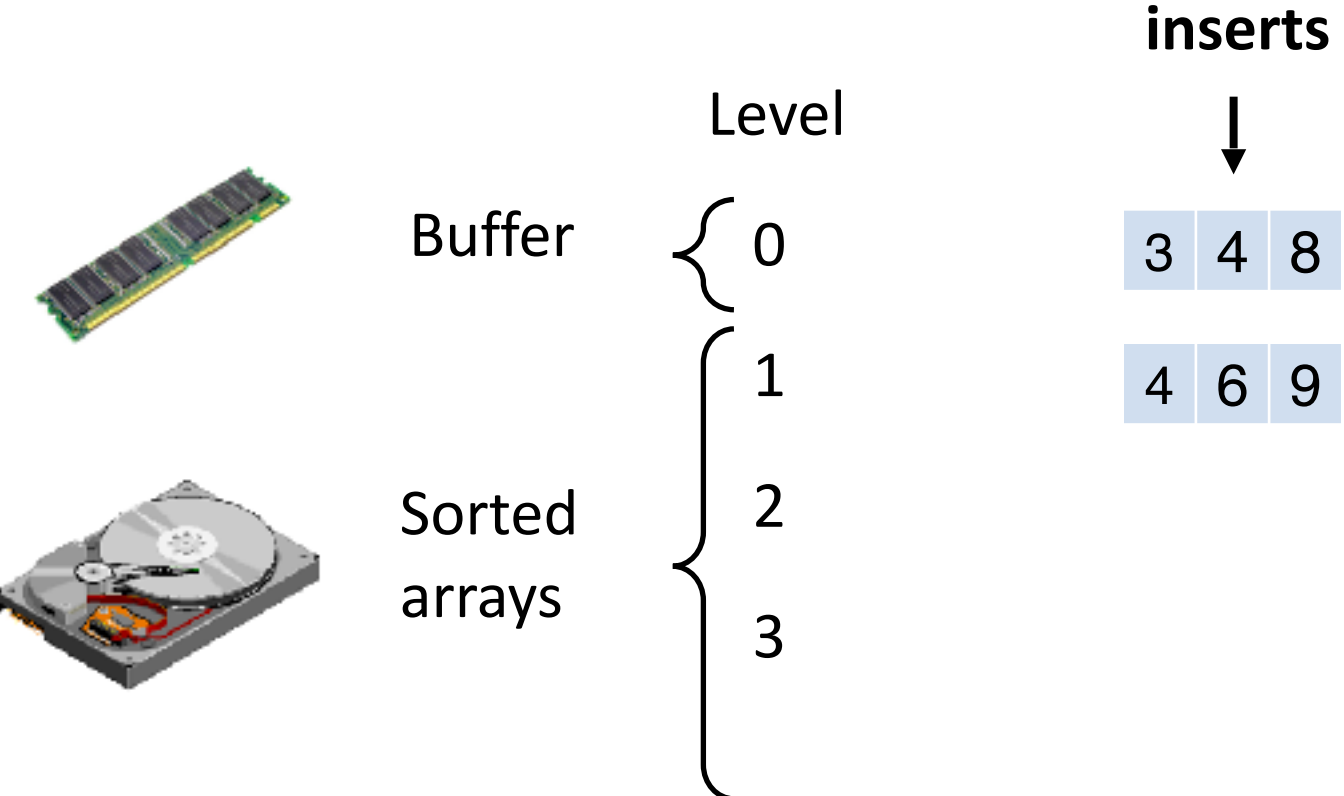
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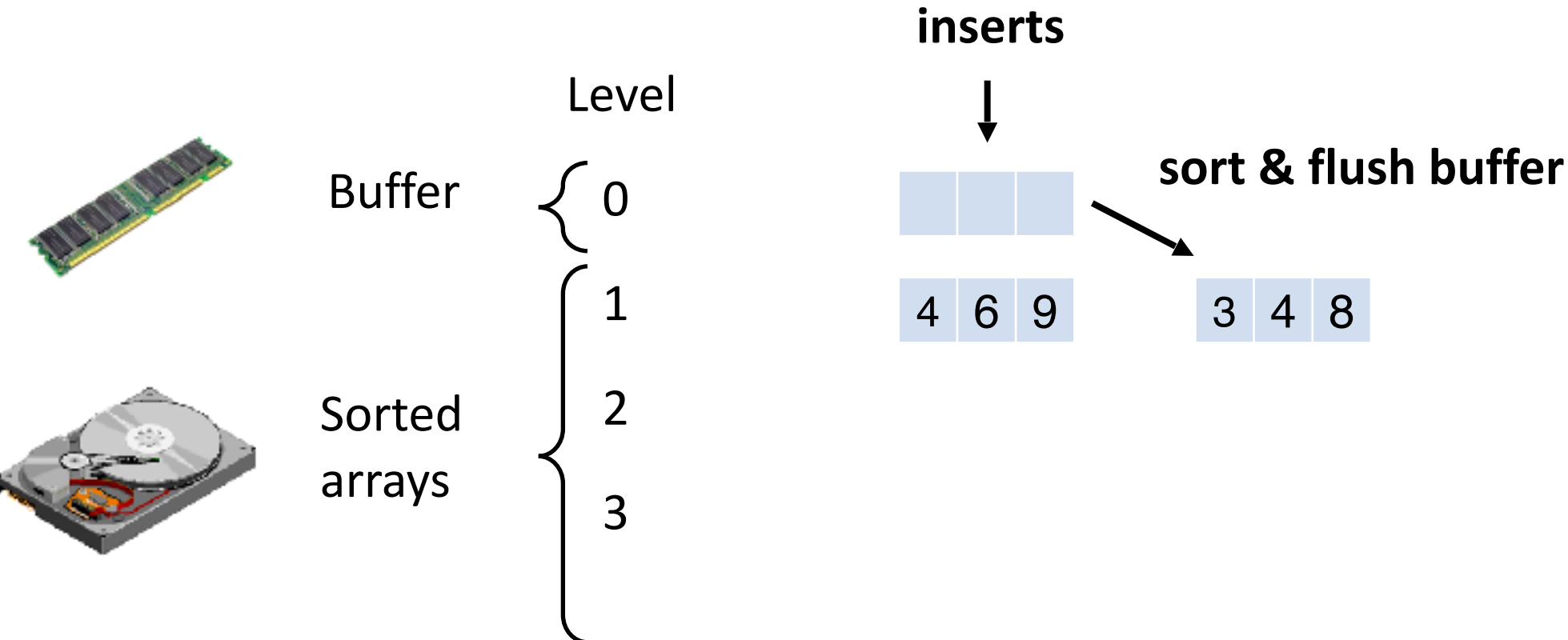
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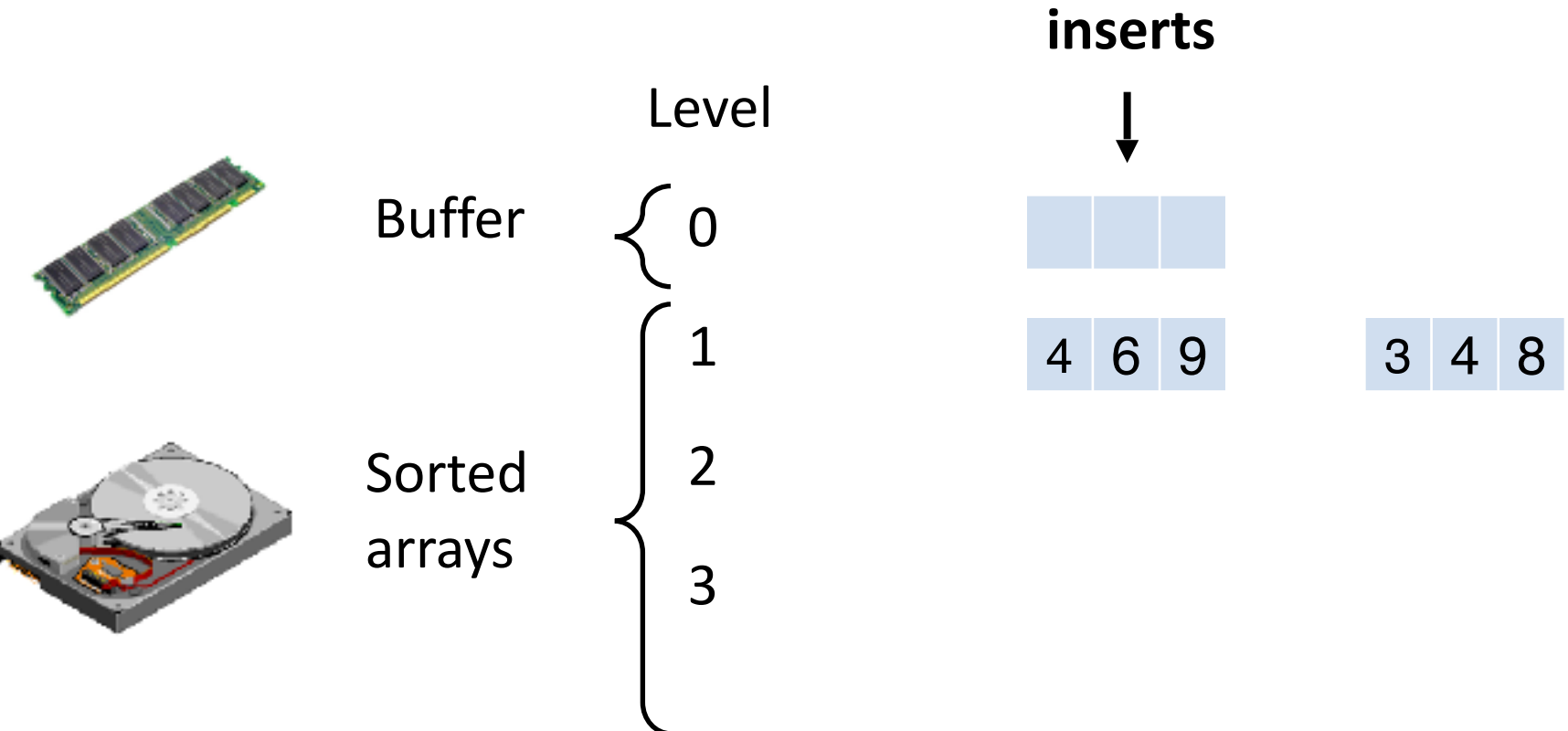
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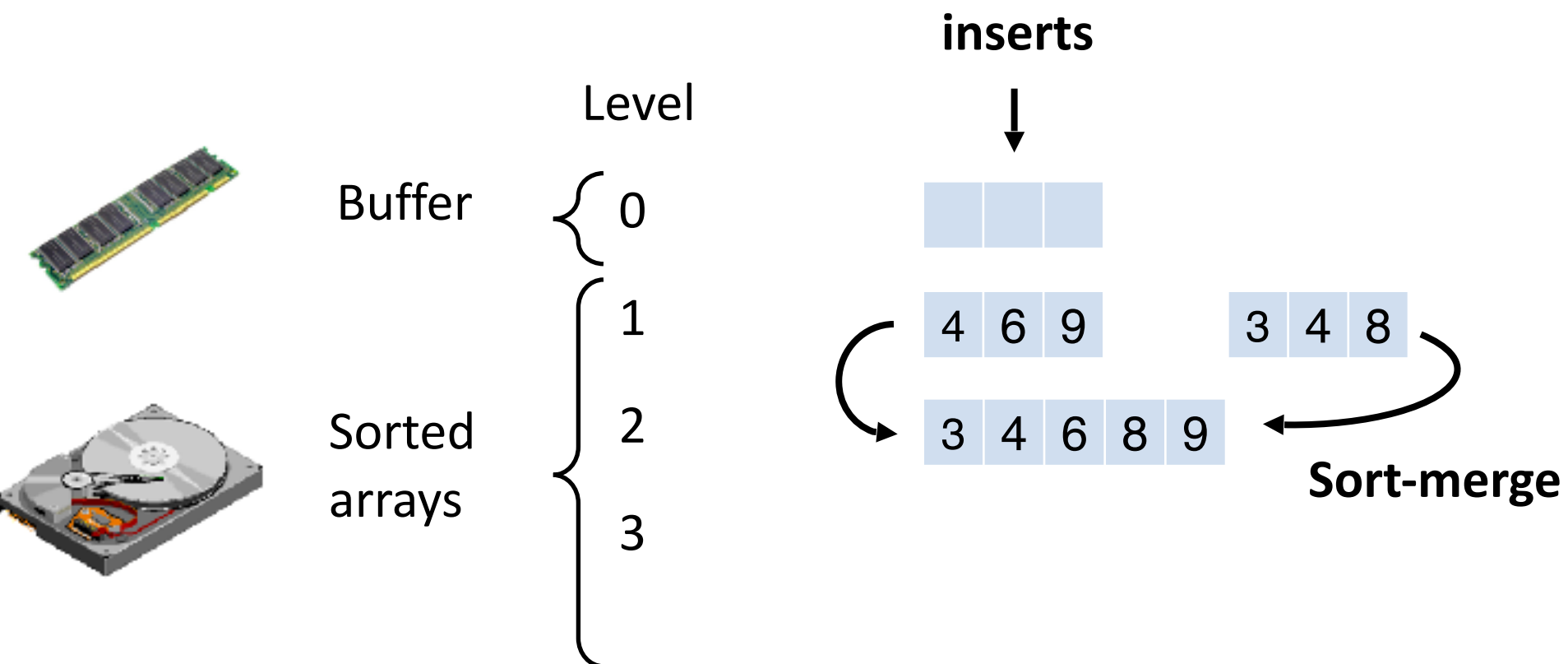
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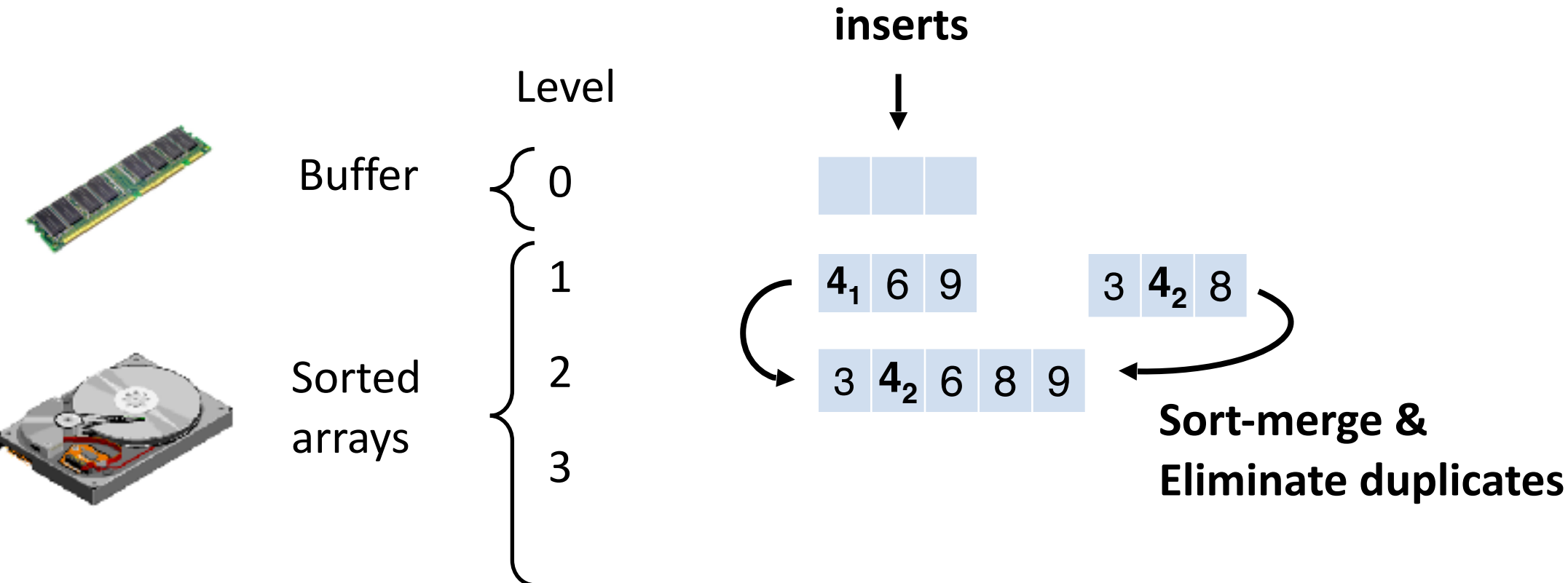
Basic LSM-tree – Example



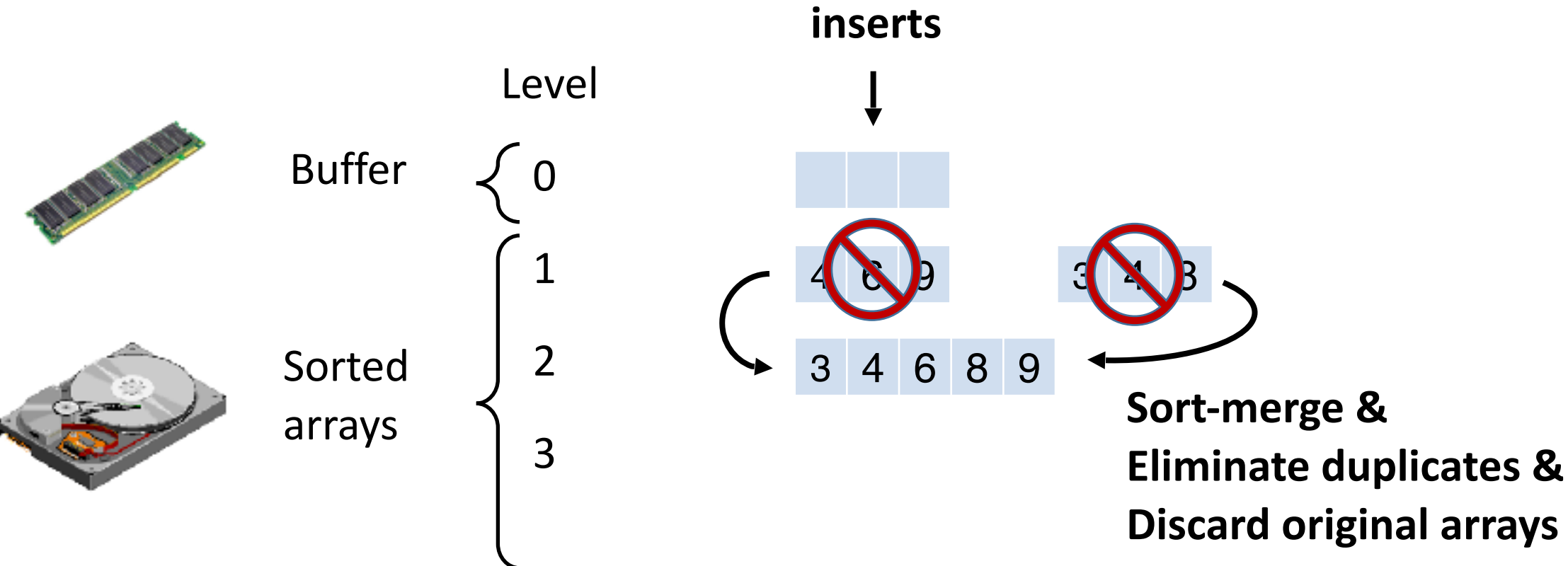
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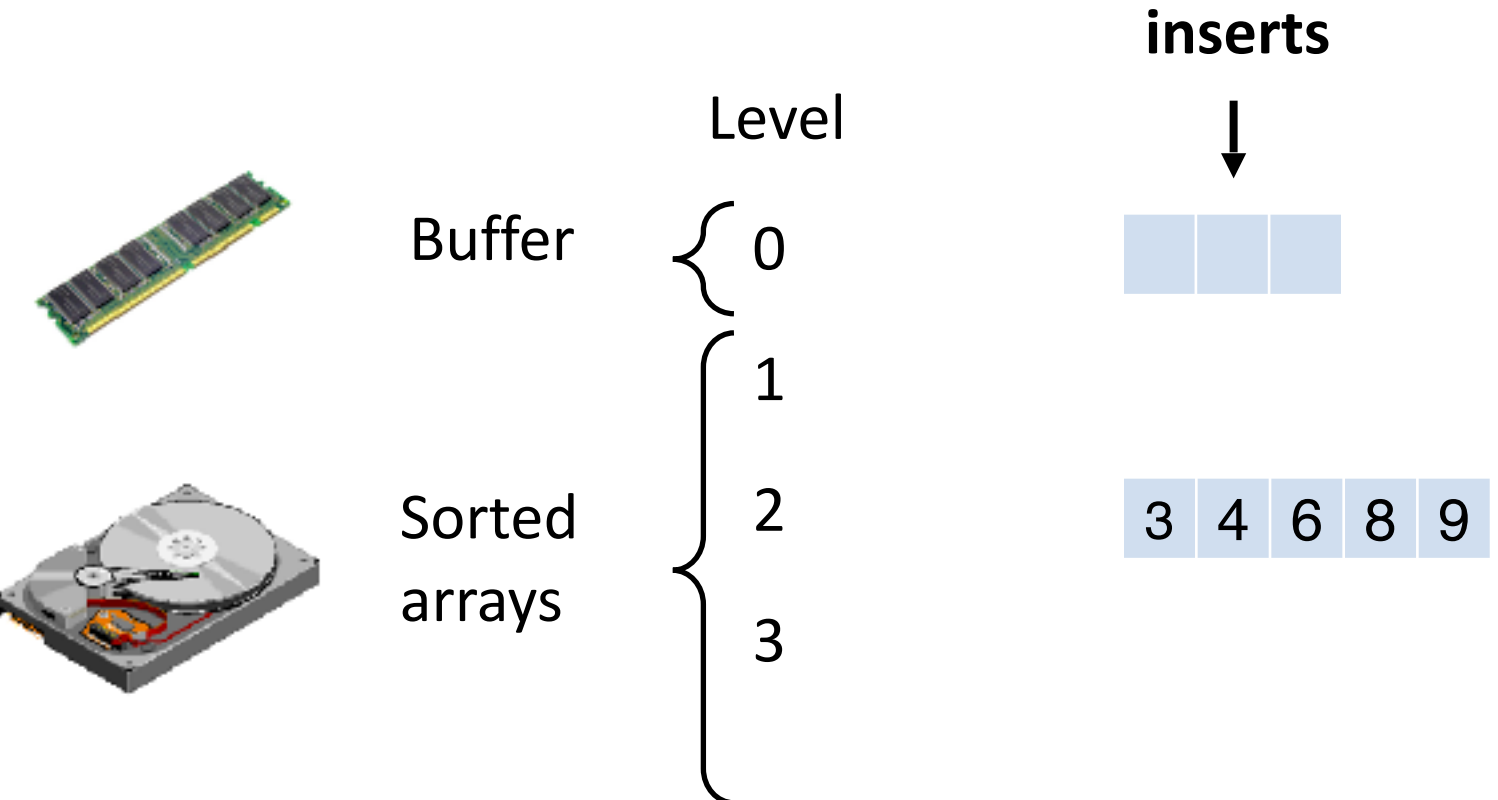
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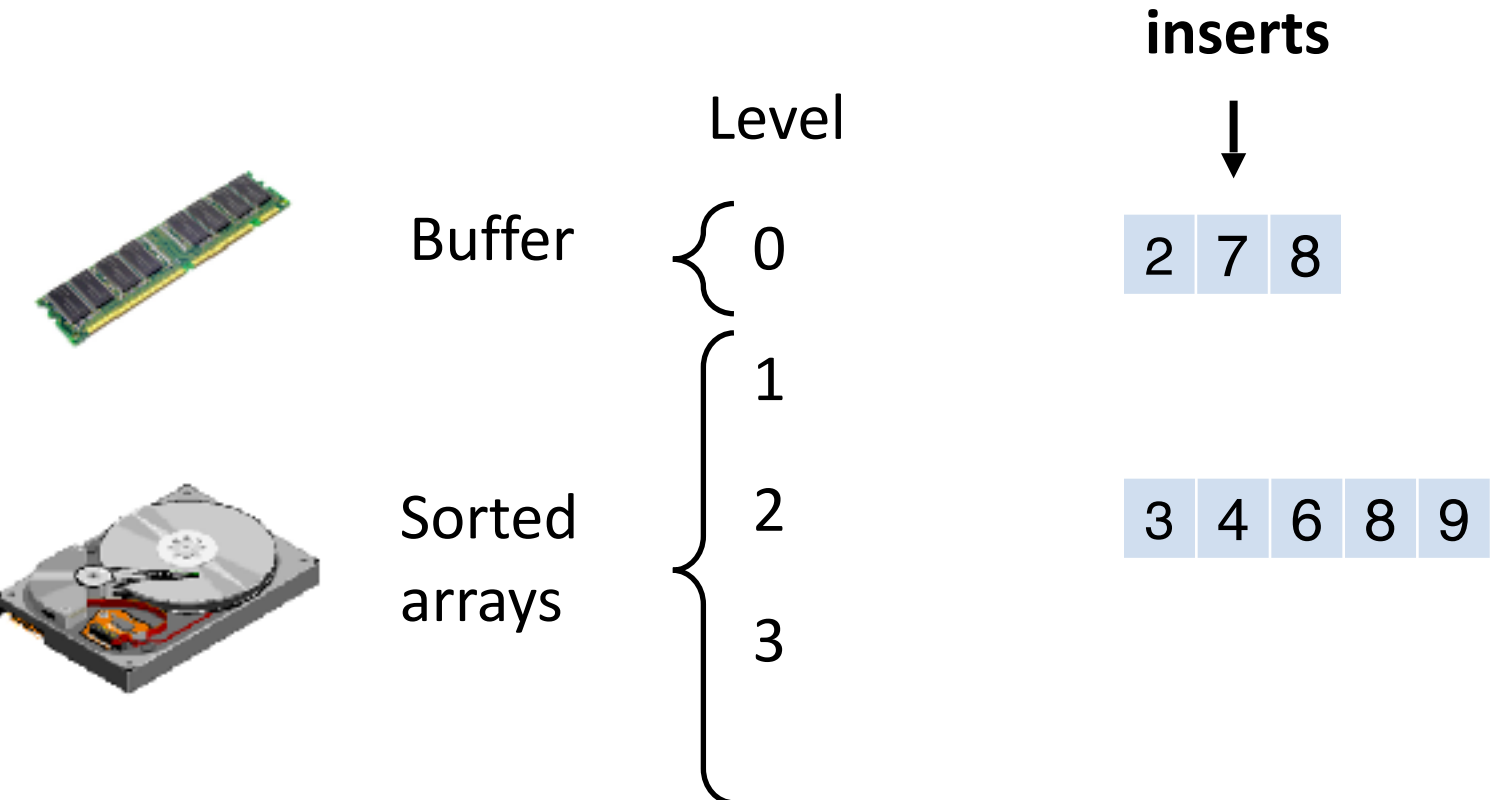
Basic LSM-tree – Example



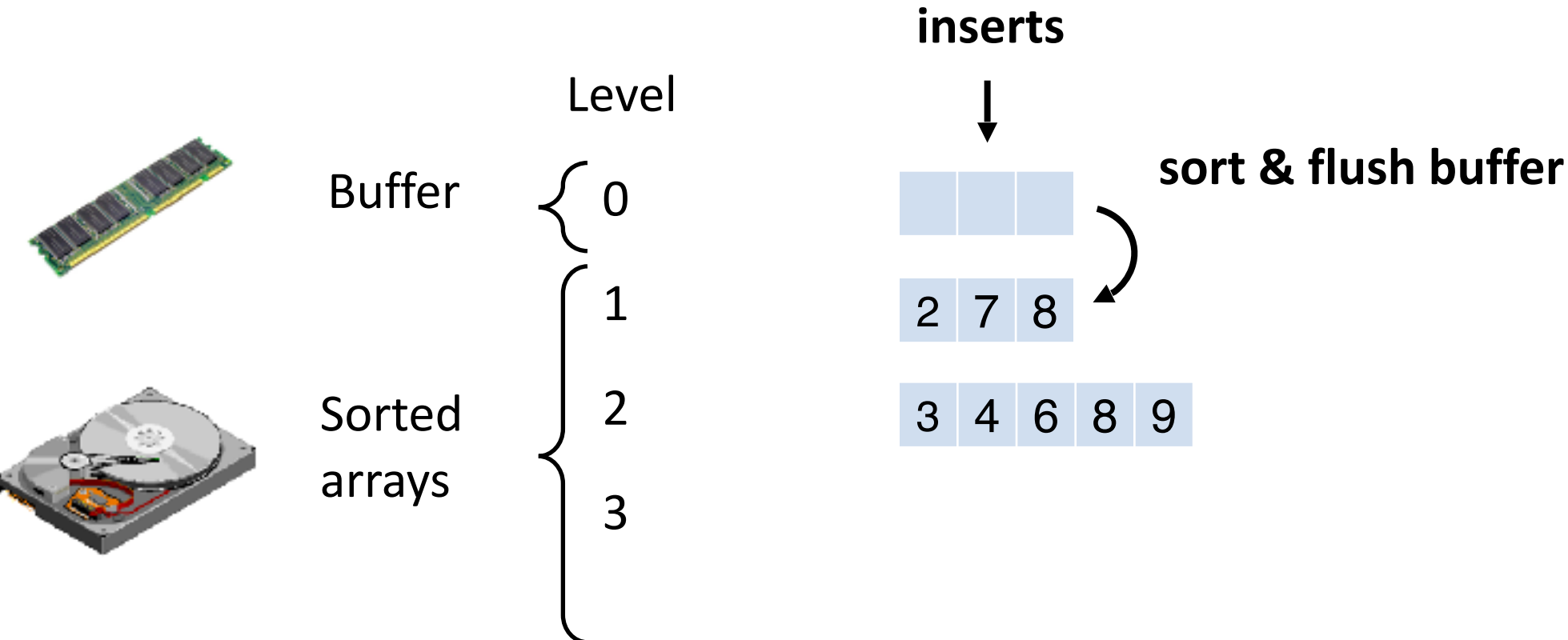
Basic LSM-tree – Example



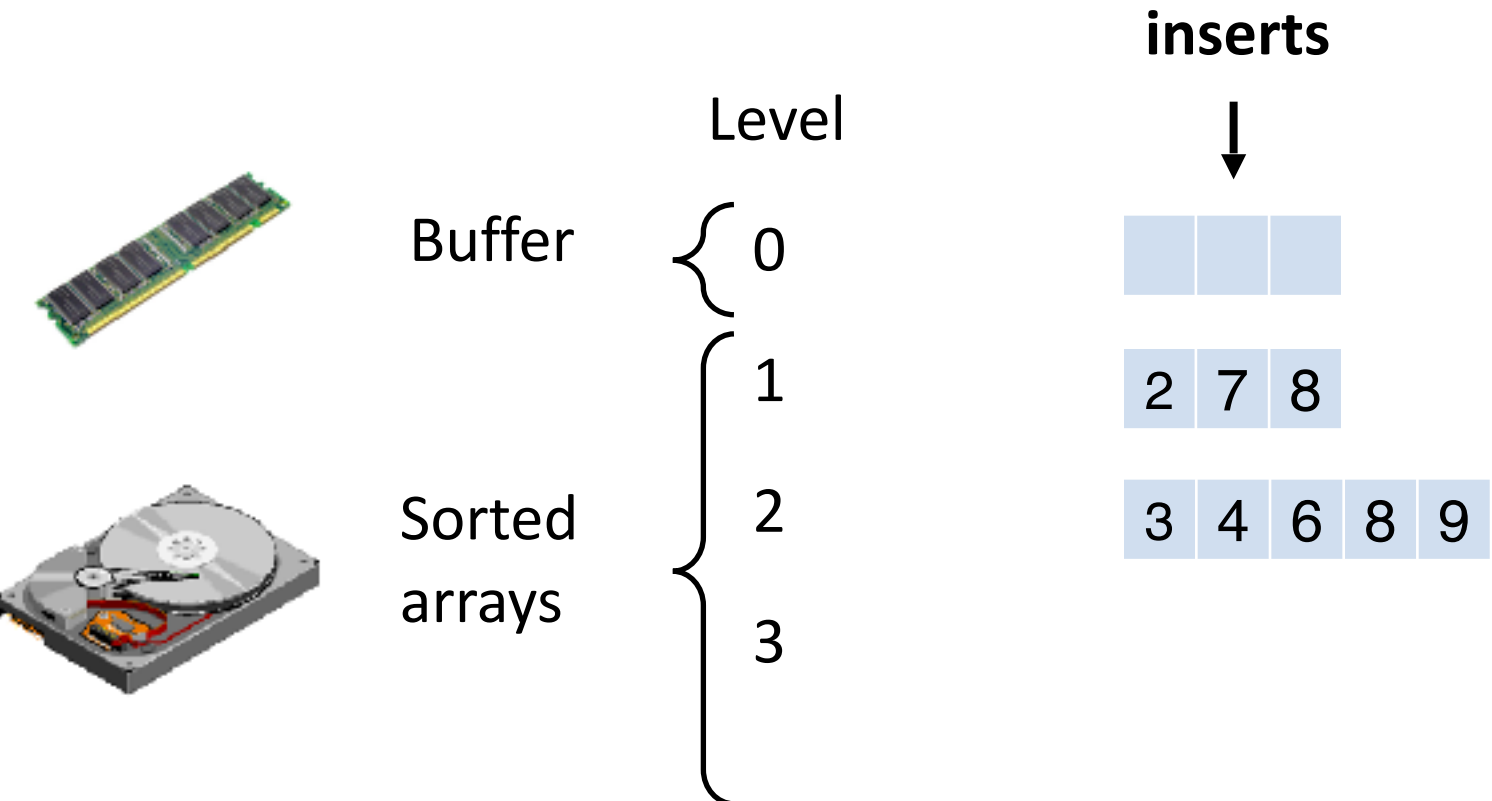
Basic LSM-tree – Example



Basic LSM-tree – Example

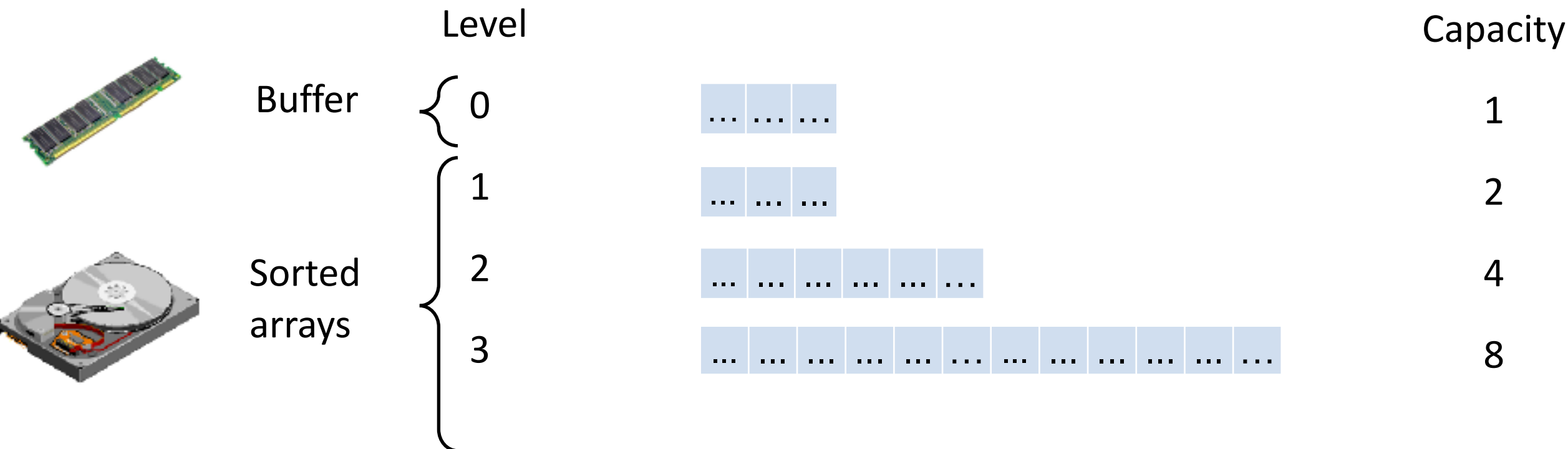


Basic LSM-tree – Example



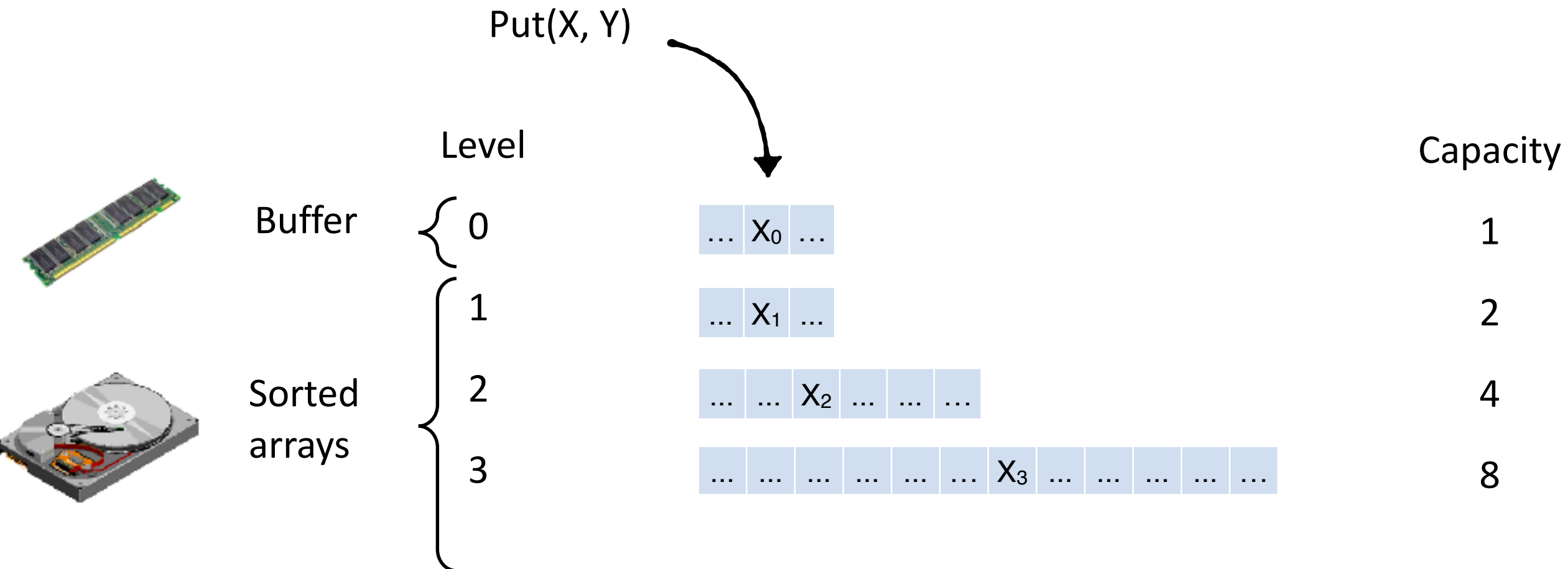
Basic LSM-tree

Levels have exponentially increasing capacities.



Basic LSM-tree - Updates

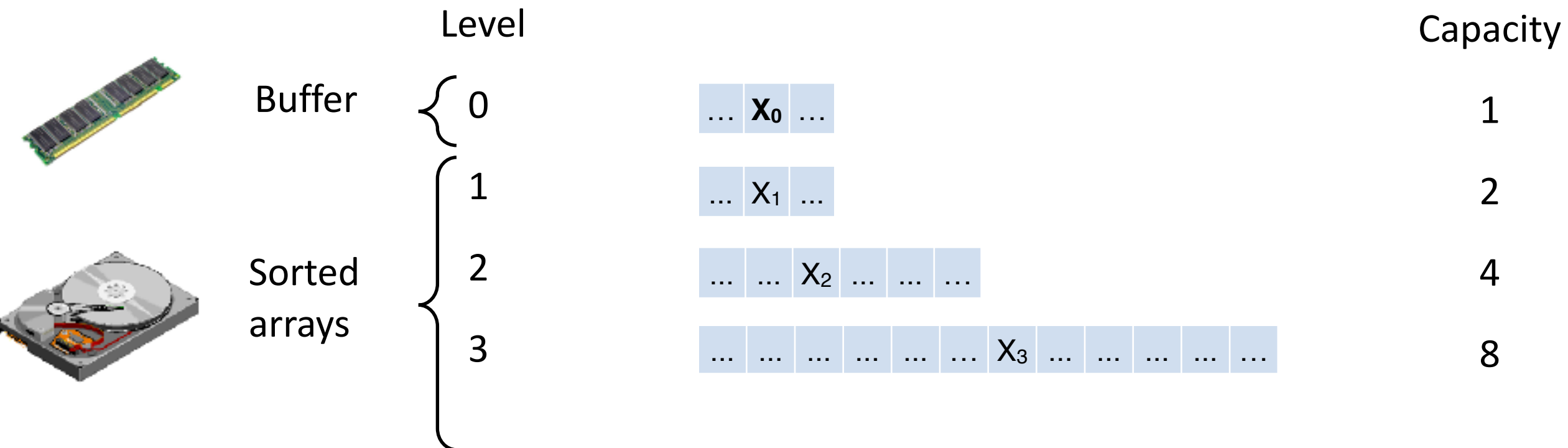
Can be made out-of-place through an insertion into the buffer



Basic LSM-tree - Updates

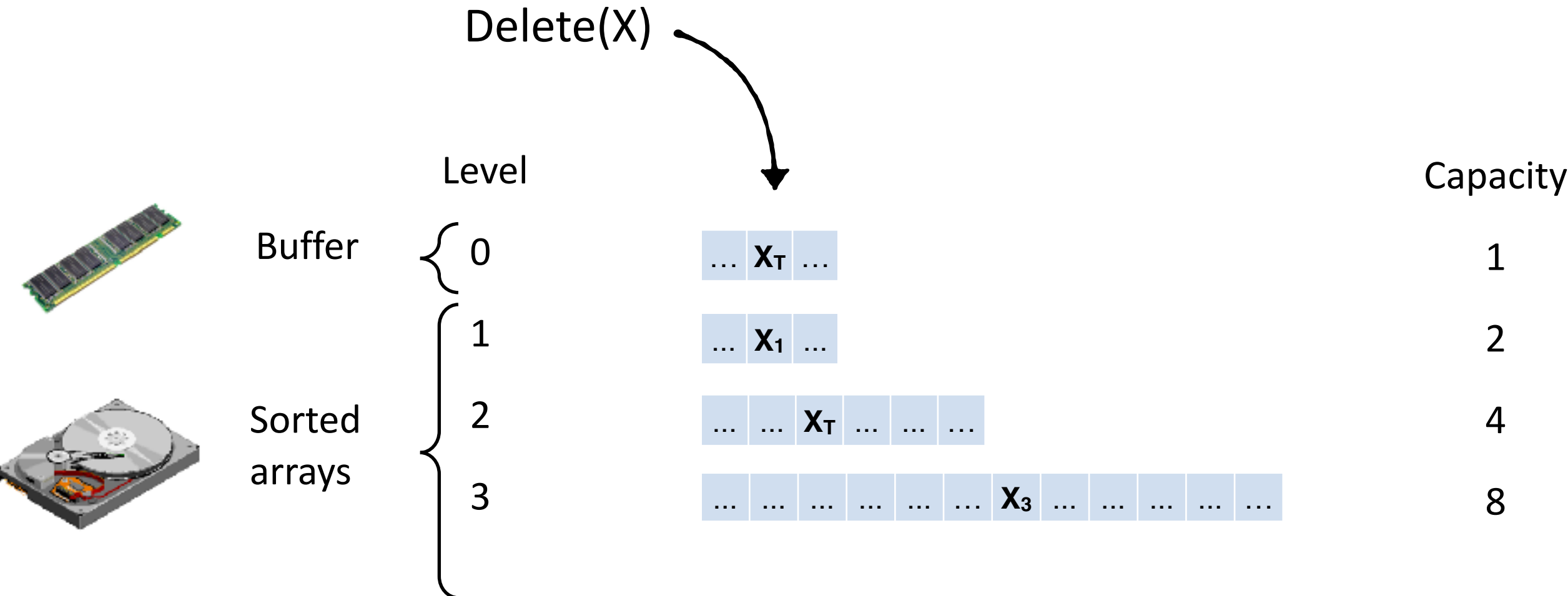
Can be made out-of-place through an insertion into the buffer

Only the most recent version counts and should be returned to users during queries.



Basic LSM-tree - Deletes

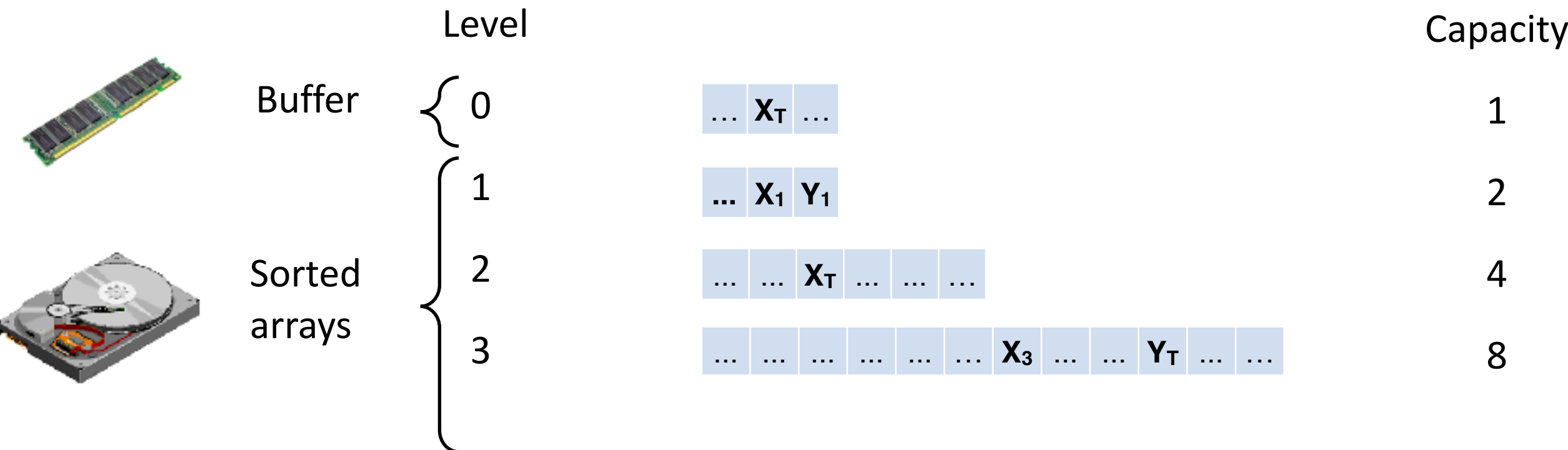
Delete an entry by inserting a tombstone



Basic LSM-tree - Deletes

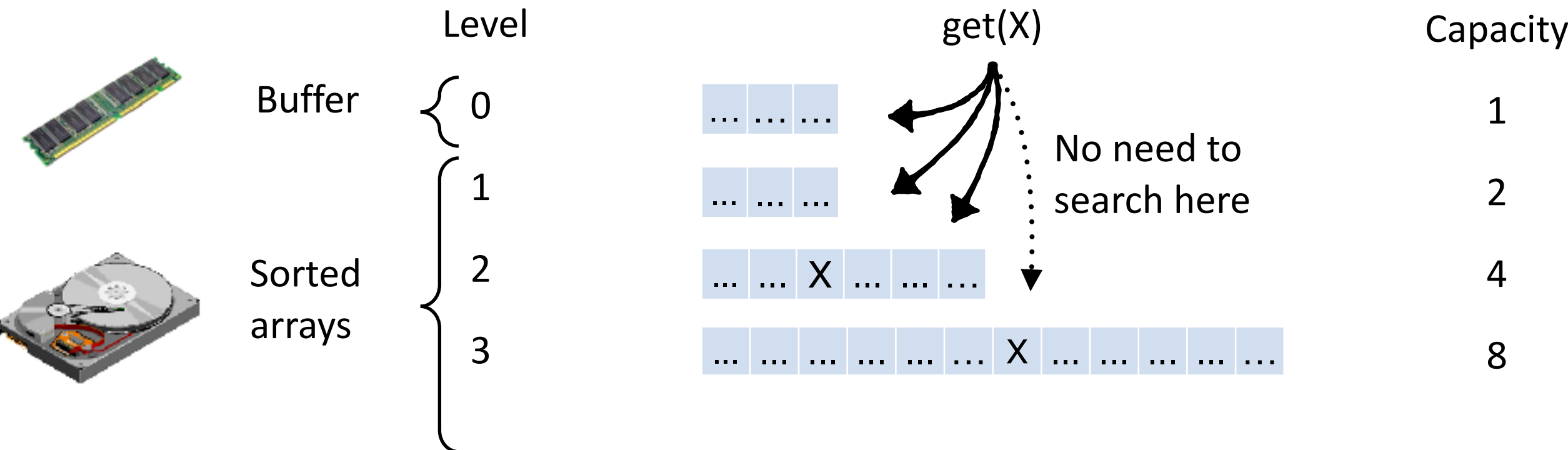
Delete an entry by inserting a tombstone

If the most recent version of an entry is a tombstone, it's considered deleted. (X is deleted by Y isn't in this example)



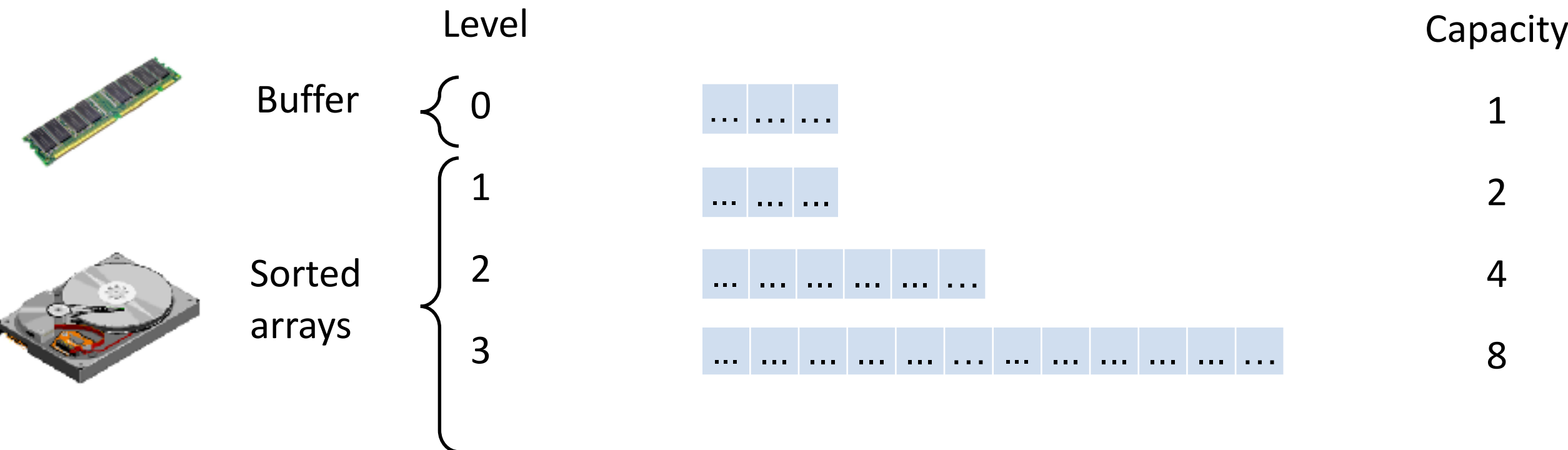
Basic LSM-tree – Get Queries

A get query searches the LSM-tree from smaller to larger levels. They stop when they find the first matching entry, as entries at larger levels are older and thus superseded.



Basic LSM-tree – Get Queries Cost

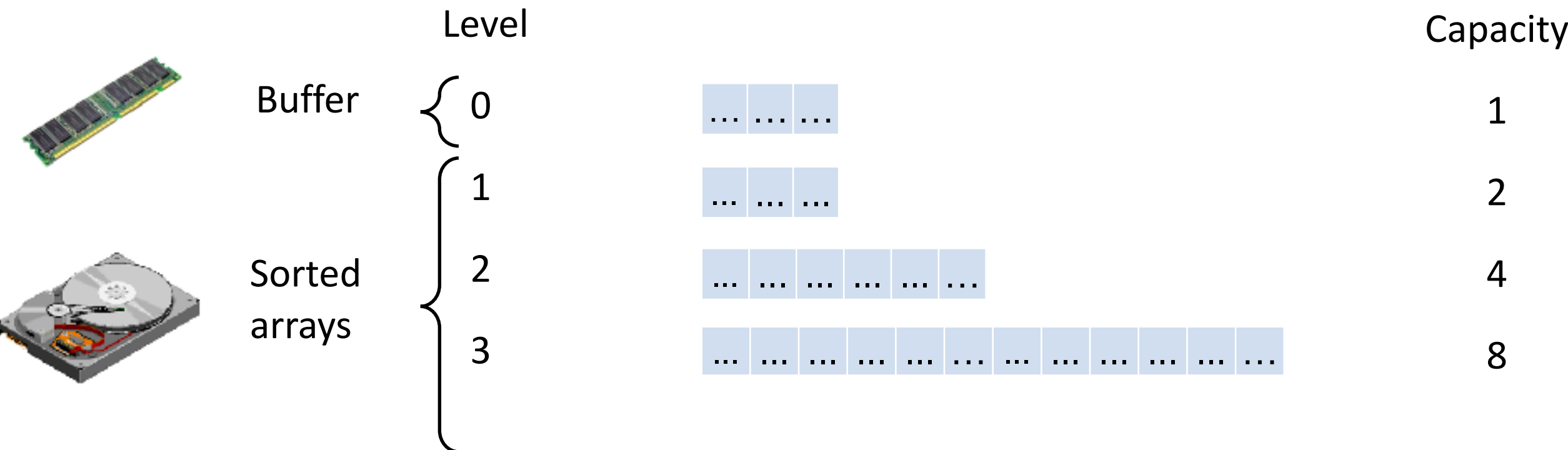
How many levels to search?



Basic LSM-tree – Get Queries Cost

How many levels to search?

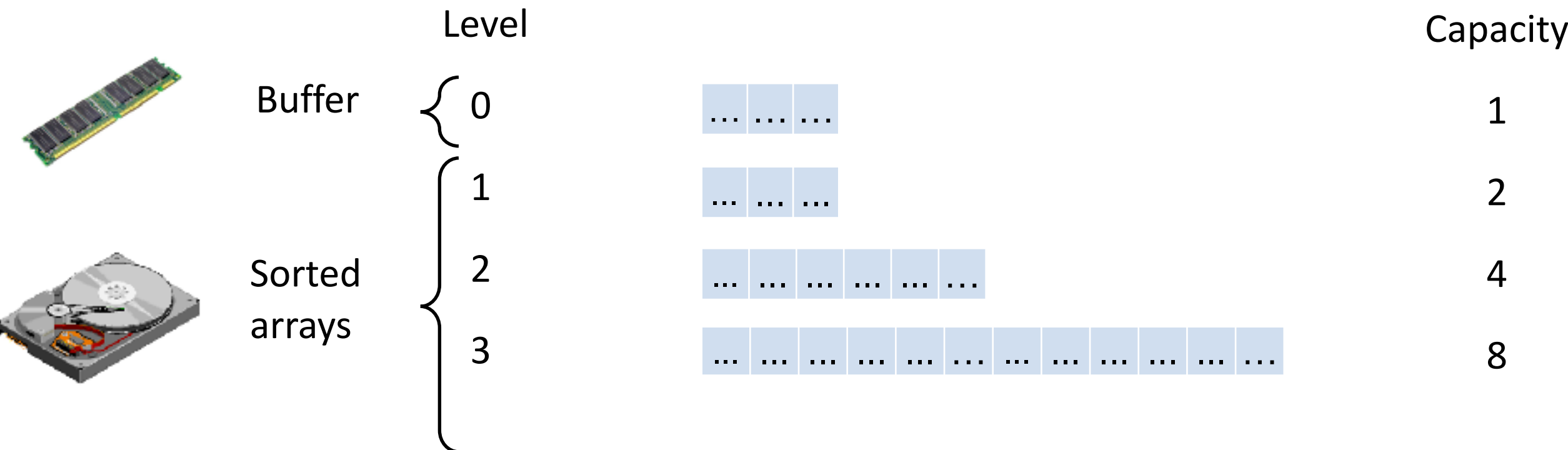
$O(\log_2 N/B)$



Basic LSM-tree – Get Queries Cost

How many levels to search? $O(\log_2 N/B)$

Cost per searching each level?



Basic LSM-tree – Get Queries Cost

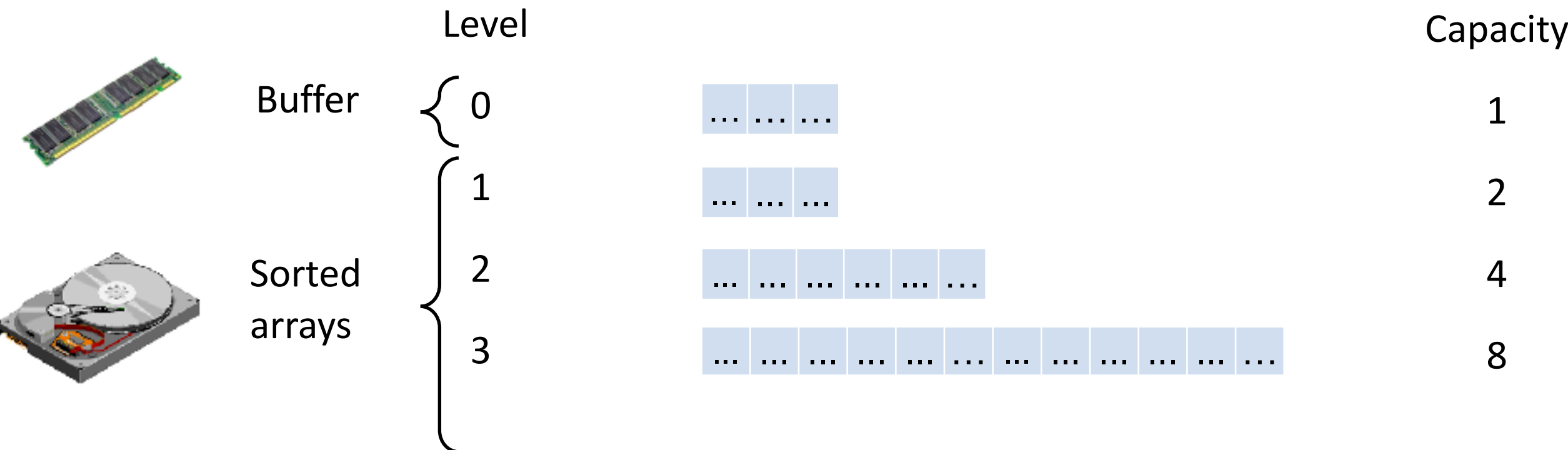
How many levels to search?

$O(\log_2 N/B)$

Cost per searching each level?

$O(\log_2 N/B)$

w. binary search

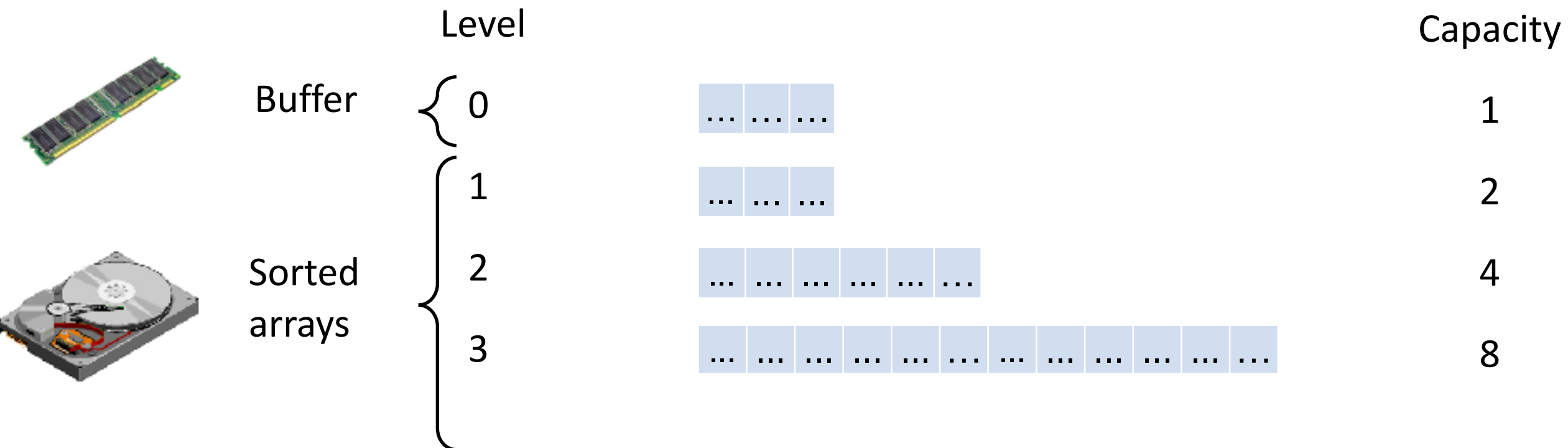


Basic LSM-tree – Get Queries Cost

How many levels to search? $O(\log_2 N/B)$

Cost per searching each level? $O(\log_2 N/B)$

Total search cost: $O(\log_2(N/B)^2)$



Basic LSM-tree – Get Queries Cost

We can do slightly better by structuring each file (SST) as a static B-tree.
How would this impact search cost?

Total search cost: $O(\log_2(N/B)^2)$



SST static B-tree structure

Basic LSM-tree – Get Queries Cost

We can do slightly better by structuring each file (SST) as a static B-tree.
How would this impact search cost?

Total search cost:

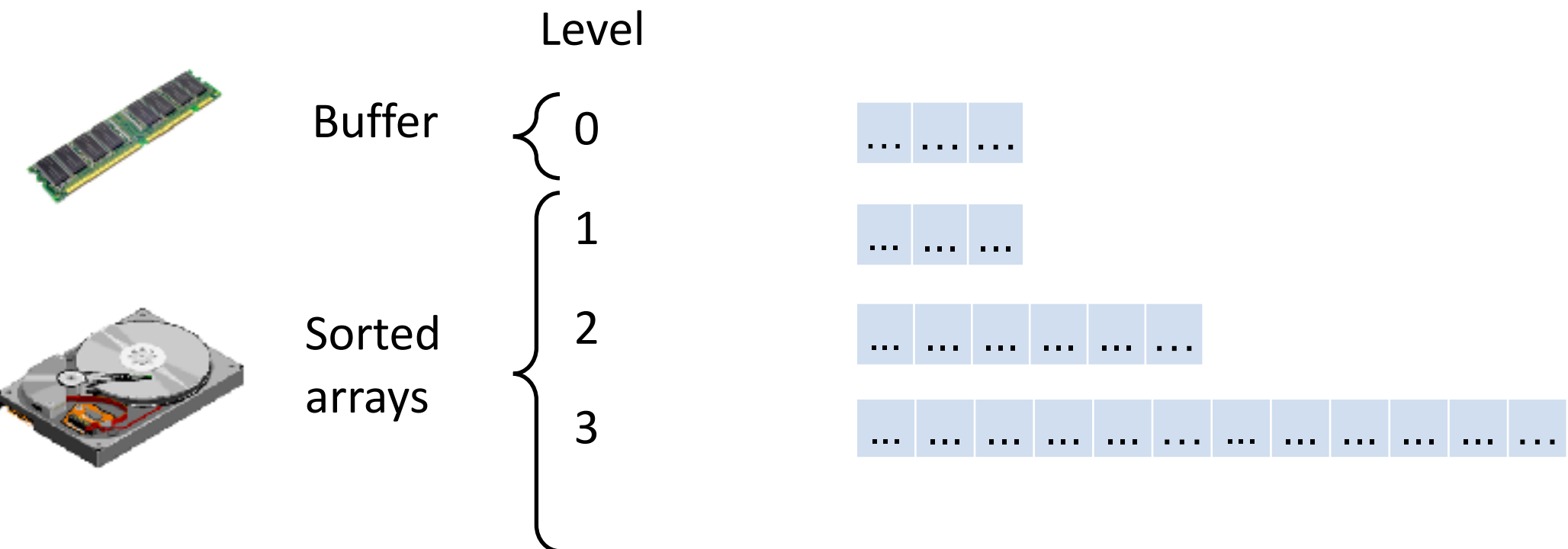
$$O(\log_2(N/B) * \log_B N)$$



SST static B-tree structure

Basic LSM-tree – Scan Queries

Return most recent version of each entry in the range across entire tree.

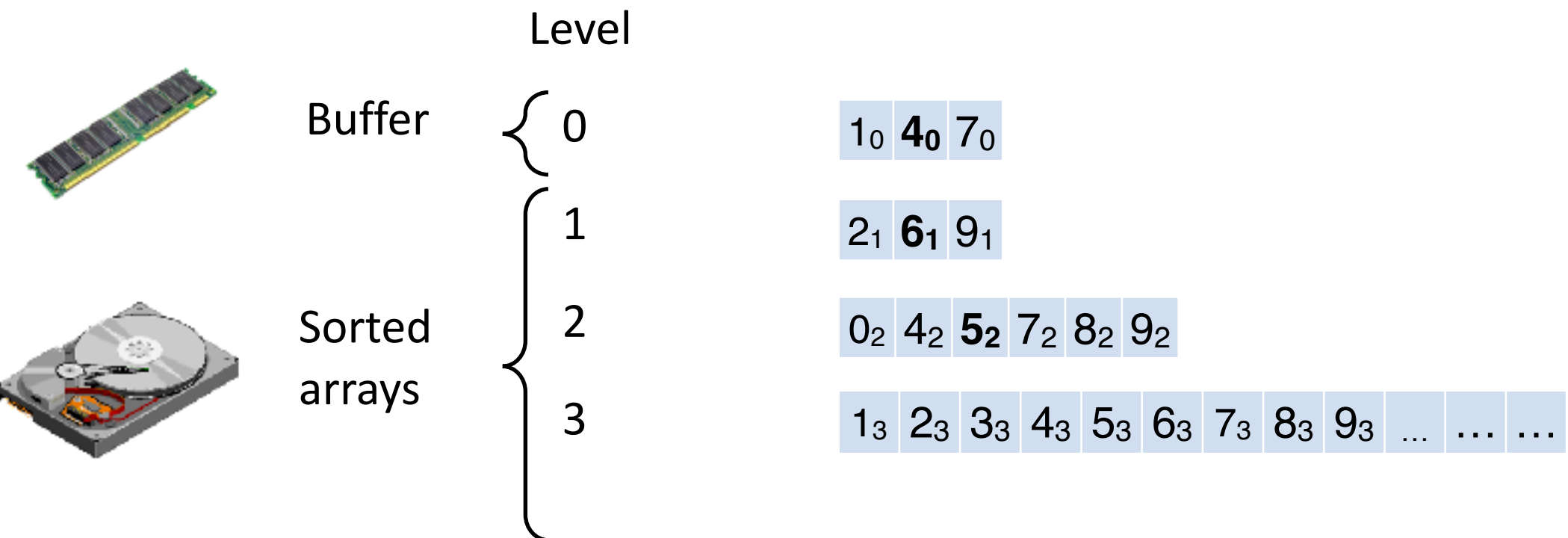


Basic LSM-tree – Scan Queries

Return most recent version of each entry in the range across entire tree.

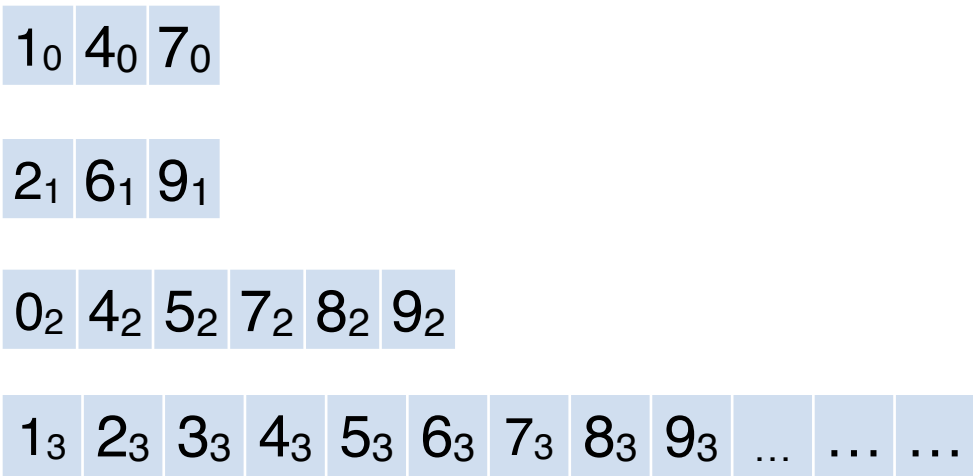
e.g., Scan(4, 6)

Expected output: $4_0\ 5_2\ 6_1$

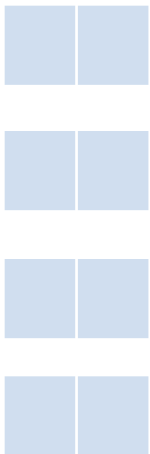


Basic LSM-tree – Scan Queries

- 1. Allocate an in-memory buffer (>1 page) for each level



LSM-tree in storage

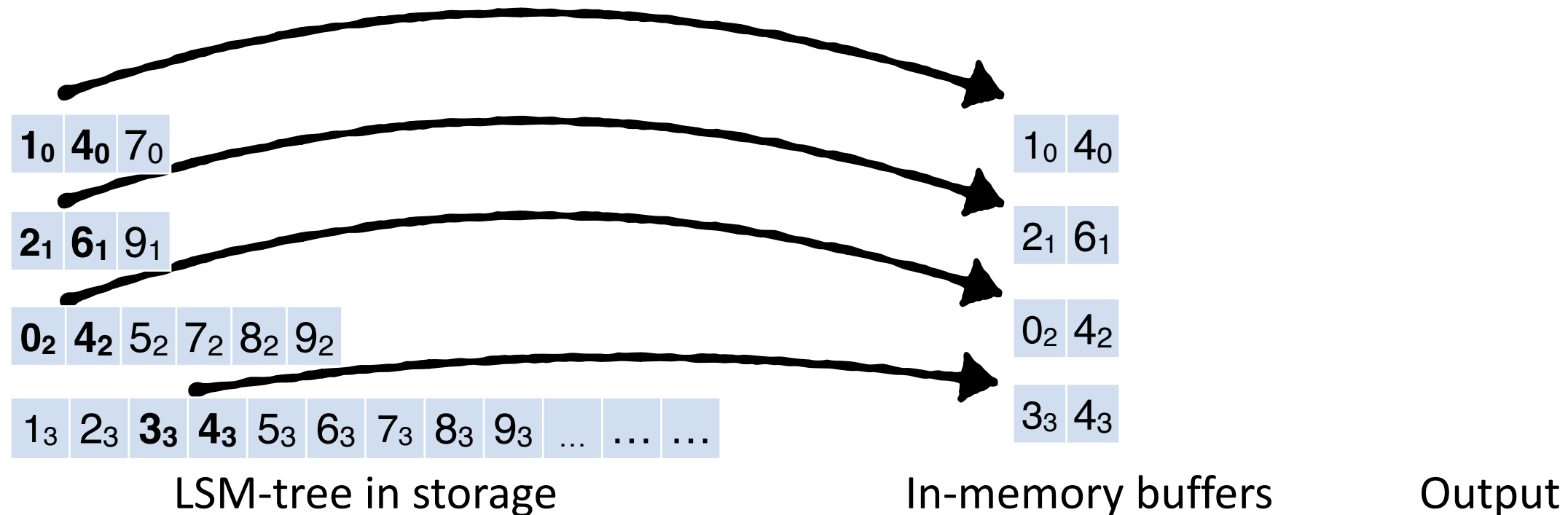


In-memory buffers

Output

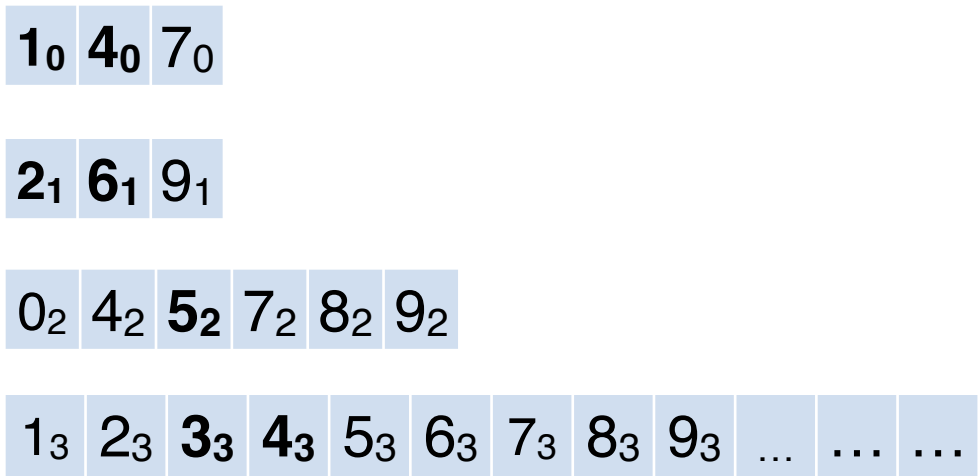
Basic LSM-tree – Scan Queries

- 1. Allocate an in-memory buffer (>1 page) for each level
- 2. Search for start of key range at each level



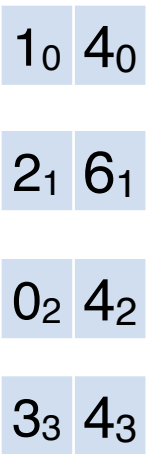
Basic LSM-tree – Scan Queries

- 1. Allocate an in-memory buffer (>1 page) for each level
- 2. Search for start of key range at each level
- 3. Initialize counter to smallest key in range



LSM-tree in storage

Counter: 4



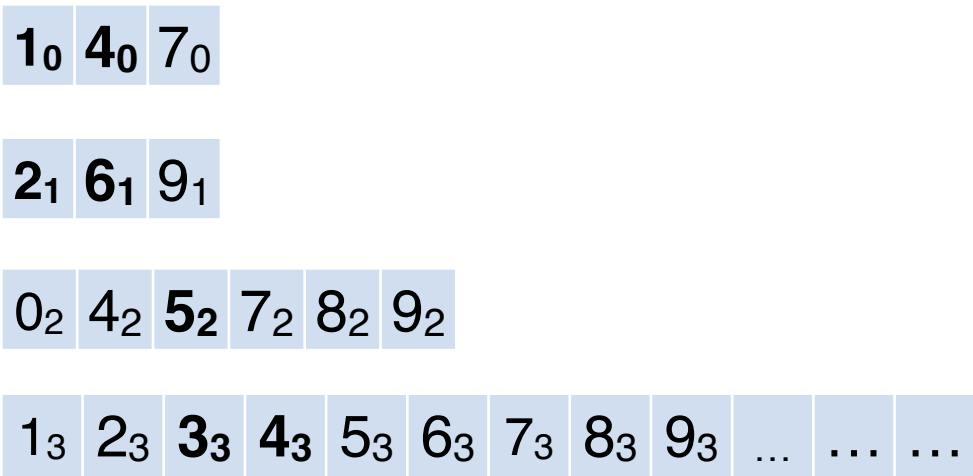
In-memory buffers

Output

Basic LSM-tree – Scan Queries

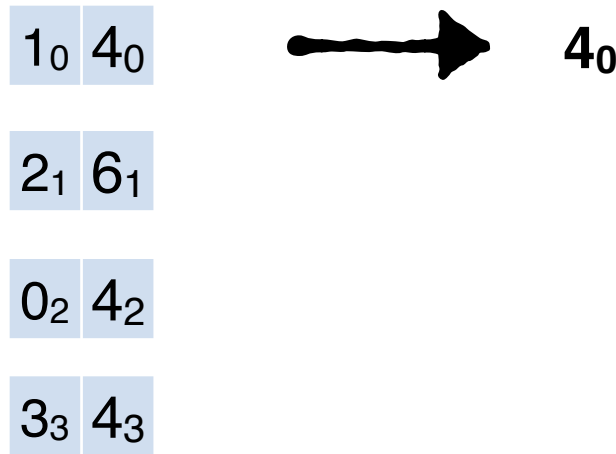
Loop until counter passes end of range

4. Bring youngest matching entry to output



LSM-tree in storage

Counter: 4



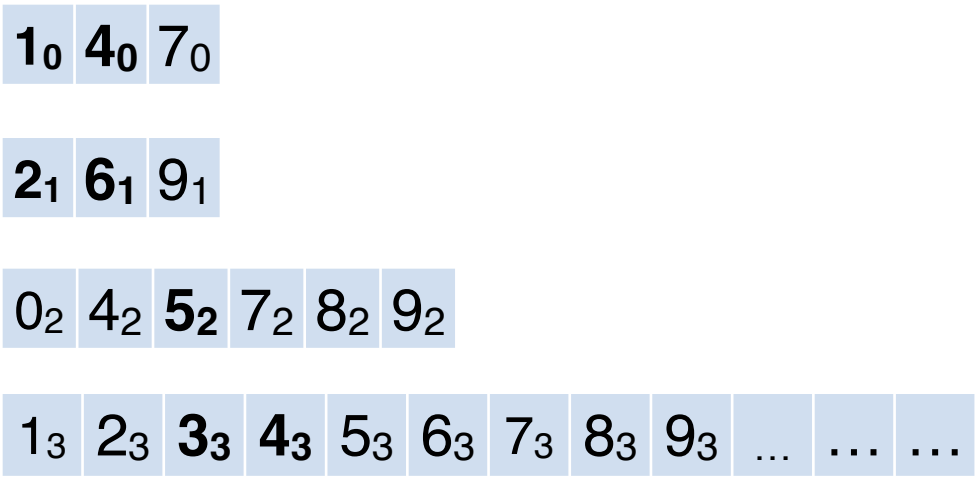
In-memory buffers

Output

Basic LSM-tree – Scan Queries

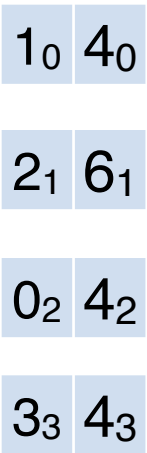
Loop until counter passes end of range

- 4. Bring youngest matching entry to output
- 5. Increment counter



LSM-tree in storage

Counter: 5



In-memory buffers

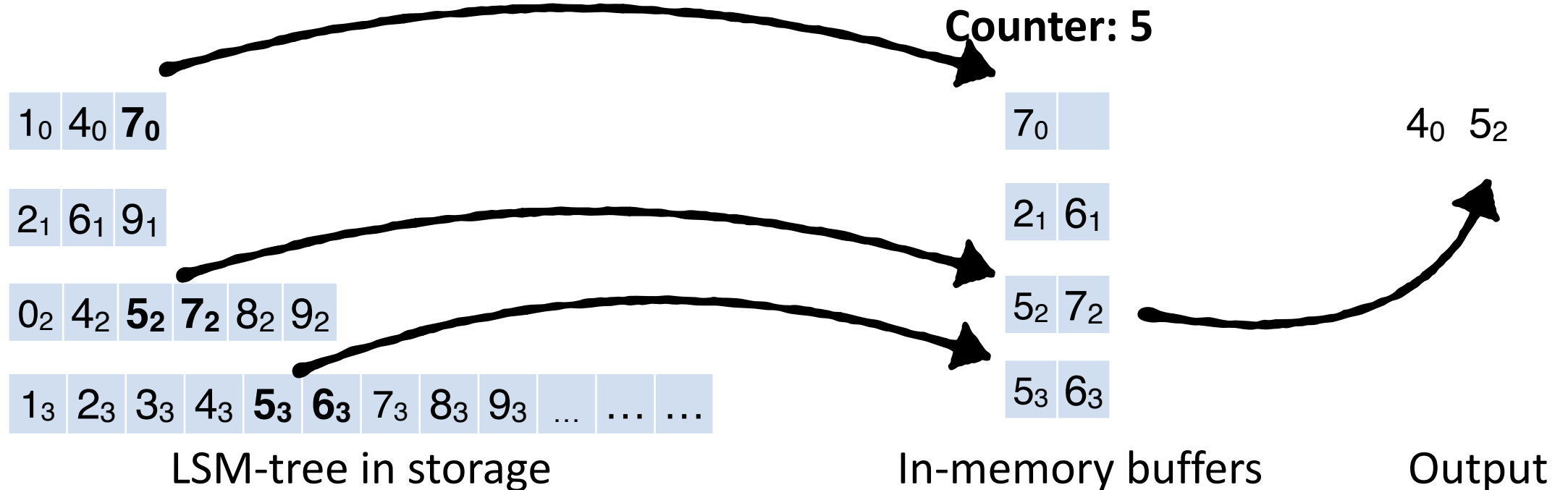
4₀

Output

Basic LSM-tree – Scan Queries

Loop until counter passes end of range

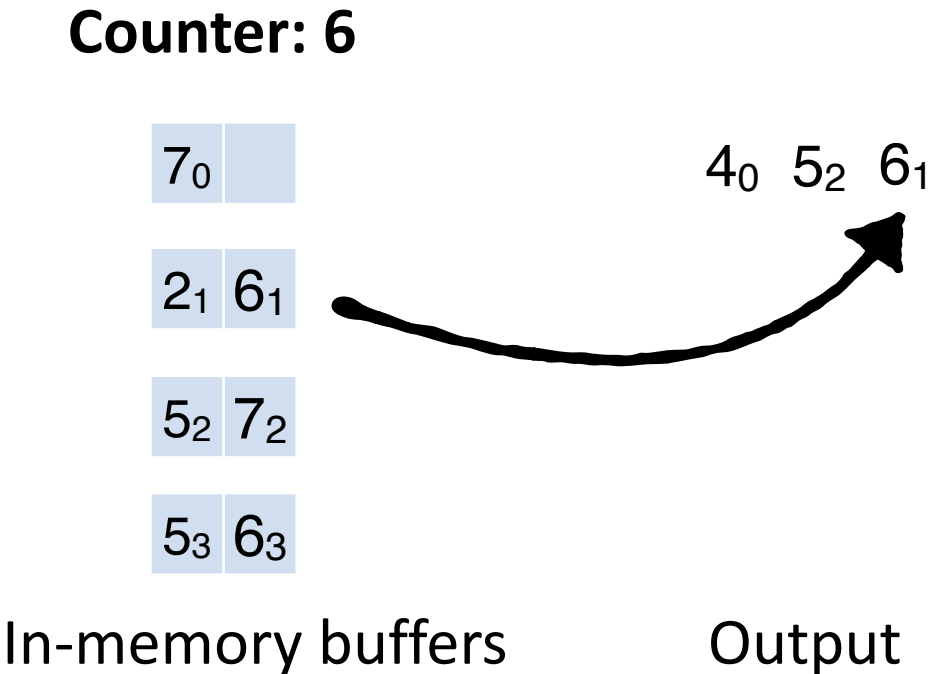
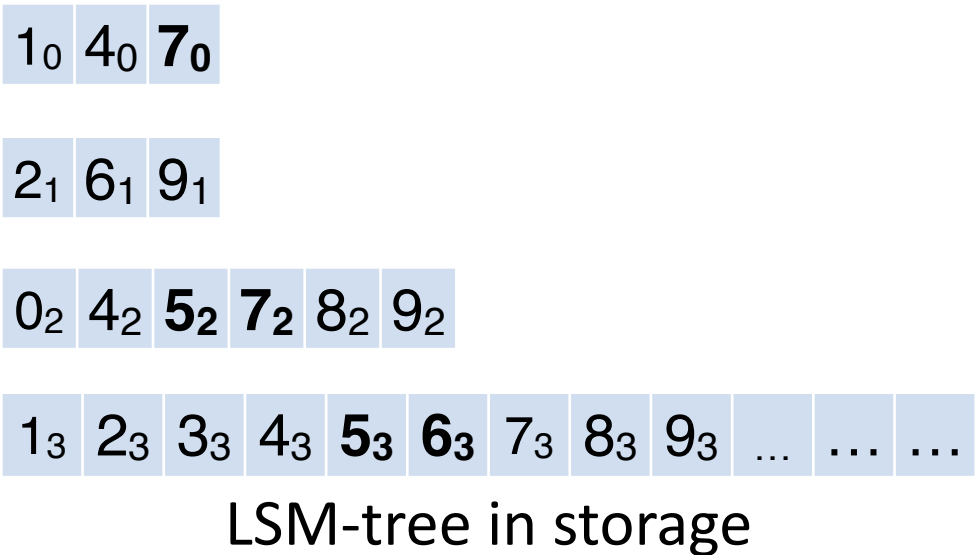
4. Bring youngest matching entry to output
5. Increment counter
6. Bring more pages to buffers if needed



Basic LSM-tree – Scan Queries

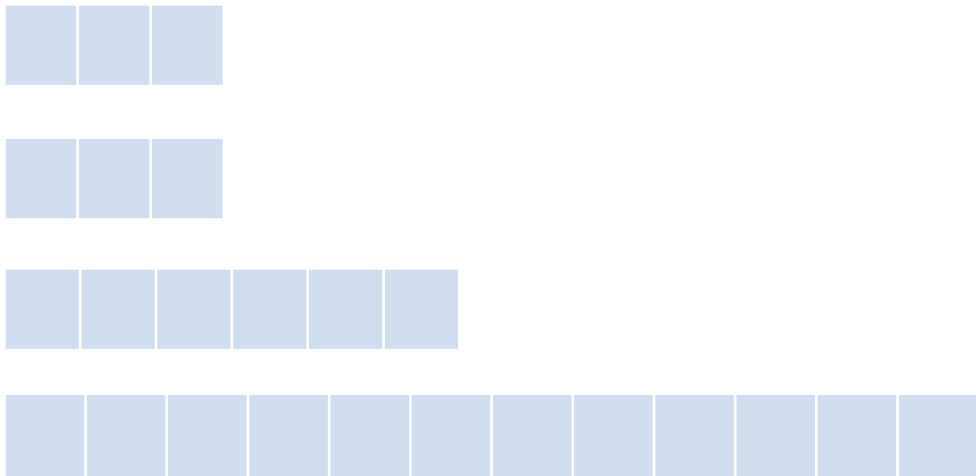
Loop until counter passes end of range

- 4. Bring youngest matching entry to output
- 5. Increment counter
- 6. Bring more pages to buffers if needed

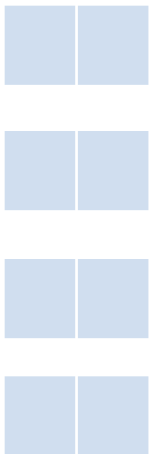


Basic LSM-tree – Scan Queries I/O Cost

$$O(\log_2(N/B) * \log_B(N) + S/B)$$



LSM-tree in storage



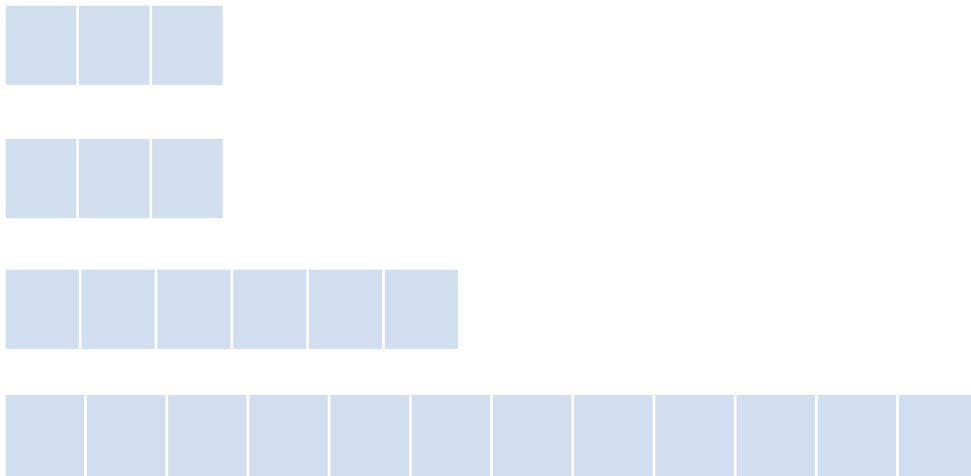
In-memory buffers

Basic LSM-tree – Scan Queries I/O Cost

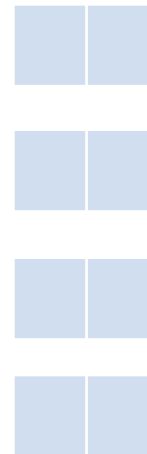
lvls



$$O(\log_2(N/B) * \log_B(N) + S/B)$$

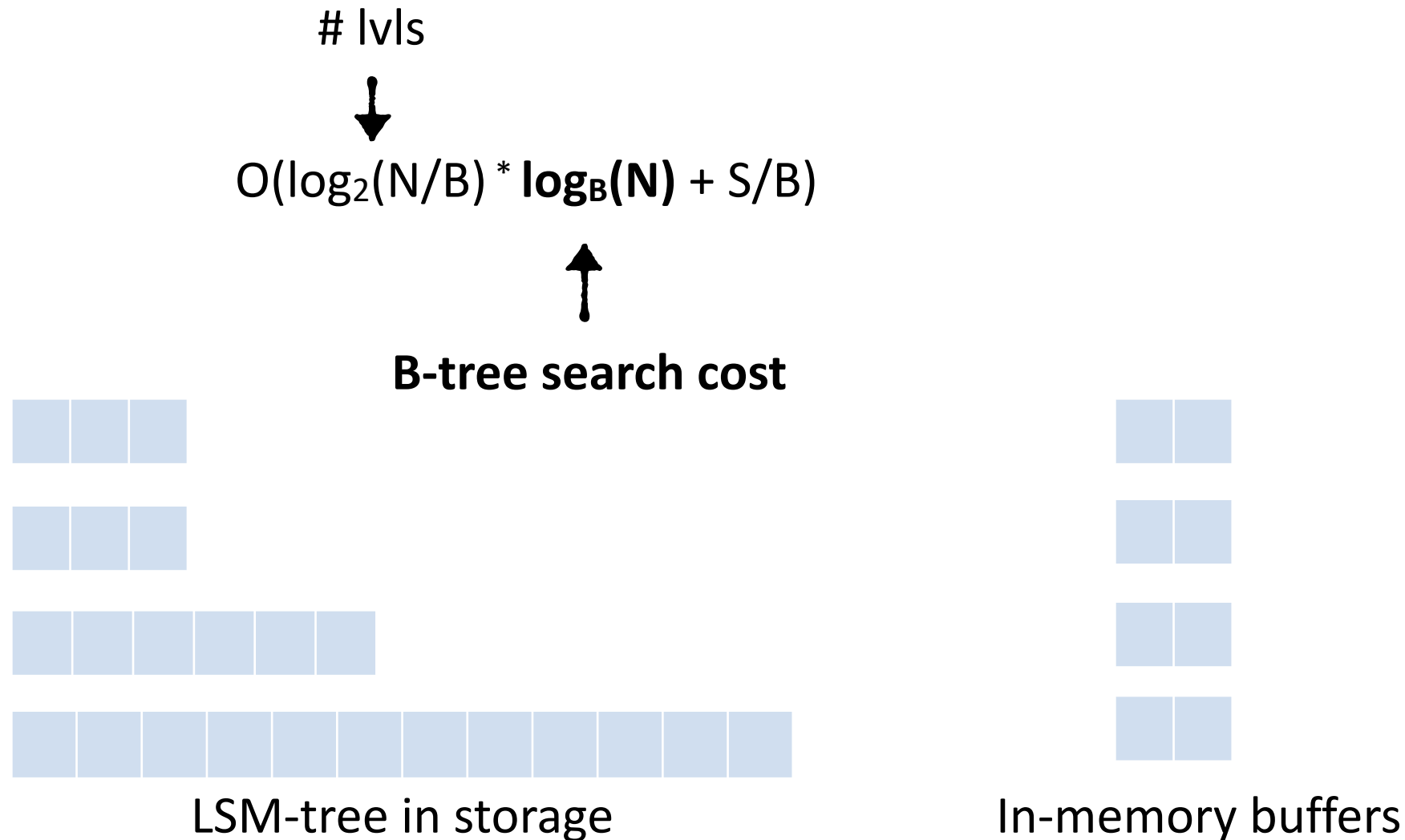


LSM-tree in storage

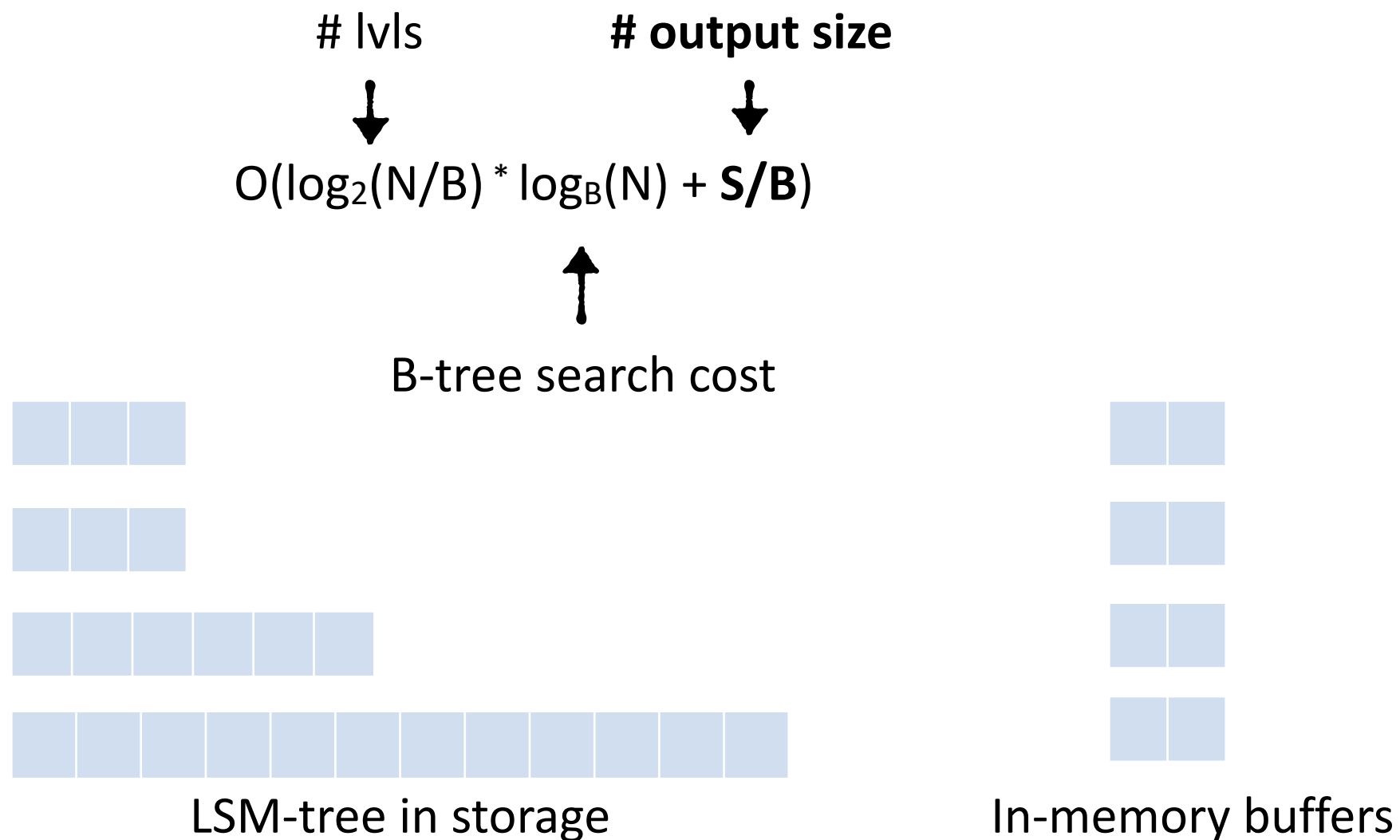


In-memory buffers

Basic LSM-tree – Scan Queries I/O Cost

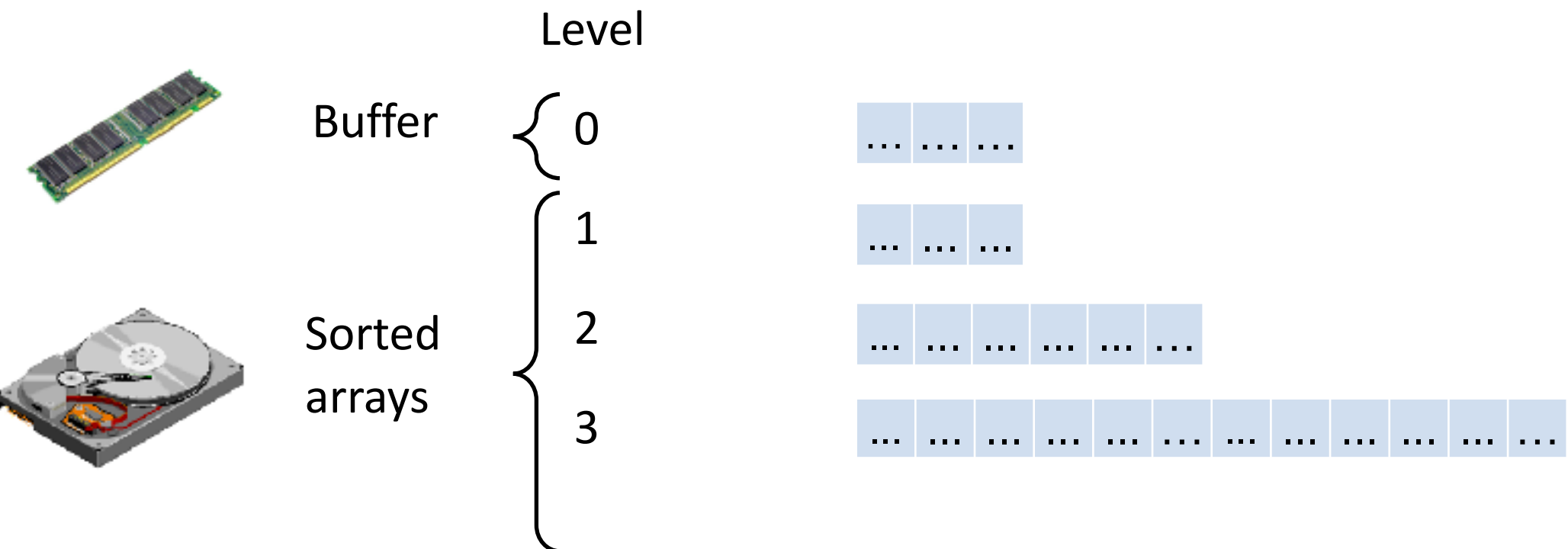


Basic LSM-tree – Scan Queries I/O Cost



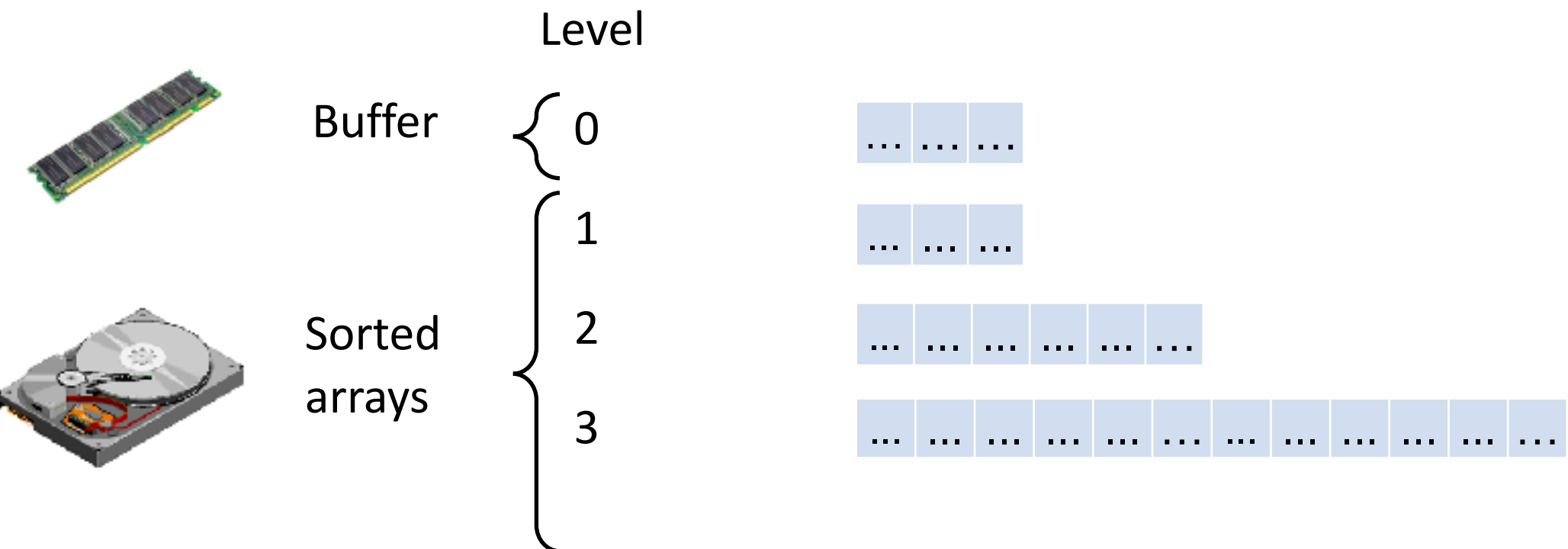
Basic LSM-tree – Insertion/Update/Delete cost

How many times is each entry copied?



Basic LSM-tree – Insertion/Update/Delete cost

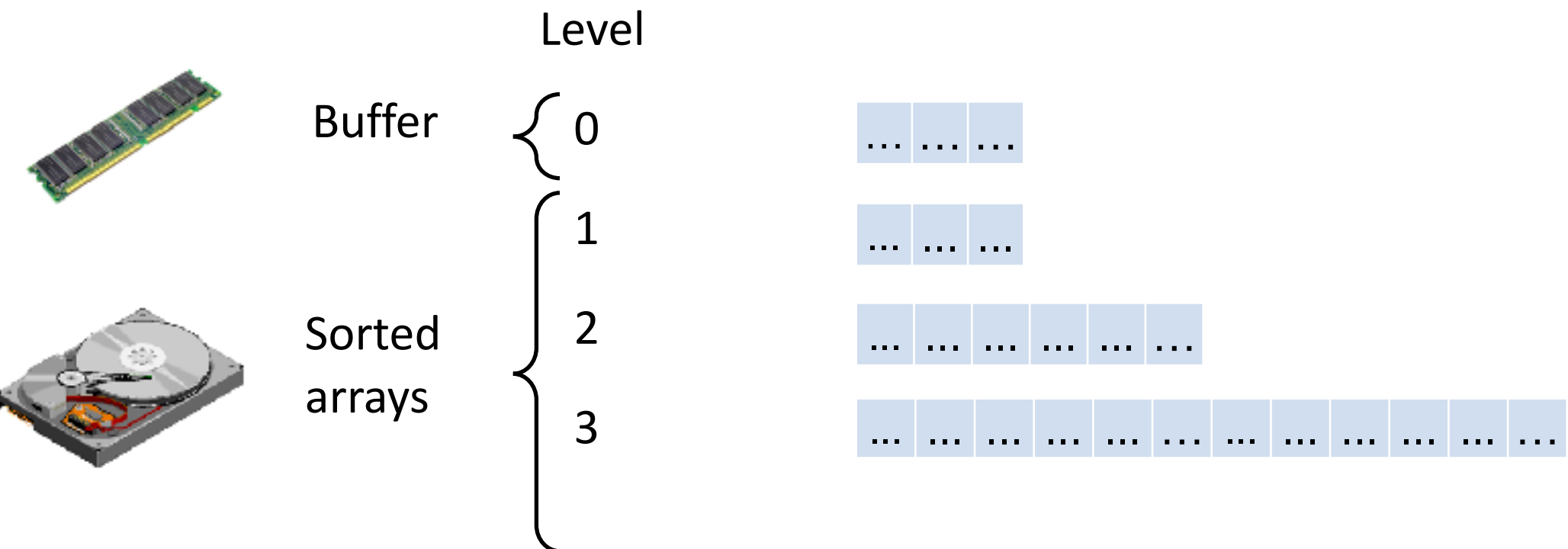
How many times is each entry copied? $O(\log_2 N/B)$



Basic LSM-tree – Insertion/Update/Delete cost

How many times is each entry copied? $O(\log_2 N/B)$

Price of each copy?



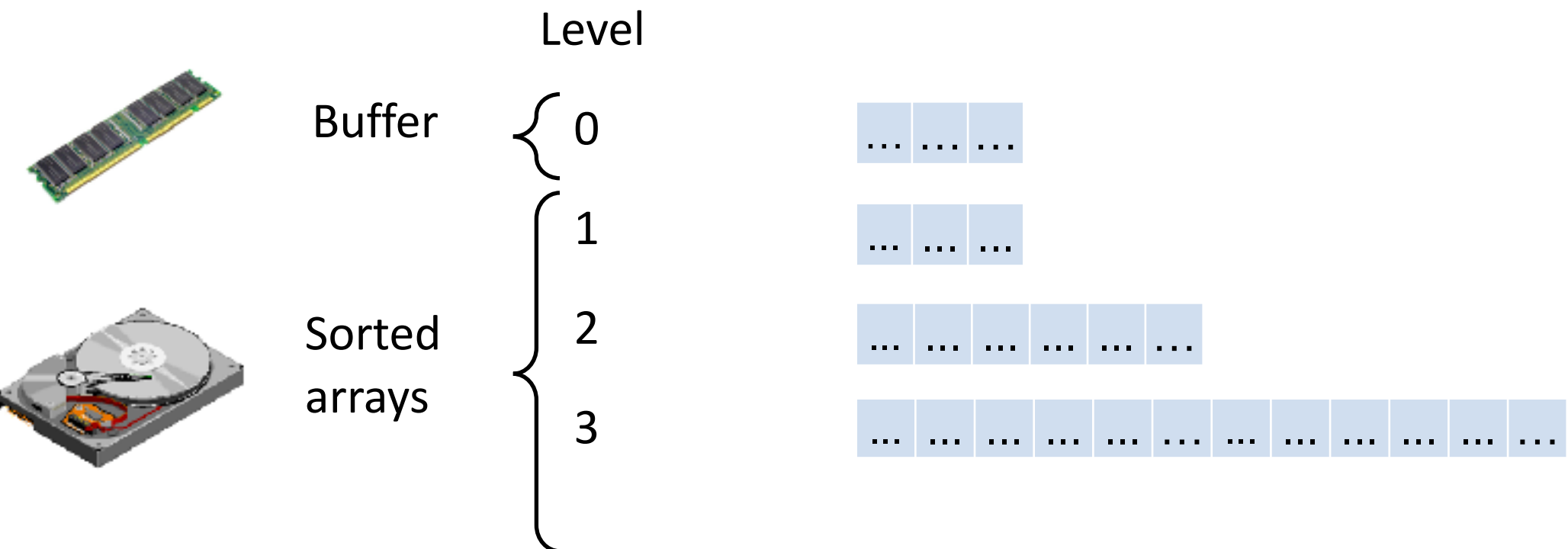
Basic LSM-tree – Insertion/Update/Delete cost

How many times is each entry copied?

$O(\log_2 N/B)$

Price of each copy?

$O(1/B)$ reads & writes



Basic LSM-tree – Insertion/Update/Delete cost

How many times is each entry copied?

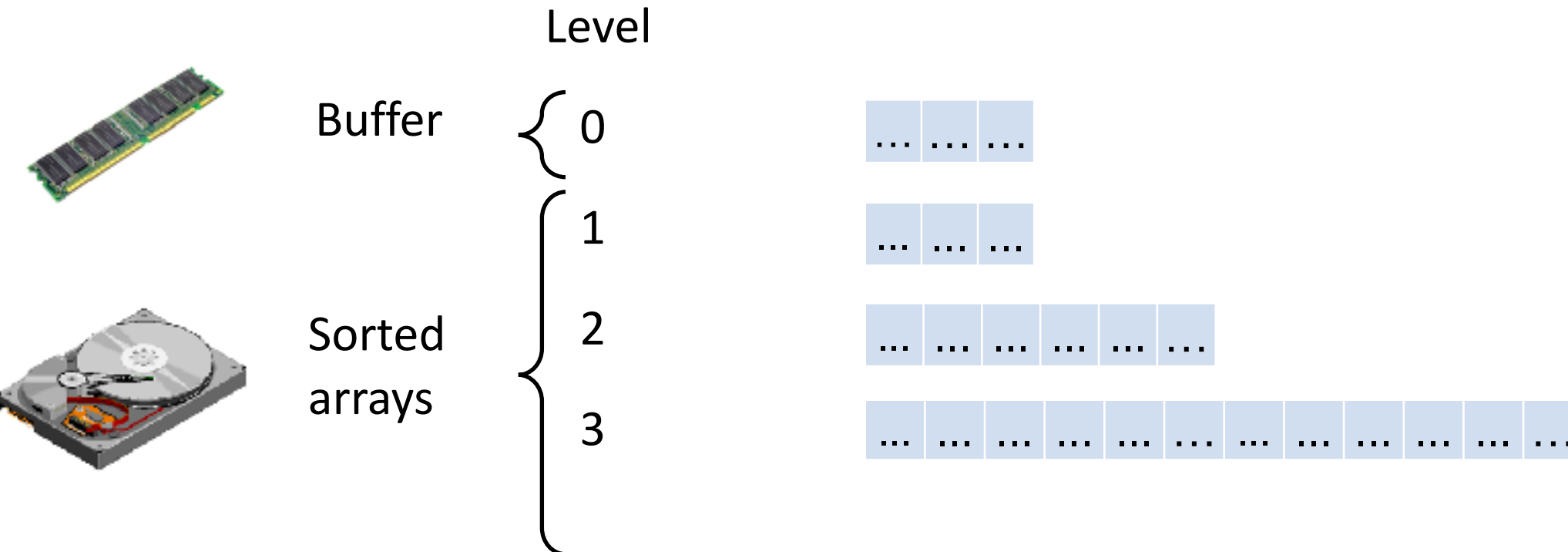
$O(\log_2 N/B)$

Price of each copy?

$O(1/B)$ reads & writes

Total cost:

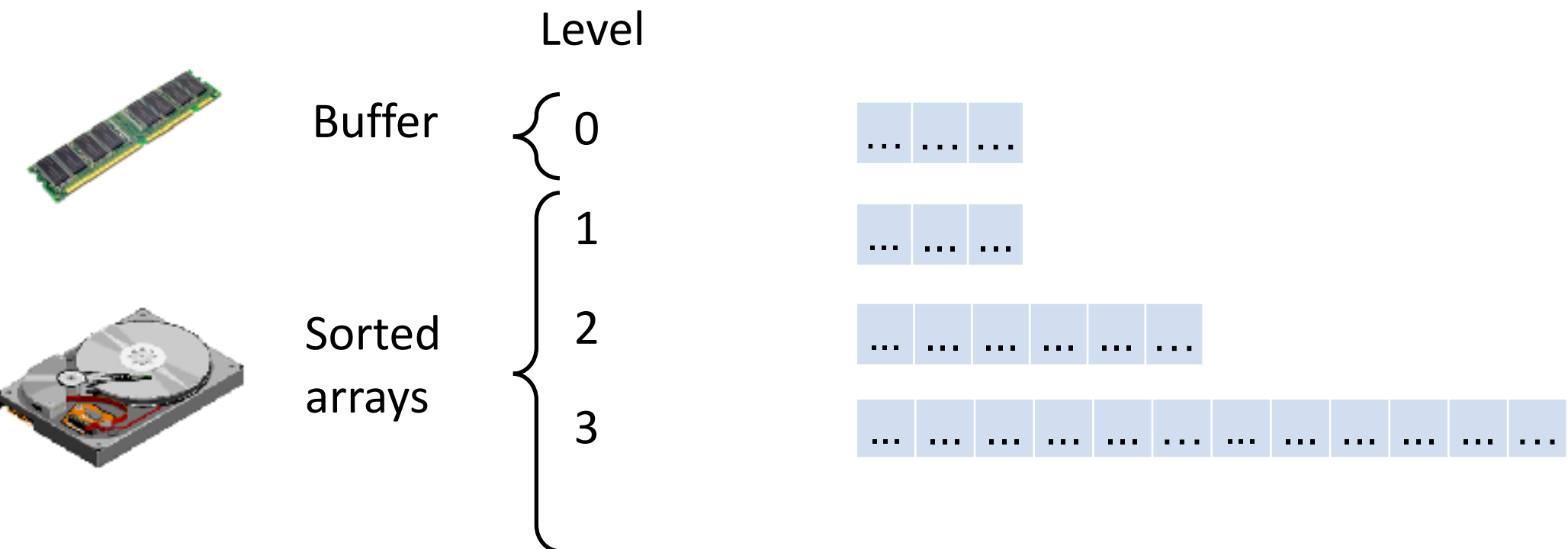
$O((\log_2 N/B)/B)$ read & write I/Os



Basic LSM-tree – Insertion/Update/Delete cost

Total cost: $O((\log_2 N/B)/B)$ read & write I/Os

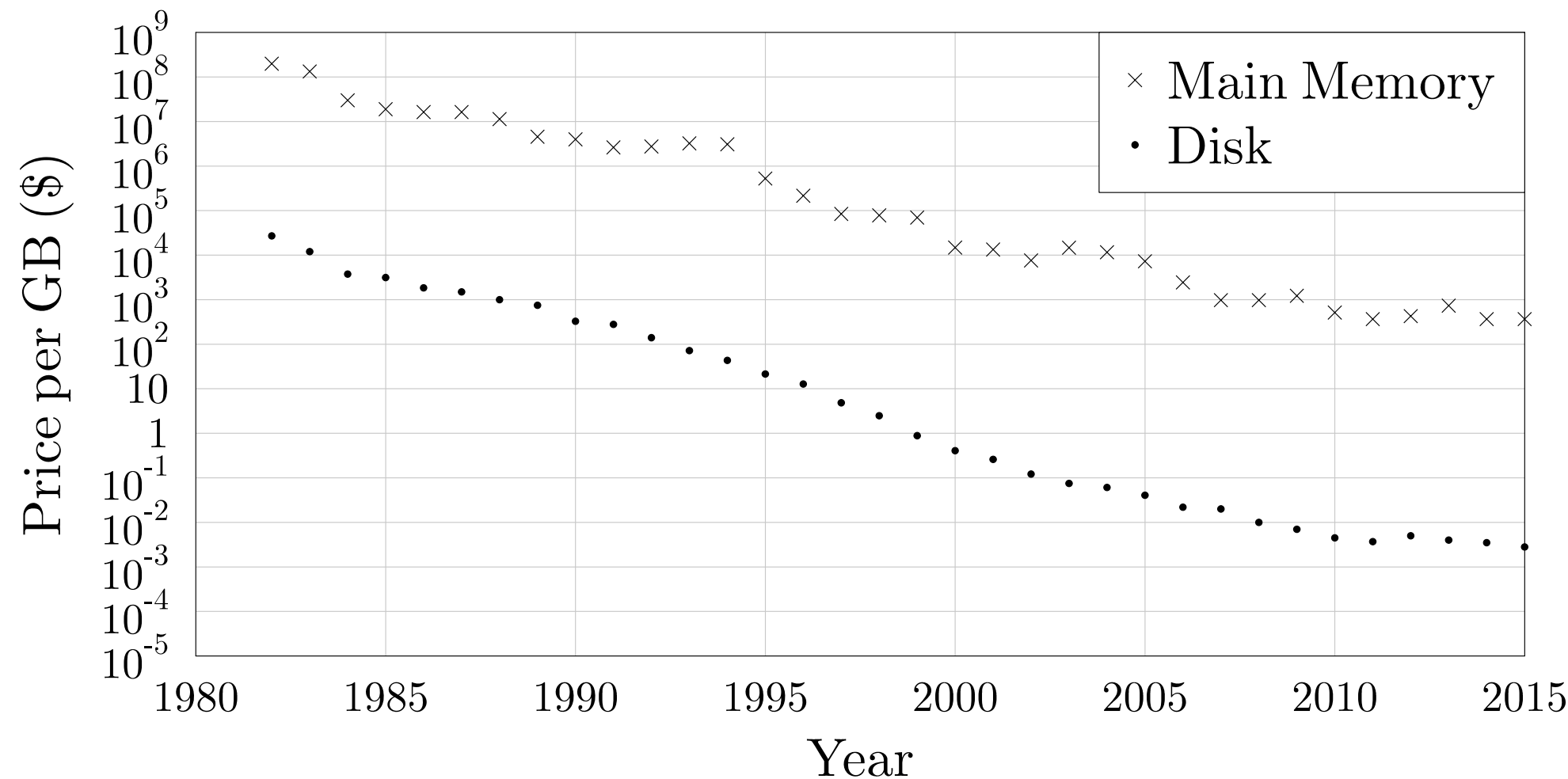
As all writes are large & sequential (rather than random), there is less SSD garbage-collection



Operation	I/O	append-only table	Basic LSM-tree table	B-Tree
Query	Reads	$O(N/B)$	$O(\log_2(N/B) * \log_B N)$	$O(\log_B N)$
Insert	Reads	0	$O((\log_2 N/B)/B)$	$O(\log_B N)$
	Writes	$O(1/B)$	$O((\log_2 N/B)/B)$	$O(1)$ & GC

Break :)

Declining Main Memory Cost



Declining Main Memory Cost

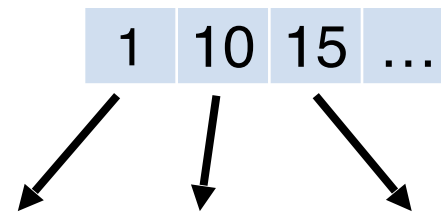
It's viable to pin the internal nodes of B-trees in memory



Fence
pointers



array

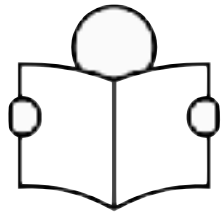


Block 1	Block 2	Block 3	...
1	10	15	...
3	11	16	...
6	13	18	...

Operation	I/O	append-only table	Basic LSM-tree table	B-Tree
Query	Reads	$O(N/B)$	$O(\log_2(N/B) * \log_{1/B} N)$	$O(\log_B N)$
Insert	Reads	0	$O((\log_2 N/B)/B)$	$O(\log_B N)$
	Writes	$O(1/B)$	$O((\log_2 N/B)/B)$	$O(1)$ & GC

Operation	I/O	append-only table	Basic LSM-tree table	B-Tree
Query	Reads	$O(N/B)$	$O(\log_2 N/B)$	$O(1)$
Insert	Reads	0	$O((\log_2 N/B)/B)$	$O(1)$
	Writes	$O(1/B)$	$O((\log_2 N/B)/B)$	$O(1)$ & GC
Memory		$O(B)$	$O(N/B)$	$O(N/B)$

Leveled LSM-tree



Basic LSM-tree

Tiered LSM-tree



Leveled LSM-tree



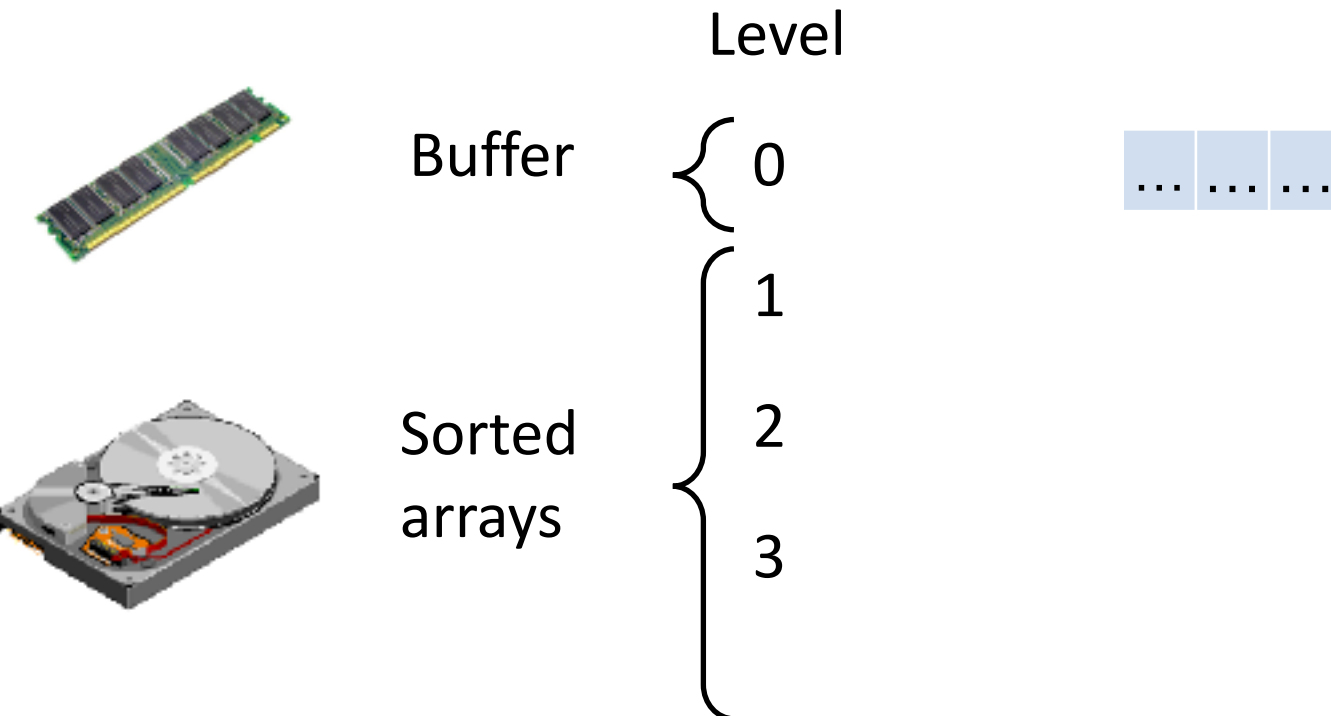
Lookup cost



Update cost

Leveled LSM-tree

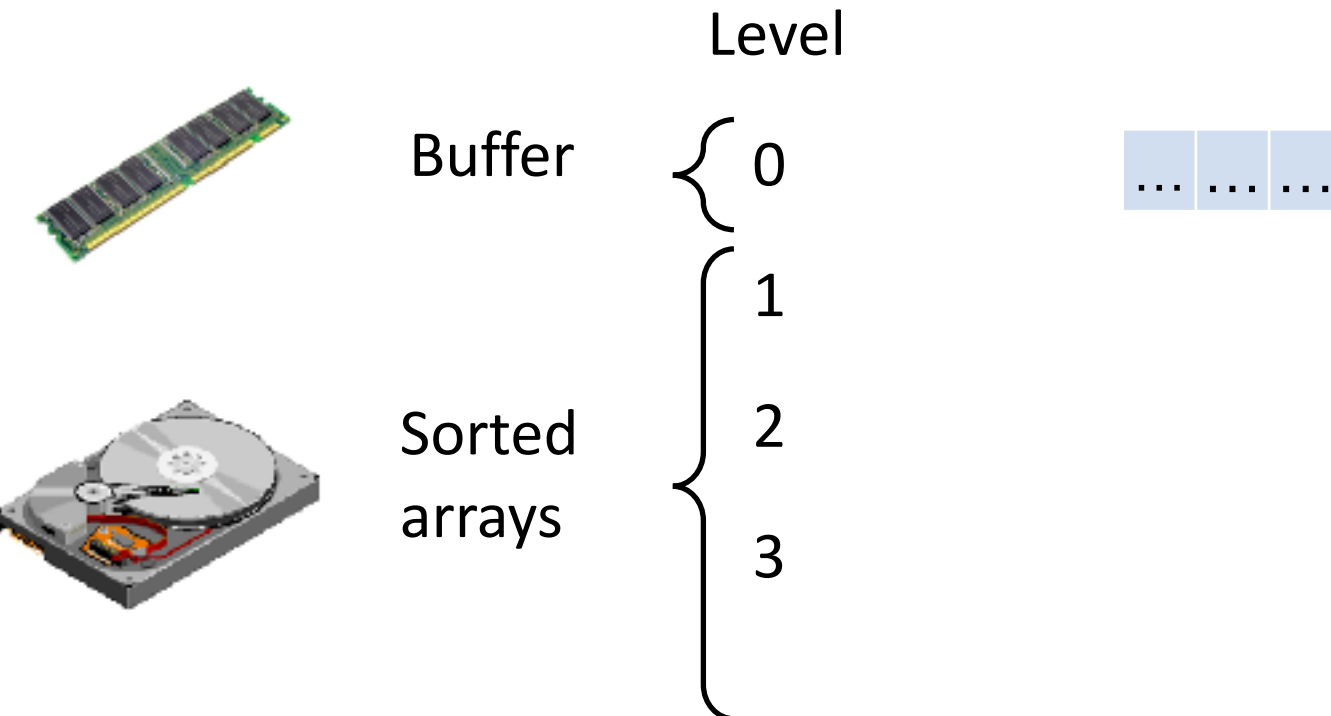
Lookup cost depends on number of levels



Leveled LSM-tree

Lookup cost depends on number of levels

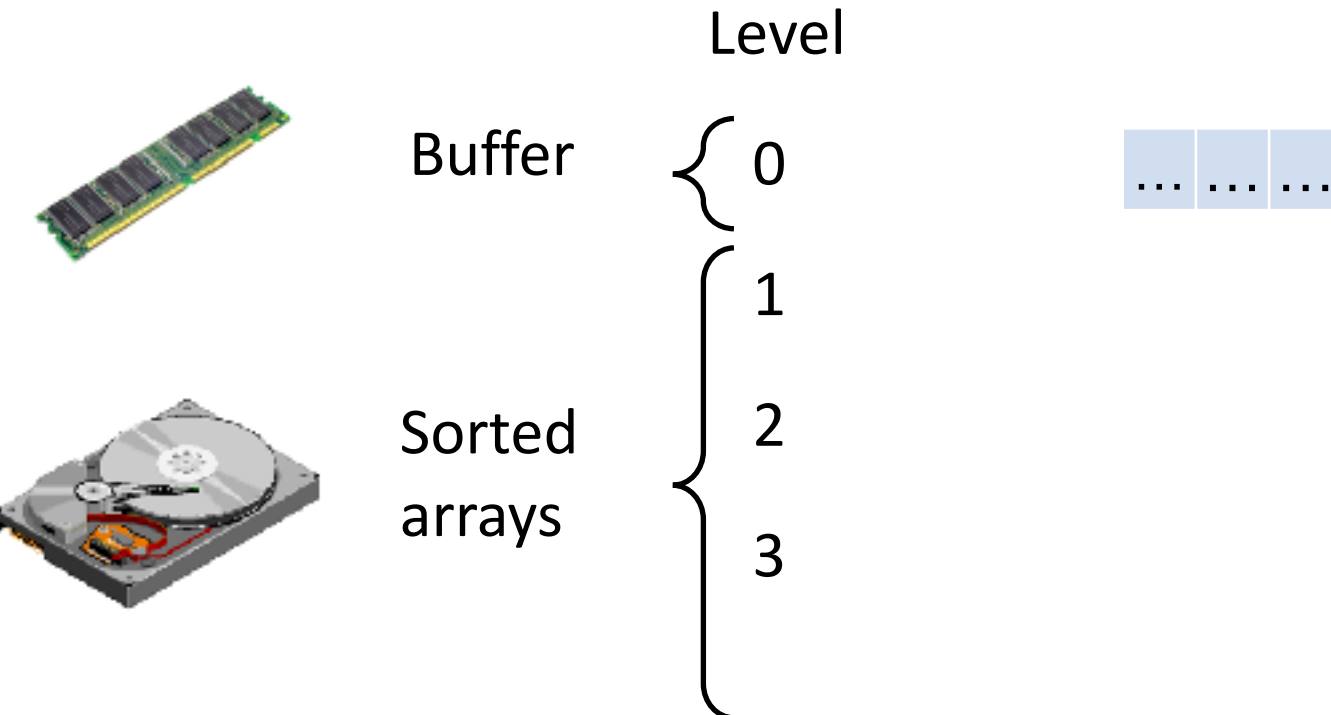
How to reduce it?



Leveled LSM-tree

Lookup cost depends on number of levels
How to reduce it?

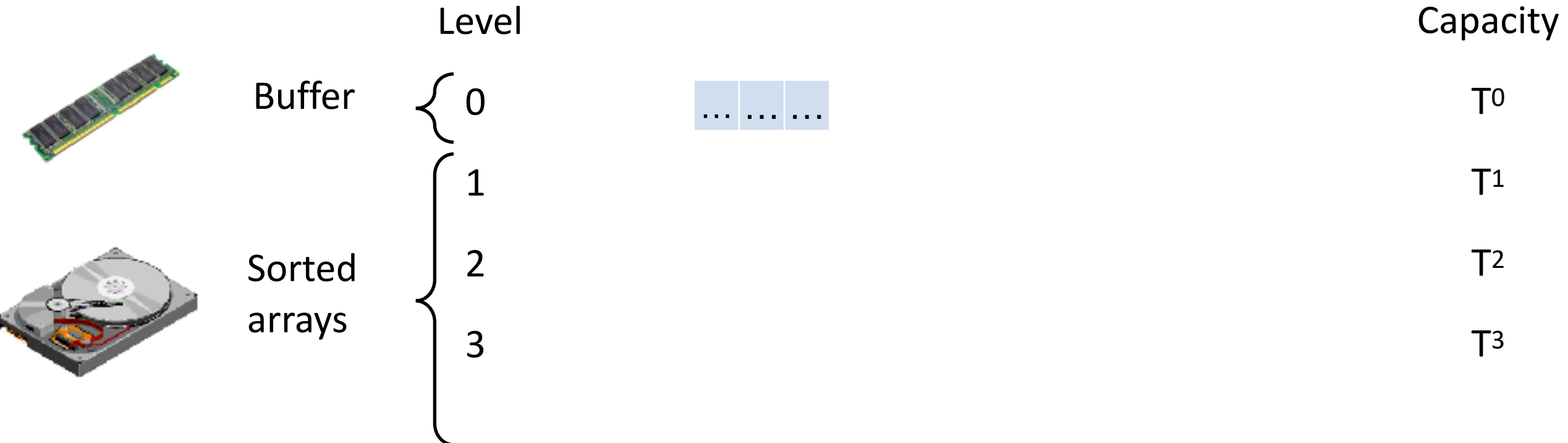
Increase size ratio T



Leveled LSM-tree

Lookup cost depends on number of levels
How to reduce it?

Increase size ratio T



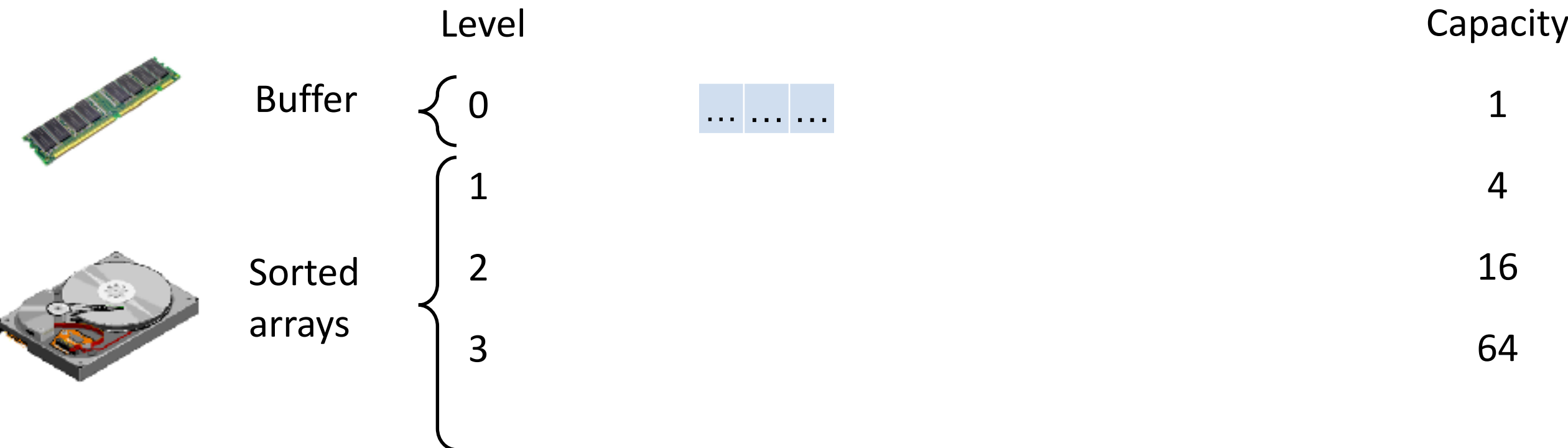
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

E.g. size ratio of 4

Increase size ratio T



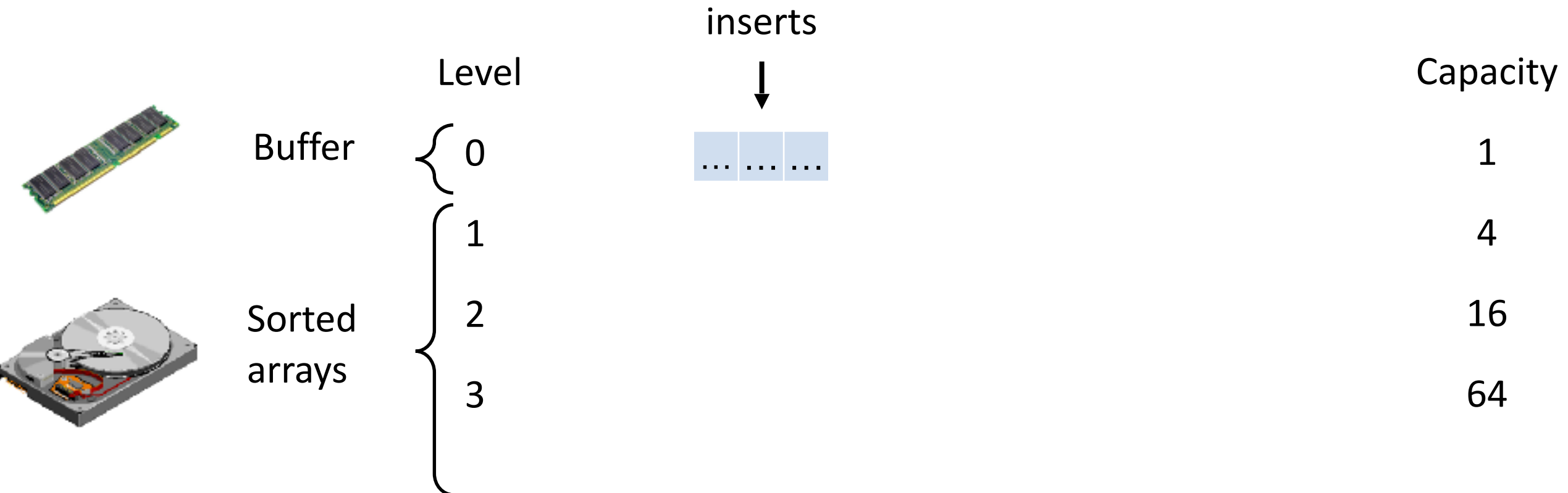
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

E.g. size ratio of 4

Increase size ratio T



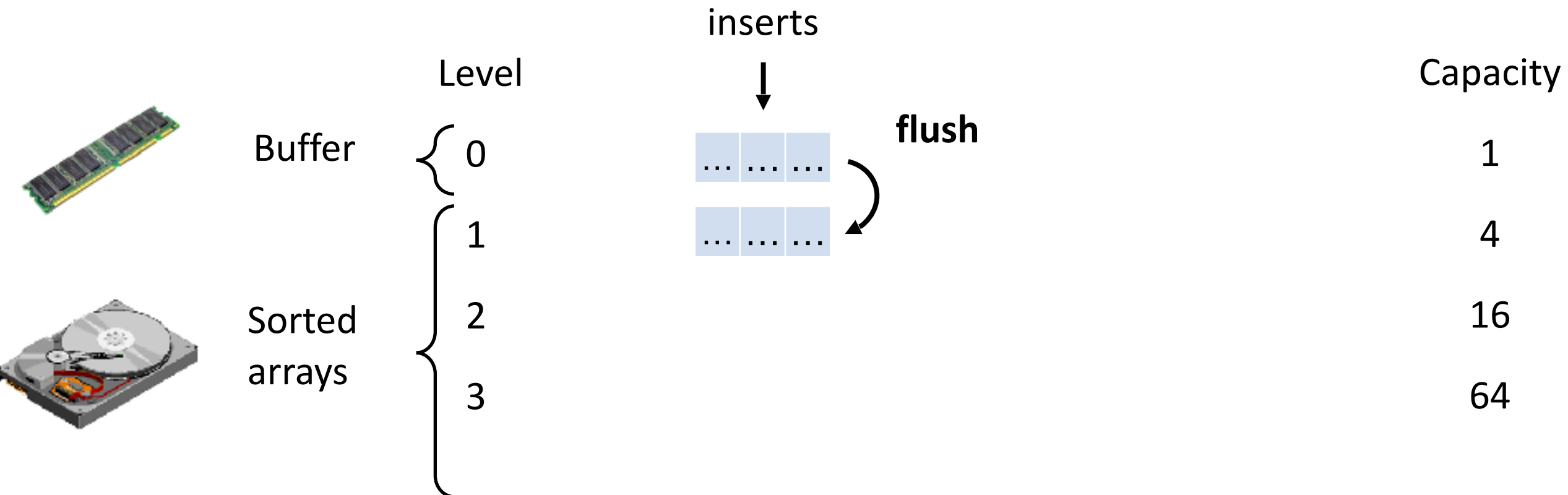
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

E.g. size ratio of 4

Increase size ratio T



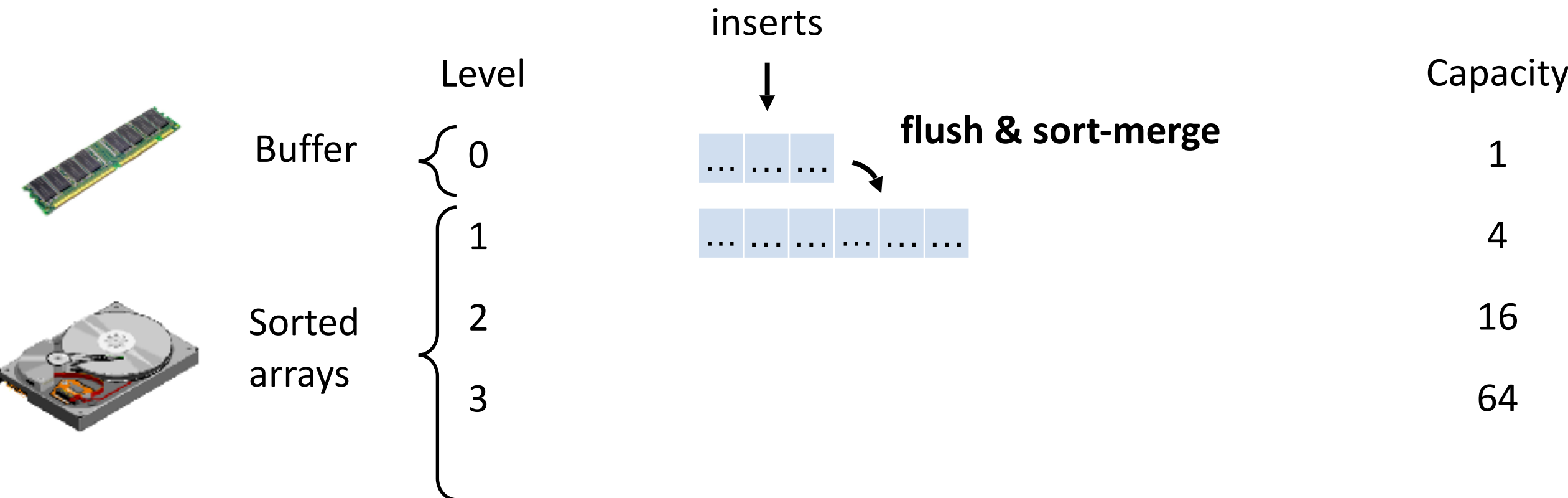
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

E.g. size ratio of 4

Increase size ratio T



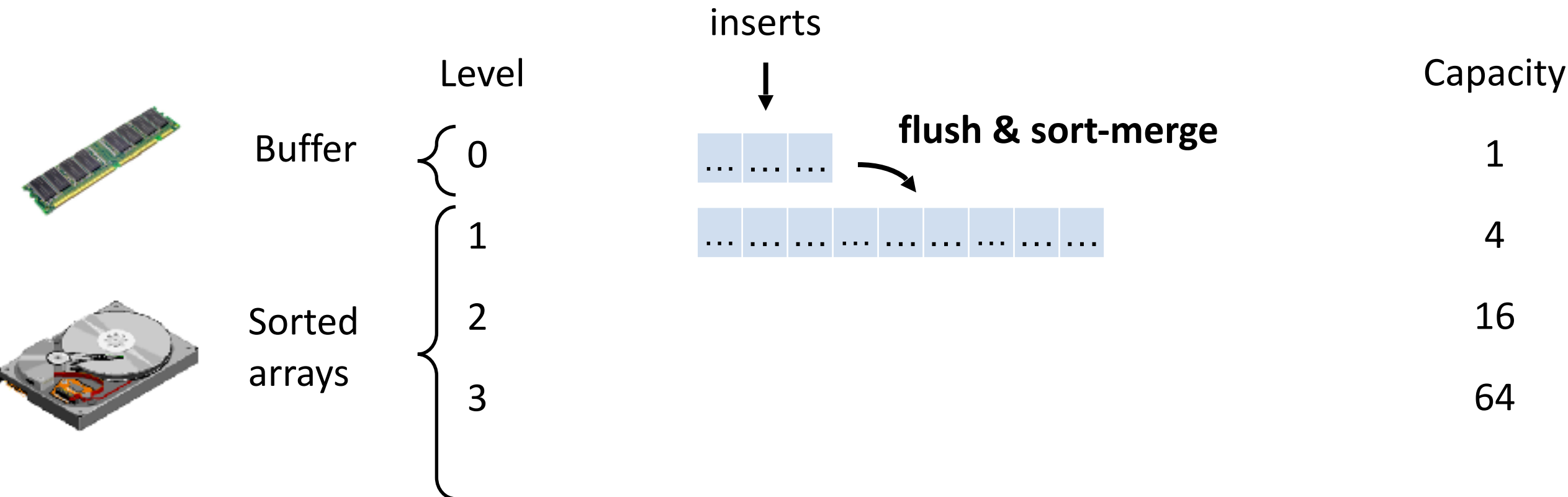
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

E.g. size ratio of 4

Increase size ratio T



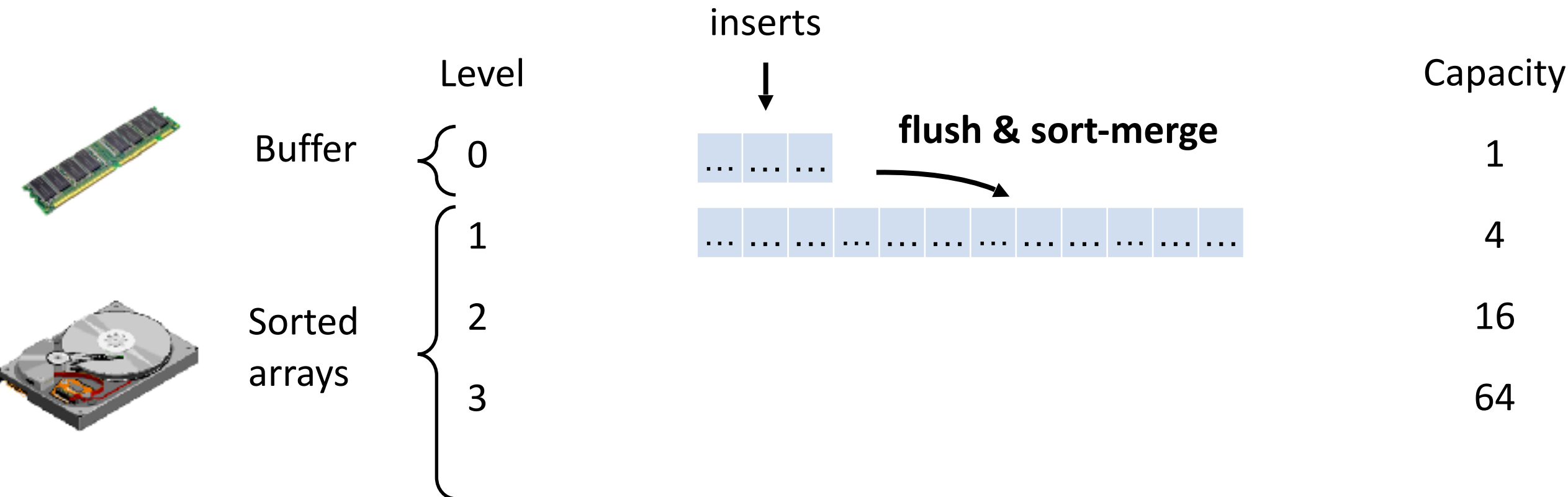
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

E.g. size ratio of 4

Increase size ratio T



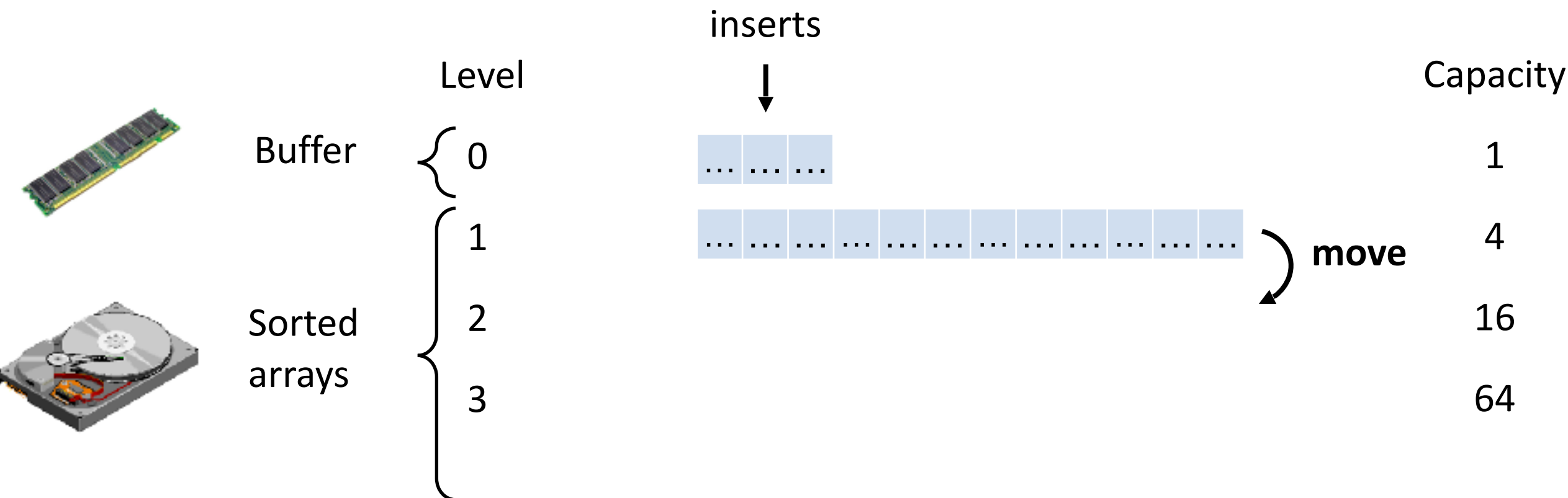
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

E.g. size ratio of 4

Increase size ratio T



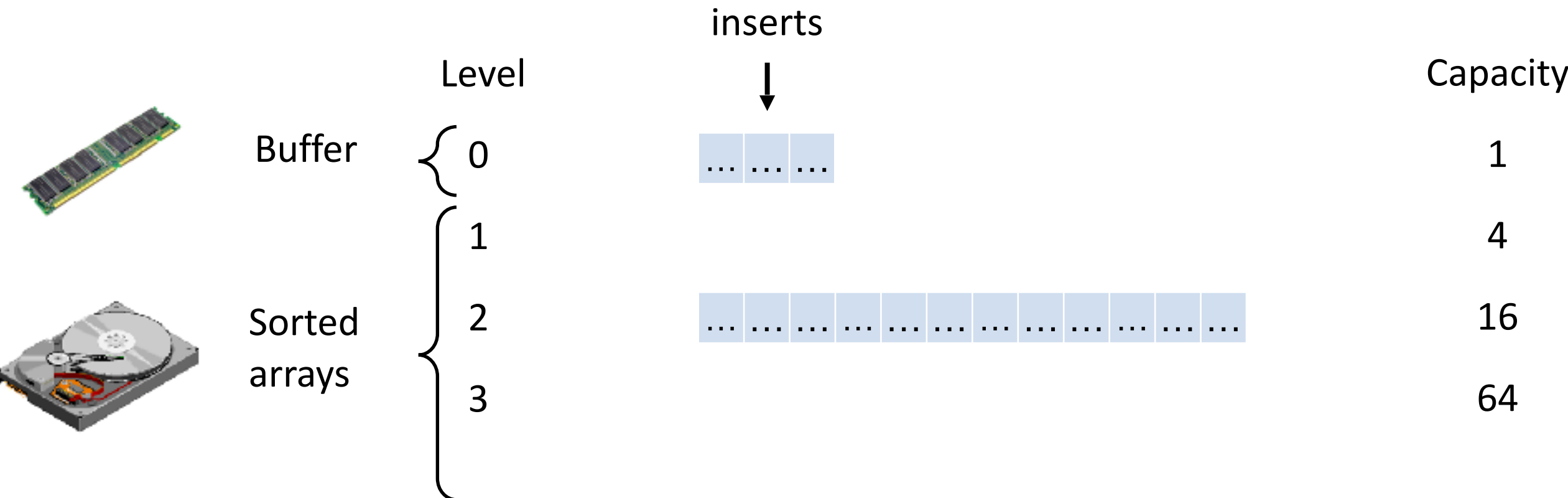
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

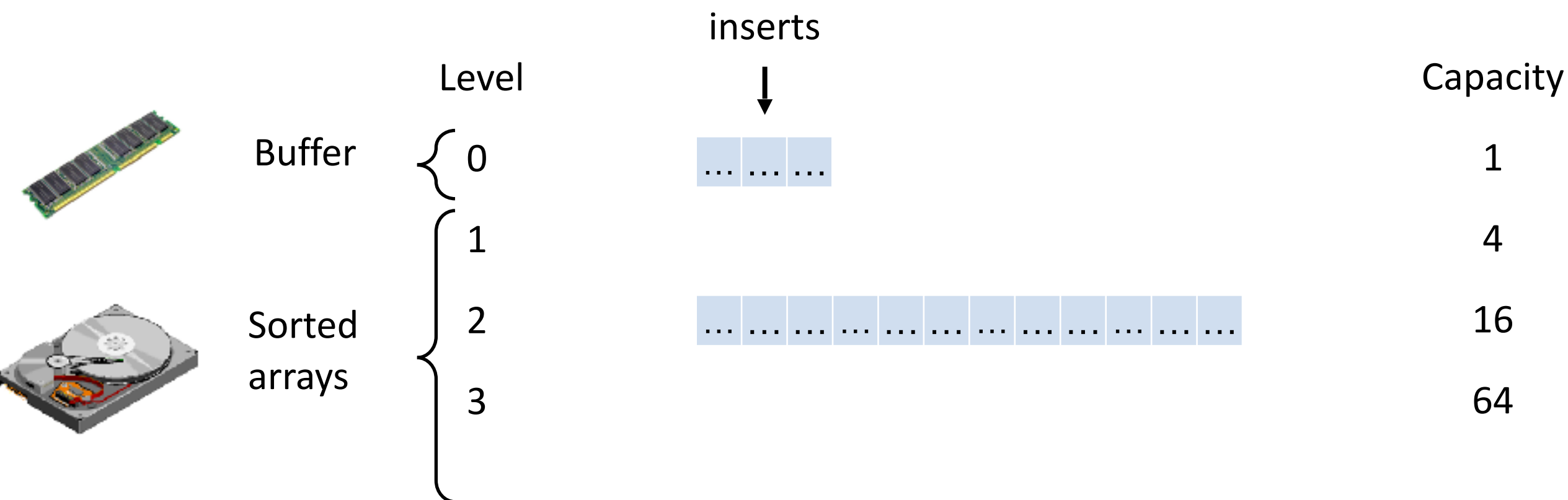
E.g. size ratio of 4

Increase size ratio T



Leveled LSM-tree

Lookup cost?



Leveled LSM-tree

Lookup cost?

$$O(\log_T(N/B))$$



Buffer

Sorted
arrays

Level

{ 0

1

2

3

inserts



Capacity

1

4

16

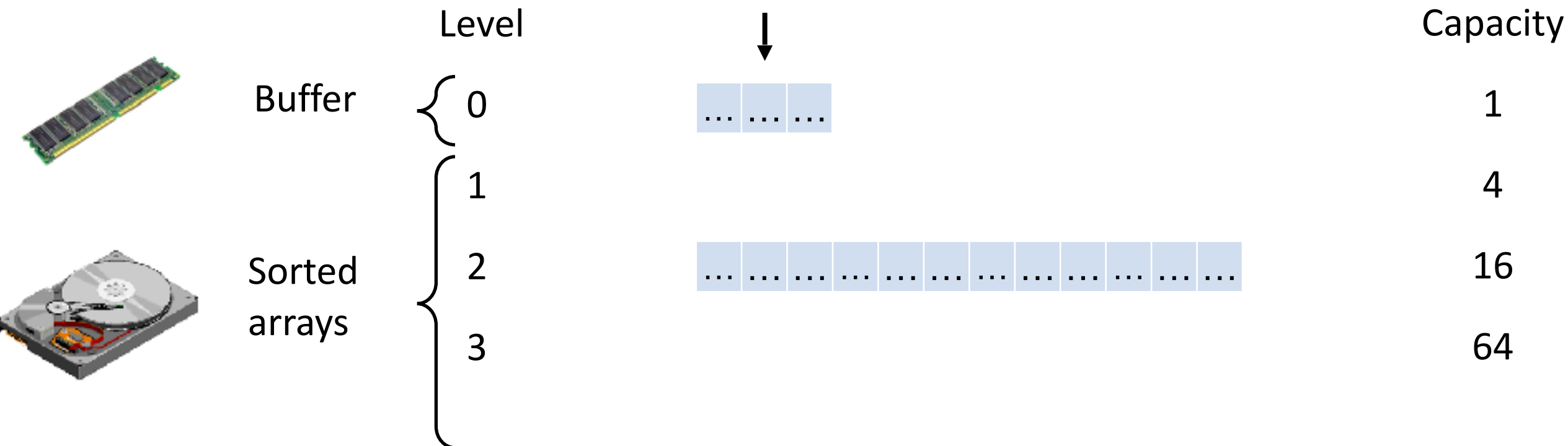
64

Leveled LSM-tree

Lookup cost?

$$O(\log_T(N/B))$$

Insertion cost?



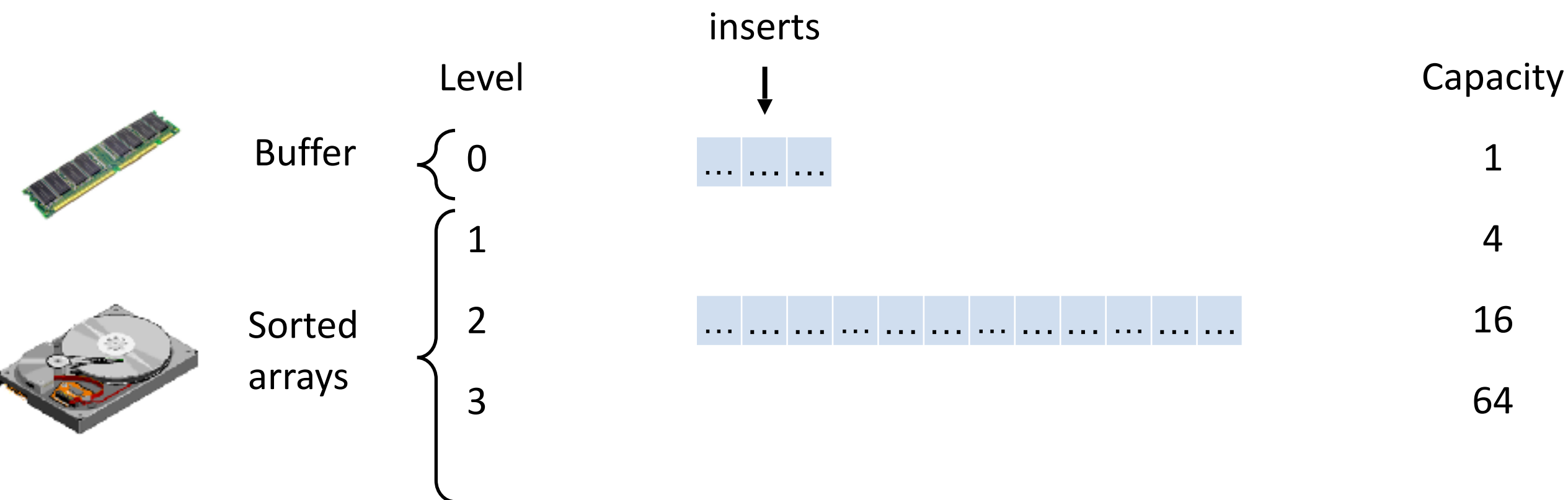
Leveled LSM-tree

Lookup cost?

$O(\log_T(N/B))$

Insertion cost?

$O(T/B \cdot \log_T(N/B))$



Leveled LSM-tree

Lookup cost?


$$O(\log_T(N/B))$$


Insertion cost?

$$O(T/B \cdot \log_T(N/B))$$

What happens as we increase the size ratio T ?


Leveled LSM-tree


 Lookup cost?
 $O(\log_T(N/B))$

Insertion cost? 
 $O(T/B \cdot \log_T(N/B))$

What happens as we increase the size ratio T ?

Leveled LSM-tree


 Lookup cost?
 $O(\log_T(N/B))$


Insertion cost? 
 $O(T/B \cdot \log_T(N/B))$

What happens as we increase the size ratio T ?

What happens when size ratio T is set to be N/B ?

Leveled LSM-tree

 Lookup cost?
 $O(\log_T(N/B))$

Insertion cost? 
 $O(T/B \cdot \log_T(N/B))$


What happens as we increase the size ratio T ?


What happens when size ratio T is set to be N/B ?

Lookup cost becomes:
 $O(1)$

Insert cost becomes:
 $O(N/B^2)$

Leveled LSM-tree

 Lookup cost?
 $O(\log_T(N/B))$

Insertion cost? 
 $O(T/B \cdot \log_T(N/B))$

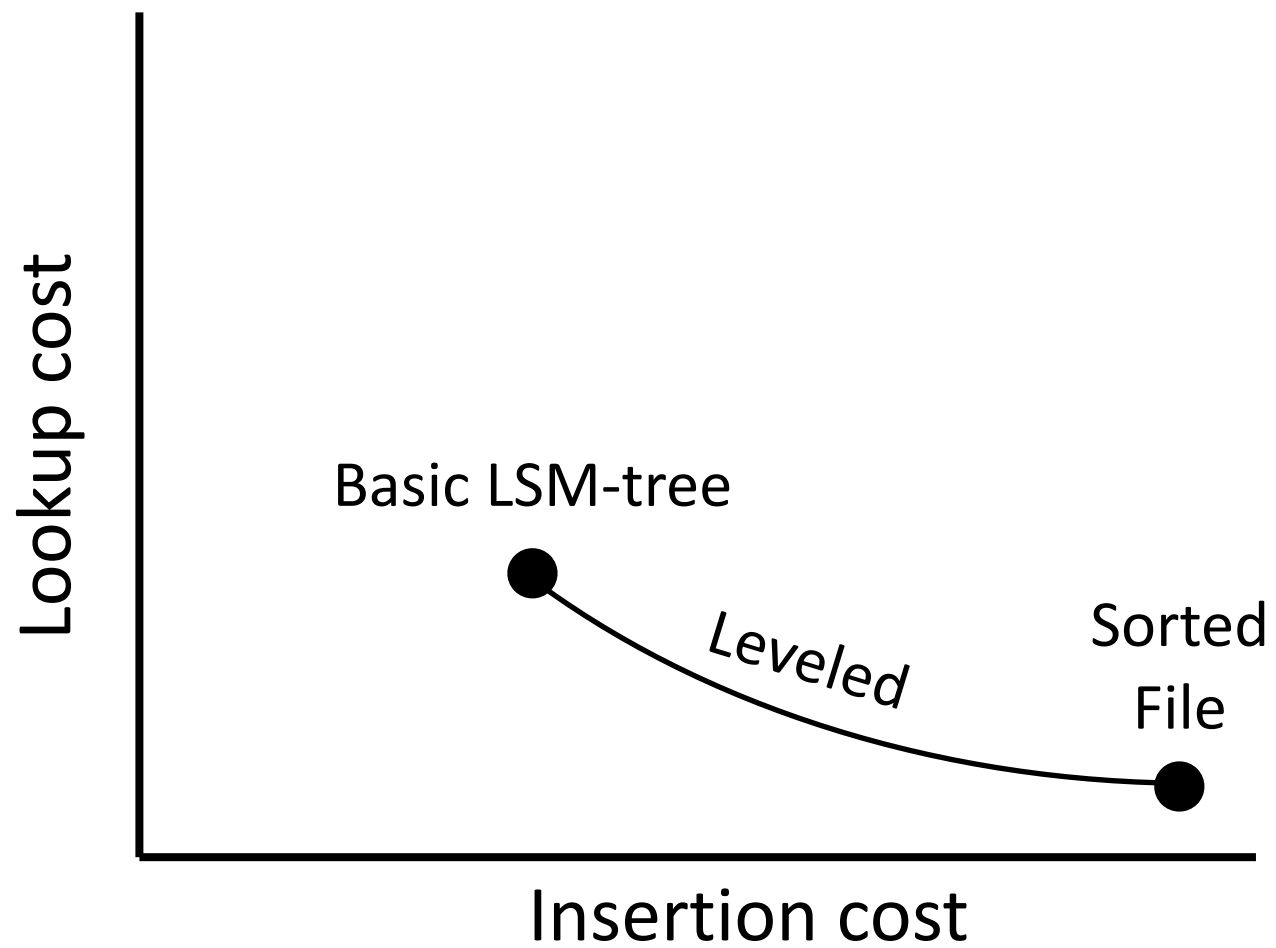
What happens as we increase the size ratio T ?

What happens when size ratio T is set to be N/B ?

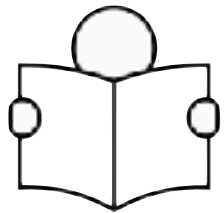
Lookup cost becomes:
 $O(1)$

Insert cost becomes:
 $O(N/B^2)$

The LSM-tree becomes a sorted file!



Leveled LSM-tree



Basic LSM-tree

Tiered LSM-tree



Tiered LSM-tree



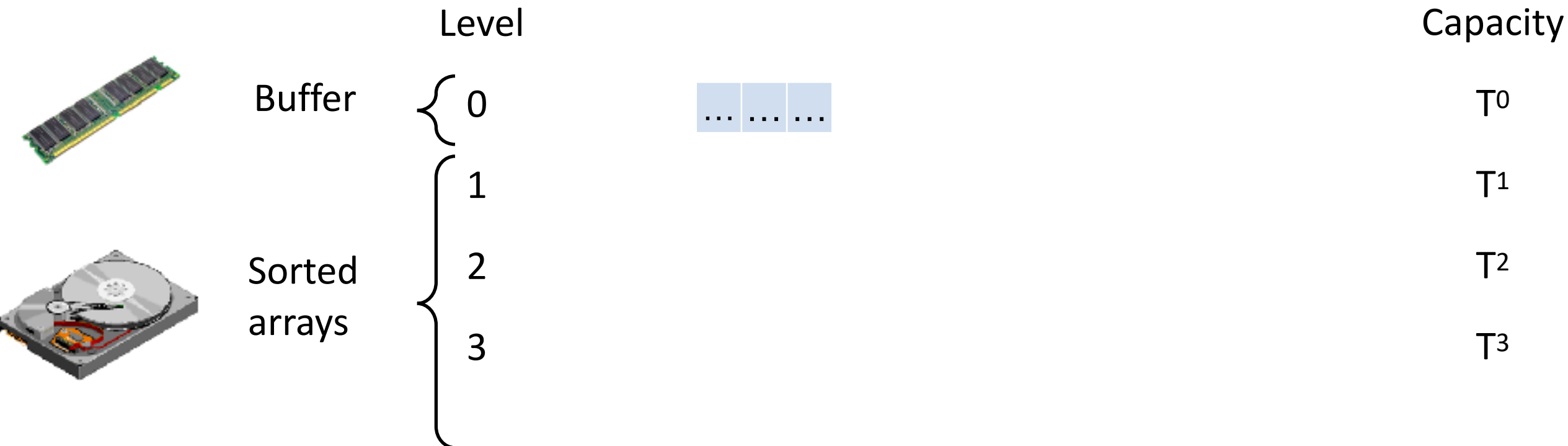
Lookup cost



Insertion cost

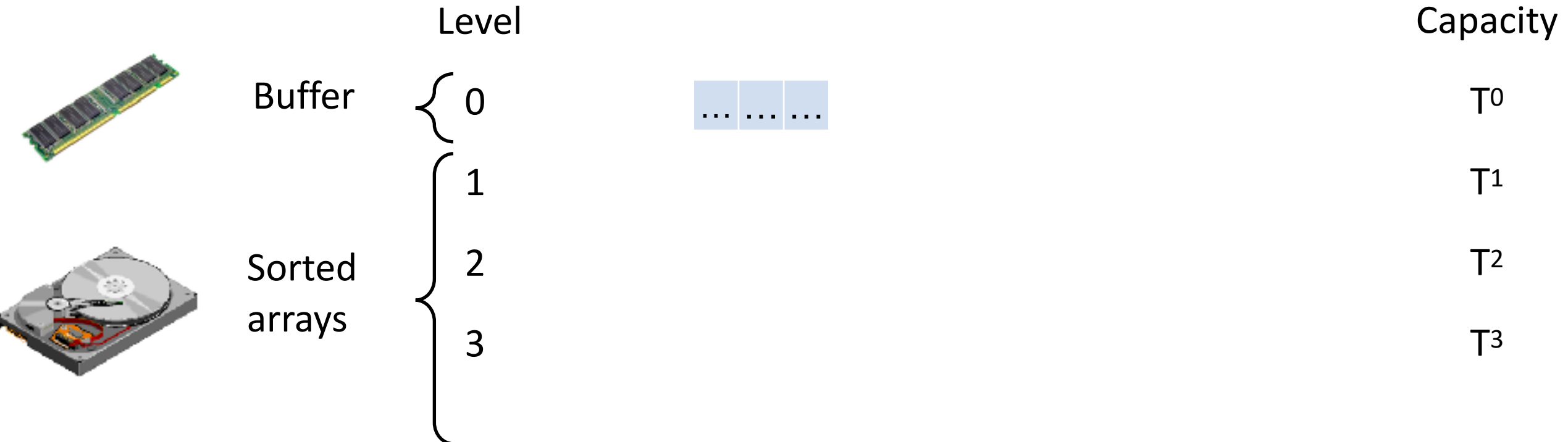
Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.



Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.
Do not merge within a level.

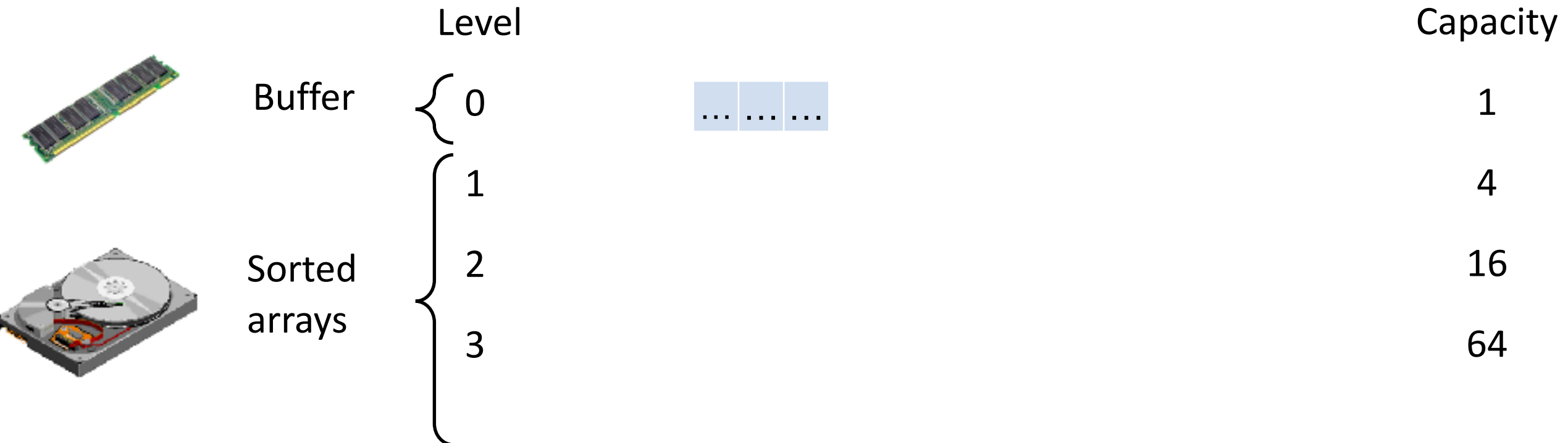


Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

Do not merge within a level.

E.g. size ratio of 4

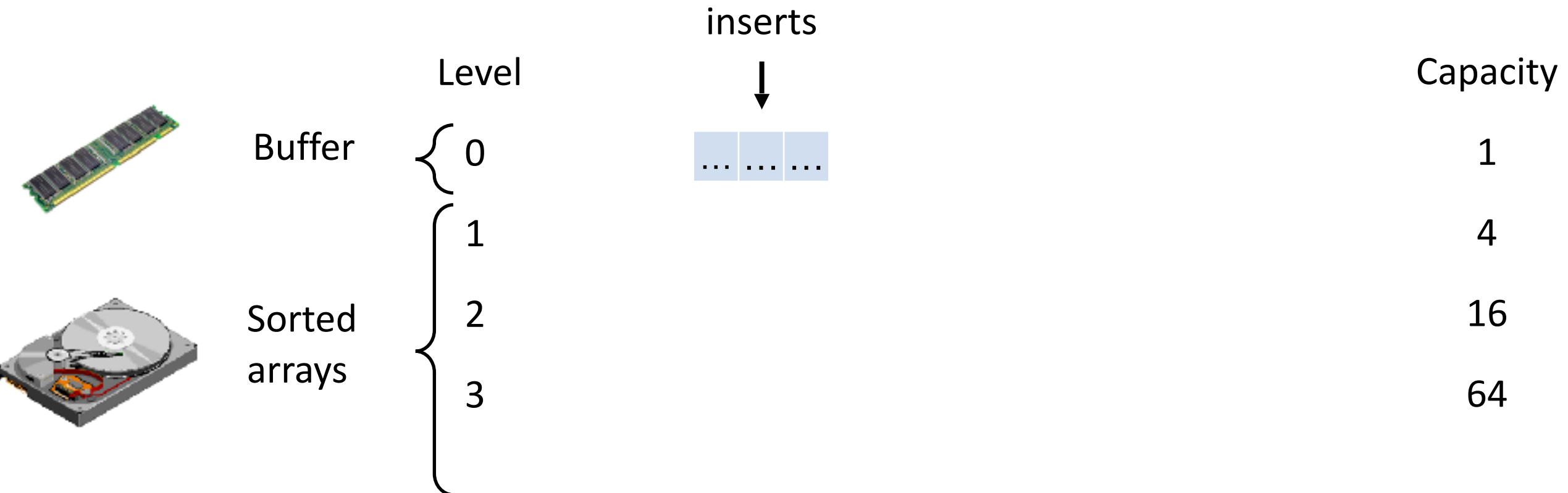


Tiered LSM-tree

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E.g. size ratio of 4

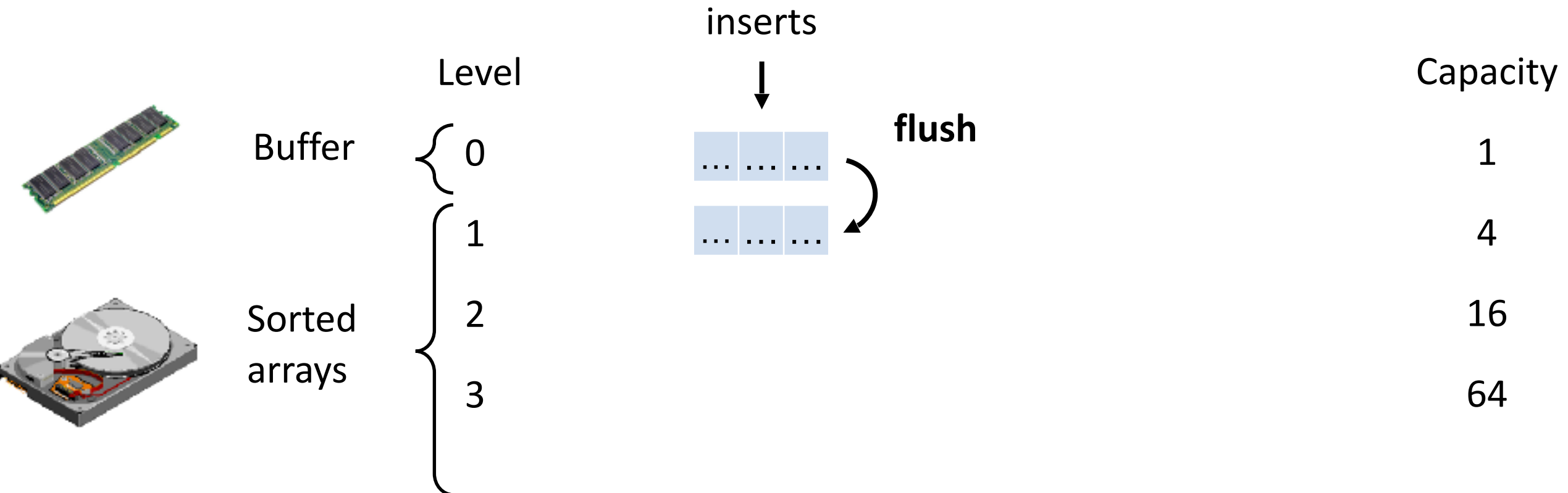


Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

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E.g. size ratio of 4

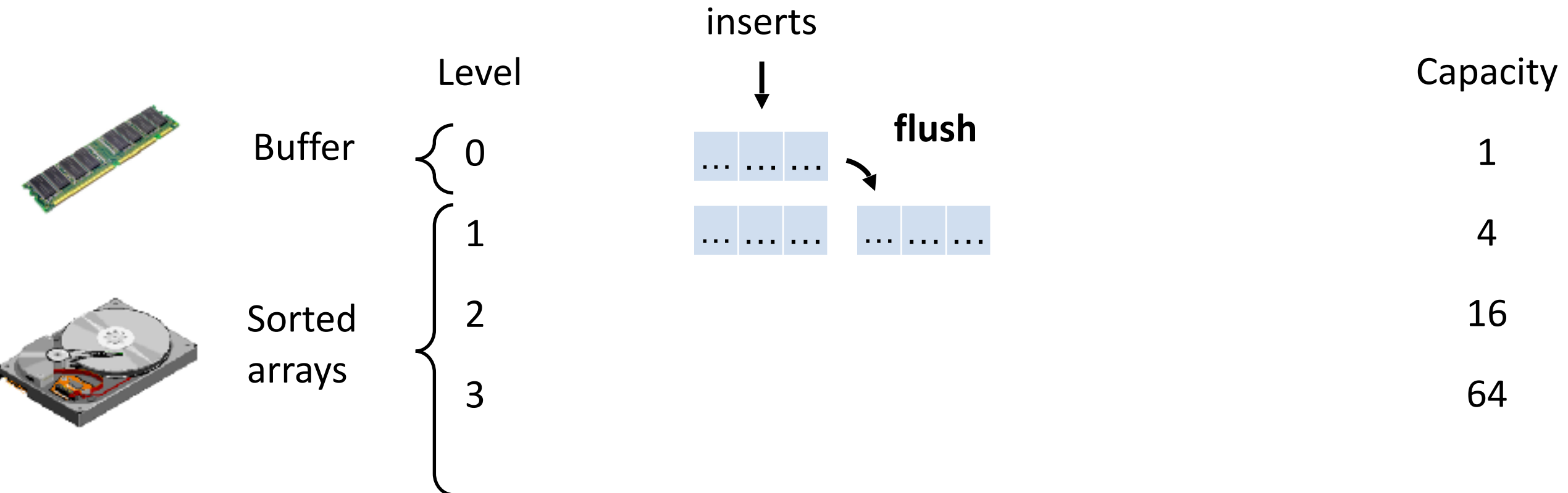


Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

Do not merge within a level.

E.g. size ratio of 4

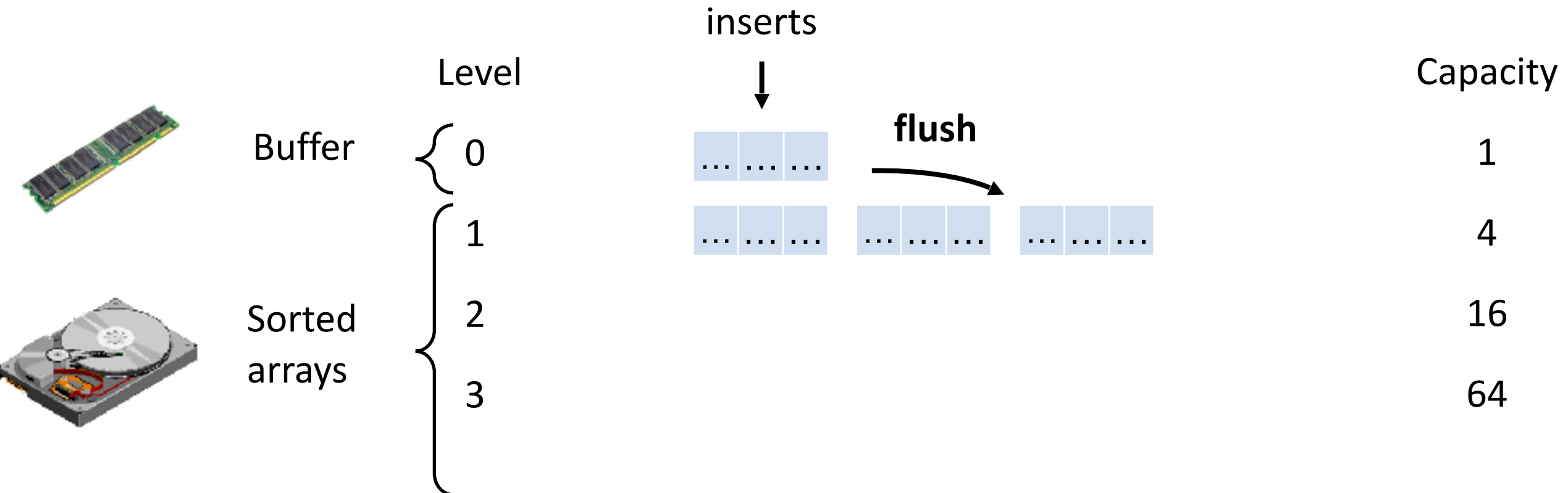


Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

Do not merge within a level.

E.g. size ratio of 4

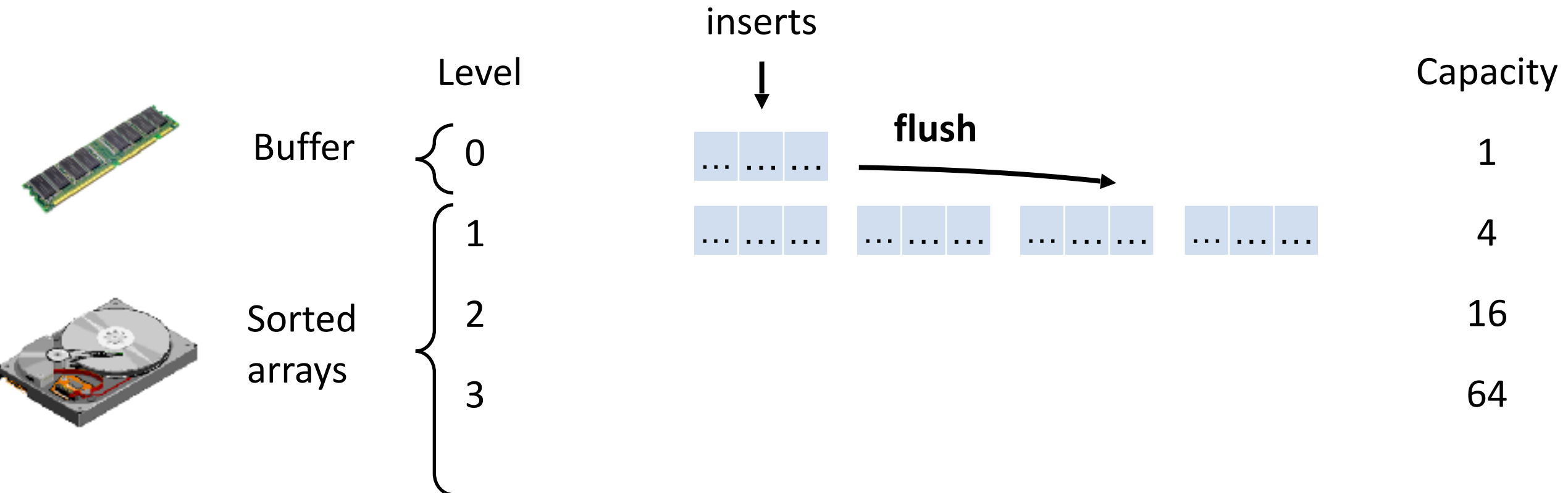


Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

Do not merge within a level.

E.g. size ratio of 4

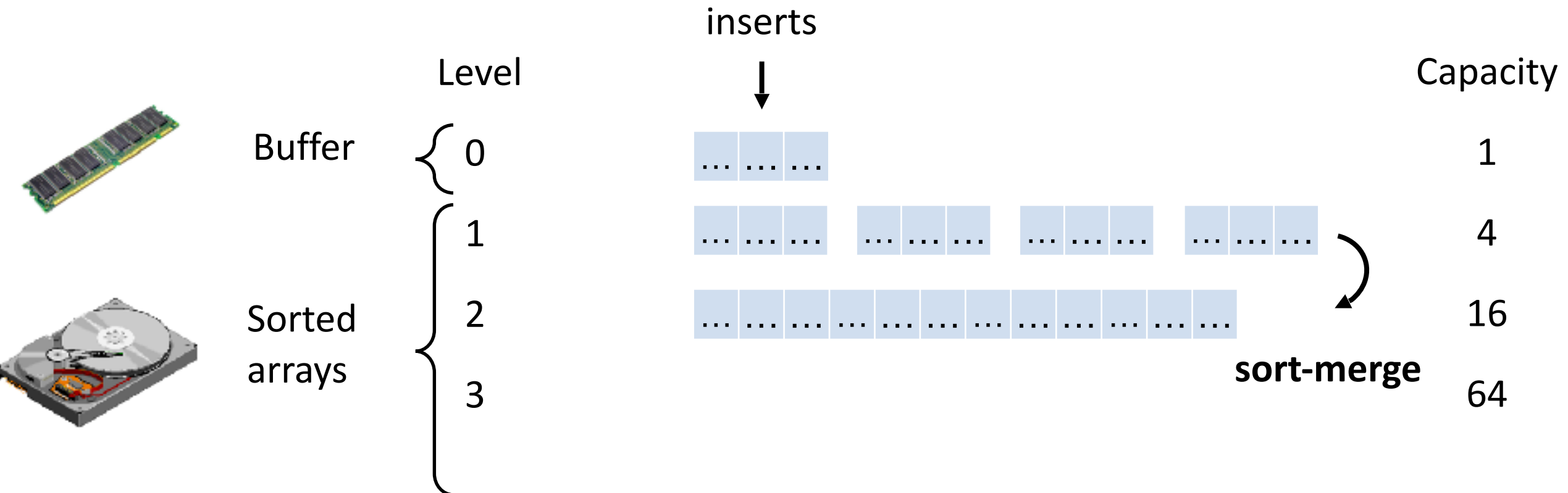


Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

Do not merge within a level.

E.g. size ratio of 4

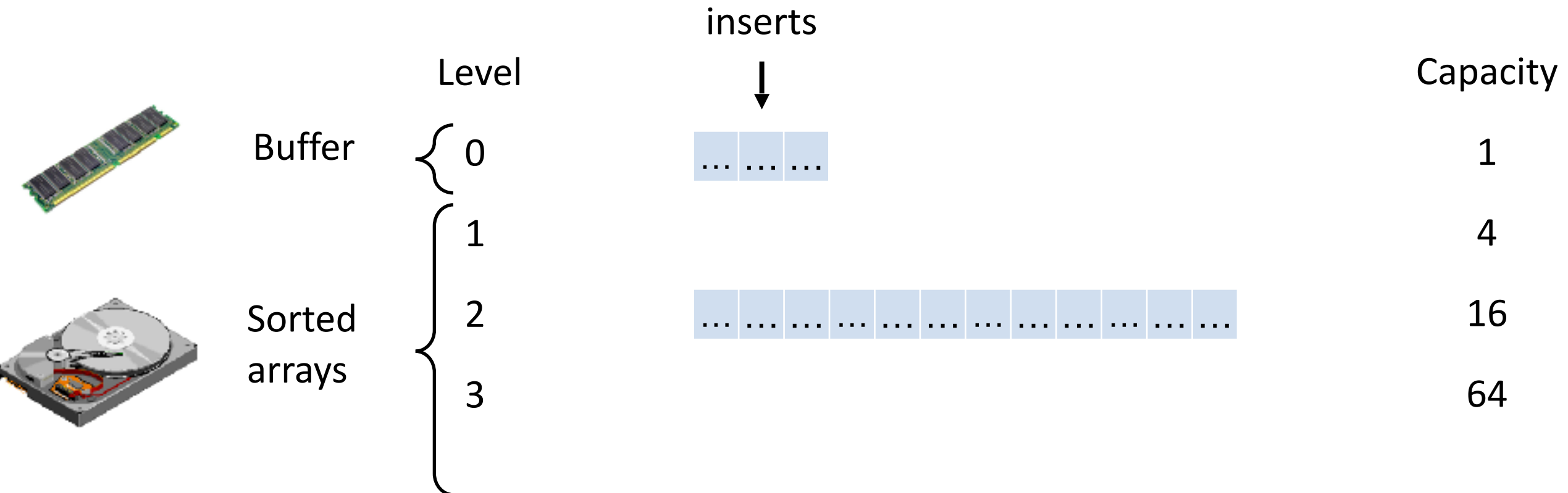


Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

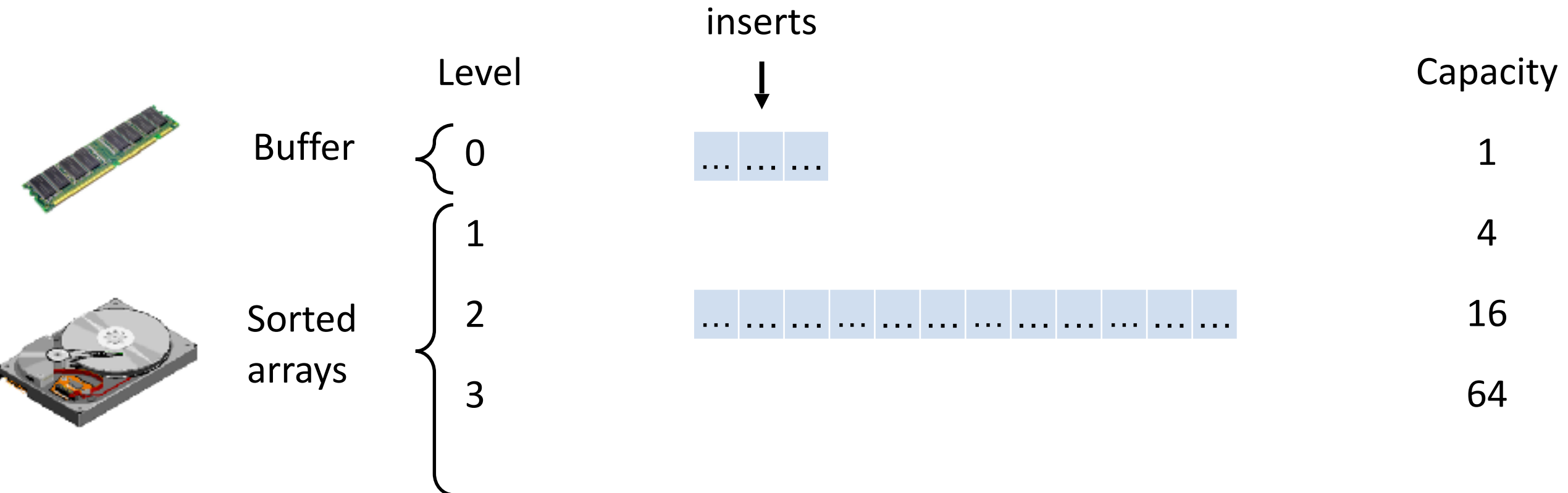
Do not merge within a level.

E.g. size ratio of 4



Tiered LSM-tree

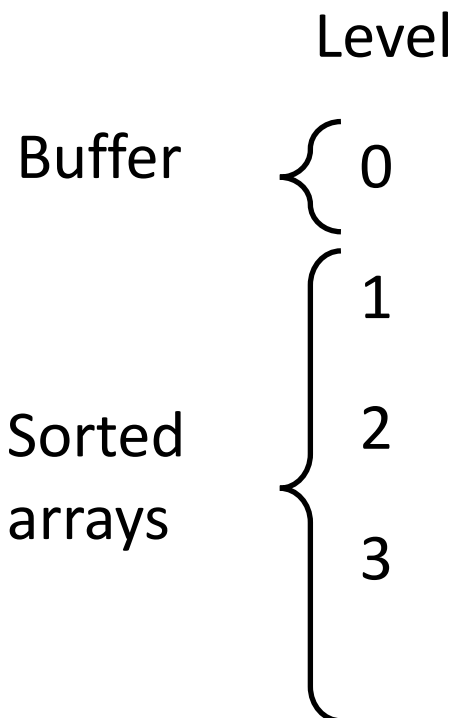
Lookup cost?



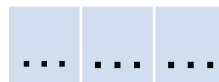
Tiered LSM-tree

Lookup cost?

$$O(T \bullet \log_T(N/B))$$



inserts



Capacity

1

4

16

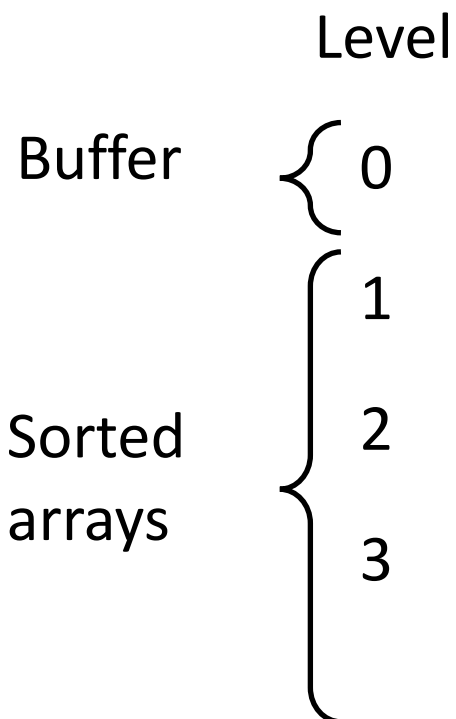
64

Tiered LSM-tree

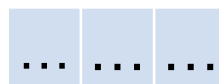
Lookup cost?

$$O(T \bullet \log_T(N/B))$$

Insertion cost?



inserts



Capacity

1

4

16

64

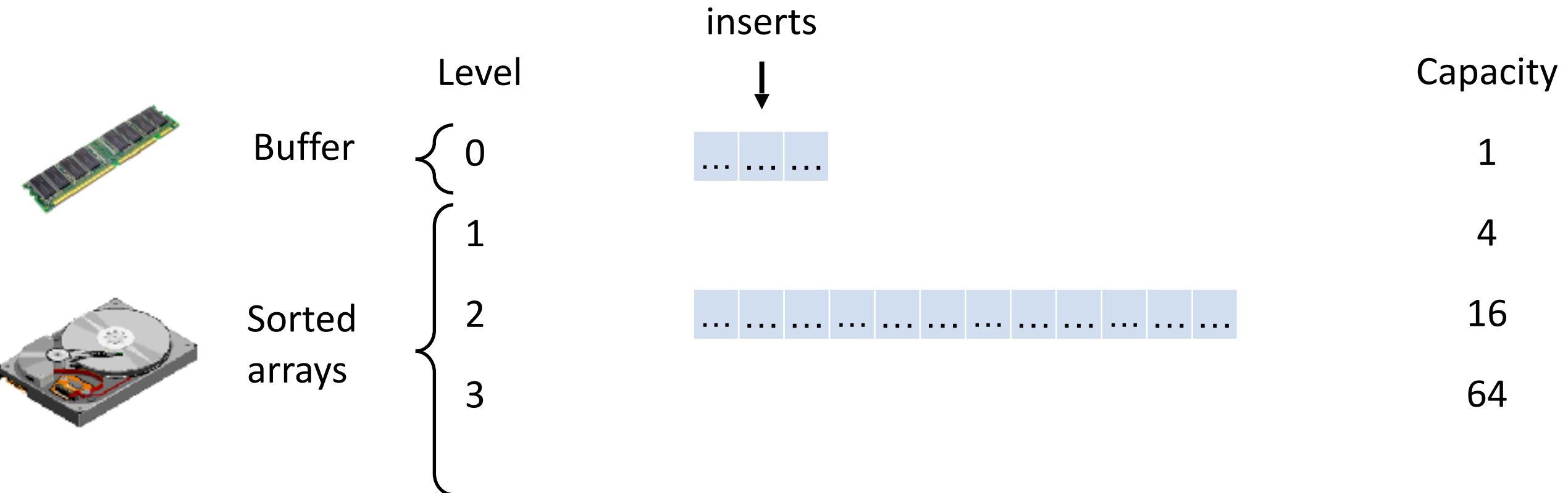
Tiered LSM-tree

Lookup cost?

$$O(T \cdot \log_T(N/B))$$

Insertion cost?

$$O(1/B \cdot \log_T(N/B))$$



Tiered LSM-tree

Lookup cost?

$$O(T \cdot \log_T(N/B))$$

Insertion cost?

$$O(1/B \cdot \log_T(N/B))$$

What happens as we increase the size ratio T ?

Tiered LSM-tree

Lookup cost?



$$O(T \cdot \log_T(N/B))$$

Insertion cost?

$$O(1/B \cdot \log_T(N/B))$$



What happens as we increase the size ratio T?

Tiered LSM-tree

Lookup cost?



$$O(T \cdot \log_T(N/B))$$

Insertion cost?

$$O(1/B \cdot \log_T(N/B))$$



What happens as we increase the size ratio T ?

What happens when size ratio T is set to be N/B ?

Tiered LSM-tree

Lookup cost?

 $O(T \cdot \log_T(N/B))$

Insertion cost?

$O(1/B \cdot \log_T(N/B))$ 

What happens as we increase the size ratio T ?

What happens when size ratio T is set to be N/B ?

Lookup cost becomes:

$O(N/B)$

Insert cost becomes:

$O(1/B)$

Tiered LSM-tree

Lookup cost?

 $O(T \cdot \log_T(N/B))$

Insertion cost?

$O(1/B \cdot \log_T(N/B))$ 

What happens as we increase the size ratio T ?

What happens when size ratio T is set to be N/B ?

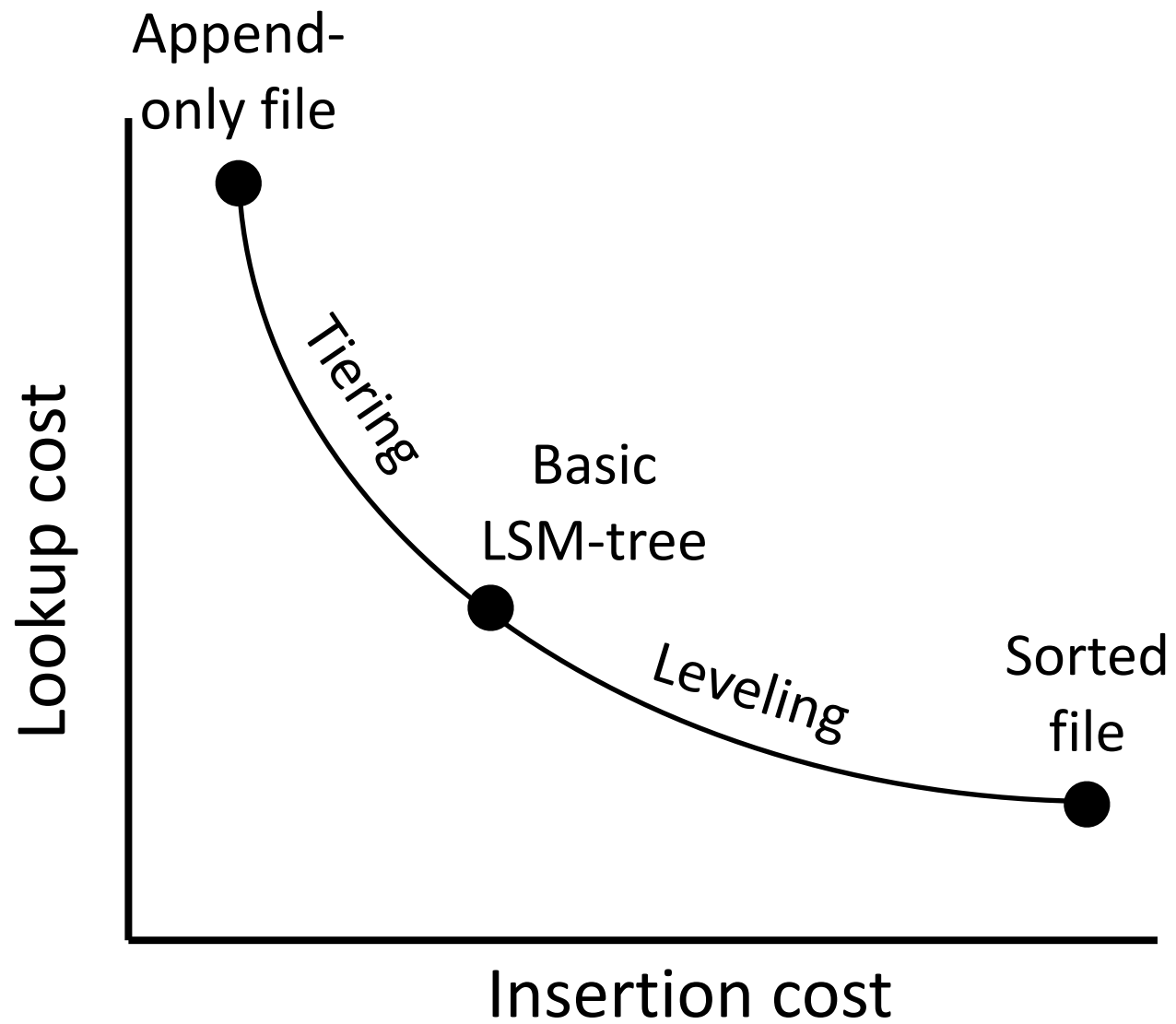
Lookup cost becomes:

$O(N/B)$

Insert cost becomes:

$O(1/B)$

The tiered LSM-tree becomes an append-only file!

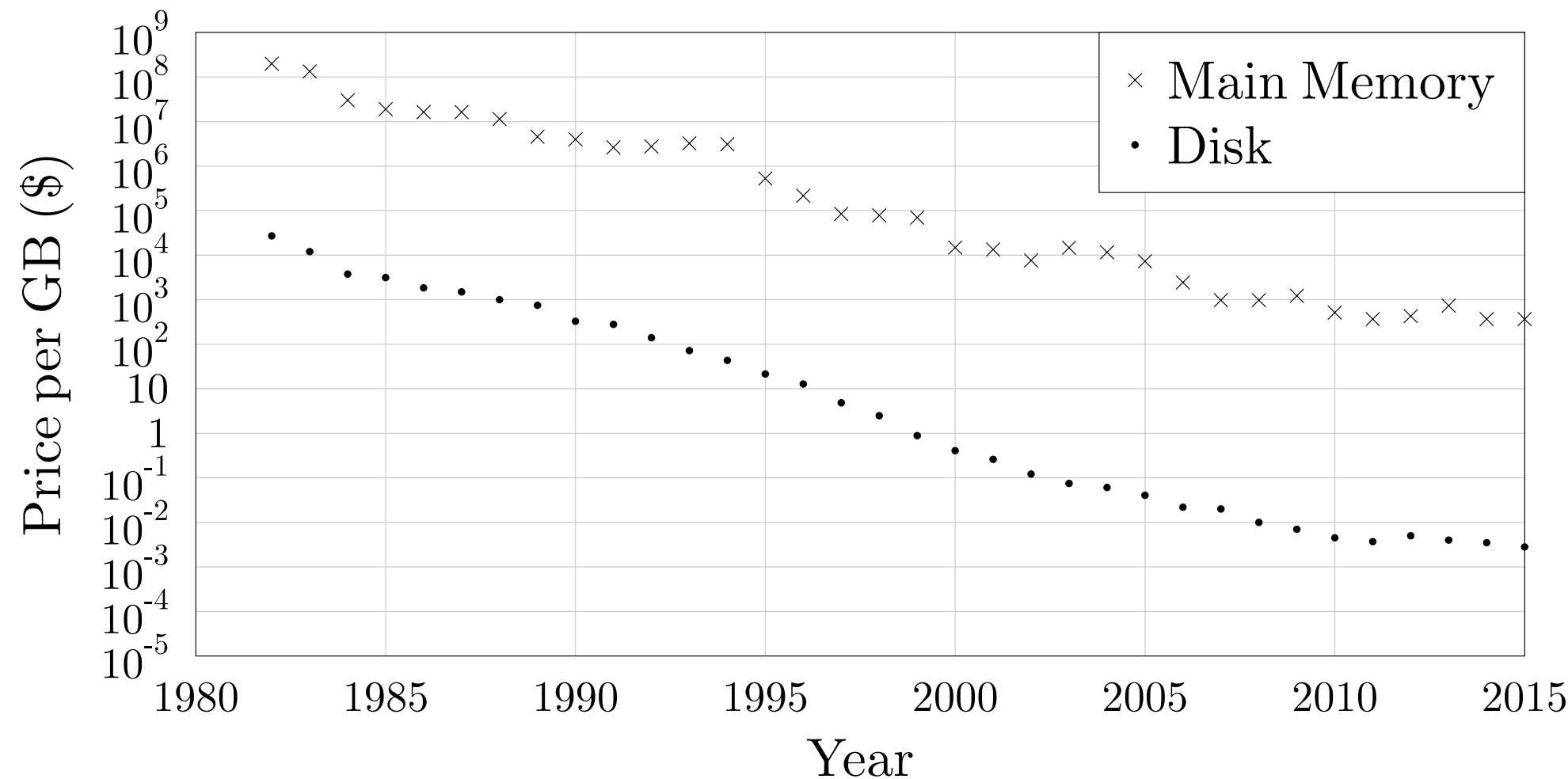


Operation		Unordered File	Leveled LSM-tree	Tiered LSM-tree	B-Tree
Query	Reads	$O(N/B)$	$O(L)$	$O(L * T)$	$O(1)$
	Writes	$O(1/B)$	$O((L * T)/B)$	$O(L/B)$	$O(1) \text{ \& GC}$
Memory		$O(B)$	$O(N/B)$	$O(N/B)$	$O(N/B)$

We let $L = \log_T(N/B)$

Bloom filters

Declining Main Memory Cost



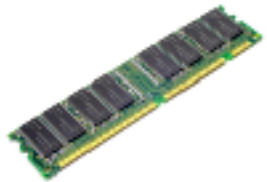
Bloom Filters

Answers set-membership queries

Smaller than data it represents

Purpose: avoid accessing storage if entry is not present

Subtlety: may return false positives.



filters



Bloom filter



array



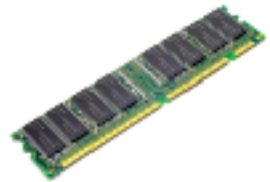
Bloom Filters

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filters



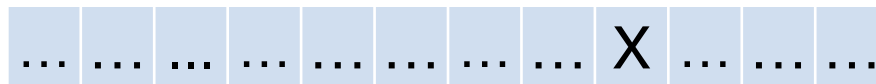
array



Lookup for X



Bloom filter



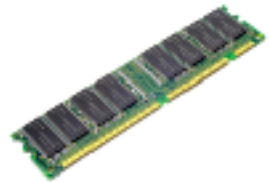
Bloom Filters

Answers set-membership queries

Smaller than data it represents

Purpose: avoid accessing storage if entry is not present

Subtlety: may return false positives.



filters



array



Lookup for X



Bloom filter



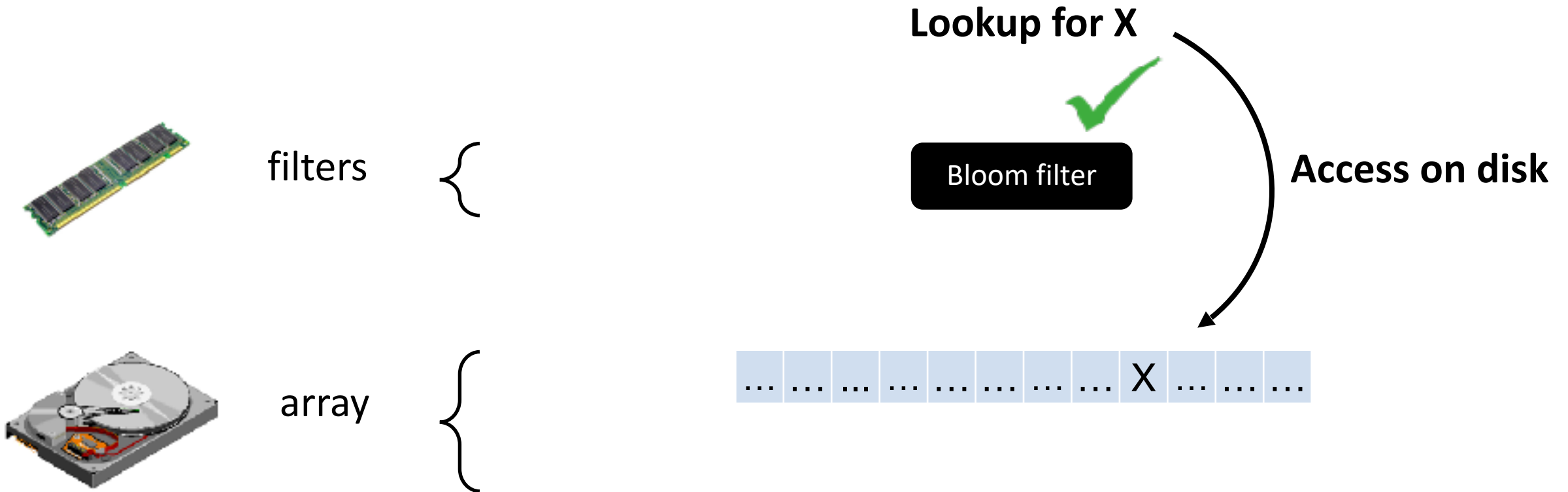
Bloom Filters

Answers set-membership queries

Smaller than data it represents

Purpose: avoid accessing storage if entry is not present

Subtlety: may return false positives.



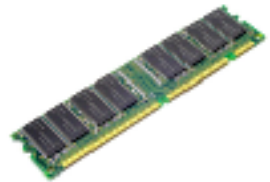
Bloom Filters

Answers set-membership queries

Smaller than data it represents

Purpose: avoid accessing storage if entry is not present

Subtlety: may return false positives.



filters



array



Lookup for Y



Bloom filter



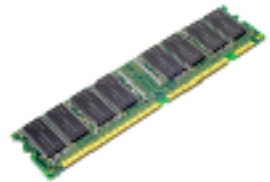
Bloom Filters

Answers set-membership queries

Smaller than data it represents

Purpose: avoid accessing storage if entry is not present

Subtlety: may return false positives.



filters



array



Lookup for Y



Bloom filter



Bloom Filters

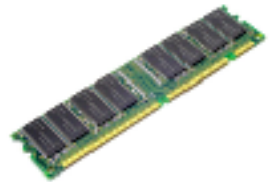
Answers set-membership queries

Smaller than data it represents

Purpose: avoid accessing storage if entry is not present

Subtlety: may return false positives.

Lookup for Y



filters



Bloom filter



array



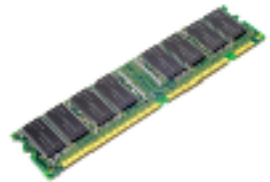
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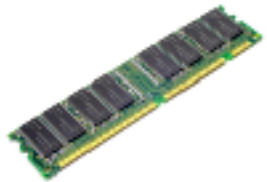
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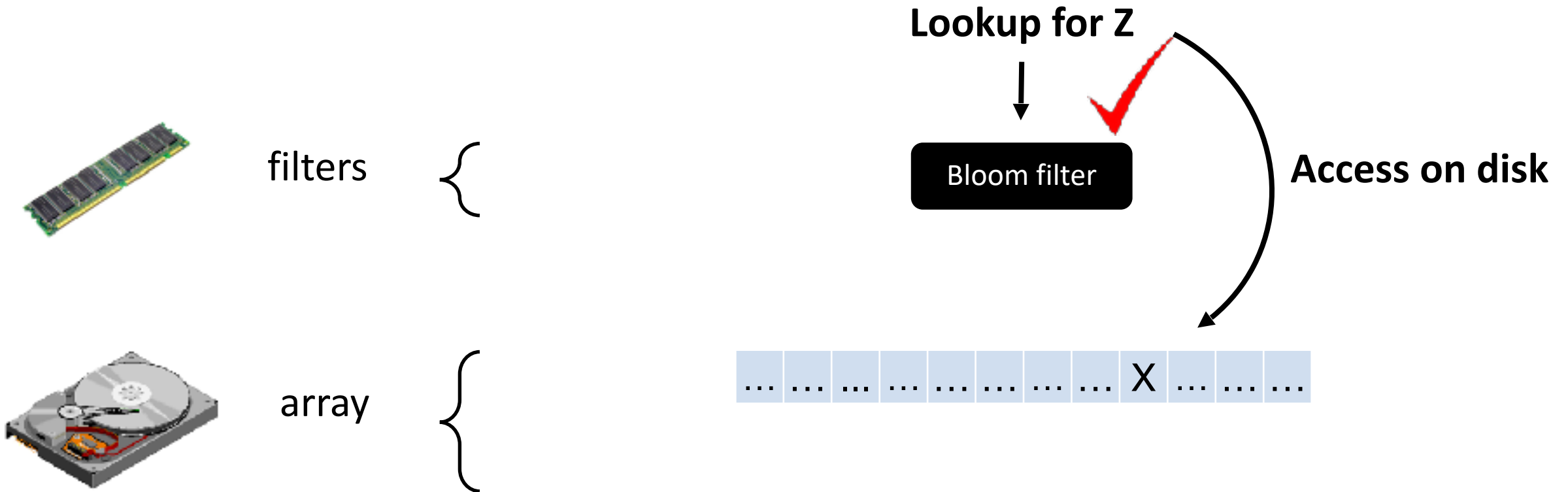
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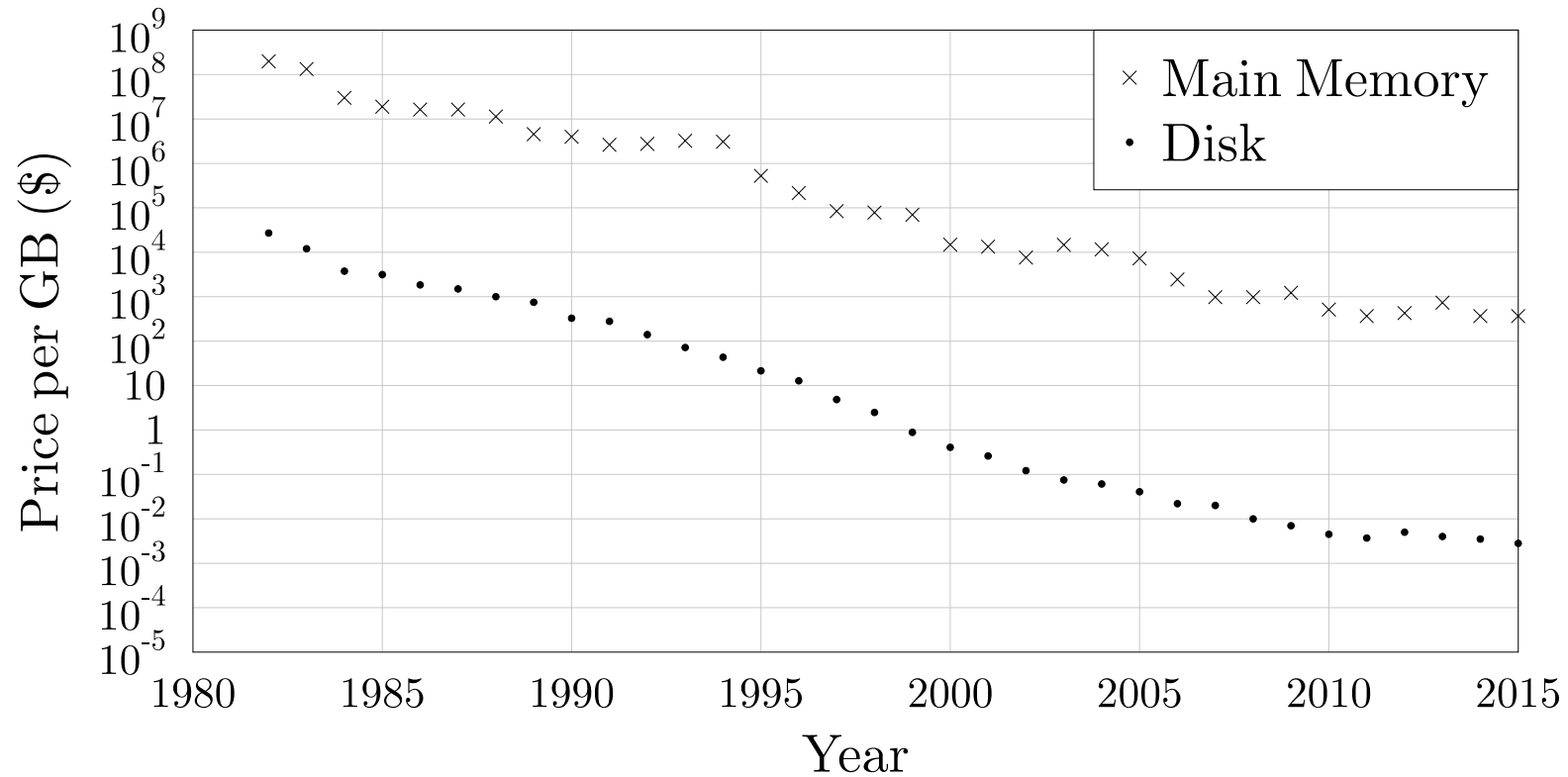
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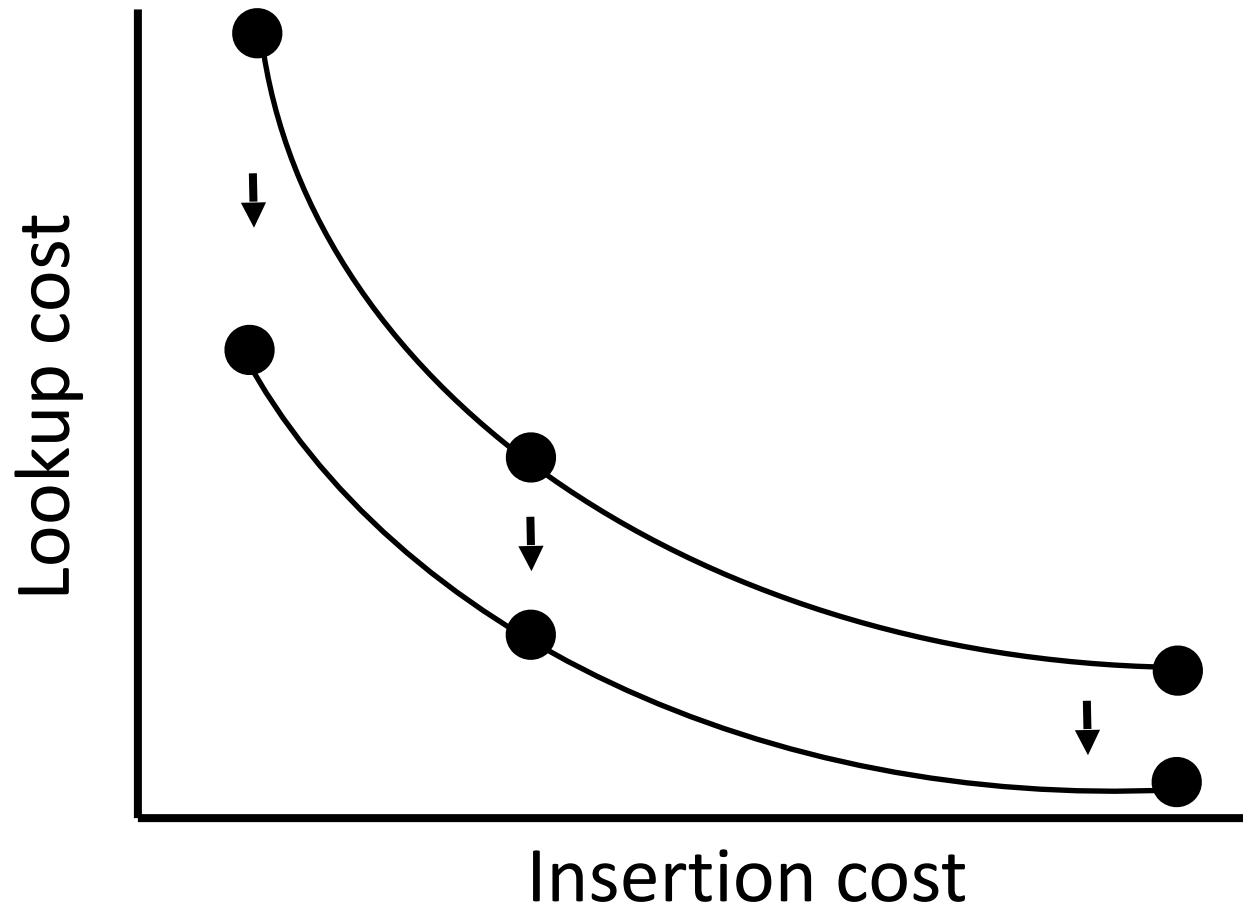
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The short-term future

Today: office hours after class in my office, 5230 in Bahen.

Thursday: Indexing exercises in tutorial this week.

Next week: research lecture. Important for your project.