Write-Optimized Indexing

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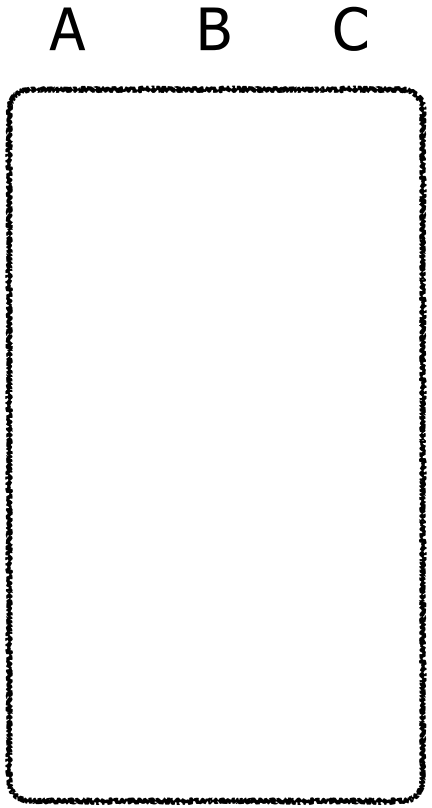
31 January, 2023

We will begin at 2:10 pm

We are trying to optimize the following kinds of queries



select * from table where A = “…”

select * from table where B > “…” and B < “…”

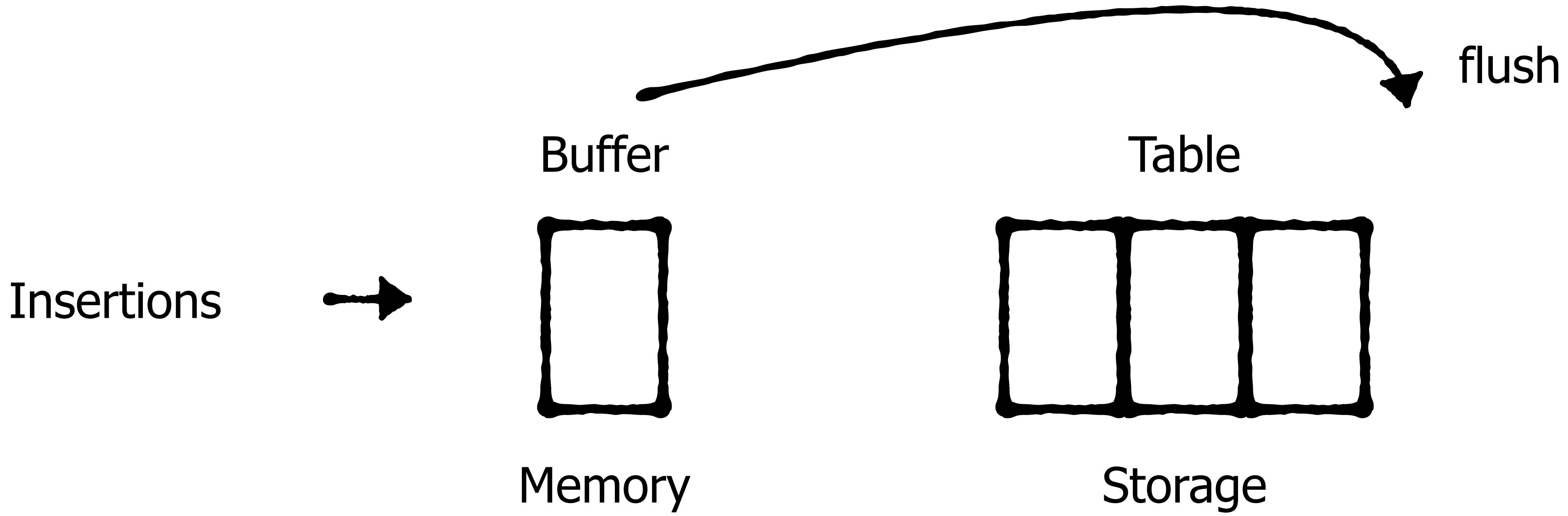
Let’s reconsider four baselines

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

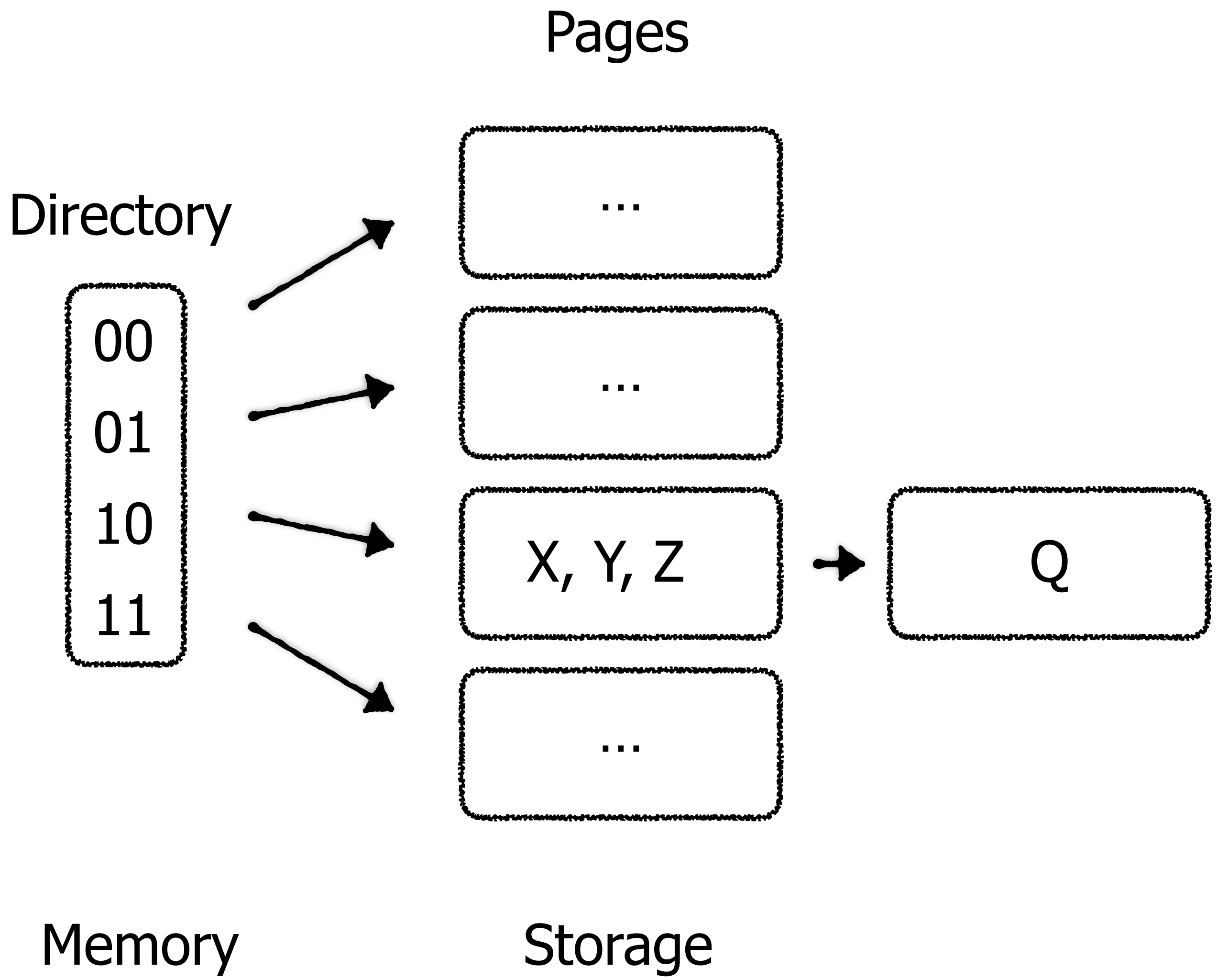
Let’s reconsider four baselines

Append-Only Table | Sorted Table | Extendible Hashing | B-tree

Extendible Hashing

A directory maps pages in storage with a given hash prefix

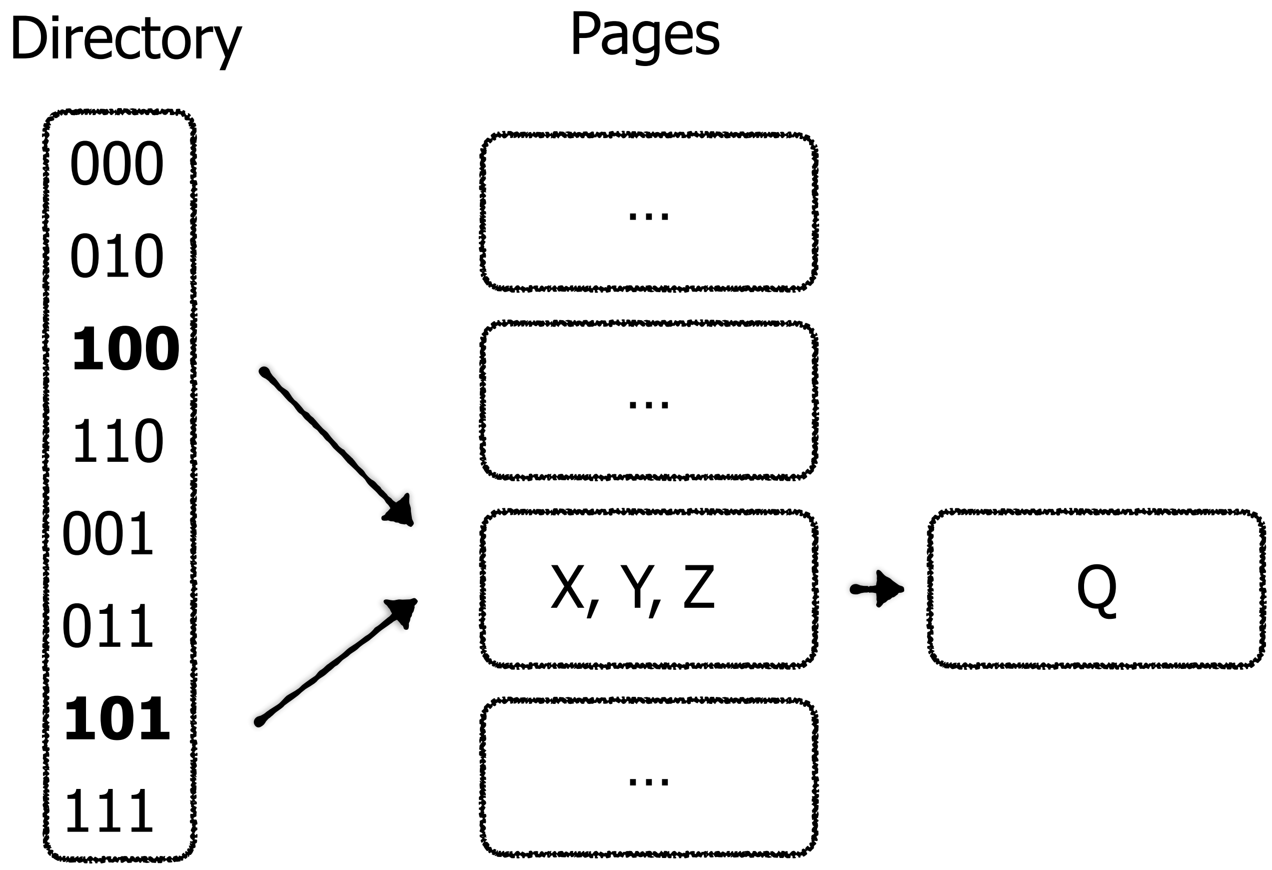
Handle overflows via chaining



Extendible Hashing

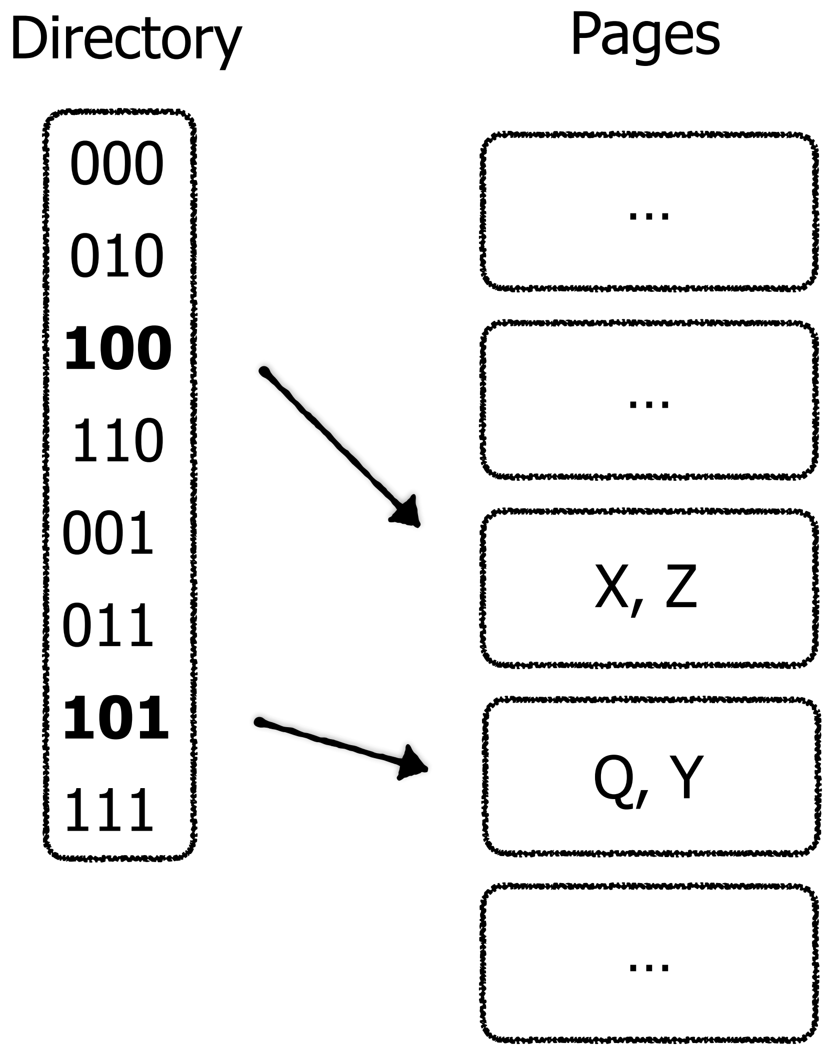
When we reach capacity, double directory size.

New directory slots still point to previous pages



Extendible Hashing

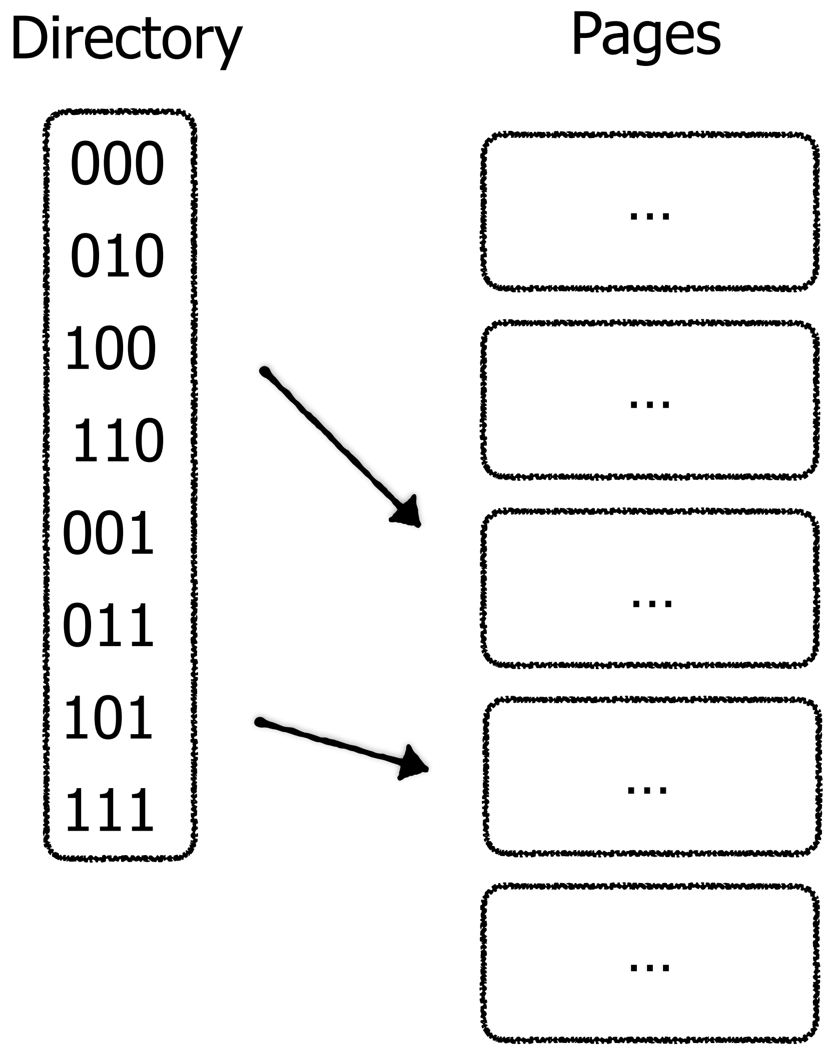
Split one overflowing bucket at a time by rehashing entries.



Extendible Hashing

Query cost: O(1) read I/O

Insertion cost:
- O(1) read I/O
- O(1) write I/O

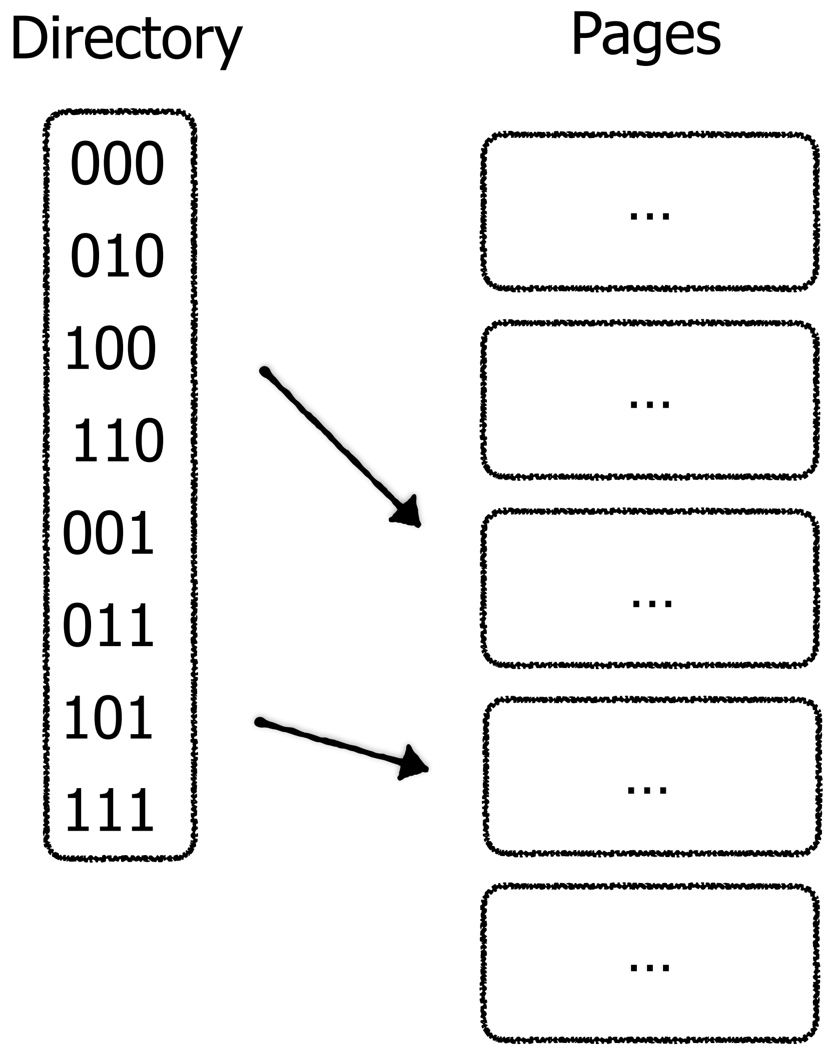


Extendible Hashing

Query cost: O(1) read I/O

Insertion cost:
O(1) read I/O
O(1) * **GC** write I/O

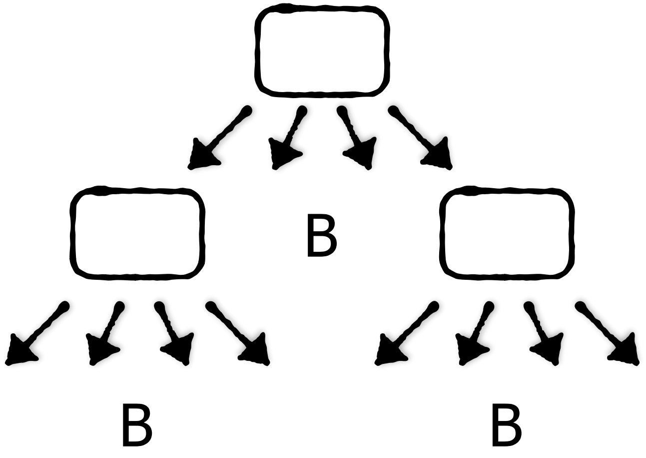
Random writes to storage entail SSD garbage-collection



Let’s reconsider four baselines

Append-Only Table | Sorted Table | Extendible Hashing | B-Tree

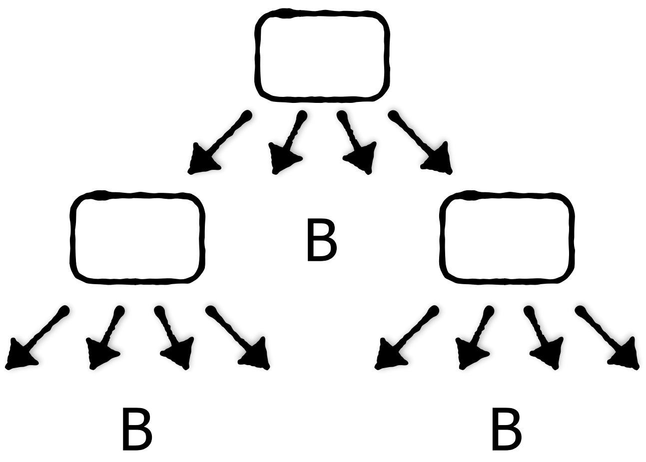
B-Tree



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

& $O(1)$ * GC write I/O

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

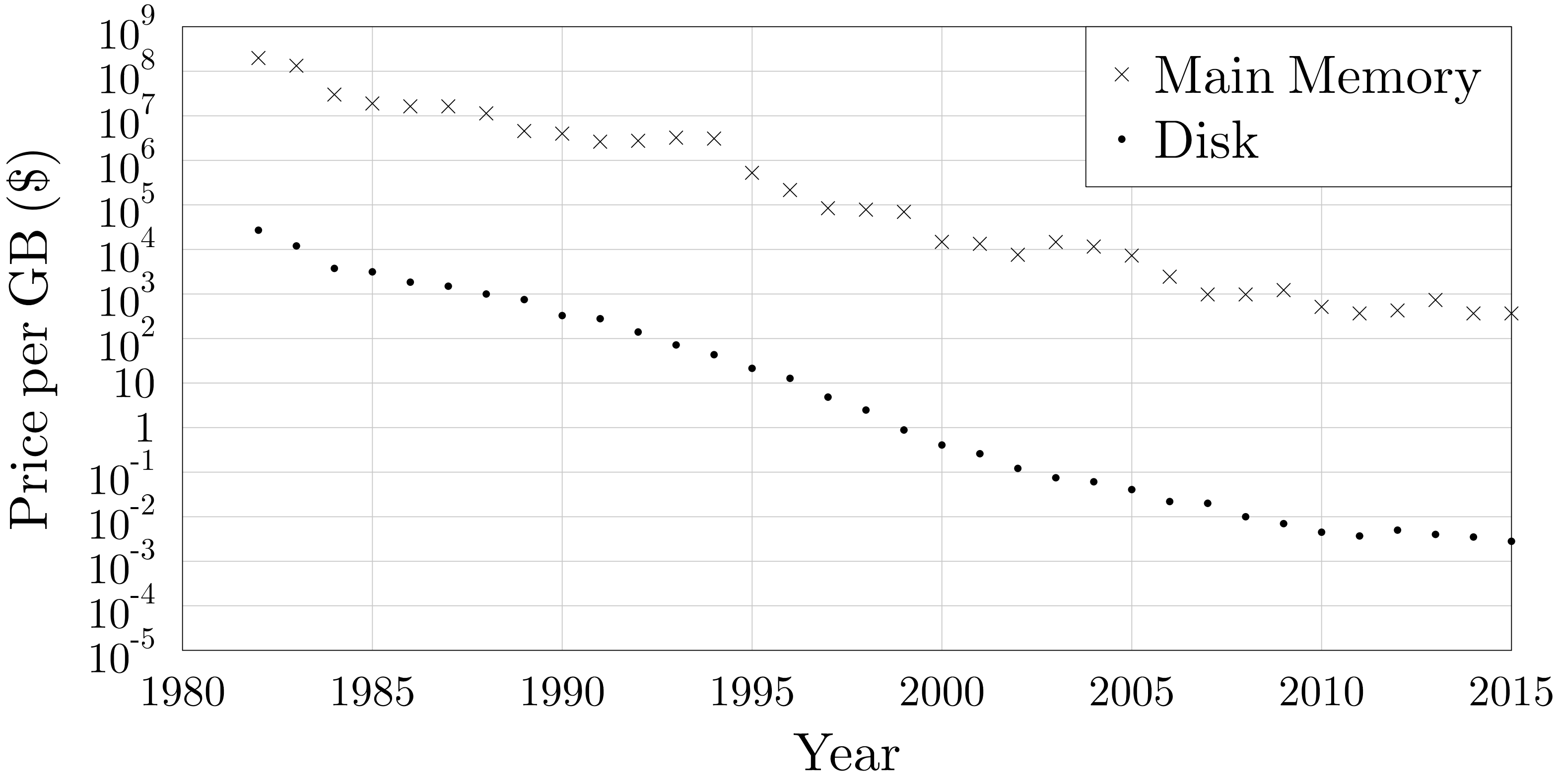
Google's BigTable adopts LSM-tree — 2005

LSM-tree is widely used — Today

B-tree is invented	LSM-tree is invented	Google’s BigTable adopts LSM-tree	LSM-tree is widely used
1970	1996	2005	Today

Why was it not invented and used sooner?

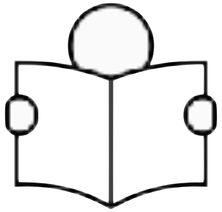
The declining costs of storage allow us to store more data cheaply.
Hence, application workloads are becoming more write-intensive.
This drives a need to optimize for data ingestion.



Leveled LSM-tree

Basic LSM-tree

Tiered LSM-tree



Basic LSM-tree

Level

Buffer 0

1

2

Sorted arrays 3

Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Level

Buffer

0

1

2

3

Sorted
arrays

Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Inserts

Level

Buffer — 0

… … …

Sorted arrays — 1, 2, 3

Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Inserts

Level

Buffer 0

sort & flush buffer

1 ... ...

Sorted arrays

2

3

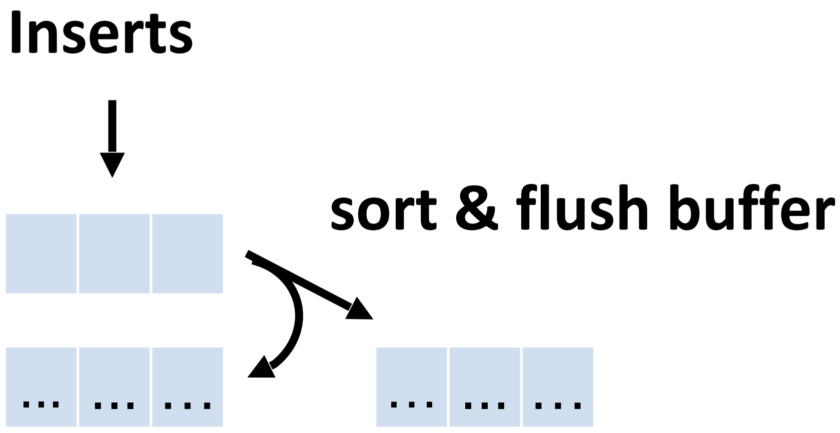
Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Level

Buffer — 0

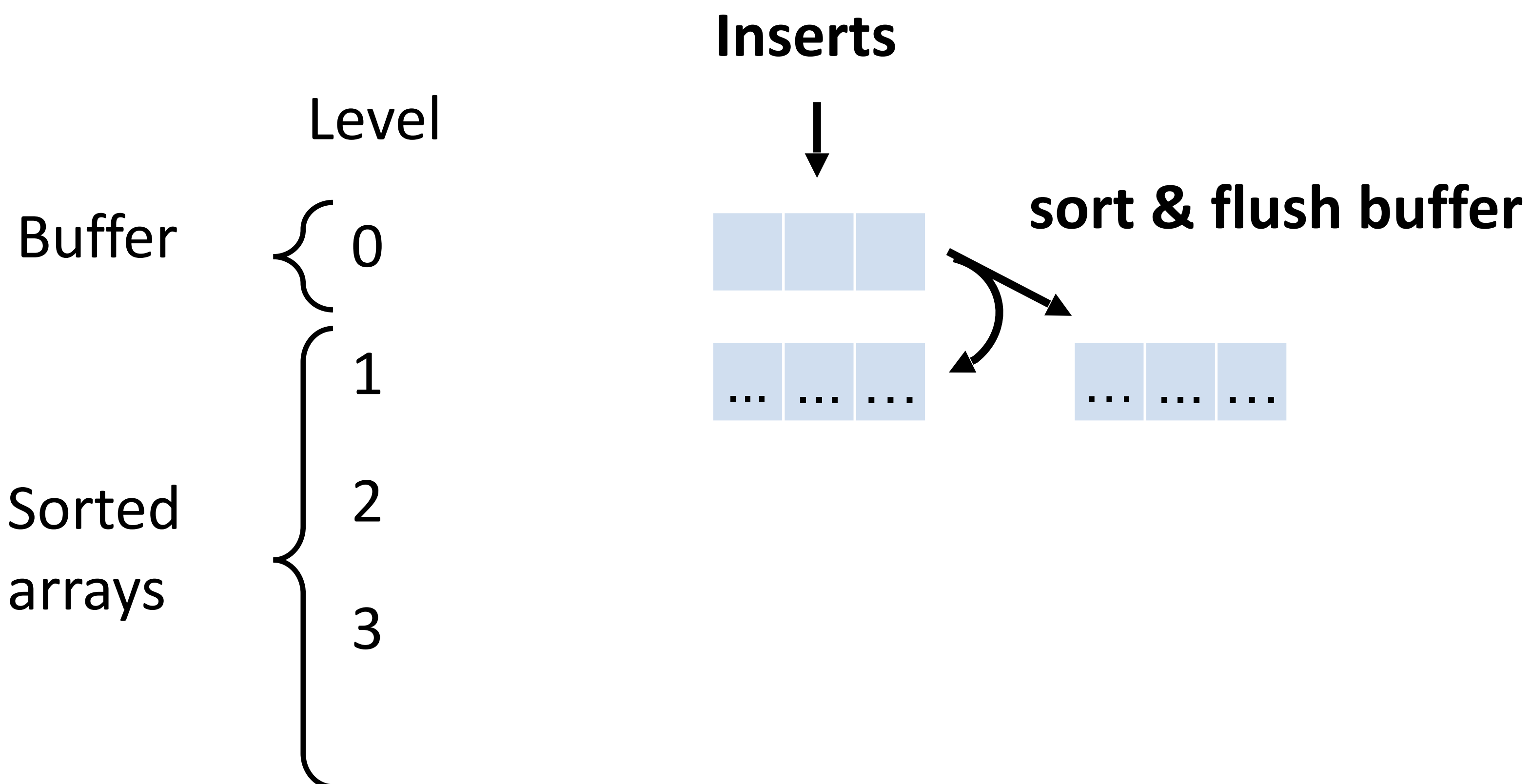
Sorted arrays — 1, 2, 3



Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Design principle #2: optimize for lookups by sort-merging SSTs



Basic LSM-tree

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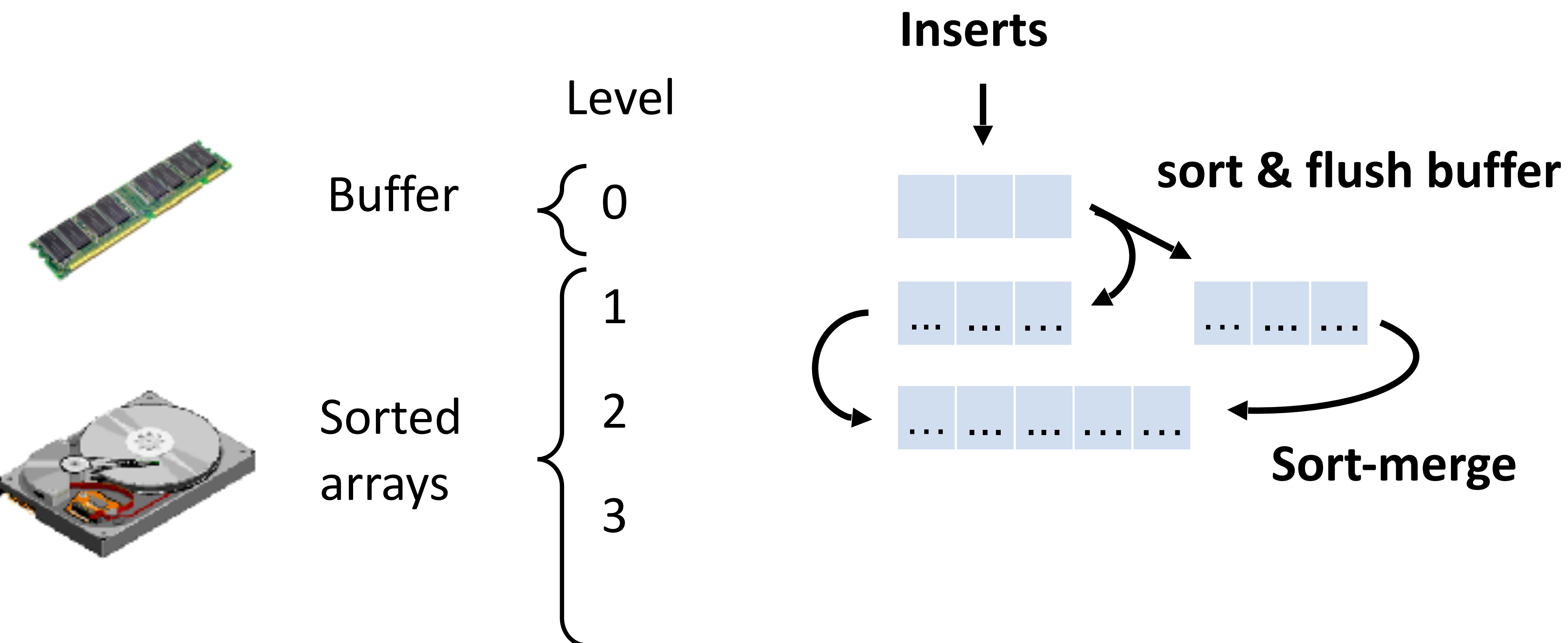
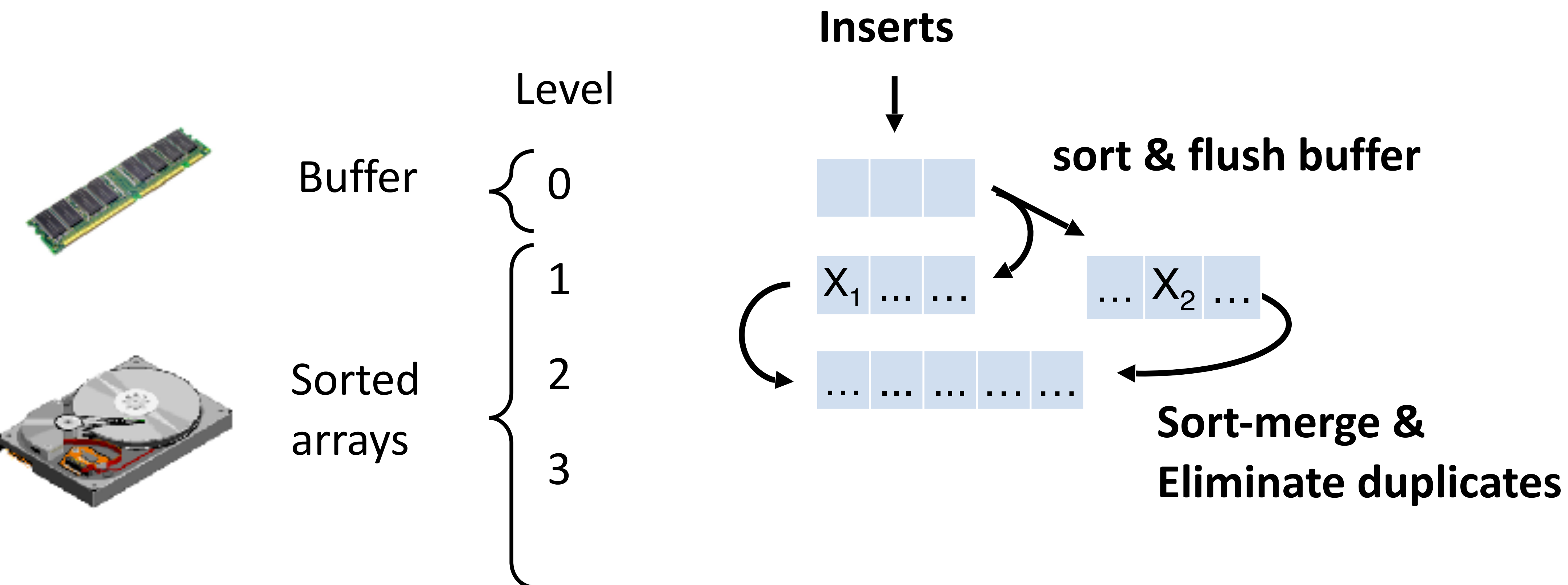


Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Design principle #2: optimize for lookups by sort-merging SSTs



Basic LSM-tree

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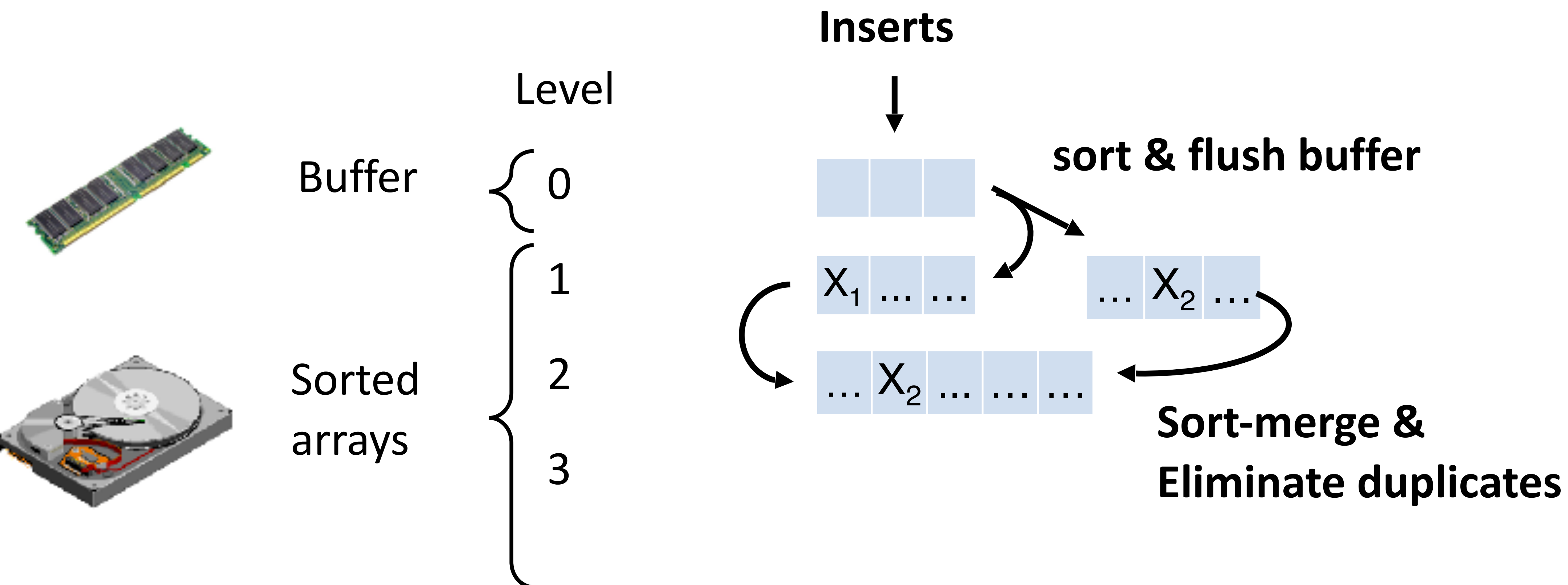

Basic LSM-tree

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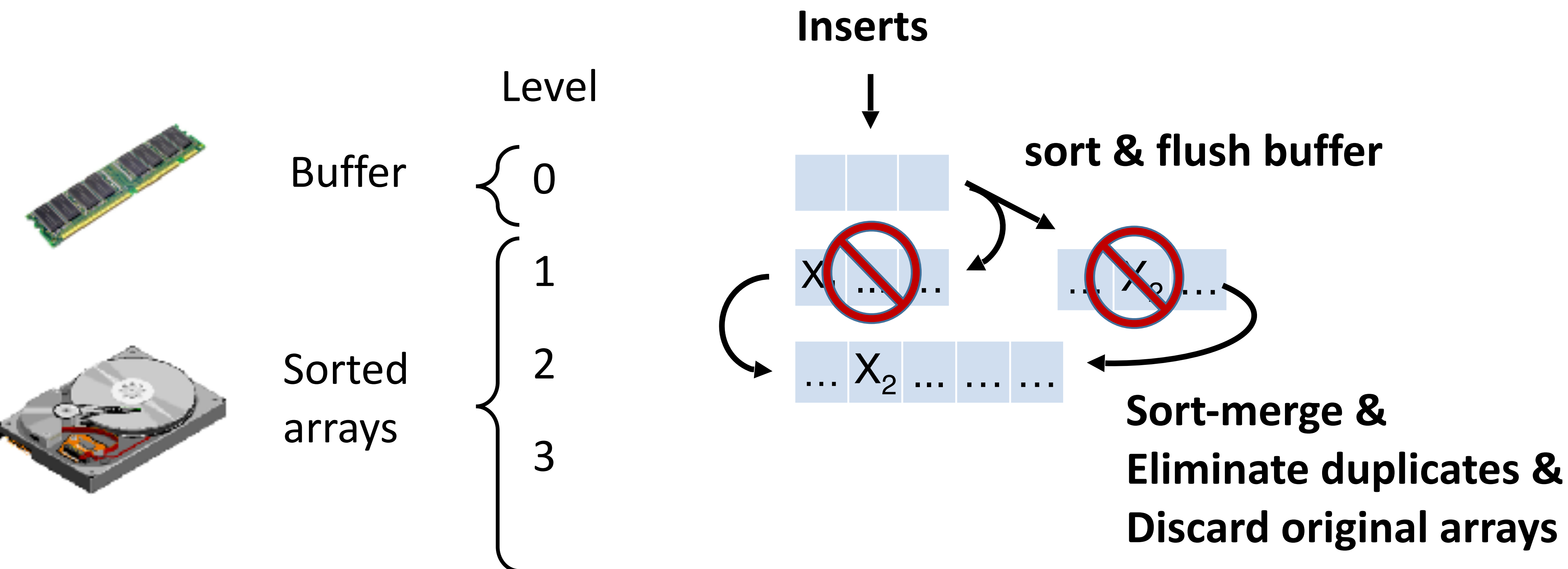
Design principle #2: optimize for lookups by sort-merging SSTs



Basic LSM-tree – Example

Level

Buffer

0

1

Sorted arrays

2

3

Basic LSM-tree – Example

inserts

Level

Buffer

0

4	6	9

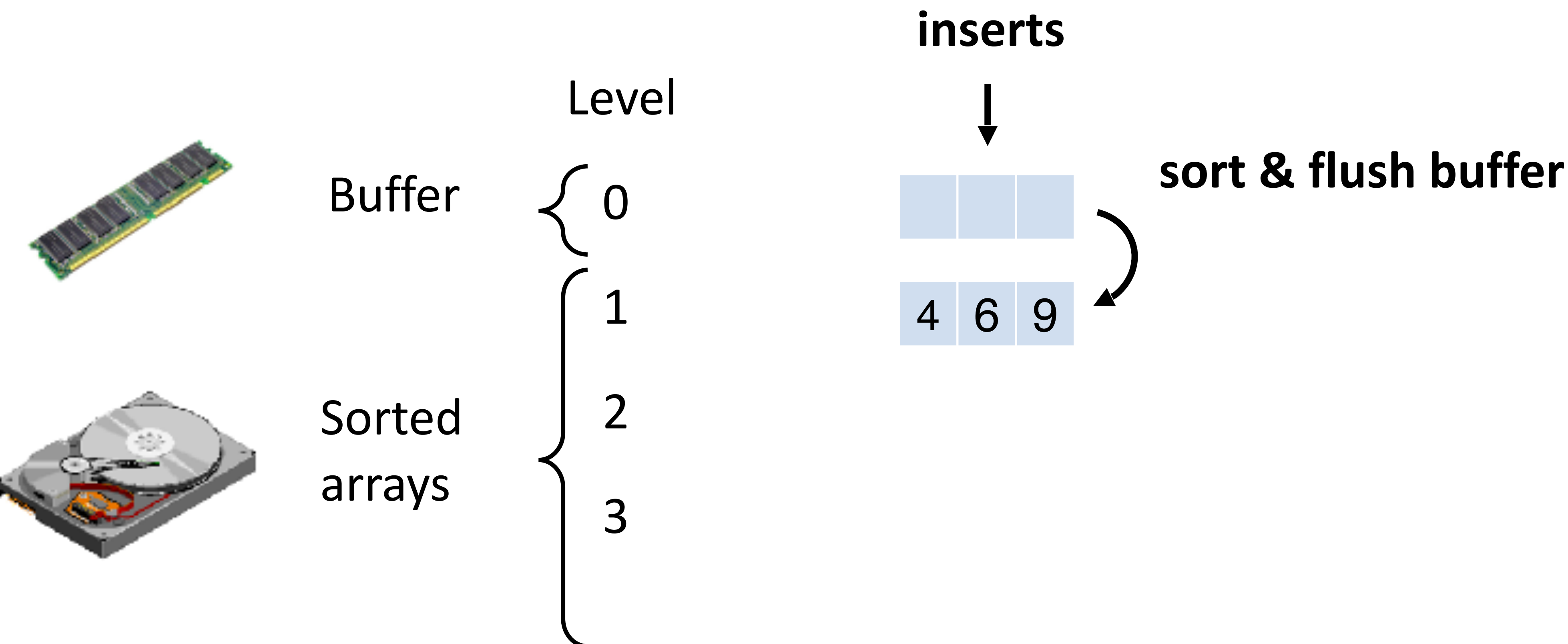
1

Sorted arrays

2

3

Basic LSM-tree – Example



Basic LSM-tree – Example

inserts

Level

Buffer

0

1

4	6	9

Sorted arrays

2

3

Basic LSM-tree – Example

inserts

Level

Buffer 0

3 4 8

1

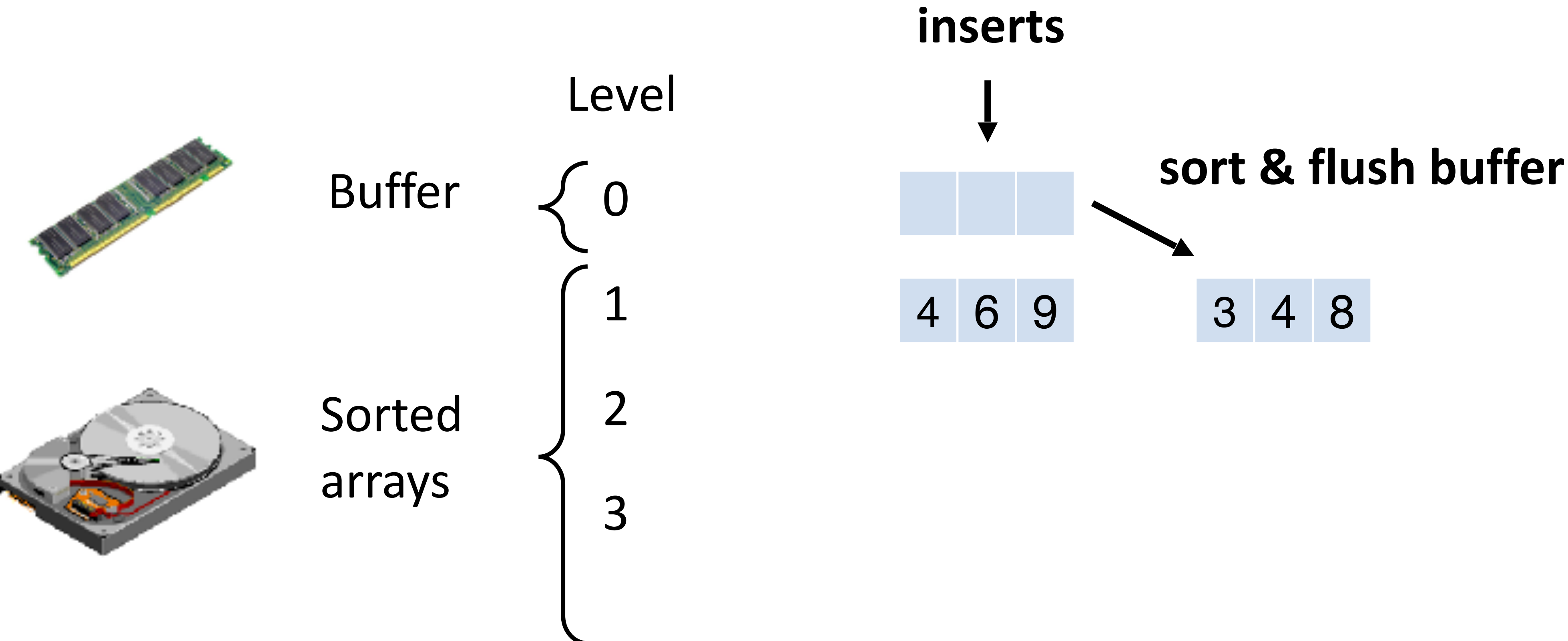
4 6 9

Sorted arrays

2

3

Basic LSM-tree – Example



Basic LSM-tree – Example

inserts

Level

Buffer

0

1

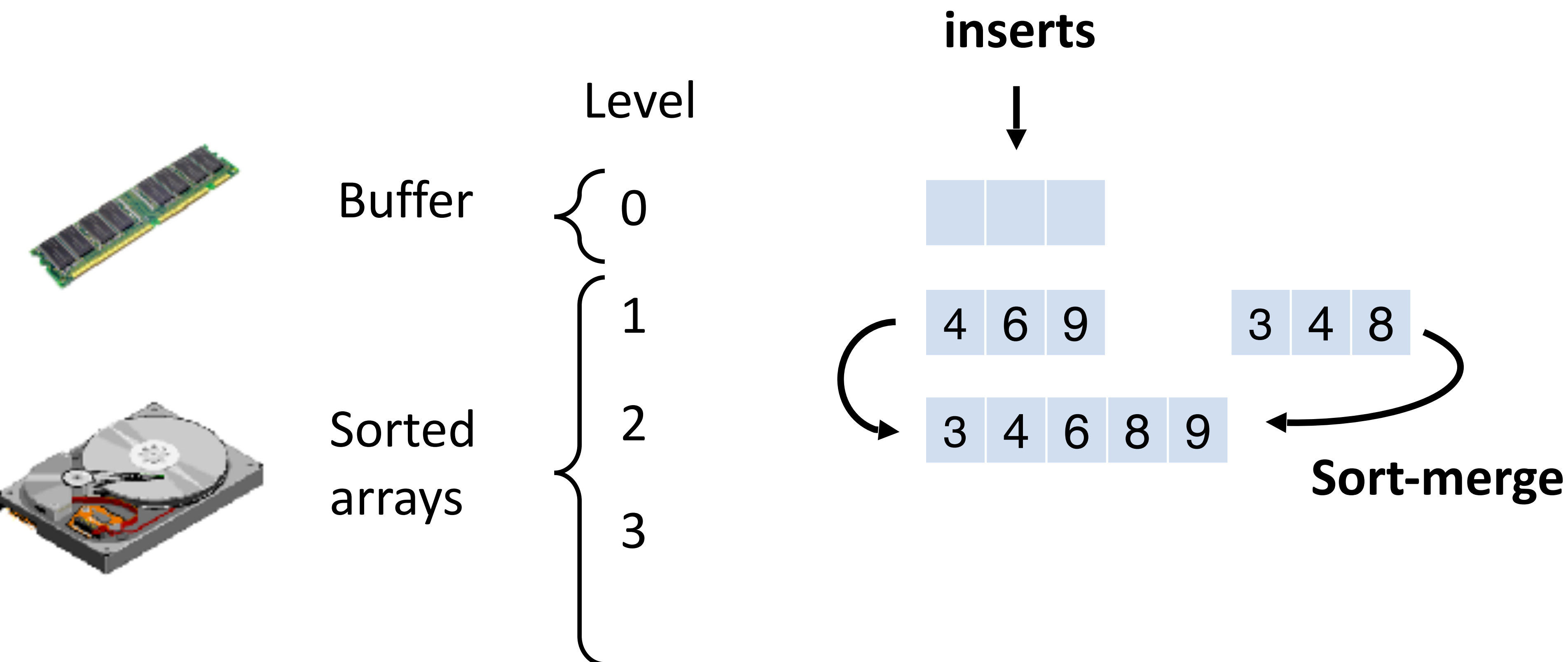
4	6	9		3	4	8	

Sorted arrays

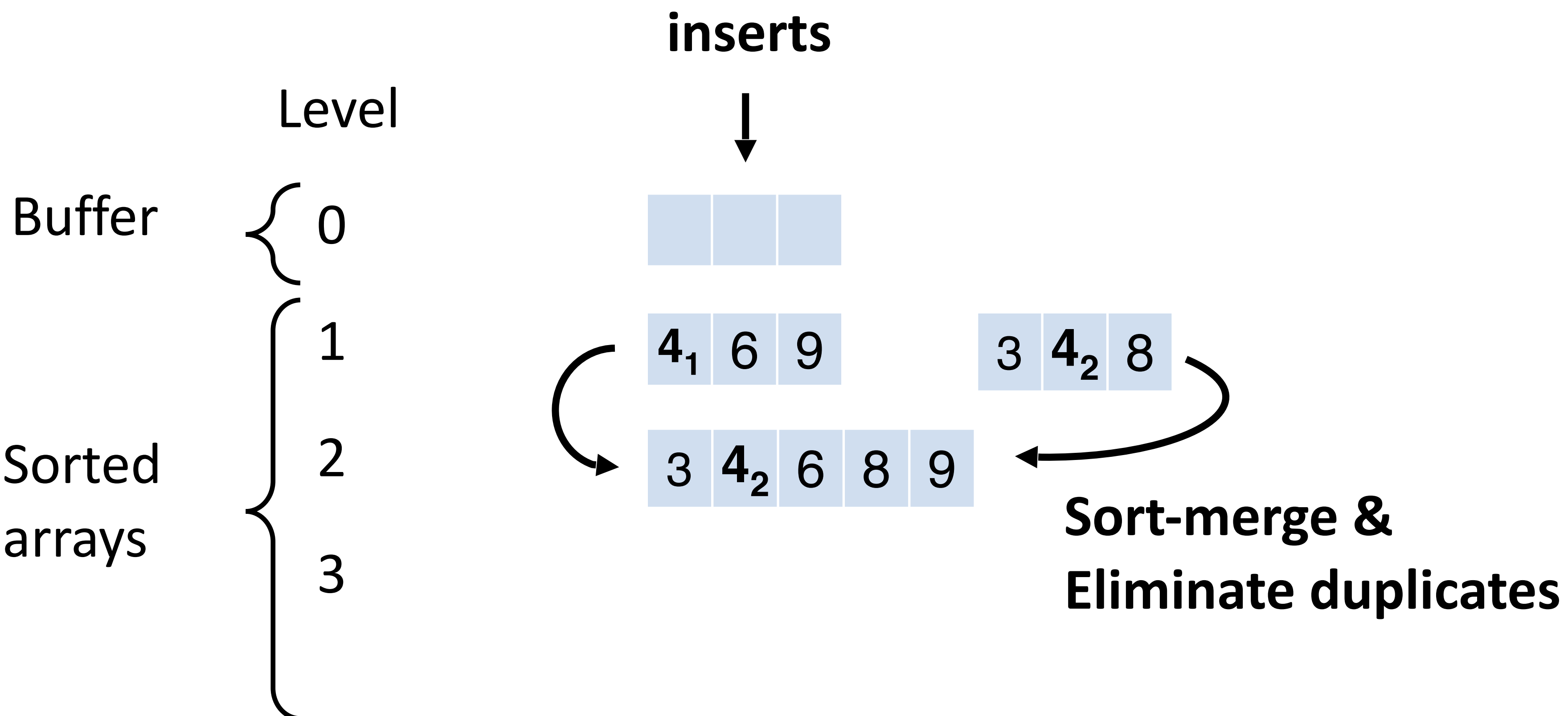
2

3

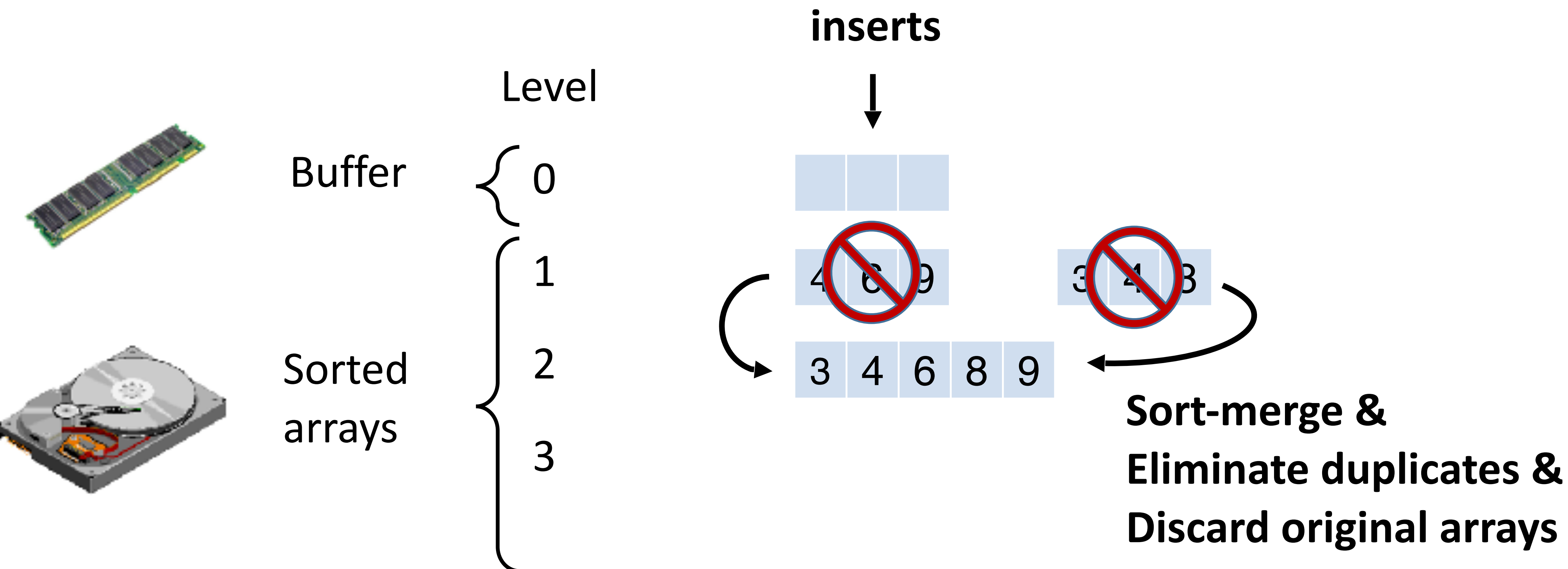
Basic LSM-tree – Example



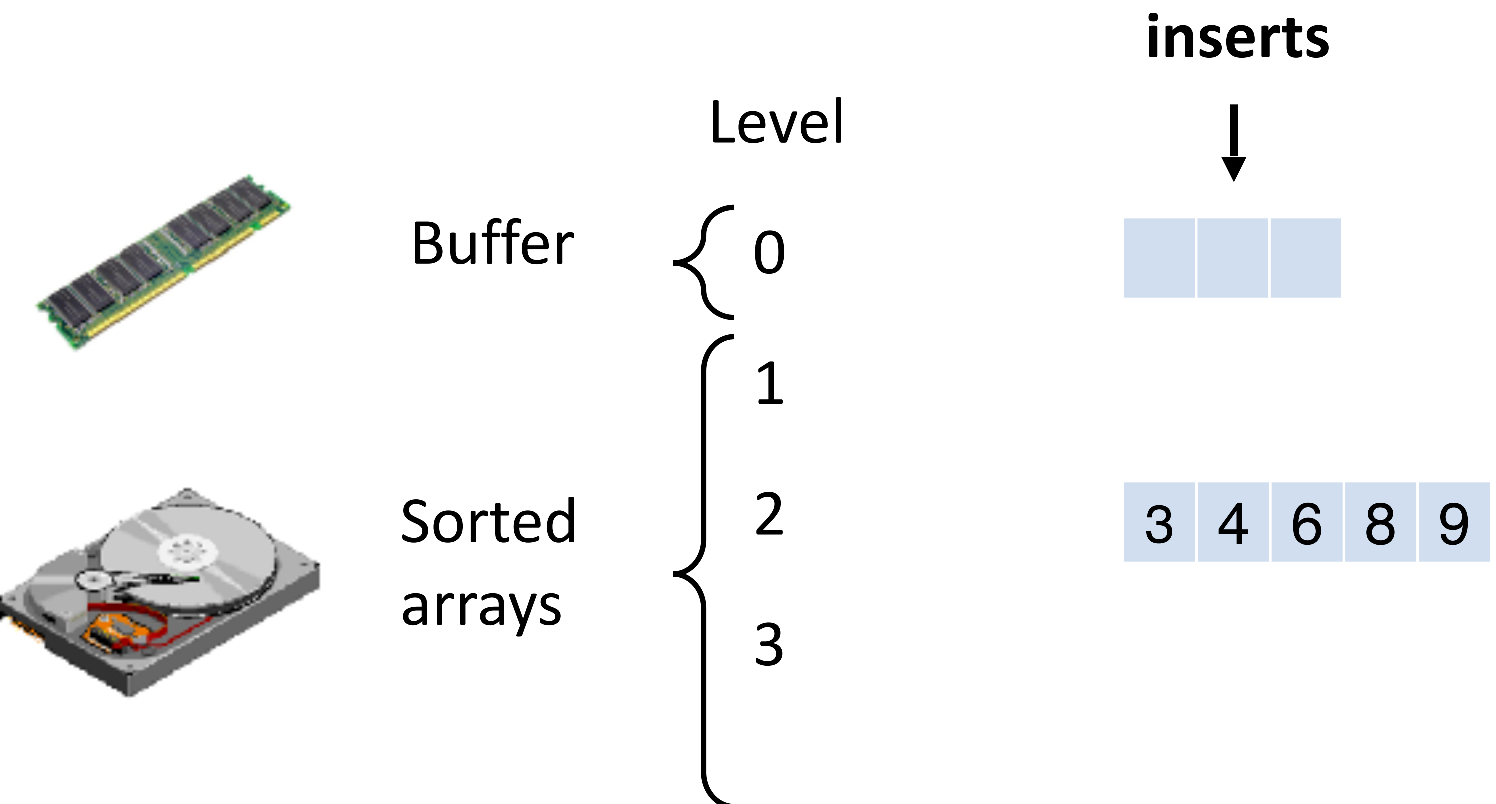
Basic LSM-tree – Example



Basic LSM-tree – Example



Basic LSM-tree – Example



Basic LSM-tree – Example

inserts

Level

Buffer

0: | 2 | 7 | 8 |

1

Sorted arrays

2: | 3 | 4 | 6 | 8 | 9 |

3

Basic LSM-tree – Example

inserts

Level

sort & flush buffer

Buffer

0

Sorted
arrays

1 2 7 8

2 3 4 6 8 9

3

Basic LSM-tree – Example

inserts

Level

Buffer 0

1

2	7	8

Sorted arrays

2

3	4	6	8	9

3

Basic LSM-tree

Levels have exponentially increasing capacities.

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree - Updates

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

Put(X, Y)

	Level		Capacity
Buffer	0	… X_0 …	1
Sorted arrays	1	… X_1 …	2
	2	… … X_2 … … …	4
	3	… … … … … … X_3 … … … … …	8

Basic LSM-tree - Updates

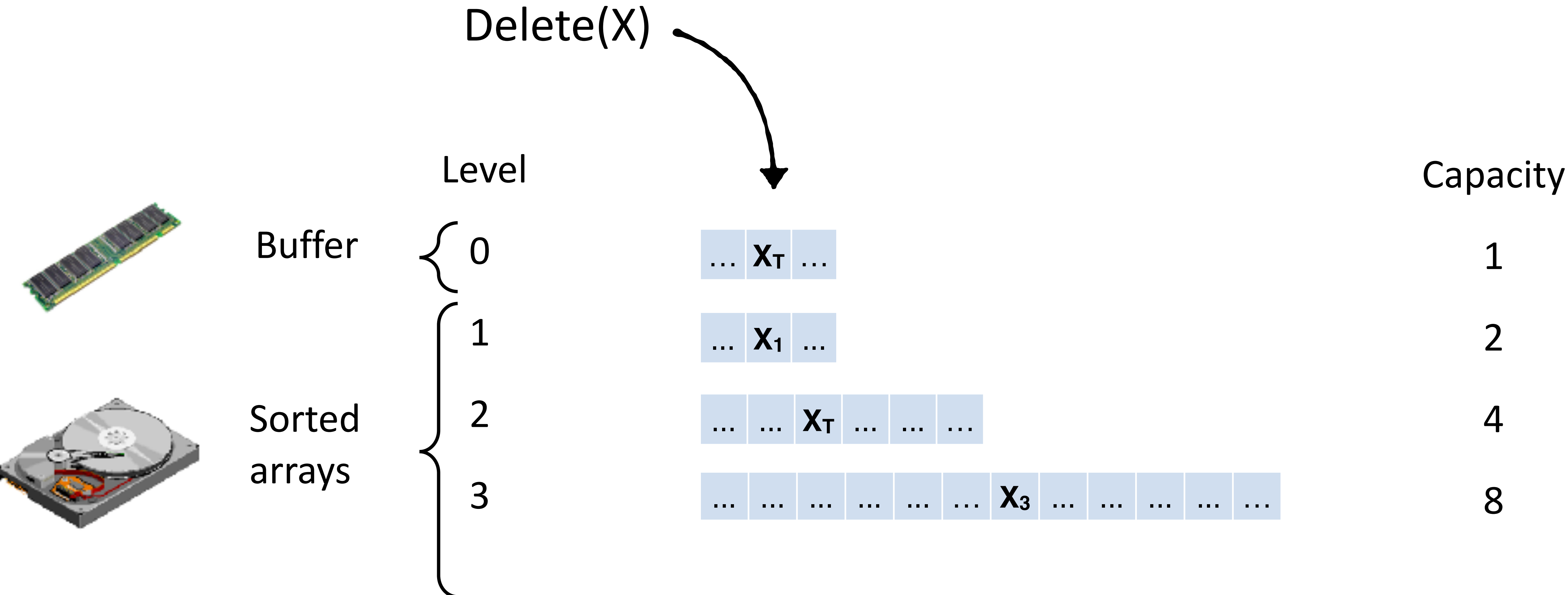
Can be made out-of-place through an insertion into the buffer

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

	Level		Capacity
Buffer	0	… **X_0** …	1
Sorted arrays	1	… X_1 …	2
	2	… … X_2 … … …	4
	3	… … … … … … X_3 … … … … …	8

Basic LSM-tree - Deletes

Delete an entry by inserting a tombstone



Basic LSM-tree - Deletes

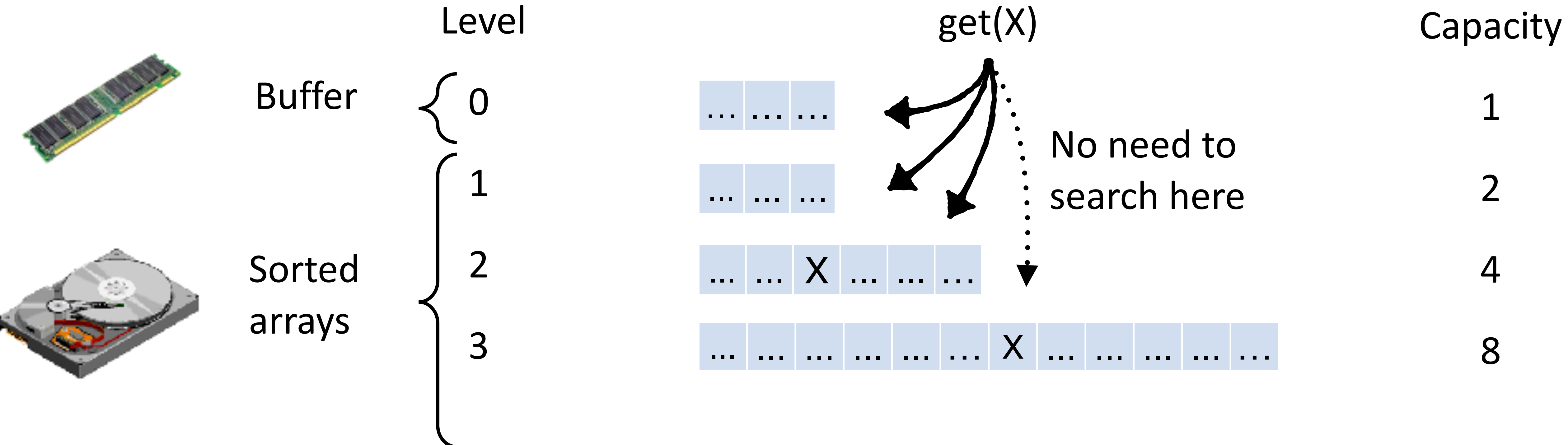
Delete an entry by inserting a tombstone

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)

	Level		Capacity
Buffer	0	… X_T …	1
Sorted arrays	1	… X_1 Y_1	2
	2	… … X_T … … …	4
	3	… … … … … … X_3 … … Y_T … …	8

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?

		Level		Capacity
	Buffer	0	… … …	1
		1	… … …	2
	Sorted arrays	2	… … … … … …	4
		3	… … … … … … … … … … … …	8

Basic LSM-tree – Get Queries Cost

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

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Get Queries Cost

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

Cost per searching each level?

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Get Queries Cost

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

Cost per searching each level? $\mathbf{O(\log_2 N/B)}$ **w. binary search**

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Get Queries Cost

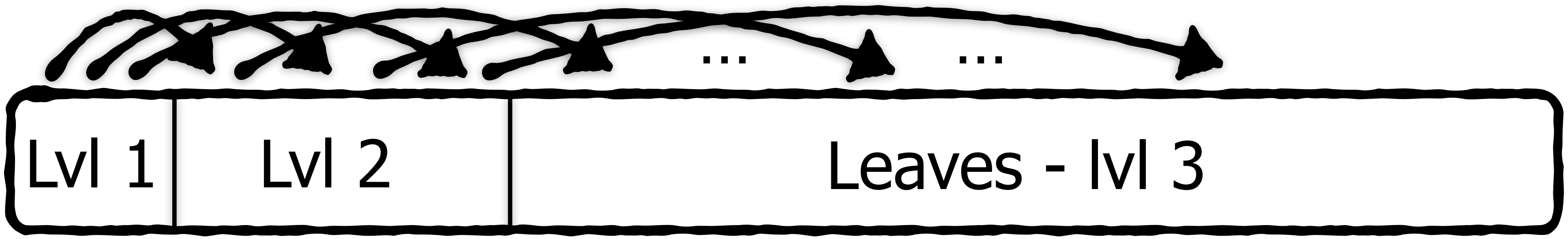
How many levels to search?	$O(\log_2 N)$
Cost per searching each level?	$O(\log_2 N/B)$
Total search cost:	$\mathbf{O(\log_2 N * \log_2 N/B)}$

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

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: $O(\log_2 N * \mathbf{\log_2 N/B})$

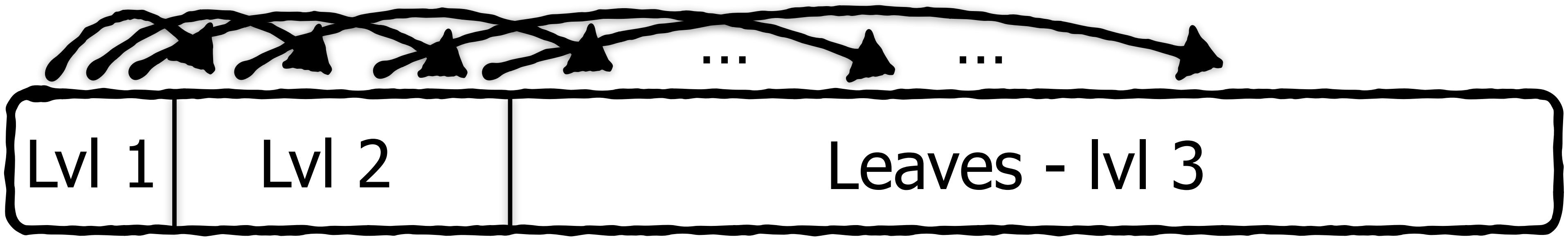


SST static B-tree structure

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: $O(\log_2 N * \mathbf{\log_B N})$



SST static B-tree structure

Basic LSM-tree – Scan Queries

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

	Level	
Buffer	0	… … …
Sorted arrays	1	… … …
	2	… … … … … …
	3	… … … … … … … … … … … …

Basic LSM-tree – Scan Queries

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

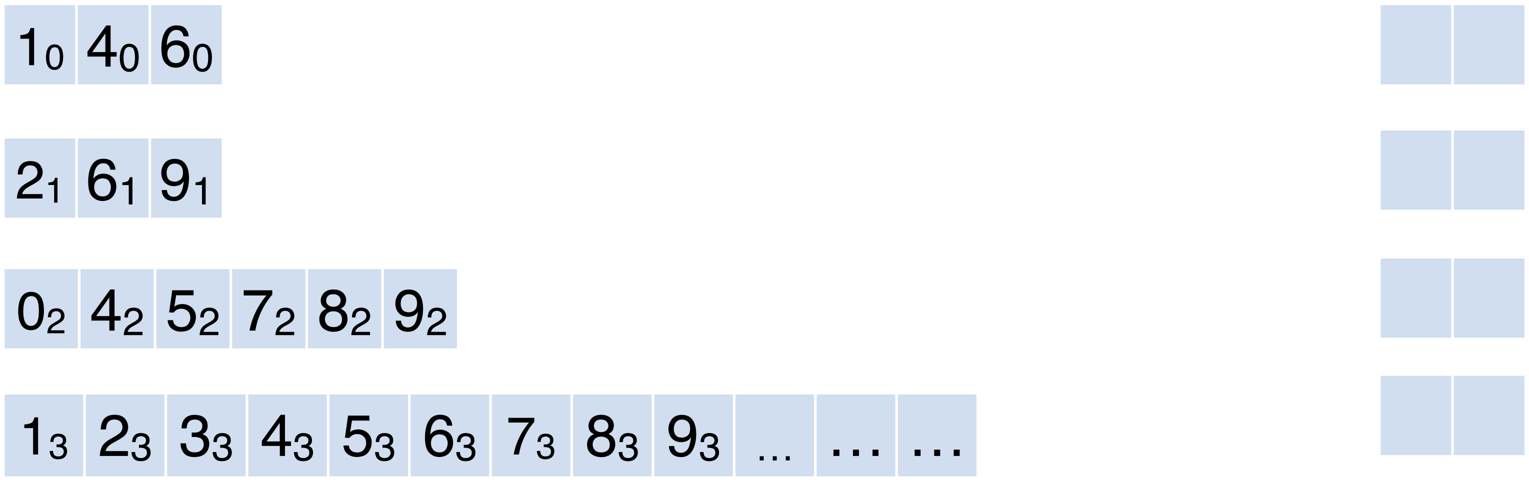
e.g., Scan(4, 6)

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

	Level	
Buffer	0	1_0 $\mathbf{4_0}$ 6_0
Sorted arrays	1	2_1 $\mathbf{6_1}$ 9_1
	2	0_2 4_2 $\mathbf{5_2}$ 7_2 8_2 9_2
	3	1_3 2_3 3_3 4_3 5_3 6_3 7_3 8_3 9_3 … … …

Basic LSM-tree – Scan Queries

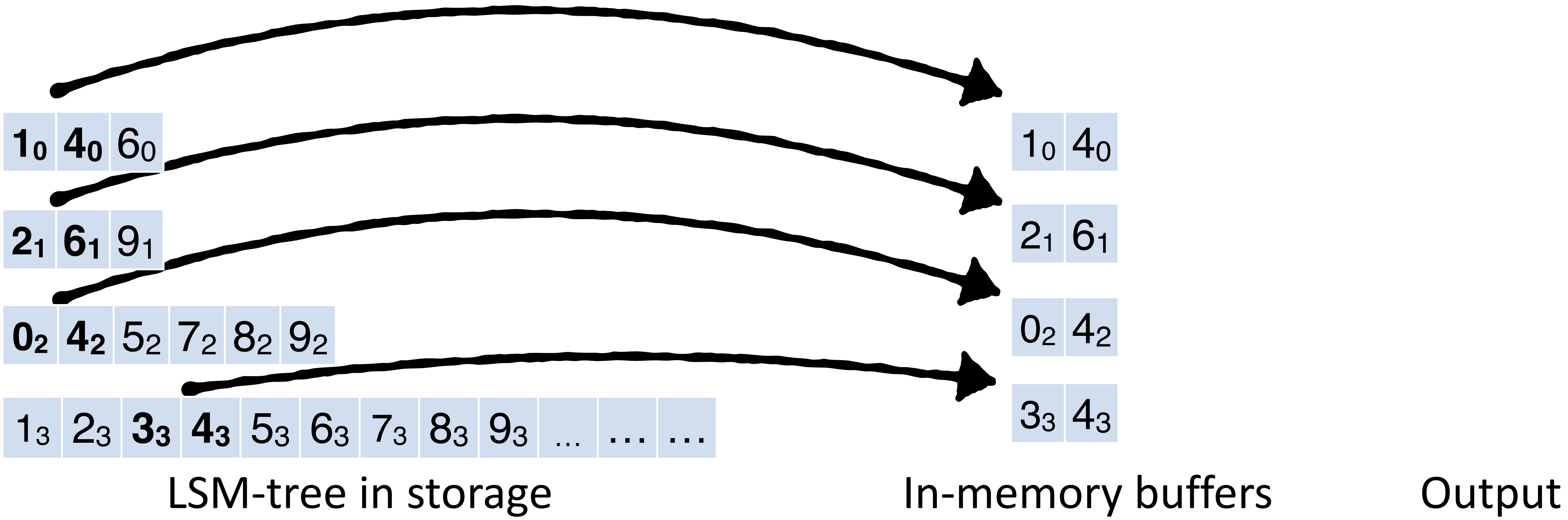
1. Allocate an in-memory buffer (>1 page) for each level



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

Counter: 4

$\mathbf{1_0}$	$\mathbf{4_0}$	6_0									
$\mathbf{2_1}$	$\mathbf{6_1}$	9_1									
0_2	4_2	$\mathbf{5_2}$	7_2	8_2	9_2						
1_3	2_3	$\mathbf{3_3}$	$\mathbf{4_3}$	5_3	6_3	7_3	8_3	9_3	…	…	…

LSM-tree in storage

1_0	4_0
2_1	6_1
0_2	4_2
3_3	4_3

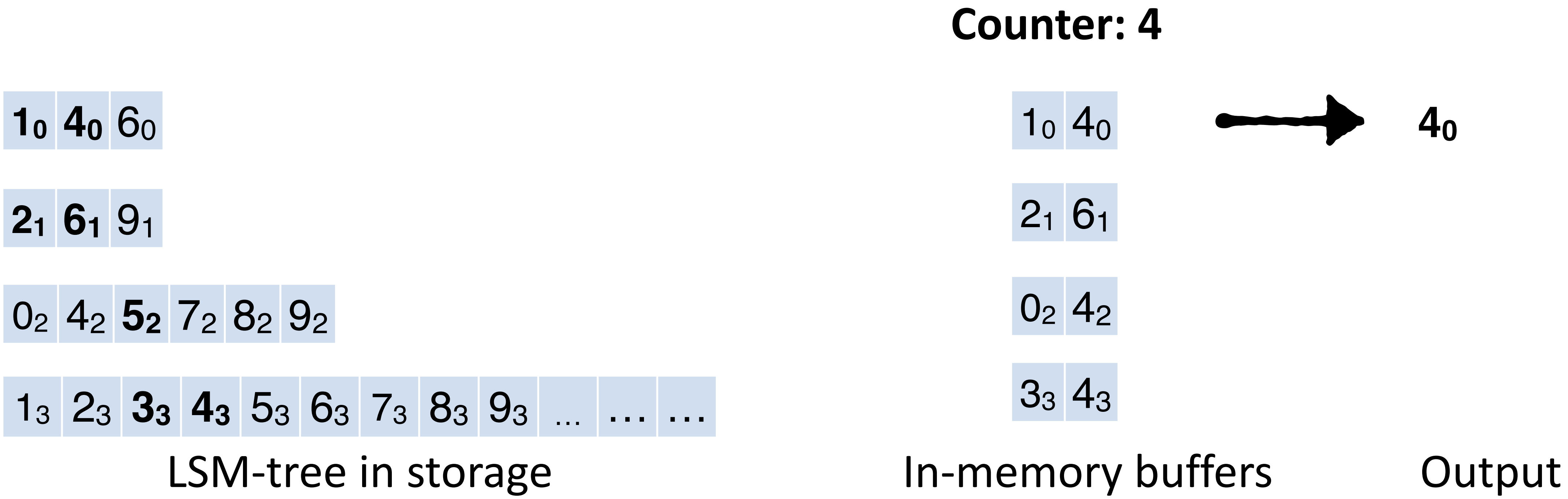
In-memory buffers

Output

Basic LSM-tree – Scan Queries

Loop until counter passes end of range

4. Bring youngest matching entry to output



Basic LSM-tree – Scan Queries

Loop until counter passes end of range

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

Counter: 5

LSM-tree in storage

$\mathbf{1_0}$ $\mathbf{4_0}$ 6_0

$\mathbf{2_1}$ $\mathbf{6_1}$ 9_1

0_2 4_2 $\mathbf{5_2}$ 7_2 8_2 9_2

1_3 2_3 $\mathbf{3_3}$ $\mathbf{4_3}$ 5_3 6_3 7_3 8_3 9_3 … … …

In-memory buffers

1_0 4_0

2_1 6_1

0_2 4_2

3_3 4_3

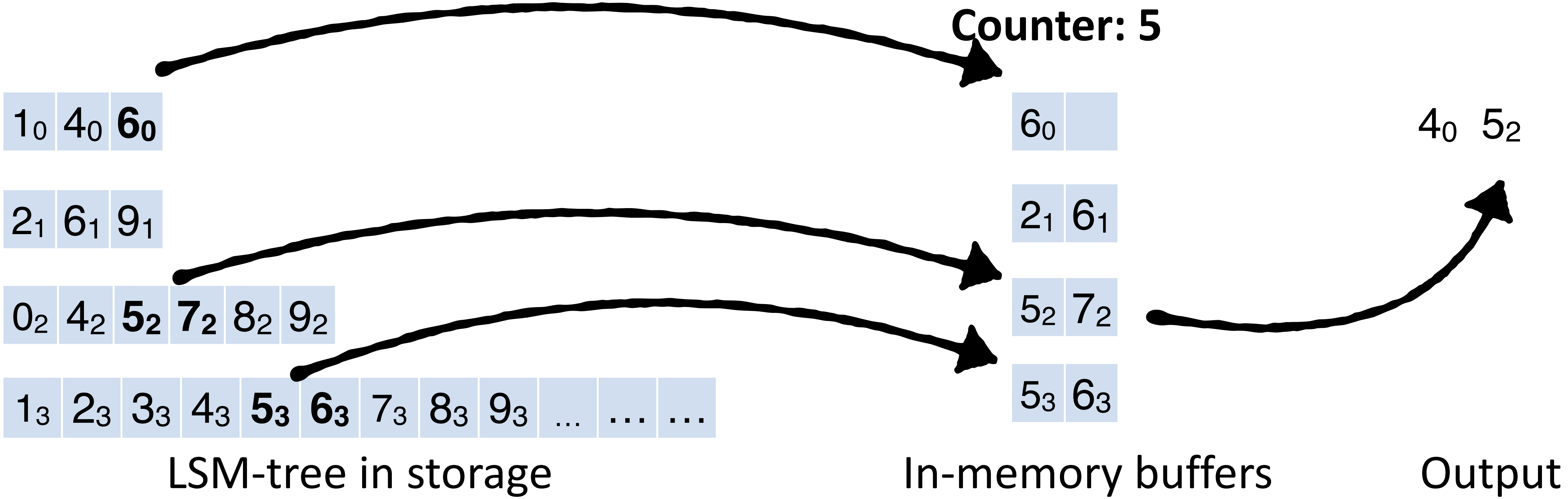
Output

4_0

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

Counter: 6

1_0 4_0 $\mathbf{6_0}$

2_1 6_1 9_1

0_2 4_2 $\mathbf{5_2}$ $\mathbf{7_2}$ 8_2 9_2

1_3 2_3 3_3 4_3 $\mathbf{5_3}$ $\mathbf{6_3}$ 7_3 8_3 9_3 … … …

LSM-tree in storage

6_0

2_1 6_1

5_2 7_2

5_3 6_3

In-memory buffers

4_0 5_2 6_1

Output

Basic LSM-tree – Scan Queries I/O Cost

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

LSM-tree in storage

In-memory buffers

Basic LSM-tree – Scan Queries I/O Cost

 # lvls

$$O(\underbrace{\boldsymbol{\log_2 N}}_{\text{}} * \log_B N + S/B)$$

LSM-tree in storage

In-memory buffers

Basic LSM-tree – Scan Queries I/O Cost

\# lvls

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

B-tree search cost

LSM-tree in storage

In-memory buffers

Basic LSM-tree – Scan Queries I/O Cost

lvls

 # output size

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

B-tree search cost

LSM-tree in storage

In-memory buffers

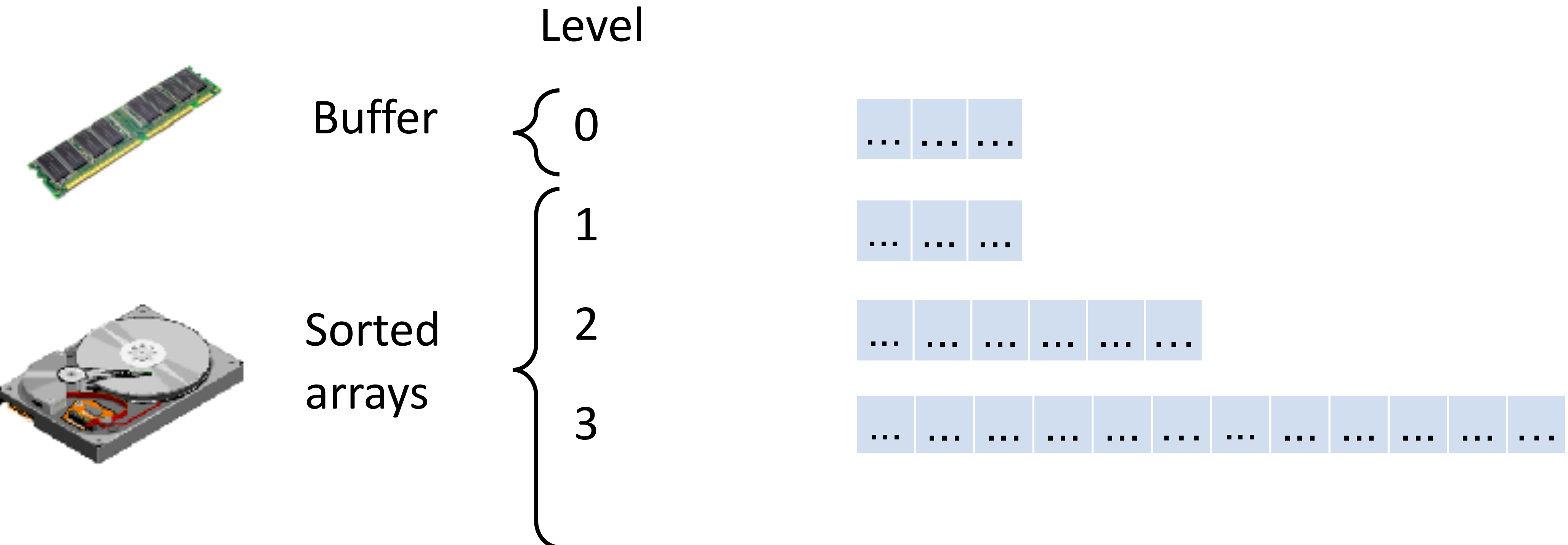
Basic LSM-tree – Insertion/Update/Delete cost

How many times is each entry copied?

		Level	
	Buffer	0	… … …
		1	… … …
	Sorted arrays	2	… … … … … …
		3	… … … … … … … … … … … …

Basic LSM-tree – Insertion/Update/Delete cost

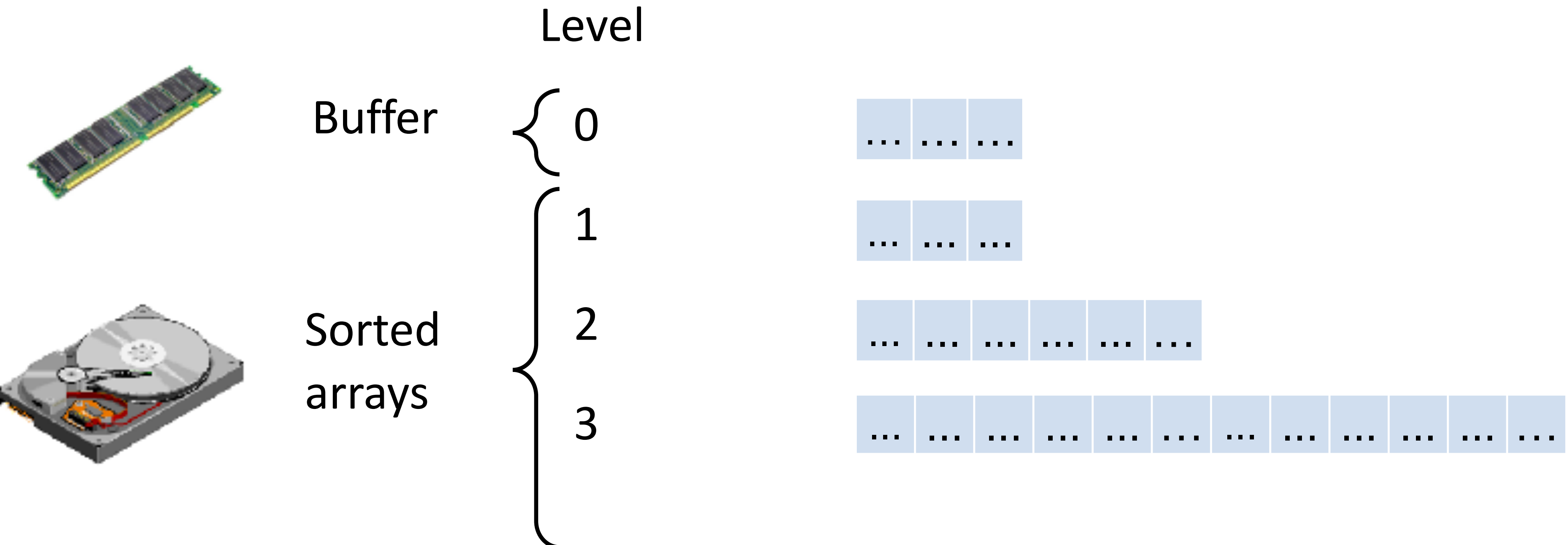
How many times is each entry copied? **$O(\log_2 N/B)$**



Basic LSM-tree – Insertion/Update/Delete cost

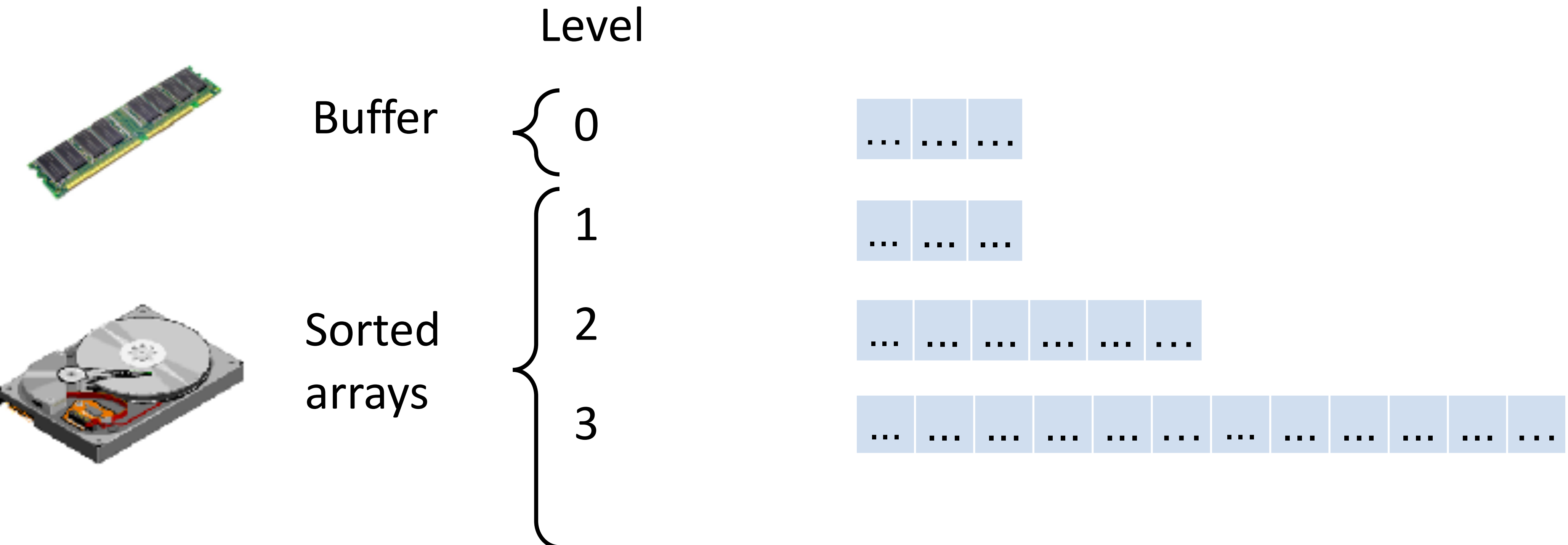
How many times is each entry copied? O($\log_2 N/B$)

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

Level

Buffer

0 … … …

Sorted arrays

1 … … …

2 … … … … … …

3 … … … … … … … … … … … …

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

Level

Buffer 0: … … …

Sorted arrays

1: … … …

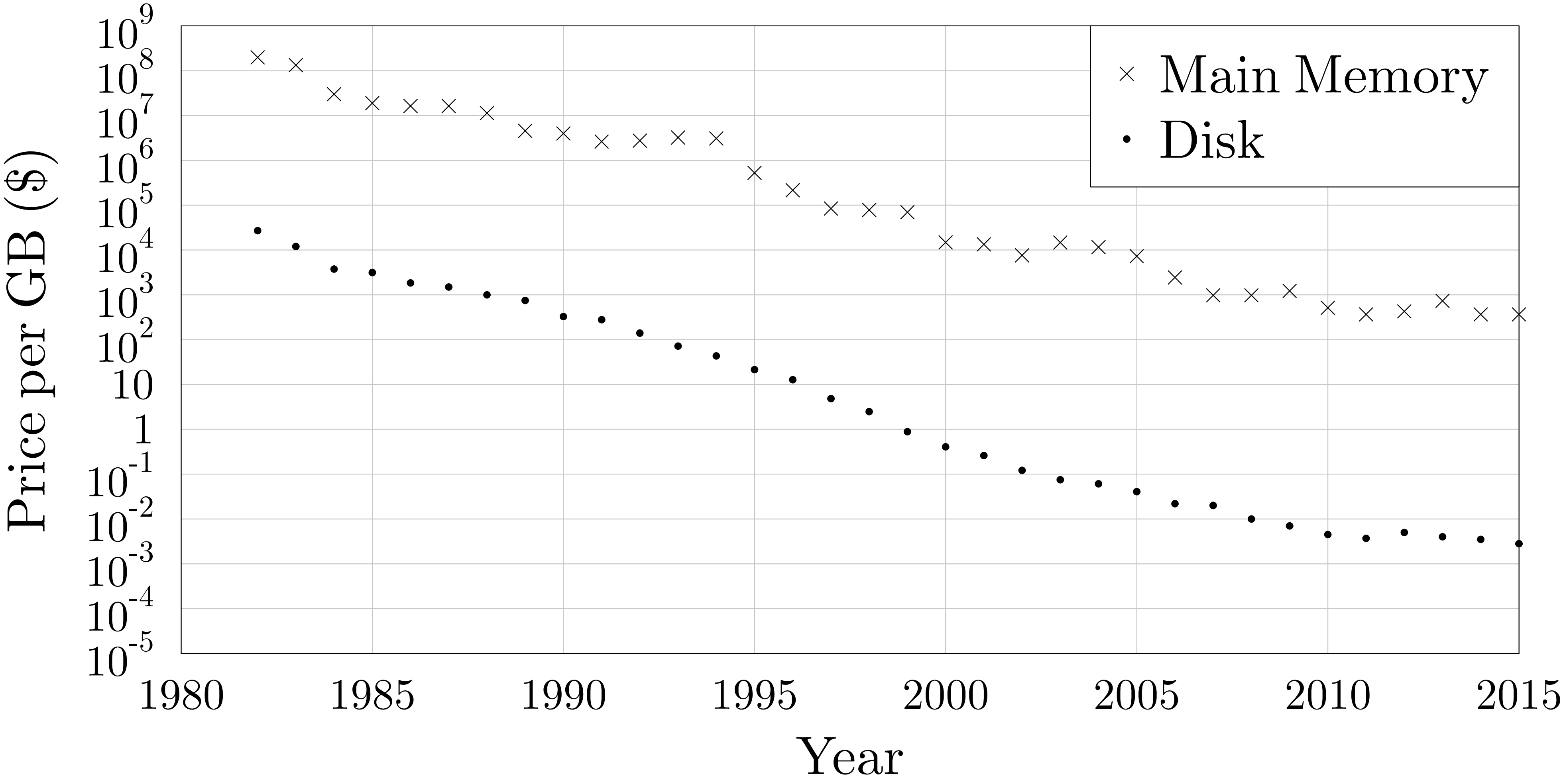
2: … … … … … …

3: … … … … … … … … … … … …

Operation	I/O	append-only table	Basic LSM-tree table	B-Tree
Query	Reads	O(N/B)	**$O(\log_2 N * \log_B N)$**	$O(\log_B N)$
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

1	10	15	…

array

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

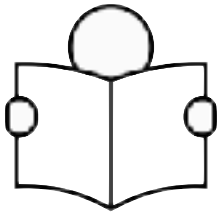
Operation	I/O	append-only table	**Basic LSM-tree table**	**B-Tree**
Query	Reads	$O(N/B)$	$O(\log_2 N * \cancel{\log_B N})$	$O(\cancel{\log_B N})$
Insert	Reads	0	$O((\log_2 N/B)/B)$	$O(\log_B N)$
	Writes	$O(1/B)$	$O((\log_2 N/B)/B)$	$O(1)$ & GC

Operation	I/O	append-only table	**Basic LSM-tree table**	**B-Tree**
Query	Reads	O(N/B)	$O(\log_2 N)$	O(1)
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
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

Level

Buffer

0

…	…	…

1

2

3

Sorted arrays

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

Level

Buffer

0

… … …

Sorted arrays

1

2

3

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

Level

Buffer 0 … … …

1

2

Sorted arrays 3

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

Increase size ratio T

	Level		Capacity
Buffer	0	… … …	T^0
Sorted arrays	1		T^1
	2		T^2
	3		T^3

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2		16
	3		64

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2		16
	3		64

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4

inserts

flush

	Level		Capacity
 Buffer	0	… … …	1
Sorted arrays 	1	… … …	4
	2		16
	3		64

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4

inserts

flush & sort-merge

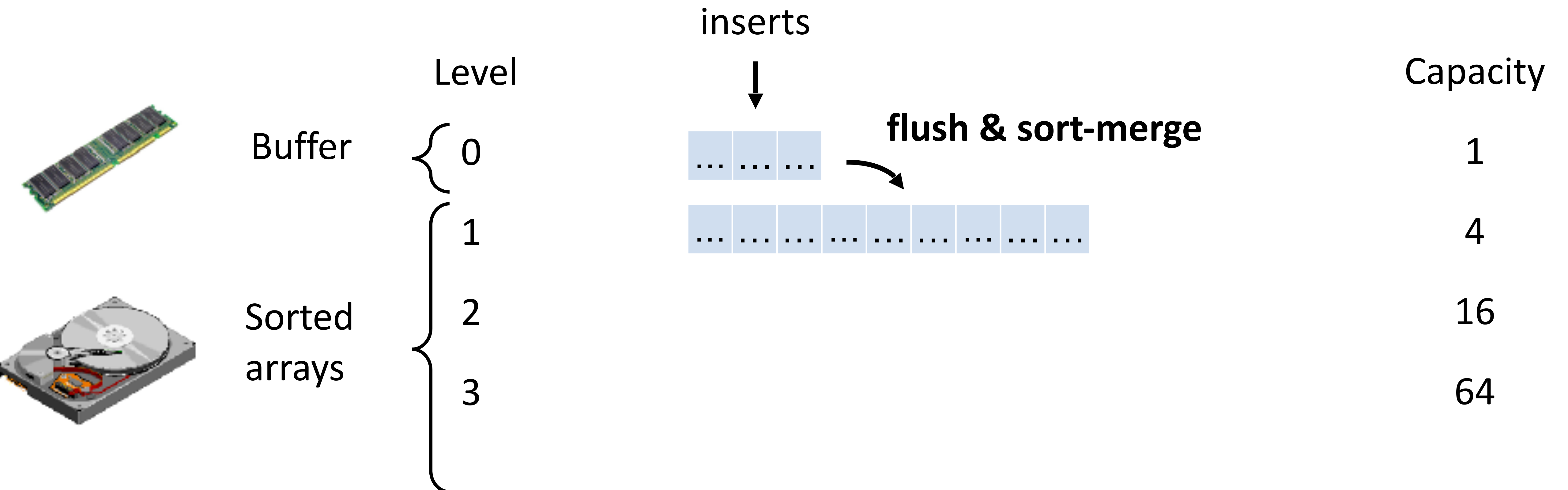
	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … … … … …	4
	2		16
	3		64

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4



Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … … … … … … … … … … …	4
	2		16
	3		64

flush & sort-merge

Leveled LSM-tree

Lookup cost depends on number of levels

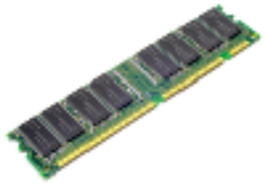
How to reduce it? Increase size ratio T

E.g. size ratio of 4

inserts

Level		Capacity
Buffer 0	… … …	1
Sorted arrays 1	… … … … … … … … … … … …	4
2		16
3		64

move



Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2	… … … … … … … … … … … …	16
	3		64

Leveled LSM-tree

Lookup cost?

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2	… … … … … … … … … … … …	16
	3		64

Leveled LSM-tree

Lookup cost?

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

inserts

	Level		Capacity
Buffer	0	… … …	1
	1		4
Sorted arrays	2	… … … … … … … … … … … …	16
	3		64

Leveled LSM-tree

Lookup cost?

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

Insertion cost?

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2	… … … … … … … … … … … …	16
	3		64

Leveled LSM-tree

Lookup cost?

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

Insertion cost?

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

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2	… … … … … … … … … … … …	16
	3		64

Leveled LSM-tree

Lookup cost?

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

Insertion cost?

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

What happens as we increase the size ratio T?

Leveled LSM-tree

Lookup cost?

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

Insertion cost?

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

What happens as we increase the size ratio T?

Leveled LSM-tree

Lookup cost?

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

Insertion cost?

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

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?

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

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?

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

What happens as we increase the size ratio T?

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

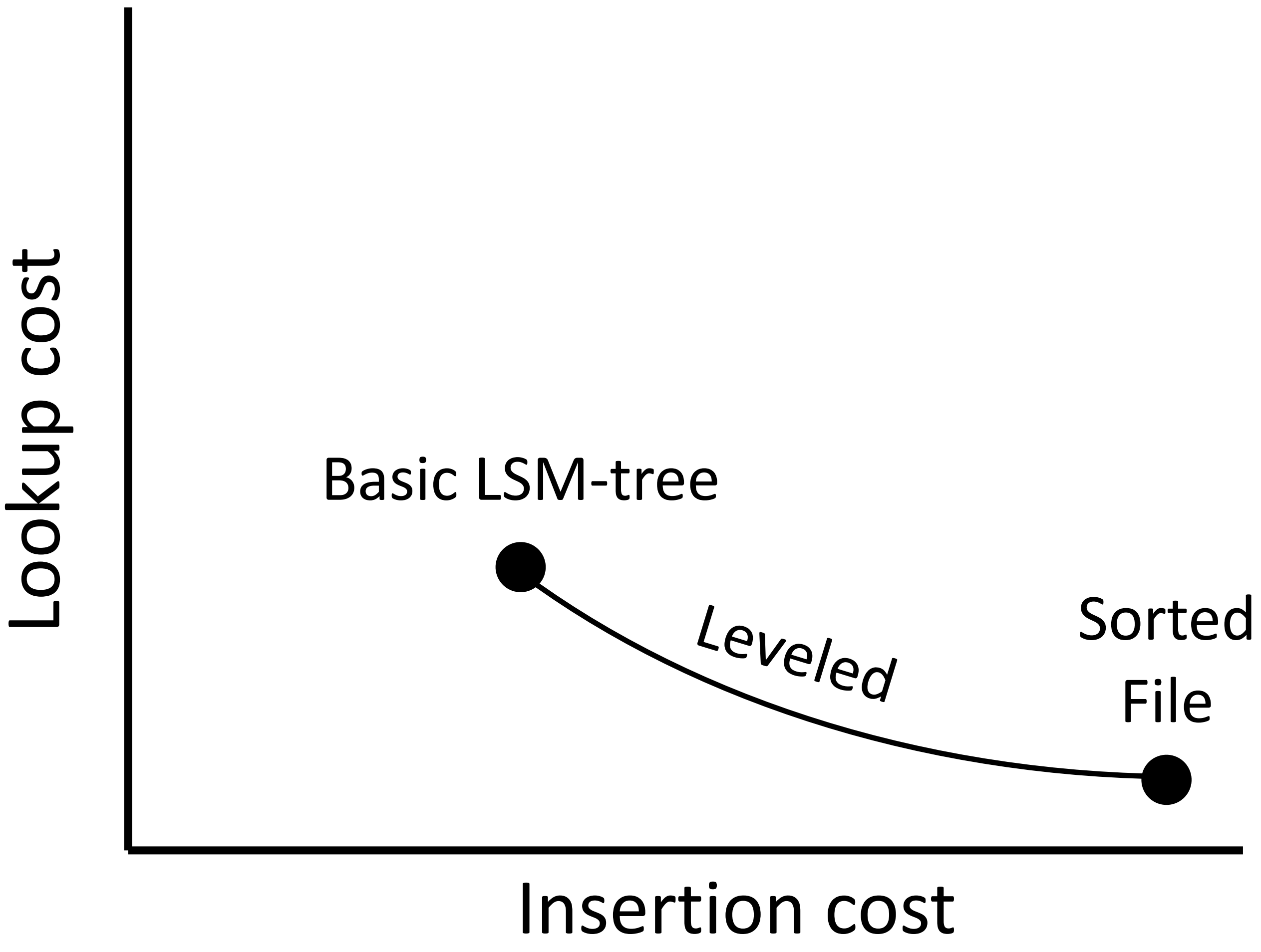
Lookup cost becomes:

$O(1)$

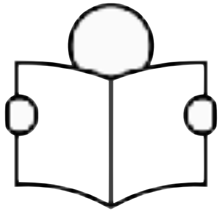
Insert cost becomes:

$O(N/B^2)$

The LSM-tree becomes a sorted file!


Lookup cost
Basic LSM-tree
Leveled
Sorted
File
Insertion cost

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.

		Level		Capacity
	Buffer	0	… … …	T^0
		1		T^1
	Sorted arrays	2		T^2
		3		T^3

Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

Do not merge within a level.

	Level		Capacity
Buffer	0	… … …	T^0
Sorted arrays	1		T^1
	2		T^2
	3		T^3

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

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2		16
	3		64

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

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2		16
	3		64

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

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	4
	2		16
	3		64

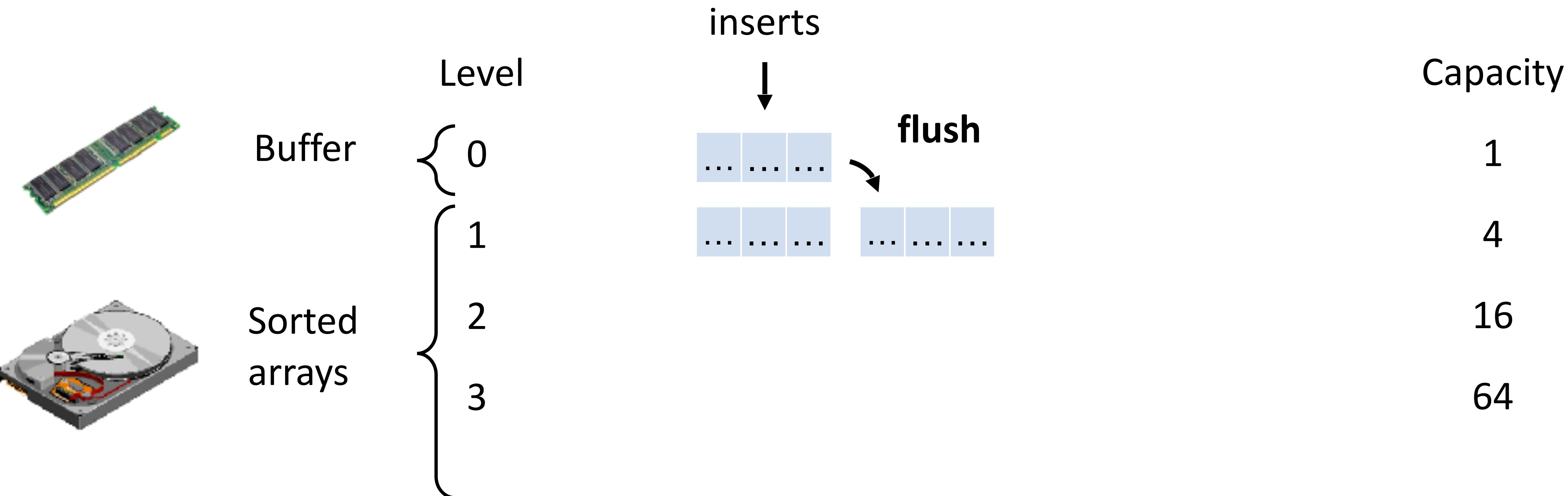
flush

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

inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … … … … … … … …	4
	2		16
	3		64

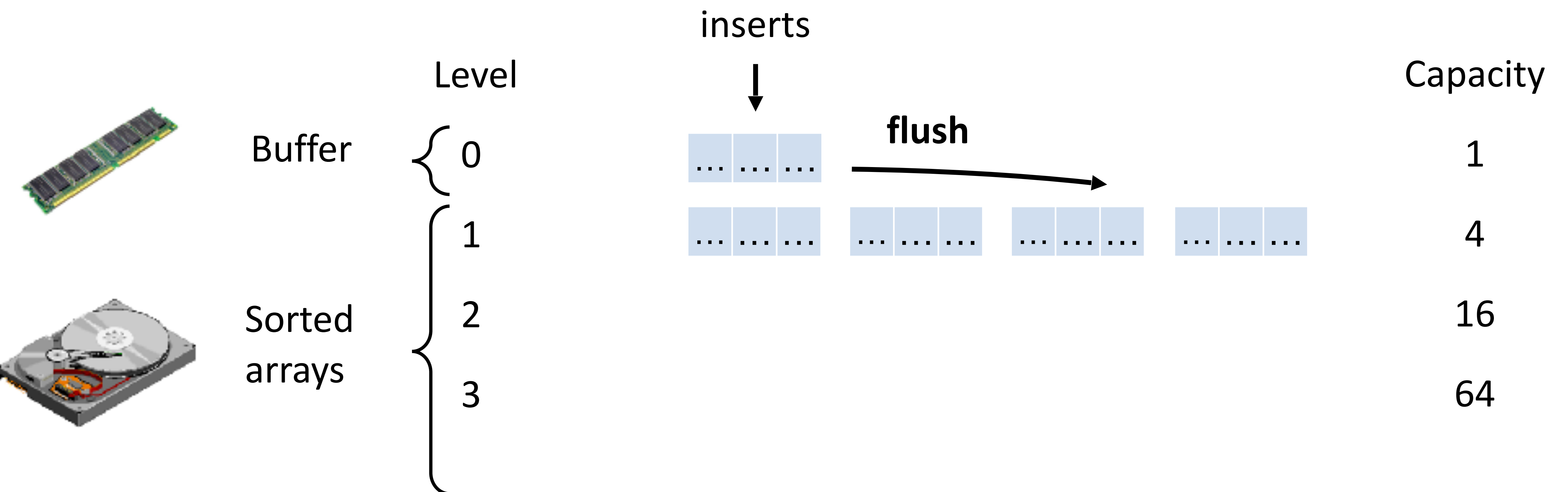
flush

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

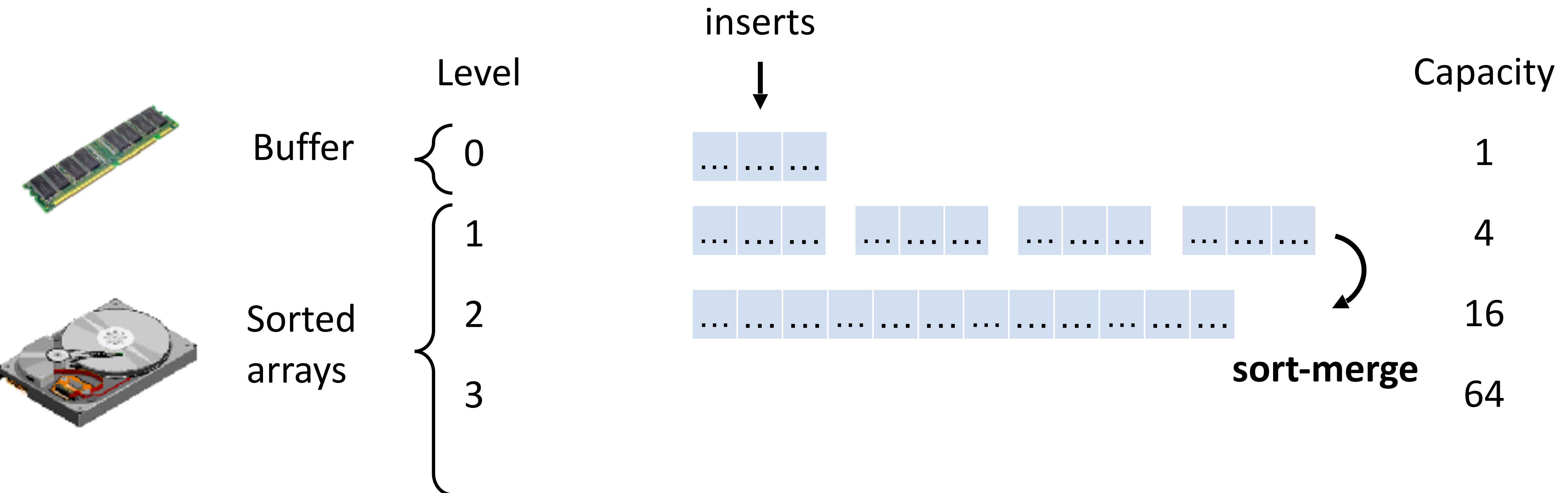


Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

Do not merge within a level.

E.g. size ratio of 4

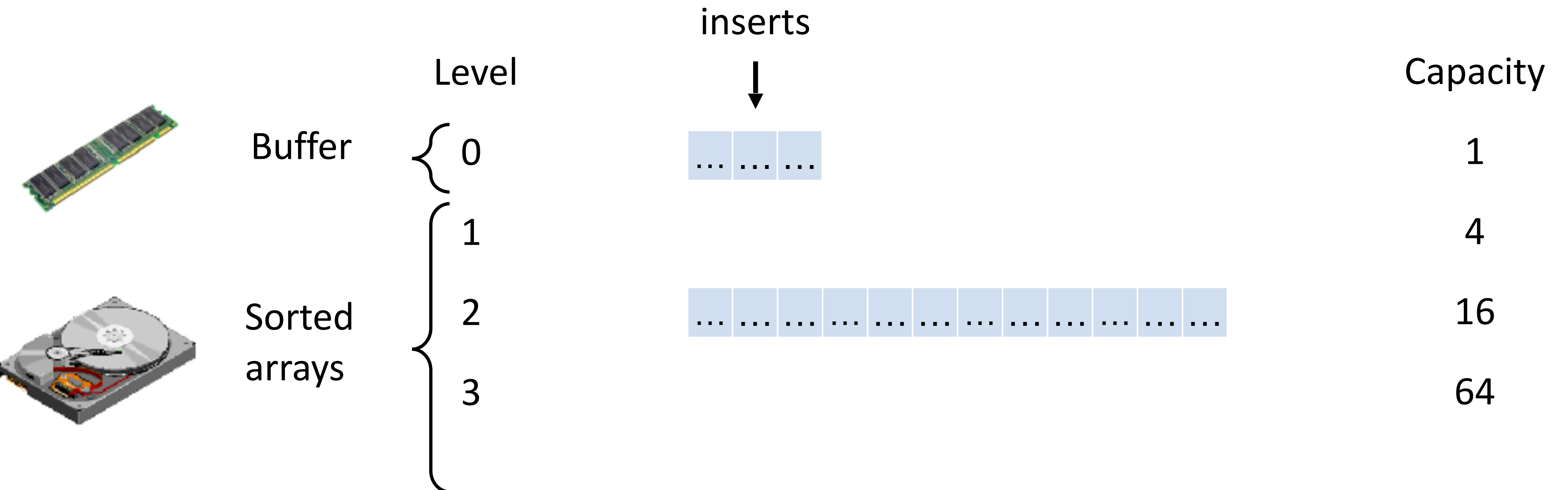


Tiered LSM-tree

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?

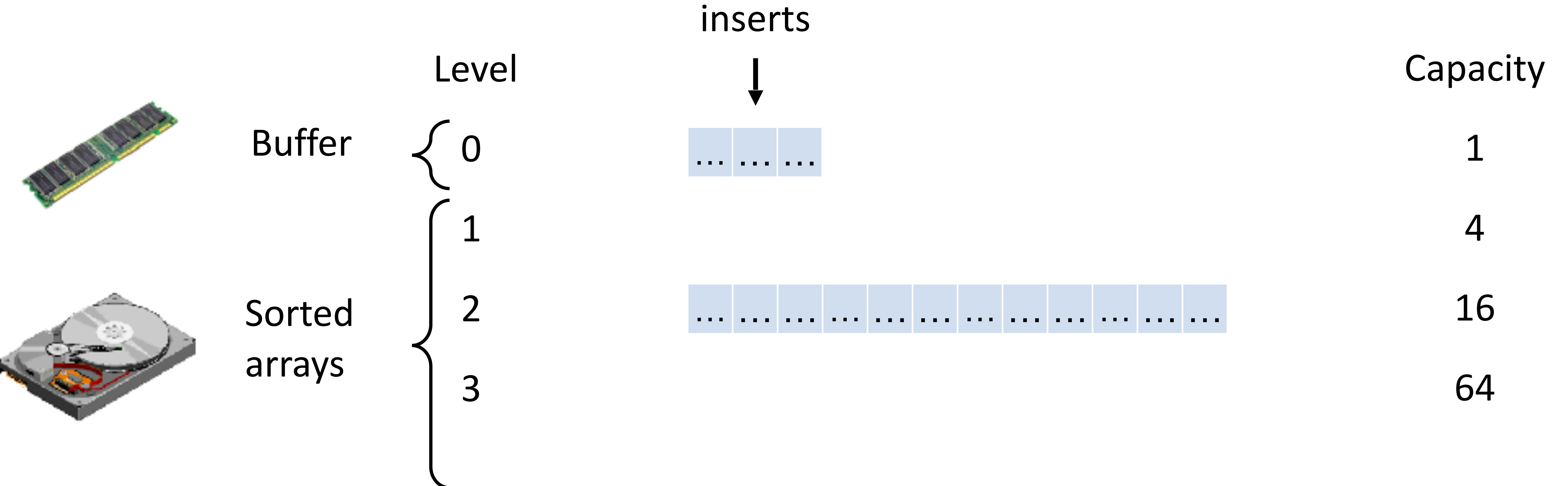
inserts

	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2	… … … … … … … … … … … …	16
	3		64

Tiered LSM-tree

Lookup cost?

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

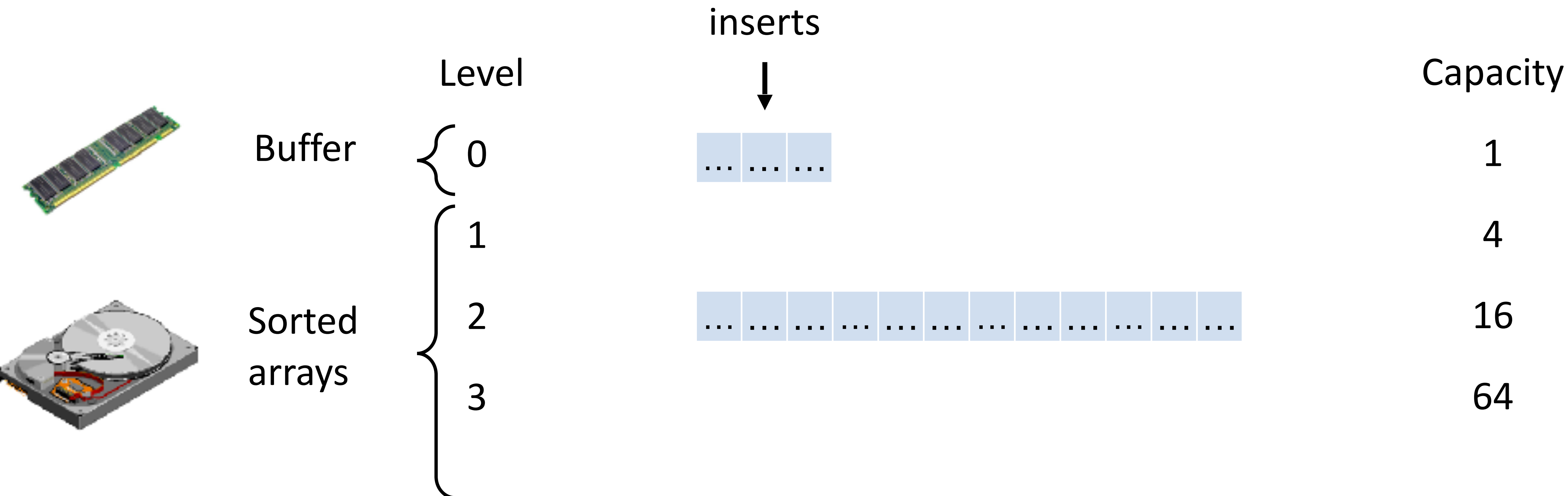


Tiered LSM-tree

Lookup cost?

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

Insertion cost?



Tiered LSM-tree

Lookup cost?

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

Insertion cost?

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

inserts

	Level		Capacity
 Buffer	0	… … …	1
 Sorted arrays	1		4
	2	… … … … … … … … … … … …	16
	3		64

Tiered LSM-tree

Lookup cost?

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

Insertion cost?

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

Tiered LSM-tree

Lookup cost?

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

Insertion cost?

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

What happens as we increase the size ratio T?

Tiered LSM-tree

Lookup cost?

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

Insertion cost?

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

What happens as we increase the size ratio T?

Tiered LSM-tree

Lookup cost?

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

Insertion cost?

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

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?

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

Insertion cost?

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

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?

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

Insertion cost?

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

What happens as we increase the size ratio T?

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

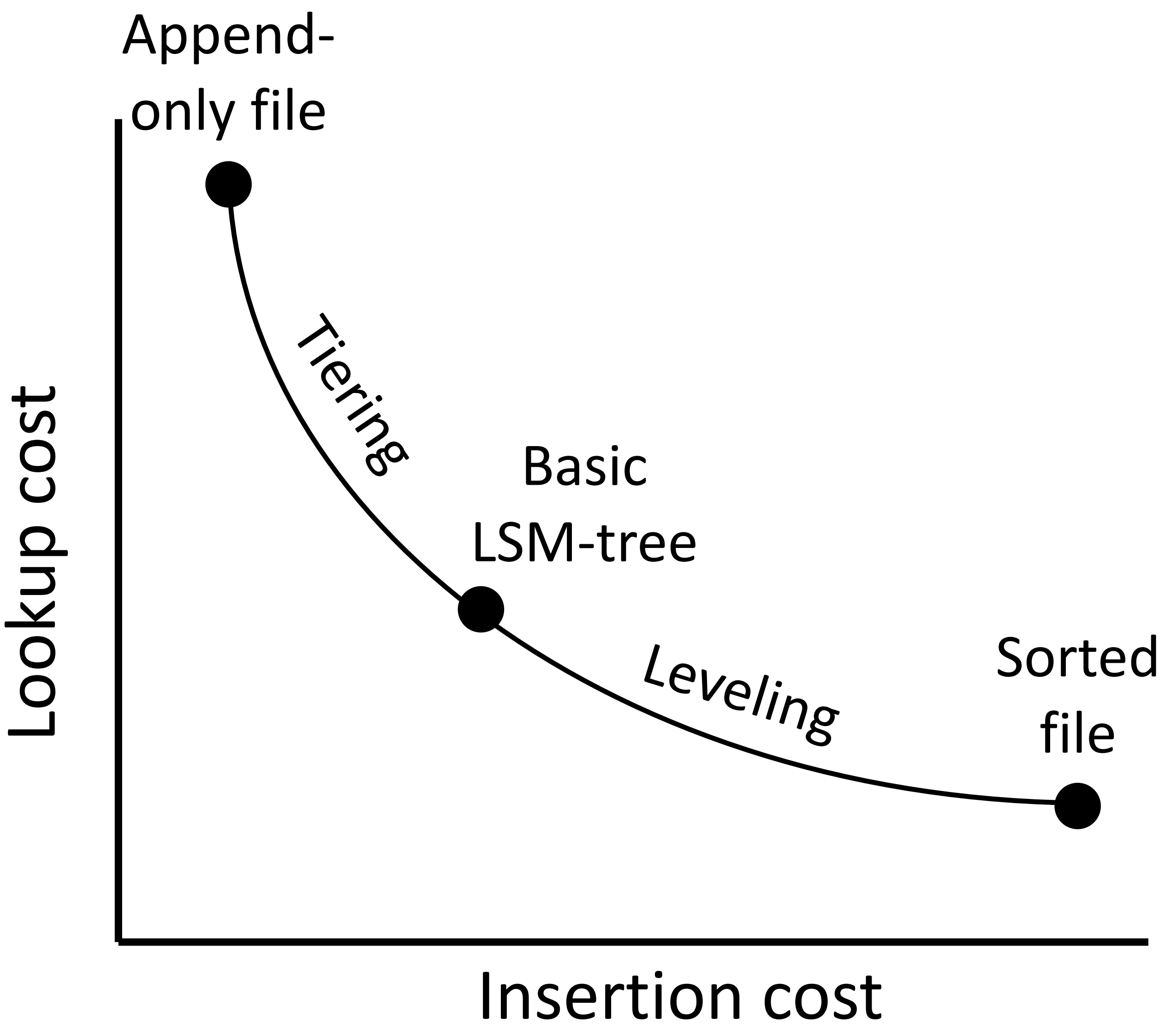
Lookup cost becomes:

$O(N/B)$

Insert cost becomes:

$O(1/B)$

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

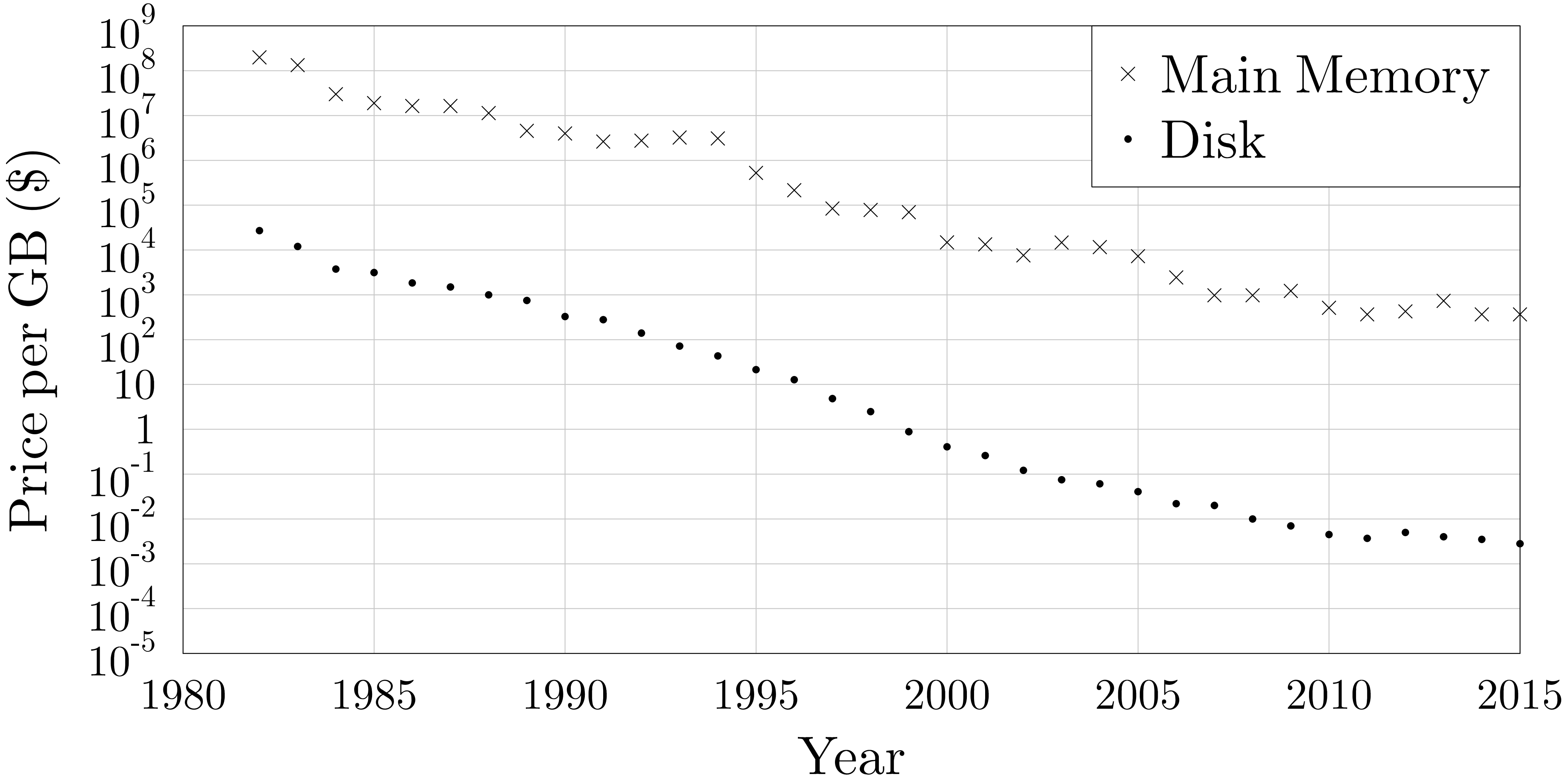

Append-
only file
Tiering
Basic
LSM-tree
Leveling
Sorted
file
Lookup cost
Insertion cost

Operation		**Unordered File**	**Leveled LSM-tree**	**Tiered LSM-tree**	**B-Tree**
Query	Reads	O(N/B)	O(L)	O(T * K)	O(1)
Insert	Reads	0	O((L * T)/B)	O(L/B)	O($\log_B$ N)
	Writes	O(1/B)	O((L * T)/B)	O(L/B)	O(1) & 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

…	…	…	…	…	…	…	…	X	…	…	…

Bloom Filters

Answers set-membership queries

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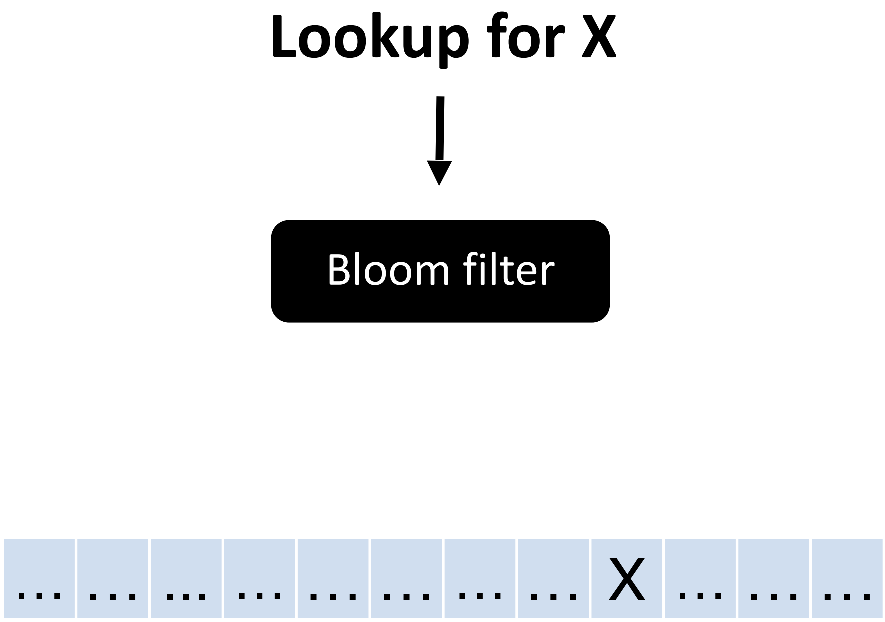
array



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 X

filters

Bloom filter

array

…	…	…	…	…	…	…	…	X	…	…	…

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 X

Bloom filter

Access on disk

filters

array

…	…	…	…	…	…	…	…	X	…	…	…

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

…	…	…	…	…	…	…	…	X	…	…	…

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

…	…	…	…	…	…	…	…	X	…	…	…

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

…	…	…	…	…	…	…	…	X	…	…	…

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 Z

filters

Bloom filter

array

…	…	…	…	…	…	…	…	X	…	…	…

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 Z

Bloom filter

filters

array

…	…	…	…	…	…	…	…	X	…	…	…

Bloom Filters

Answers set-membership queries

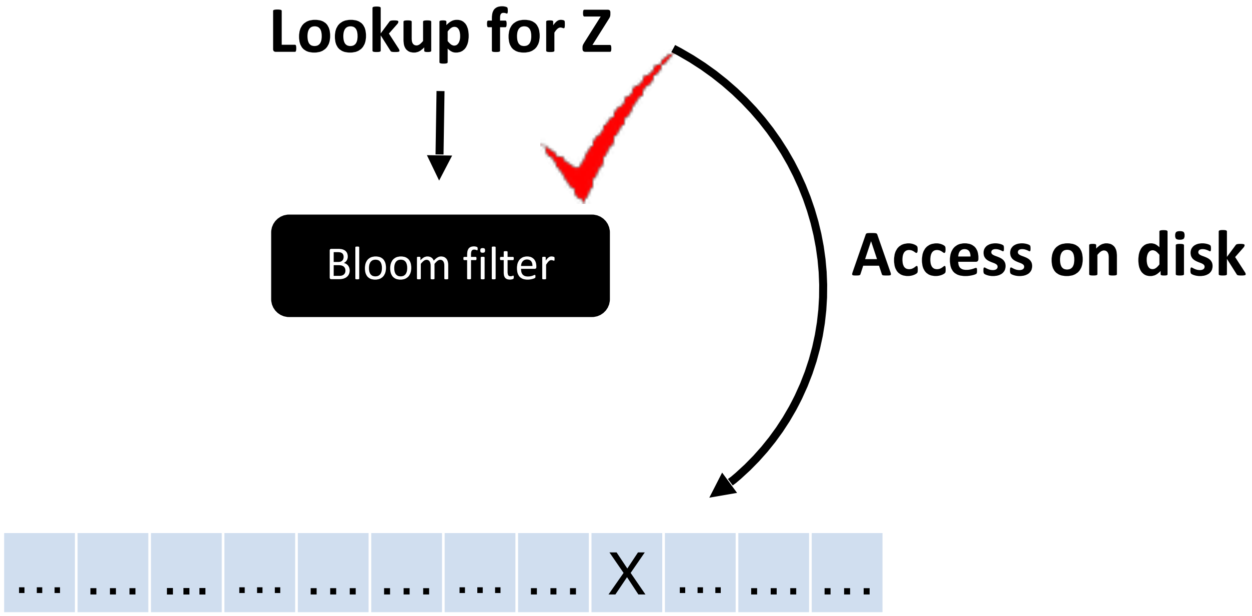
Smaller than data it represents

Purpose: avoid accessing storage if entry is not present

Subtlety: may return false positives.

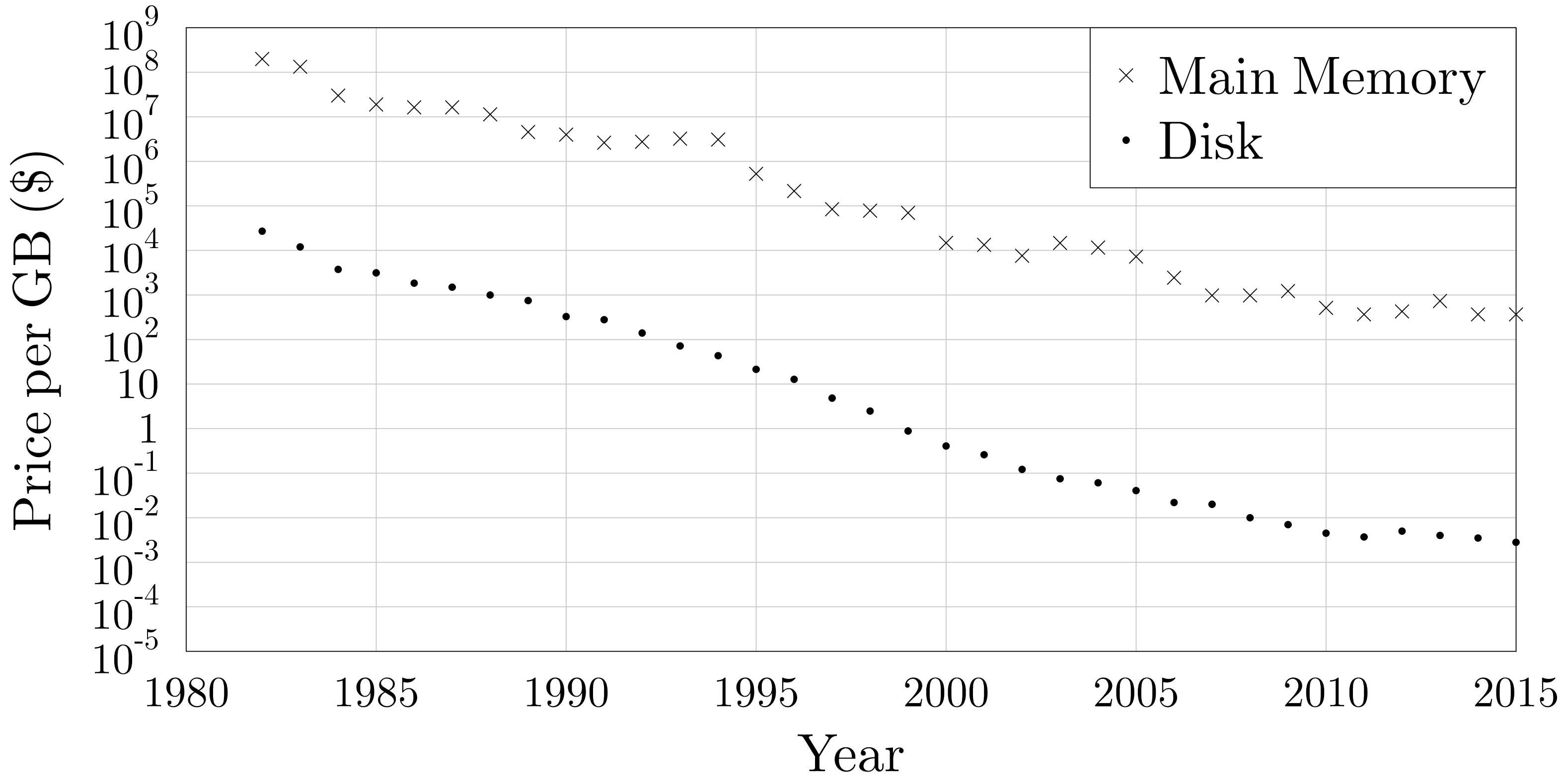
filters

array



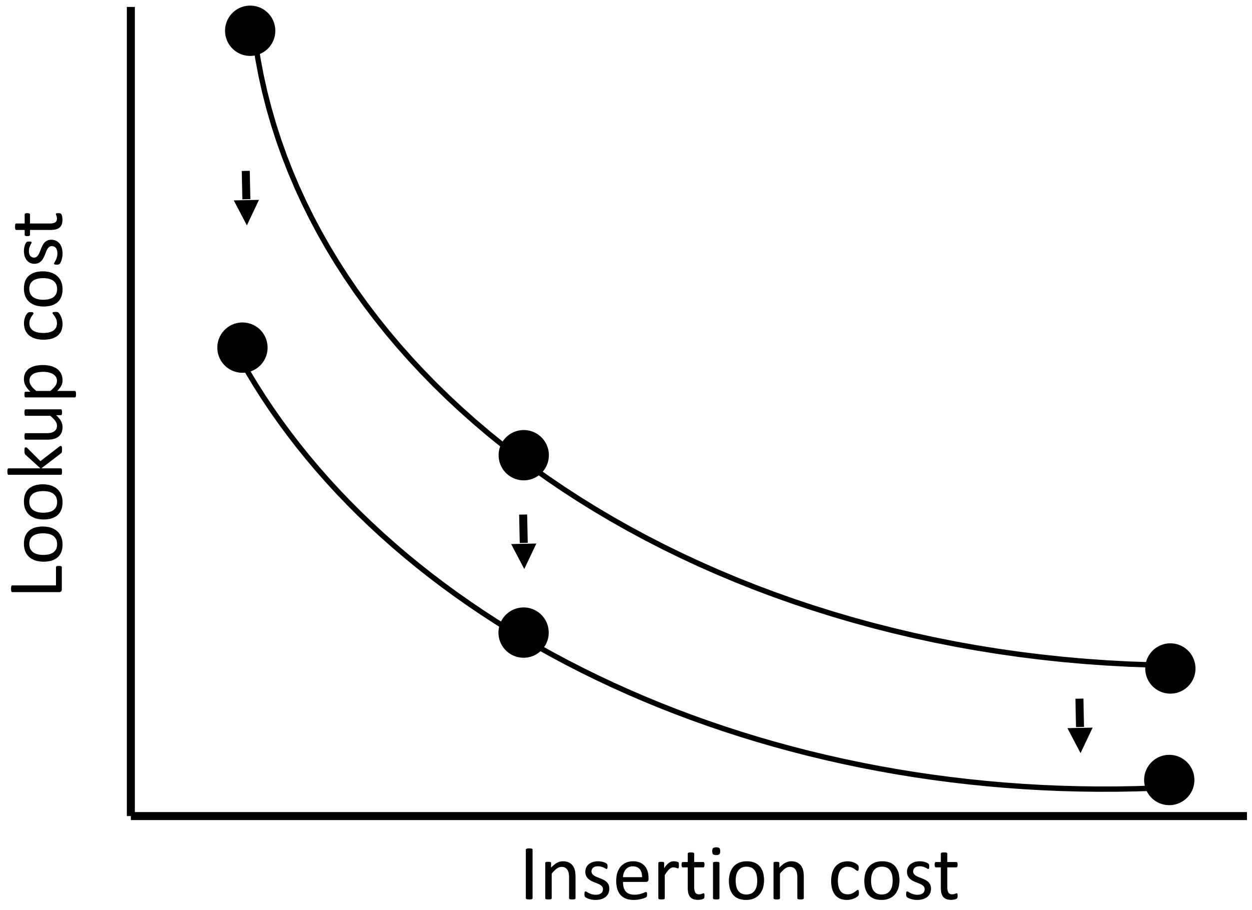
Bloom Filters

The more main memory, the less false positives $\Rightarrow$ cheaper lookups



Bloom Filters

The more main memory, the less false positives $\Longrightarrow$ cheaper lookups



Conclusions - LSM-trees are:

Write-optimized

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Highly tunable

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Backbone of many modern systems

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Trade-off between lookup and insert cost (tiering/leveling, size ratio)

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Backbone of many modern systems

Trade-off between lookup and insert cost (tiering/leveling, size ratio)

Trade main memory for lookup cost (fence pointers, Bloom filters)

Conclusions - LSM-trees are:

Write-optimized

Highly tunable

Backbone of many modern systems

Trade-off between lookup and insert cost (tiering/leveling, size ratio)

Trade main memory for lookup cost (fence pointers, Bloom filters)

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.