Log-Structured-Merge Trees

Comp115 guest lecture

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DASlab

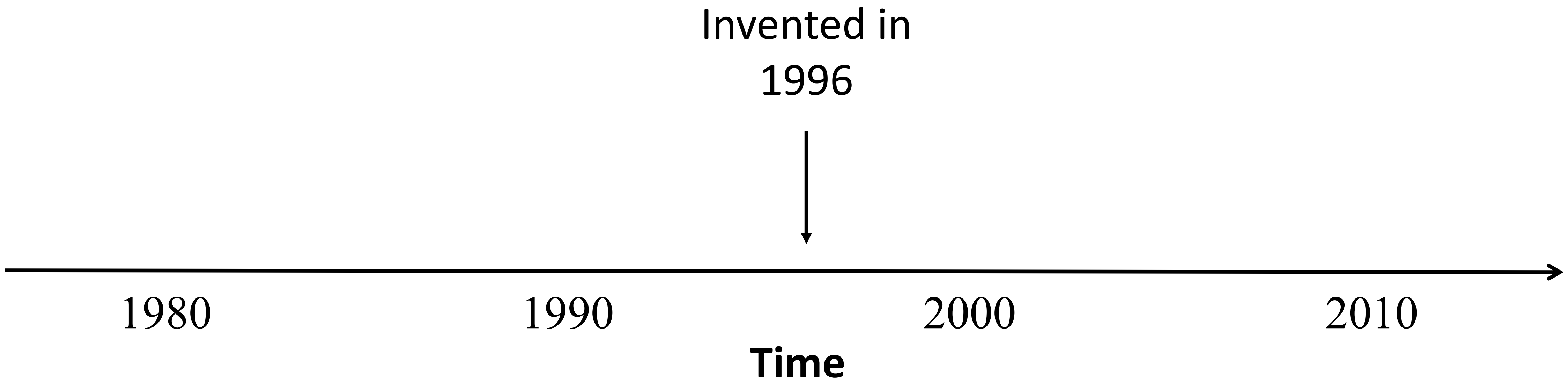
IACS INSTITUTE FOR APPLIED COMPUTATIONAL SCIENCE AT HARVARD UNIVERSITY

HARVARD School of Engineering and Applied Sciences

Useful when?

- ☑ Massive dataset
- ☑ Rapid updates/insertions
- ☑ Fast lookups

⟹ LSM-trees are for you.



Invented in 1996

Patrick O'Neil
UMass Boston

Invented in
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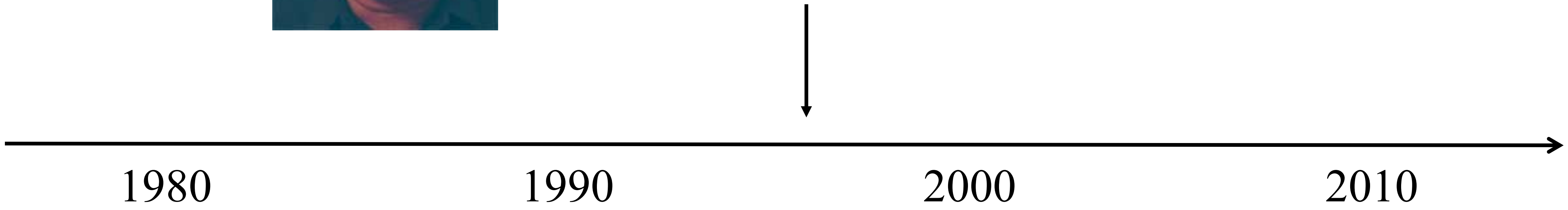

Time

Patrick O'Neil
UMass Boston

Invented in
1996

levelDB

DynamoDB

amazon web services

riak

RocksDB

cassandra

HBASE

accumulo™

1980 1990 2000 2010

Time

Why now?

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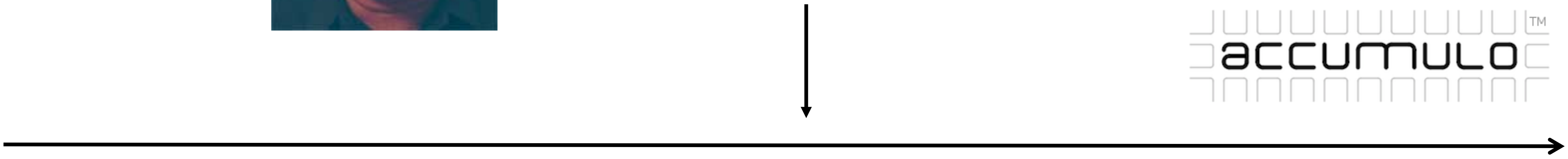


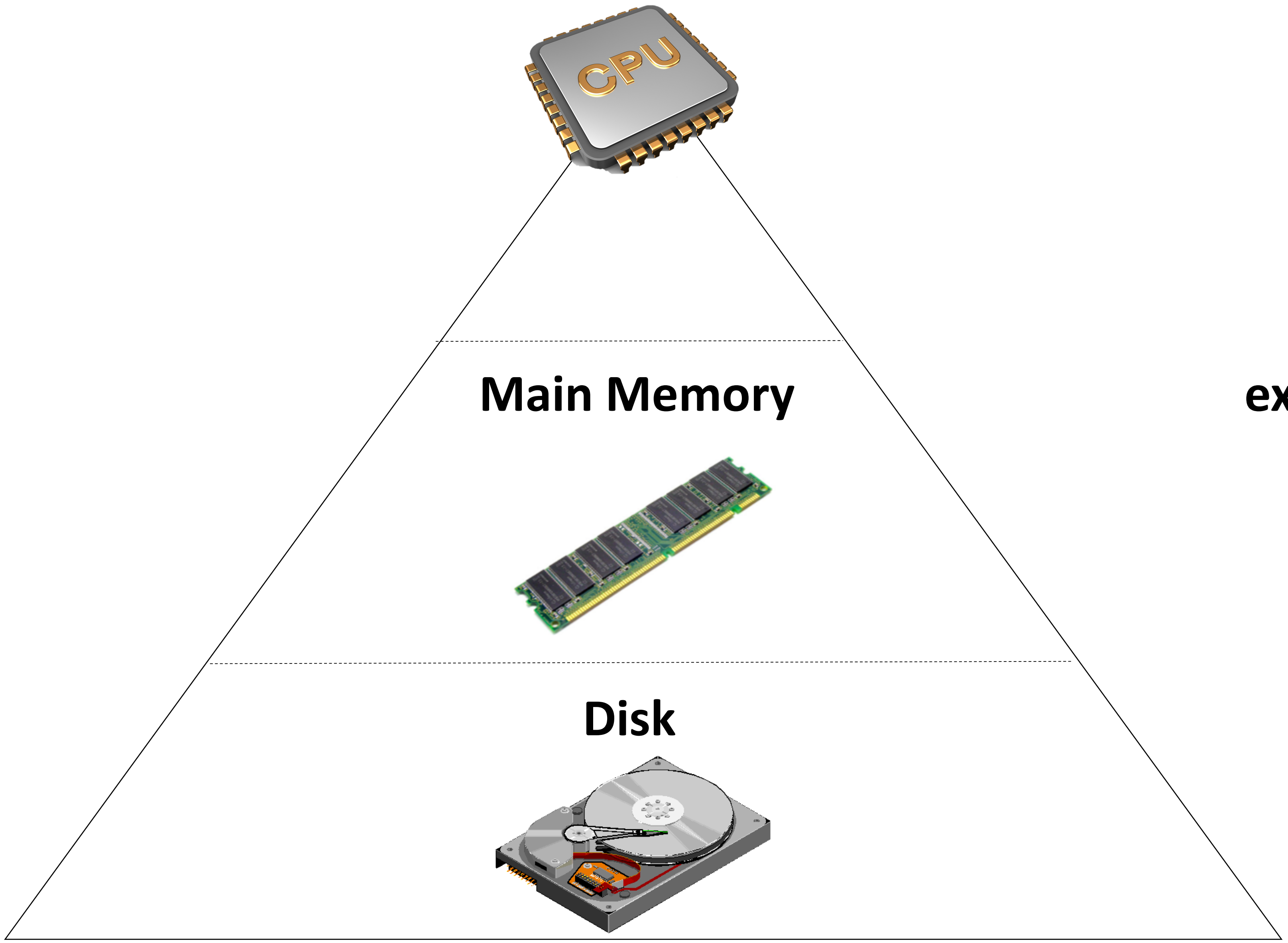
1980 1990 2000 2010

Time

Outline

1. Storage devices
2. Indexing problem & basic solutions
3. Basic LSM-trees
4. Leveled LSM-trees
5. Tiered LSM-trees
6. Bloom filters

Storage devices



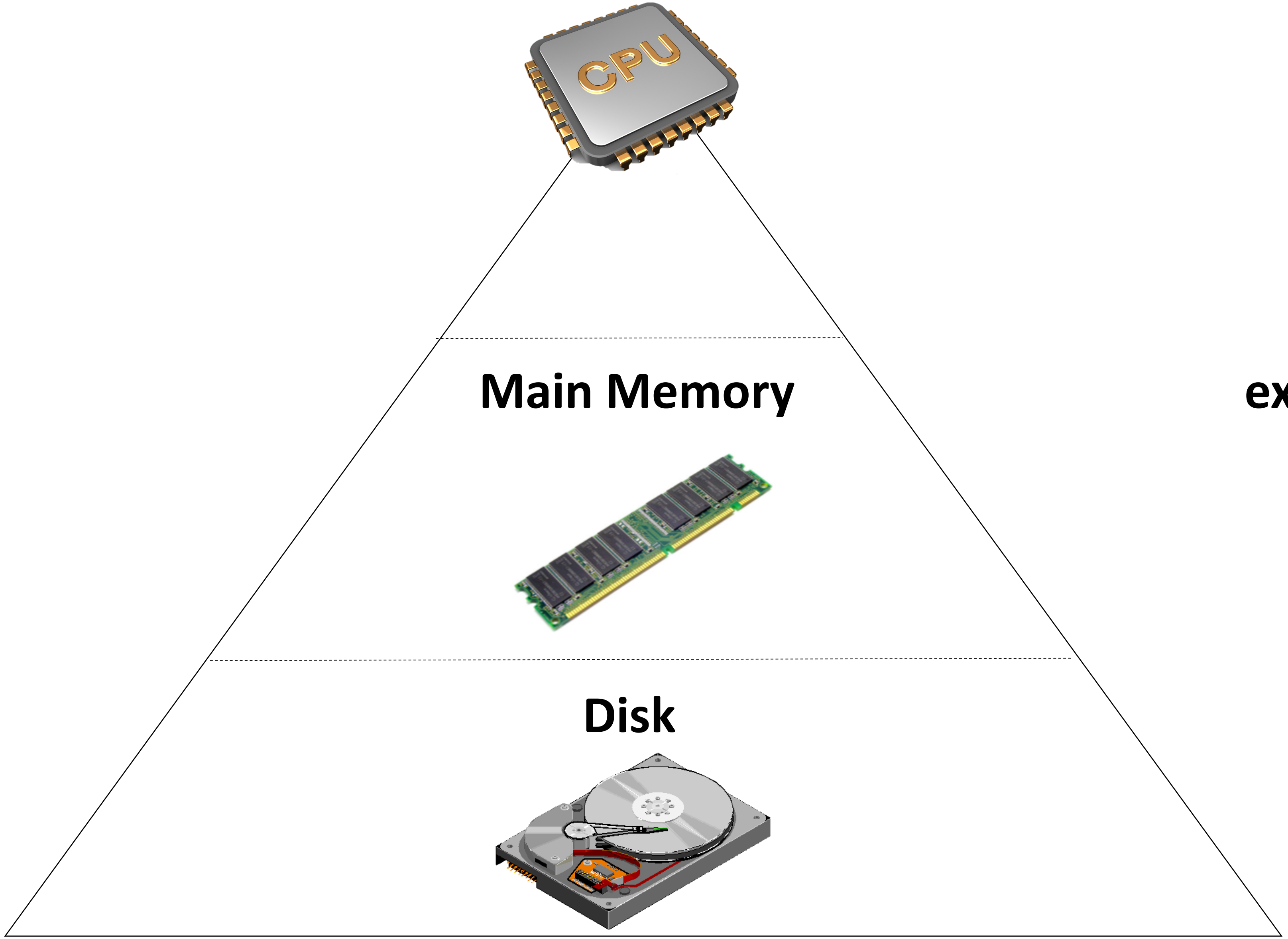
Main Memory

Disk

expensive, fast

cheap, slow

The Memory Hierarchy



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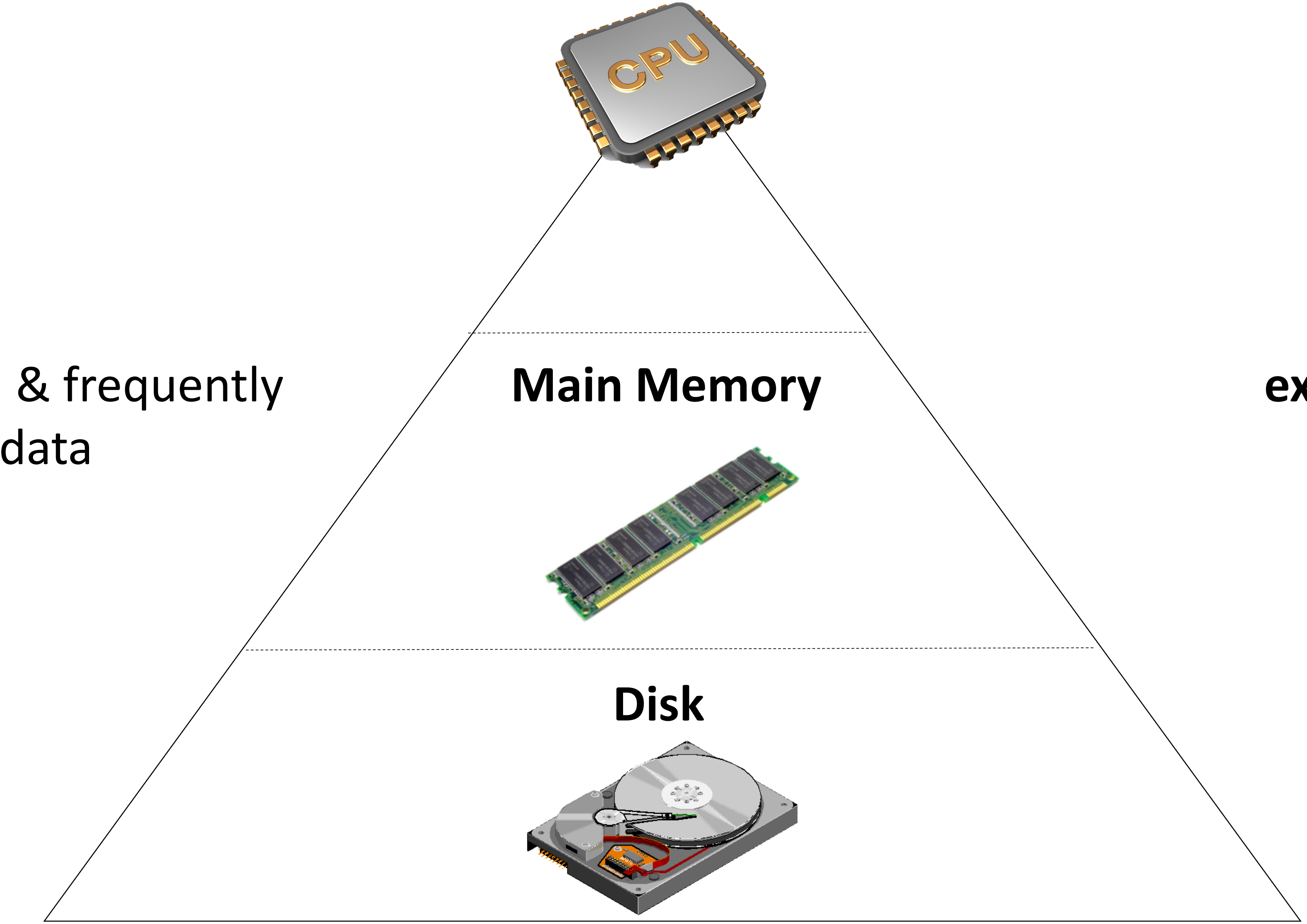
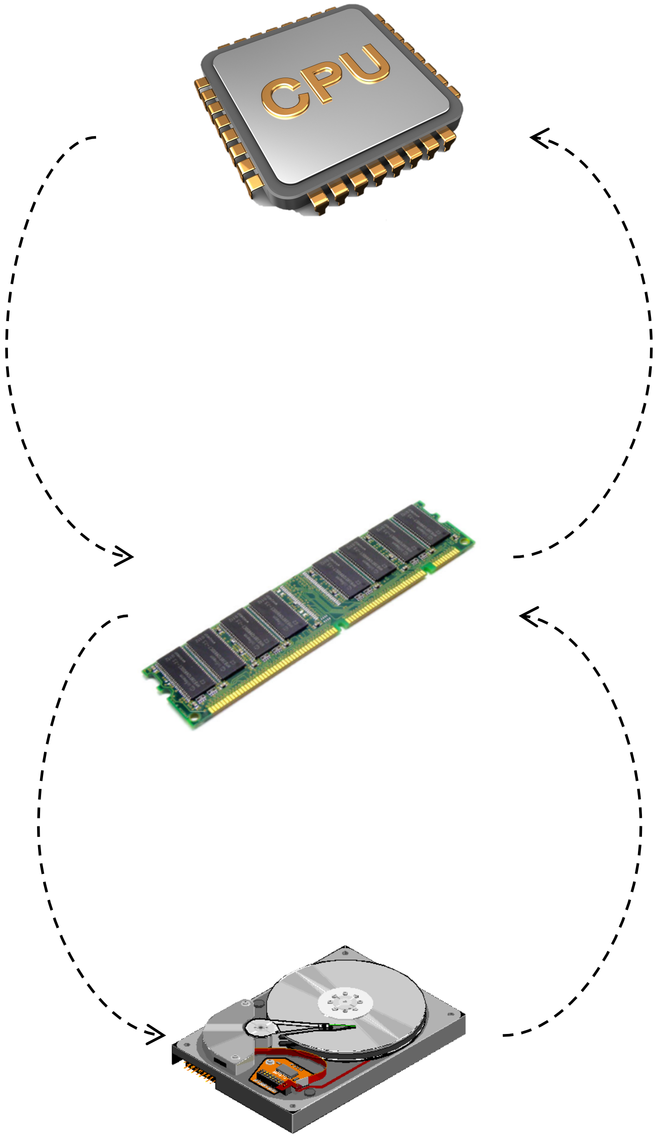


Metadata & frequently accessed data

expensive, fast

All data

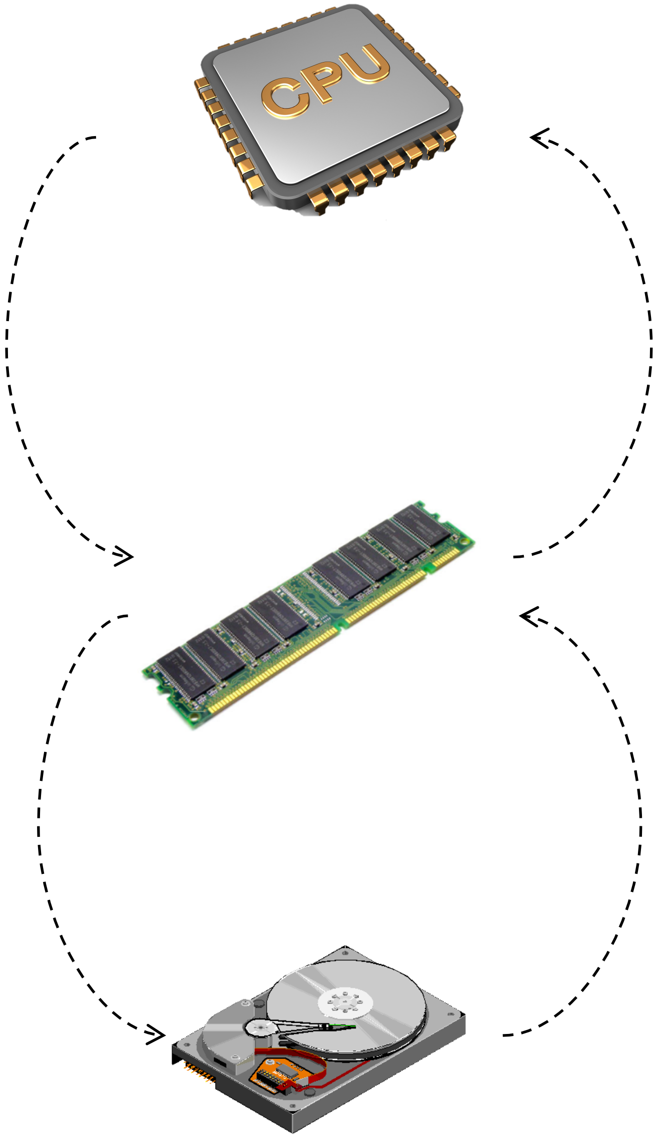
cheap, slow



≈100 ns

≈10 ms

≈5-6 order of magnitude difference



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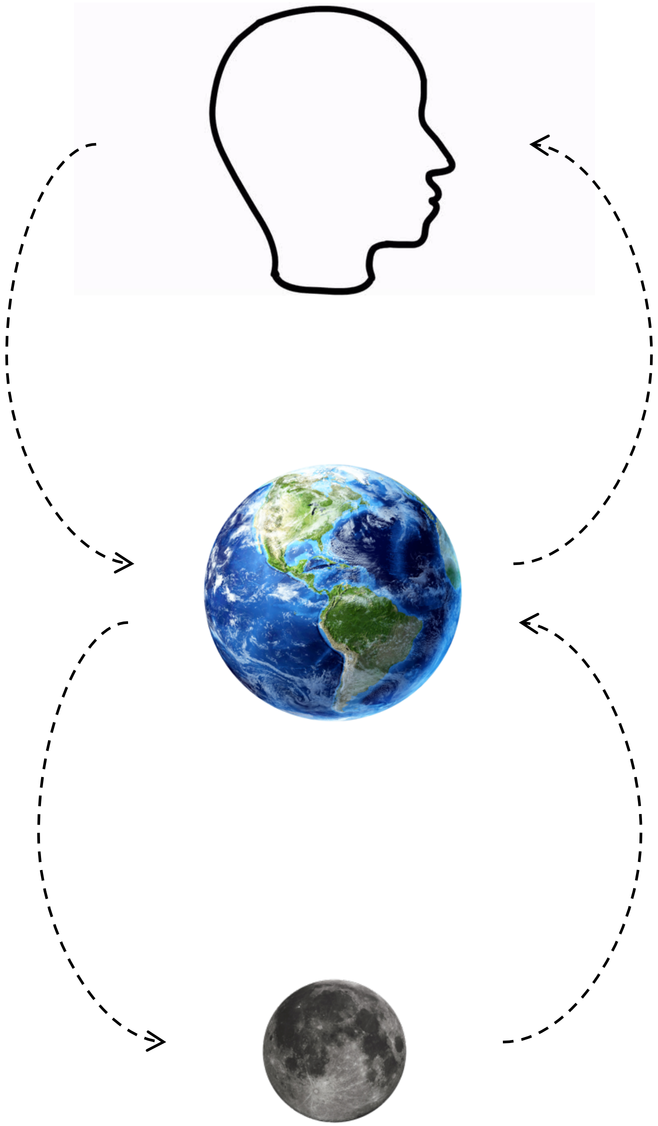
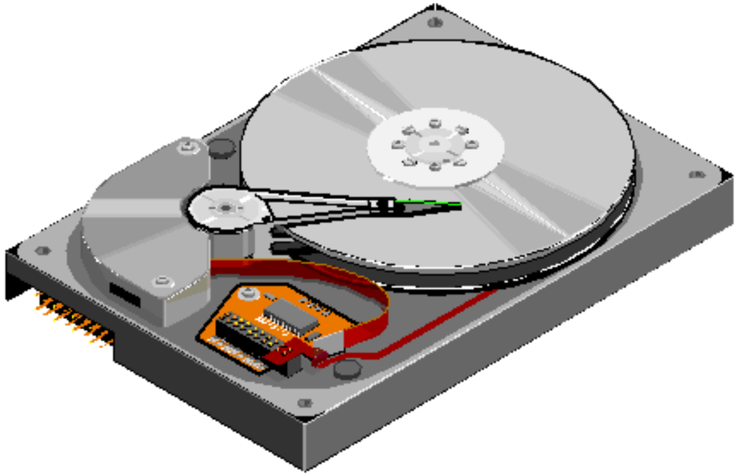


≈5-6 order of magnitude difference

Why is disk slow?



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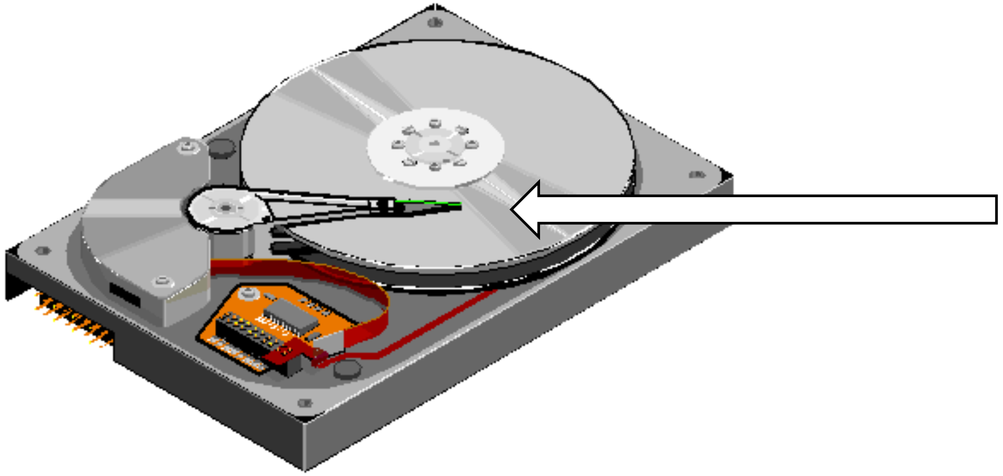
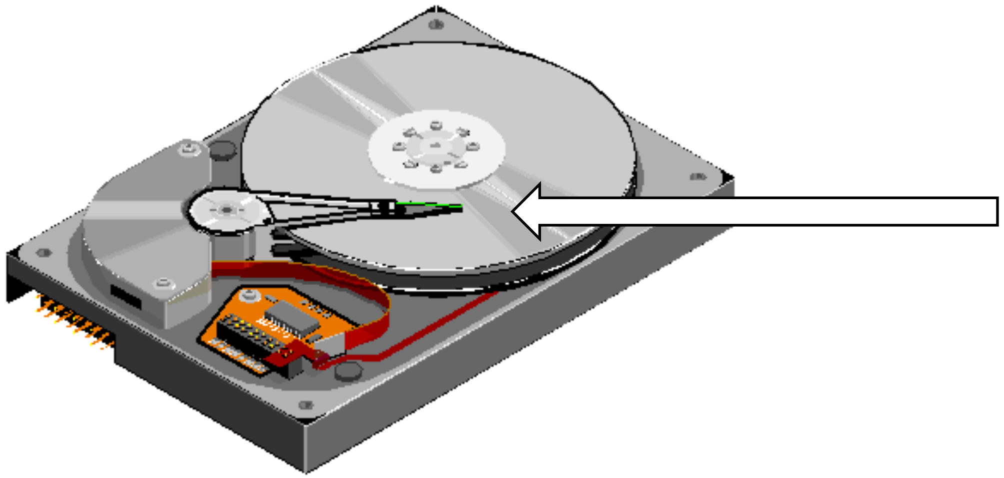


Disk head

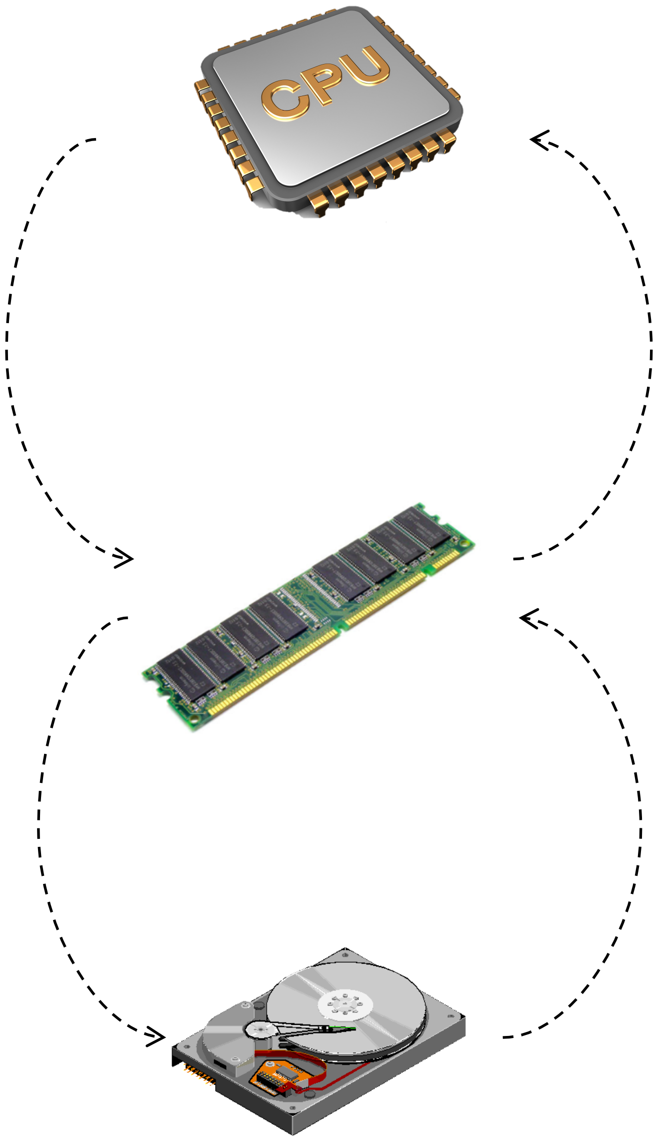
Why is disk slow?



Disk head

Random access is slow ⇒ move disk head

Sequential access is faster ⇒ let disk spin

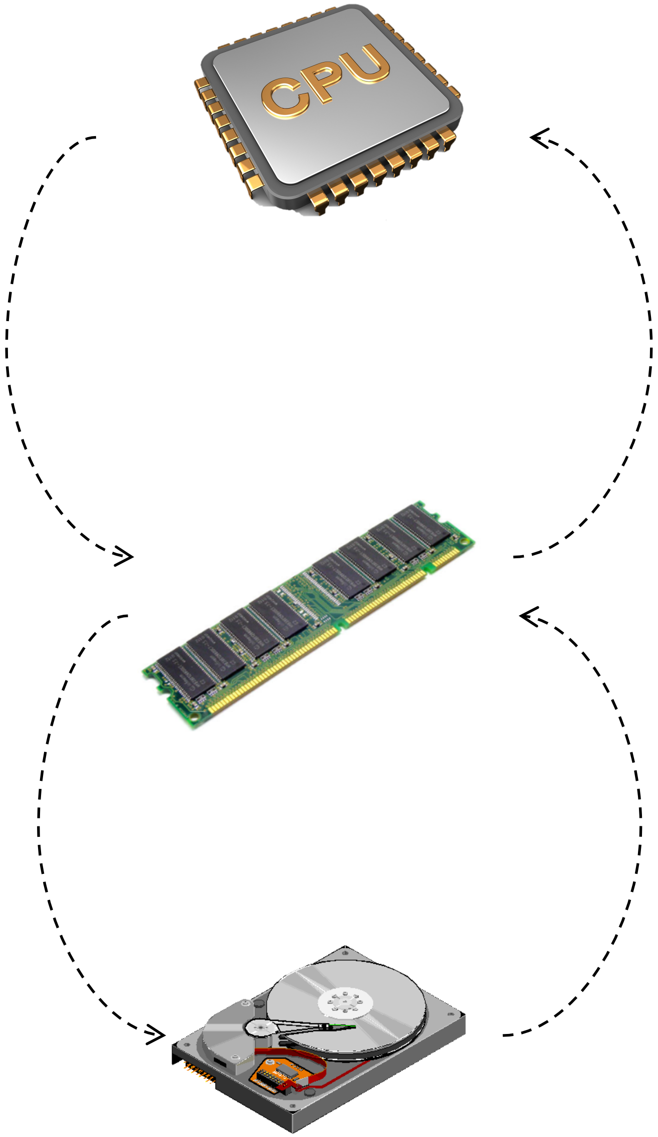


64 byte chunks
Words

Fine access granularity

4 kilobyte chunks
Blocks

Coarse access granularity



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Outline

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2. Indexing problem & basic solutions
3. Basic LSM-trees
4. Leveled LSM-trees
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Indexing Problem & Basic Solutions

Indexing Problem

names → phone numbers

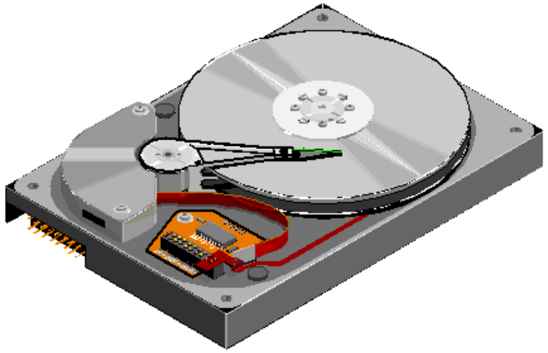
Indexing Problem

names ⇨ phone numbers

Structure on disk?

Lookup cost?

Insertion cost?



Results Catalogue

Compare and contrast data structures.

What to use when?

Data Structure	Lookup cost	Insertion cost
Sorted array		
Log		
B-tree		
Basic LSM-tree		
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue

Compare and contrast data structures.

What to use when?

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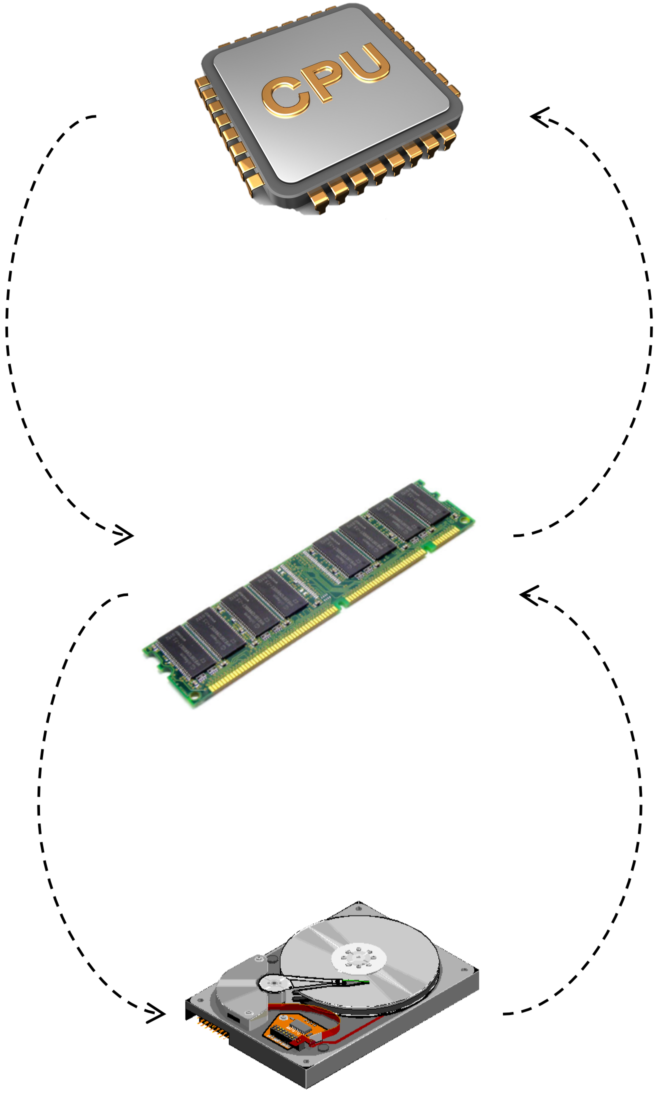
Modeling Performance



≈1 ns

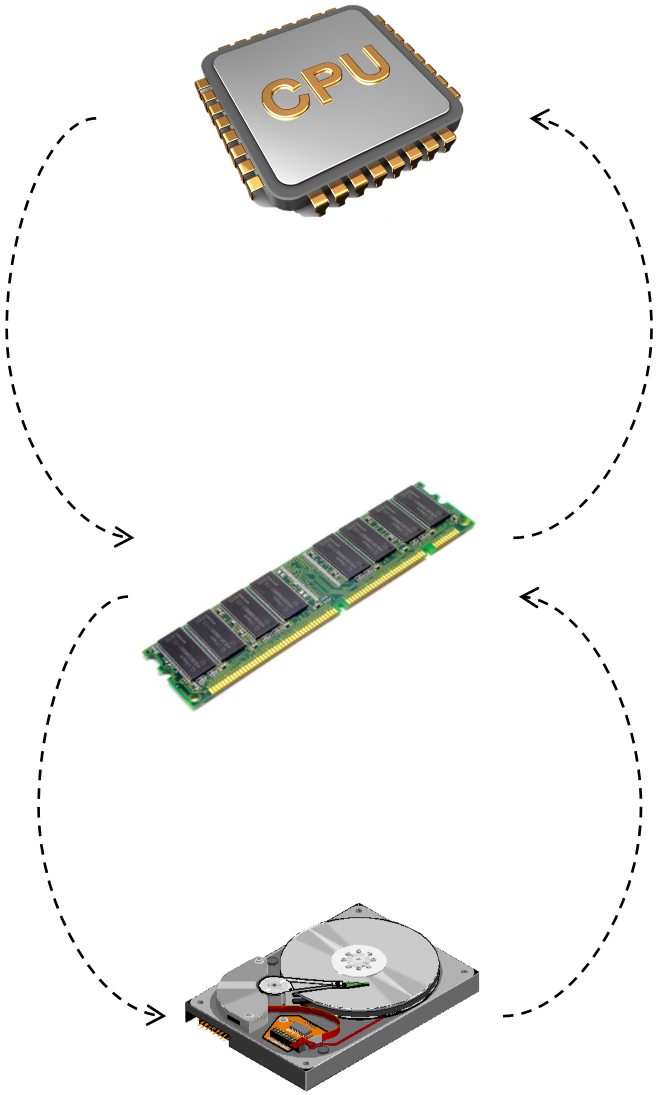
64 byte Words

≈100 ns

4 kilobyte Blocks

≈10 ms

Modeling Performance



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64 byte Words

≈100 ns

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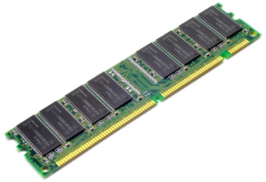
Measure bottleneck:

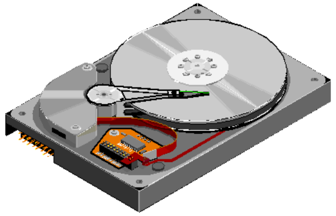
Number of block reads/writes (I/O)

Sorted Array



Buffer
James
Sara

Array size	Pointer



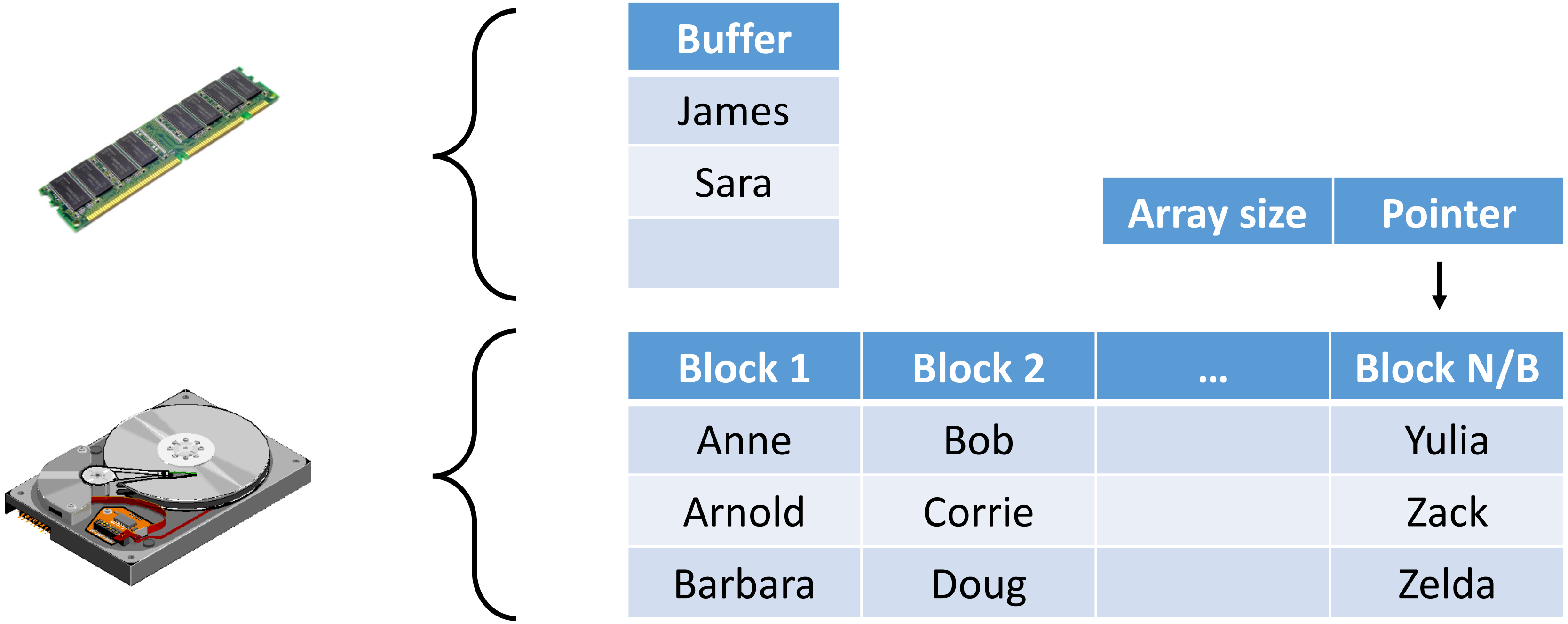
Block 1	Block 2	…	Block N/B
Anne	Bob		Yulia
Arnold	Corrie		Zack
Barbara	Doug		Zelda

Sorted Array

N entries

B entries fit into a disk block

Array spans **N/B** disk blocks



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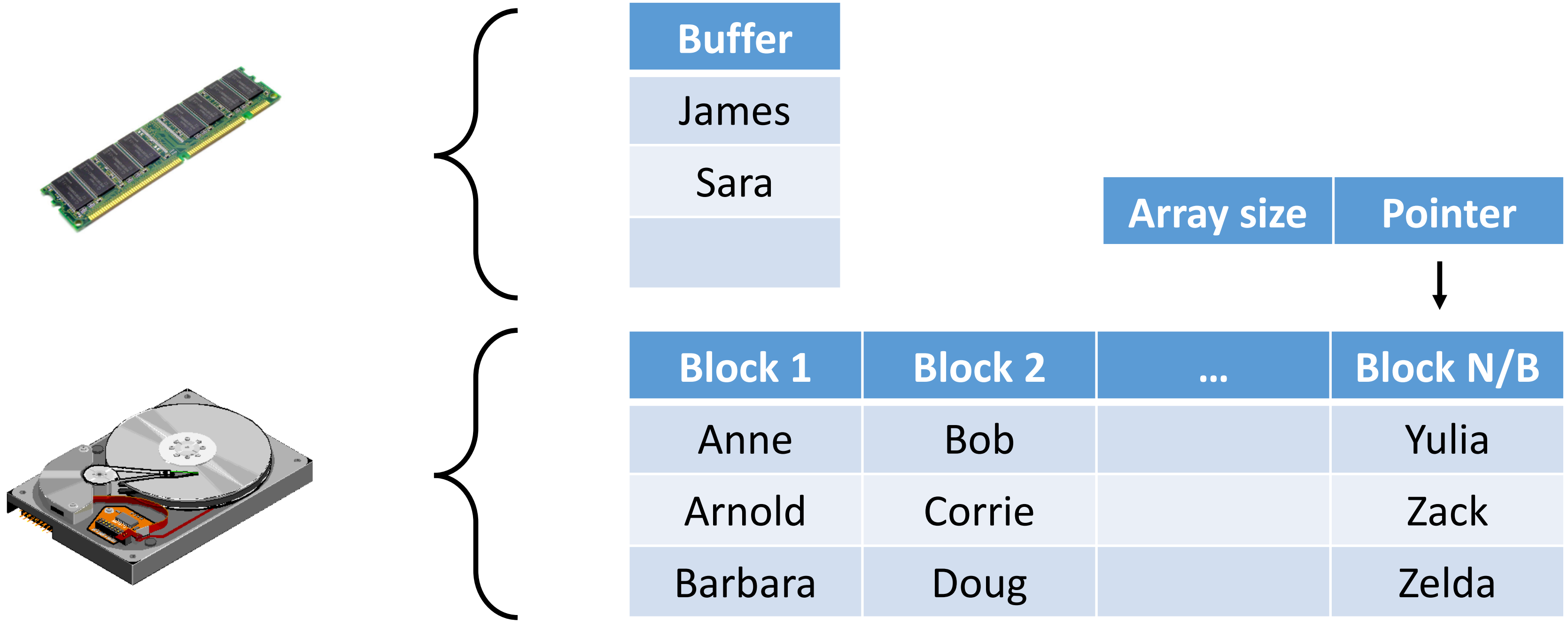
Lookup method & cost?



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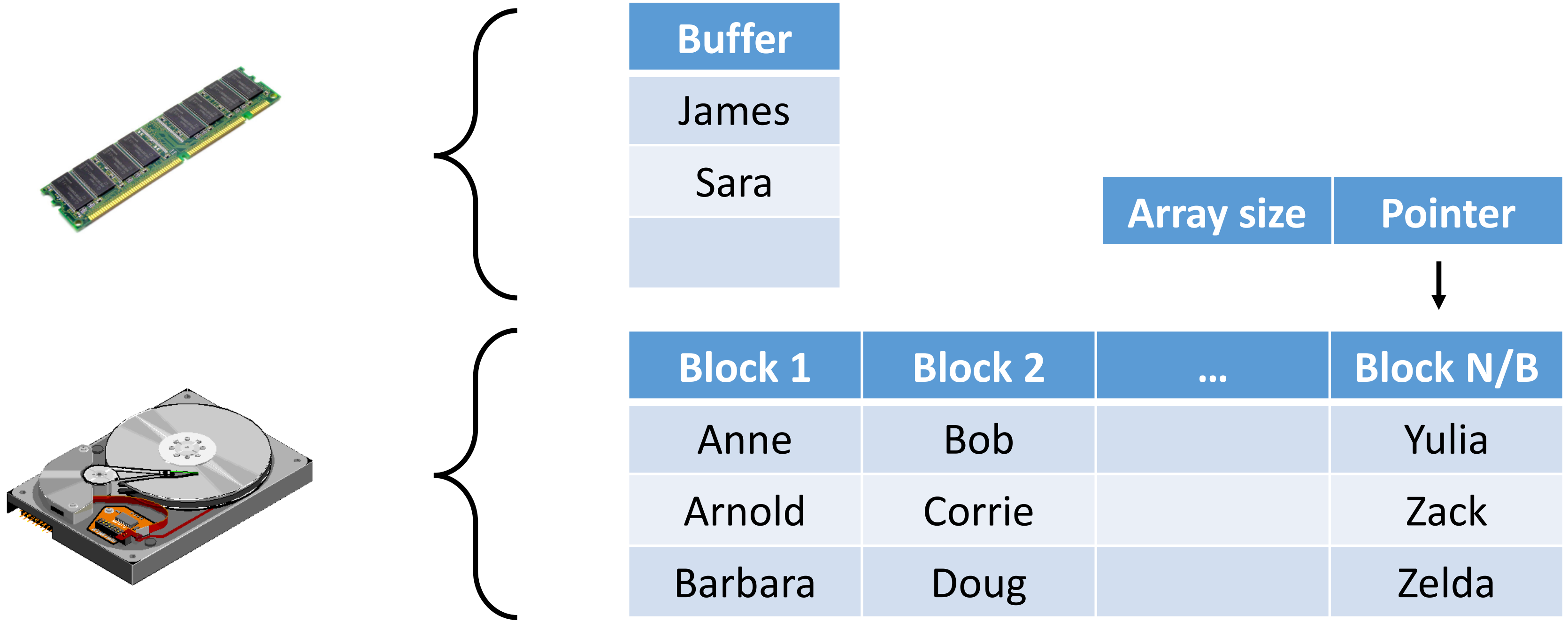

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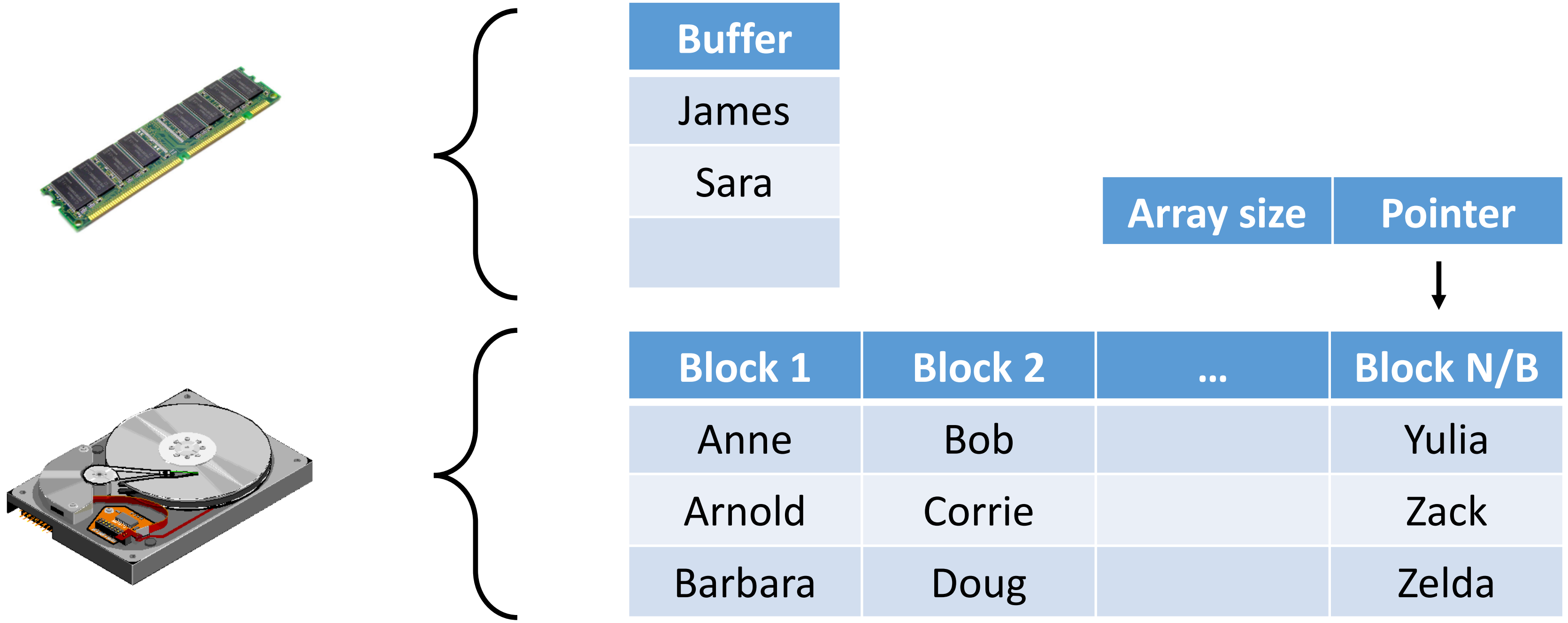

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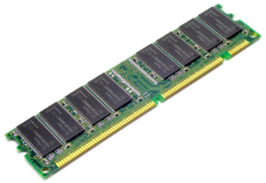
Lookup method & cost?

Binary search: $O\left(\log_2\left(\frac{N}{B}\right)\right)$ I/Os

Insertion cost?

Push entries: $O\left(\frac{1}{B}\cdot\frac{N}{B}\right)$ I/Os



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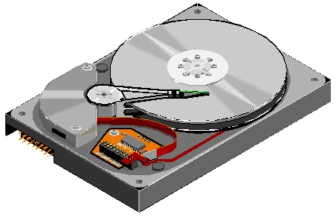

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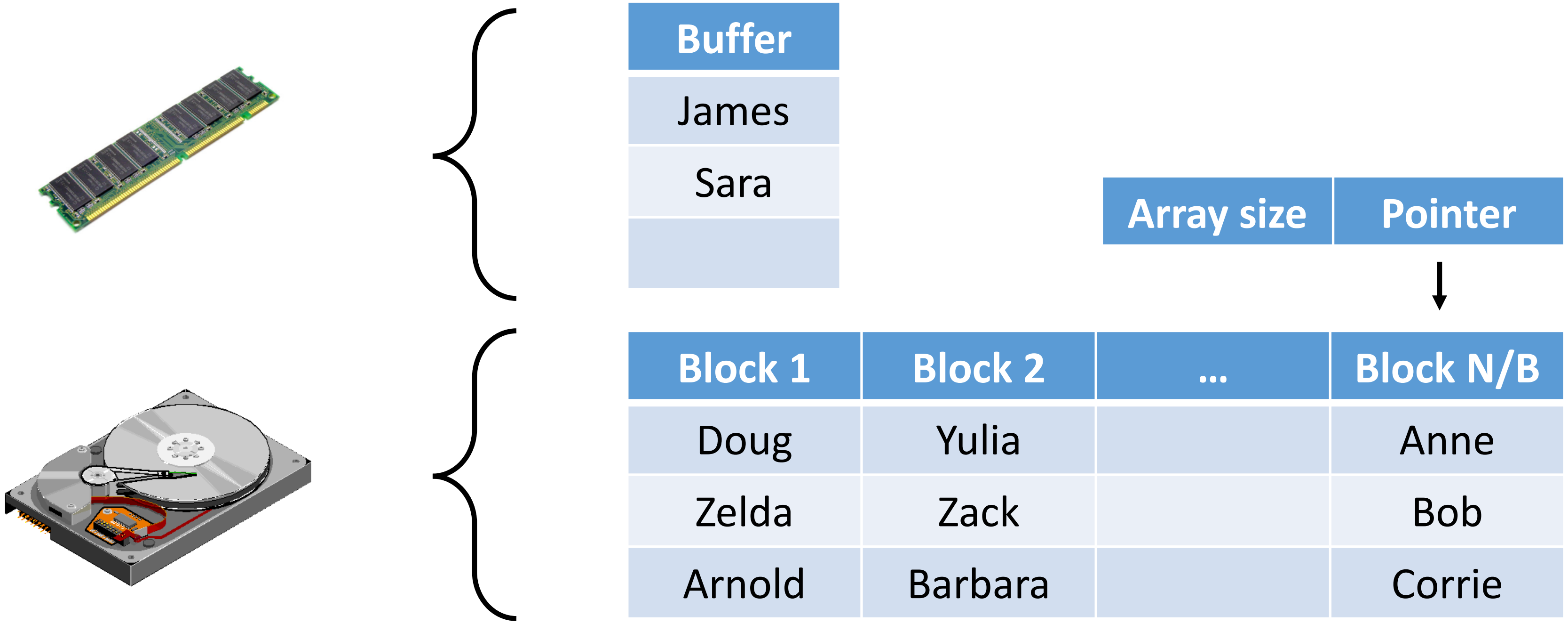
Log (append-only array)



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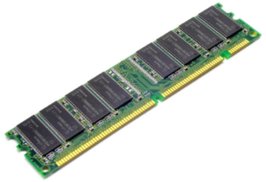

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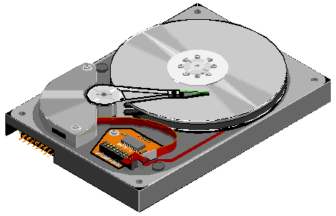

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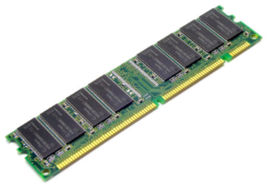

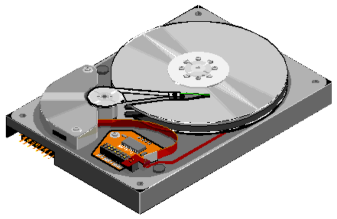

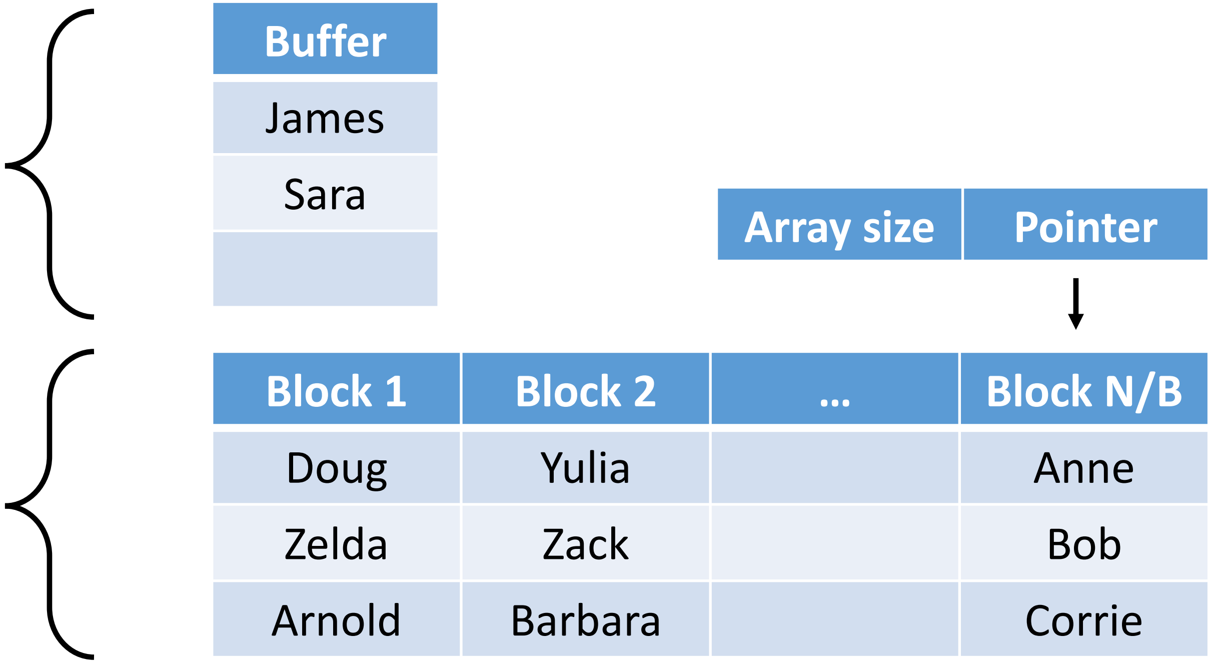

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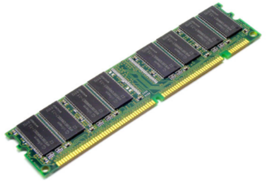
Lookup method & cost?

Scan: $O\left(\frac{N}{B}\right)$



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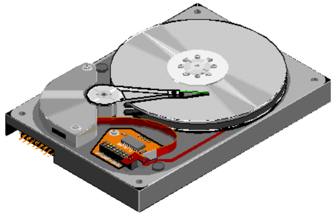

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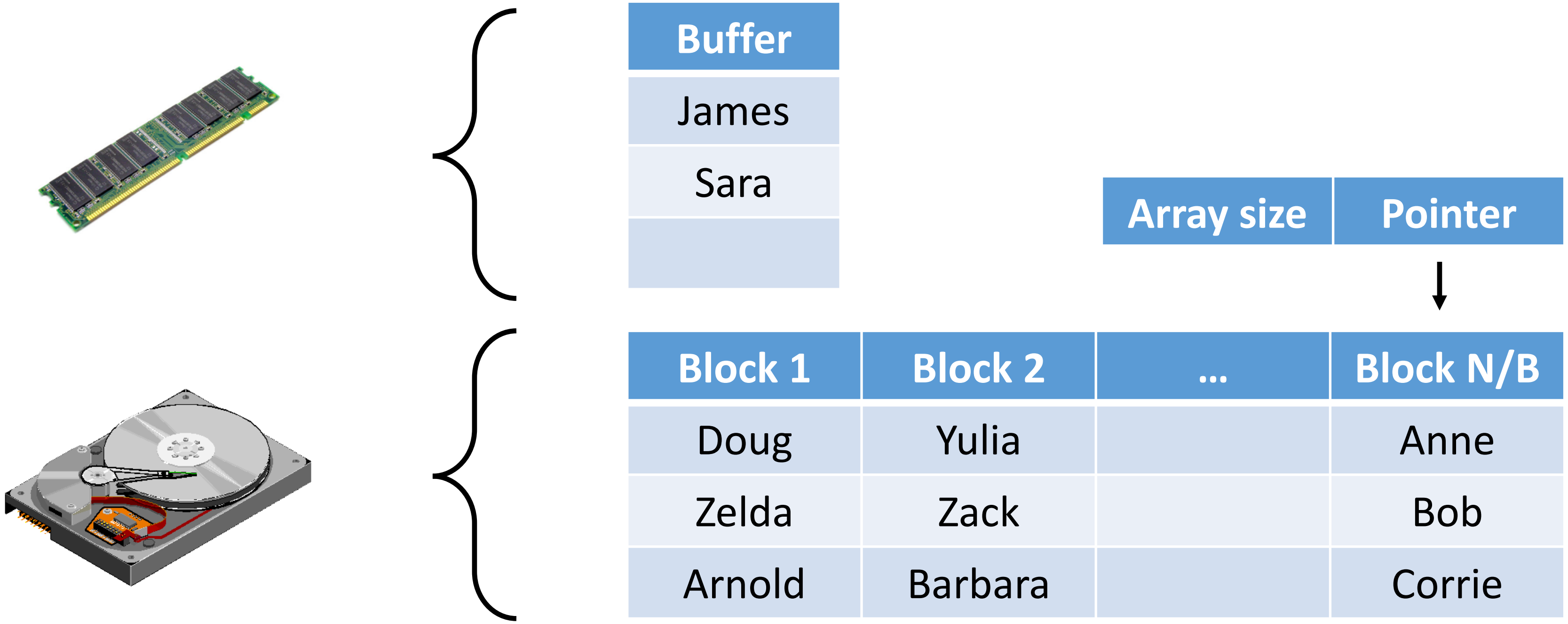
Lookup method & cost?

Scan: $O\left(\frac{N}{B}\right)$

Insertion cost?



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Lookup method & cost?

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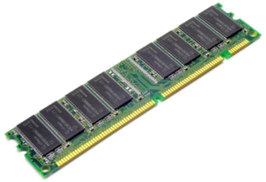
Insertion cost?

Append: $O\left(\frac{1}{B}\right)$



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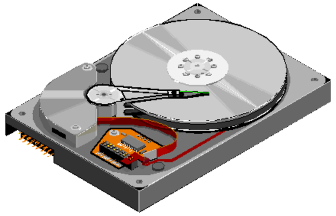

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B-tree		
Basic LSM-tree		
Leveled LSM-tree		
Tiered LSM-tree		

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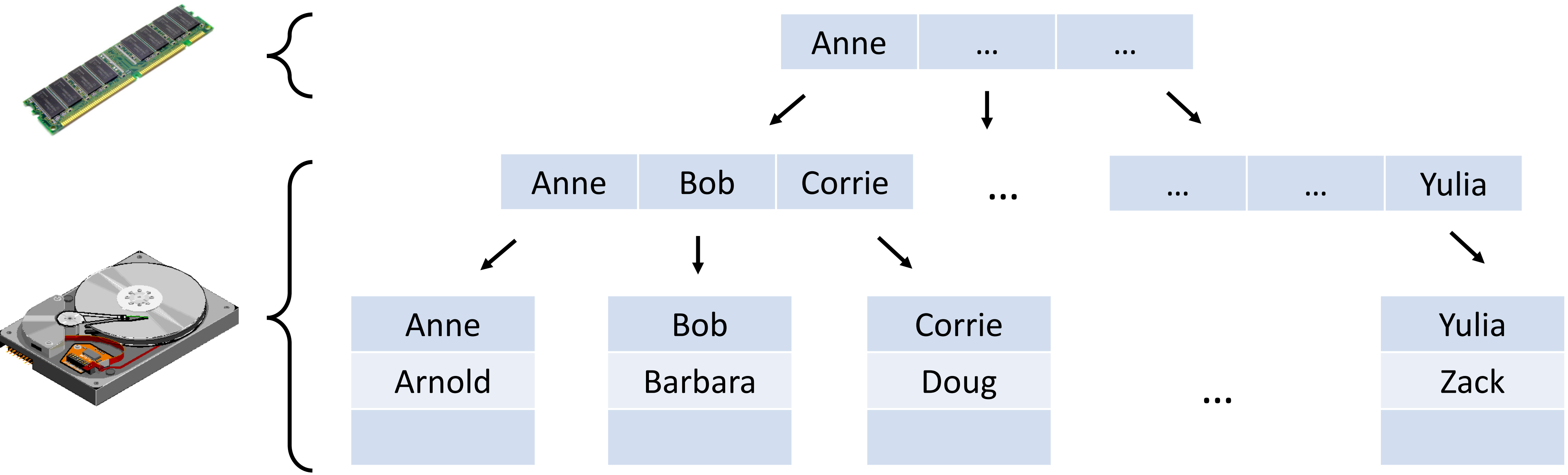
B-tree



Anne ... ...

Anne Bob Corrie ... ... Yulia

Anne
Arnold

Bob
Barbara

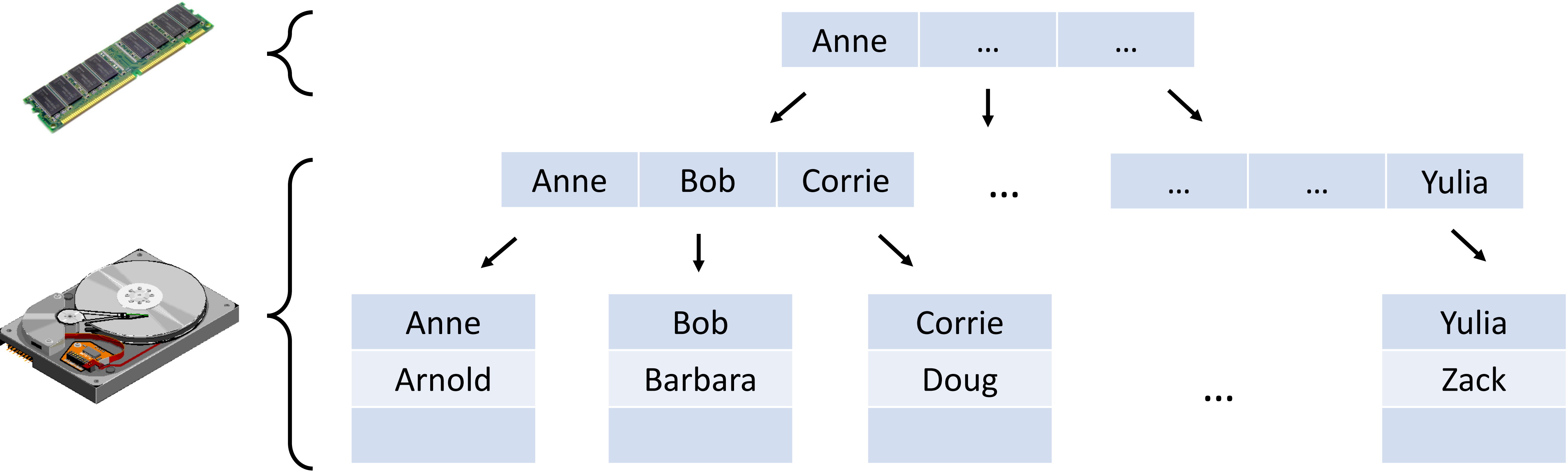
Corrie
Doug

...

Yulia
Zack

B-tree

Lookup method & cost?



Anne | ... | ...

Anne | Bob | Corrie ... ... | ... | Yulia

Anne
Arnold

Bob
Barbara

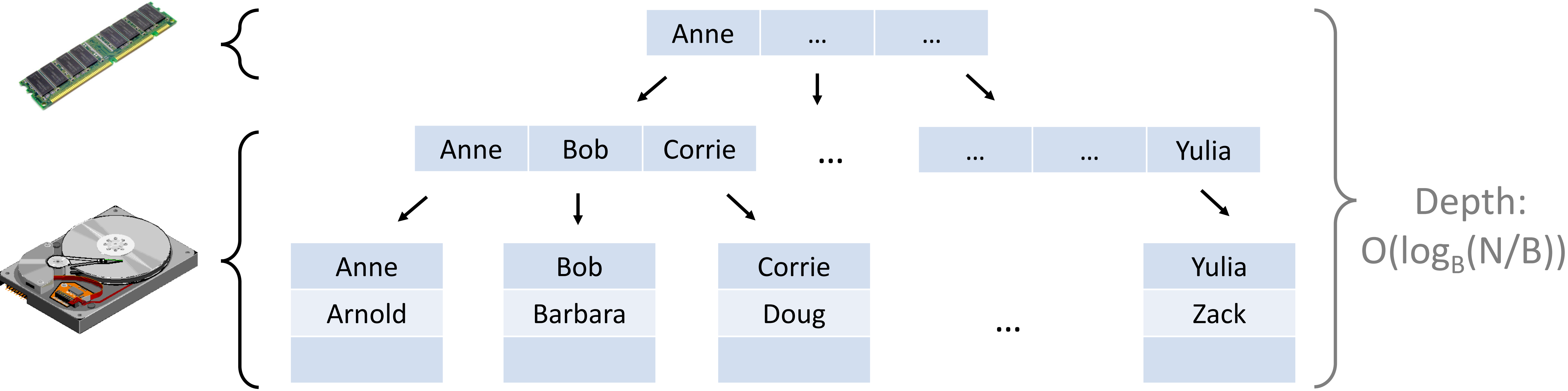
Corrie
Doug

...

Yulia
Zack

B-tree

Lookup method & cost?



Anne ... ...

Anne Bob Corrie ... ... Yulia

Anne
Arnold

Bob
Barbara

Corrie
Doug

...

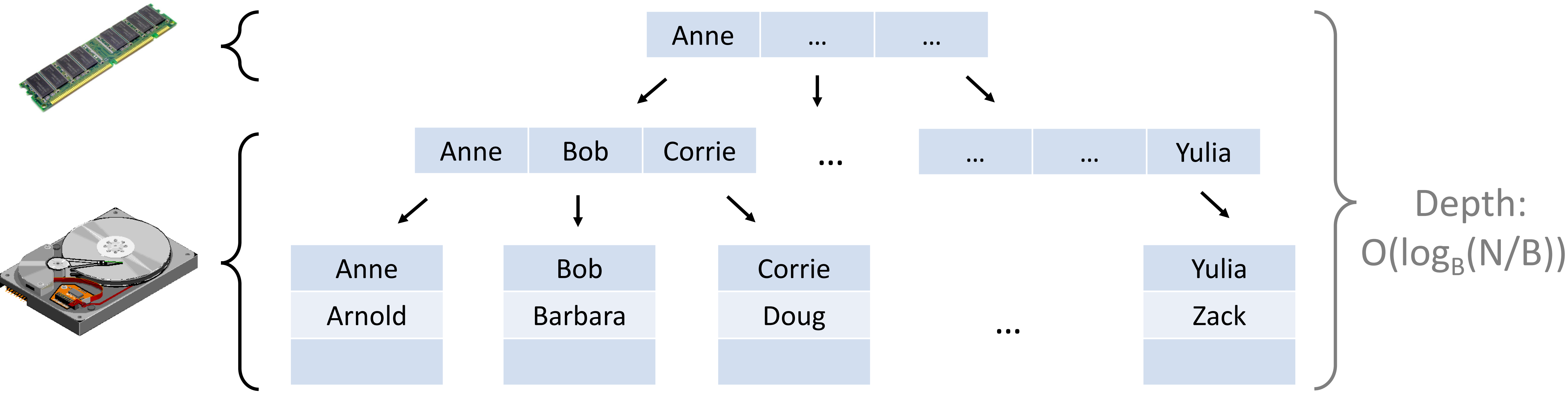
Yulia
Zack

Depth:
$O(\log_B(N/B))$

B-tree

Lookup method & cost?

Tree search: $O\left(\log_B\left(\frac{N}{B}\right)\right)$



Anne ... ...

Anne Bob Corrie ... ... Yulia

Anne
Arnold

Bob
Barbara

Corrie
Doug

...

Yulia
Zack

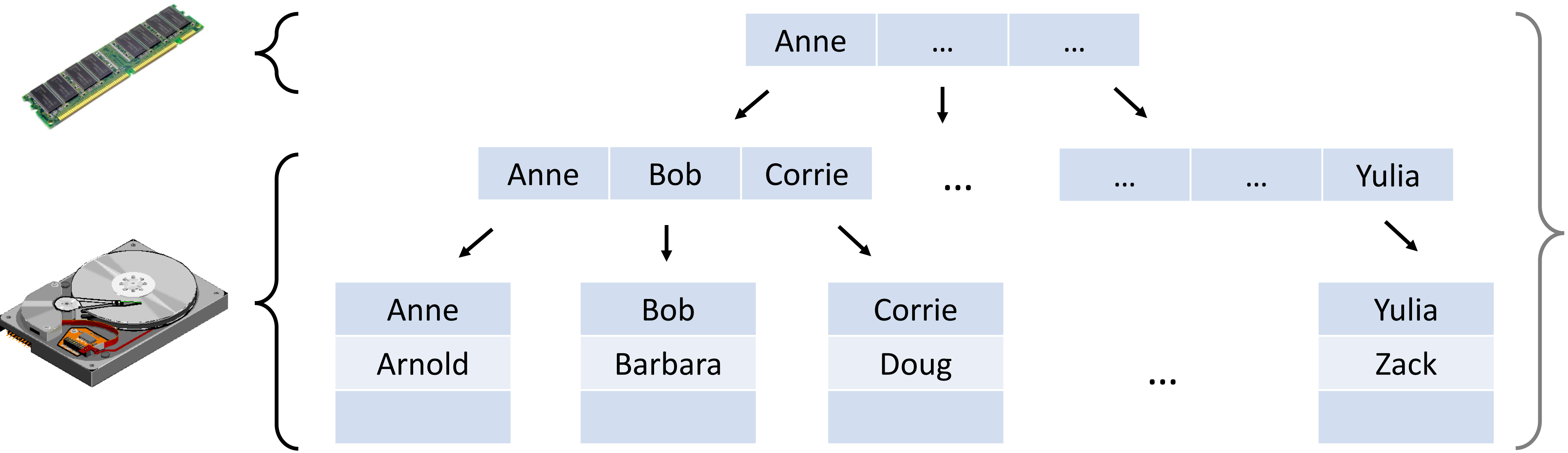
Depth: $O(\log_B(N/B))$

B-tree

Lookup method & cost?

Tree search: $O\left(\log_B\left(\frac{N}{B}\right)\right)$

Insertion method & cost?



Anne | … | …

Anne | Bob | Corrie … … | … | Yulia

Anne, Arnold | Bob, Barbara | Corrie, Doug | … | Yulia, Zack

Depth: $O(\log_B(N/B))$

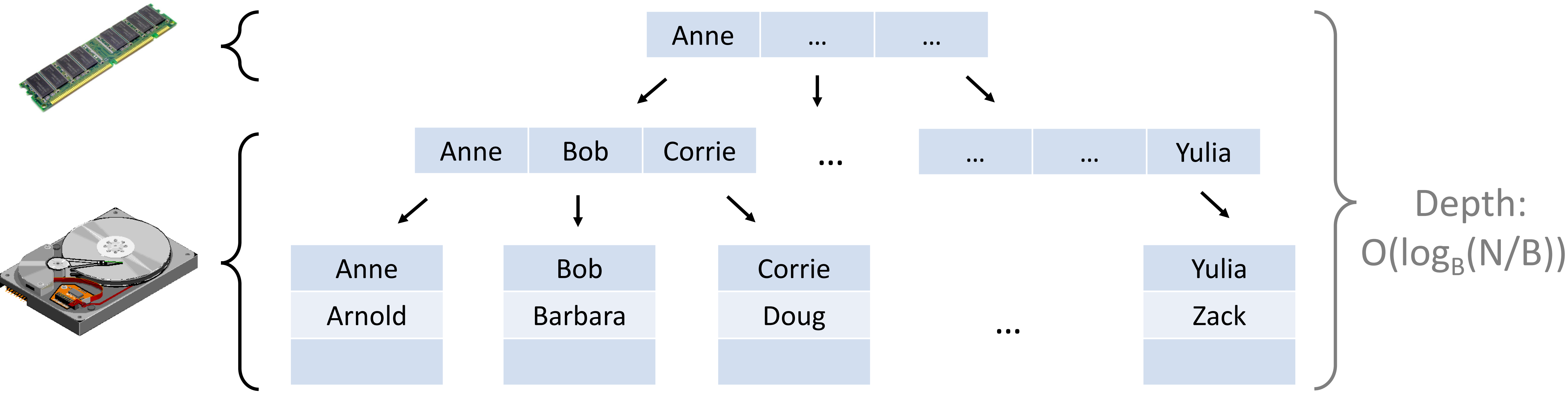
B-tree

Lookup method & cost?

Tree search: $O\left(\log_B\left(\frac{N}{B}\right)\right)$

Insertion method & cost?

Tree search & append: $O\left(\log_B\left(\frac{N}{B}\right)\right)$



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Log	$O(N/B)$	$O(1/B)$
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree		
Leveled LSM-tree		
Tiered LSM-tree		

B-trees

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

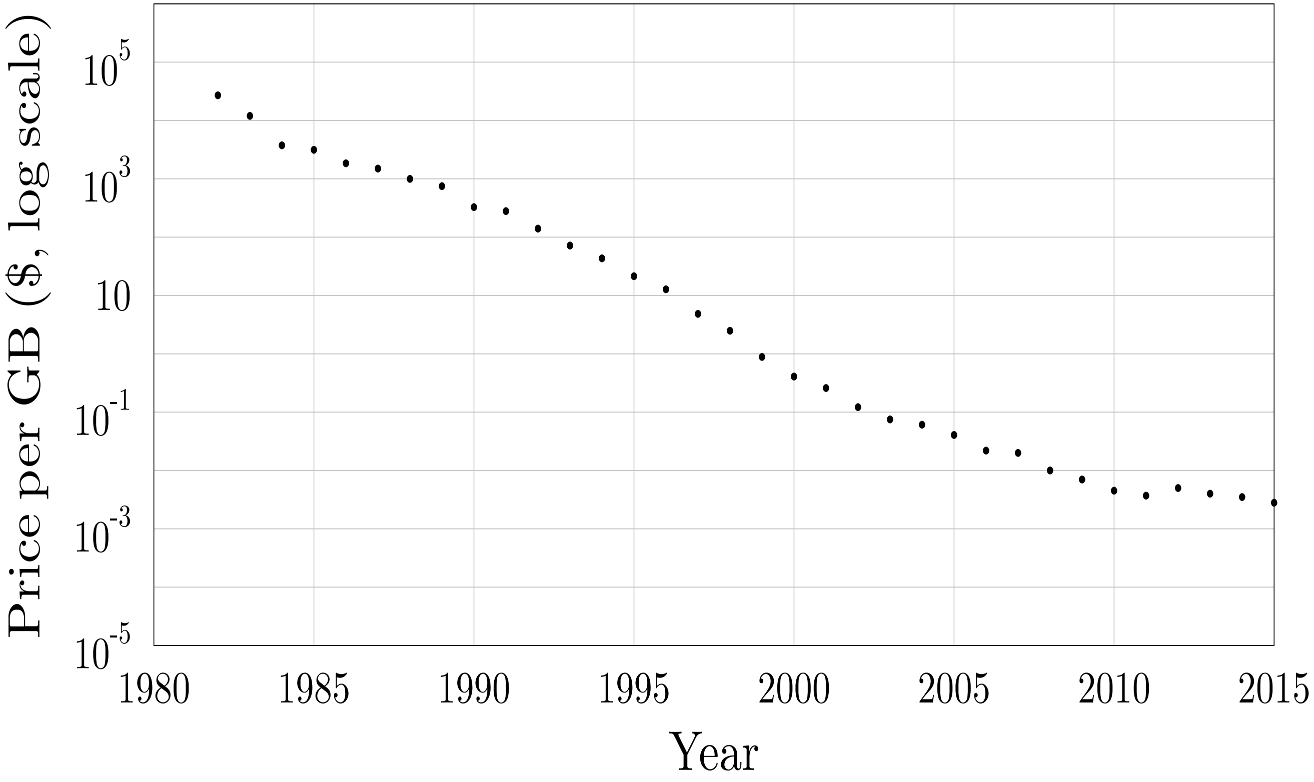
Goetz Graefe Microsoft, HP Fellow, now
Google ACM Software System Award

B-trees are no longer sufficient

Cheaper to store data

Workloads more insert-intensive

We need better insert-performance.



Results Catalogue

Goal to combine

sub-constant insertion cost
logarithmic lookup cost

	Lookup cost	Insertion cost
Sorted array	$O(\log_2(N/B))$	$O(N/B^2)$
Log	$O(N/B)$	**$O(1/B)$**
B-tree	**$O(\log_B(N/B))$**	$O(\log_B(N/B))$
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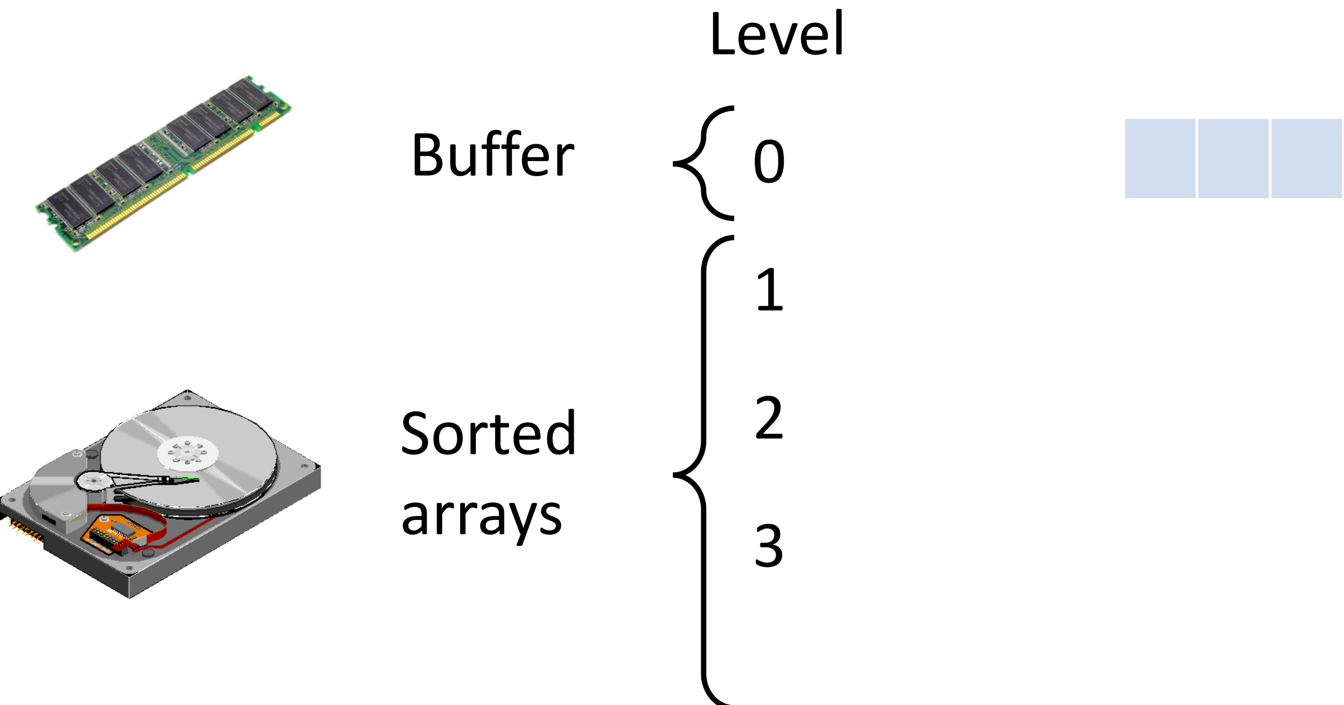
Basic LSM-trees

Basic LSM-tree



Level

Buffer

0

Sorted arrays

1

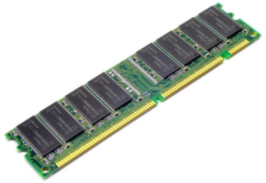
2

3

Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Level



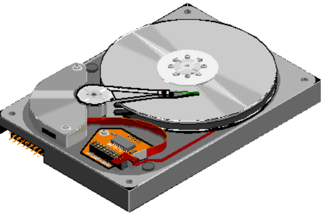
Buffer

0

1

2

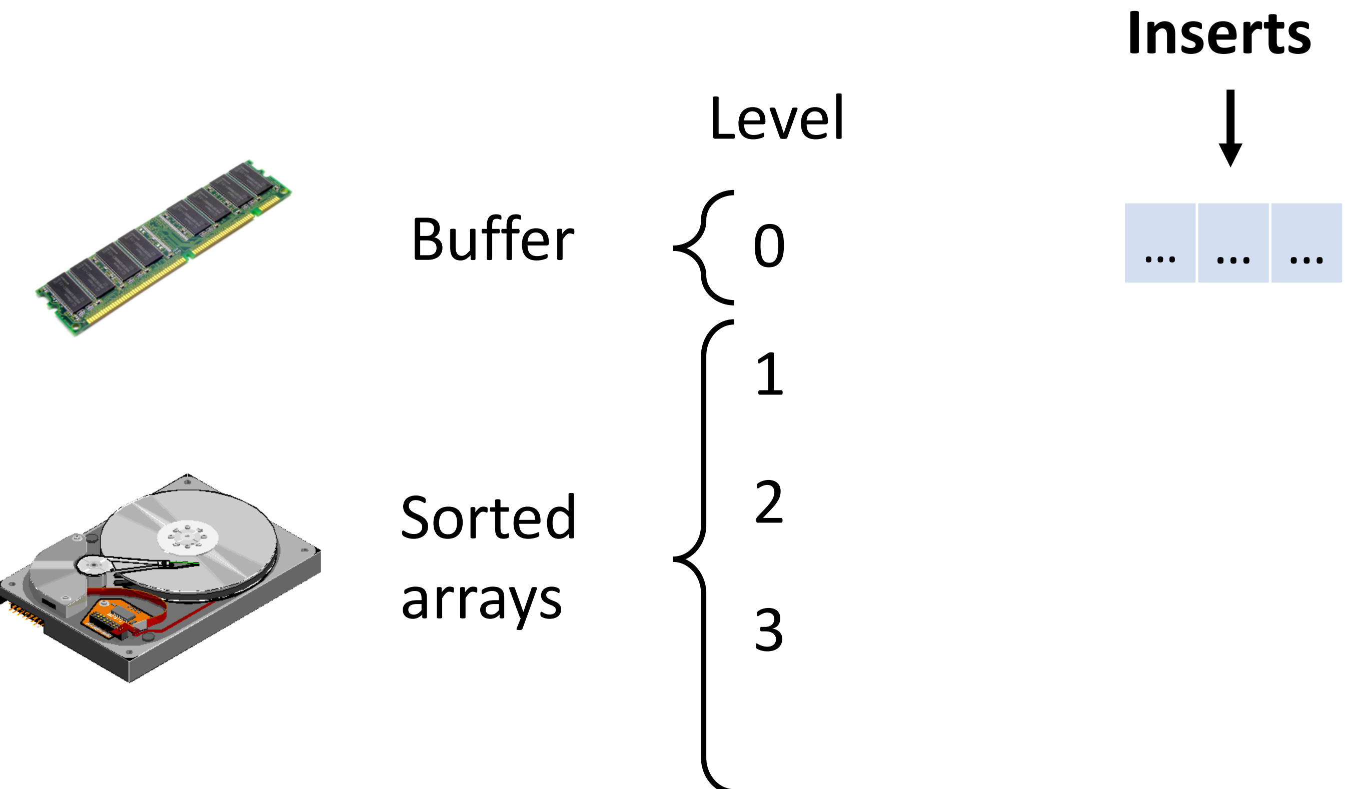
3



Sorted arrays

Basic LSM-tree

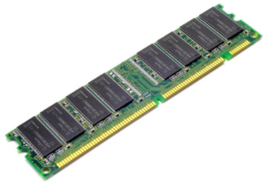
Design principle #1: optimize for insertions by buffering



Basic LSM-tree

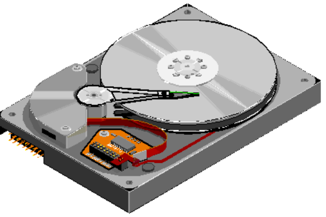
Design principle #1: optimize for insertions by buffering

Level



Buffer

0



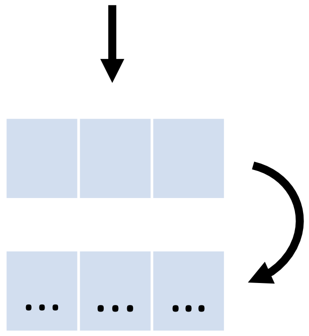
Sorted arrays

1

2

3

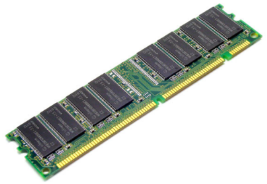
Inserts

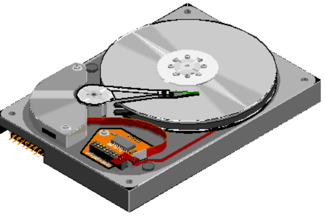


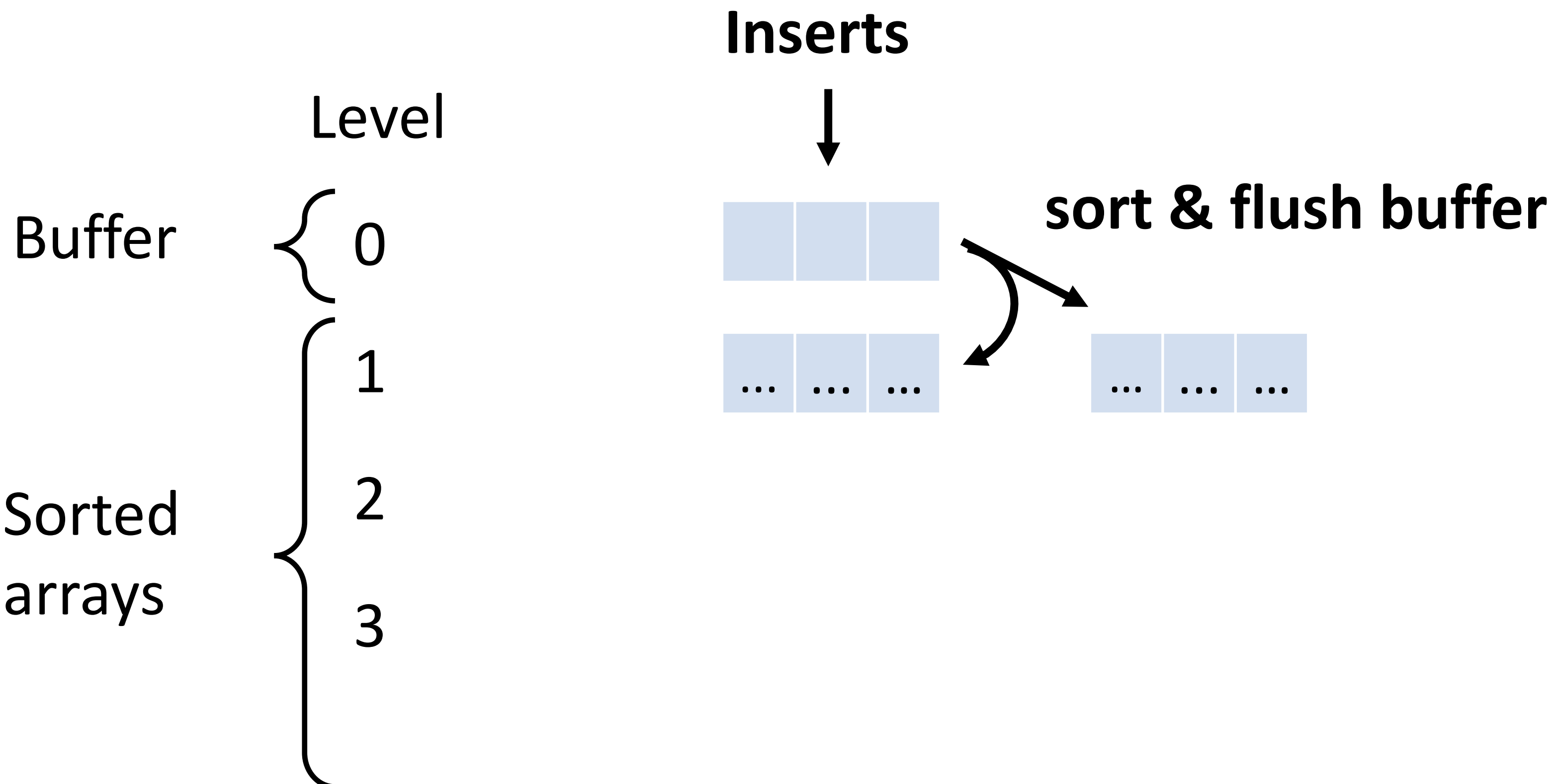
sort & flush buffer

Basic LSM-tree

Design principle #1: optimize for insertions by buffering







Inserts

Level

Buffer

0

sort & flush buffer

1

2

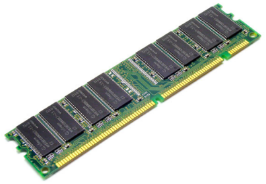
3

Sorted arrays

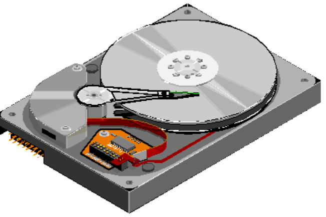
Basic LSM-tree

Design principle #1: optimize for insertions by buffering

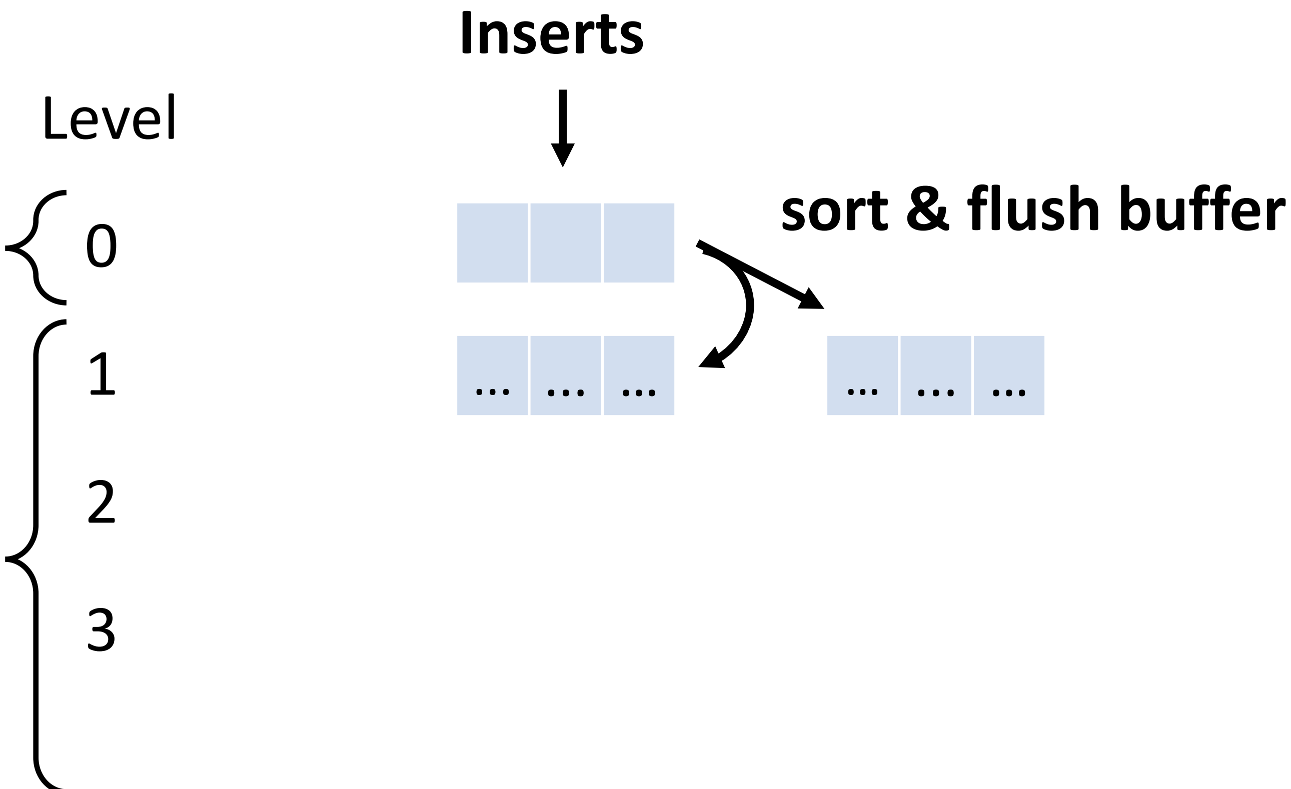
Design principle #2: optimize for lookups by sort-merging arrays



Buffer



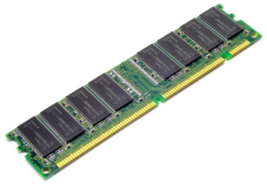
Sorted arrays

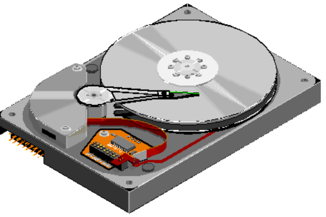


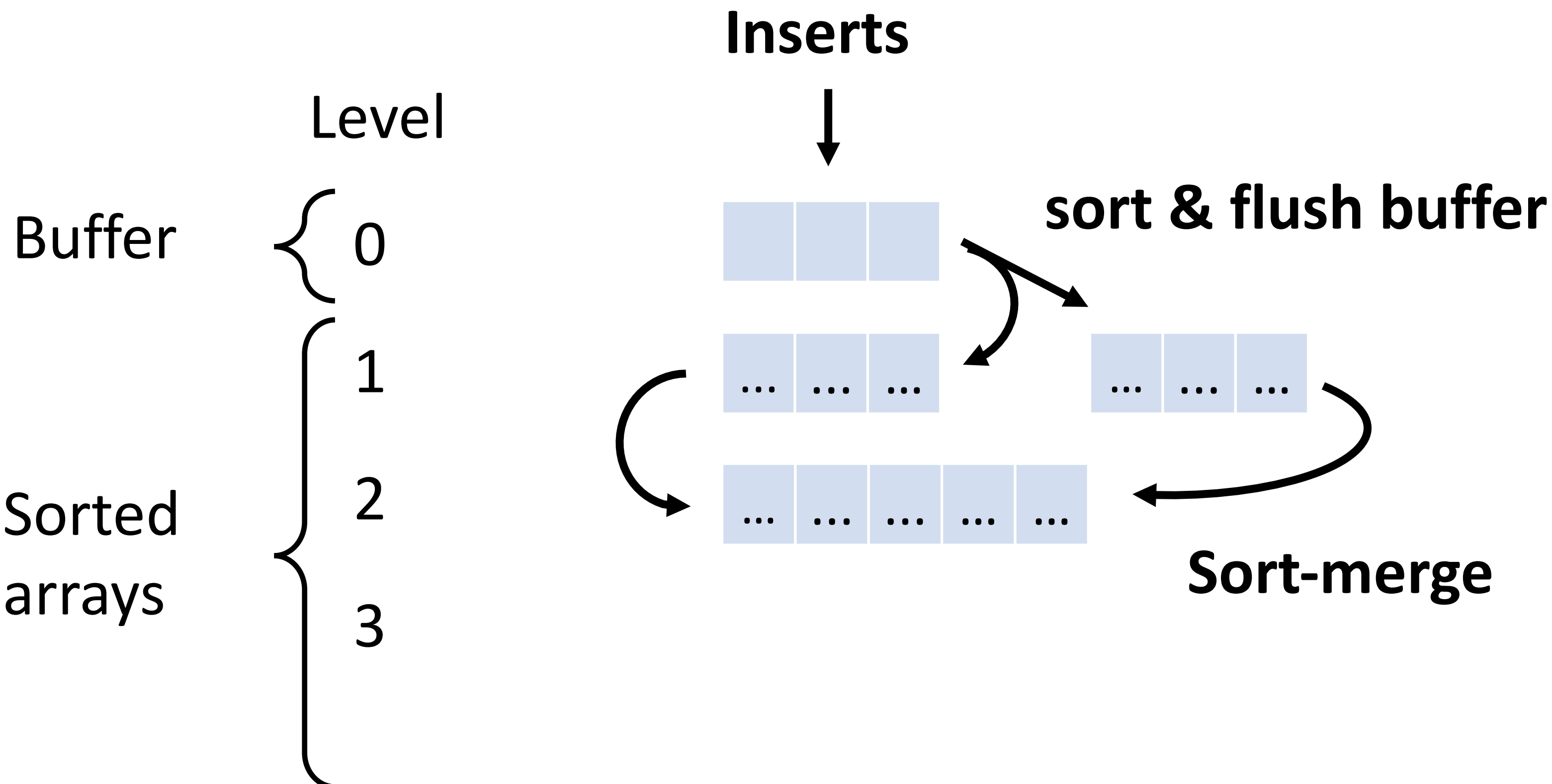
Basic LSM-tree

Design principle #1: optimize for insertions by buffering

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



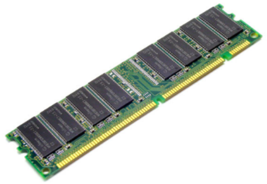




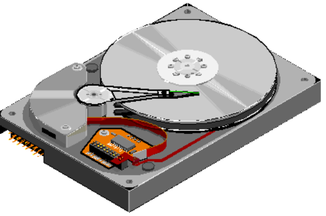
Basic LSM-tree

Design principle #1: optimize for insertions by buffering

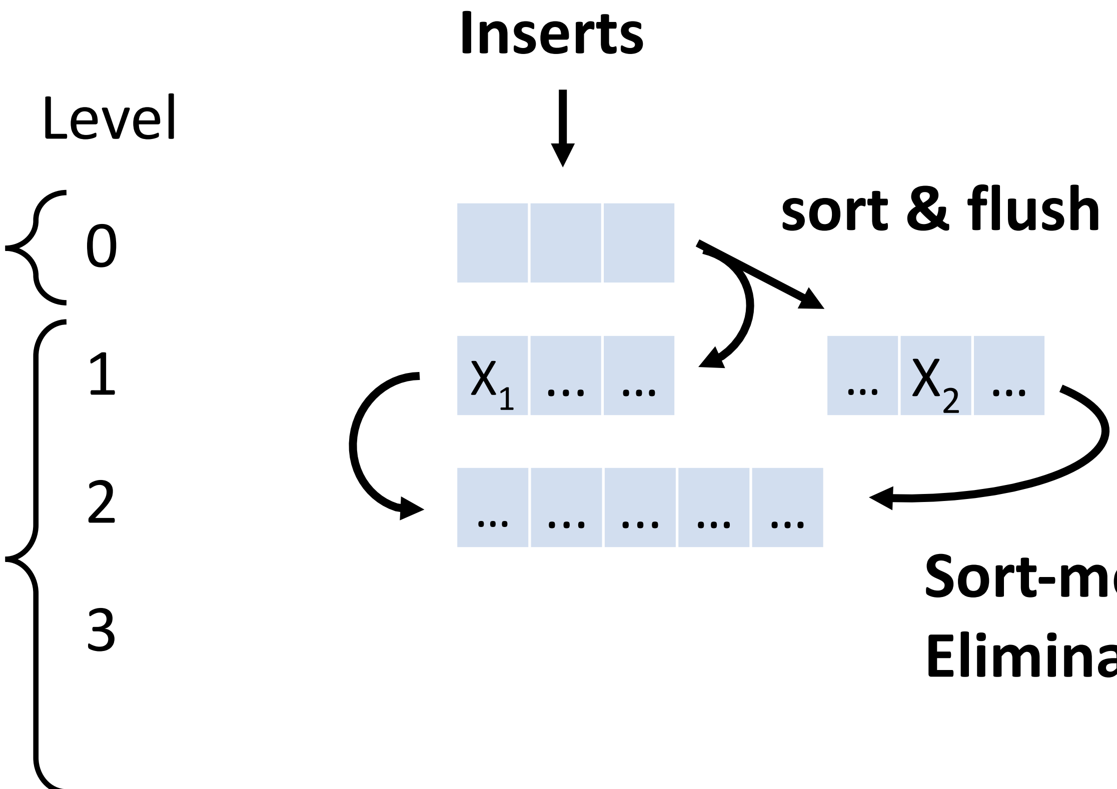
Design principle #2: optimize for lookups by sort-merging arrays



Buffer



Sorted arrays



sort & flush buffer

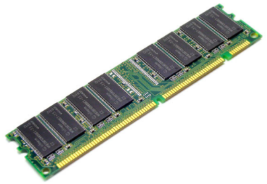
Sort-merge & Eliminate duplicates

Basic LSM-tree

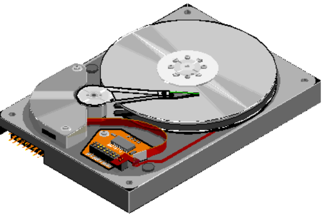
Design principle #1: optimize for insertions by buffering

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

Level

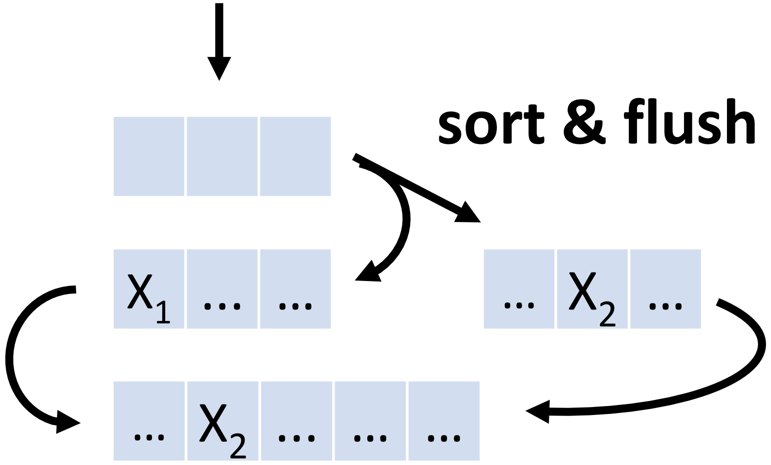


Buffer { 0



Sorted arrays { 1, 2, 3

Inserts



sort & flush buffer

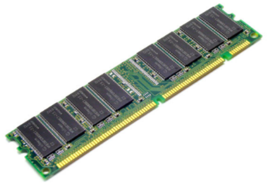
Sort-merge & Eliminate duplicates

Basic LSM-tree

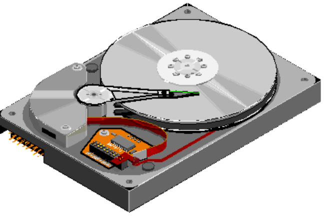
Design principle #1: optimize for insertions by buffering

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

Level

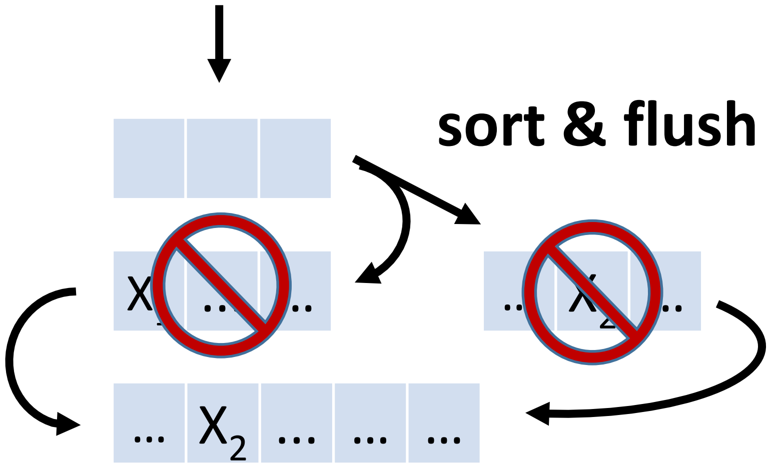


Buffer { 0



Sorted arrays { 1 2 3

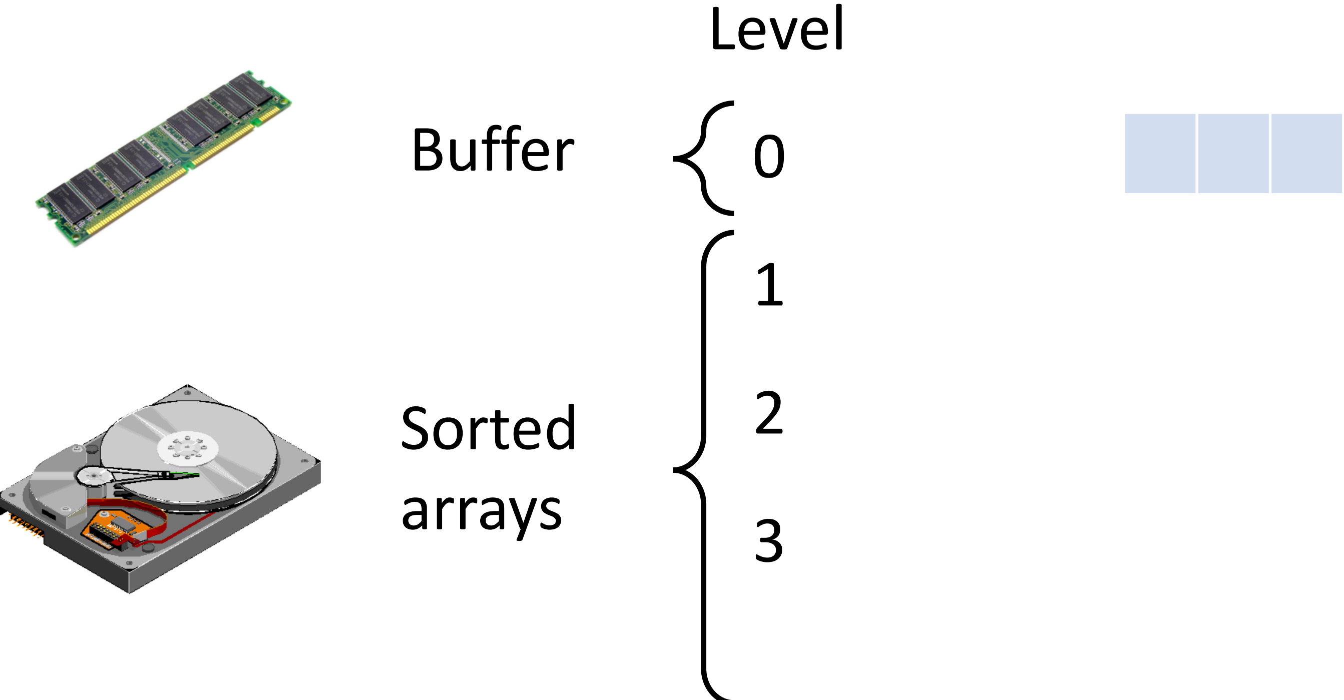
Inserts



sort & flush buffer

Sort-merge &
Eliminate duplicates &
Discard original arrays

Basic LSM-tree – Example



Level

Buffer

0

Sorted arrays

1

2

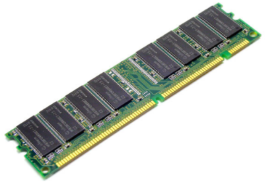
3

Basic LSM-tree – Example

inserts

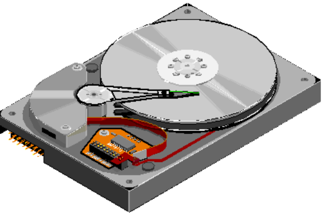
↓

Level



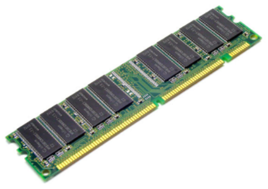
Buffer { 0

4	6	9

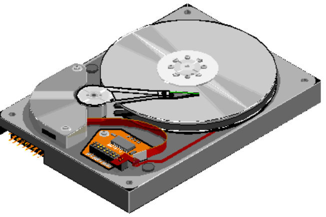


Sorted arrays { 1, 2, 3

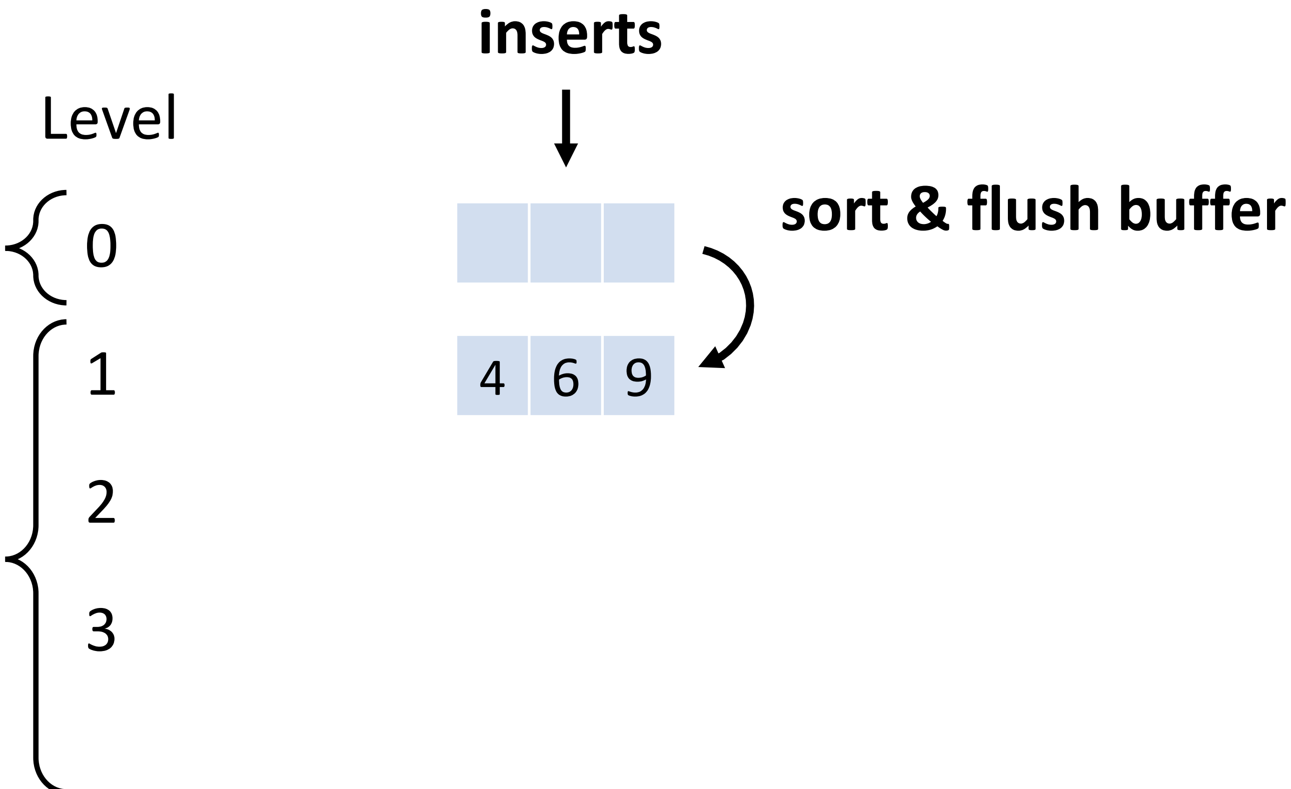
Basic LSM-tree – Example



Buffer



Sorted arrays



Level

0

1

2

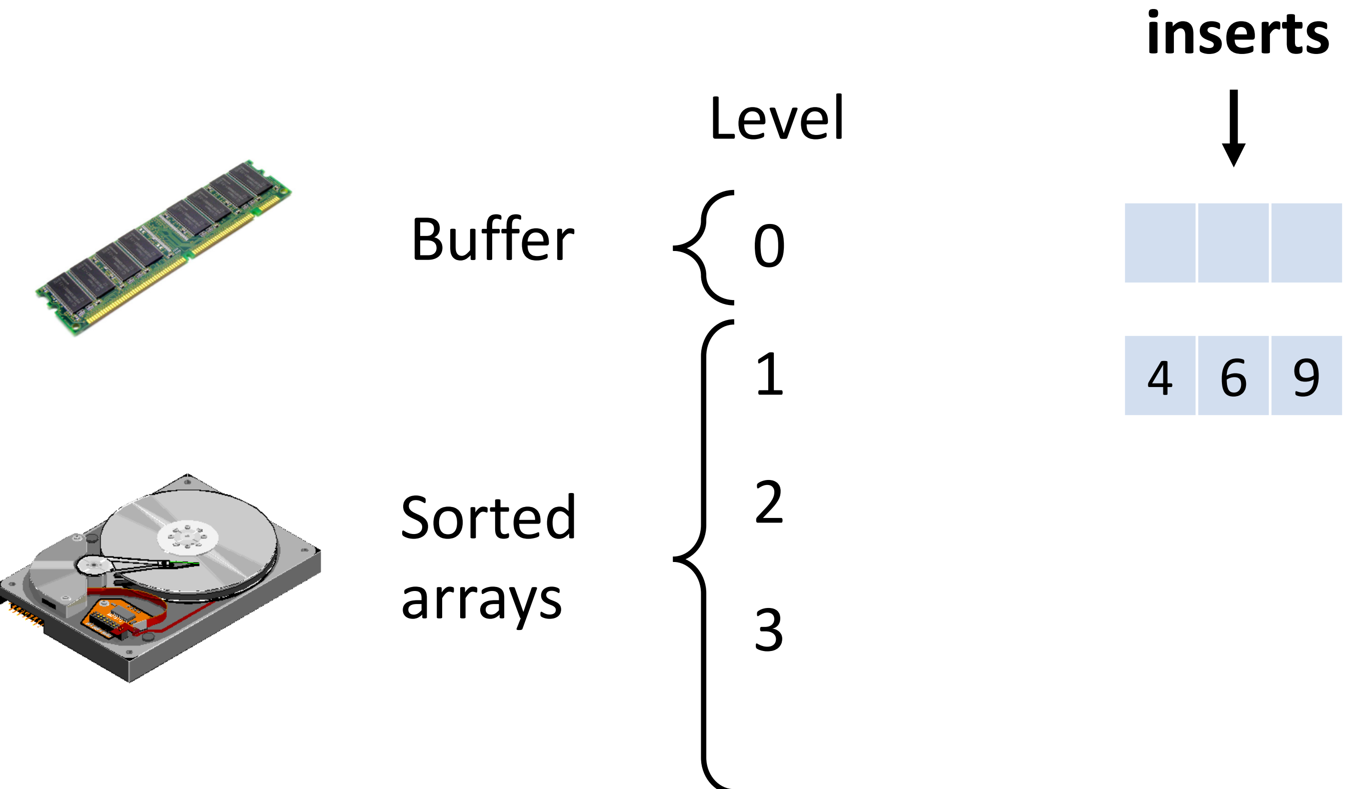
3

inserts

4	6	9

sort & flush buffer

Basic LSM-tree – Example



inserts

Level

Buffer

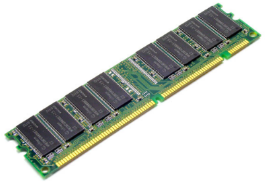
Sorted arrays

Level	
0	
1	4 6 9
2	
3	

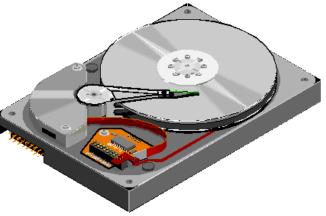
Basic LSM-tree – Example

inserts

Level	
0	3 4 8
1	4 6 9
2	
3	

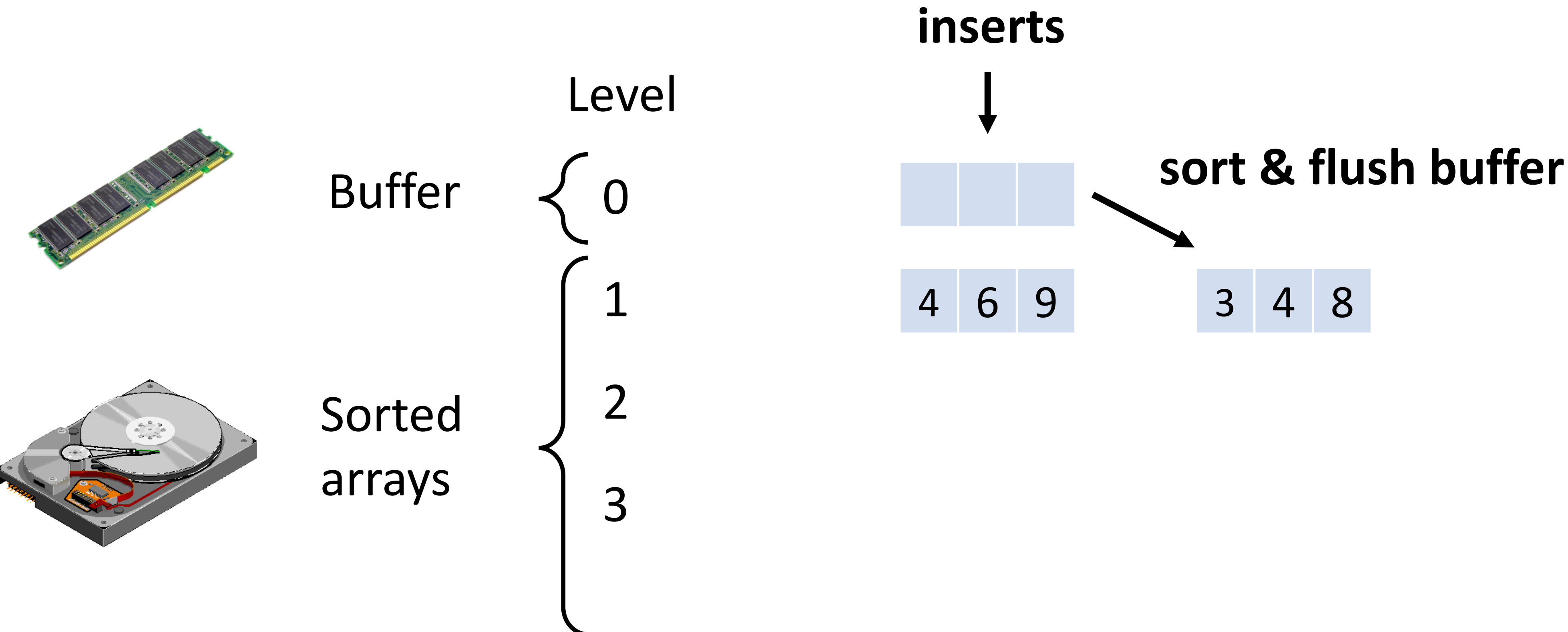


Buffer

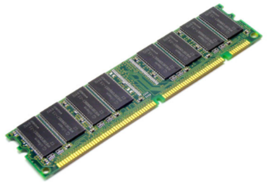


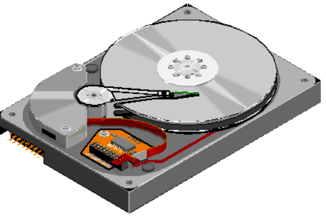
Sorted arrays

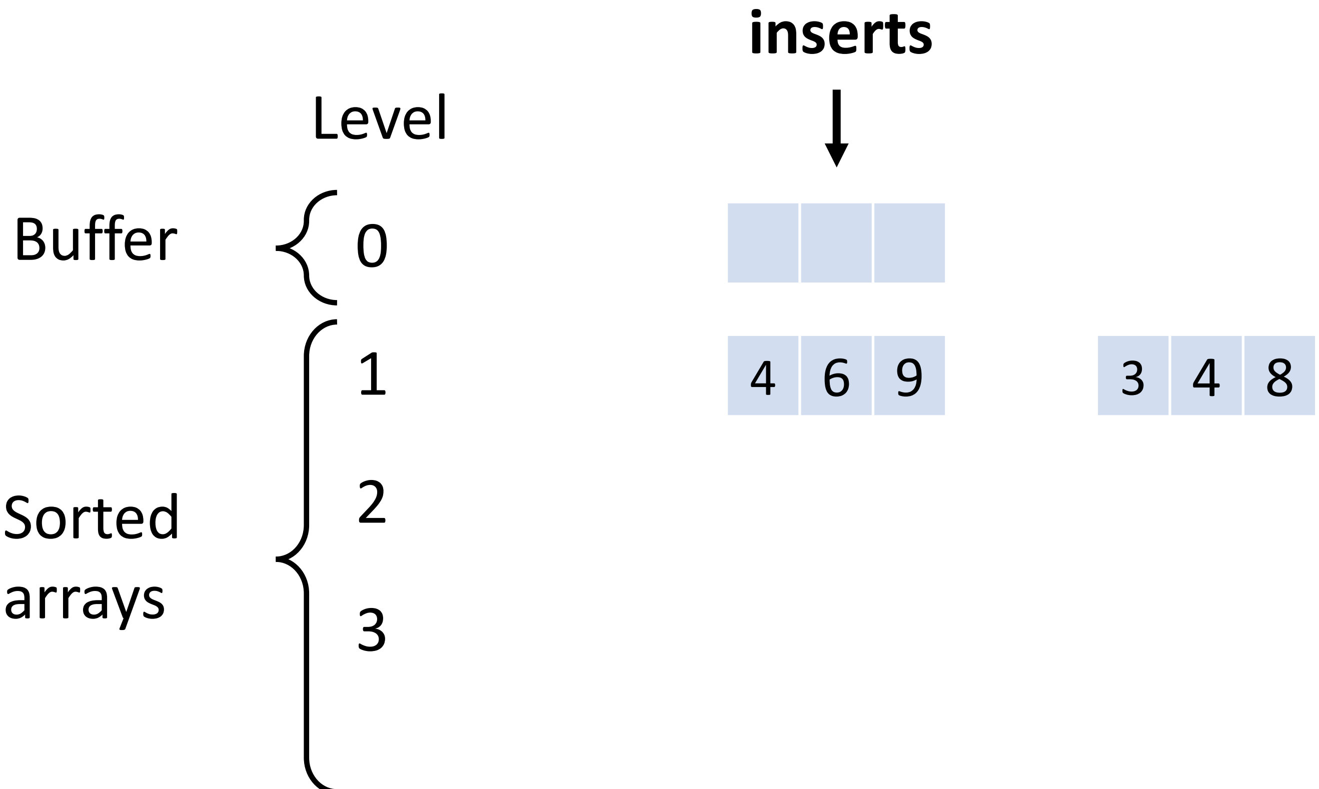
Basic LSM-tree – Example



Basic LSM-tree – Example







inserts

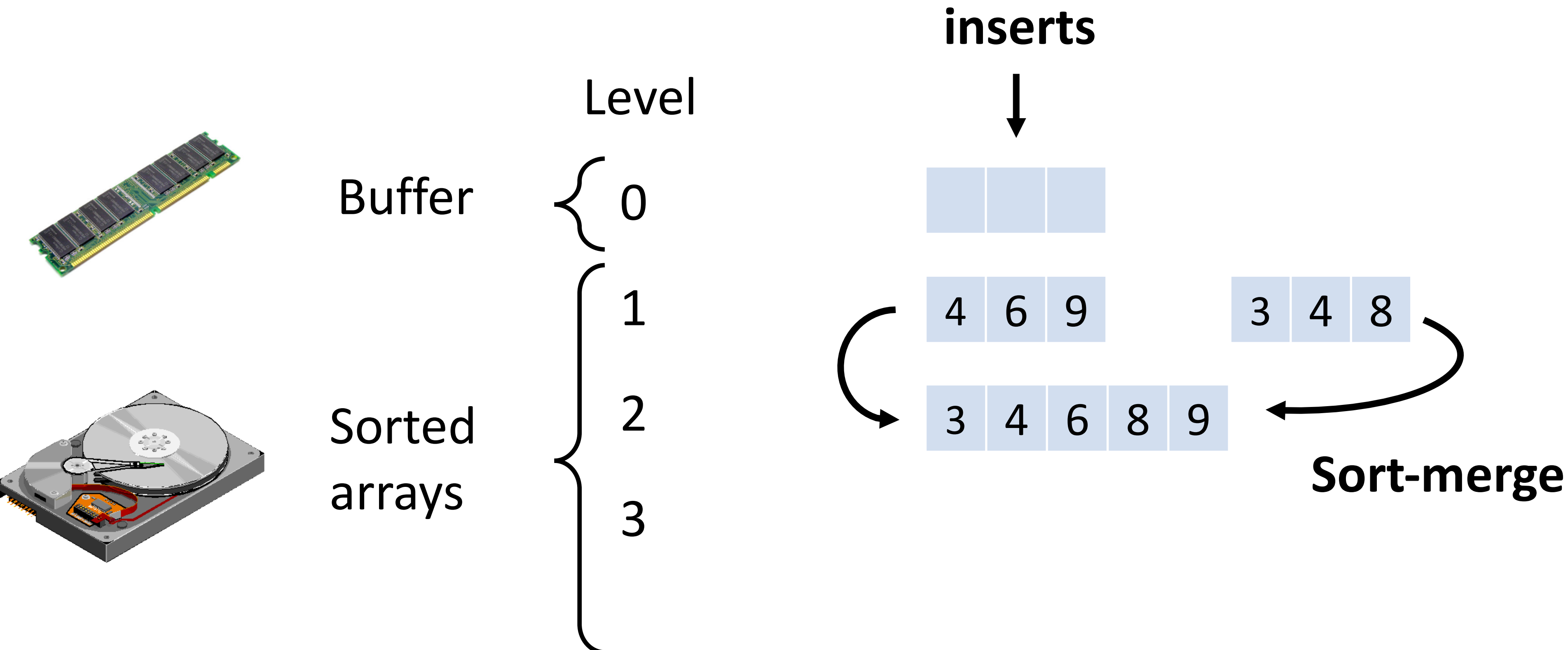
Level

Buffer 0

Sorted arrays 1 2 3

4 6 9   3 4 8

Basic LSM-tree – Example



inserts

Level

Buffer 0

Sorted arrays 1 2 3

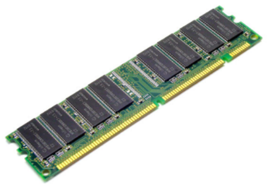
4 6 9

3 4 8

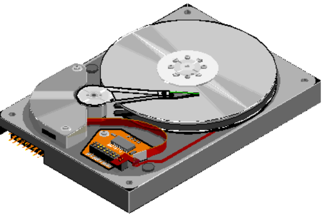
3 4 6 8 9

Sort-merge

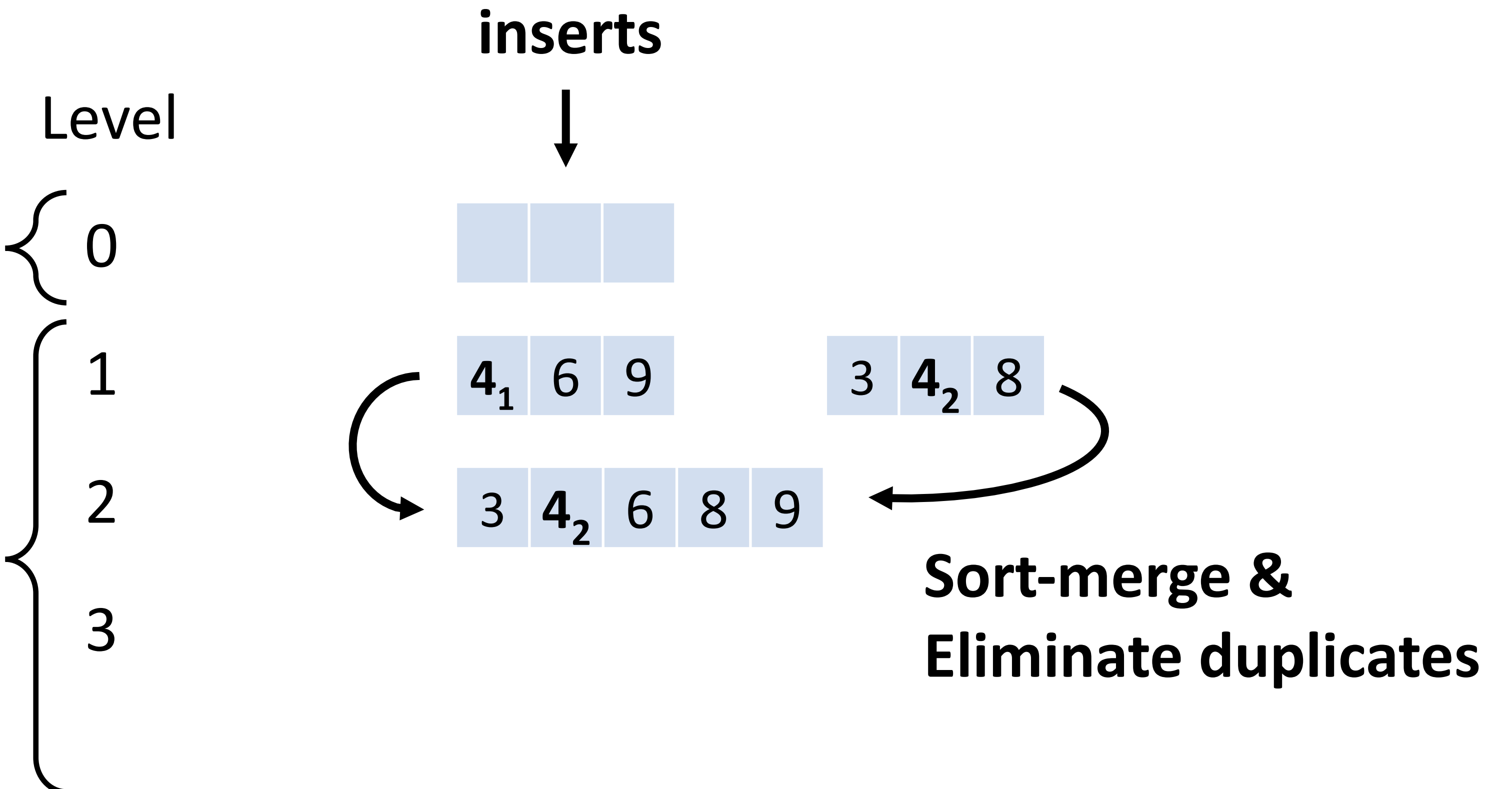
Basic LSM-tree – Example



Buffer



Sorted arrays



inserts

Level

0

1

2

3

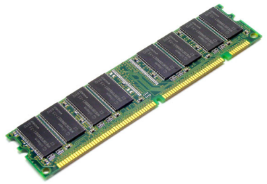
4_1 6 9

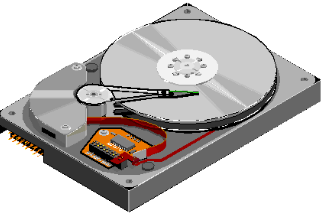
3 4_2 8

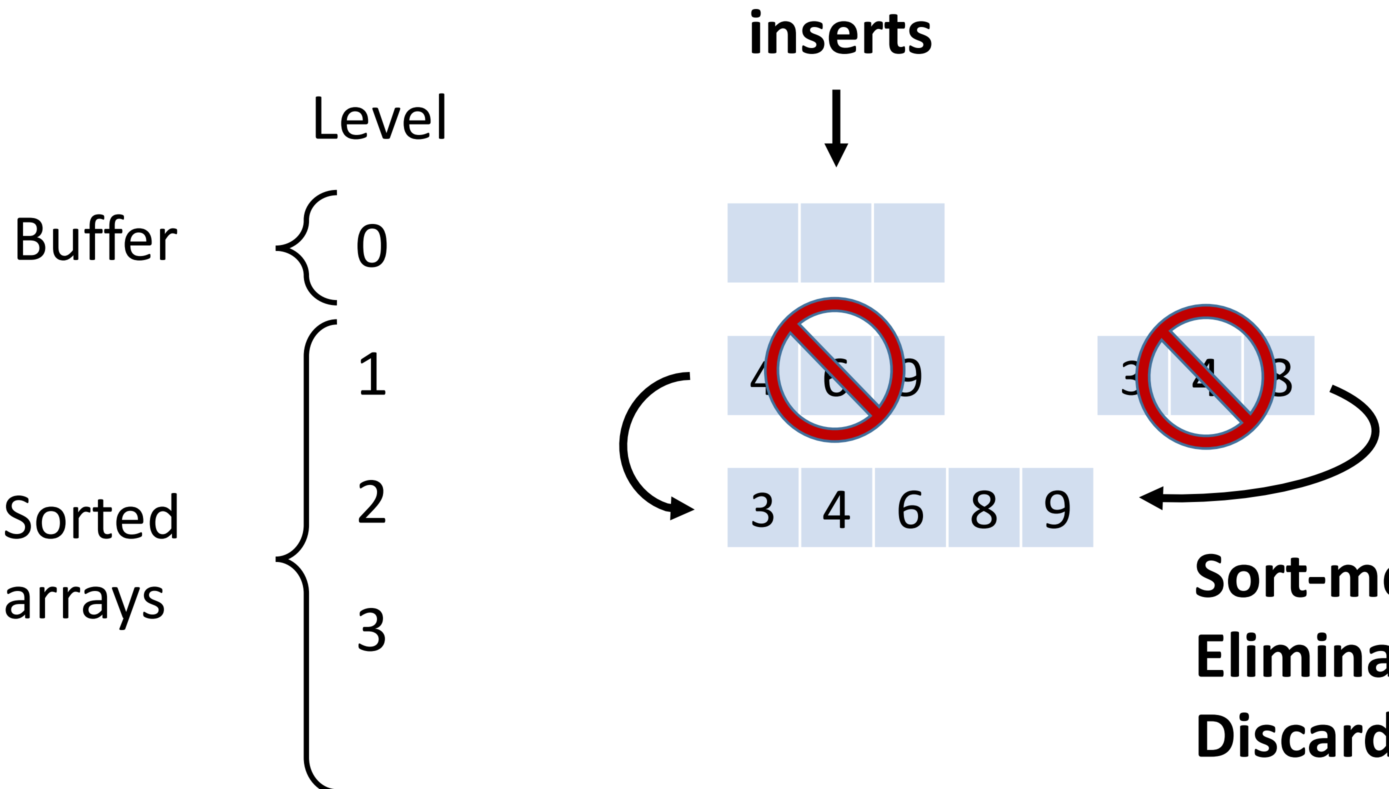
3 4_2 6 8 9

Sort-merge & Eliminate duplicates

Basic LSM-tree – Example

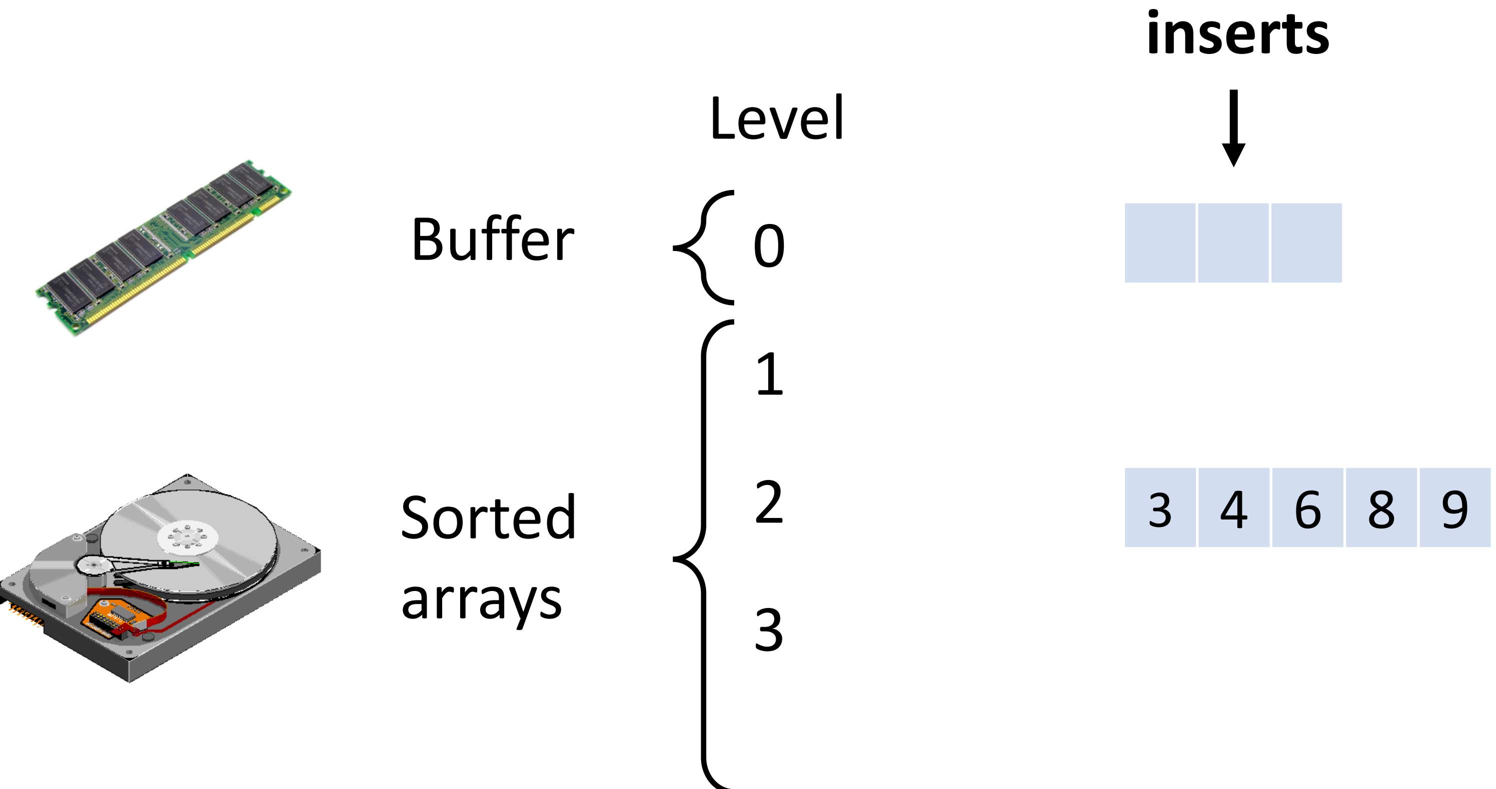






Sort-merge &
Eliminate duplicates &
Discard original arrays

Basic LSM-tree – Example

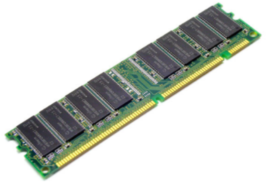


3	4	6	8	9

Basic LSM-tree – Example

inserts

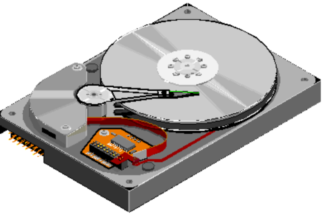
Level



Buffer

0: 2 7 8

1

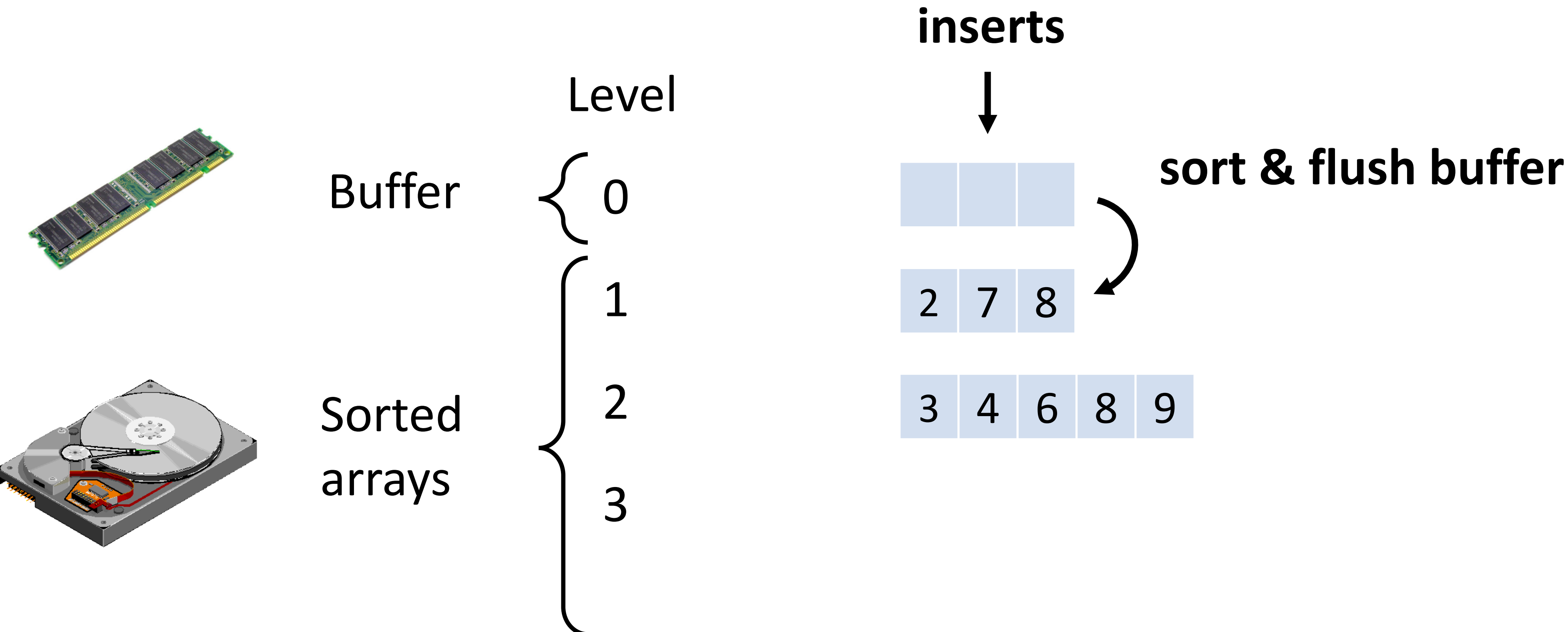


Sorted arrays

2: 3 4 6 8 9

3

Basic LSM-tree – Example

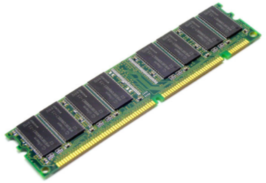


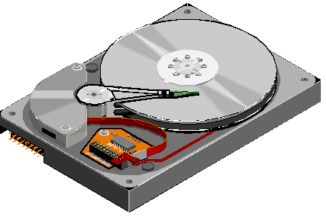
inserts

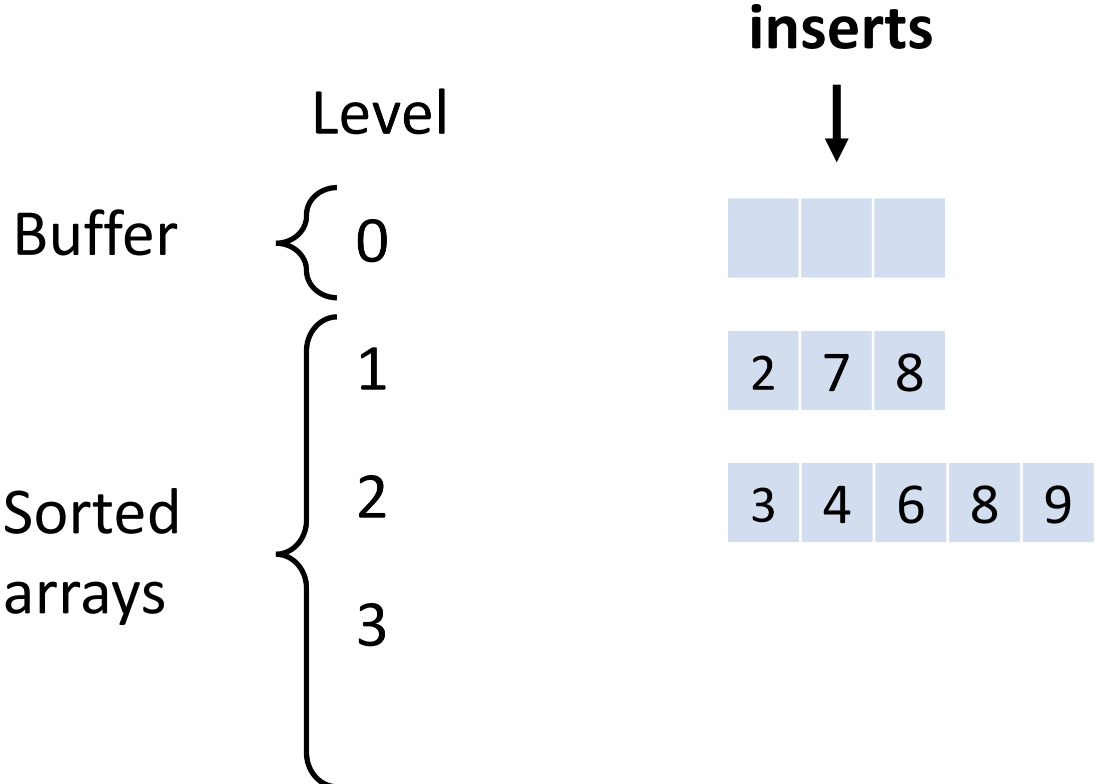
sort & flush buffer

Level		
Buffer	0	
Sorted arrays	1	2 7 8
	2	3 4 6 8 9
	3	

Basic LSM-tree – Example

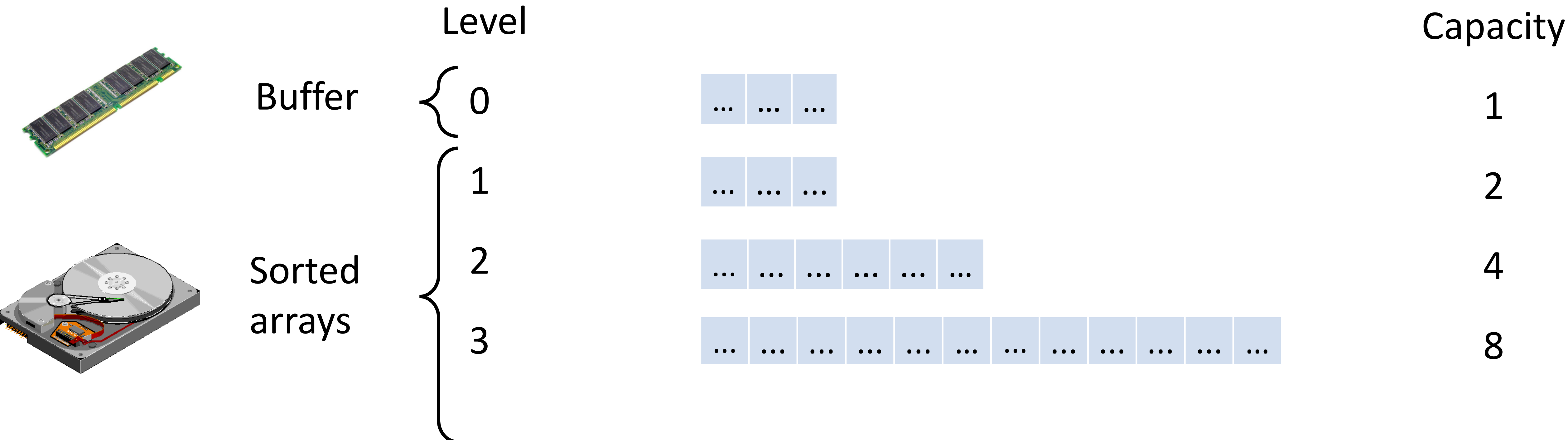






Basic LSM-tree

Levels have exponentially increasing capacities.



Level

Capacity

Buffer 0 … … … 1

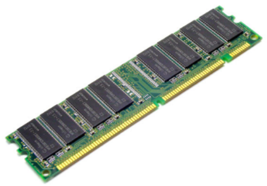
Sorted arrays

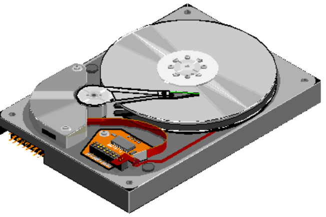
1 … … … 2

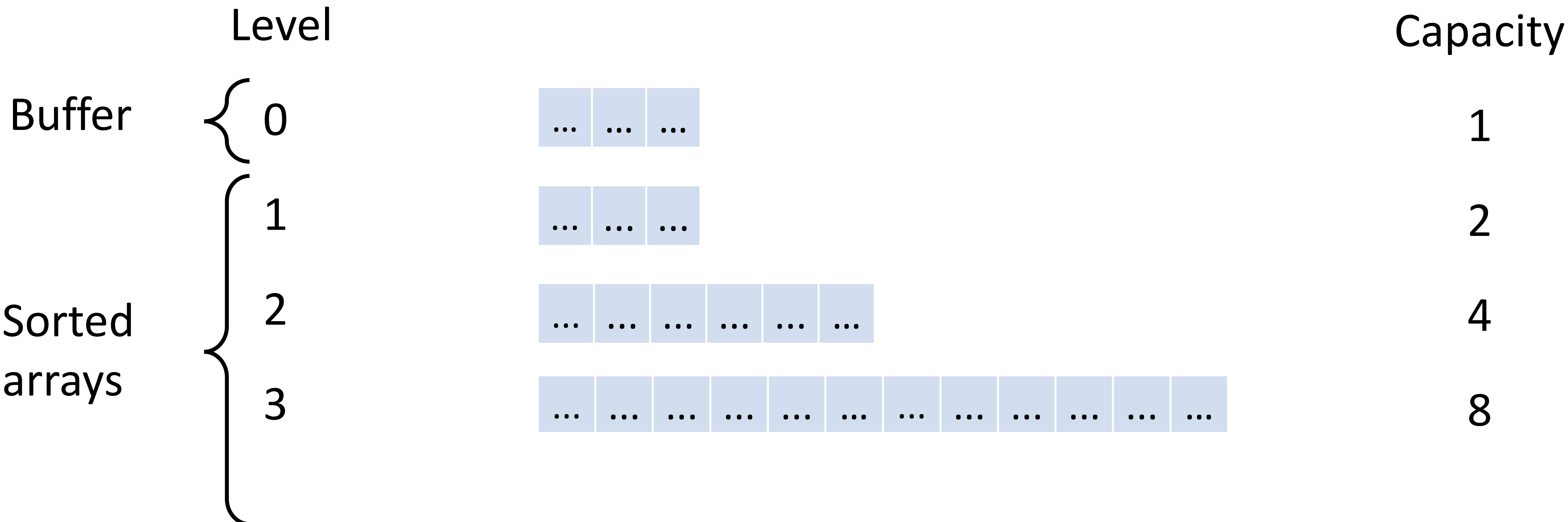
2 … … … … … … 4

3 … … … … … … … … … … … … 8

Basic LSM-tree – Lookup cost



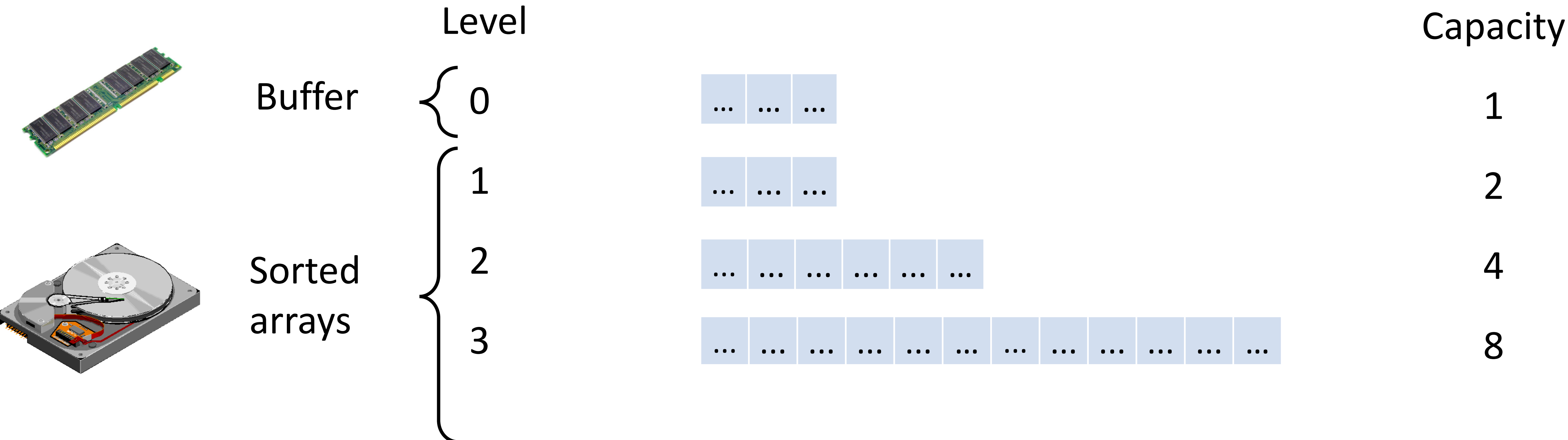




	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Lookup cost

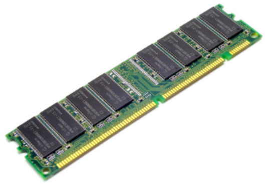
Lookup method?

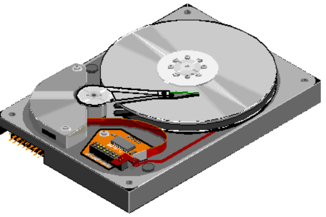


	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Lookup cost

Lookup method? Search youngest to oldest. $O\left(\log_2\left(\frac{N}{B}\right)\right)$



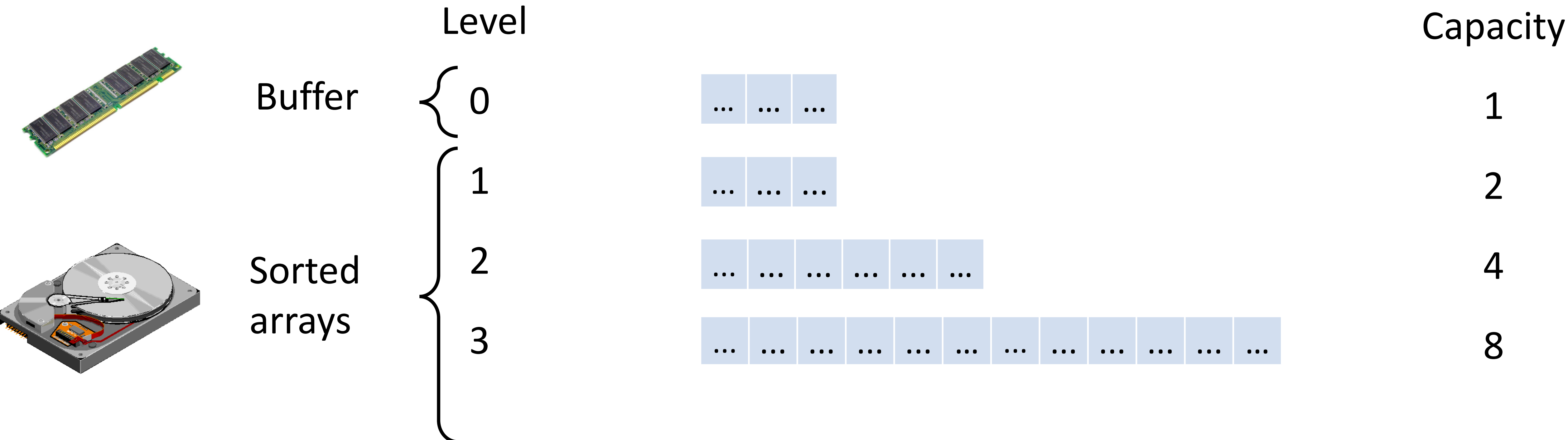


	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Lookup cost

Lookup method? Search youngest to oldest. $O\left(\log_2\left(\frac{N}{B}\right)\right)$

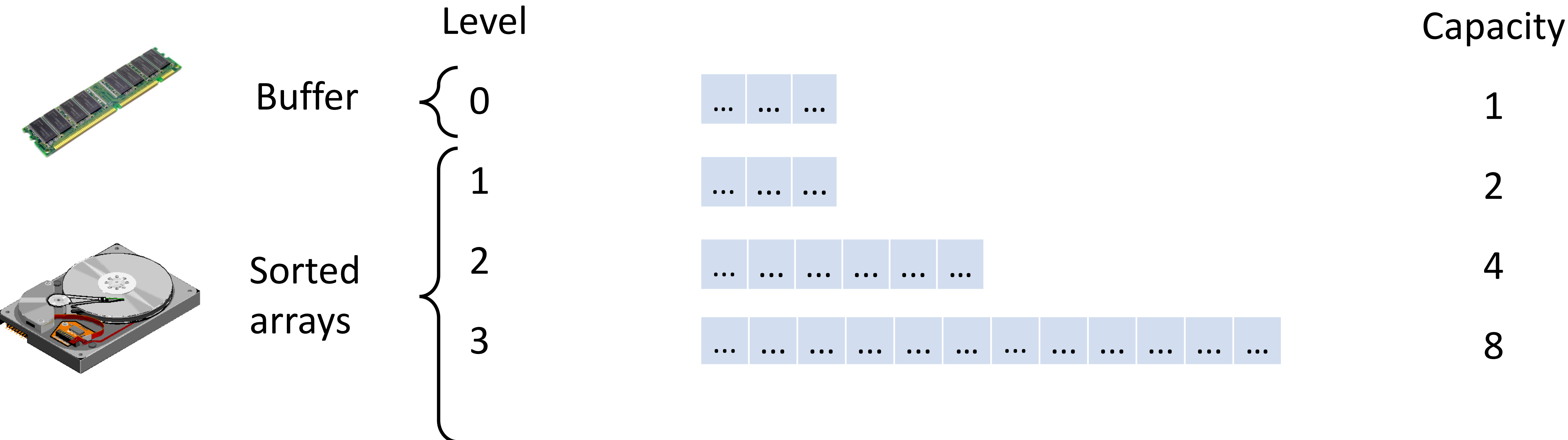
How?



Basic LSM-tree – Lookup cost

Lookup method? Search youngest to oldest. $O\left(\log_2\left(\frac{N}{B}\right)\right)$

How? Binary search. $O\left(\log_2\left(\frac{N}{B}\right)\right)$



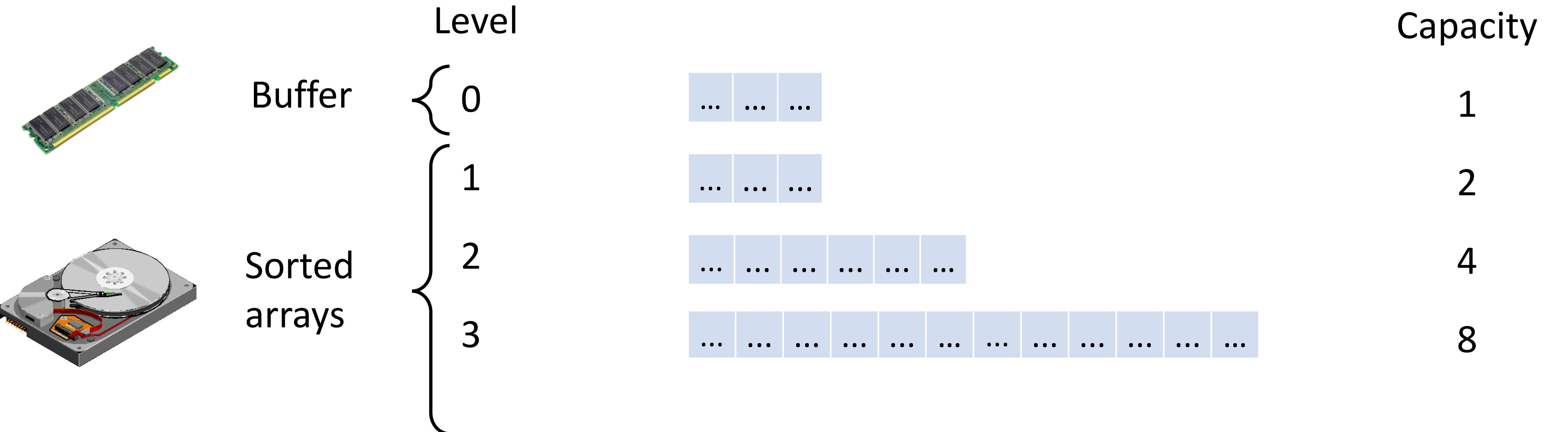
	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Lookup cost

Lookup method? Search youngest to oldest. $O\left(\log_2\left(\frac{N}{B}\right)\right)$

How? Binary search. $O\left(\log_2\left(\frac{N}{B}\right)\right)$

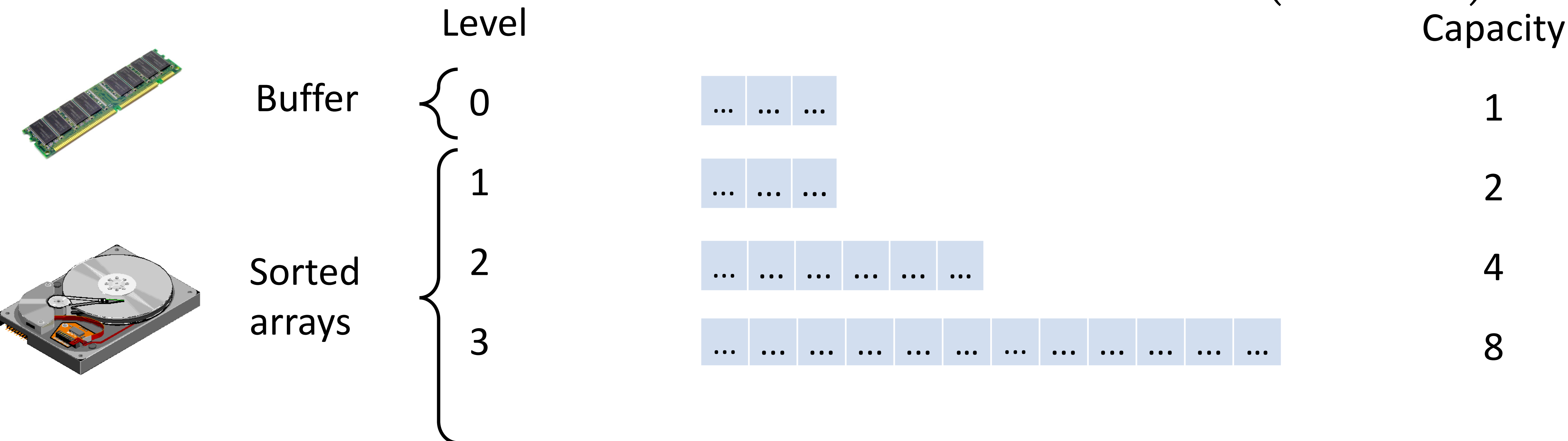
Lookup cost?



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

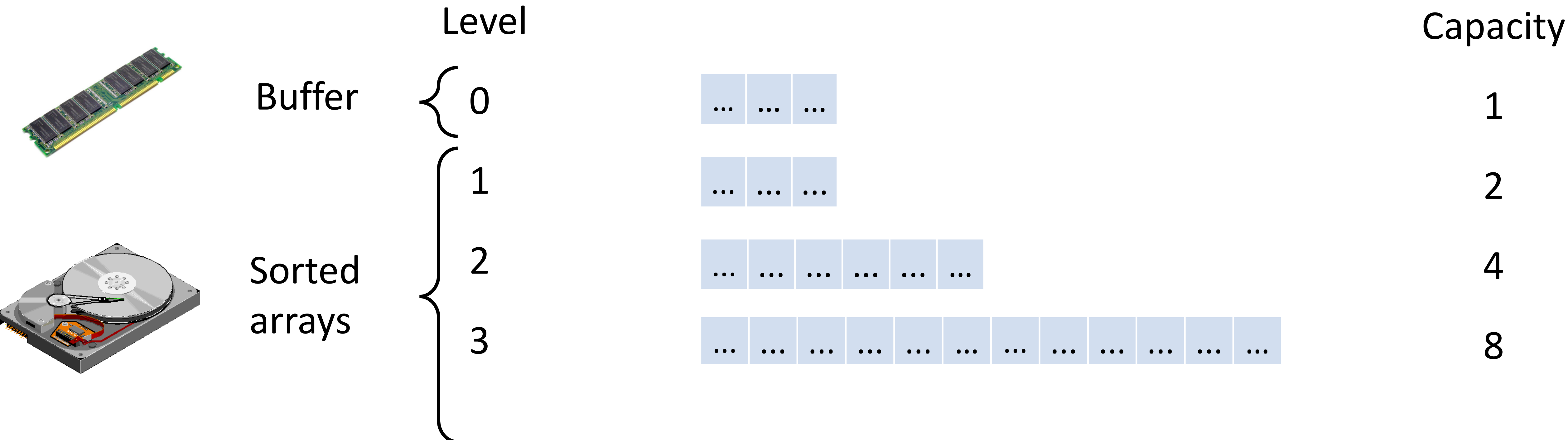
Basic LSM-tree – Lookup cost

Lookup method?	Search youngest to oldest.	$O\left(\log_2\left(\frac{N}{B}\right)\right)$
How?	Binary search.	$O\left(\log_2\left(\frac{N}{B}\right)\right)$
Lookup cost?		$O\left(\log_2\left(\frac{N}{B}\right)^2\right)$



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

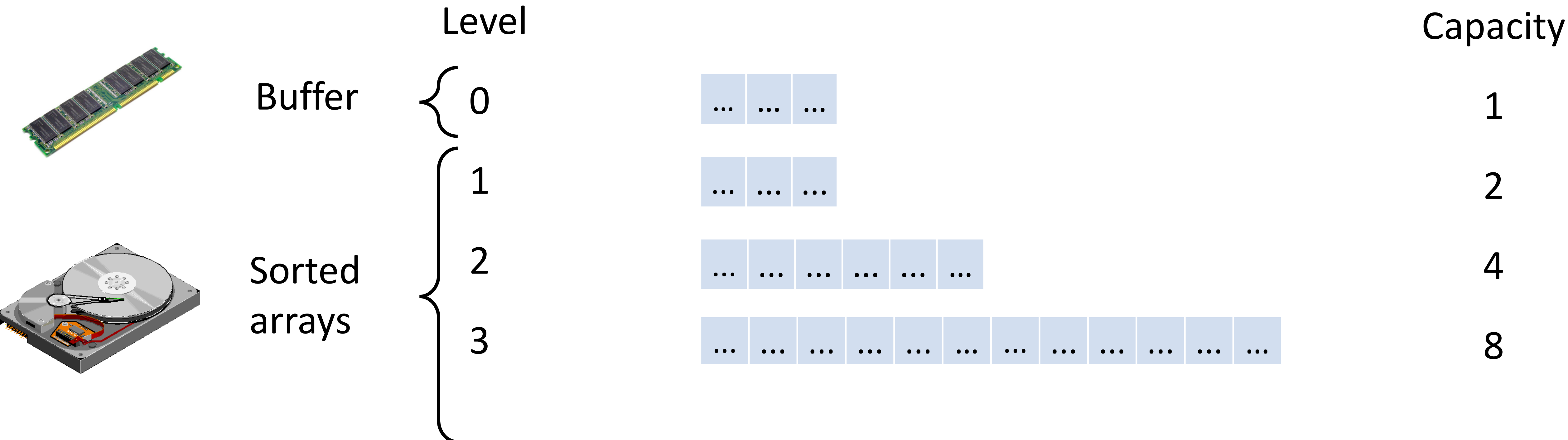
Basic LSM-tree – Insertion cost



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

Basic LSM-tree – Insertion cost

How many times is each entry copied?



Level

Capacity

Buffer

0 … … … 1

1 … … … 2

Sorted arrays

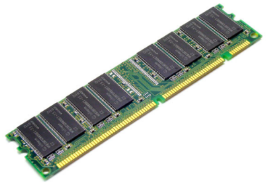
2 … … … … … … 4

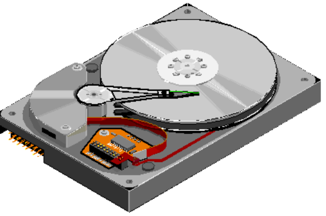
3 … … … … … … … … … … … … 8

Basic LSM-tree – Insertion cost

How many times is each entry copied?

$$O\left(\log_2\left(\frac{N}{B}\right)\right)$$



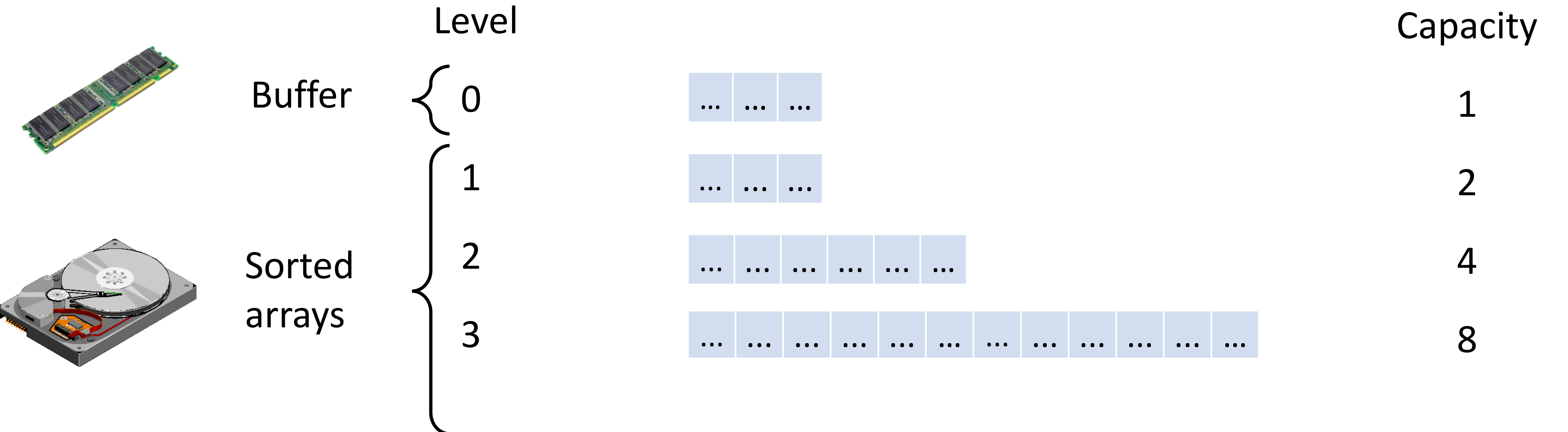


	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Insertion cost

How many times is each entry copied? $O\left(\log_2\left(\frac{N}{B}\right)\right)$

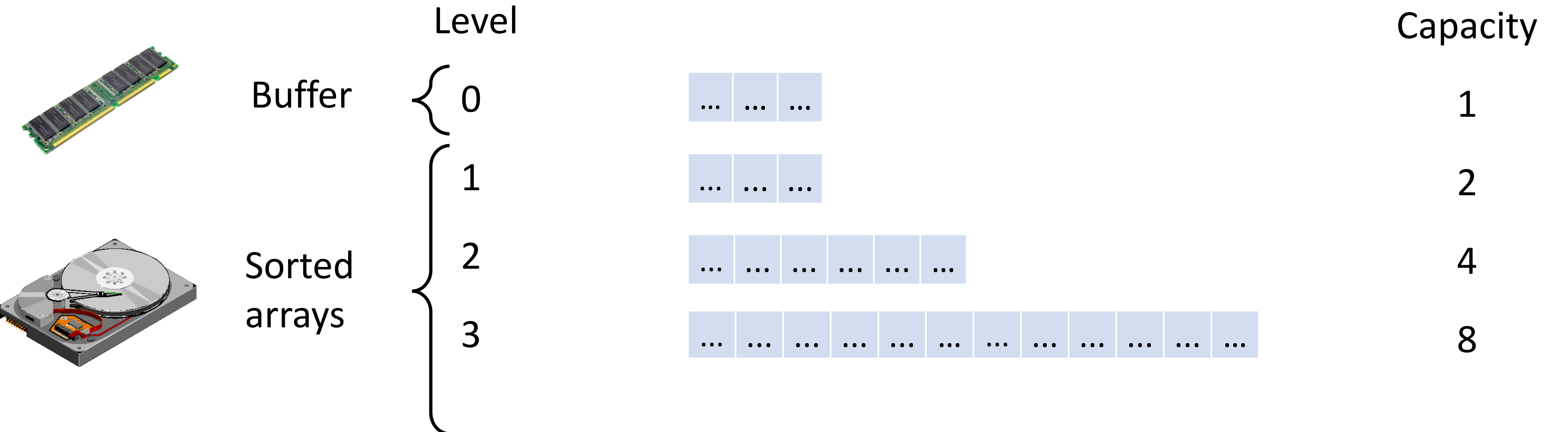
What is the price of each copy?



Basic LSM-tree – Insertion cost

How many times is each entry copied? $O\left(\log_2\left(\frac{N}{B}\right)\right)$

What is the price of each copy? $O\left(\frac{1}{B}\right)$



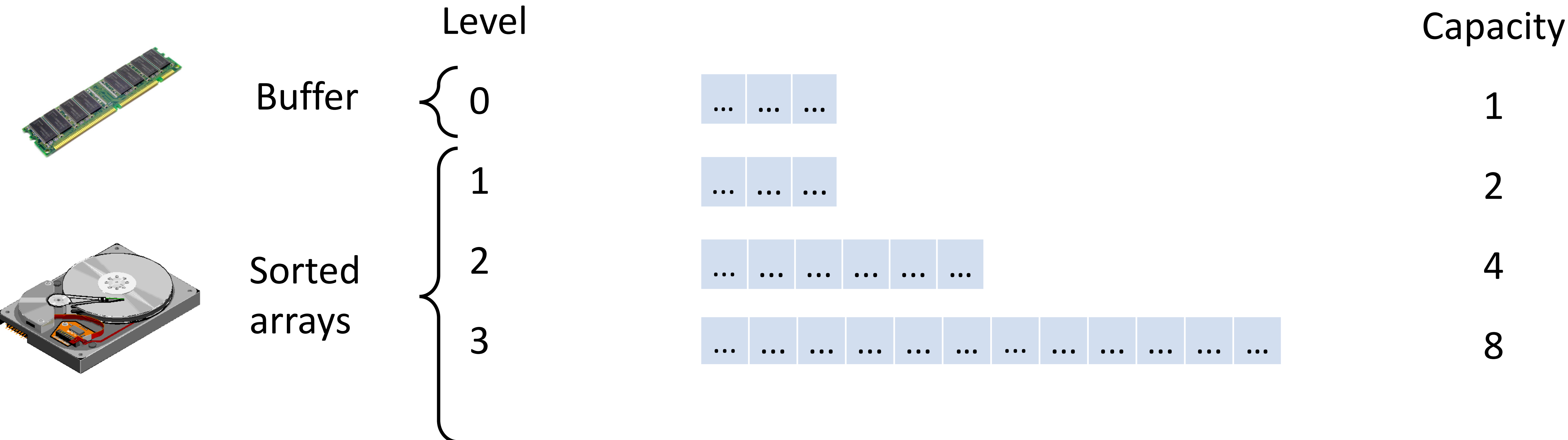
	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Insertion cost

How many times is each entry copied? $O\left(\log_2\left(\frac{N}{B}\right)\right)$

What is the price of each copy? $O\left(\frac{1}{B}\right)$

Total insert cost?



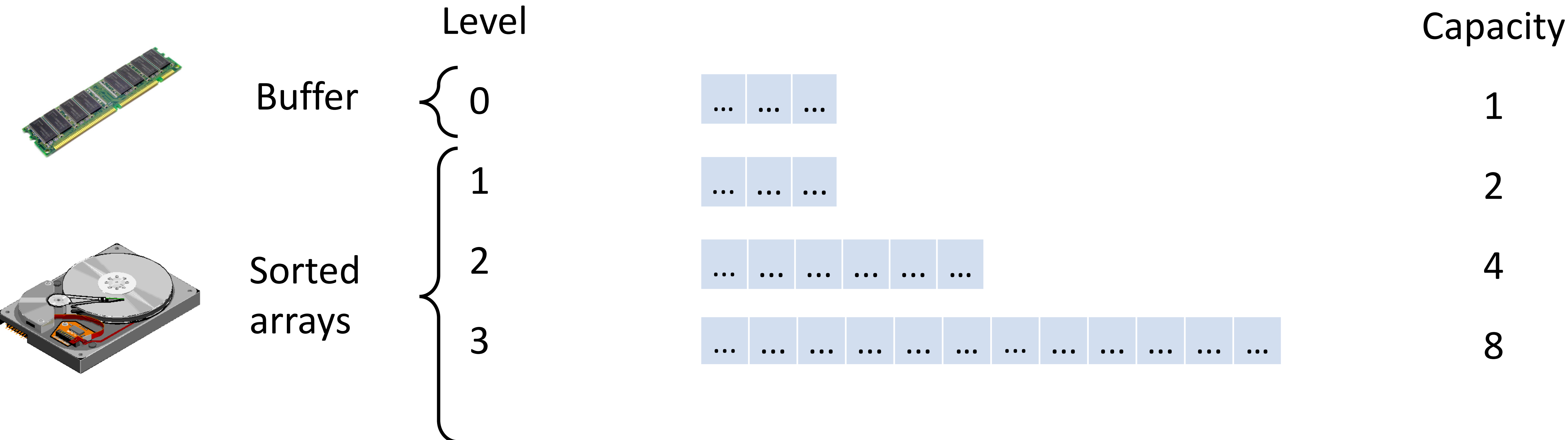
	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1	… … …	2
	2	… … … … … …	4
	3	… … … … … … … … … … … …	8

Basic LSM-tree – Insertion cost

How many times is each entry copied? $O\left(\log_2\left(\frac{N}{B}\right)\right)$

What is the price of each copy? $O\left(\frac{1}{B}\right)$

Total insert cost? $O\left(\frac{1}{B}\cdot\log_2\left(\frac{N}{B}\right)\right)$



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

Results Catalogue

	Lookup cost	Insertion cost
Sorted array	$O(\log_2(N/B))$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue

Better insert cost and worst lookup cost compared with B-trees

	Lookup cost	Insertion cost
Sorted array	$O(\log_2(N/B))$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

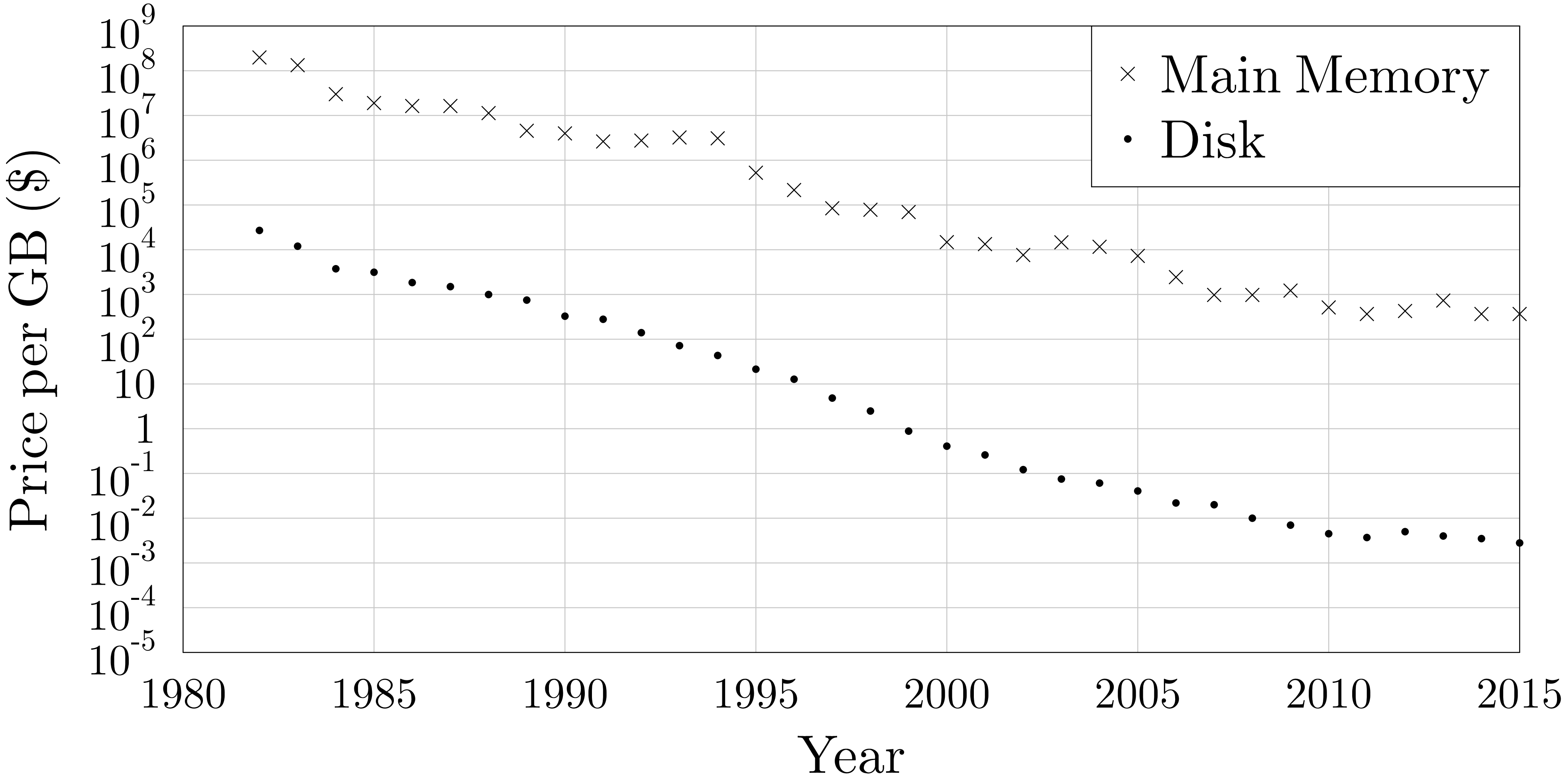
Results Catalogue

Better insert cost and worst lookup cost compared with B-trees

Can we improve lookup cost?

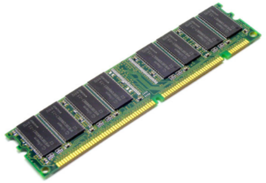
	Lookup cost	Insertion cost
Sorted array	$O(\log_2(N/B))$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Declining Main Memory Cost

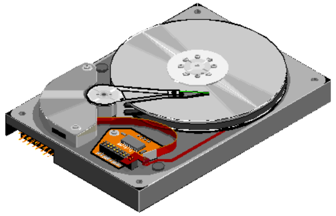


Declining Main Memory Cost

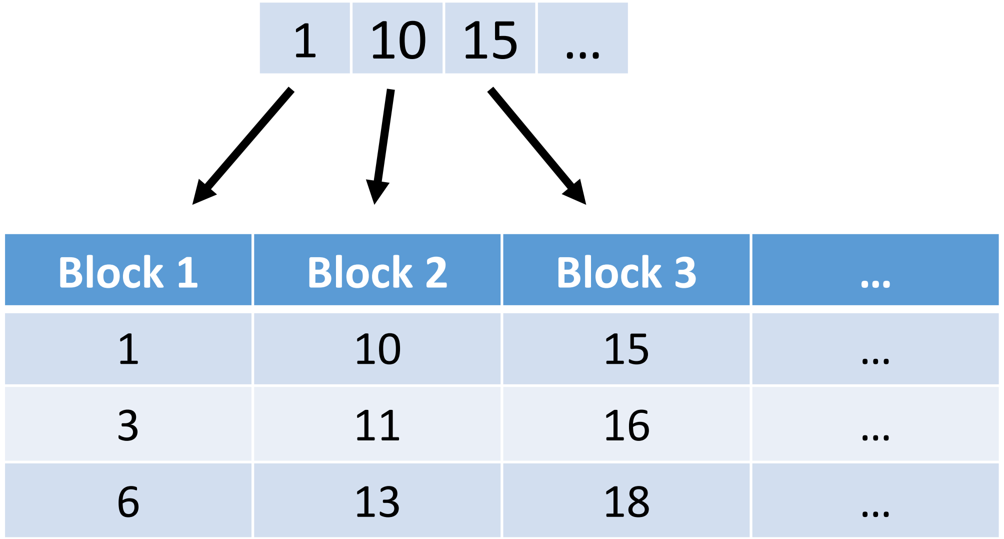
Store a fence pointer for every block in main memory



Fence pointers



array



1	10	15	…

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

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	$O(\log_2(N/B))$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	$O(\log_2(N/B))$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	$O(1)$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	$O(1)$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	O(1)	O(N/B)
Log	O(N/B)	O(1/B)
B-tree	$O(\log_B(N/B))$	$O(\log_B(N/B))$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	$O(1)$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(1)$	$O(1)$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	$O(1)$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(1)$	$O(1)$
Basic LSM-tree	$O(\log_2(N/B)^2)$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	O(1)	O(N/B)
Log	O(N/B)	O(1/B)
B-tree	O(1)	O(1)
Basic LSM-tree	$O(\log_2(N/B))$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

Quick sanity check:	suppose	$N = 2^{42}$
	and	$B = 2^{10}$

	Lookup cost	Insertion cost
Sorted array	O(1)	O(N/B)
Log	O(N/B)	O(1/B)
B-tree	O(1)	O(1)
Basic LSM-tree	$O(\log_2(N/B))$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree		
Tiered LSM-tree		

Results Catalogue – with fence pointers

Quick sanity check: suppose $N = 2^{42}$
and $B = 2^{10}$

	Lookup cost	Insertion cost
Sorted array	$O(1)$	$O(2^{32})$
Log	$O(2^{32})$	$O(2^{-10})$
B-tree	$O(1)$	$O(1)$
Basic LSM-tree	$O(5)$	$O(2^{-10} \cdot 5)$
Leveled LSM-tree		
Tiered LSM-tree		

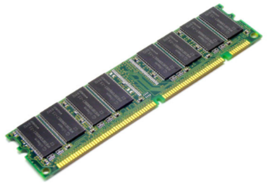
Leveled LSM-tree

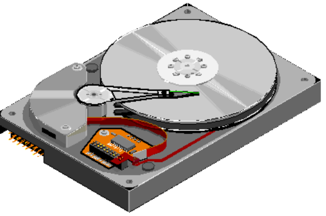
↓ Lookup cost

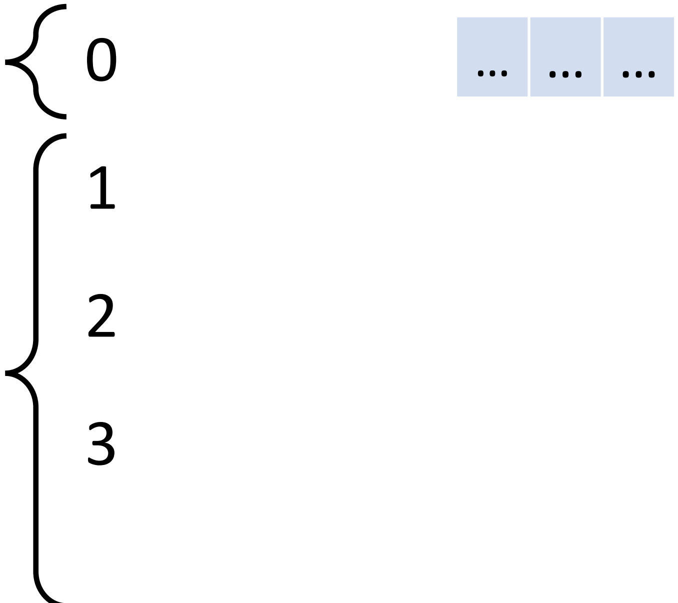
↑ Update cost

Leveled LSM-tree

Lookup cost depends on number of levels



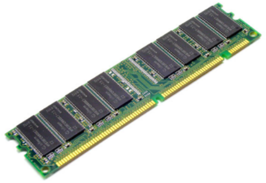




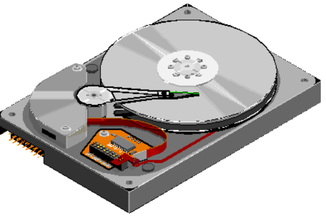
Leveled LSM-tree

Lookup cost depends on number of levels

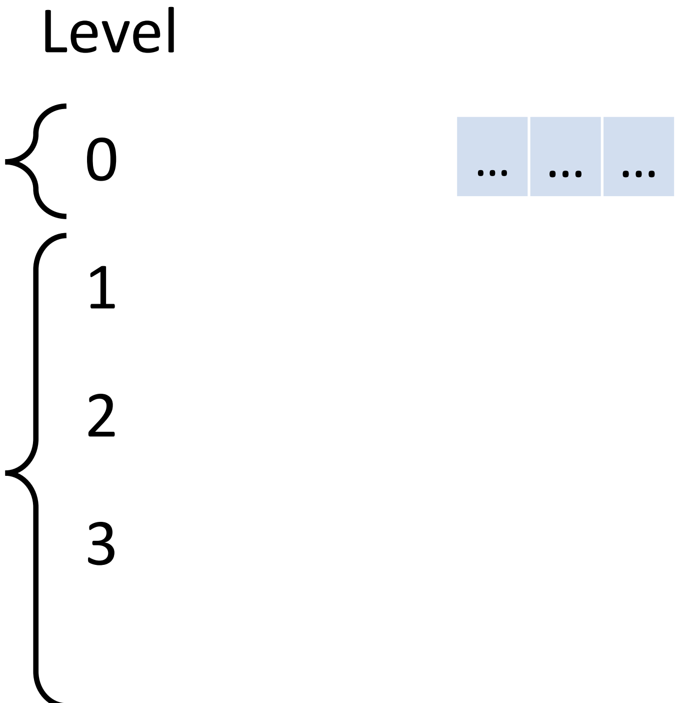
How to reduce it?



Buffer



Sorted arrays

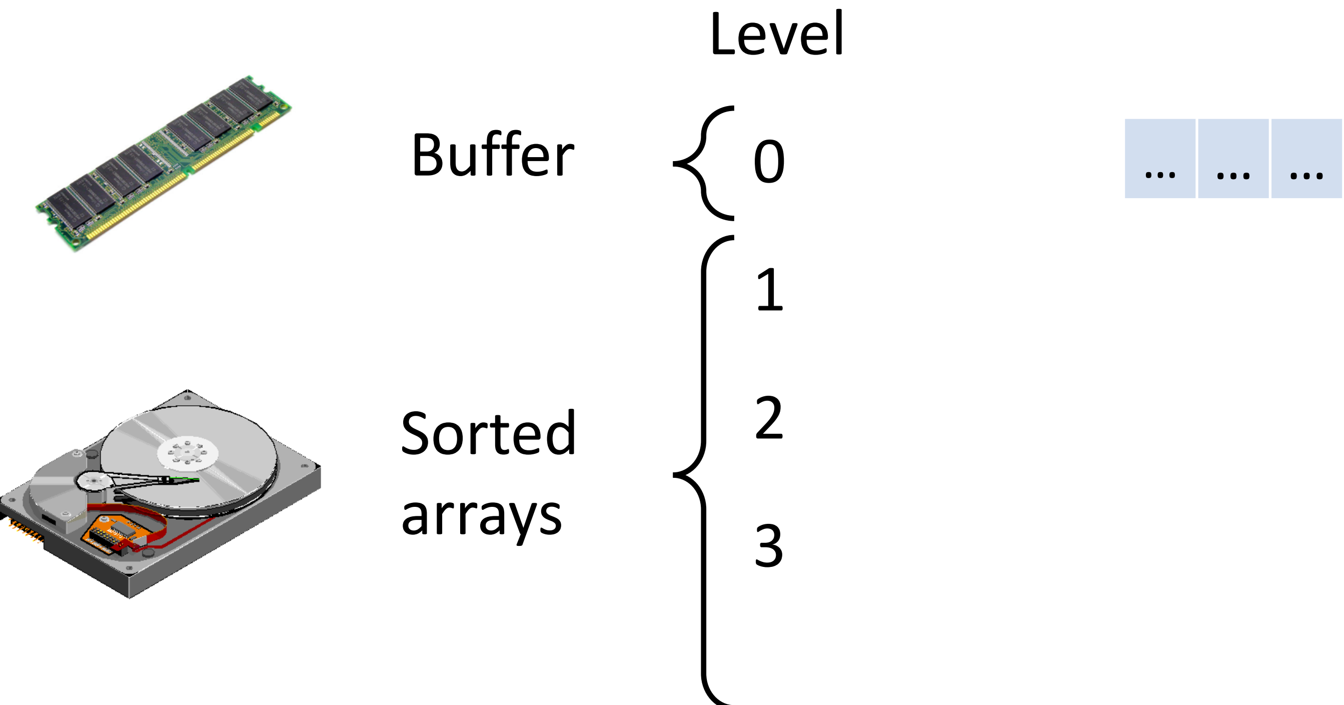


Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

Increase size ratio T

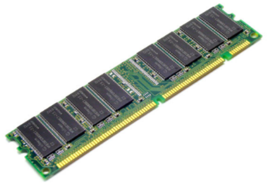


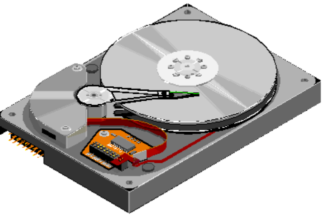
Leveled LSM-tree

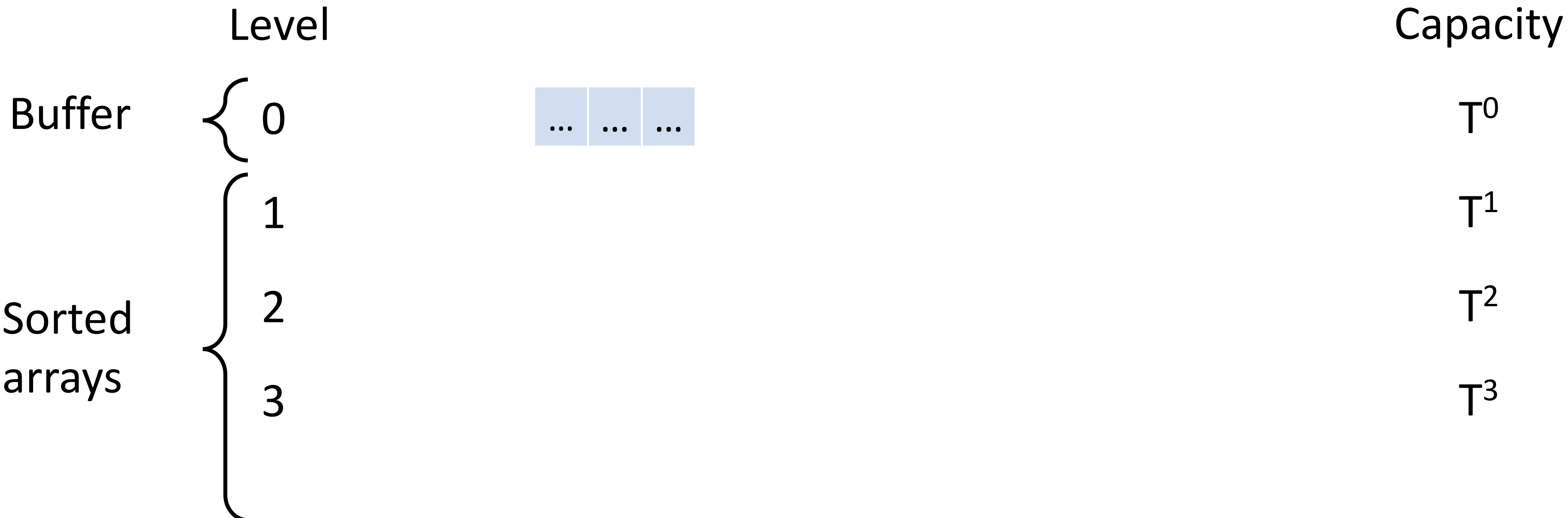
Lookup cost depends on number of levels

How to reduce it?

Increase size ratio T







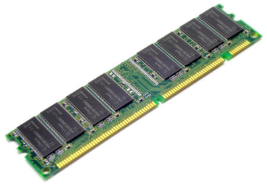
	Level		Capacity
Buffer	0	… … …	T^0
Sorted arrays	1		T^1
	2		T^2
	3		T^3

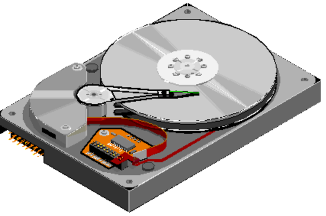
Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4





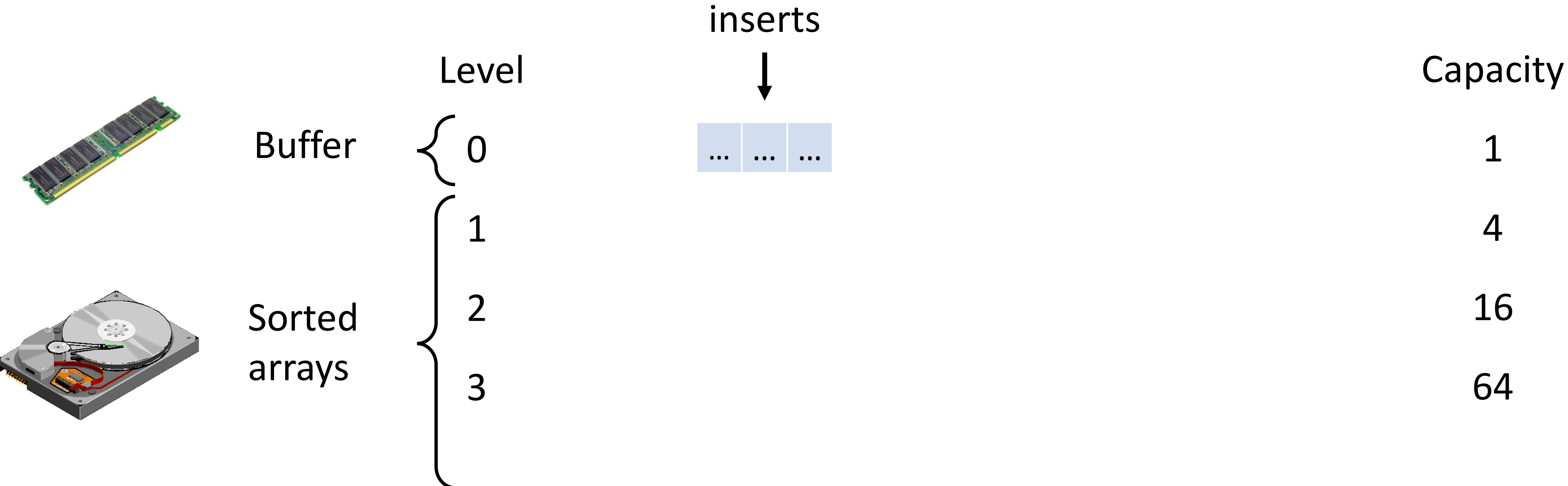
	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2		16
	3		64

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

... ...

Buffer

Sorted arrays

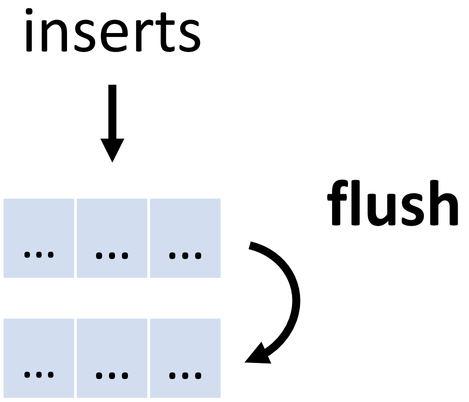
Level	Capacity
0	1
1	4
2	16
3	64

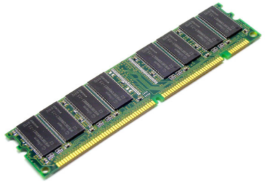
Leveled LSM-tree

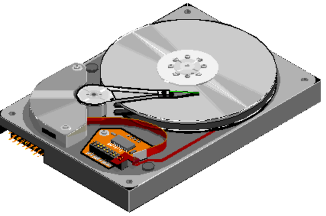
Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4







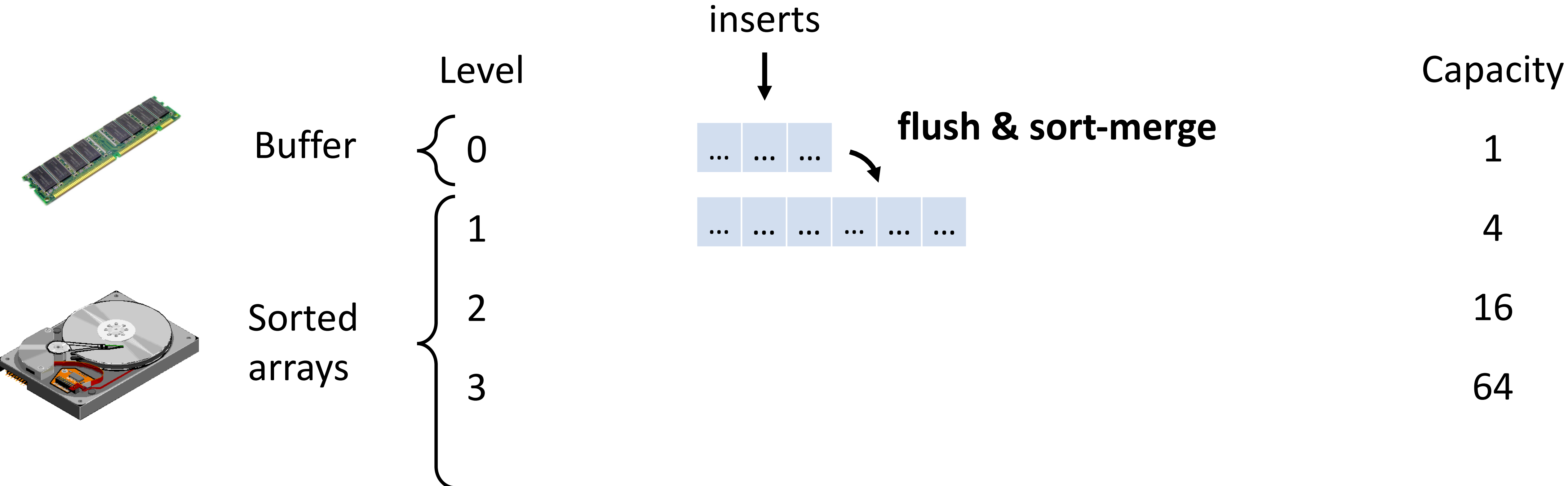
	Level	Capacity
Buffer	0	1
Sorted arrays	1	4
	2	16
	3	64

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

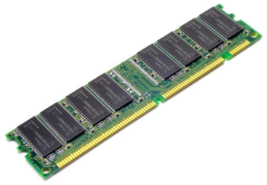
	Level	Capacity
Buffer	0	1
Sorted arrays	1	4
	2	16
	3	64

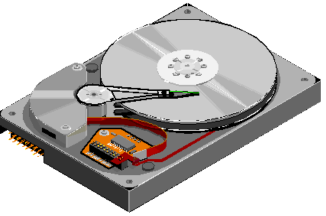
Leveled LSM-tree

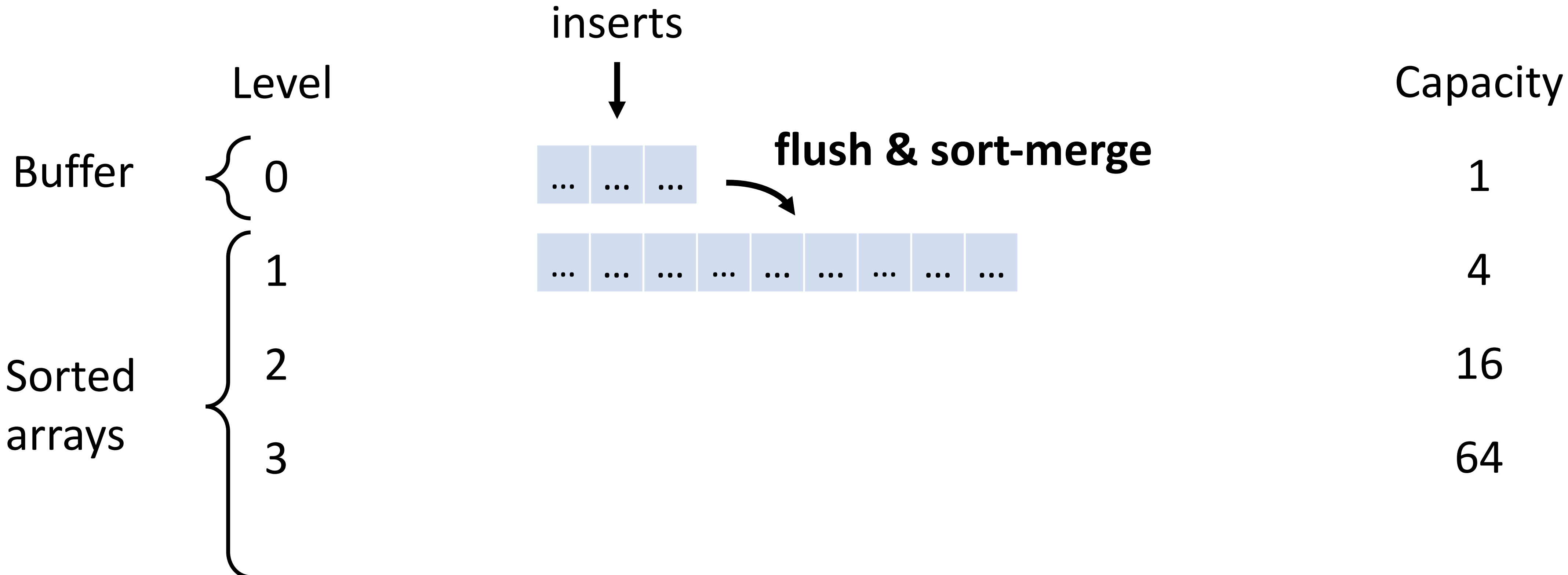
Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4







inserts

flush & sort-merge

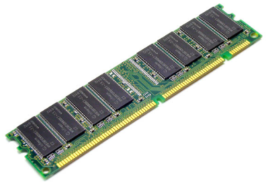
	Level	Capacity
Buffer	0	1
Sorted arrays	1	4
	2	16
	3	64

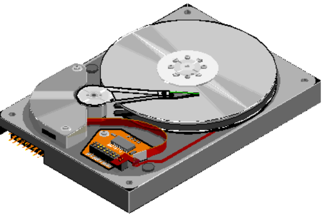
Leveled LSM-tree

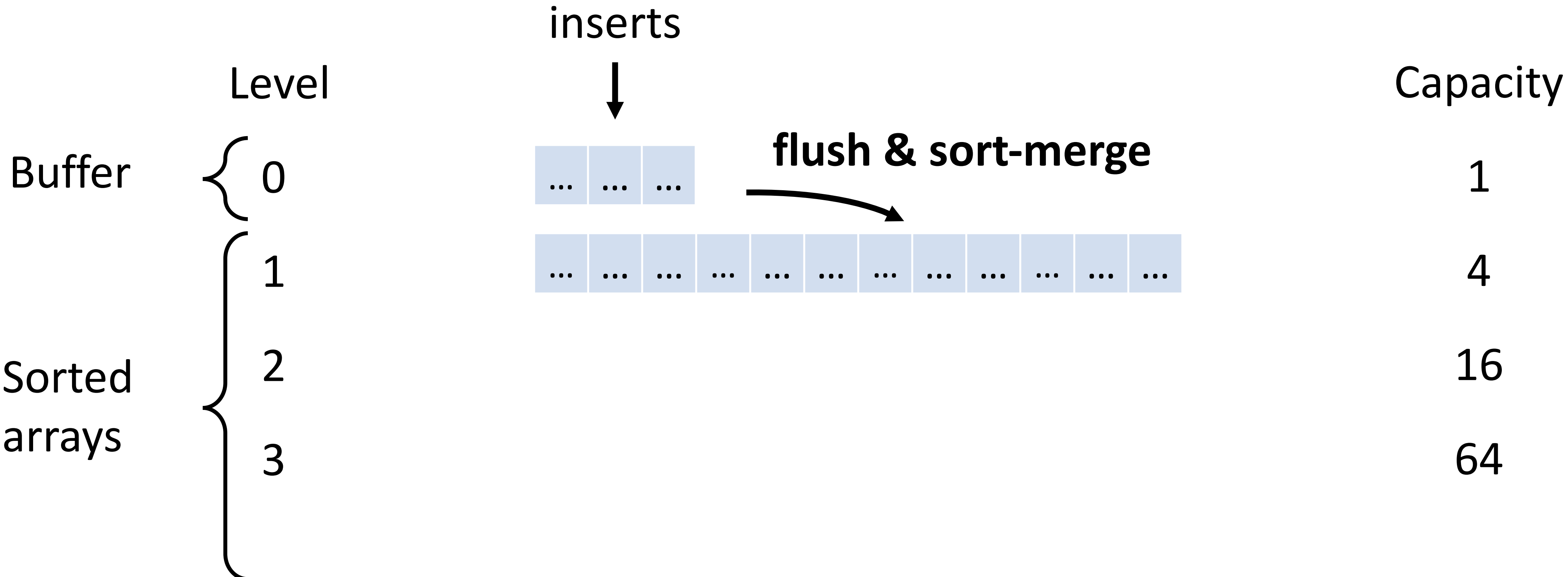
Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4







inserts

flush & sort-merge

Buffer

Sorted arrays

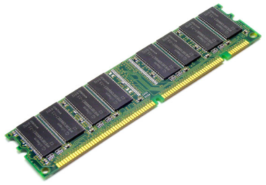
Level	Capacity
0	1
1	4
2	16
3	64

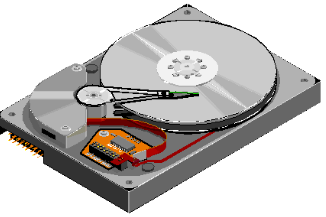
Leveled LSM-tree

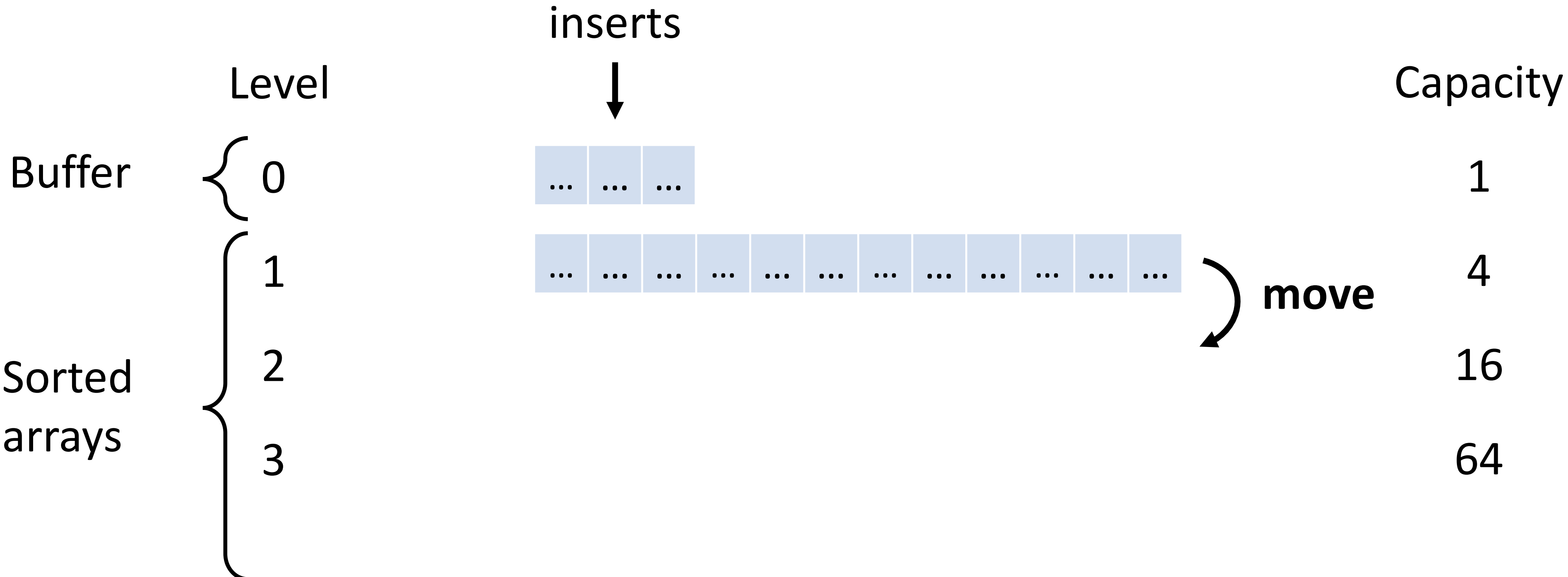
Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4





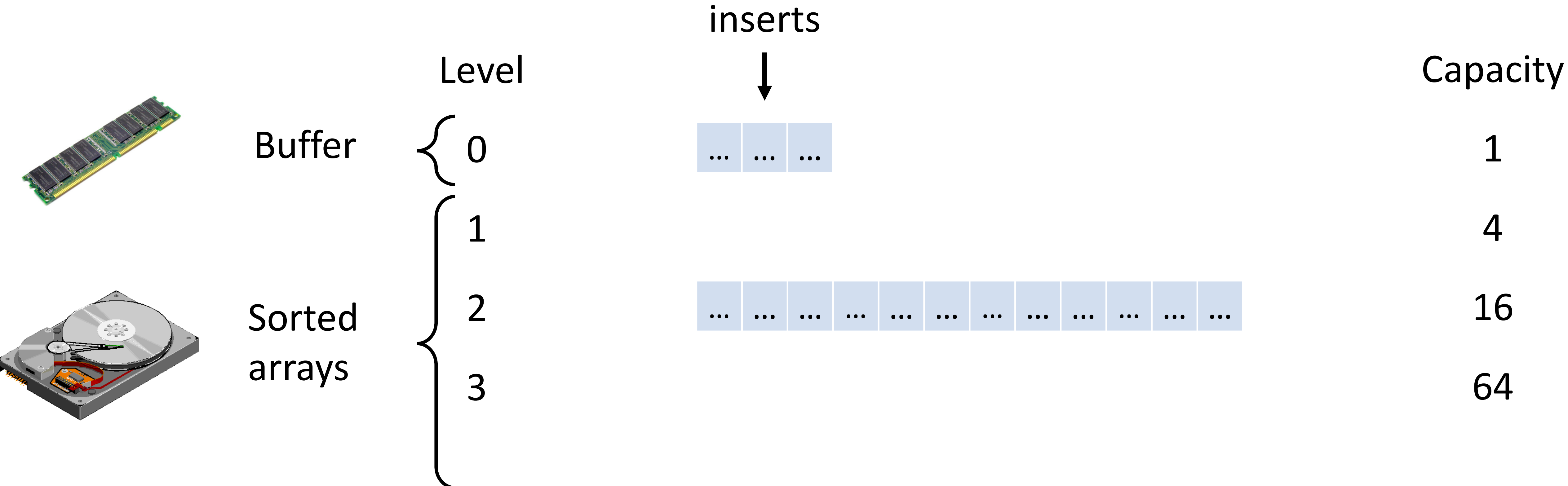


Leveled LSM-tree

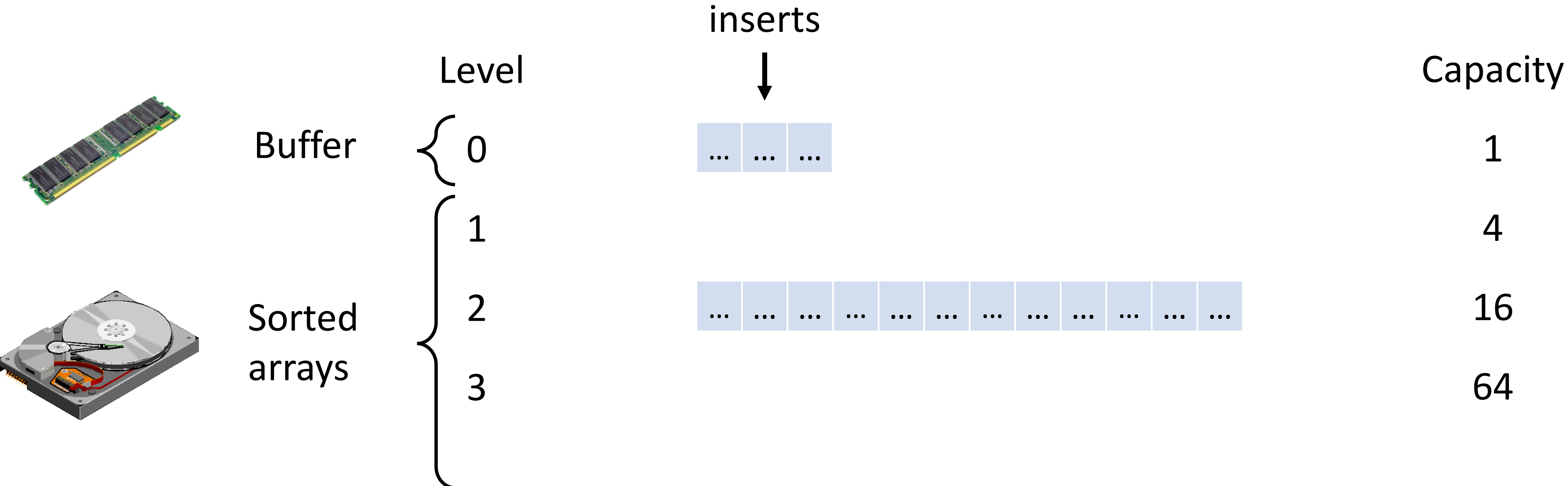
Lookup cost depends on number of levels

How to reduce it? Increase size ratio T

E.g. size ratio of 4



Leveled LSM-tree

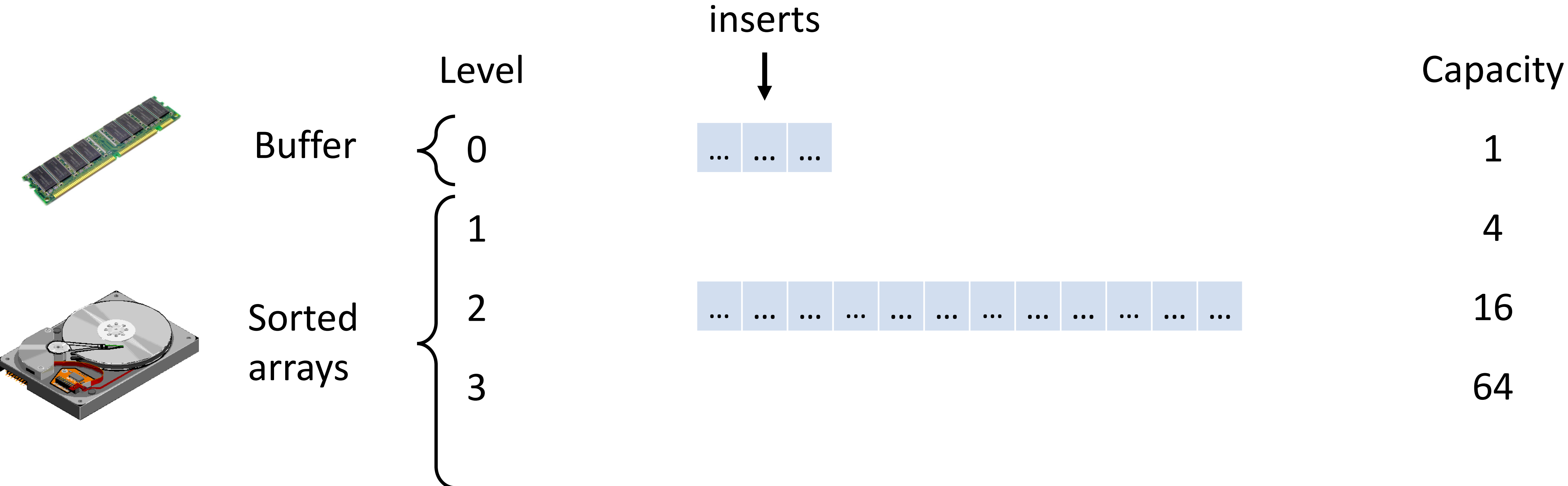


inserts

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

Leveled LSM-tree

Lookup cost?



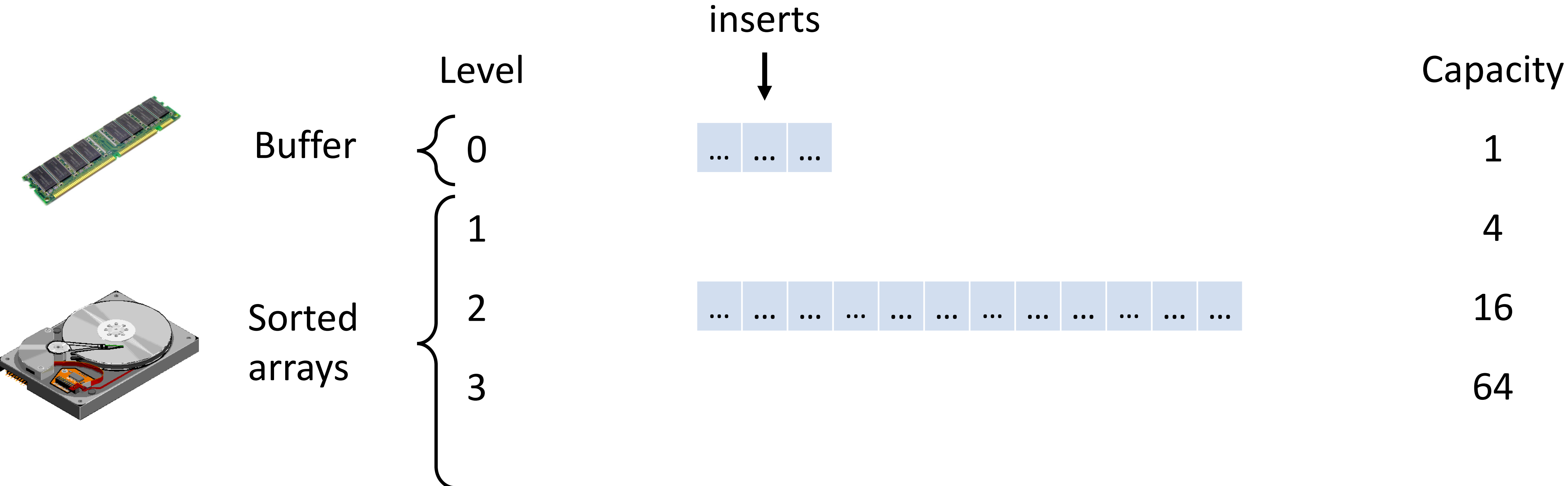
inserts

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

Leveled LSM-tree

Lookup cost?

$$O\left(\log_T\left(\frac{N}{B}\right)\right)$$

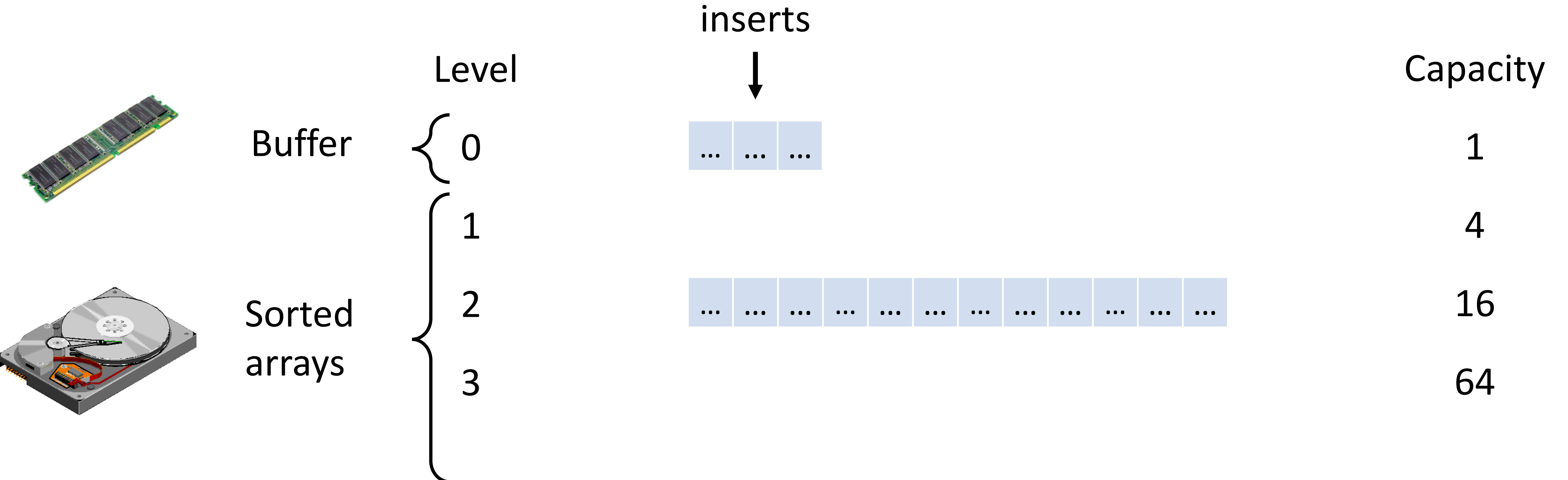


Leveled LSM-tree

Lookup cost?

$O\left(\log_T\left(\frac{N}{B}\right)\right)$

Insertion cost?



inserts

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

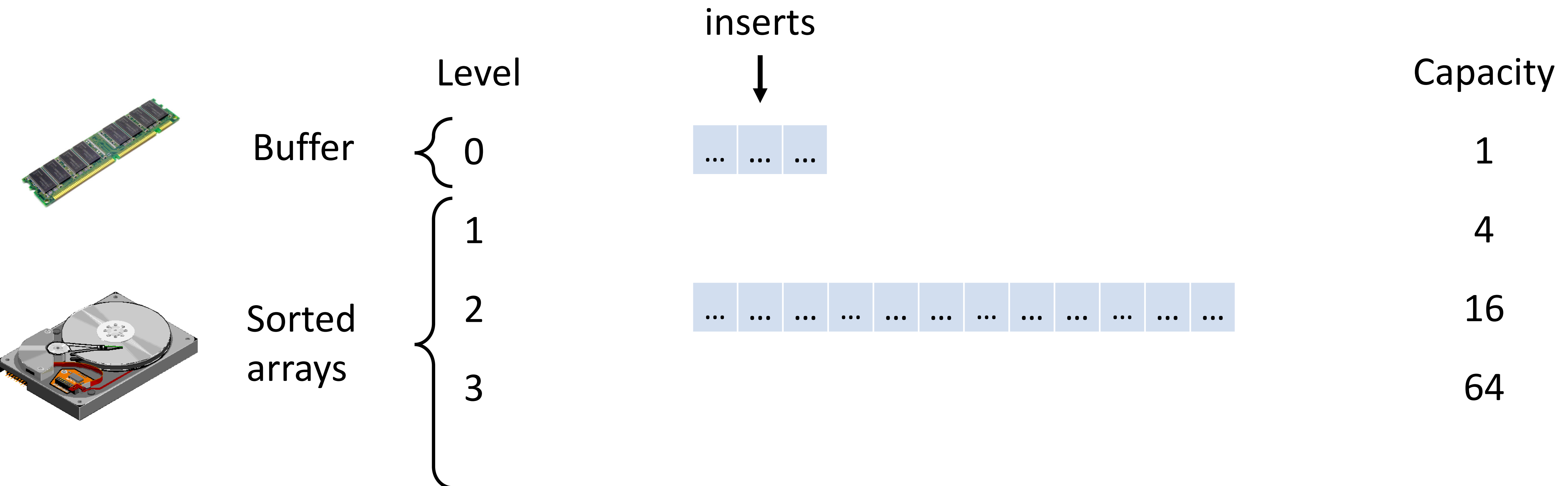
Leveled LSM-tree

Lookup cost?

$$O\left(\log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost?

$$O\left(\frac{T}{B}\cdot\log_T\left(\frac{N}{B}\right)\right)$$



inserts

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

Leveled LSM-tree

Lookup cost?

$$O\left(\log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost?

$$O\left(\frac{T}{B}\cdot\log_T\left(\frac{N}{B}\right)\right)$$

Leveled LSM-tree

Lookup cost?

$$O\left(\log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost?

$$O\left(\frac{T}{B}\cdot\log_T\left(\frac{N}{B}\right)\right)$$

What happens as we increase the size ratio T?

Leveled LSM-tree

↓ Lookup cost?

$$O\left(\log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost? ↑

$$O\left(\frac{T}{B}\cdot\log_T\left(\frac{N}{B}\right)\right)$$

What happens as we increase the size ratio T?

Leveled LSM-tree

⬇ Lookup cost?

$$O\left(\log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost? ⬆

$$O\left(\frac{T}{B}\cdot\log_T\left(\frac{N}{B}\right)\right)$$

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?

$$O\left(\log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost? ↑

$$O\left(\frac{T}{B}\cdot\log_T\left(\frac{N}{B}\right)\right)$$

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?

$$O\left(\log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost? ↑

$$O\left(\frac{T}{B}\cdot\log_T\left(\frac{N}{B}\right)\right)$$

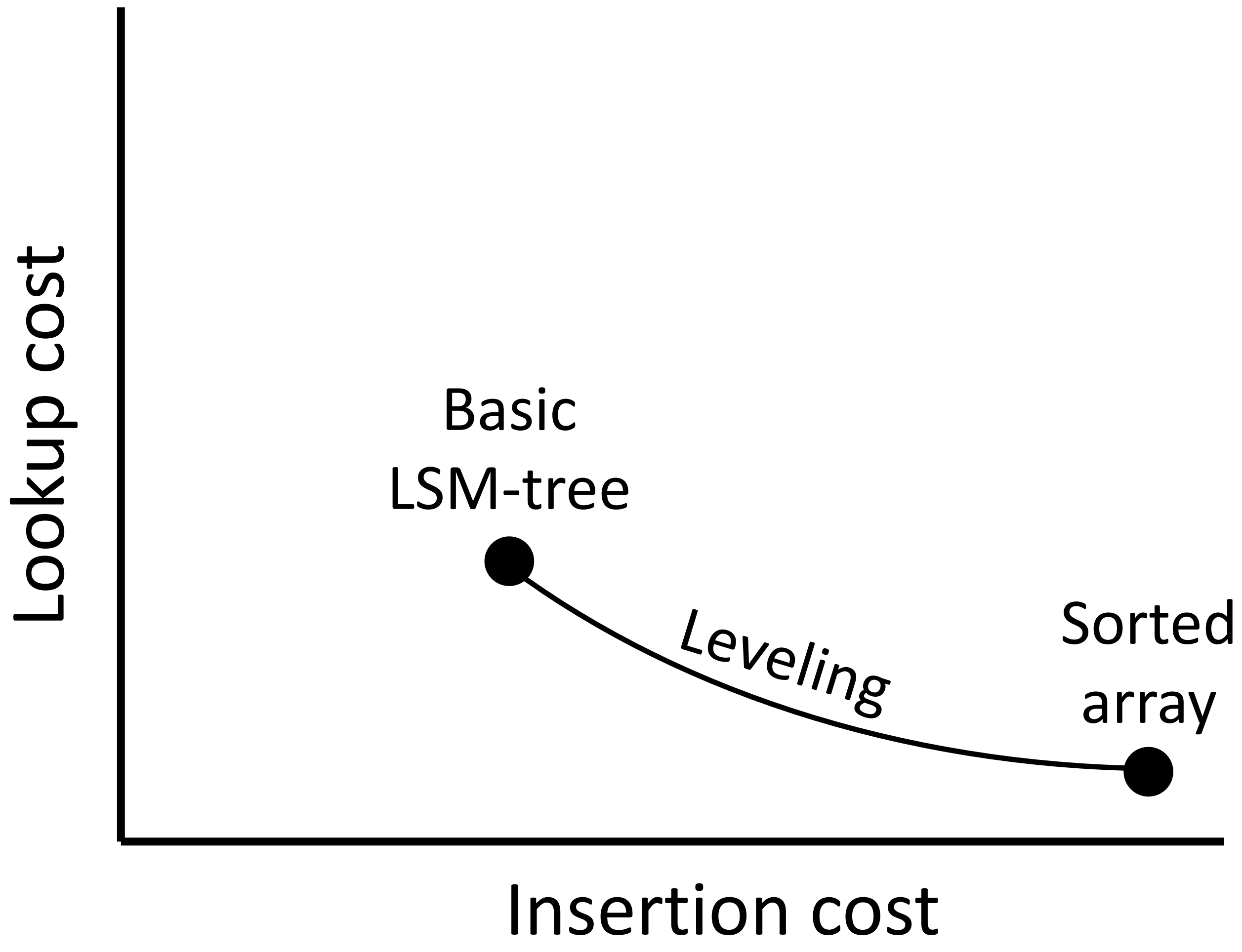
What happens as we increase the size ratio T?

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 array!


Lookup cost
Basic LSM-tree
Leveling
Sorted array
Insertion cost

Results Catalogue – with fence pointers

	Lookup cost	Insertion cost
Sorted array	$O(1)$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(1)$	$O(1)$
Basic LSM-tree	$O(\log_2(N/B))$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree	$O(\log_T(N/B))$	$O(T/B \cdot \log_T(N/B))$
Tiered LSM-tree		

Tiered LSM-tree

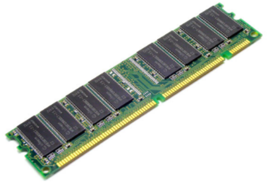
Tiered LSM-tree

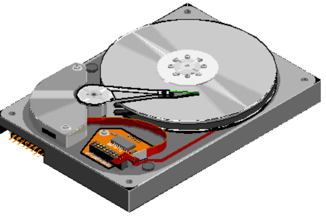
⬆ Lookup cost

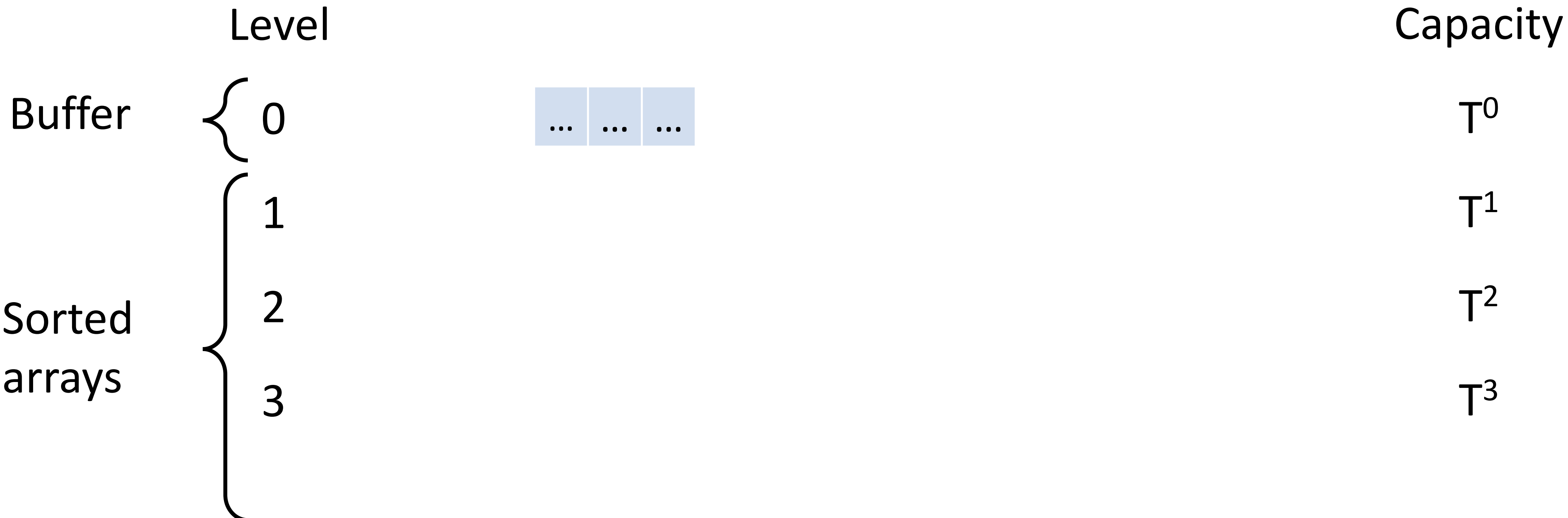
⬇ Insertion cost

Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.



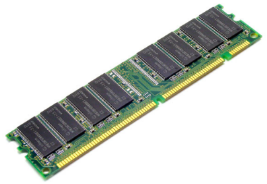


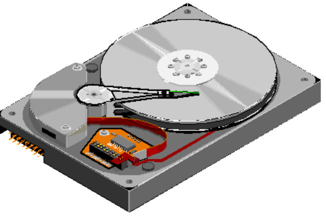


Level		Capacity
Buffer 0	… … …	T^0
Sorted arrays 1		T^1
2		T^2
3		T^3

Tiered LSM-tree

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





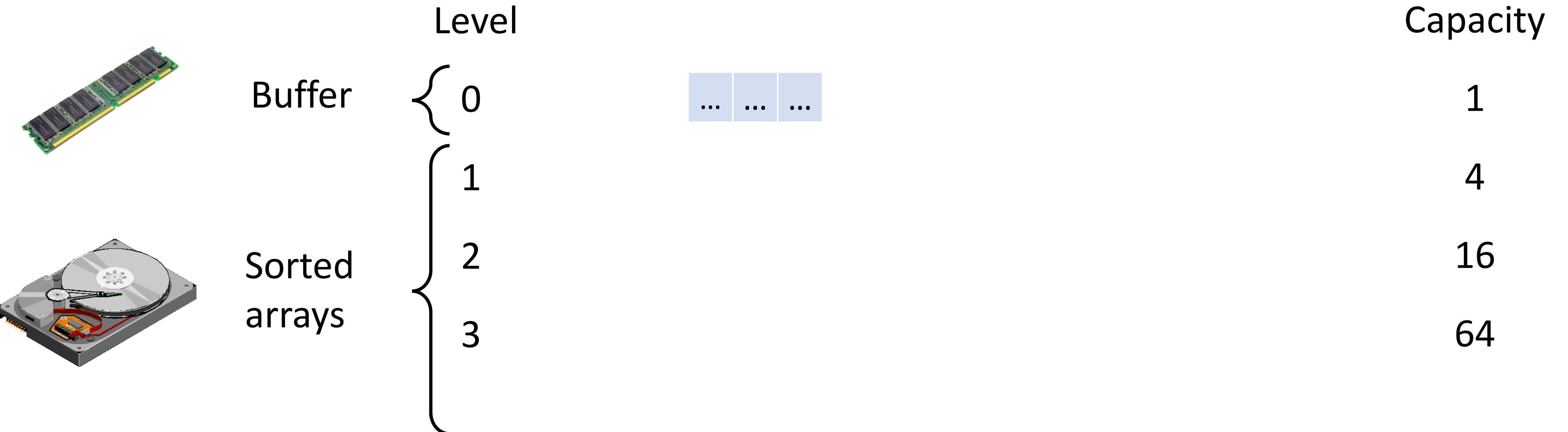
	Level		Capacity
Buffer	0	… … …	T^0
Sorted arrays	1		T^1
	2		T^2
	3		T^3

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

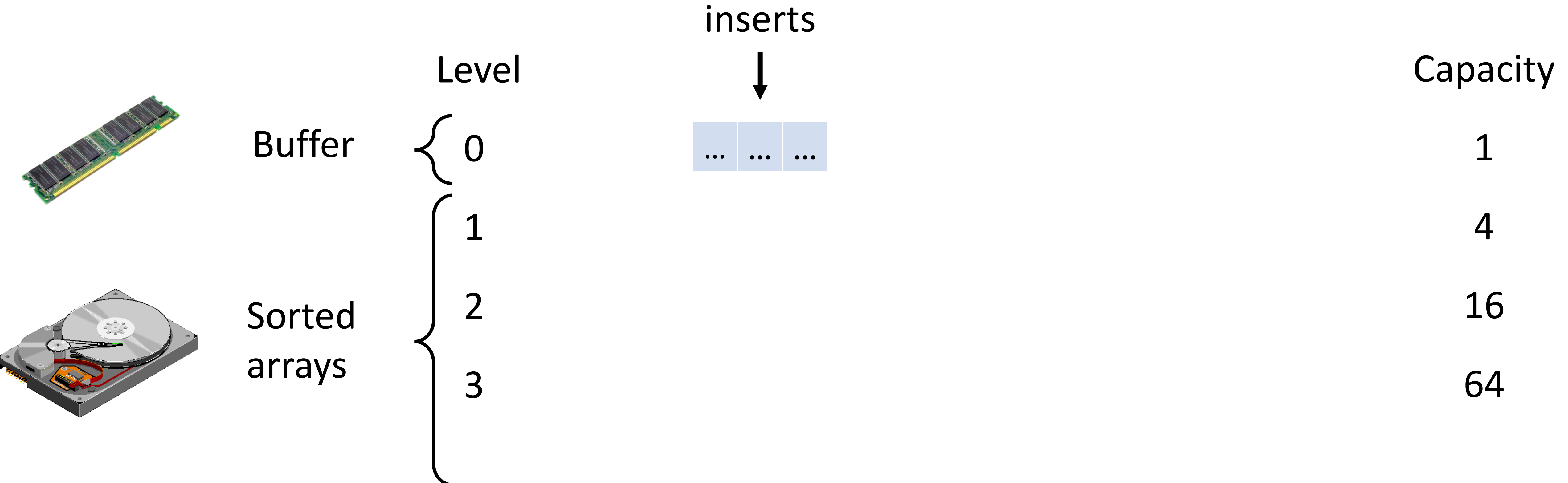


Tiered LSM-tree

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

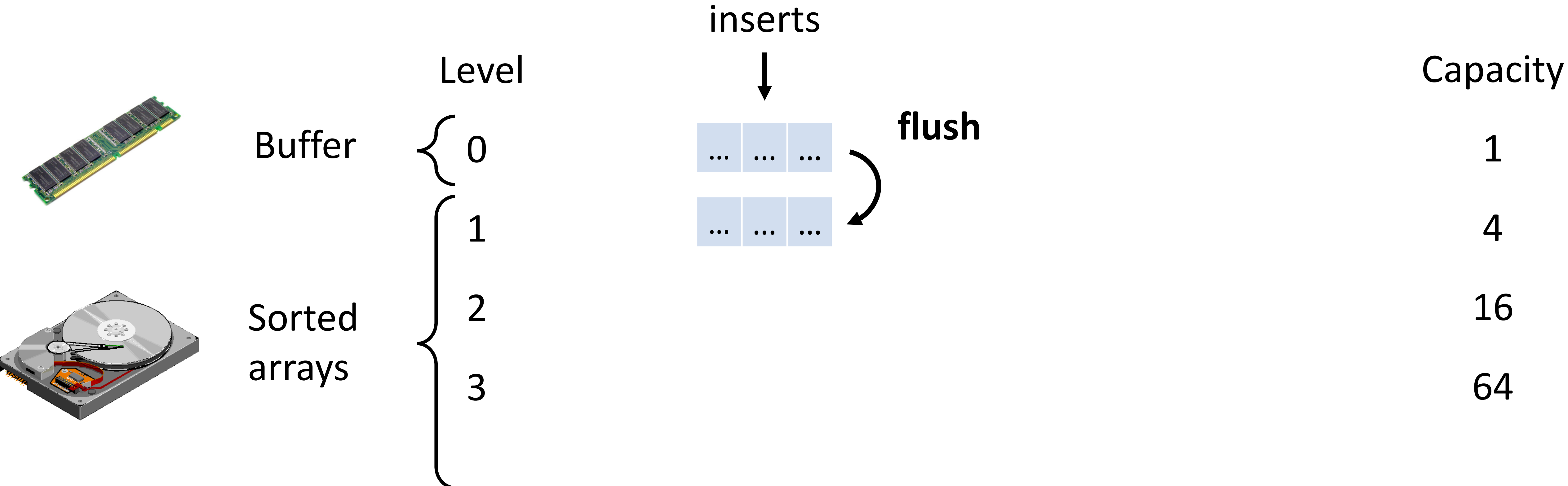
64

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



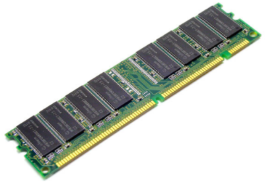
Level	Capacity
0	1
1	4
2	16
3	64

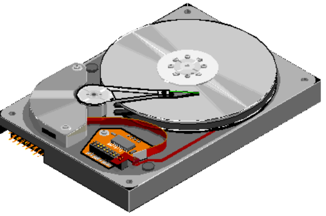
Tiered LSM-tree

Reduce the number of levels by increasing the size ratio.

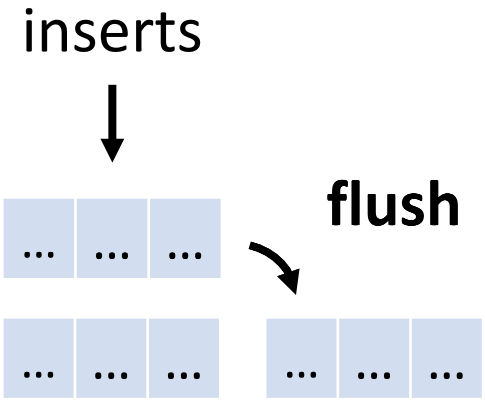
Do not merge within a level.

E.g. size ratio of 4





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

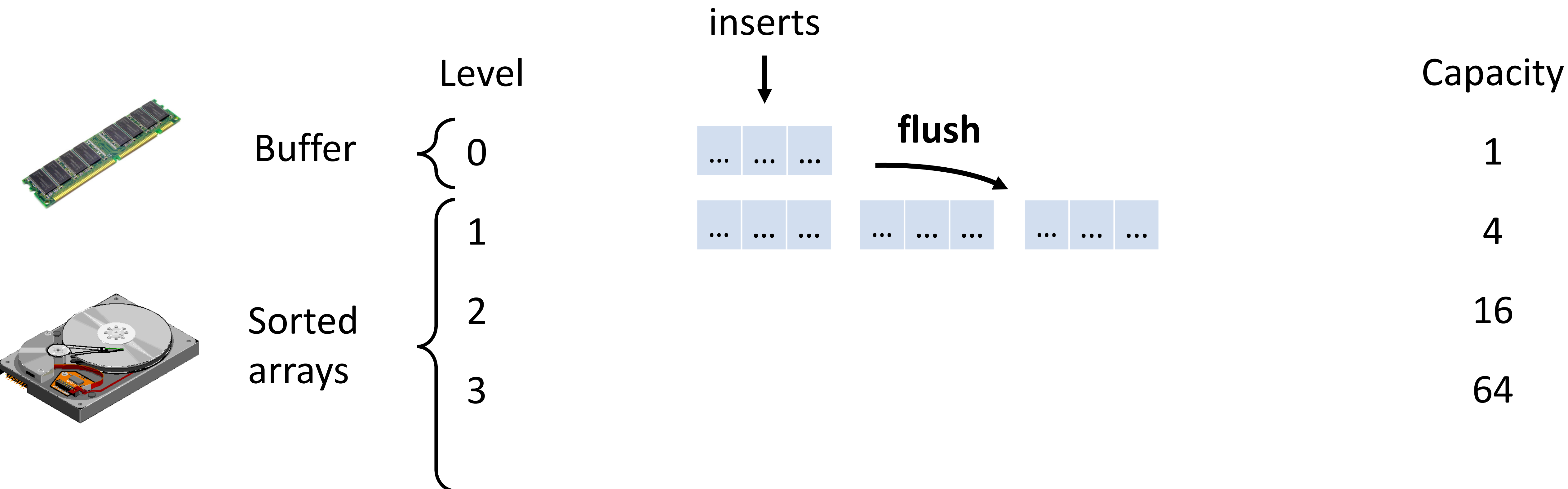


Tiered LSM-tree

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

… … …

flush

1

Sorted arrays

1

… … … … … … … … …

4

2

16

3

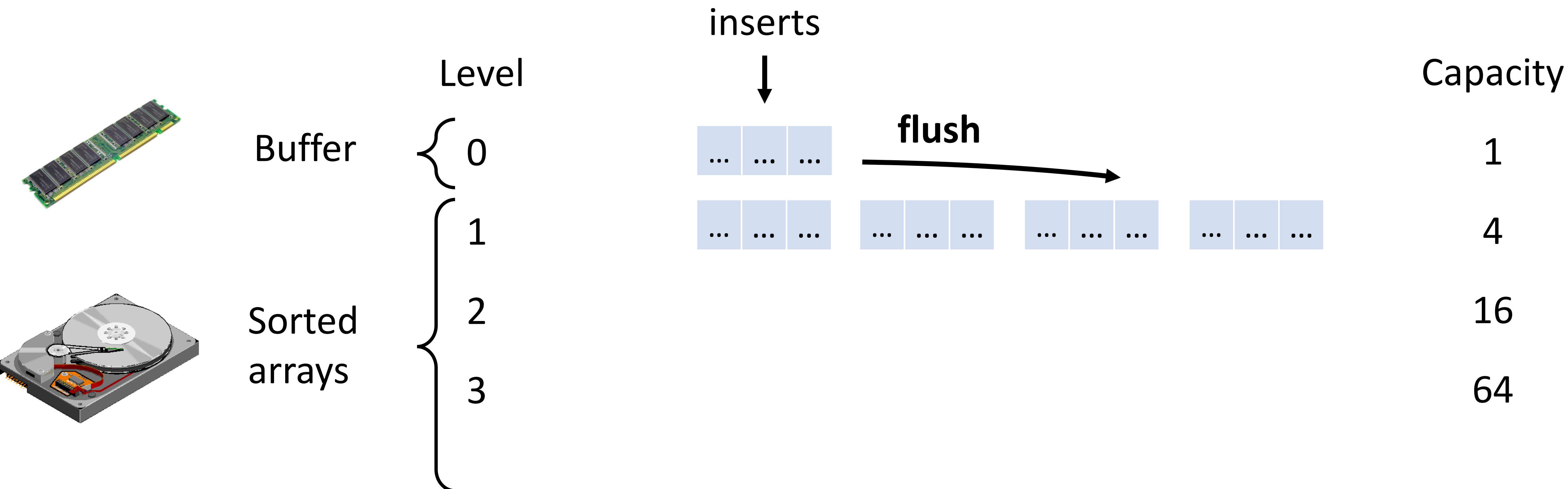
64

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

flush

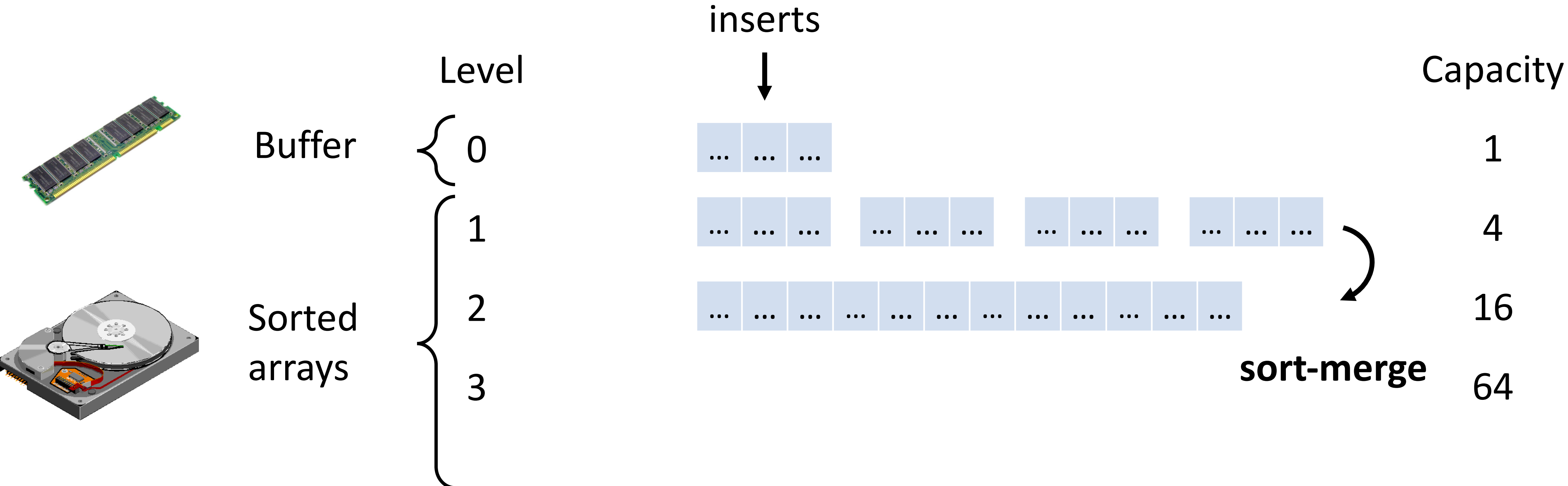
Level		Capacity
Buffer	0	1
Sorted arrays	1	4
	2	16
	3	64

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

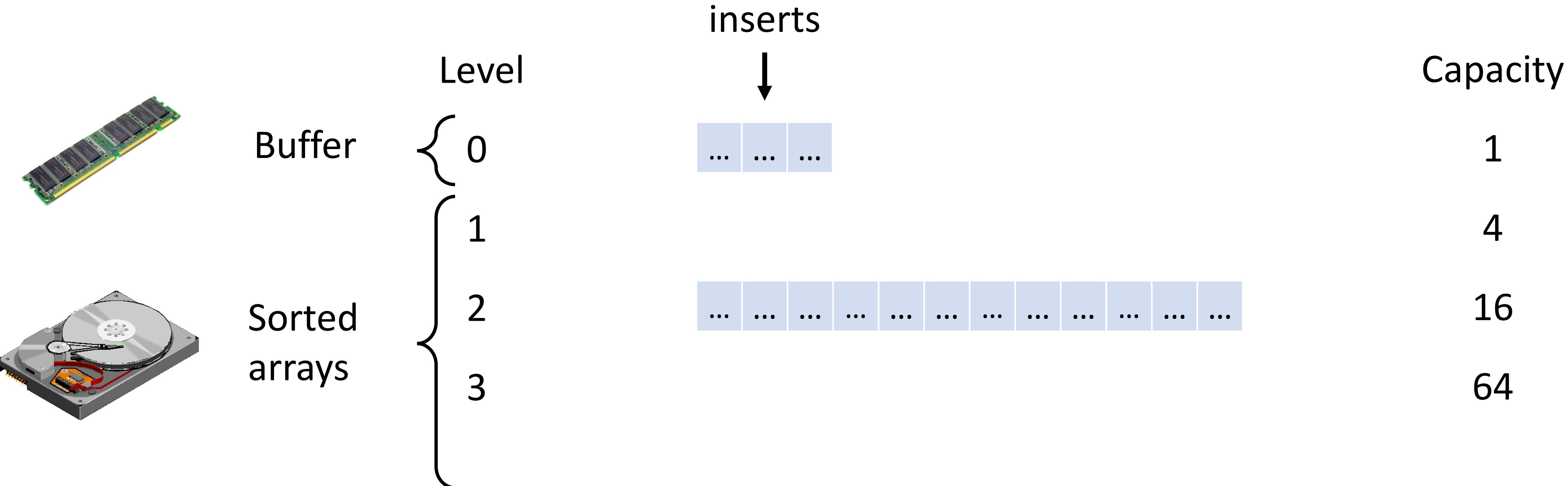
3

64

sort-merge

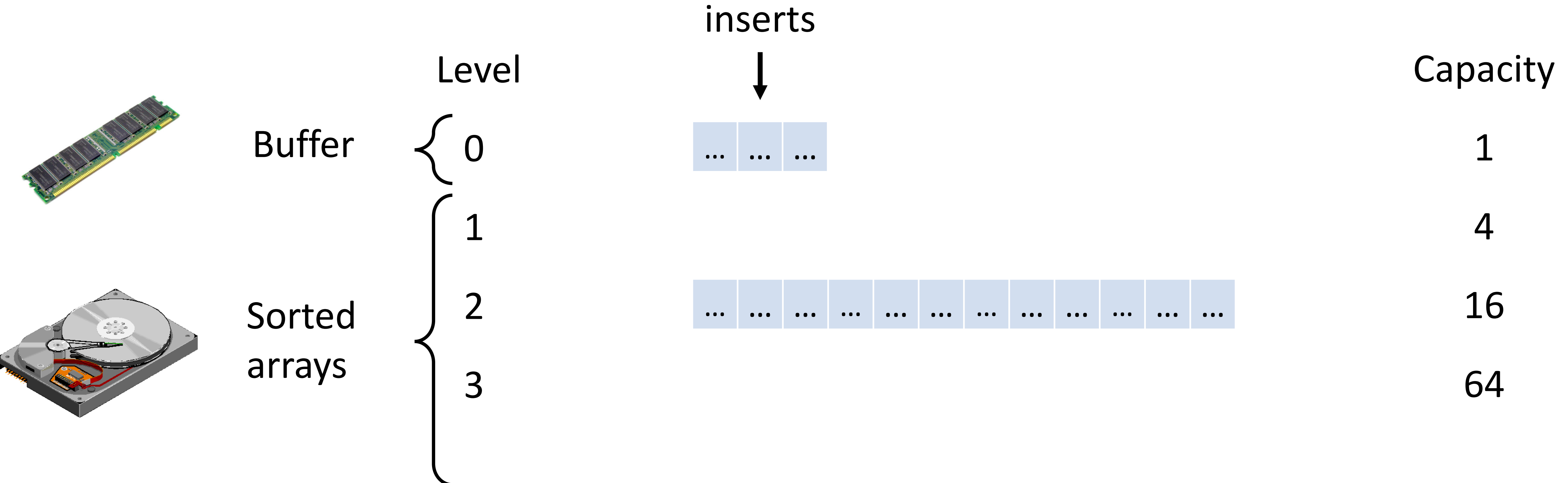
Tiered LSM-tree

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?



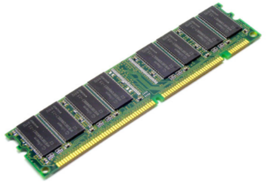
inserts

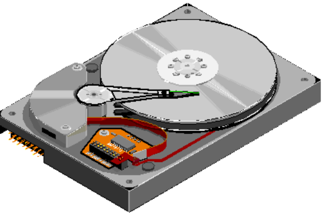
	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2	… … … … … … … … … … … …	16
	3		64

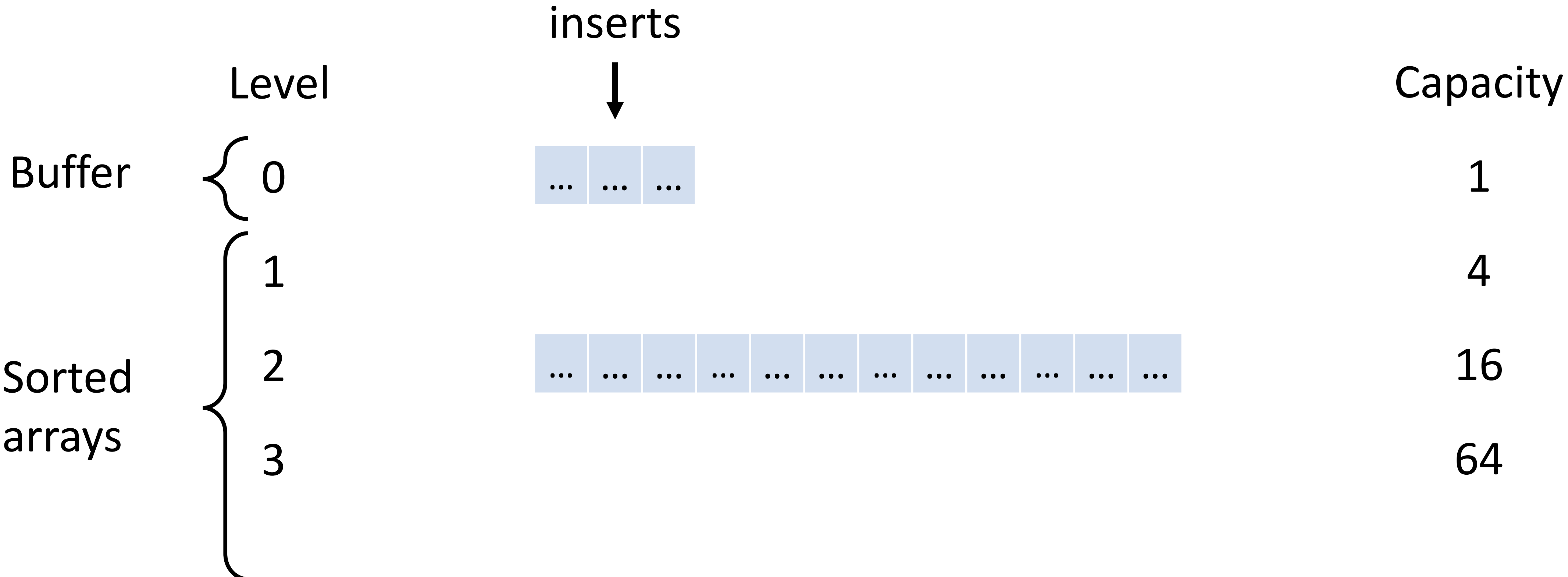
Tiered LSM-tree

Lookup cost?

$$O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$$







inserts

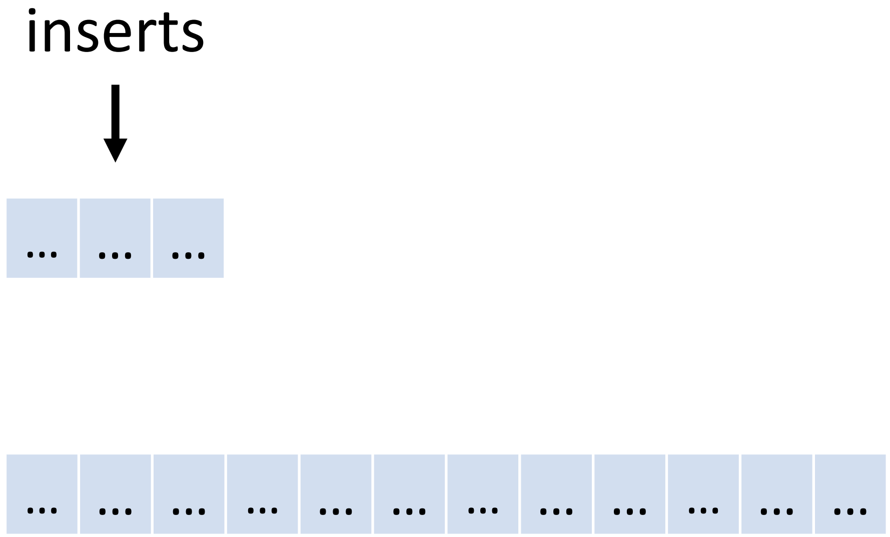
	Level		Capacity
Buffer	0	… … …	1
Sorted arrays	1		4
	2	… … … … … … … … … … … …	16
	3		64

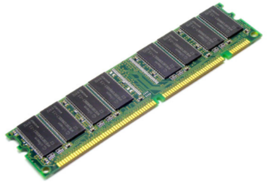
Tiered LSM-tree

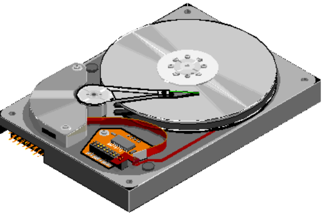
Lookup cost?

$O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$

Insertion cost?







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

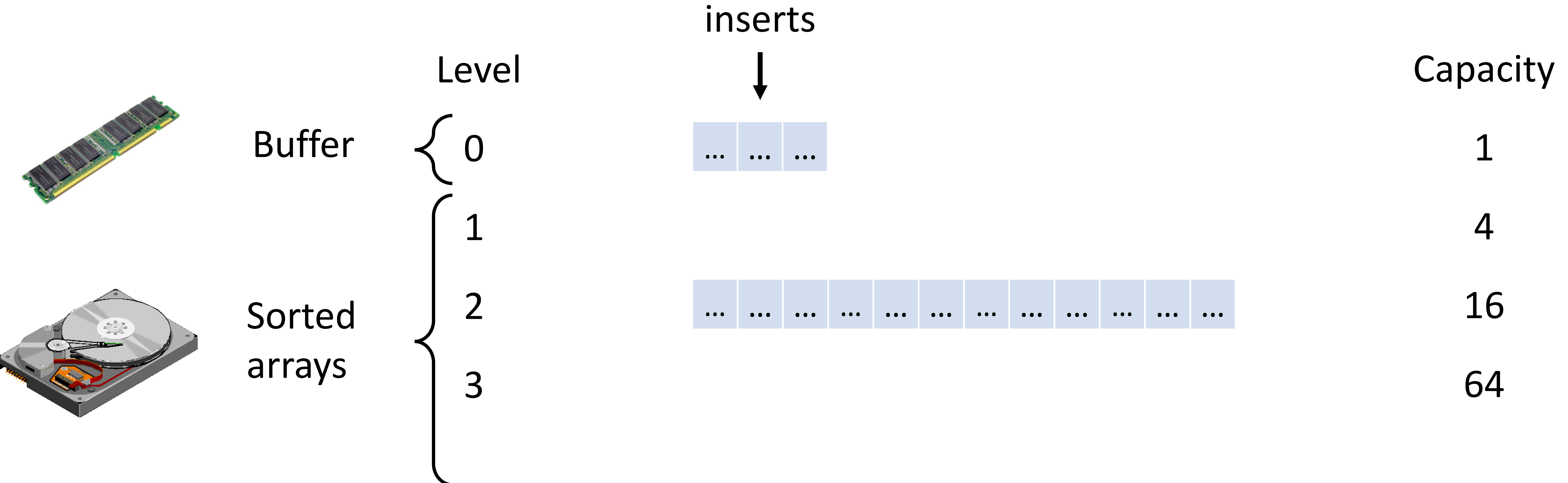
Tiered LSM-tree

Lookup cost?

$$O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost?

$$O\left(\frac{1}{B} \cdot \log_T\left(\frac{N}{B}\right)\right)$$



Tiered LSM-tree

Lookup cost?

$$O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost?

$$O\left(\frac{1}{B} \cdot \log_T\left(\frac{N}{B}\right)\right)$$

Tiered LSM-tree

Lookup cost?

$$O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$$

Insertion cost?

$$O\left(\frac{1}{B} \cdot \log_T\left(\frac{N}{B}\right)\right)$$

What happens as we increase the size ratio T?

Tiered LSM-tree

Lookup cost?

⬆ $O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$

Insertion cost?

$O\left(\frac{1}{B} \cdot \log_T\left(\frac{N}{B}\right)\right)$ ⬇

What happens as we increase the size ratio T?

Tiered LSM-tree

Lookup cost?

↑ $O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$

Insertion cost?

$O\left(\frac{1}{B} \cdot \log_T\left(\frac{N}{B}\right)\right)$ ↓

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?

⬆ $O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$

Insertion cost?

$O\left(\frac{1}{B} \cdot \log_T\left(\frac{N}{B}\right)\right)$ ⬇

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?

⬆ $O\left(T \cdot \log_T\left(\frac{N}{B}\right)\right)$

Insertion cost?

$O\left(\frac{1}{B} \cdot \log_T\left(\frac{N}{B}\right)\right)$ ⬇

What happens as we increase the size ratio T?

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

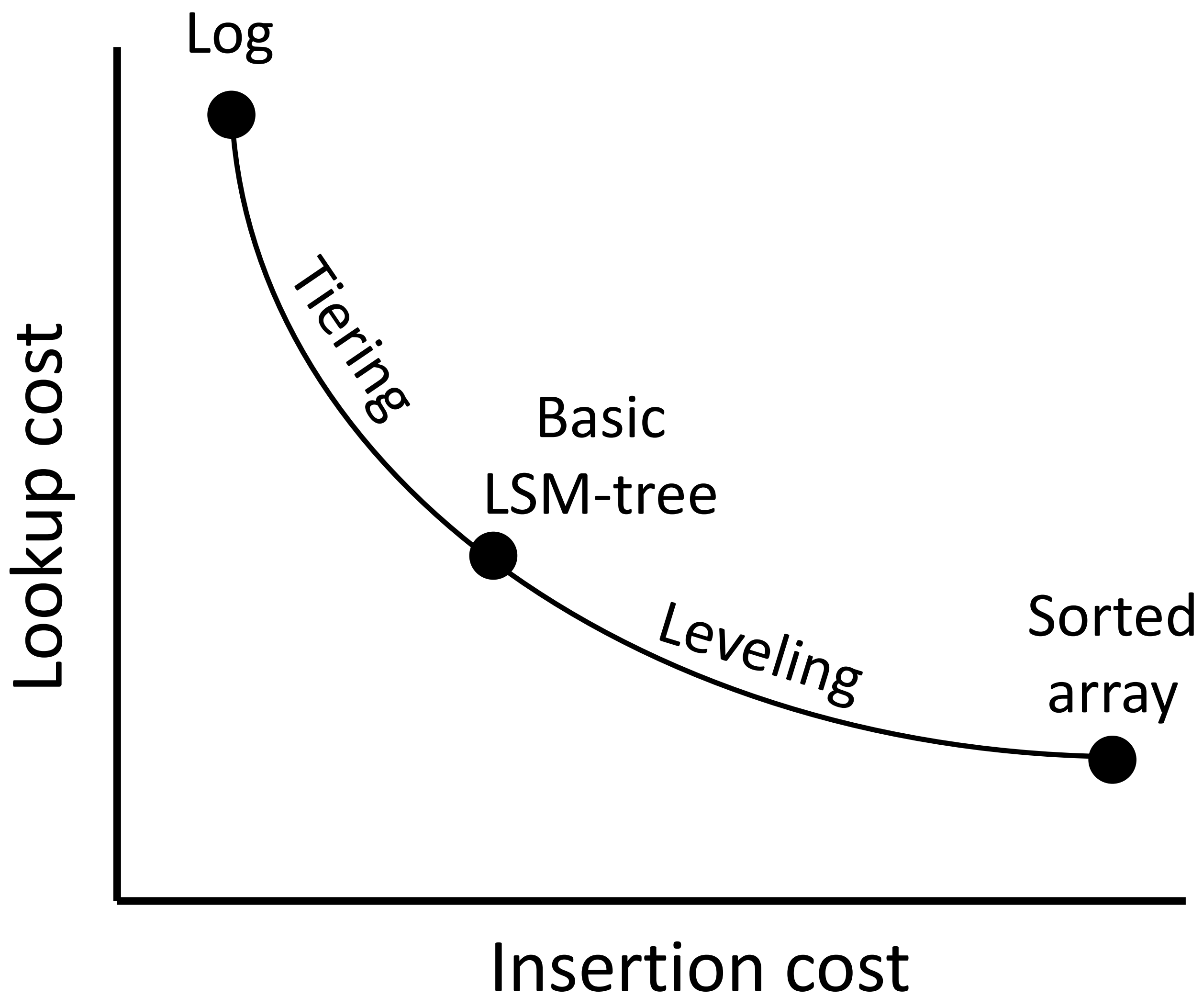
Lookup cost becomes:

O(N/B)

Insert cost becomes:

O(1/B)

The tiered LSM-tree becomes a log!

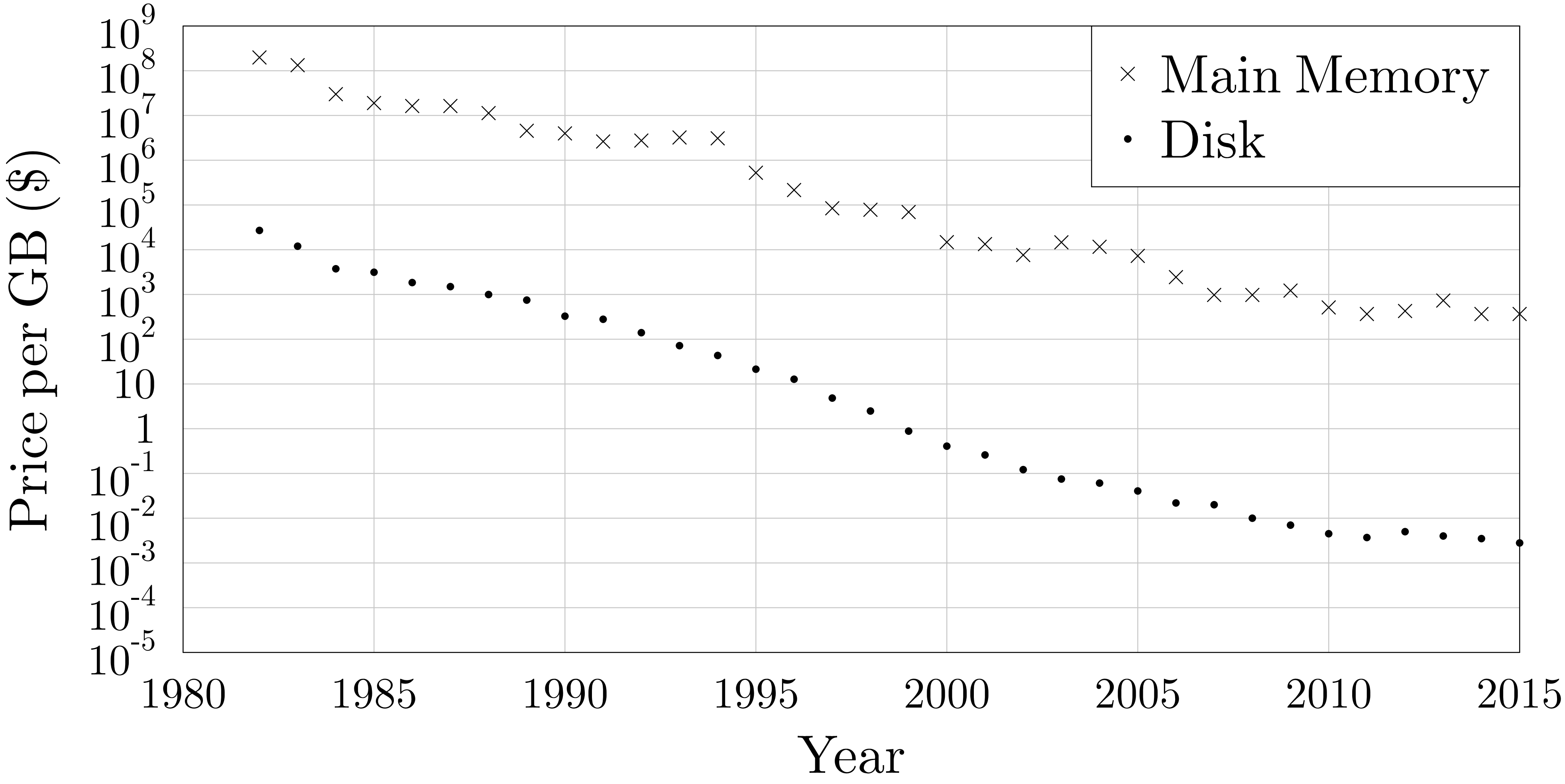

Log
Tiering
Basic LSM-tree
Leveling
Sorted array
Lookup cost
Insertion cost

Results Catalogue – with fence pointers

	Lookup cost	**Insertion cost**
Sorted array	$O(1)$	$O(N/B)$
Log	$O(N/B)$	$O(1/B)$
B-tree	$O(1)$	$O(1)$
Basic LSM-tree	$O(\log_2(N/B))$	$O(1/B \cdot \log_2(N/B))$
Leveled LSM-tree	$O(\log_T(N/B))$	$O(T/B \cdot \log_T(N/B))$
Tiered LSM-tree	$O(T \cdot \log_T(N/B))$	$O(1/B \cdot \log_T(N/B))$

Bloom filters

Declining Main Memory Cost



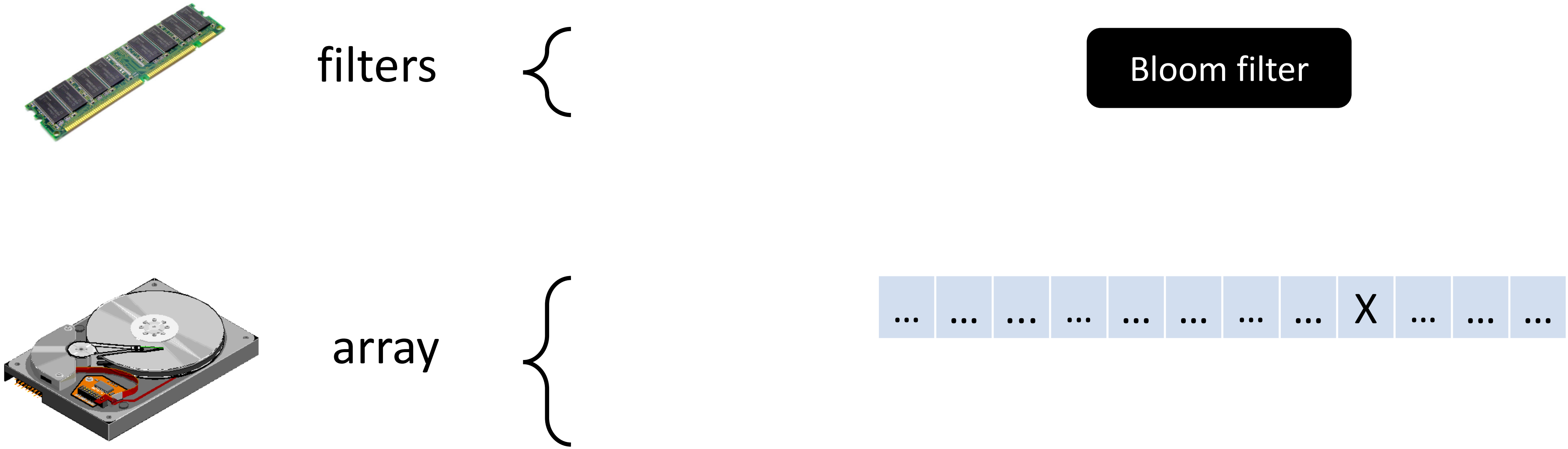
Bloom Filters

Answers set-membership queries

Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

Subtlety: may return false positives.



filters

Bloom filter

array

…	…	…	…	…	…	…	…	X	…	…	…

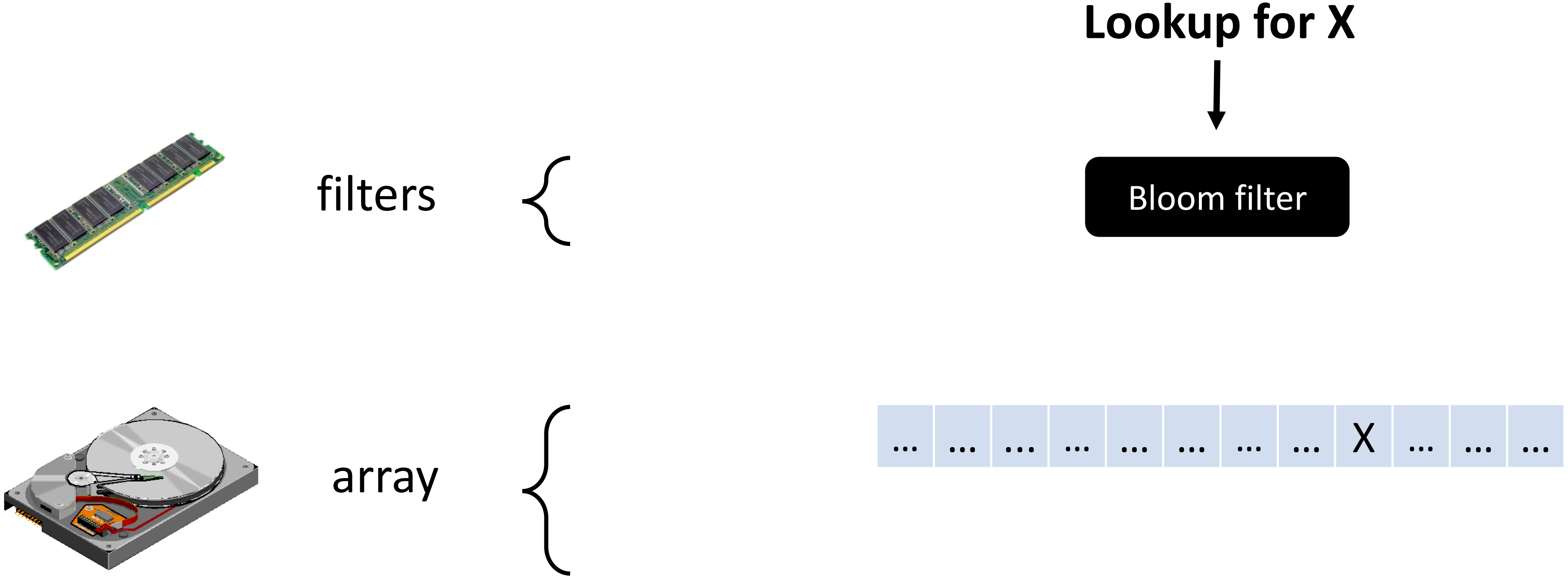
Bloom Filters

Answers set-membership queries

Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

Subtlety: may return false positives.



…	…	…	…	…	…	…	…	X	…	…	…

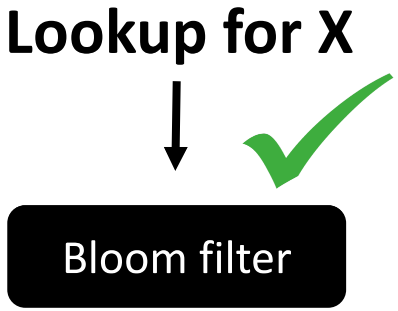
Bloom Filters

Answers set-membership queries

Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

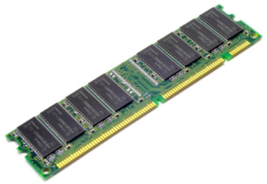
Subtlety: may return false positives.



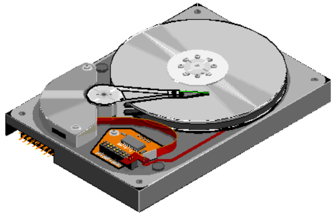
Lookup for X

✓

Bloom filter



filters {

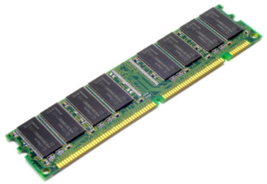


array {

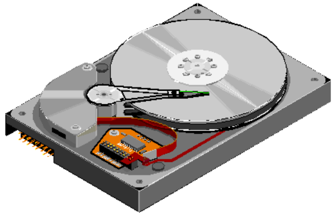
…	…	…	…	…	…	…	…	X	…	…	…

Bloom Filters

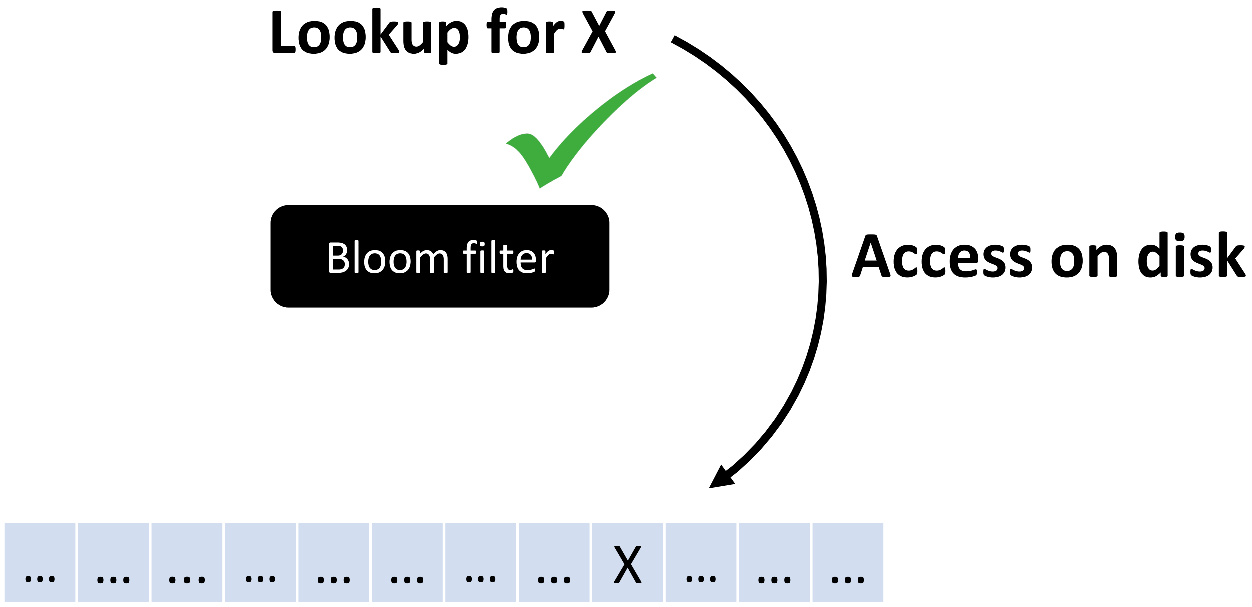
Answers set-membership queries
Smaller than array, and stored in main memory
Purpose: avoid accessing disk if entry is not in array
Subtlety: may return false positives.



filters



array



Lookup for X

Bloom filter

Access on disk

…	…	…	…	…	…	…	…	X	…	…	…

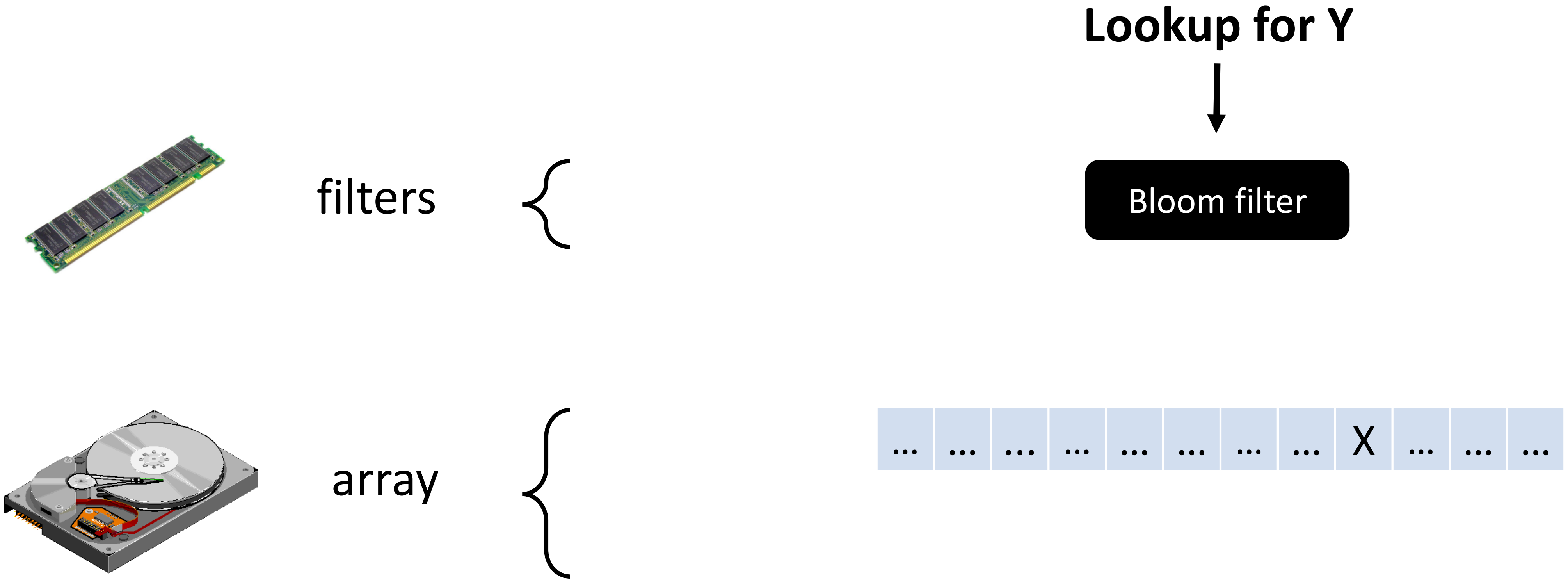
Bloom Filters

Answers set-membership queries

Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

Subtlety: may return false positives.



Lookup for Y

filters

Bloom filter

array

…	…	…	…	…	…	…	…	X	…	…	…

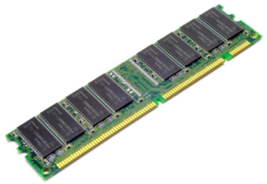
Bloom Filters

Answers set-membership queries

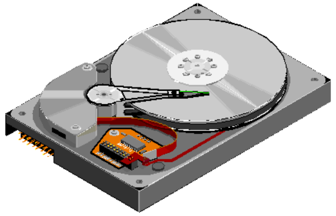
Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

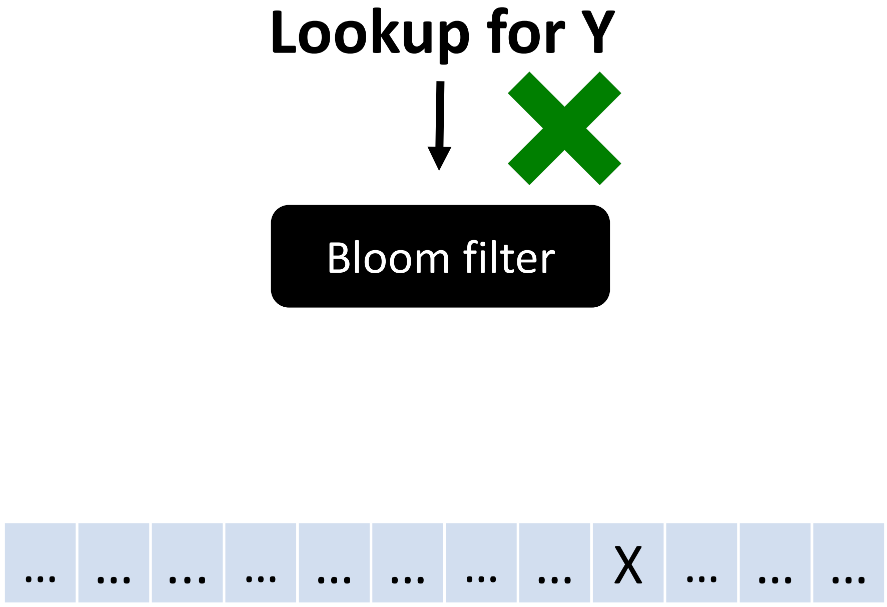
Subtlety: may return false positives.



filters



array



Lookup for Y

✗

Bloom filter

…	…	…	…	…	…	…	…	X	…	…	…

Bloom Filters

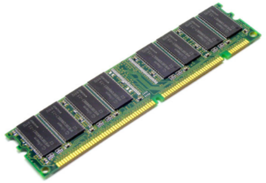
Answers set-membership queries

Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

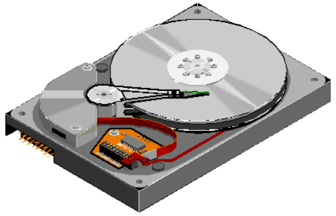
Subtlety: may return false positives.

Lookup for Y



filters {

Bloom filter



array {

…	…	…	…	…	…	…	…	X	…	…	…

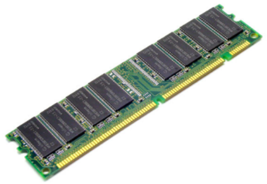
Bloom Filters

Answers set-membership queries

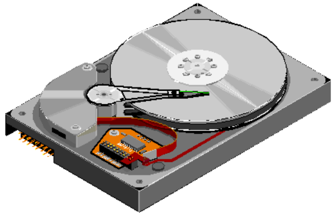
Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

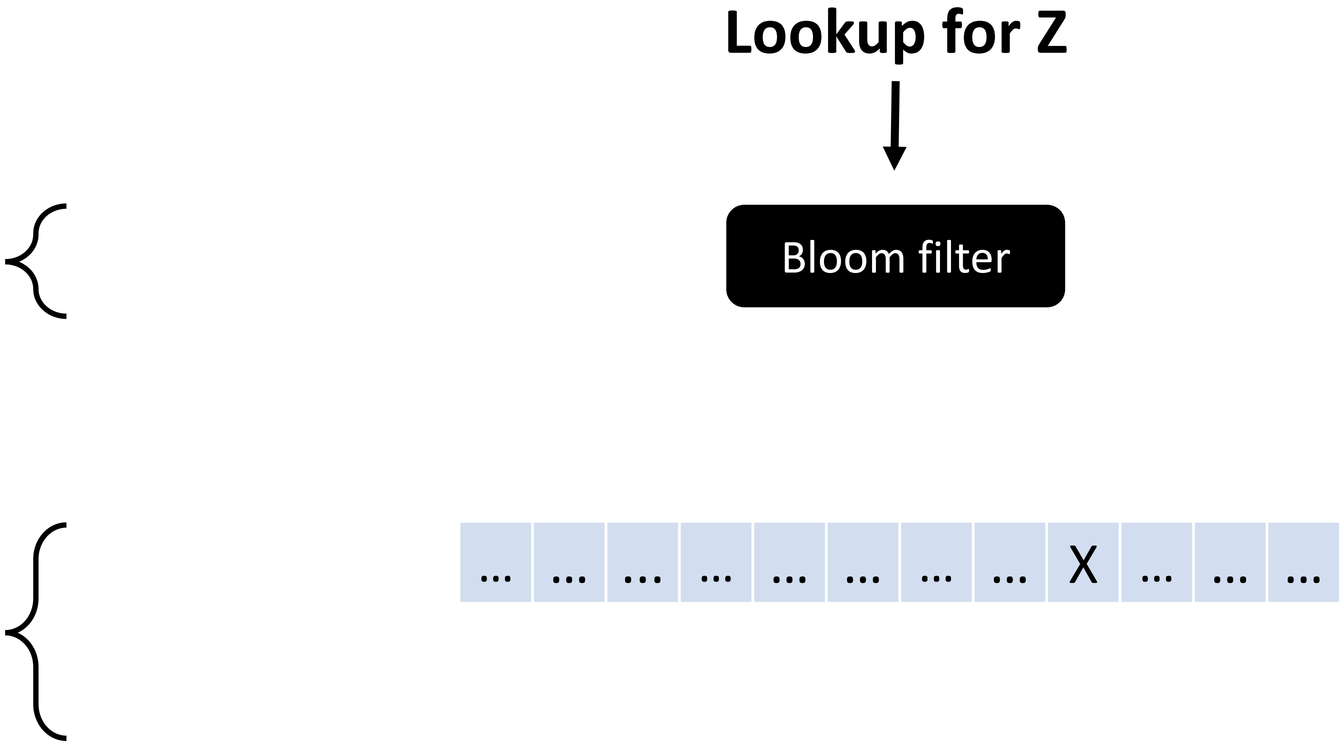
Subtlety: may return false positives.



filters



array



Lookup for Z

Bloom filter

…	…	…	…	…	…	…	…	X	…	…	…

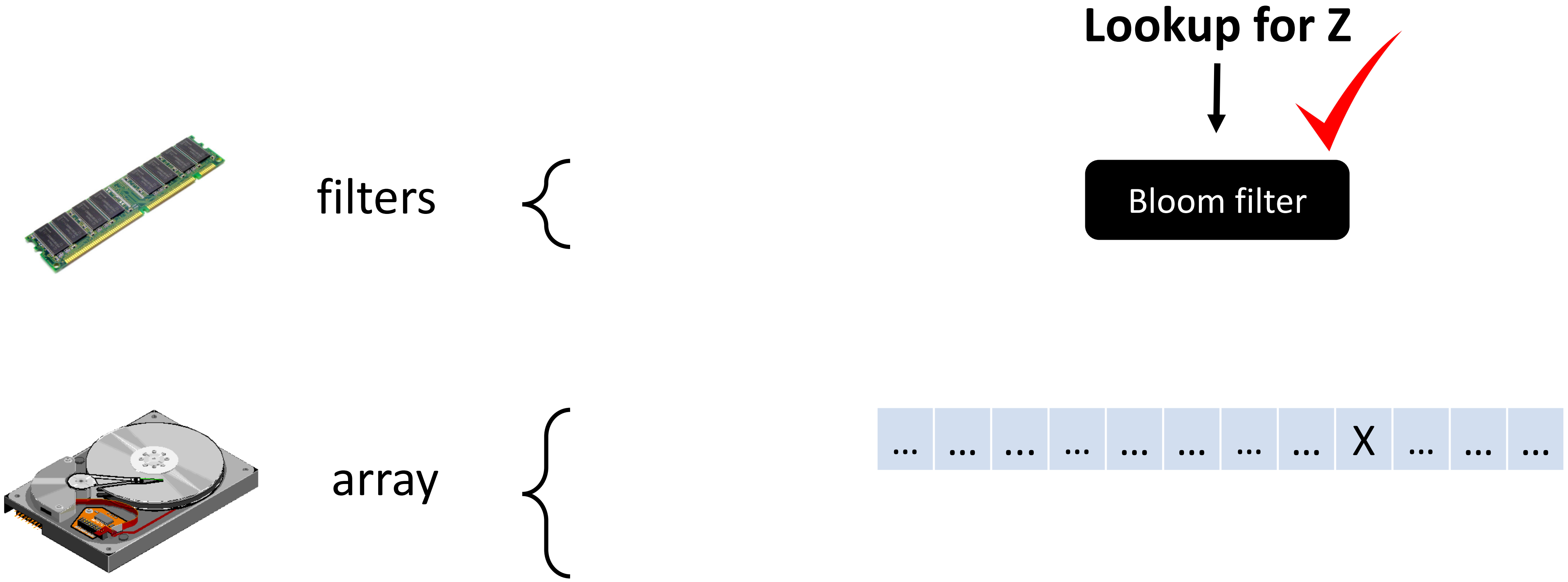
Bloom Filters

Answers set-membership queries

Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

Subtlety: may return false positives.



Lookup for Z ✓

filters

Bloom filter

array

…	…	…	…	…	…	…	…	X	…	…	…

Bloom Filters

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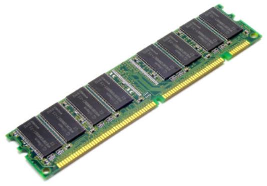
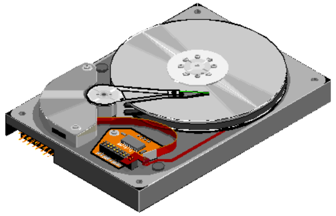
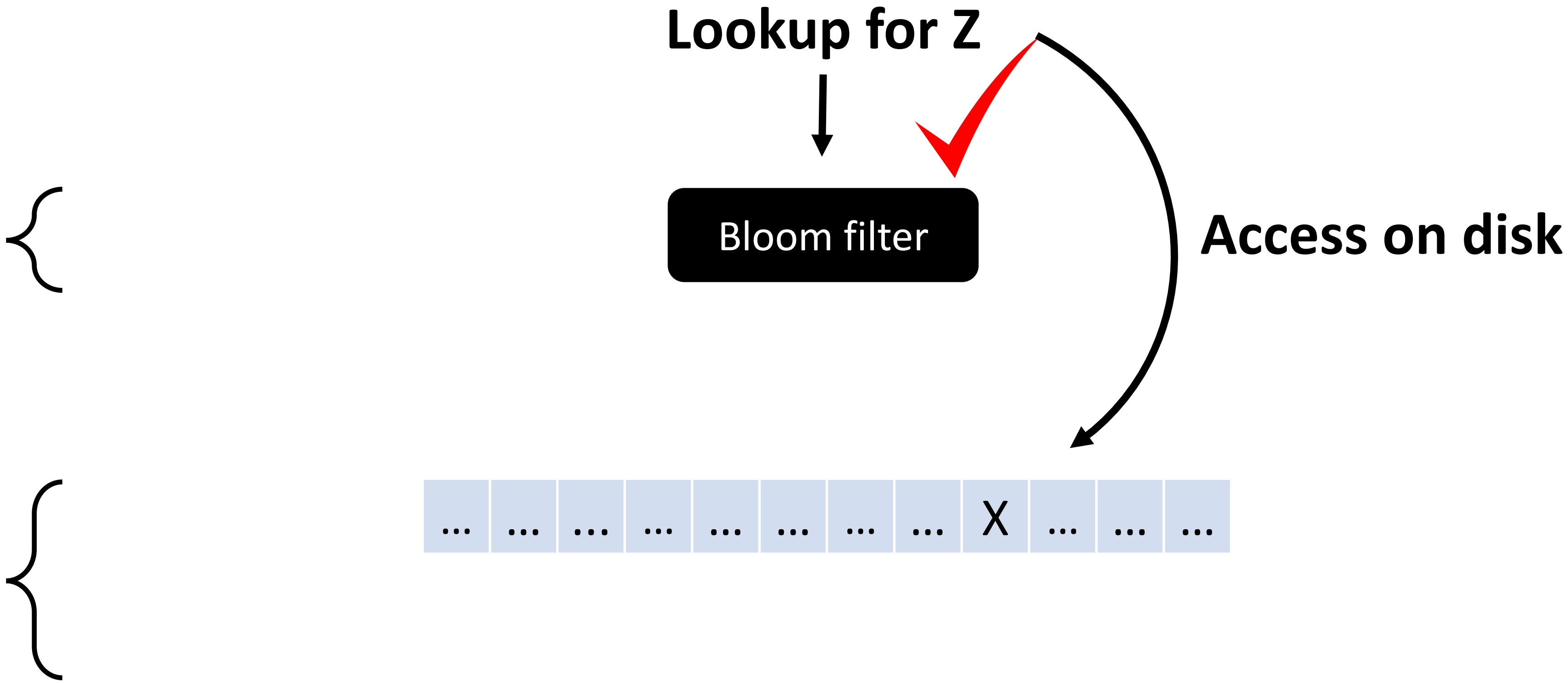


filters



array



Lookup for Z

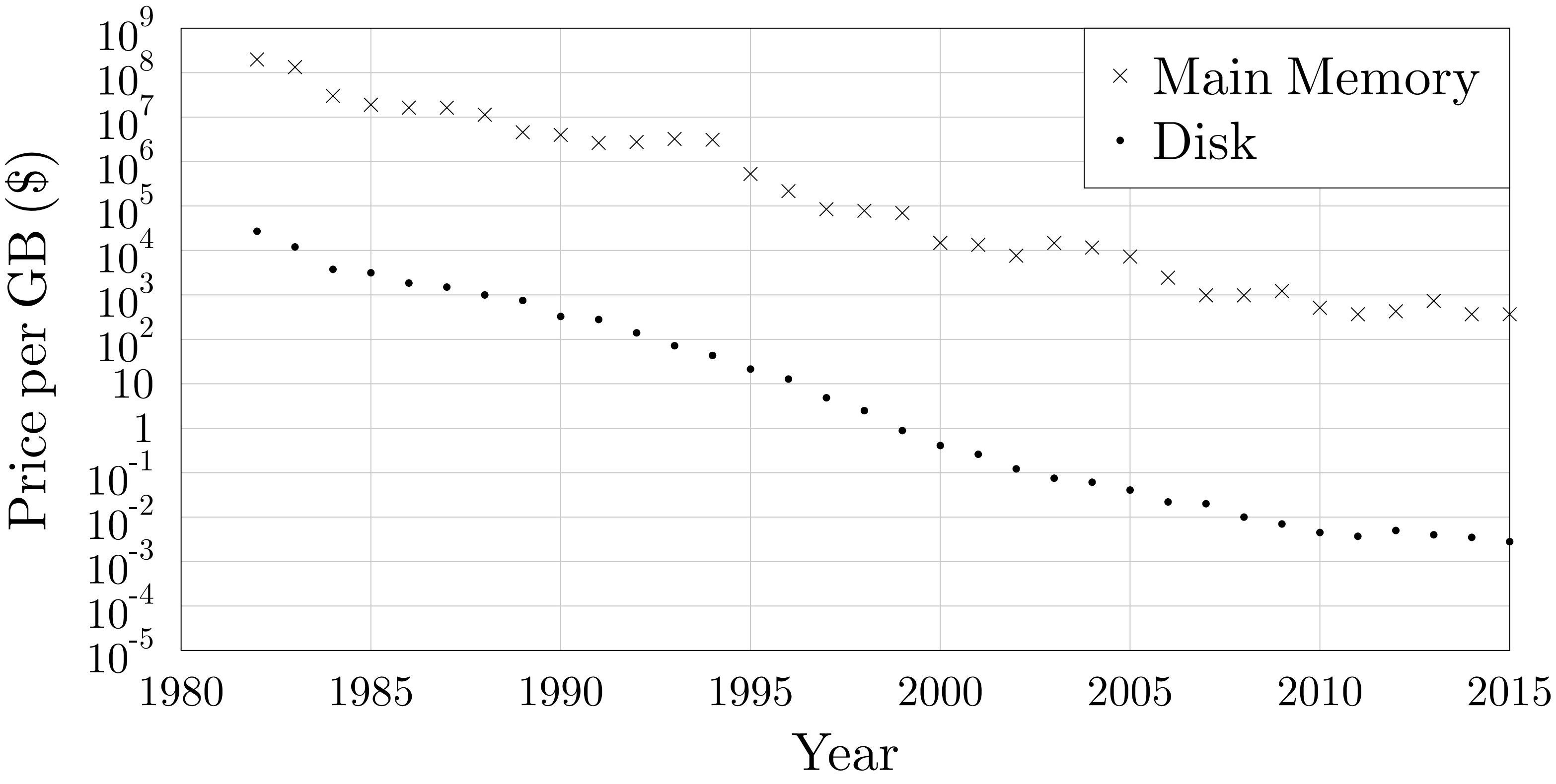
Bloom filter

Access on disk

…	…	…	…	…	…	…	…	X	…	…	…

Bloom Filters

The more main memory, the less false positives ⟹ cheaper lookups



Bloom Filters

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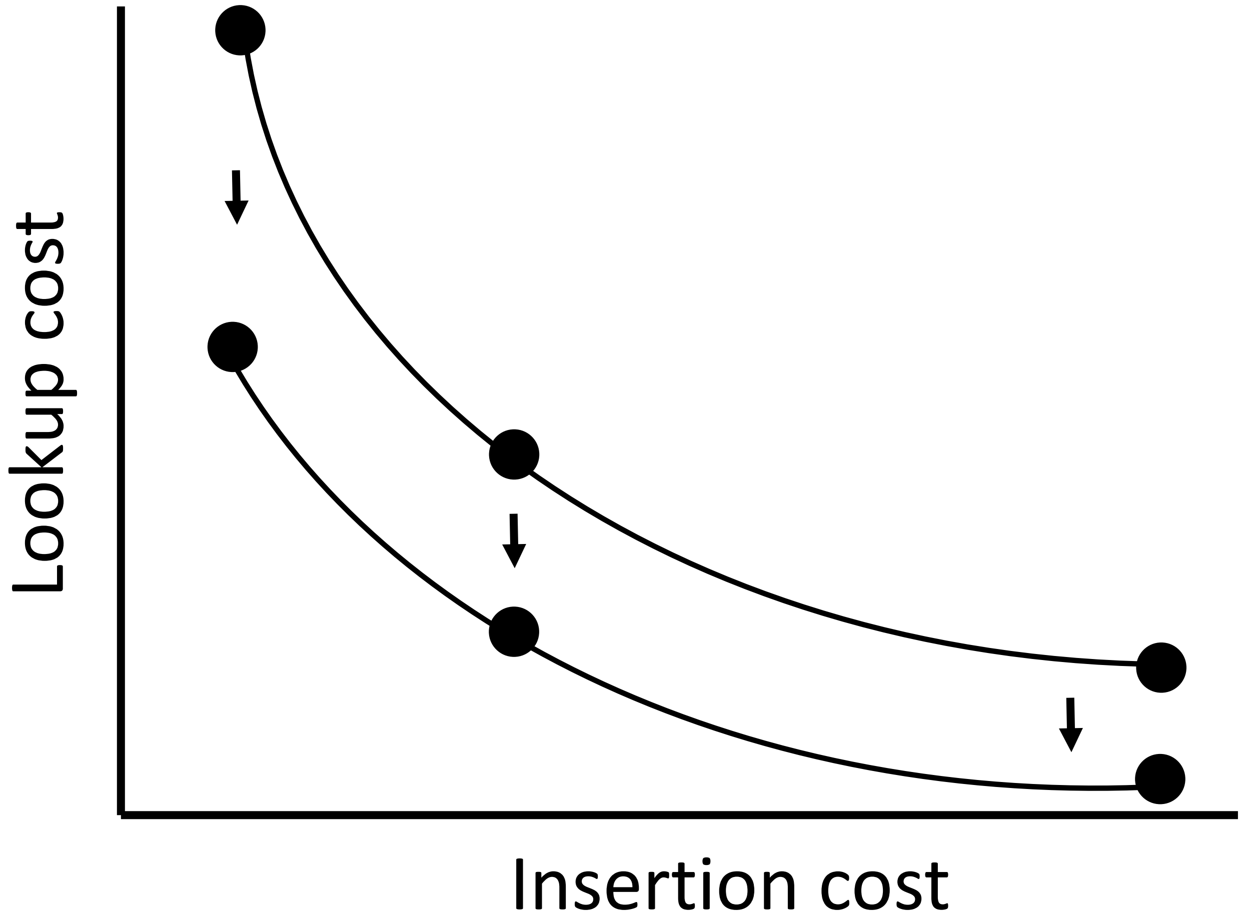

Bloom Filters

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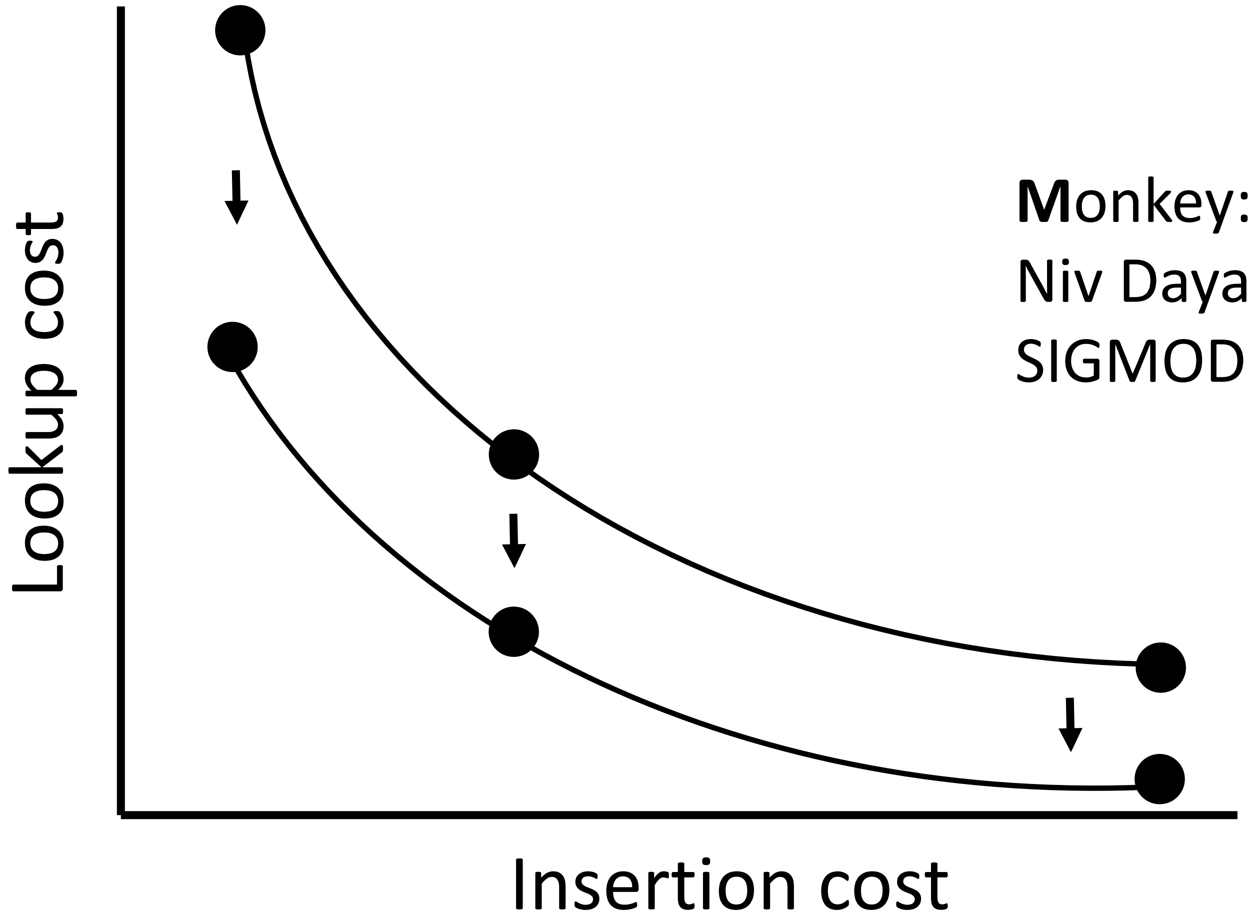

Monkey: **O**ptimal **N**avigable **Key**-Value Store
Niv Dayan, Manos Athanassoulis, Stratos Idreos
SIGMOD 2017

Conclusions

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Backbone of many modern systems

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

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Thank you!