CS460: Intro to Database Systems

Class 14: **Log-Structured-Merge Trees**

Instructor: Manos Athanassoulis

https://midas.bu.edu/classes/CS460/

based on slides from Niv Dayan

Useful when?

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

$\Rightarrow$ LSM-trees are for you.

Why now?

levelDB

DynamoDB

amazon web services

riak

RocksDB

cassandra

HBASE

accumulo

Patrick O'Neil
UMass Boston

Invented in 1996

1980 1990 2000 2010

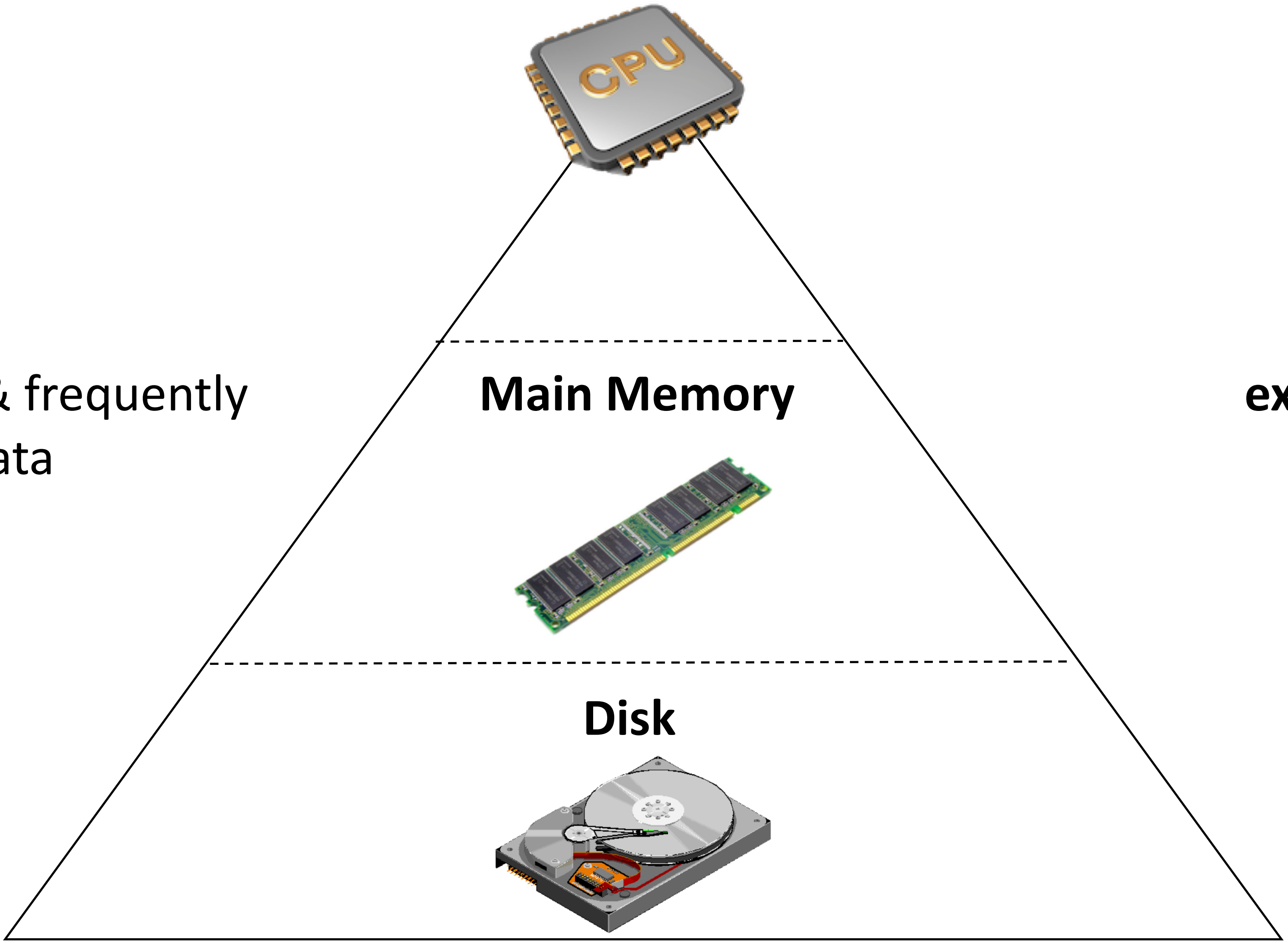
Time

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

The Memory Hierarchy

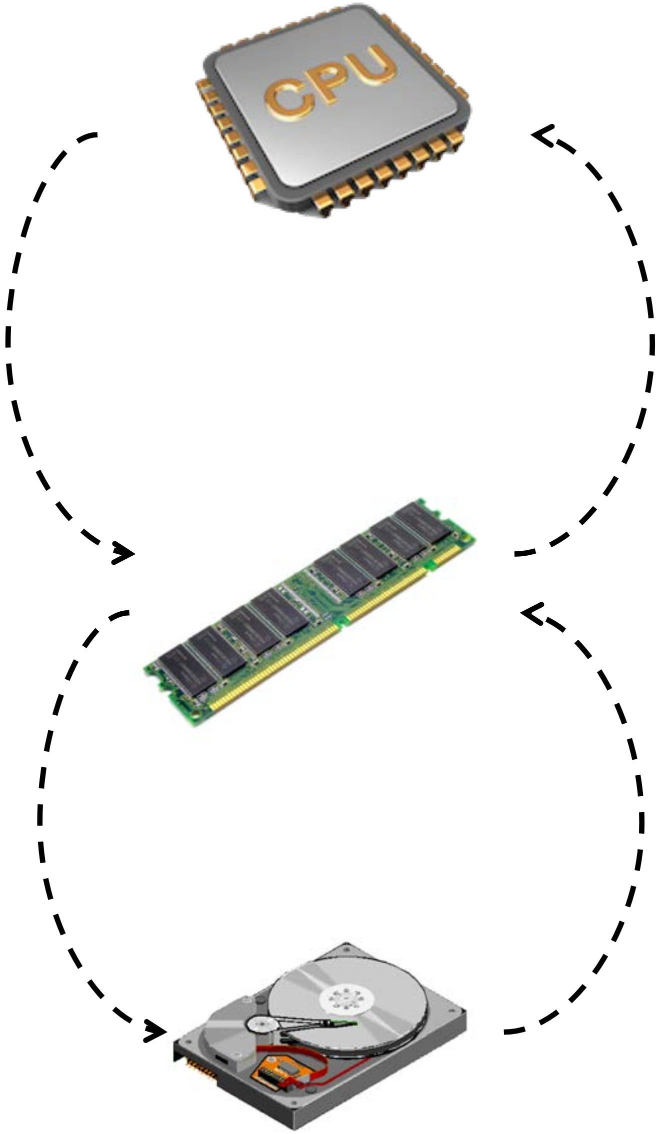


Metadata & frequently accessed data

expensive, fast

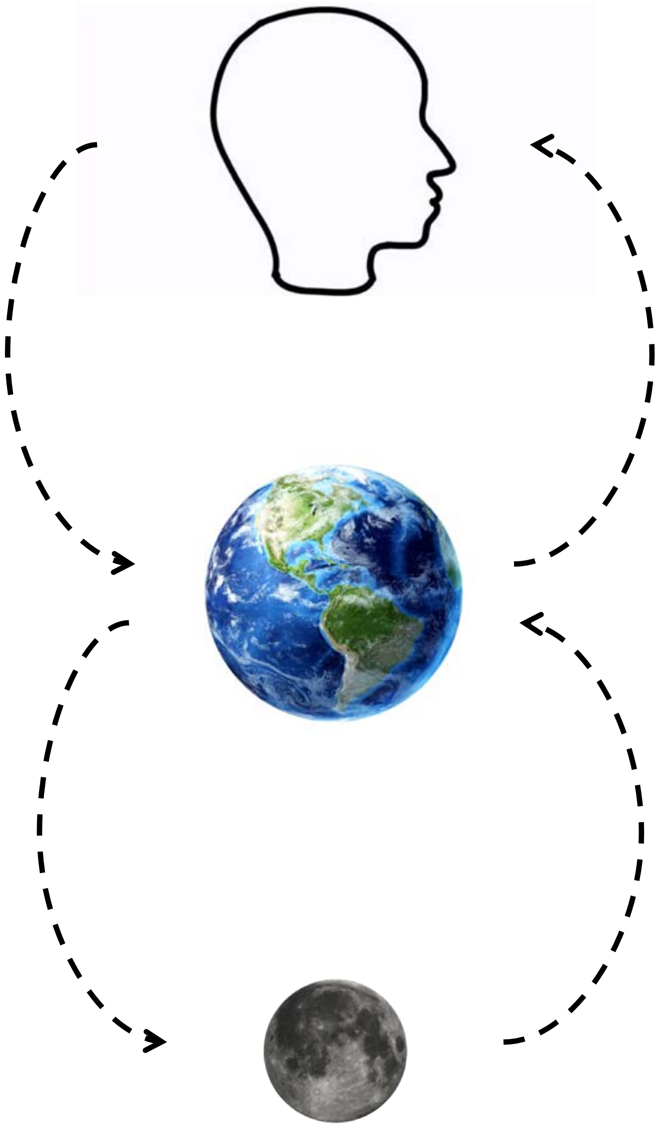
All data

cheap, slow



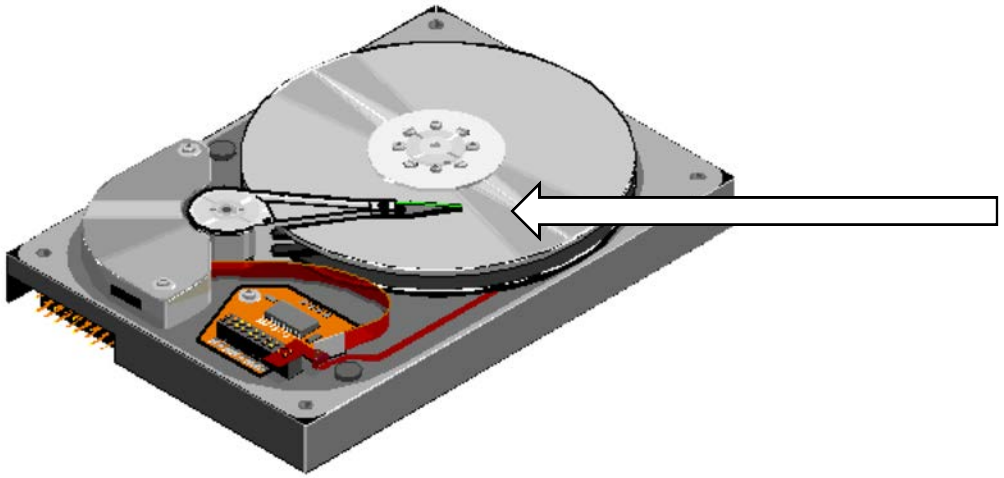
≈100 ns

≈10 ms



≈5-6 order of magnitude difference

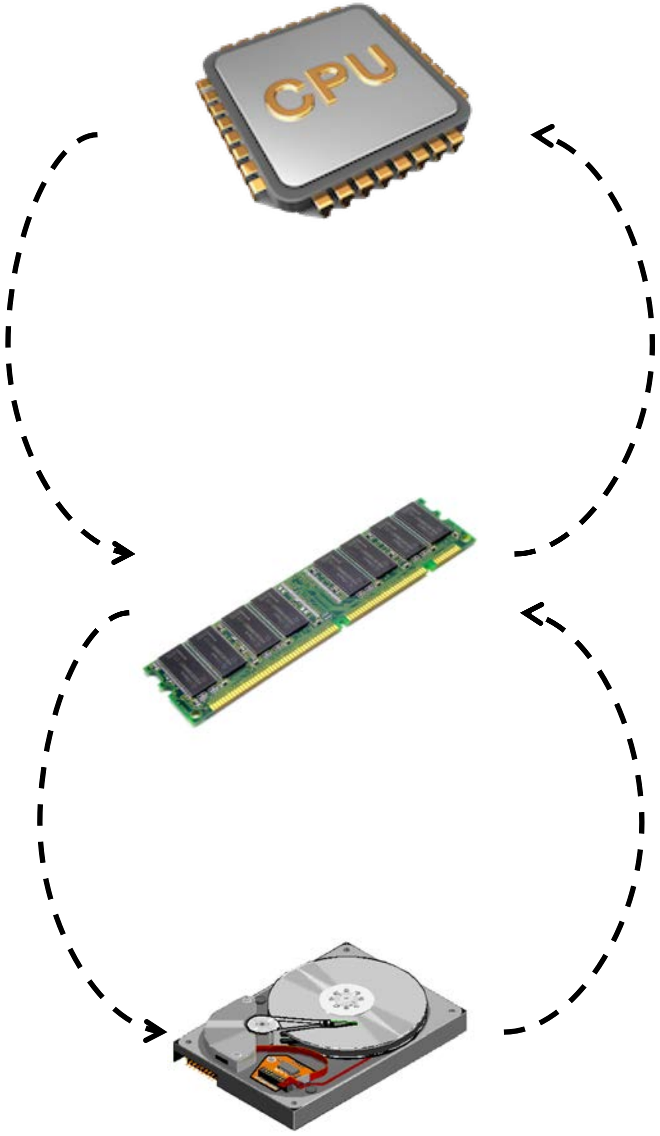
Why is disk slow?



Disk head

Random access is slow $\Rightarrow$ move disk head

Sequential access is faster $\Rightarrow$ let disk spin

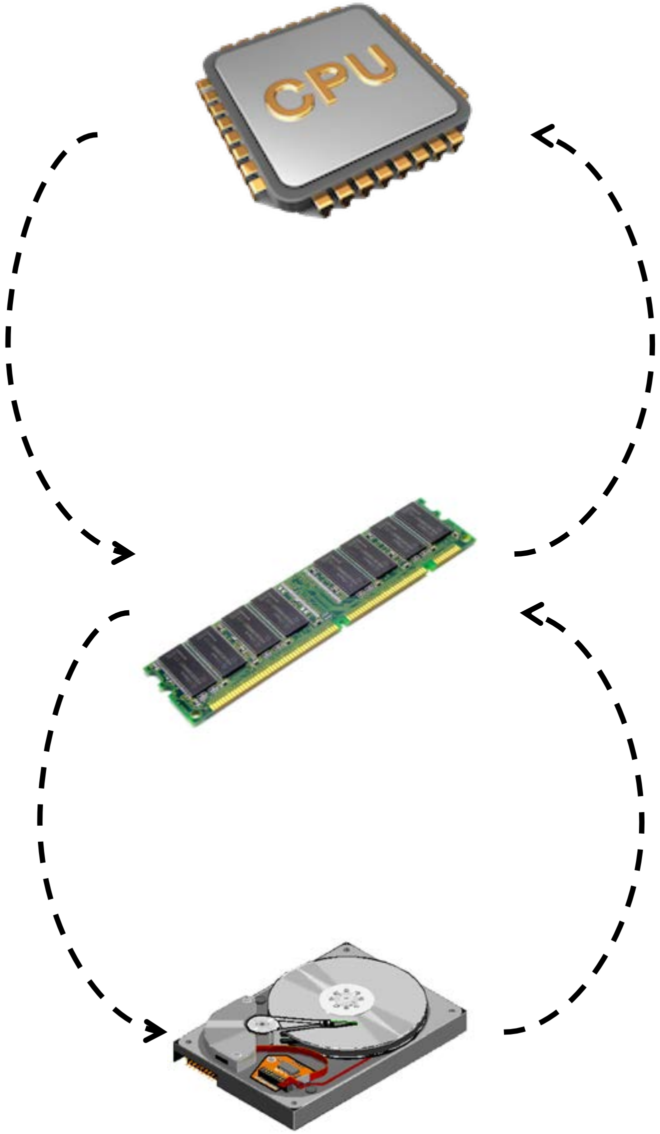


64 byte chunks
Words

Fine access granularity

4 kilobyte chunks
Blocks

Coarse access granularity



64 byte chunks
Words

Fine access granularity

4 kilobyte chunks
Blocks

Coarse access granularity

Outline

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

Outline

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

Indexing Problem & Basic Solutions

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		

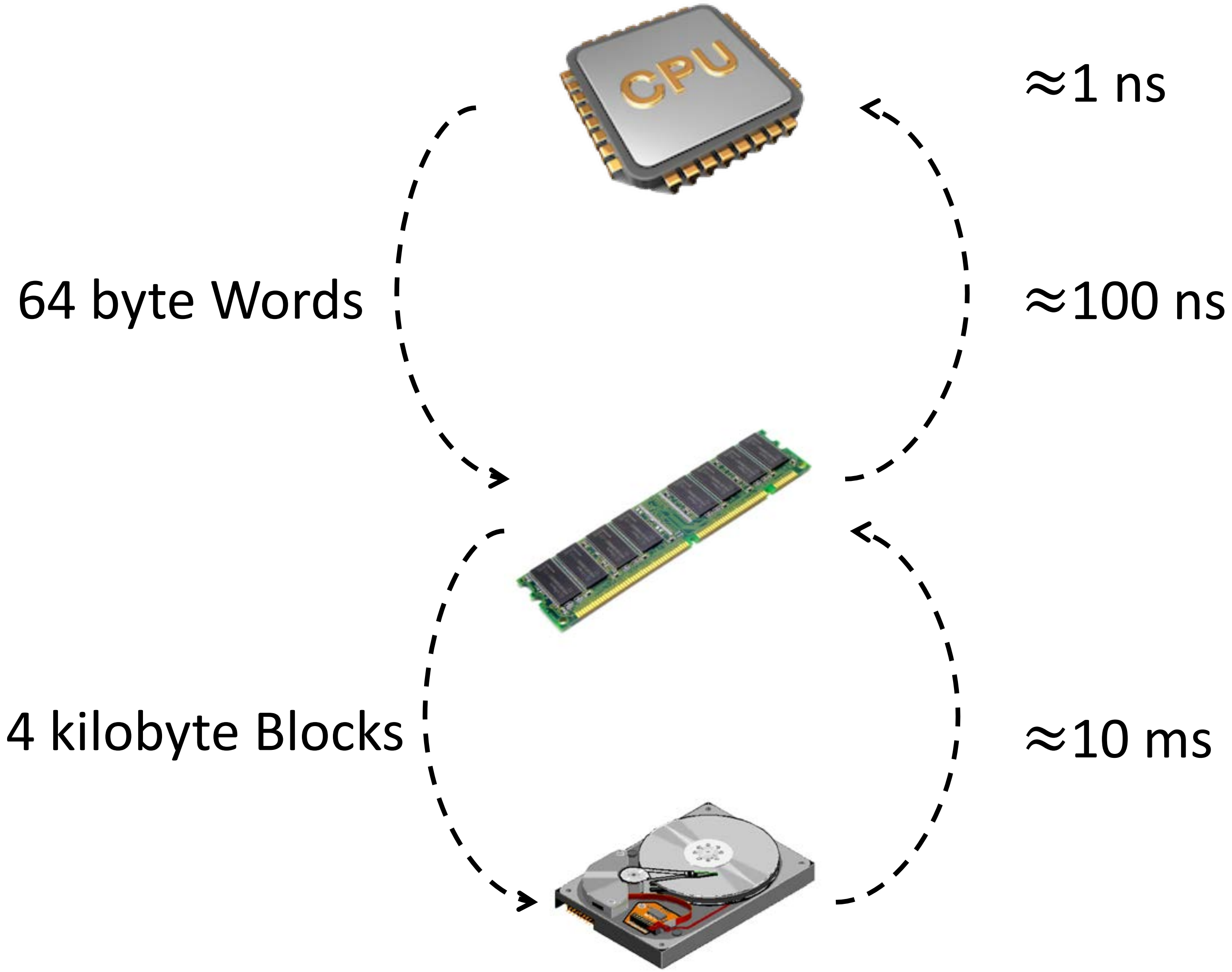
Results Catalogue

Compare and contrast data structures.

What to use when?

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

Modeling Performance



Measure bottleneck:

Number of block reads/writes (I/O)

Sorted Array

N entries

B entries fit into a disk block

Array spans **N/B** disk blocks

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

Buffer
James
Sara

Array size	Pointer

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

Results Catalogue

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

Results Catalogue

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

Log (append-only array)

N entries

B entries fit into a disk block

Array spans **N/B** disk blocks

Lookup method & cost?

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

Insertion cost?

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

Buffer
James
Sara

Array size	Pointer

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

Results Catalogue

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

Results Catalogue

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

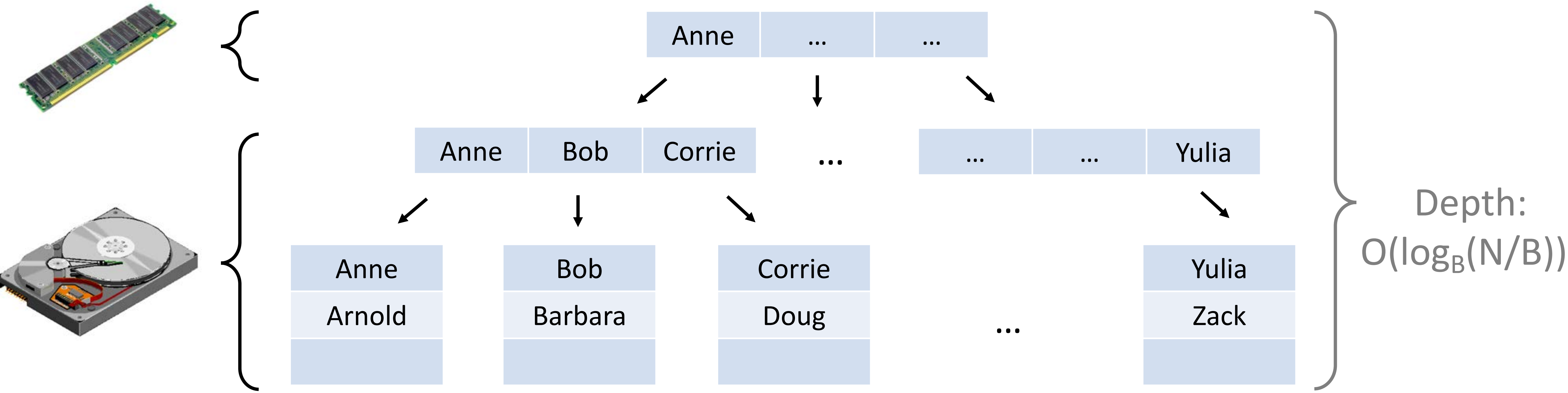
B-tree

Lookup method & cost?

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

Insertion method & cost?

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



Results Catalogue

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

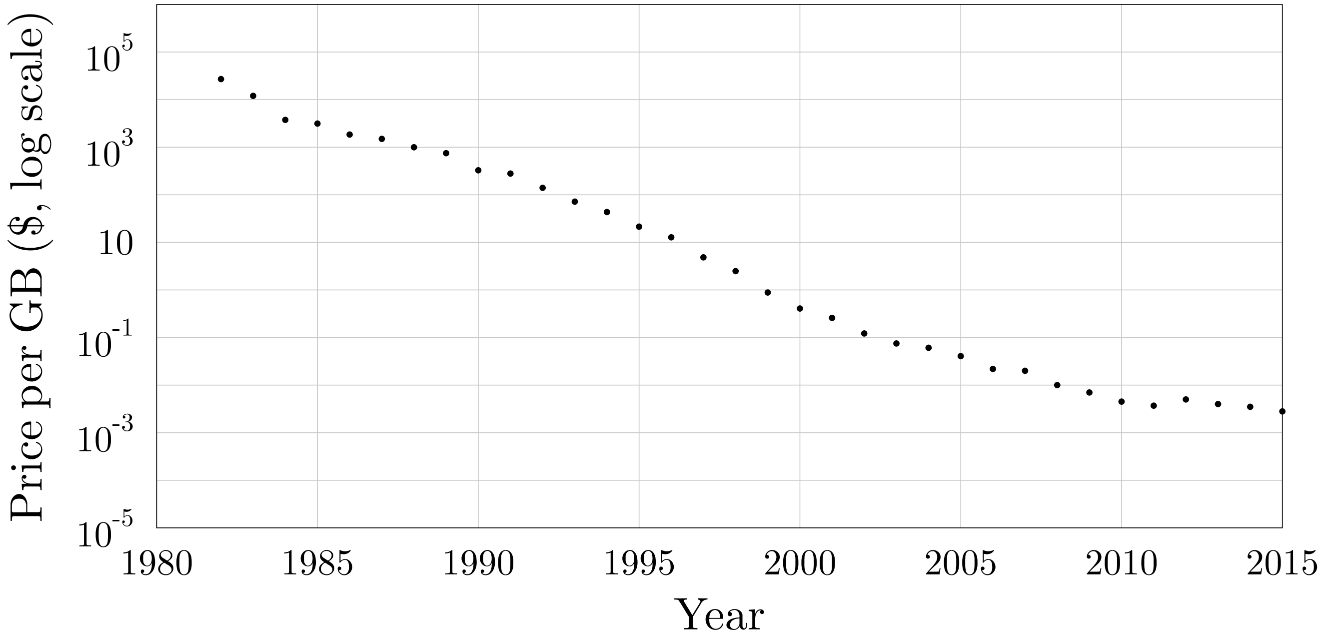
Goetz Graefe Microsoft, HP Fellow, now
Google ACM Software System Award

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

Basic LSM-trees

Basic LSM-tree

Level

Buffer

0

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

Inserts

Level

Buffer — 0

... ...

Sorted arrays — 1, 2, 3

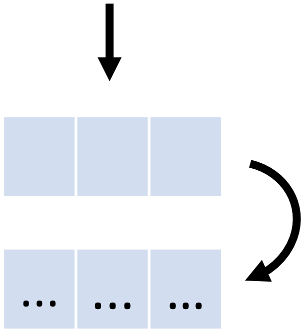
Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Inserts

Level

Buffer 0



sort & flush buffer

Sorted arrays 1 2 3

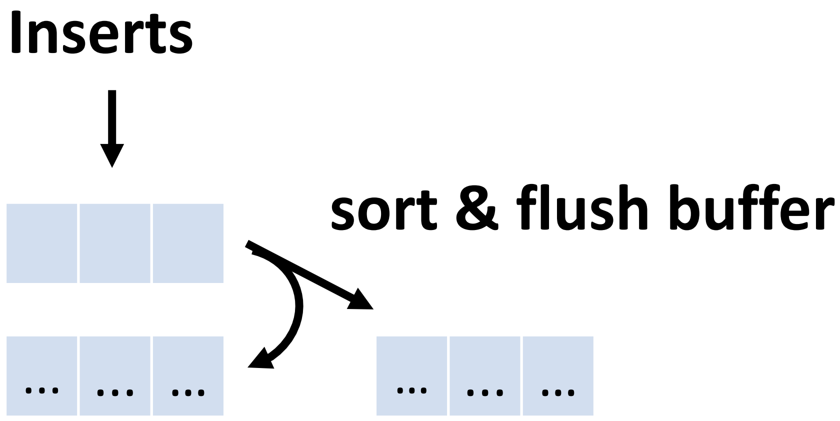
Basic LSM-tree

Design principle #1: optimize for insertions by buffering

Level

Buffer 0

Sorted arrays 1 2 3



Basic LSM-tree

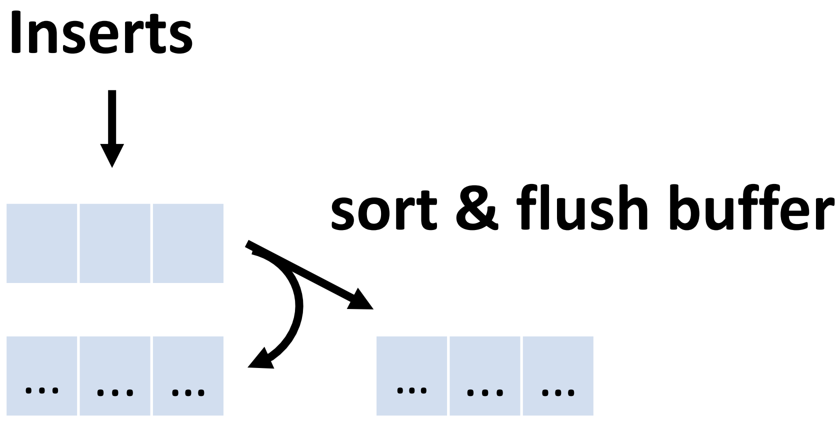
Design principle #1: optimize for insertions by buffering

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

Level

Buffer — 0

Sorted arrays — 1, 2, 3



Basic LSM-tree

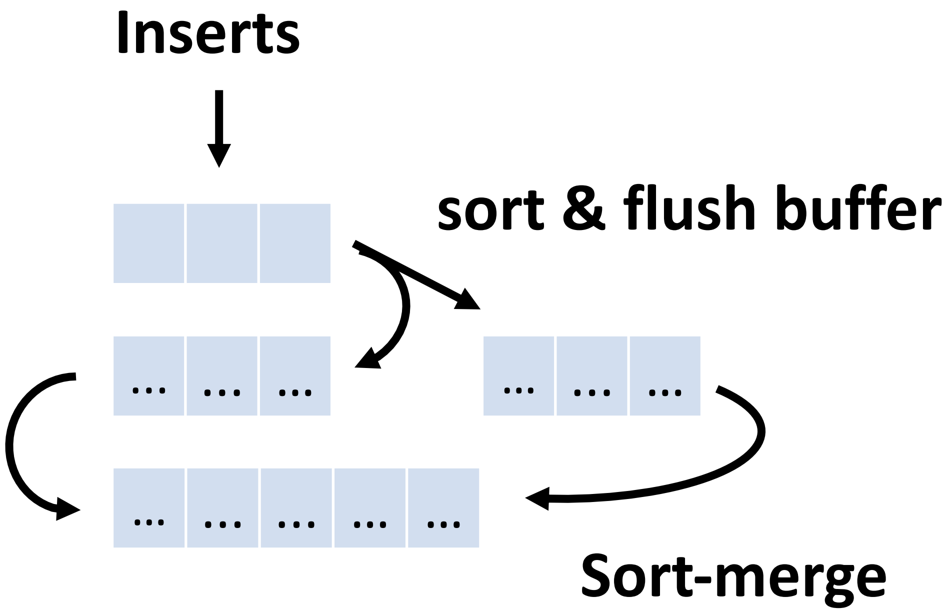
Design principle #1: optimize for insertions by buffering

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

Level

Buffer — 0

Sorted arrays — 1, 2, 3



Basic LSM-tree

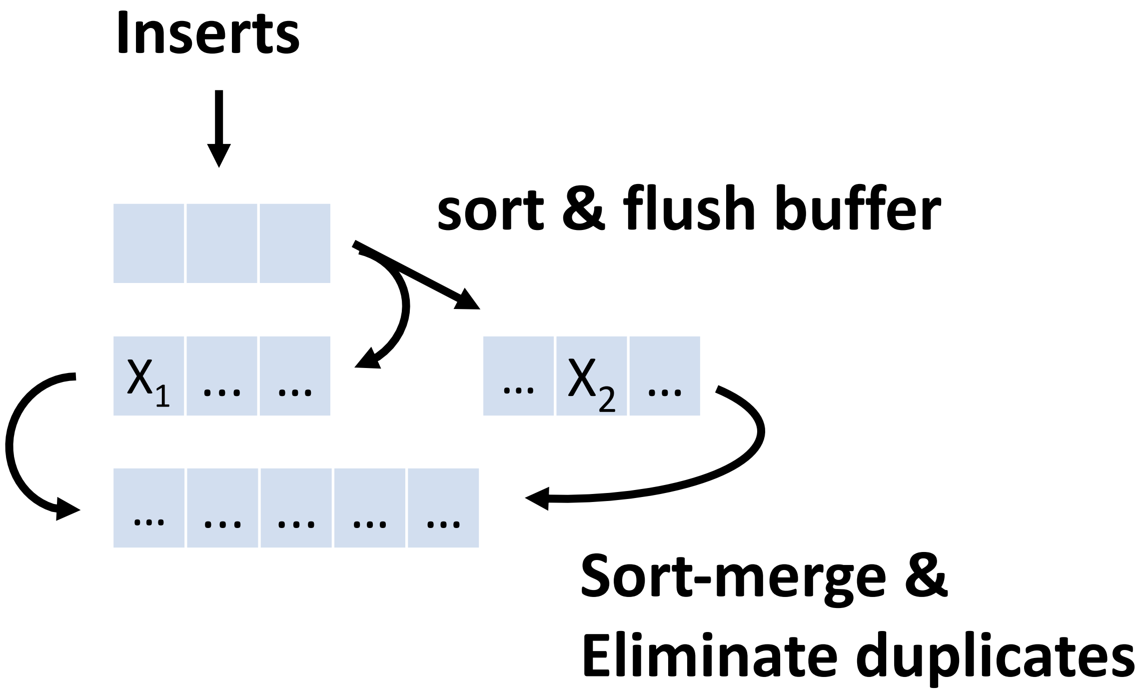
Design principle #1: optimize for insertions by buffering

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

Level

Buffer { 0

Sorted arrays { 1, 2, 3



Basic LSM-tree

Design principle #1: optimize for insertions by buffering

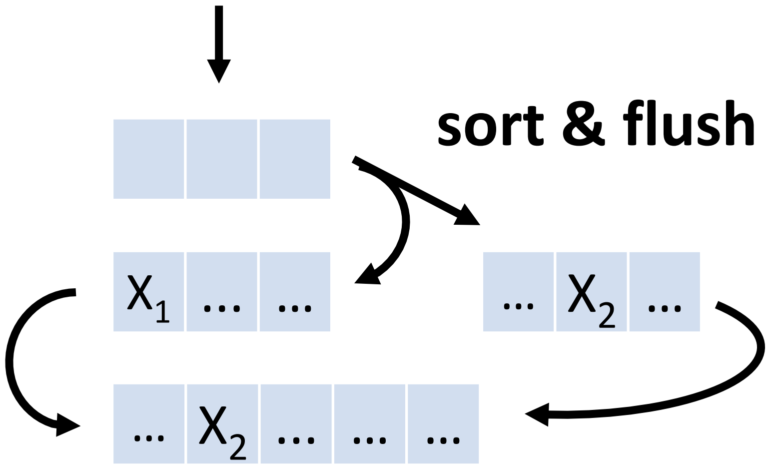
Design principle #2: optimize for lookups by sort-merging arrays

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

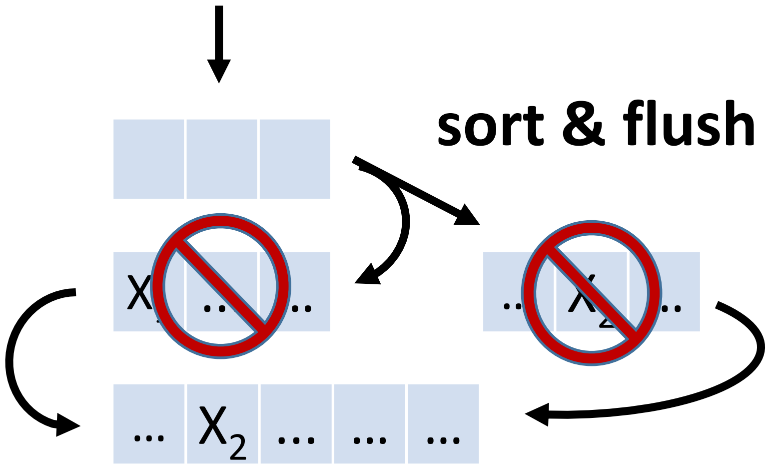
Design principle #2: optimize for lookups by sort-merging arrays

Inserts

Level

Buffer { 0

Sorted arrays { 1, 2, 3



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

Basic LSM-tree – Example

inserts

Level

Buffer

0

sort & flush buffer

1

4	6	9

Sorted arrays

2

3

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

inserts

Level

Buffer

0

sort & flush buffer

1

4 6 9

3 4 8

Sorted arrays

2

3

Basic LSM-tree – Example

inserts

Level

Buffer

0

1

4	6	9

3	4	8

Sorted arrays

2

3

Basic LSM-tree – Example

inserts

Level

Buffer

0

1

4 6 9

3 4 8

2

3 4 6 8 9

Sort-merge

Sorted arrays

3

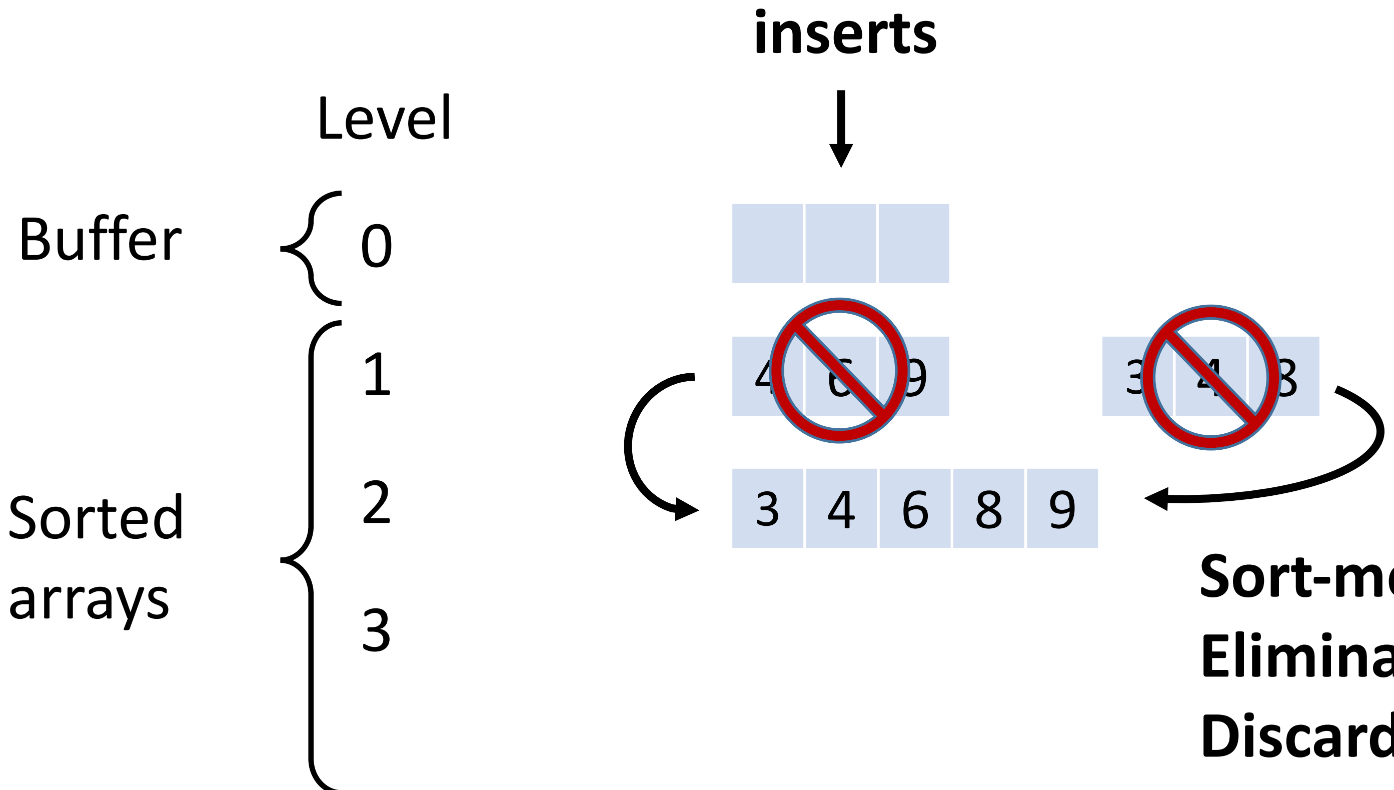
Basic LSM-tree – Example

inserts

Level		
Buffer	0	
Sorted arrays	1	$\mathbf{4_1}$ 6 9 3 $\mathbf{4_2}$ 8
	2	3 $\mathbf{4_2}$ 6 8 9
	3	

Sort-merge & Eliminate duplicates

Basic LSM-tree – Example



Sort-merge &
Eliminate duplicates &
Discard original arrays

Basic LSM-tree – Example

inserts

Level

Buffer — 0

1

Sorted arrays — 2 — | 3 | 4 | 6 | 8 | 9 |

3

Basic LSM-tree – Example

inserts

Level

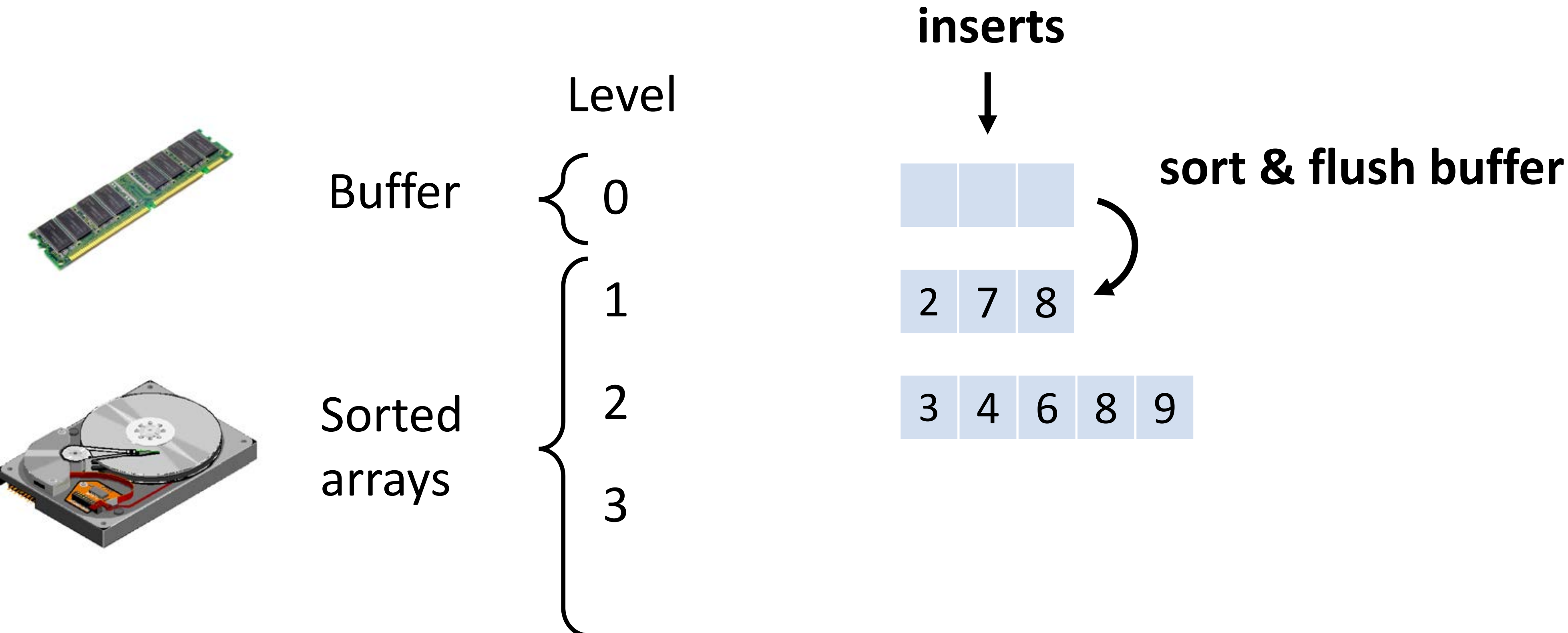
Buffer — 0: | 2 | 7 | 8 |

Sorted arrays — 1:

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

3:

Basic LSM-tree – Example



Basic LSM-tree – Example

inserts

Level

Buffer

Level	
0	
1	2 7 8
2	3 4 6 8 9
3	

Sorted arrays

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

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

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		

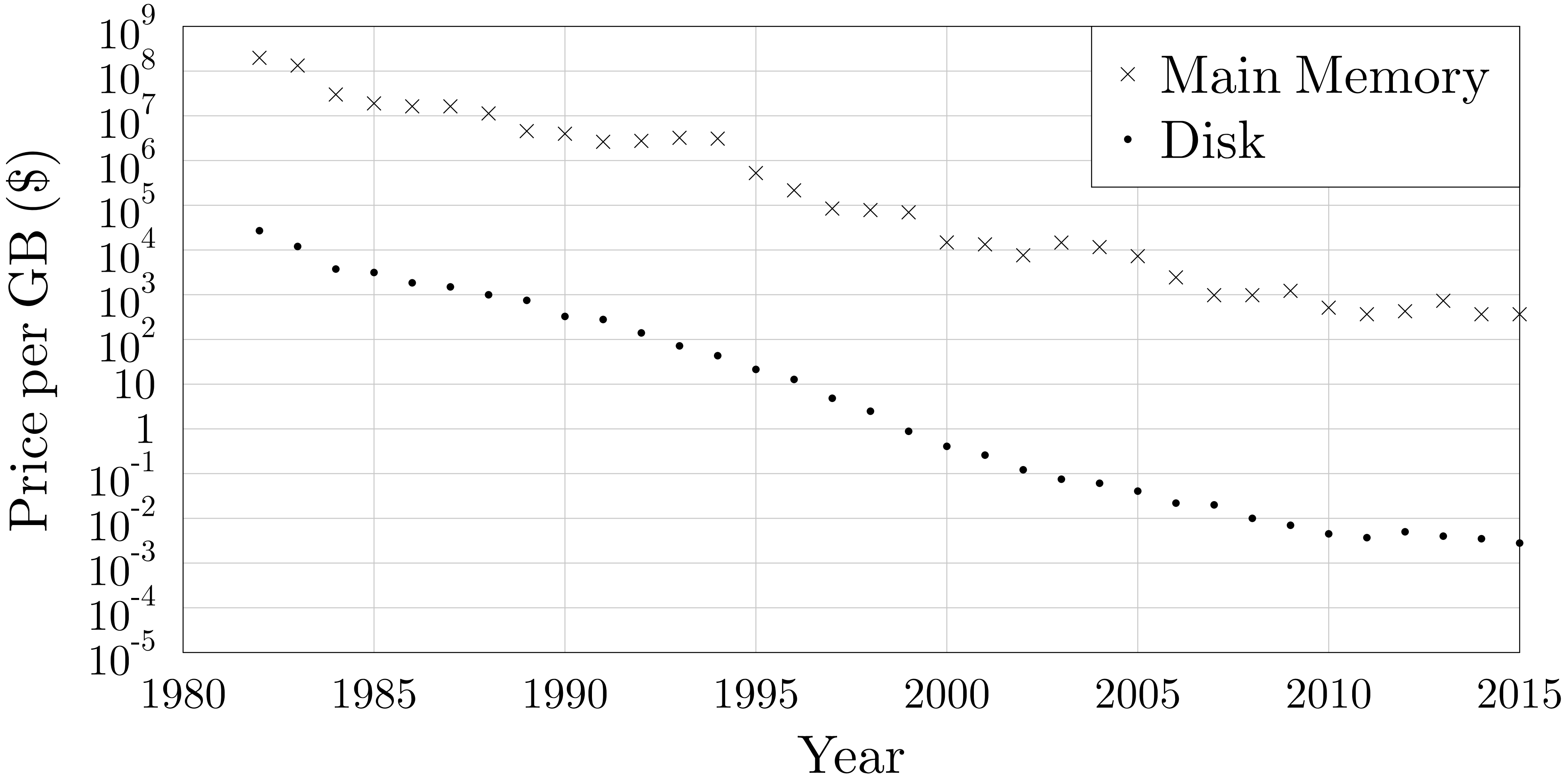
Results Catalogue

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

1	10	15	…

array

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

How to reduce it?

Increase size ratio T

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

Leveled LSM-tree

Lookup cost depends on number of levels

How to reduce it?

E.g. size ratio of 4

Increase size ratio T

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

	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

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

Level		Capacity
0	… … …	1
1	… … … … … … … … … … … …	4
2		16
3		64

move

Buffer

Sorted arrays

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?

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

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?

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

What happens as we increase the size ratio T?

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

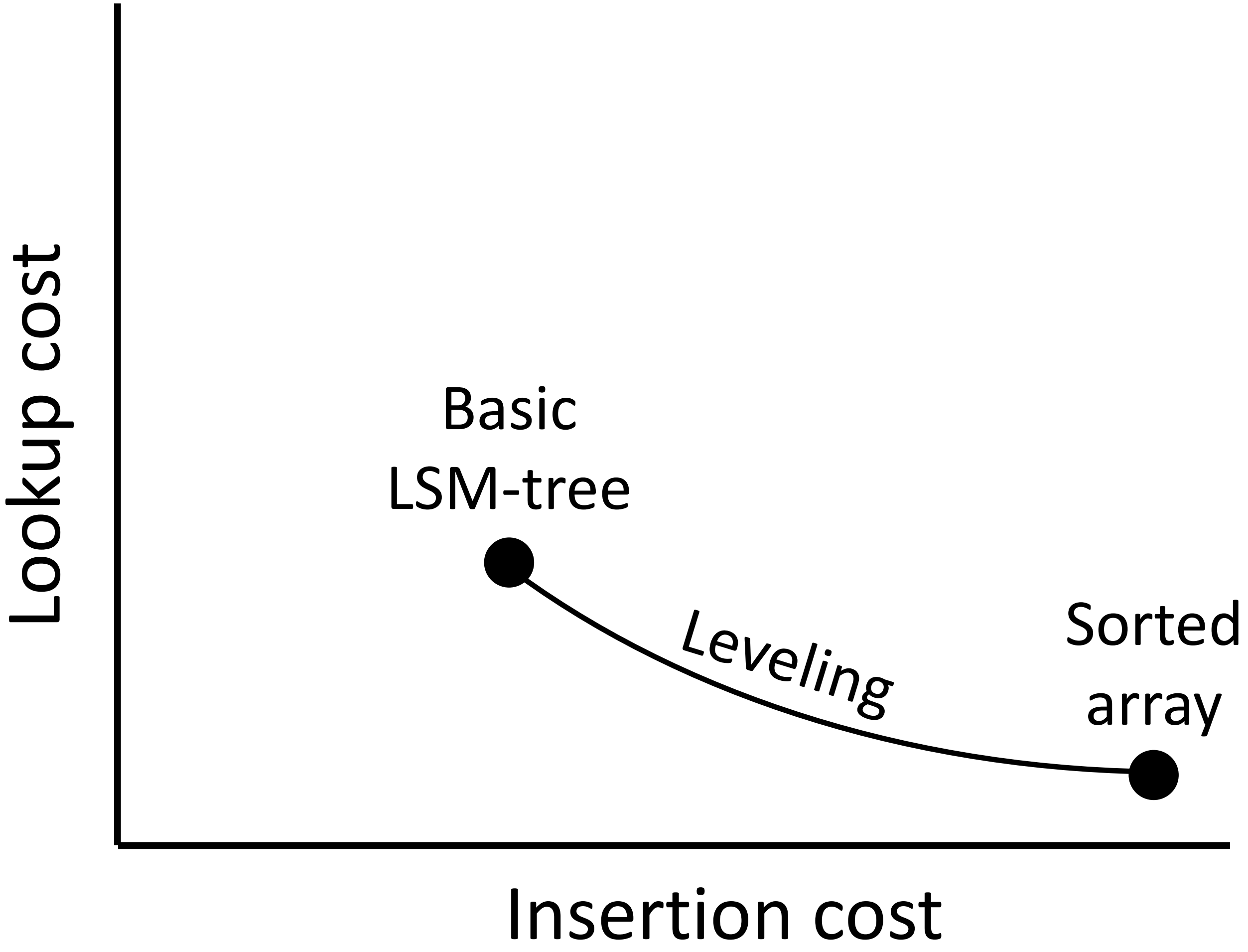
Lookup cost becomes:

$O(1)$

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

⬆ Lookup cost

⬇ Insertion cost

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	... ...	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

	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 … … … **flush** 1

1 … … … … … … … … … … … … 4

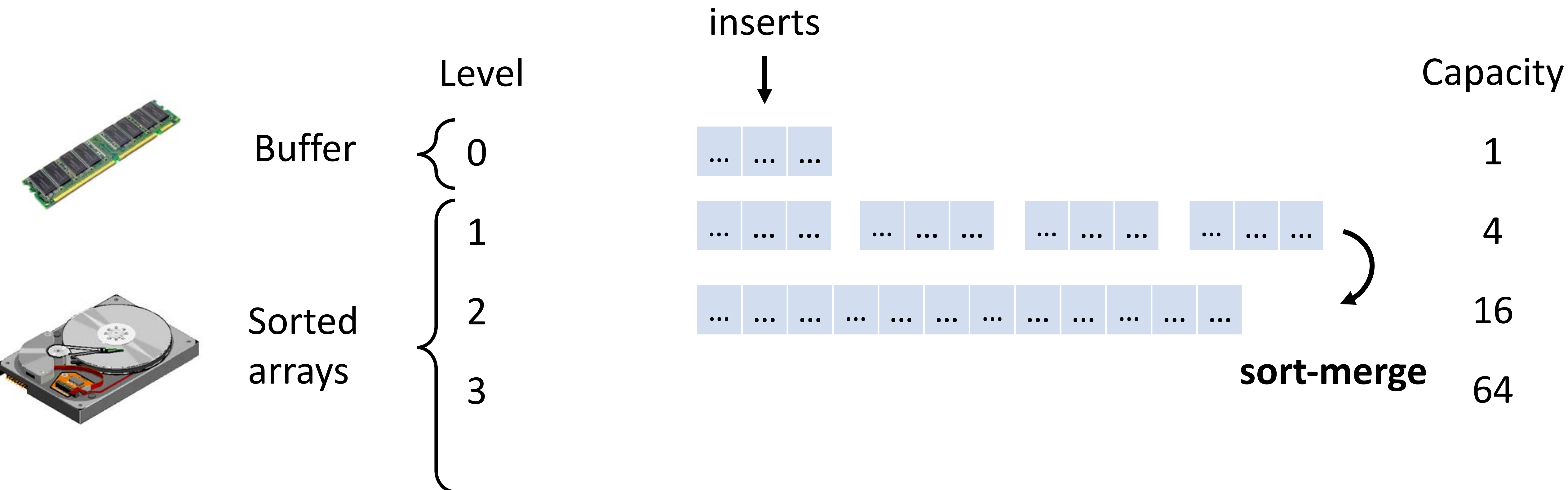
Sorted arrays

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



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

Lookup cost?

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

Insertion cost?

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

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?

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

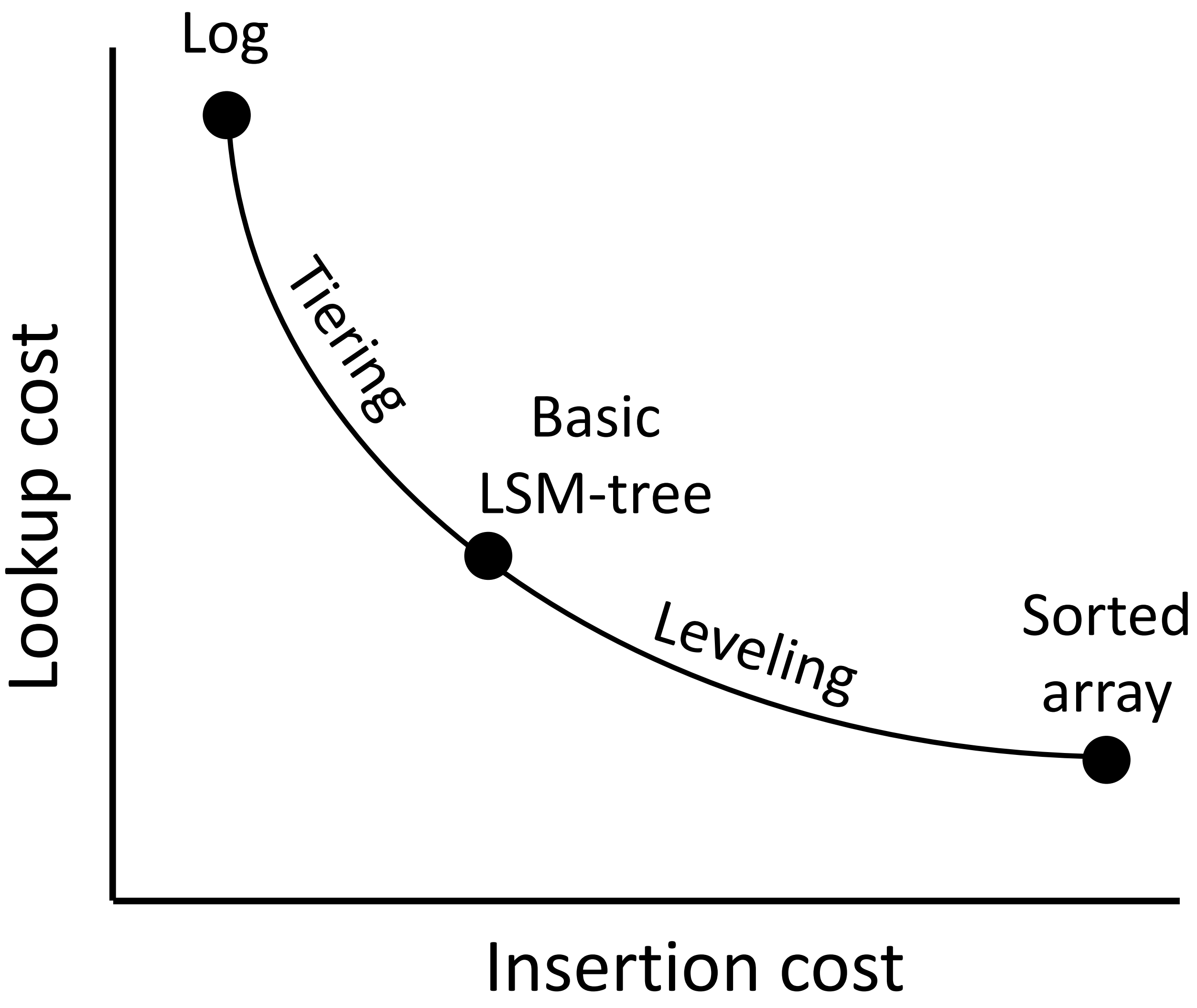
What happens as we increase the size ratio T?

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!

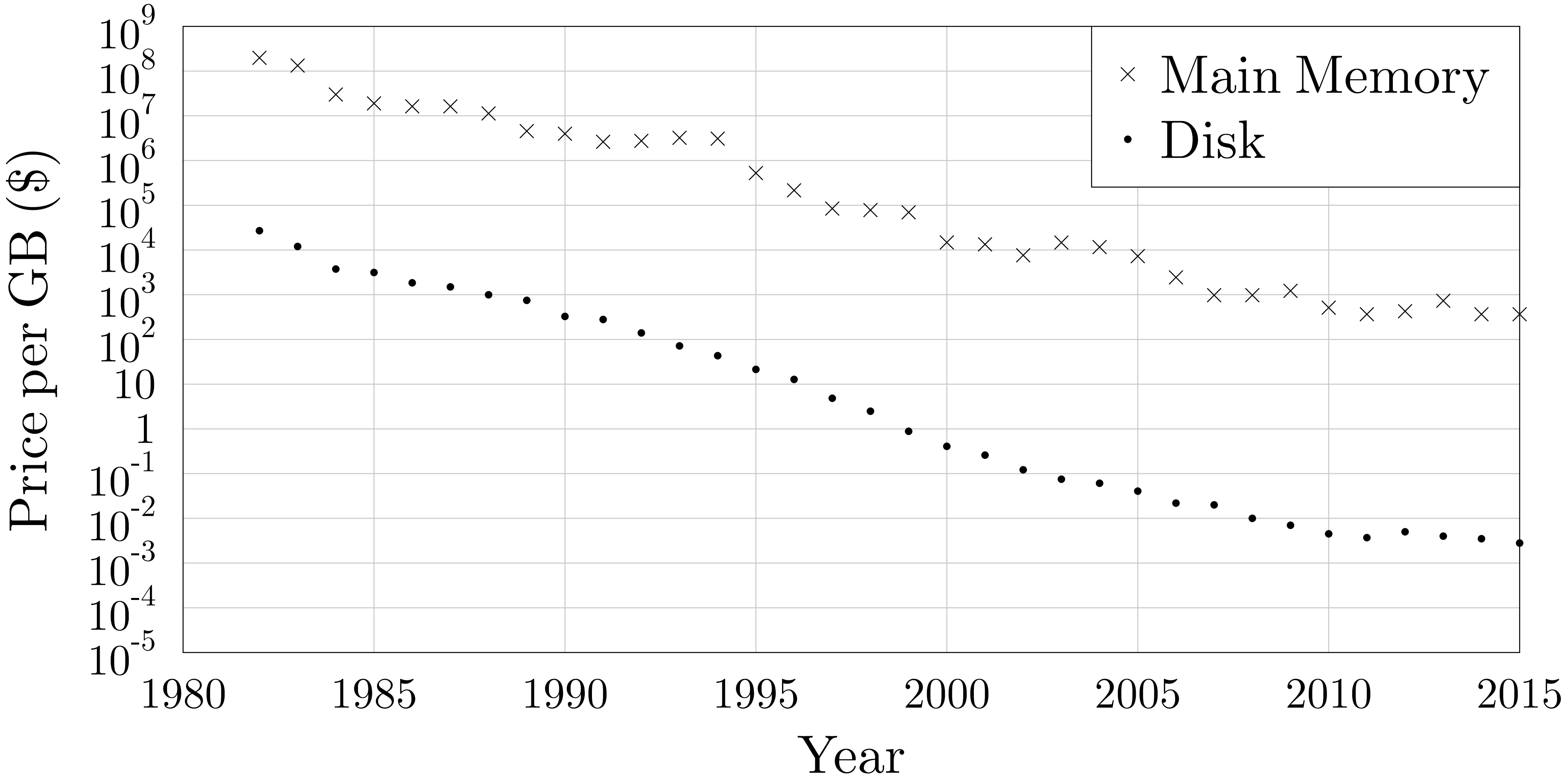

Log
Tiering
Basic
LSM-tree
Leveling
Sorted
array
Lookup cost
Insertion cost

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.

Lookup for X

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.

Lookup for X

filters

Bloom filter

array

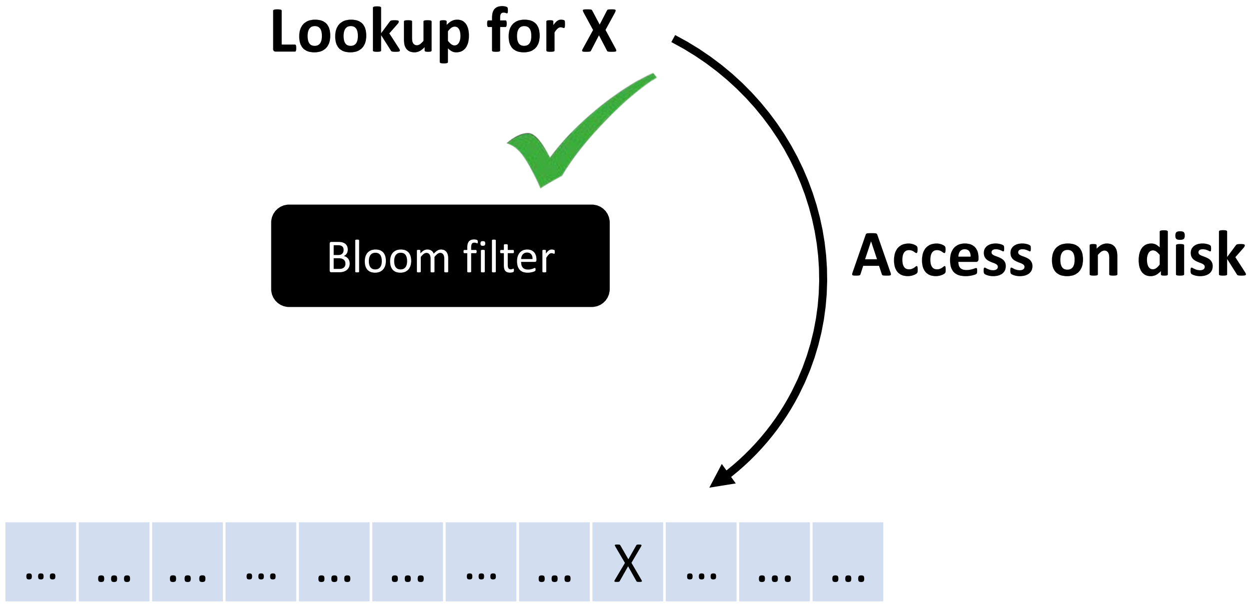
…	…	…	…	…	…	…	…	X	…	…	…

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



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

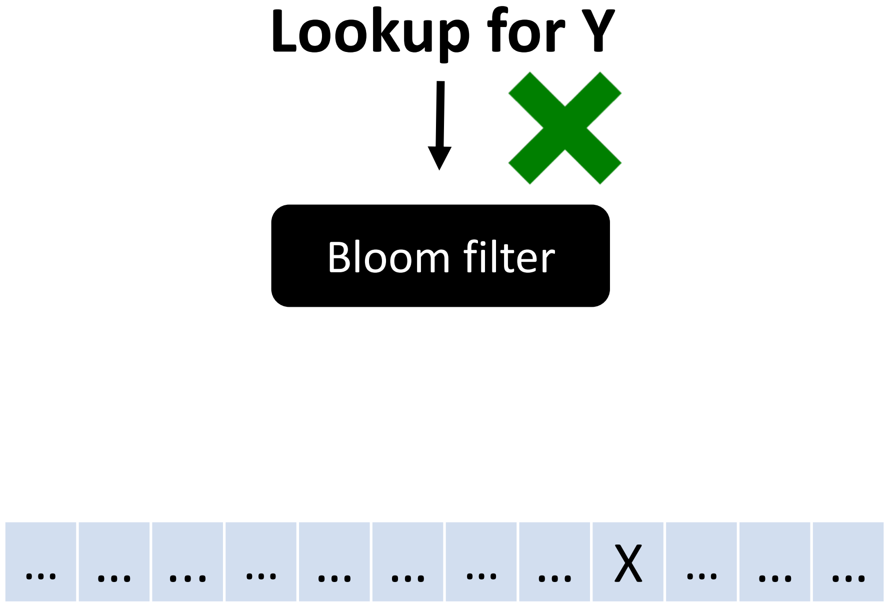
…	…	…	…	…	…	…	…	X	…	…	…

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



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.

Lookup for Z

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.

Lookup for Z

filters

Bloom filter

array

…	…	…	…	…	…	…	…	X	…	…	…

Bloom Filters

Answers set-membership queries

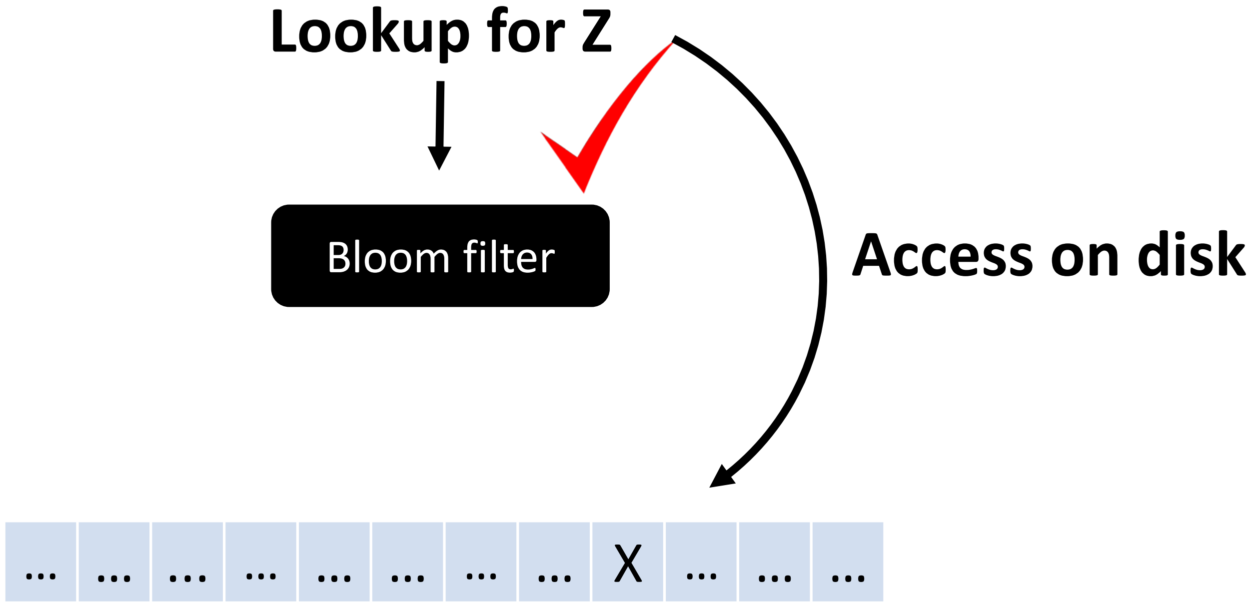
Smaller than array, and stored in main memory

Purpose: avoid accessing disk if entry is not in array

Subtlety: may return false positives.

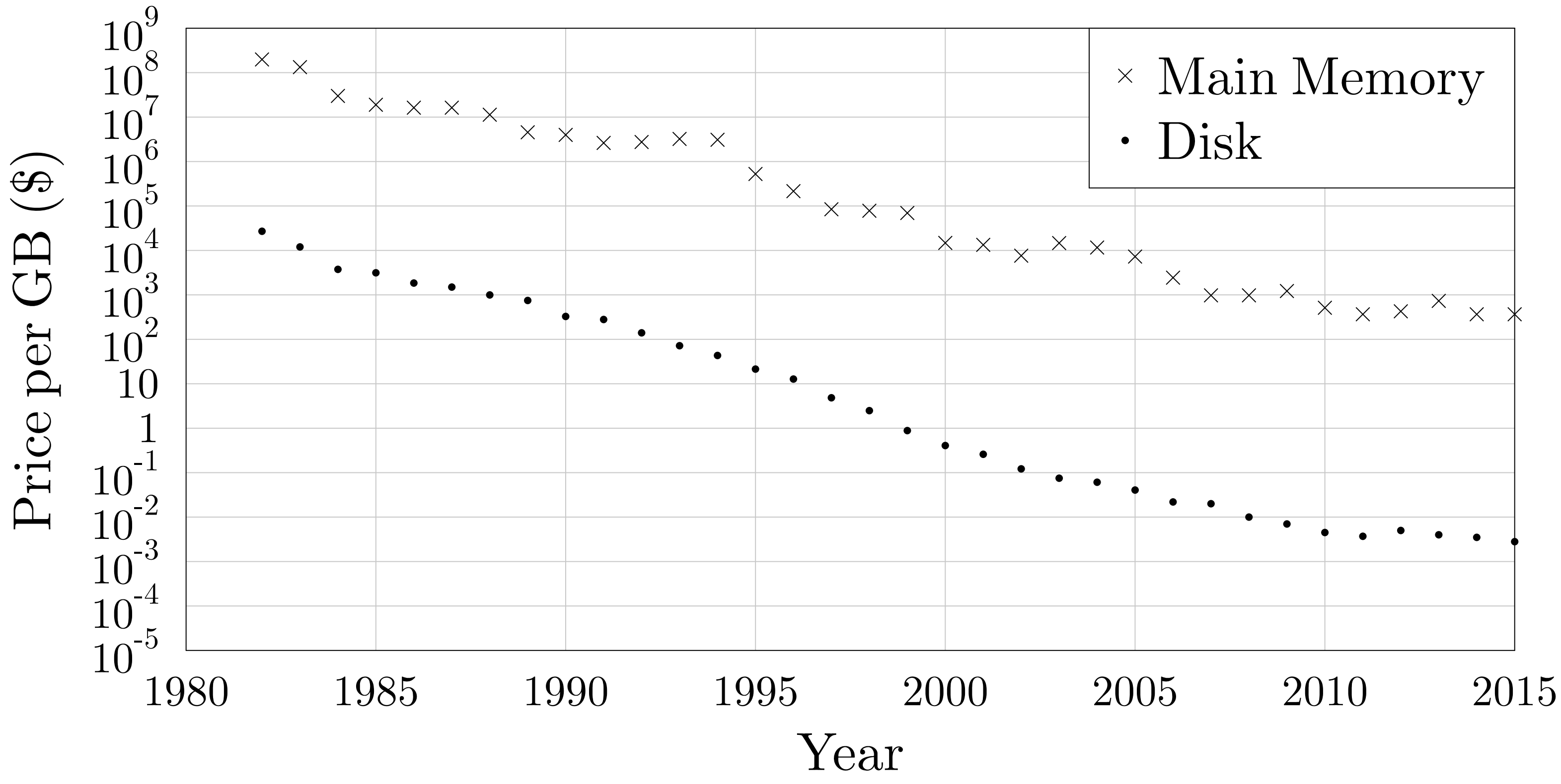
filters

array



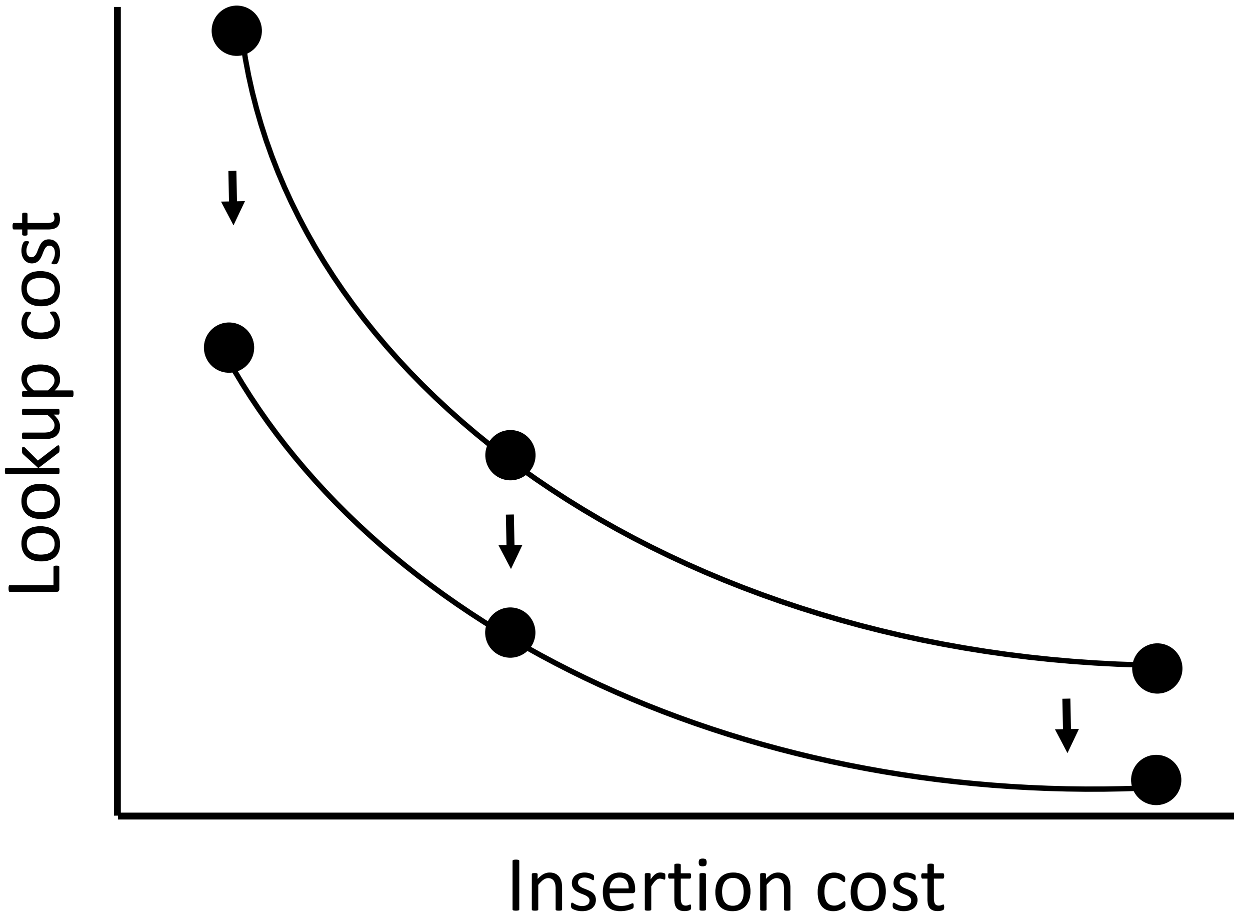
Bloom Filters

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



Bloom Filters

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



Conclusions

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)

Thank you!