CS 561: ***Data Systems Architecture***

Class 7

Compaction in LSM Trees

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BOSTON UNIVERSITY

Slide Courtesy: Dr. Subhadeep Sarkar

https://bu-disc.github.io/CS561/

DiSC lab

Updates: Logistics

Review 2 due on **02/14**

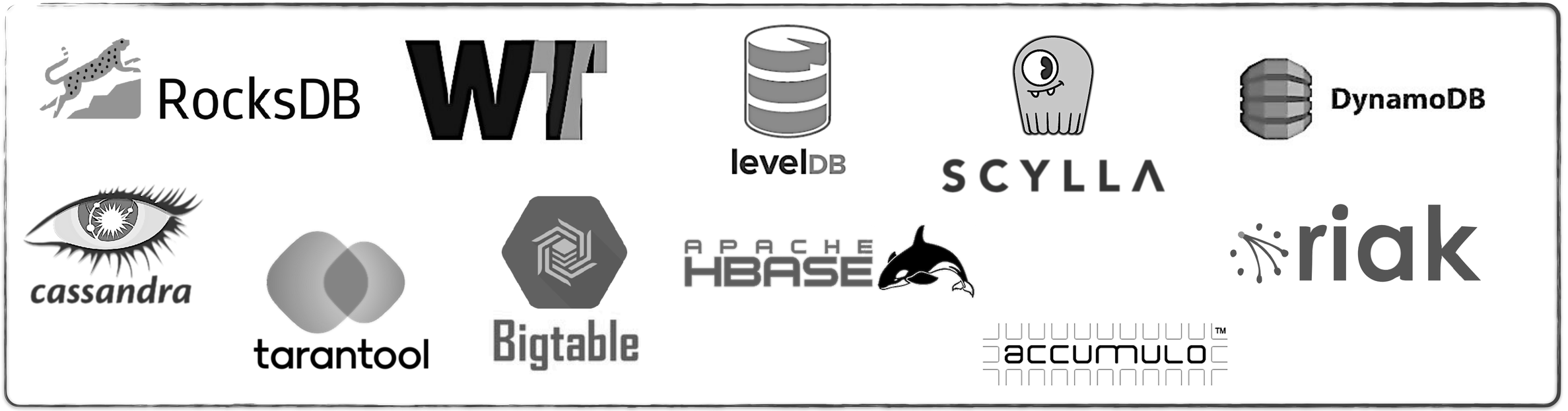
Project 1 due on **02/16**

Class project proposal due on **02/23**

LSM-tree

LSM-tree

NoSQL



relational

time-series

2023

LSM-tree

NoSQL

relational

time-series

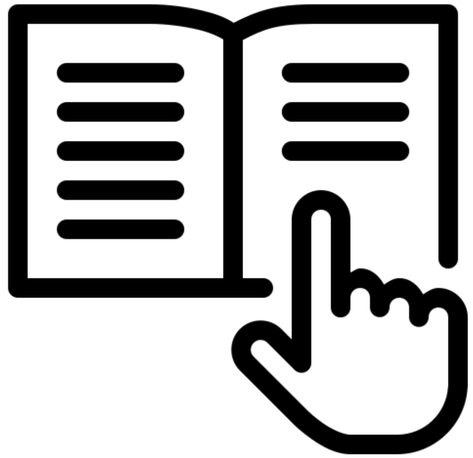
2023

Why **LSM** ?

fast ingestion

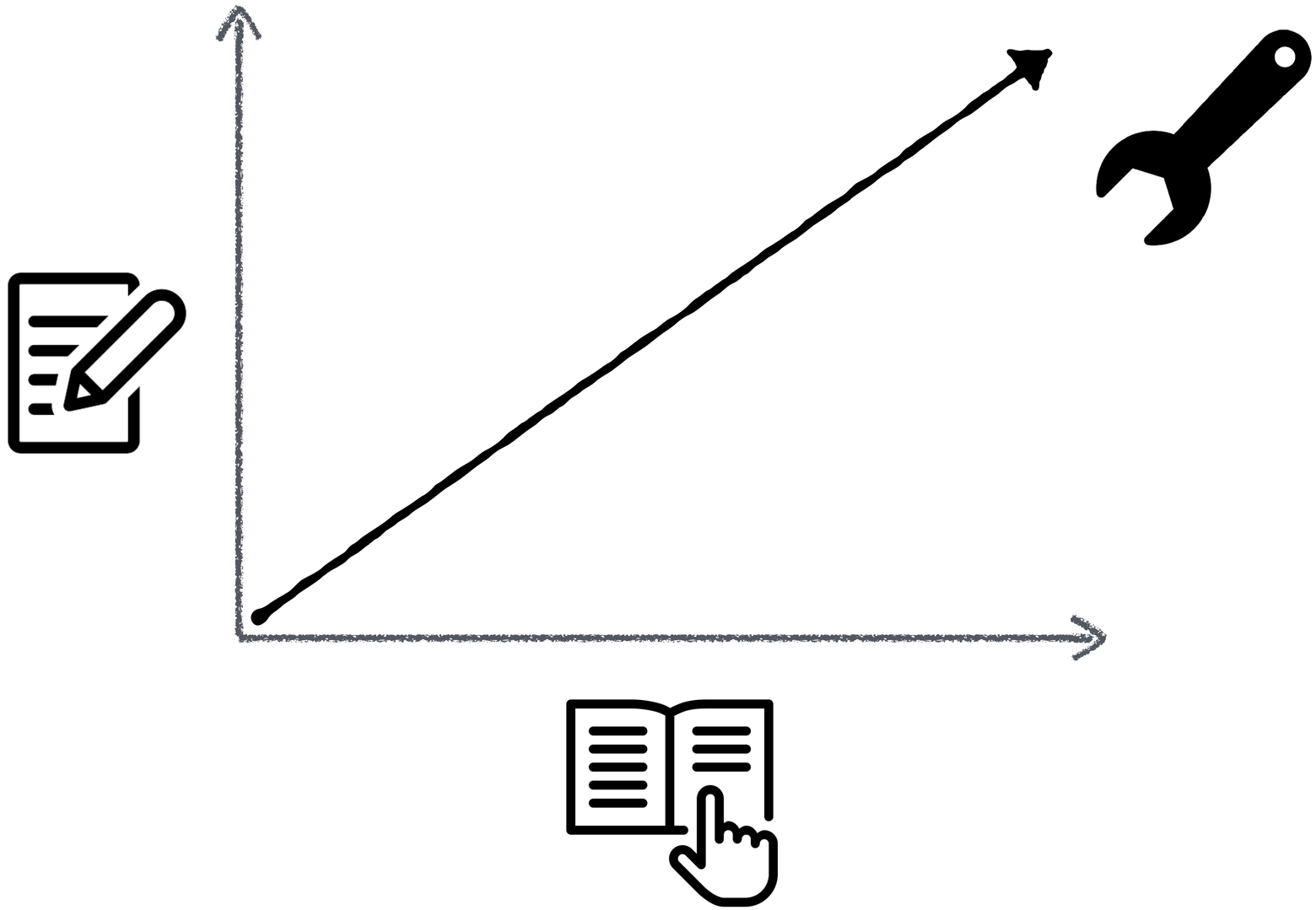
Why **LSM** ?

fast ingestion

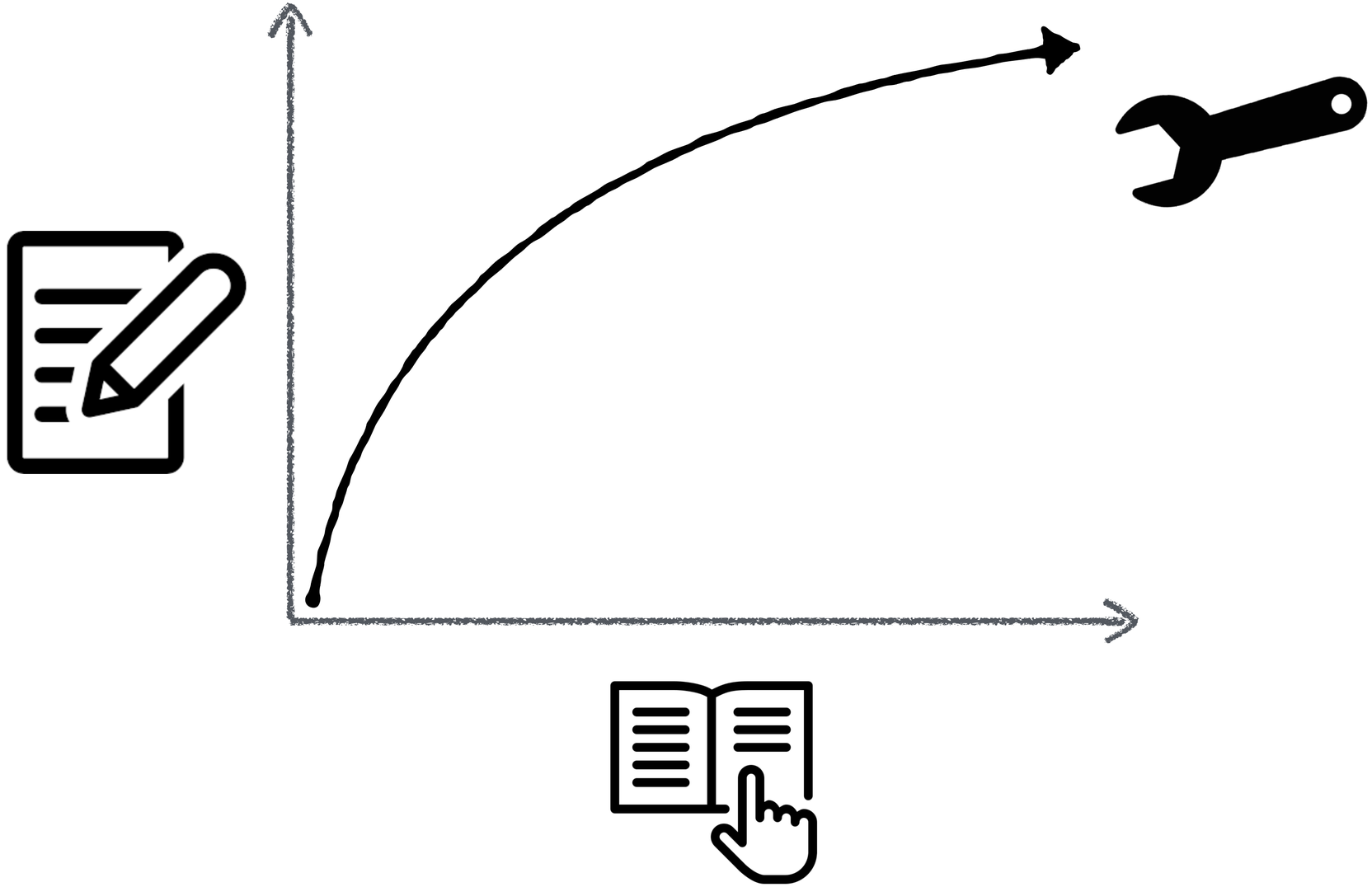


competitive reads

Why **LSM** ?



Why **LSM** ?



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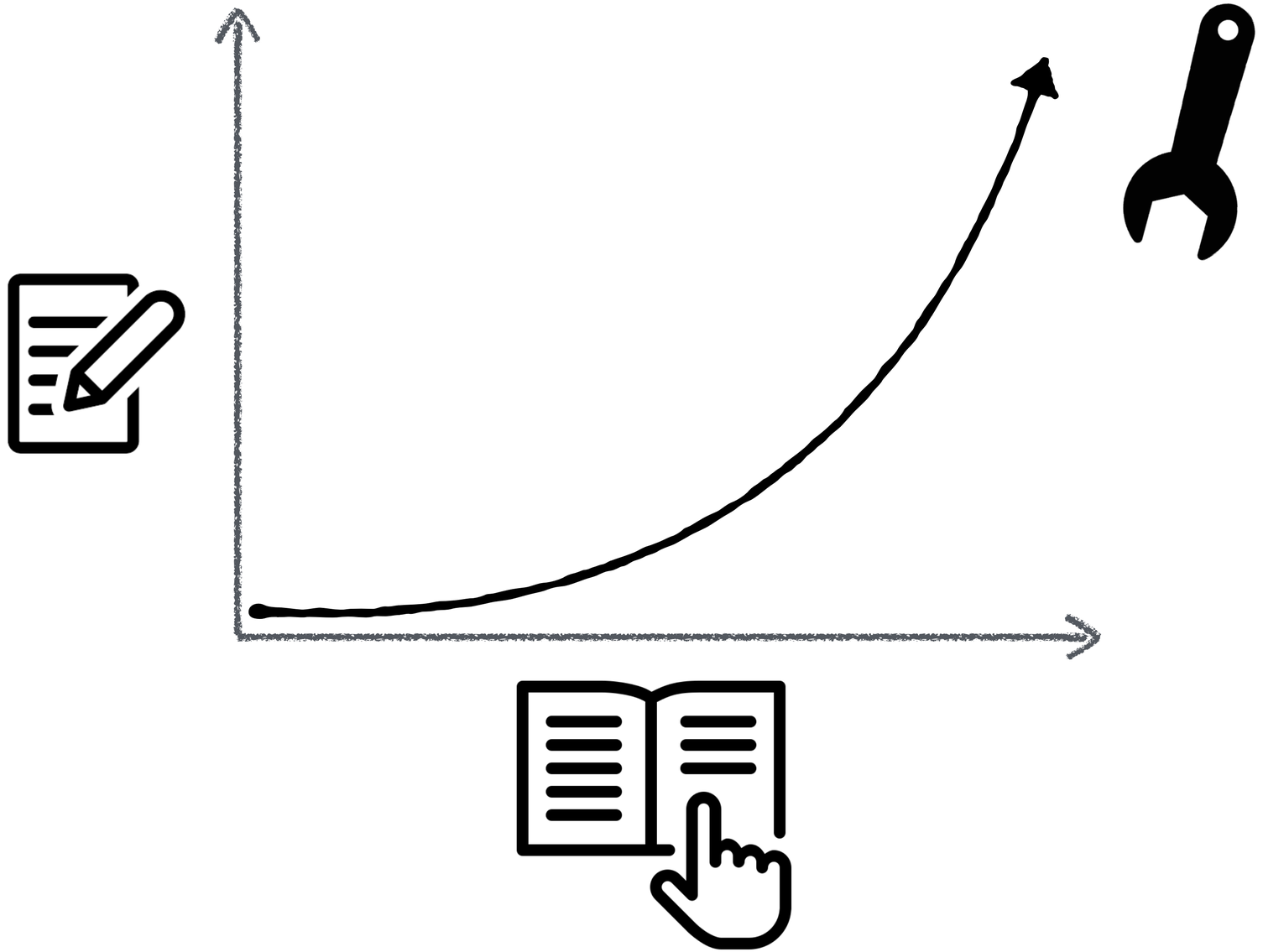
Why **LSM** ?



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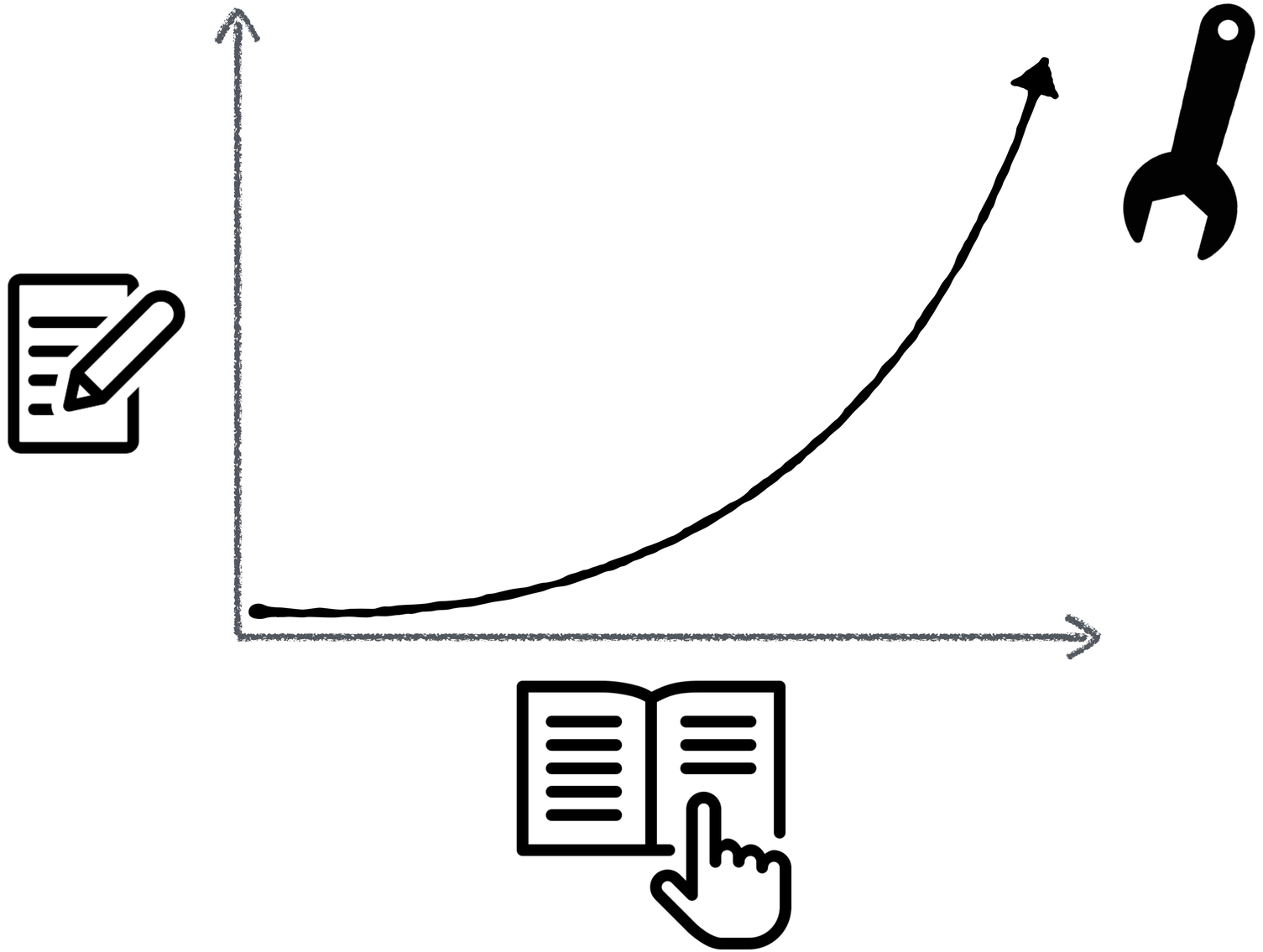
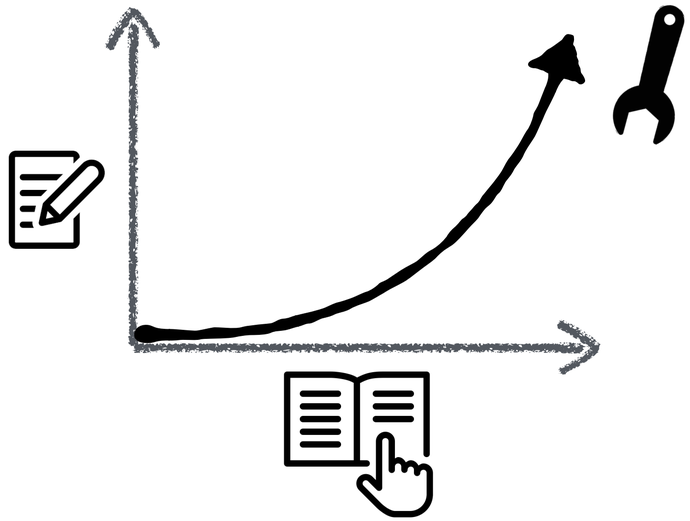
Why **LSM** ?

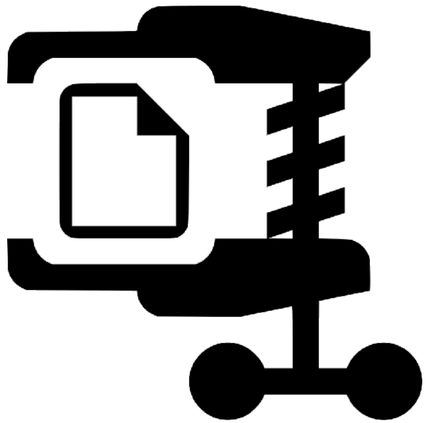


Why **LSM** ?

fast writes



tunable read-write performance



good space utilization

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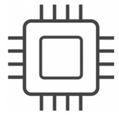
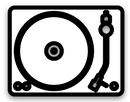
LSM **Basics**



buffer



level 1

level 2

level 3

level 4

size ratio: T

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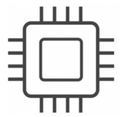
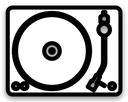
P: pages in buffer
B: entries/page
L: #levels
T: size ratio

LSM **Basics**



buffer $P \cdot B$



level 1 $P \cdot B \cdot T$

level 2 $P \cdot B \cdot T^2$

level 3 $P \cdot B \cdot T^3$

level 4 $P \cdot B \cdot T^4$

capacity (entries)

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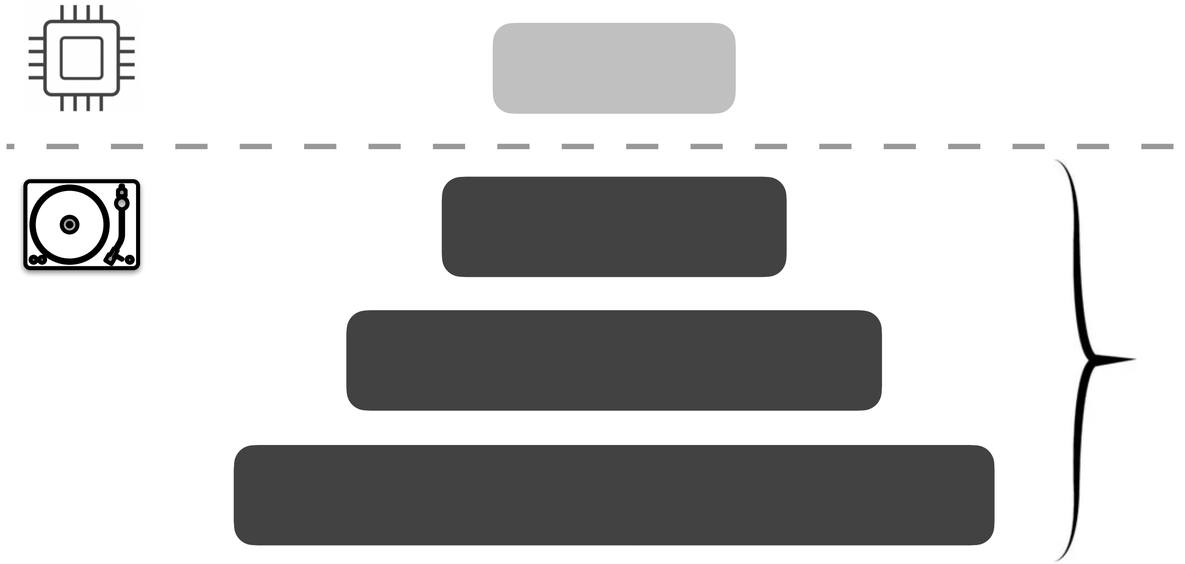
LSM Operating **Principles**

Buffering ingestion

Immutable files on storage

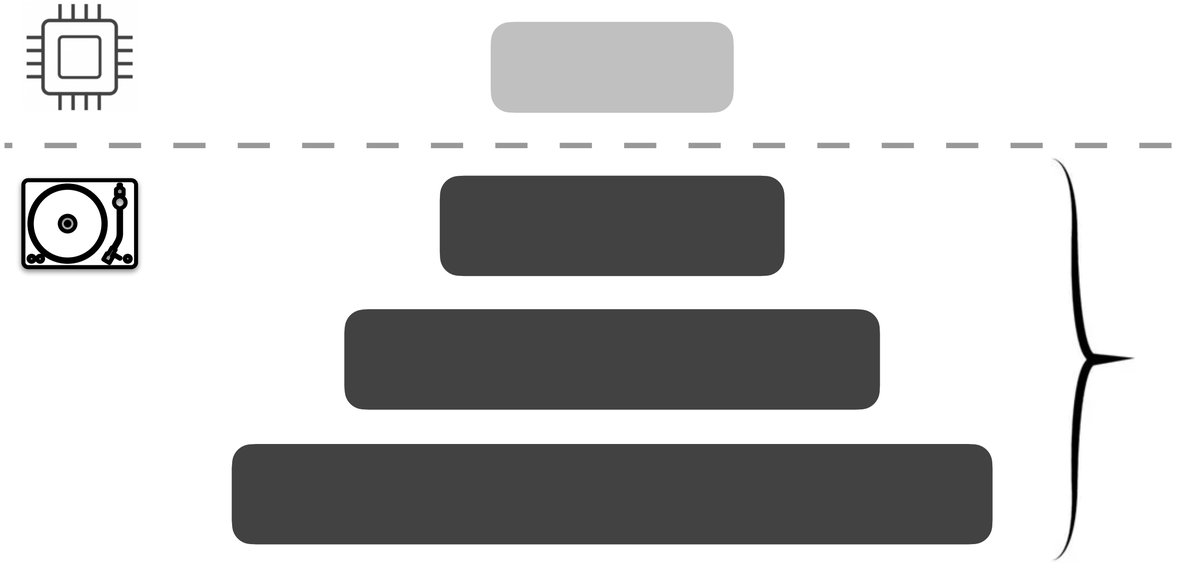
Out-of-place updates & deletes

Periodic data layout reorganization



most data
on storage

L: #levels
T: size ratio



most data
on storage

if $T = 10$ & $L = 4$

99.9% on storage

How does the storage layer affect ingestion?

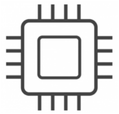
Data **Layout**

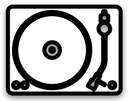
Classical LSM design: `leveling`

[eager merging]

Data **Layout**

leveling [eager]





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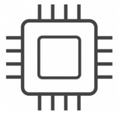
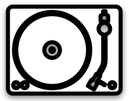
Data **Layout**

leveling [eager]





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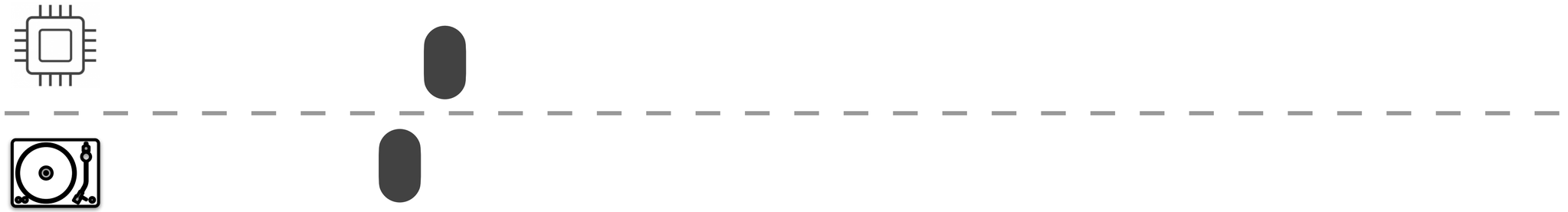
Data **Layout**

leveling [eager]



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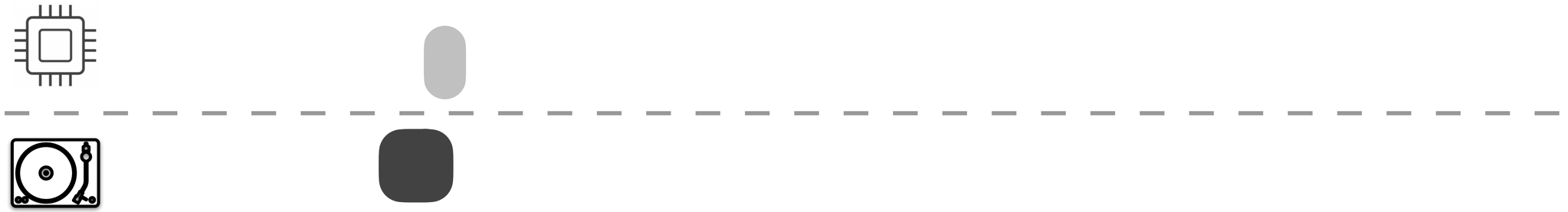
Data **Layout**

leveling [eager]



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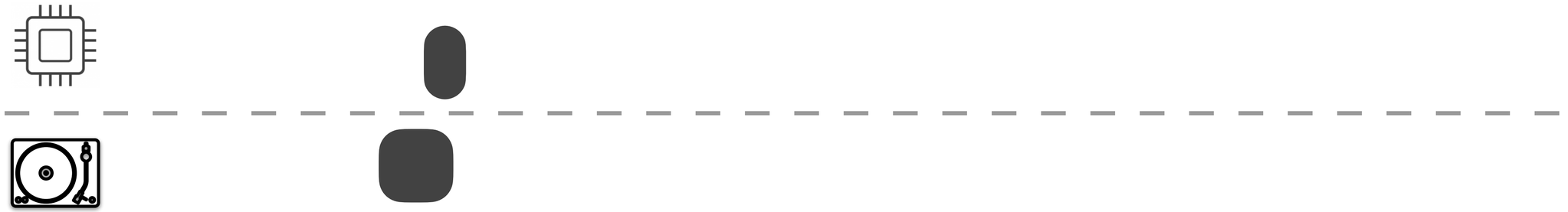
Data **Layout**

leveling [eager]



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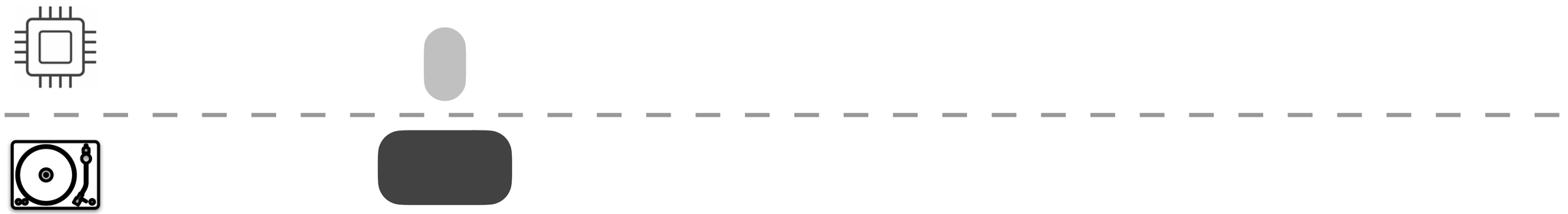
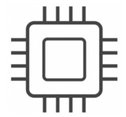
Data **Layout**

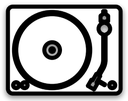
leveling [eager]

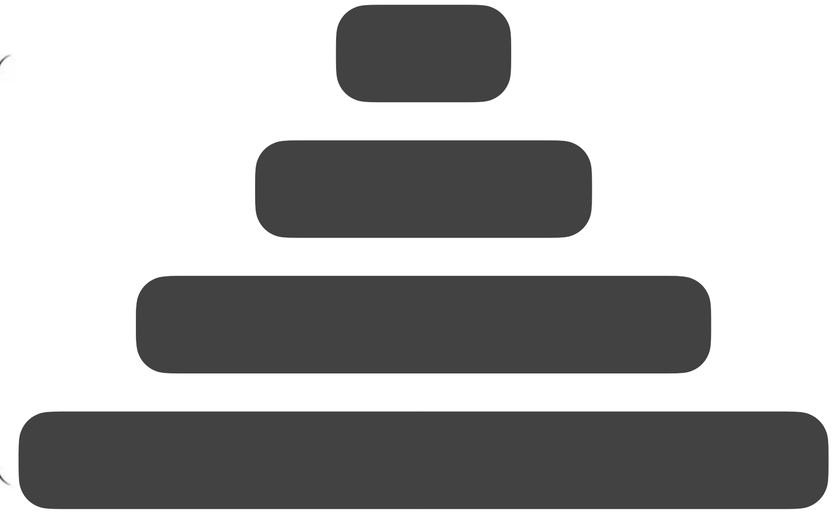


Data **Layout**

leveling [eager]







1 run per level

- good read performance
- good space amplification
- high write amplification

Seems like heaven!

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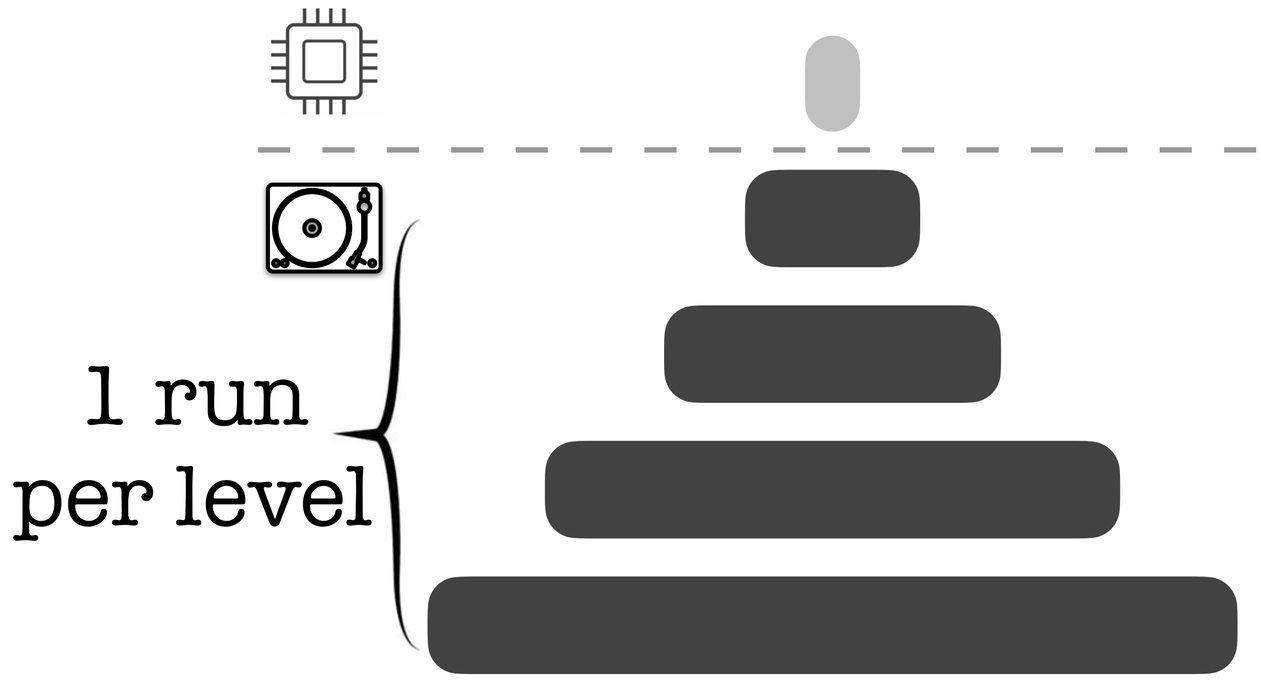
Data **Layout**

leveling [eager]

tiering [lazy]



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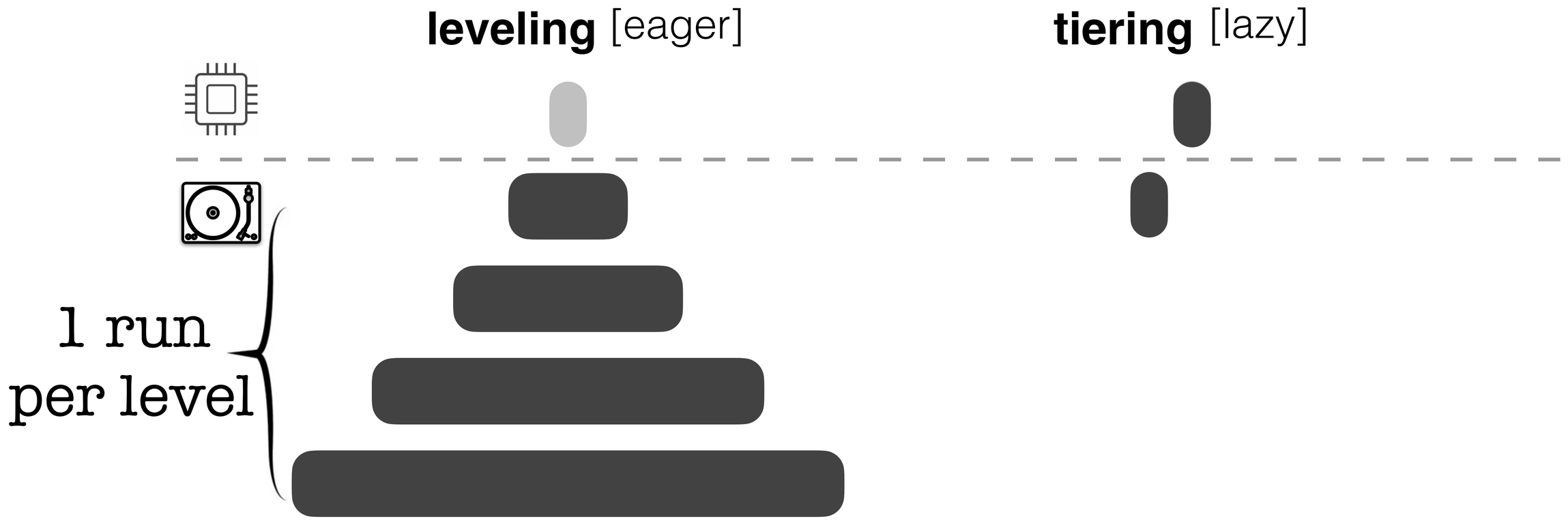
Data **Layout**



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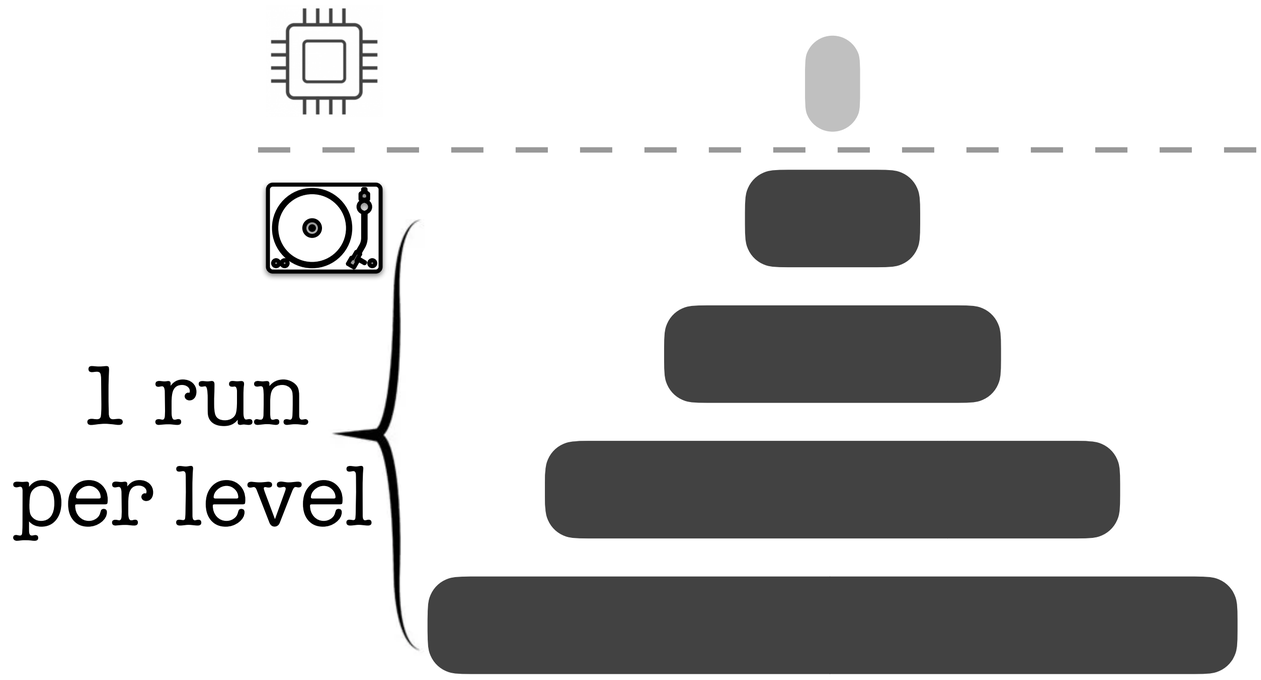
Data **Layout**

leveling [eager]

tiering [lazy]



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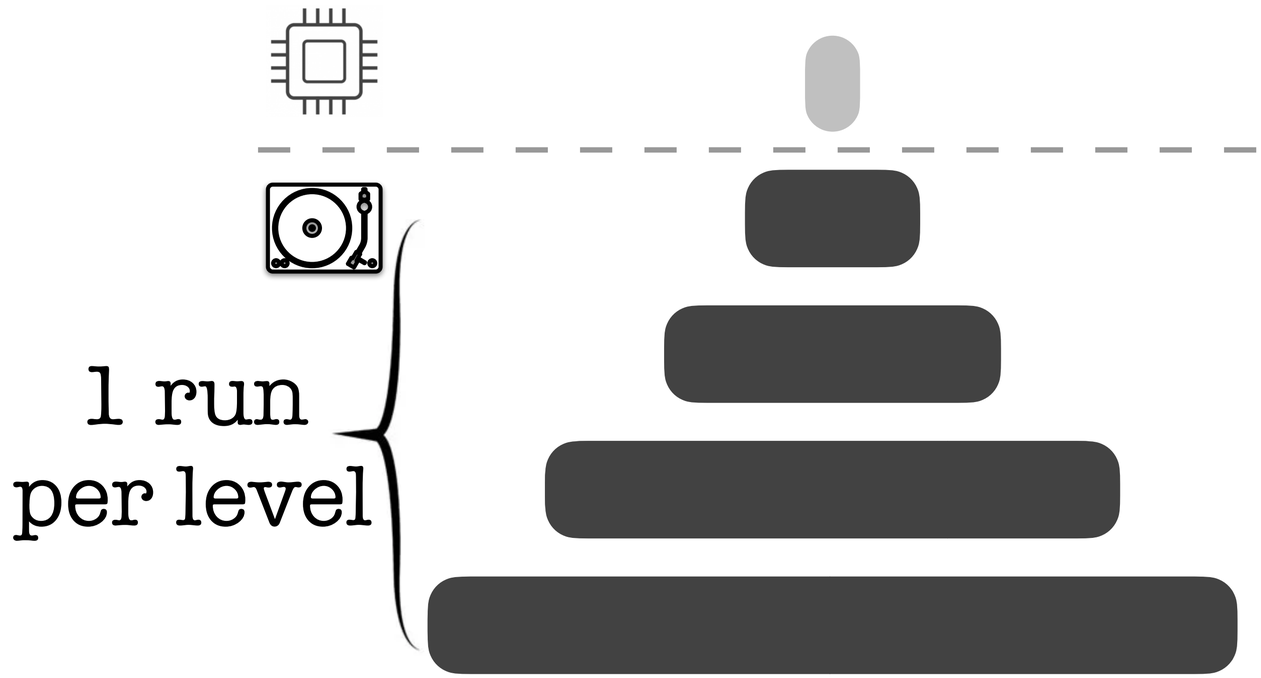

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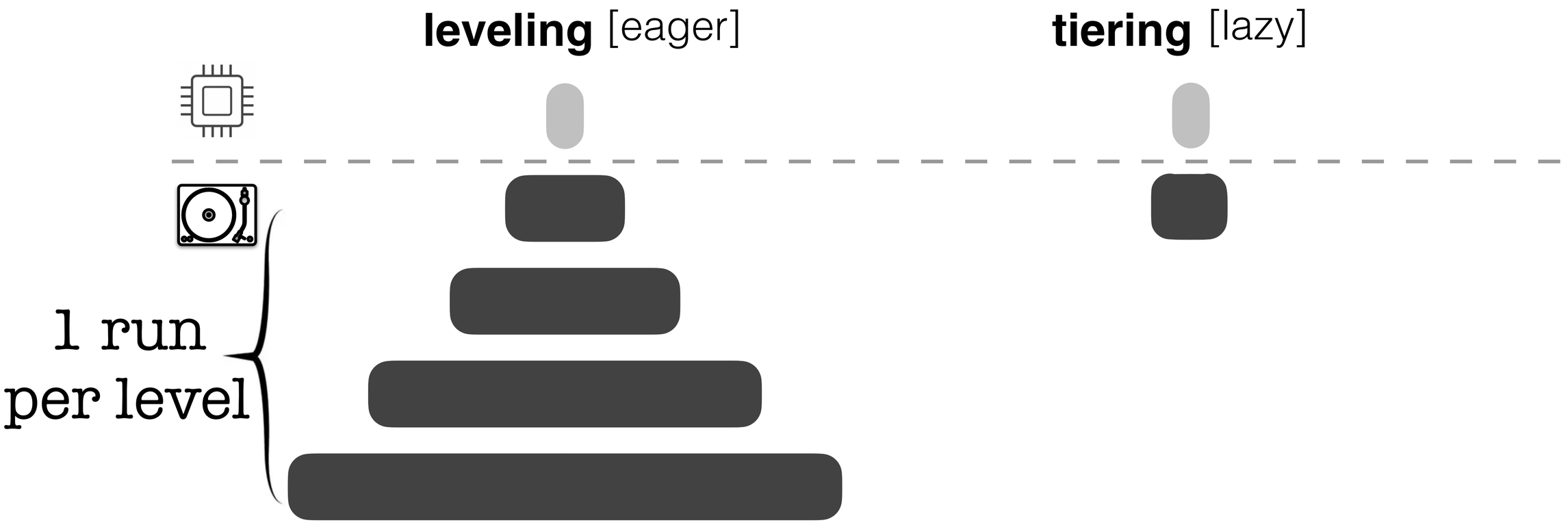

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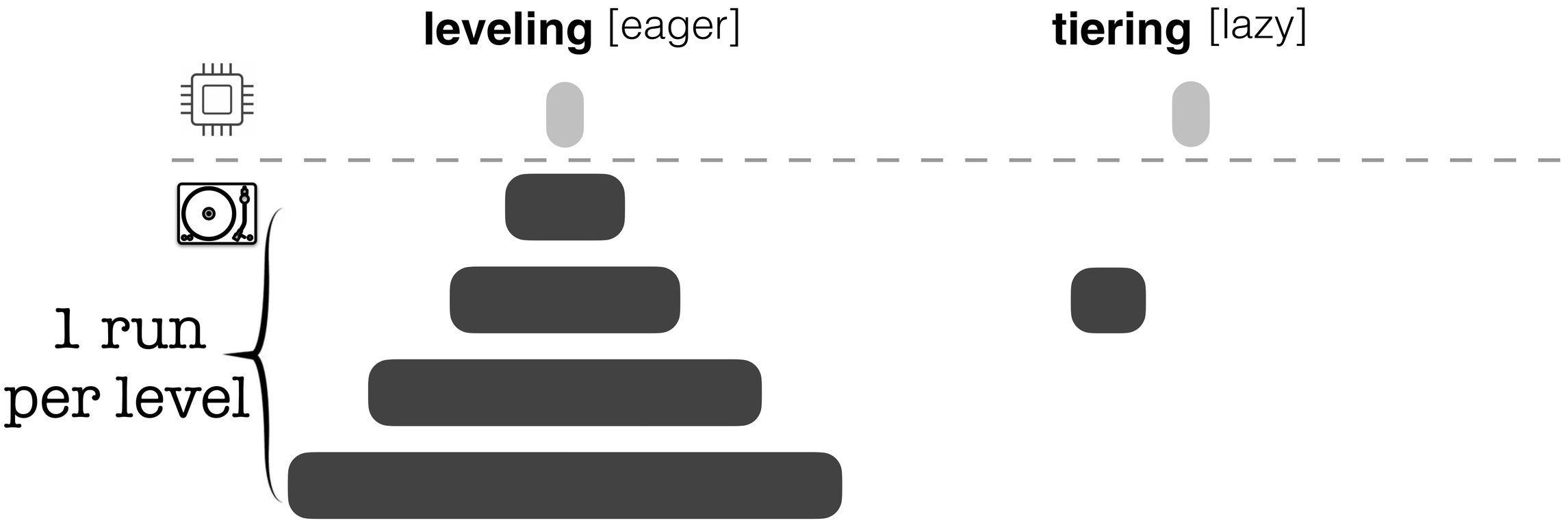

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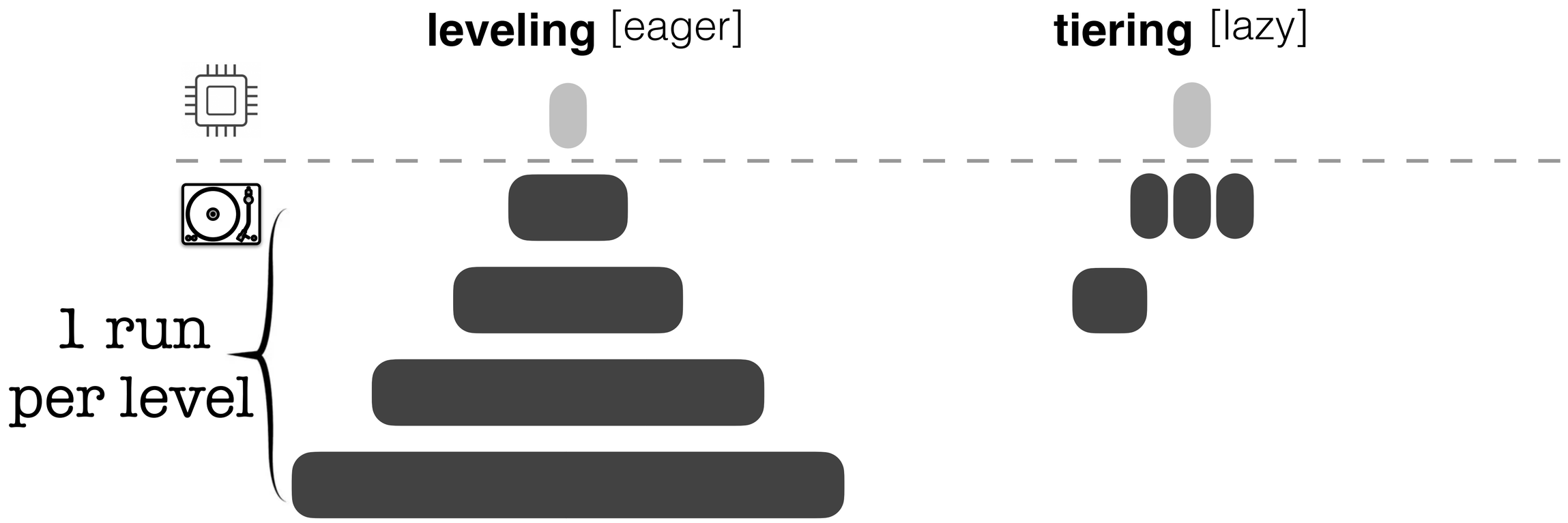

- good read performance
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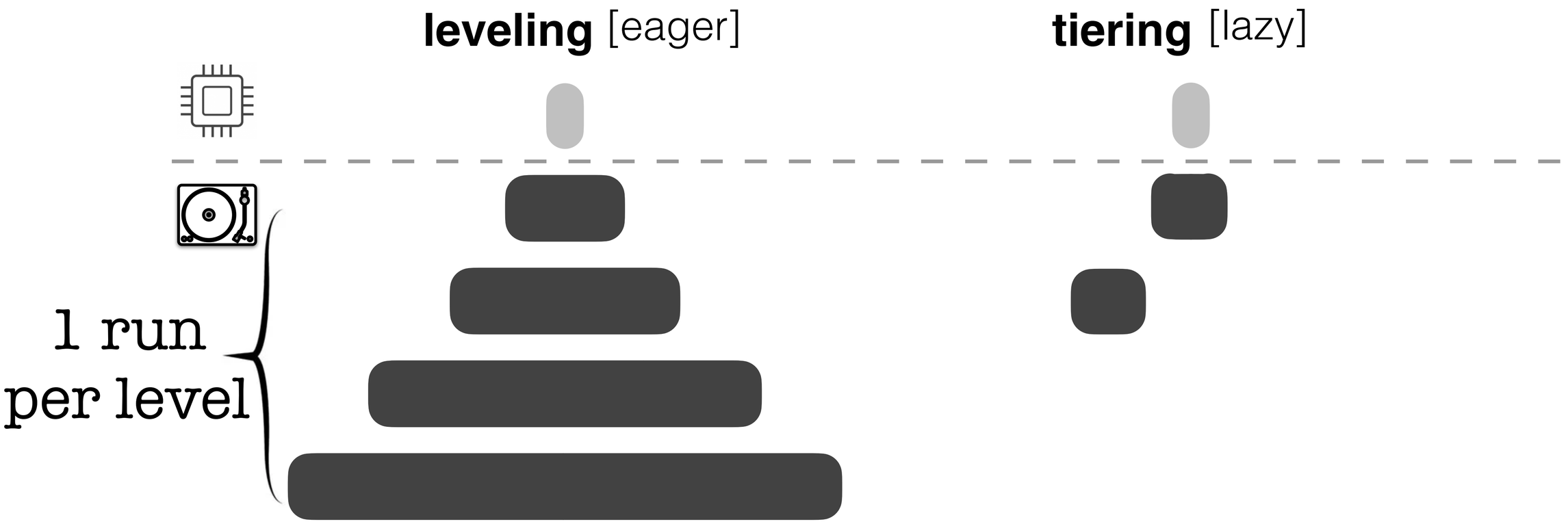
Data **Layout**



- good read performance
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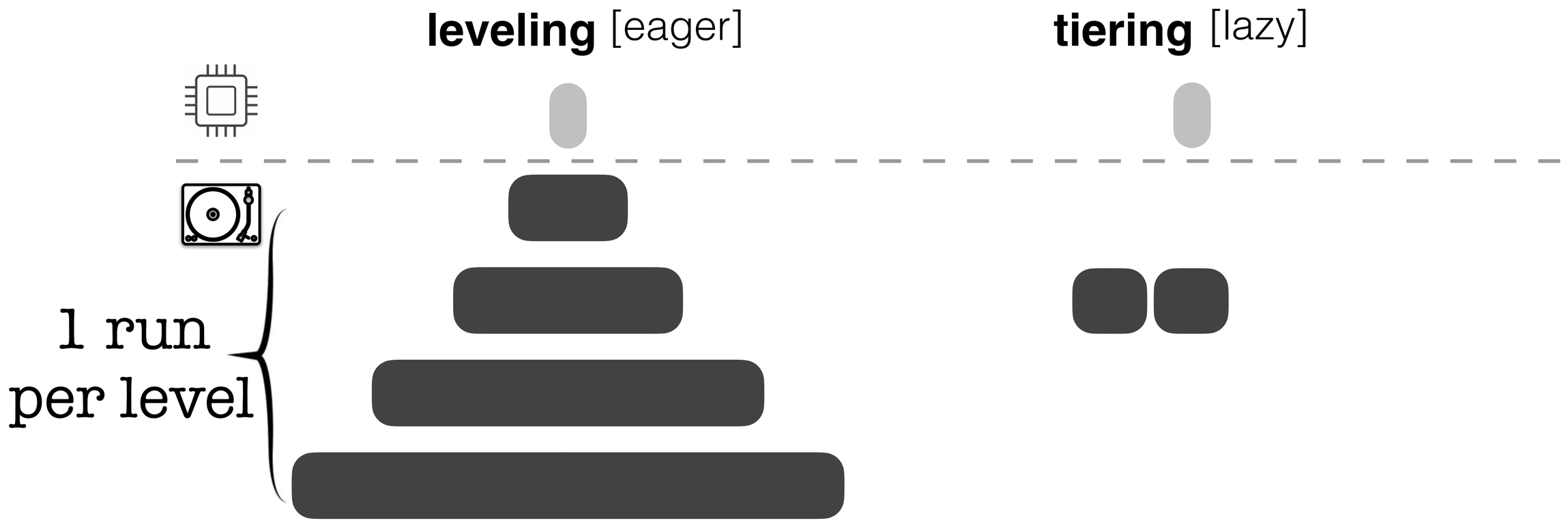

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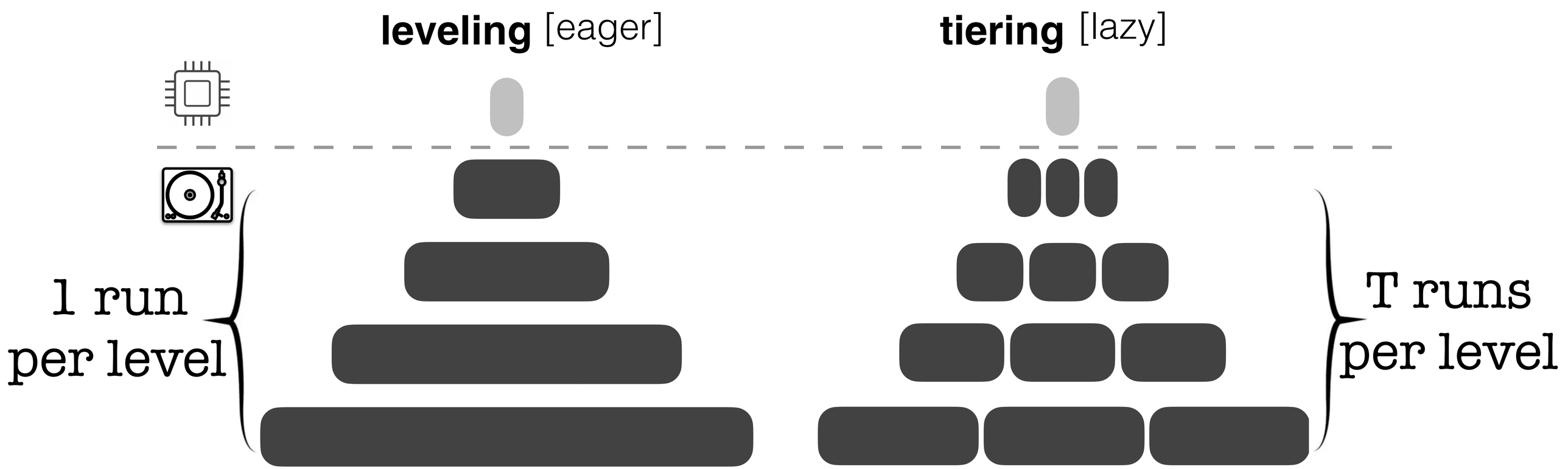

- good read performance
- good space amplification
- high write amplification

- good ingestion performance

Limitations?

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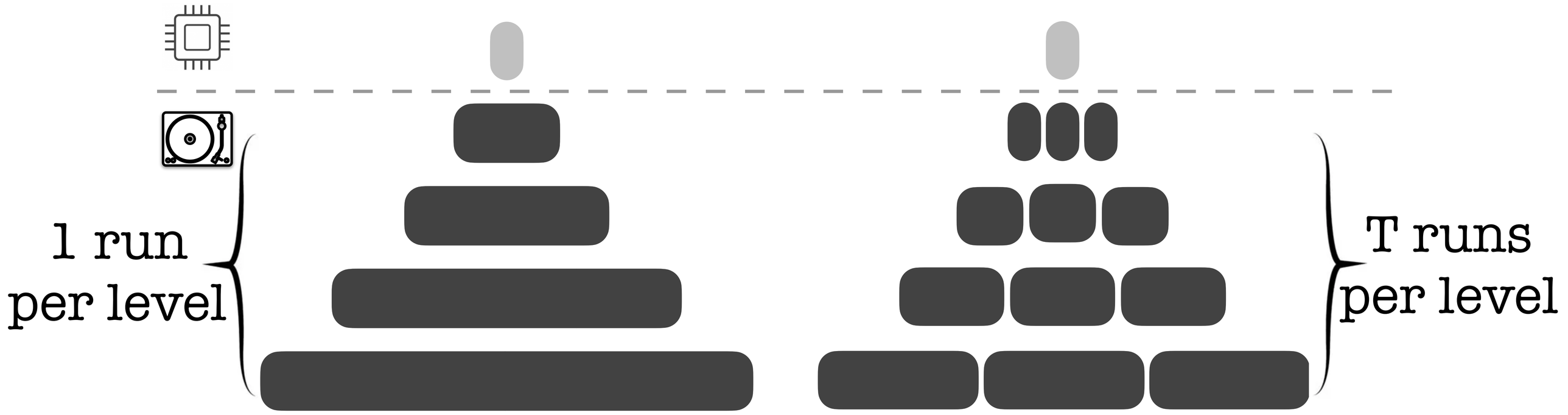
P: pages in buffer
B: entries/page
L: #levels
T: size ratio
N: #entries
ϕ : FPR of BF

Data **Layout**

leveling [eager]

tiering [lazy]



	leveling [eager]	**tiering** [lazy]
Read cost:	$\mathcal{O}(L \cdot \phi)$	$\mathcal{O}(T \cdot L \cdot \phi)$
Write cost:	$\mathcal{O}(T \cdot L/B)$	$\mathcal{O}(L/B)$
SA:	$\mathcal{O}(1/T)$	$\mathcal{O}(T)$

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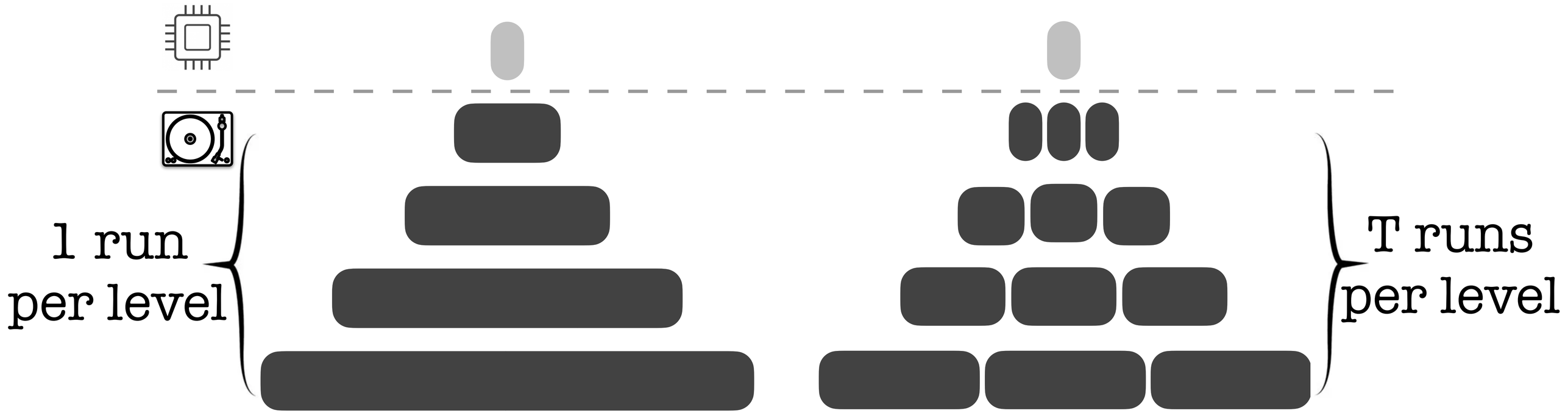
P: pages in buffer
B: entries/page
L: #levels
T: size ratio
N: #entries
ϕ : FPR of BF

Data **Layout**

leveling [eager]

tiering [lazy]



	leveling [eager]	**tiering** [lazy]
Read cost:	$\mathcal{O}(L \cdot \phi)$	$\mathcal{O}(T \cdot L \cdot \phi)$
Write cost:	$\mathcal{O}(T \cdot L/B)$	$\mathcal{O}(L/B)$
SA:	$\mathcal{O}(1/T)$	$\mathcal{O}(T)$

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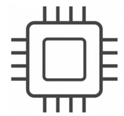
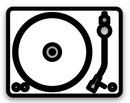
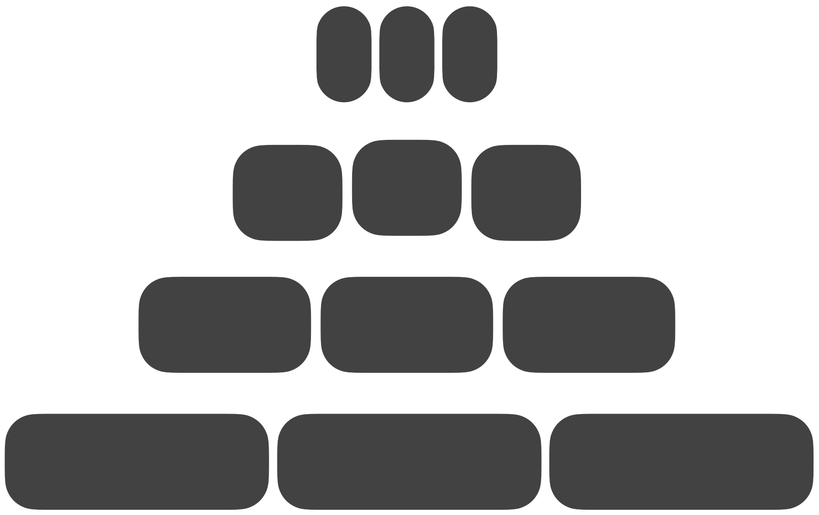
Data **Layout**

leveling [eager]

tiering [lazy]







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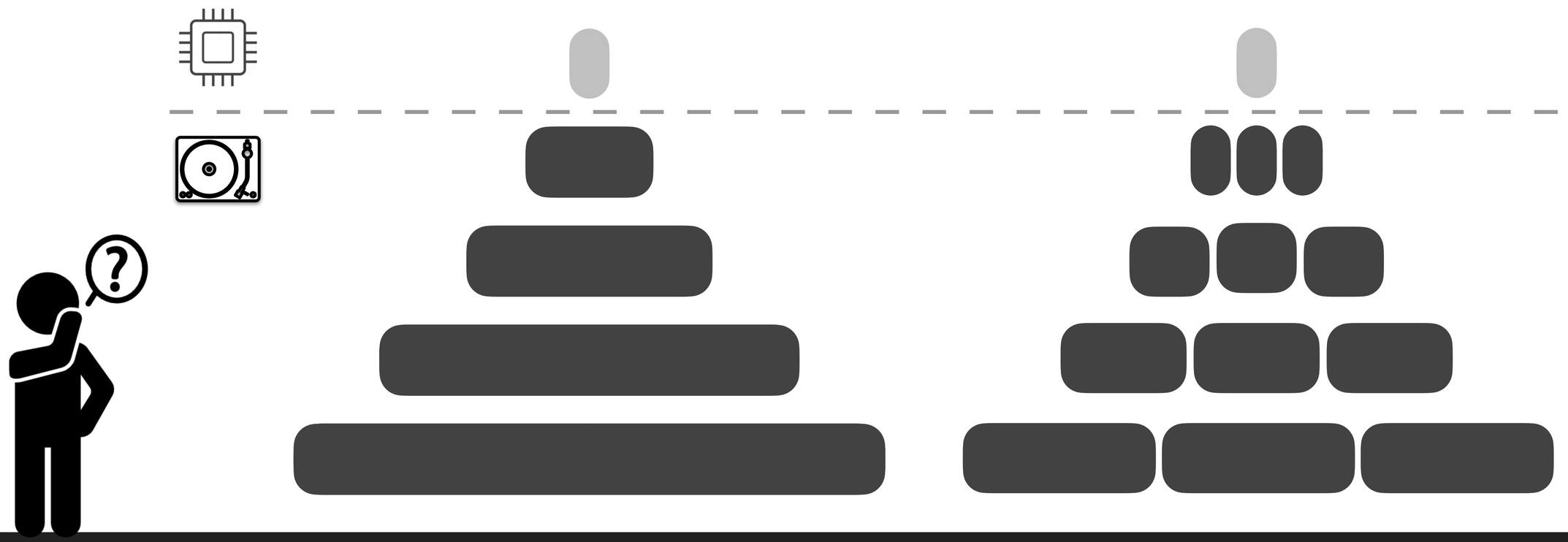
Data **Layout**

leveling [eager]

tiering [lazy]

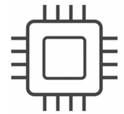


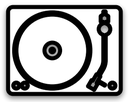
What happens if T becomes too large?

Data **Layout**

leveling [eager]

tiering [lazy]



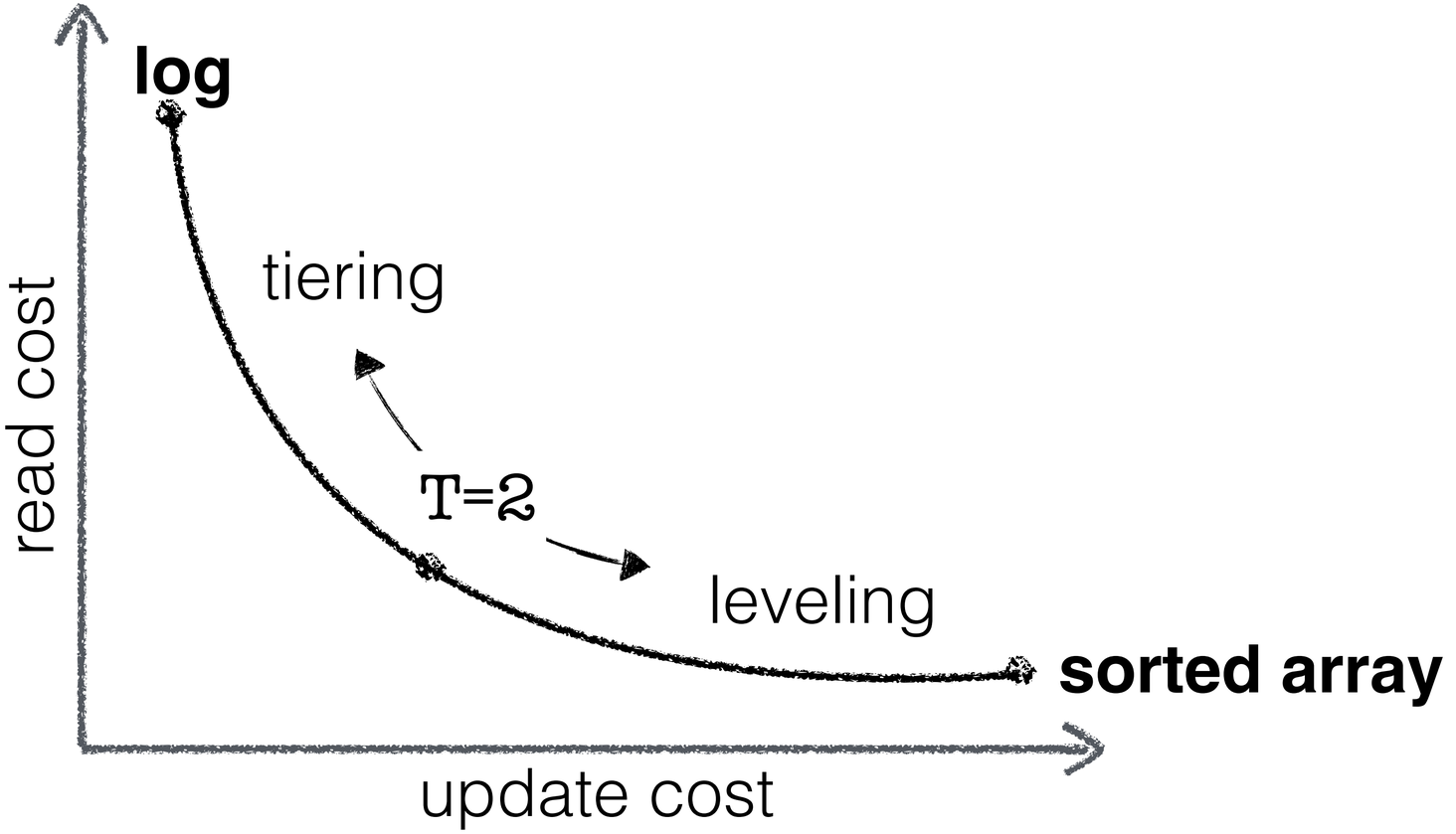


sorted array

log

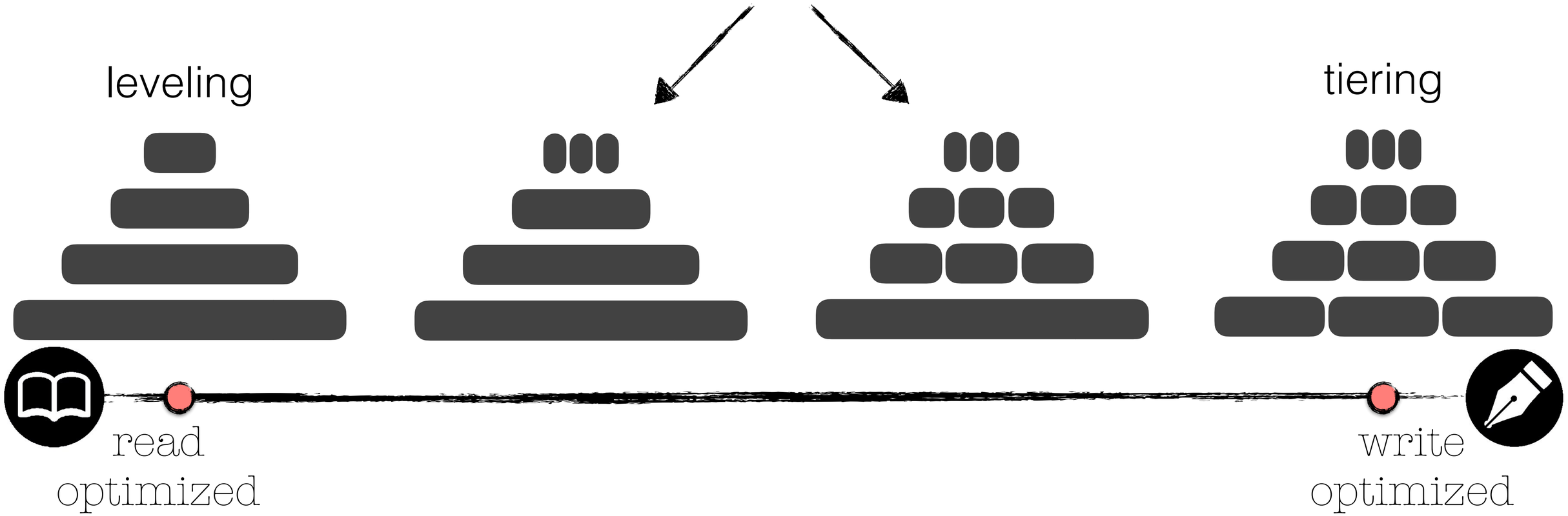
T: size ratio

Data **Layout**



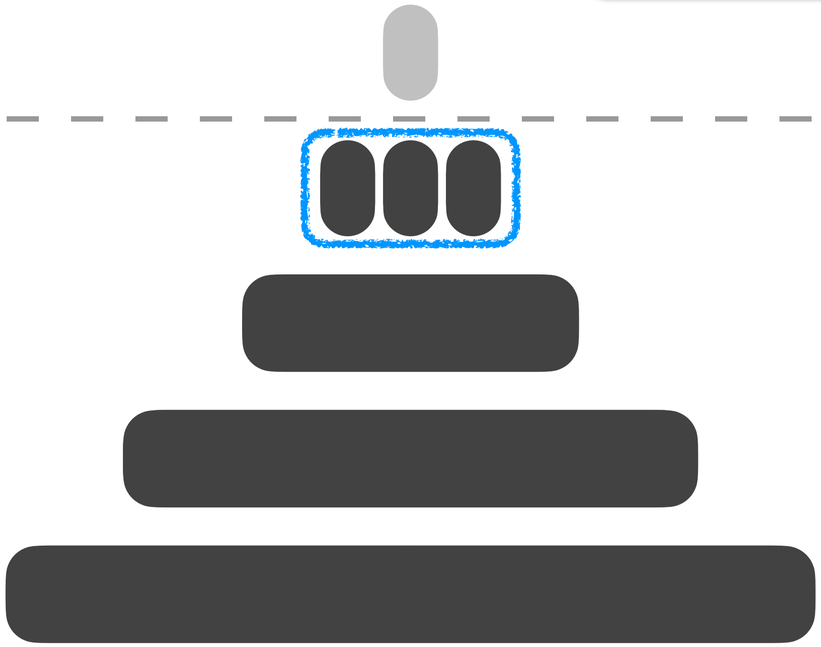
Data **Layout**

hybrid designs



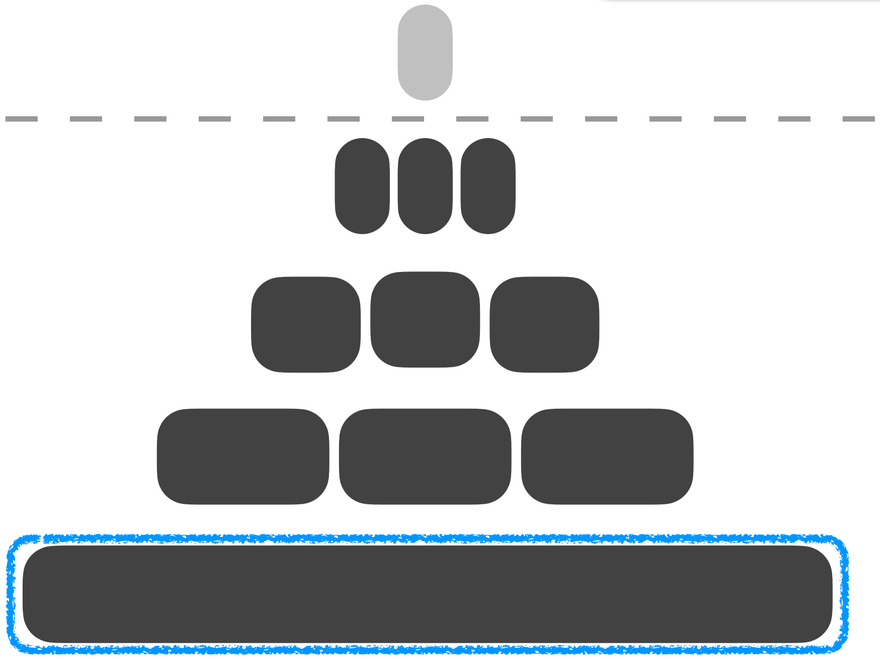
Data **Layout**

1-leveling RocksDB20



- fewer write stalls
- increased block cache hits

L-leveling DayanSIGMOD18



- low write amplification
- better read performance

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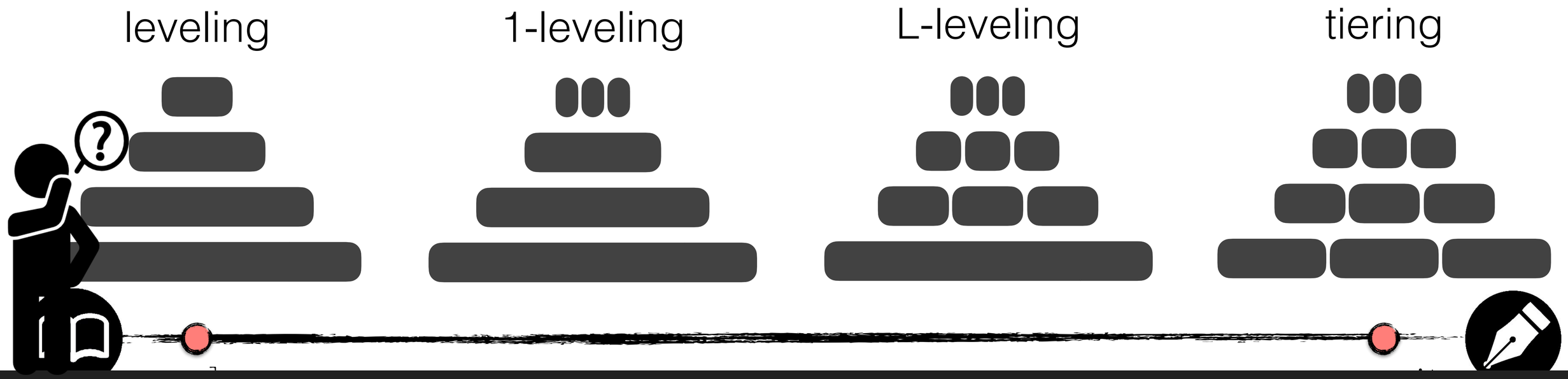
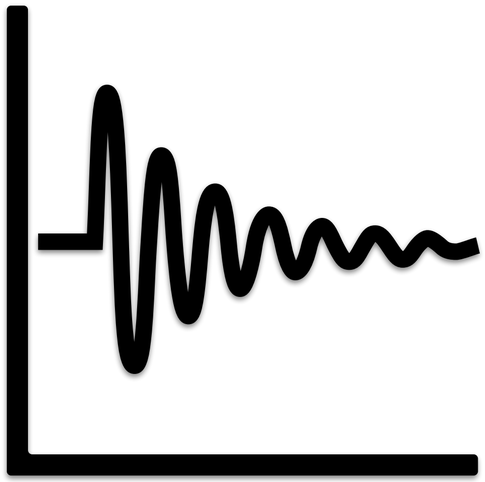
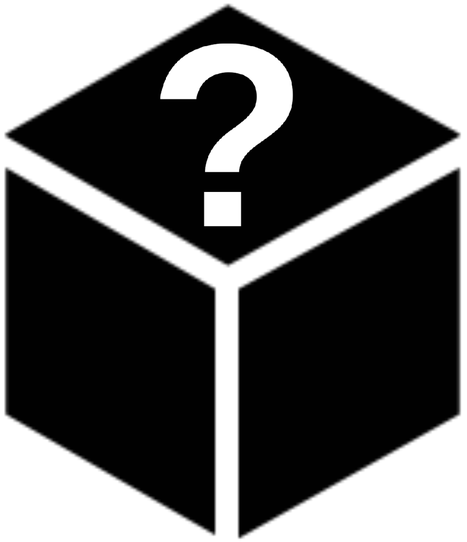
Data **Layout**



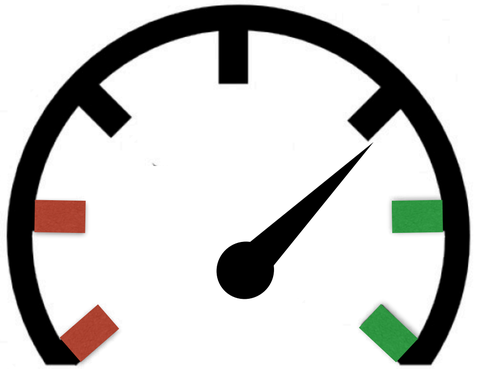
So, how do we reason about the data layout?



workload



data layout



performance

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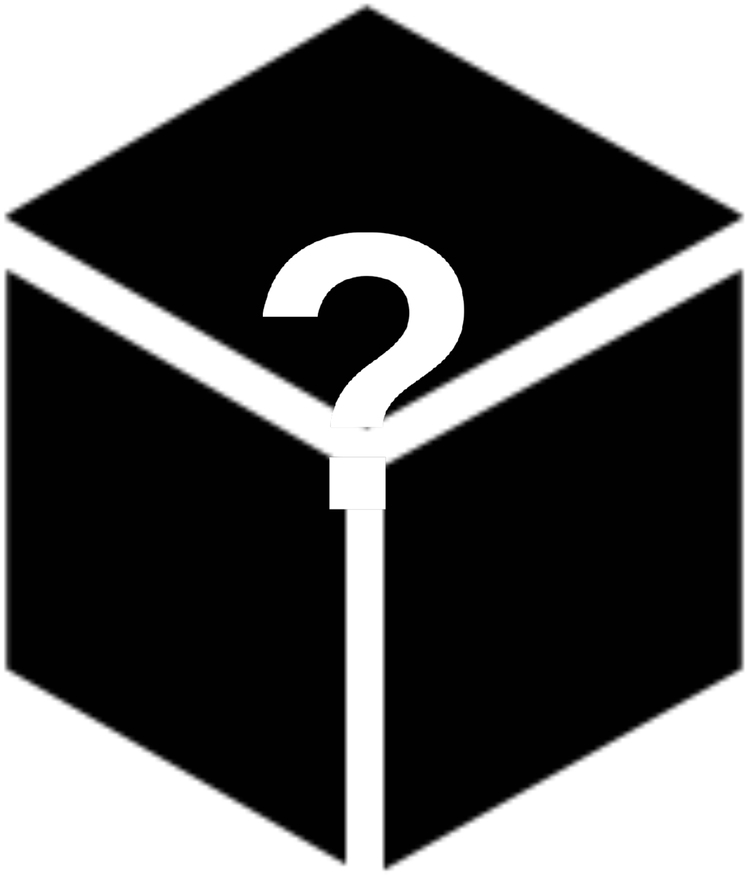

Compaction

black box




How to organize the data on device?

How much data to move at-a-time?

Which block of data to be moved?

When to re-organize the data layout?

Data Layout

How to organize the data on device? ✓

Compaction Granularity

How much data to move at-a-time?

Data Movement Policy

Which block of data to be moved?

Compaction Trigger

When to re-organize the data layout?

Compaction **Granularity**

data moved per compaction

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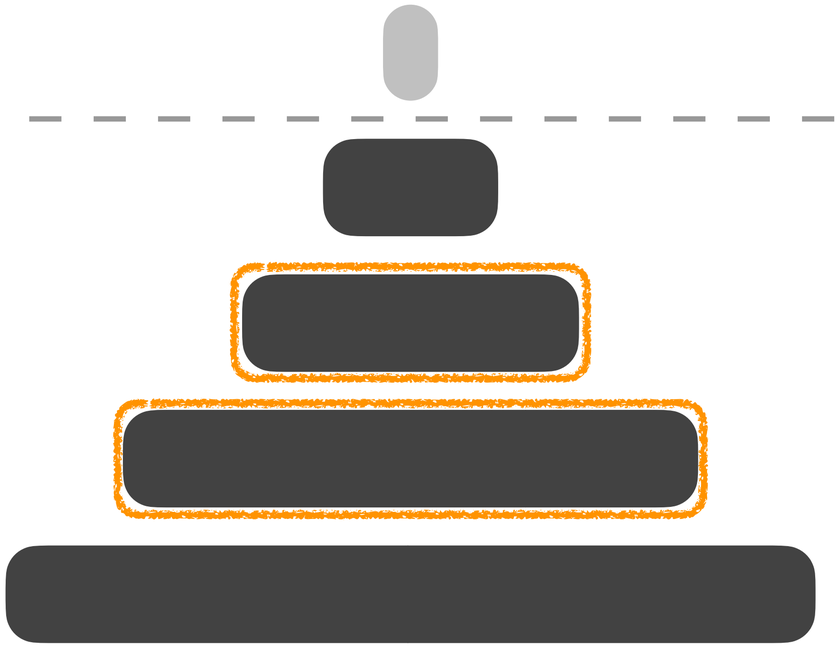
Compaction **Granularity**

data moved per compaction



consecutive levels

AsterixDB

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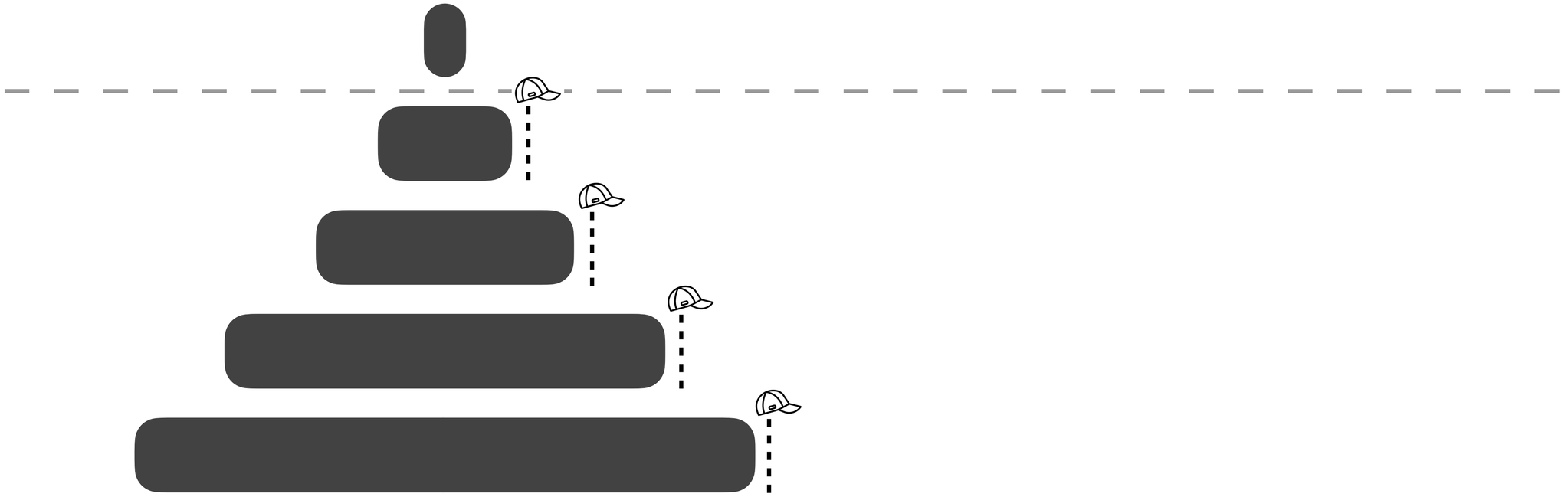
Compaction **Granularity**

data moved per compaction



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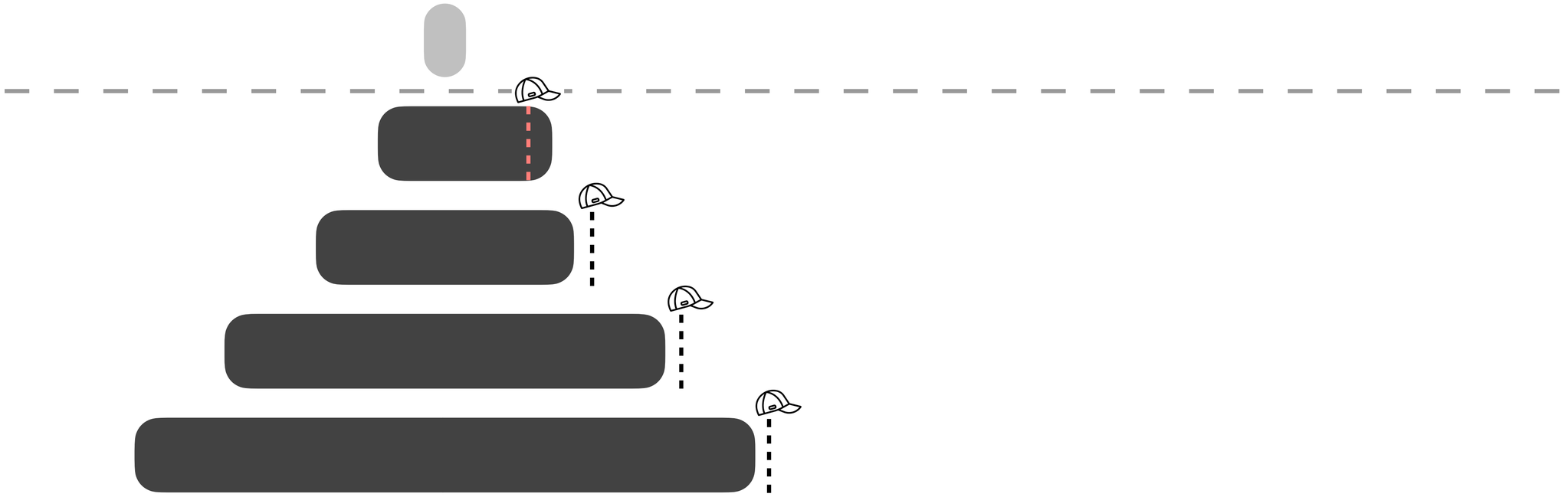
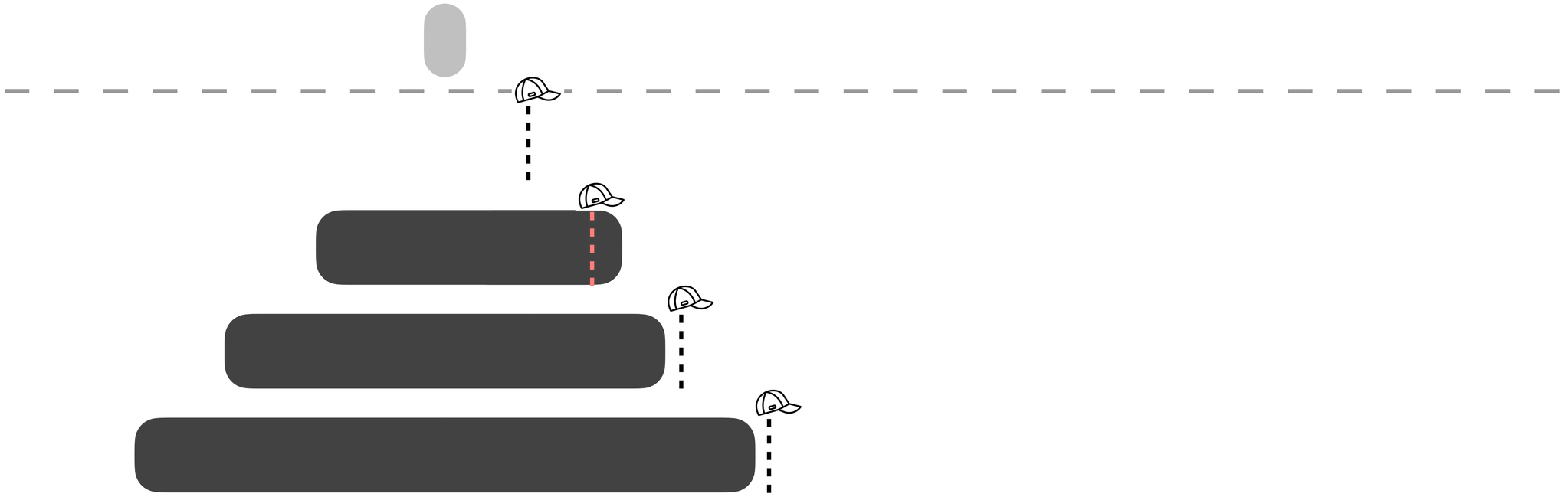
Compaction **Granularity**

data moved per compaction



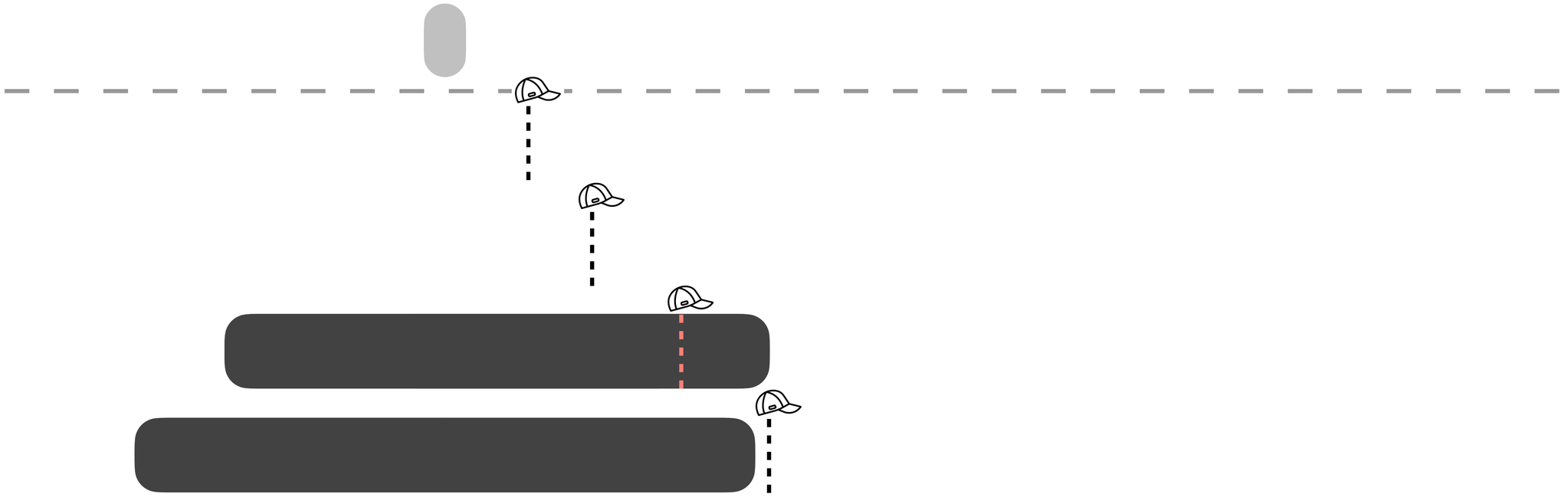
Compaction **Granularity**

data moved per compaction



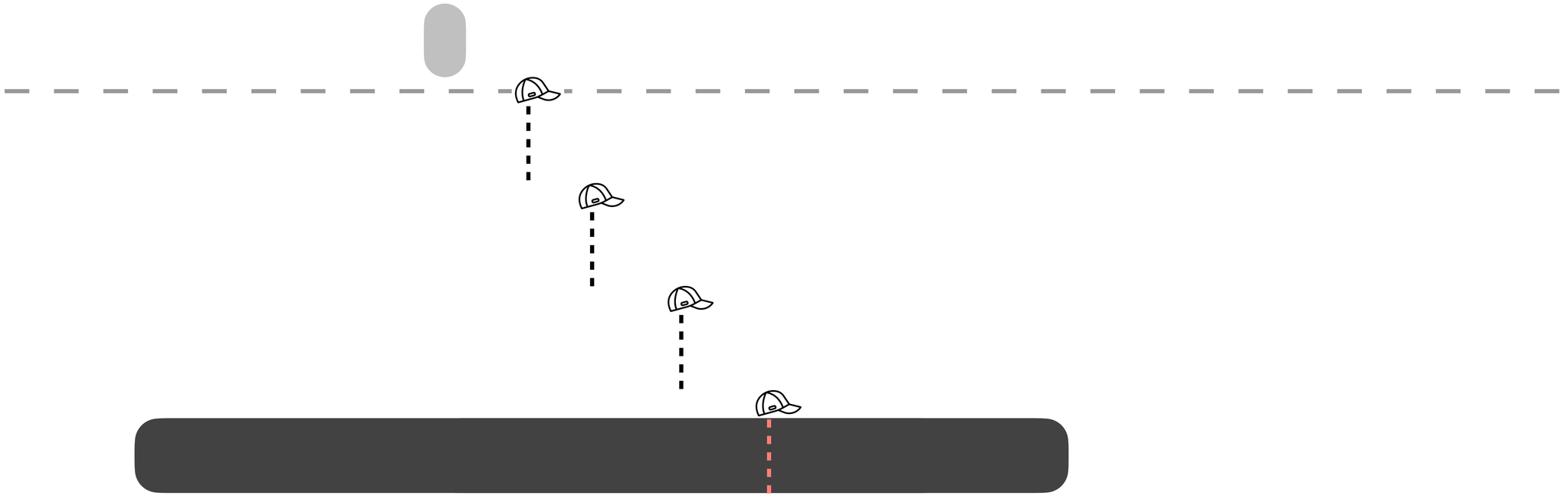
Compaction **Granularity**

data moved per compaction



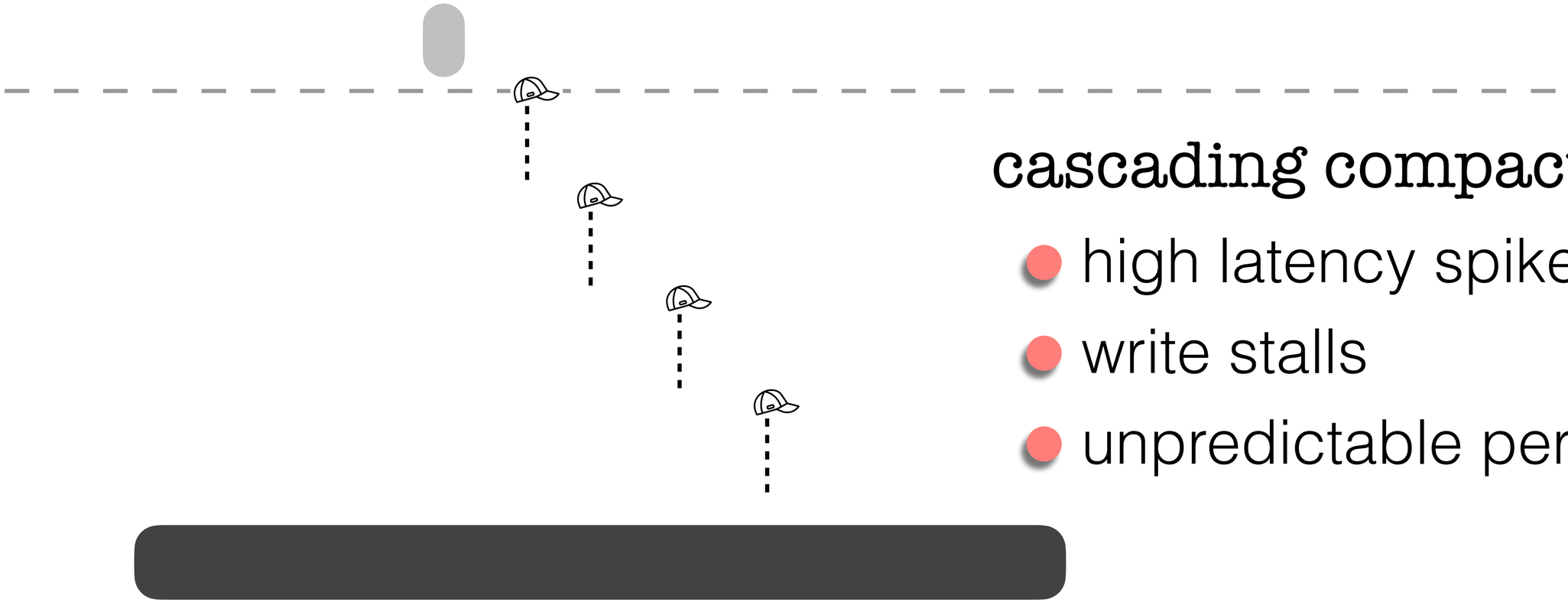
Compaction **Granularity**

data moved per compaction



Compaction **Granularity**

data moved per compaction



cascading compactions

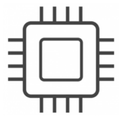
- high latency spikes
- write stalls
- unpredictable perf.

Compaction **Granularity**

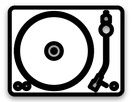
data moved per compaction

partial compaction

granularity: **files**



buffer



level 1

partial compaction

level 2

level 3

level 4

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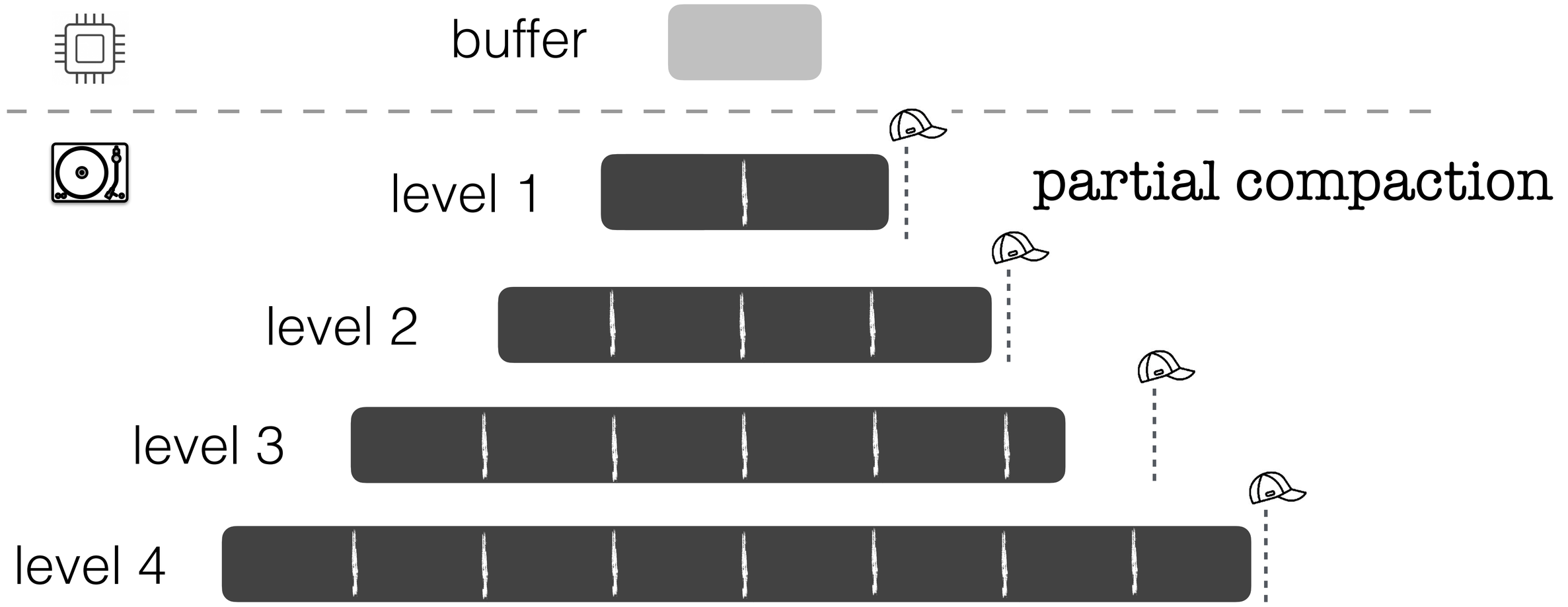
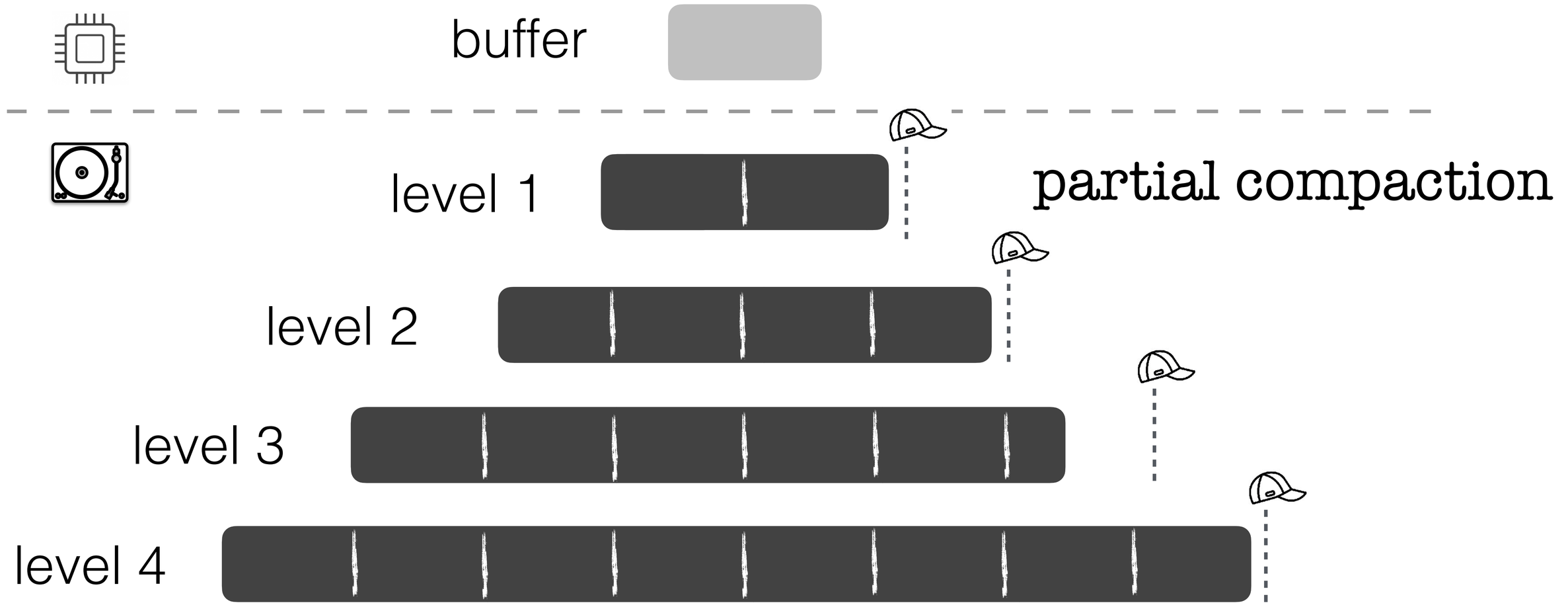
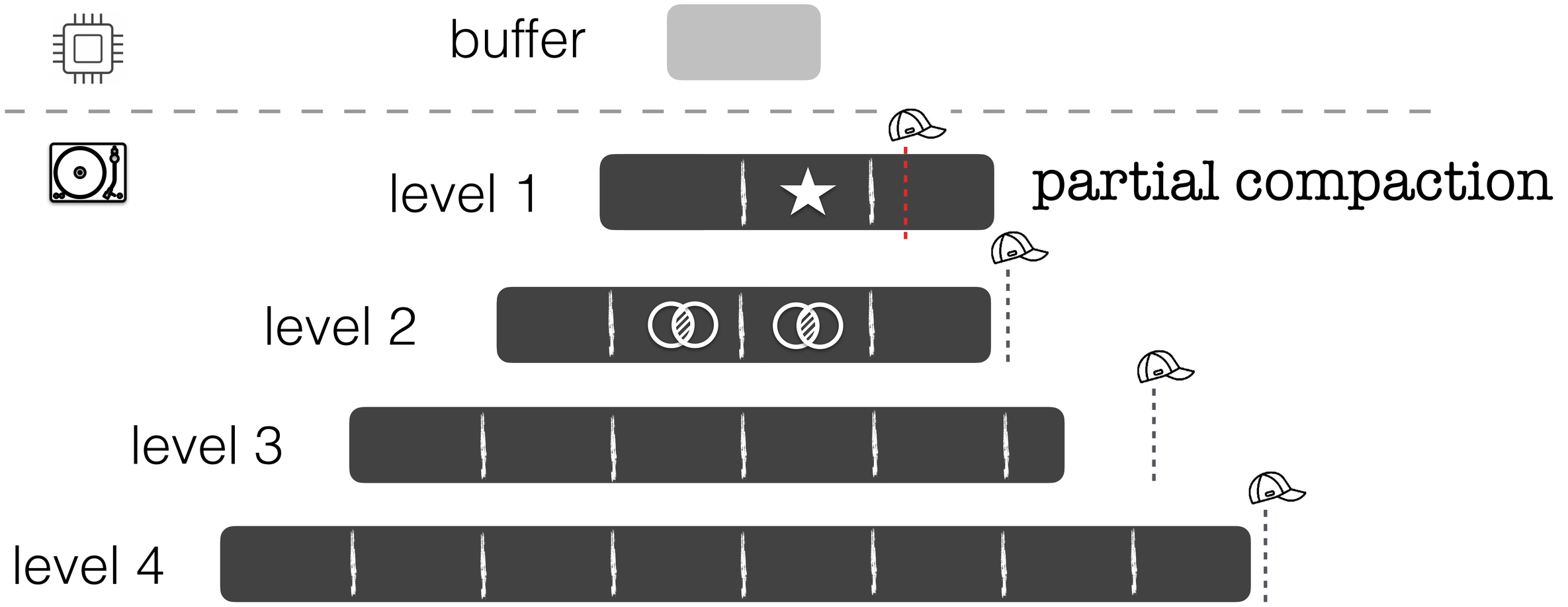
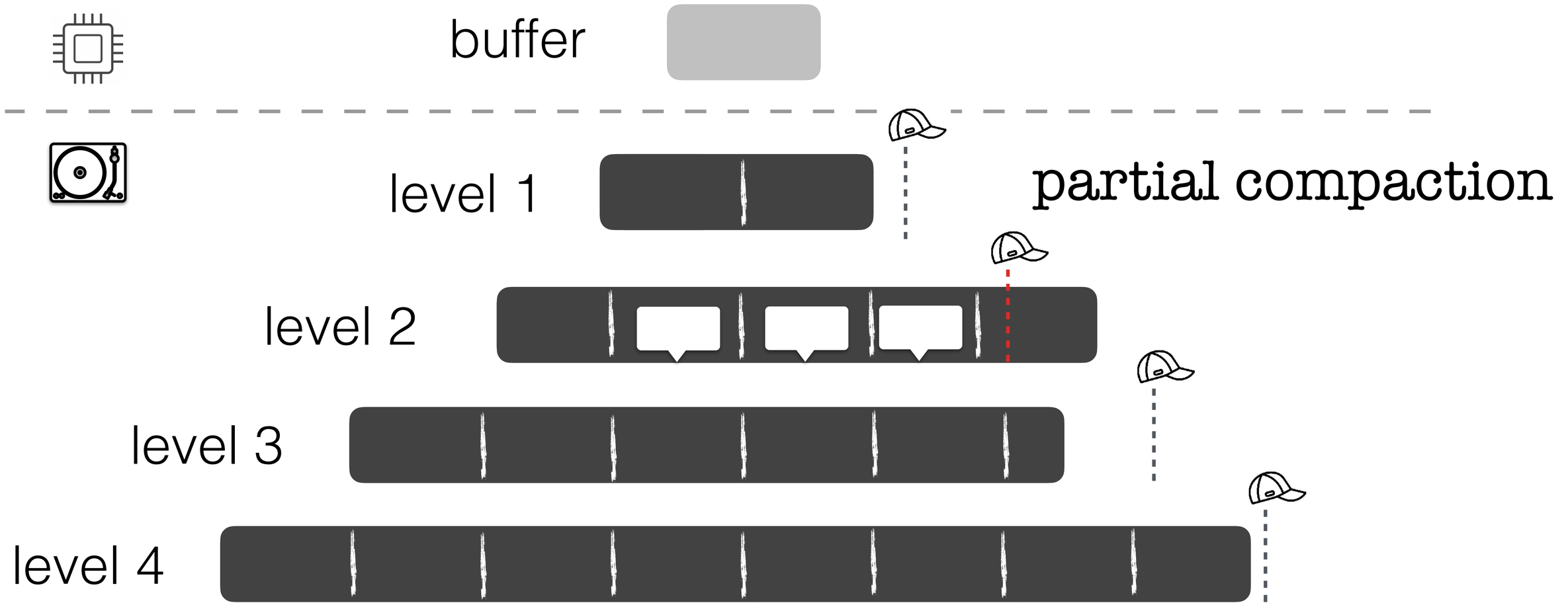
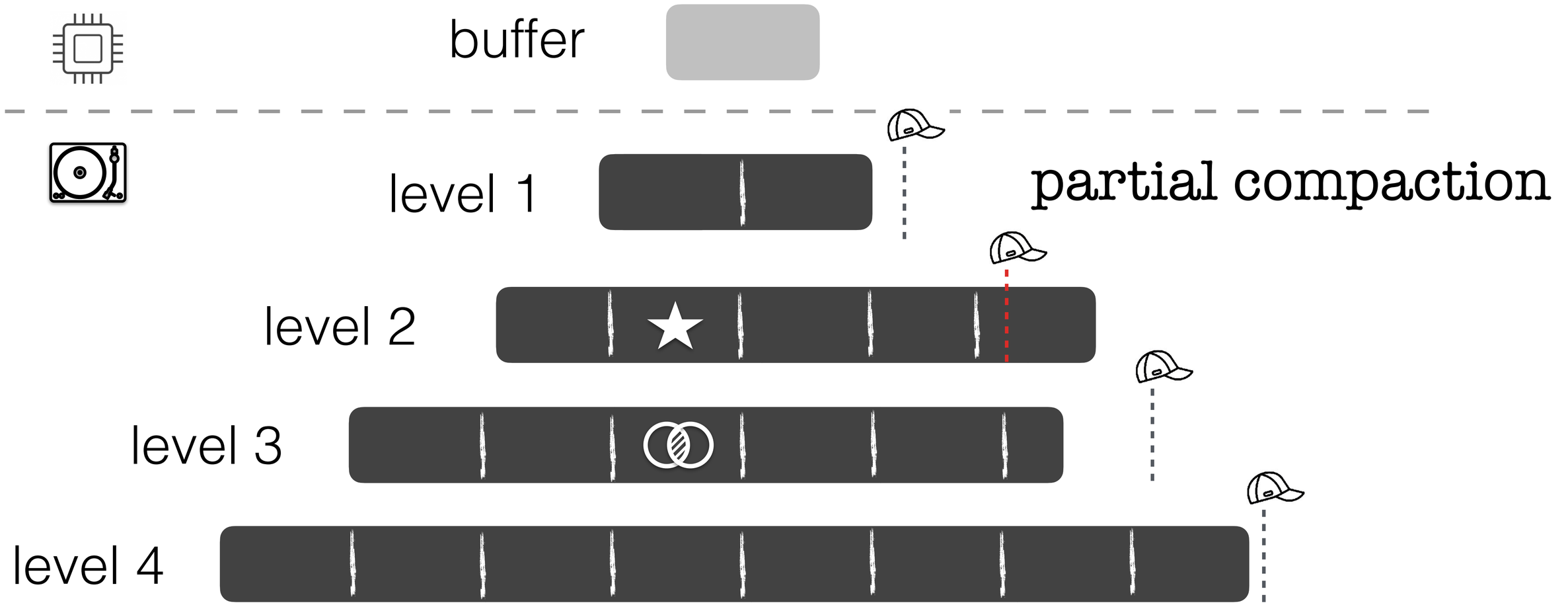
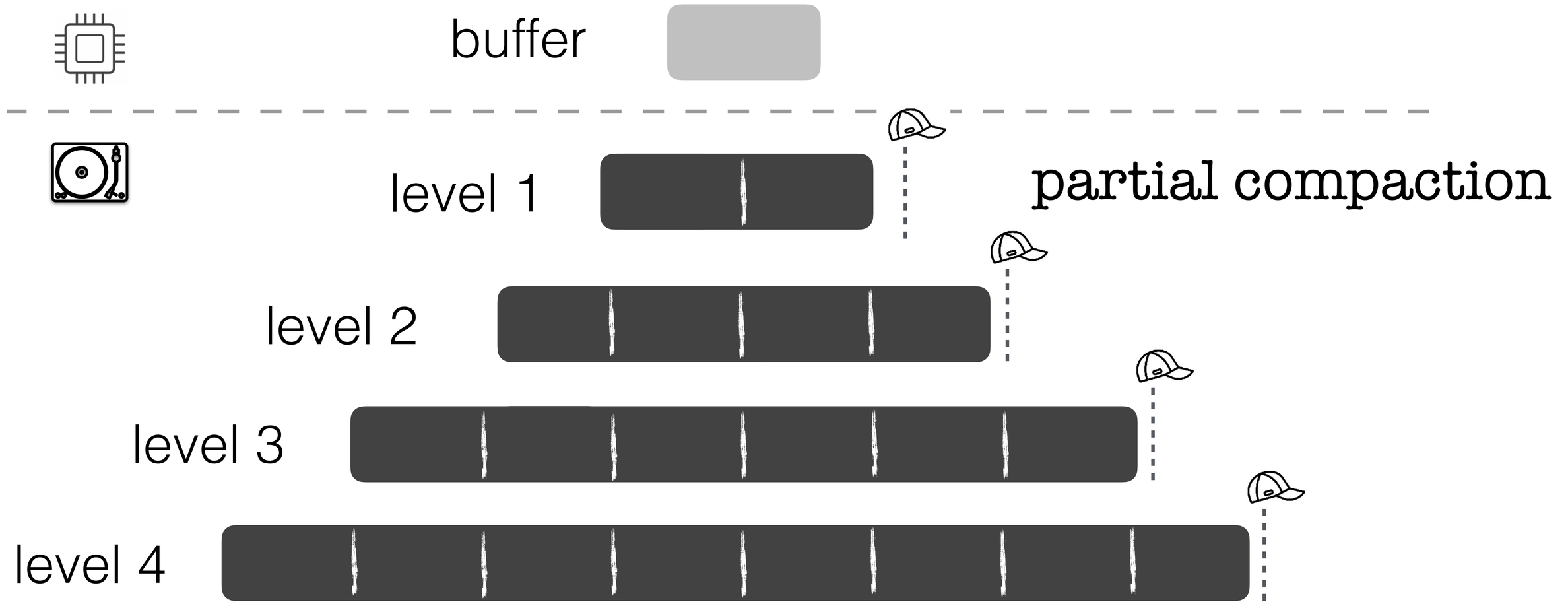





buffer
level 1
partial compaction
level 2
level 3
level 4

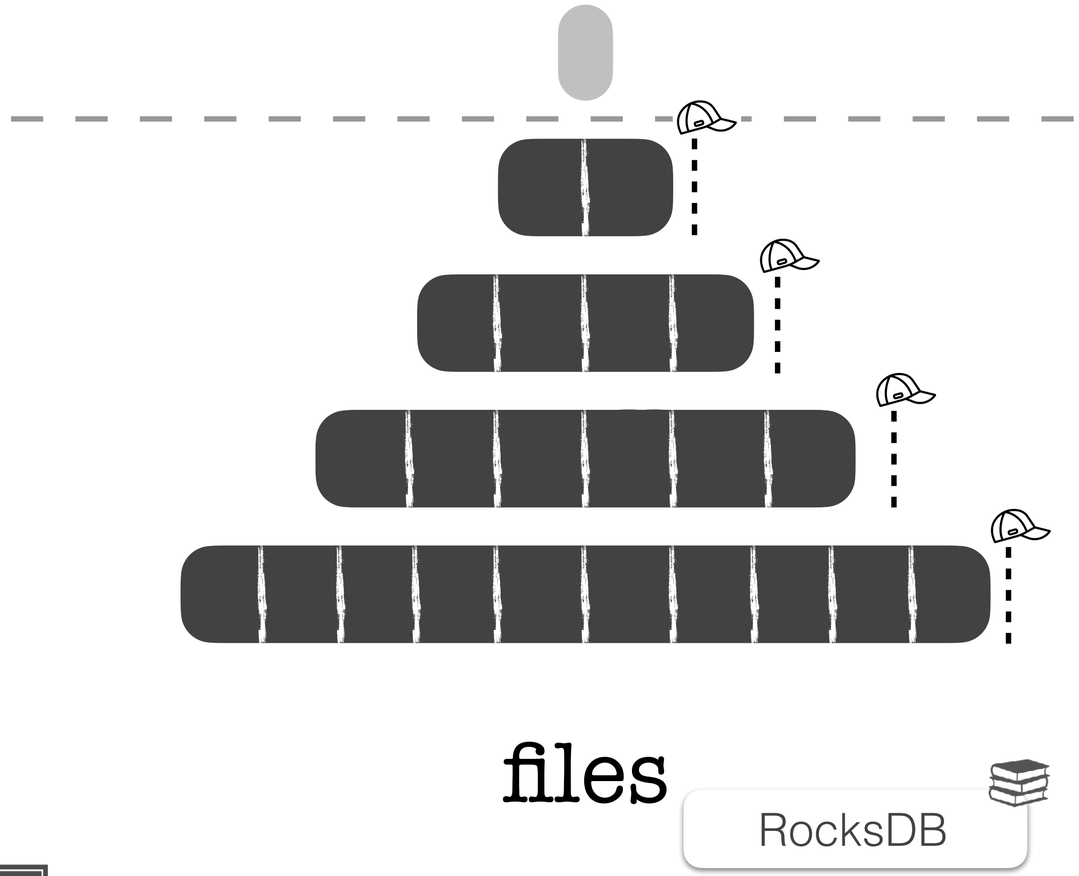

buffer
level 1
partial compaction
level 2
level 3
level 4


buffer
level 1
partial compaction
level 2
level 3
level 4


buffer
level 1
partial compaction
level 2
level 3
level 4

2 Compaction **Granularity**

data moved per compaction

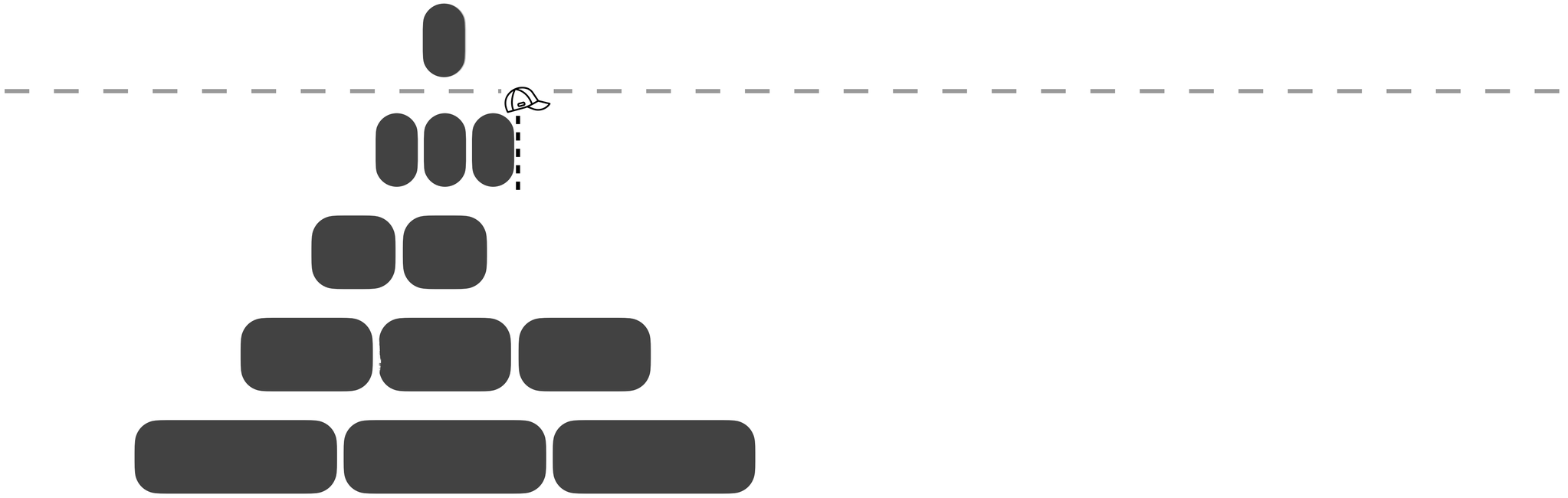


partial compaction

- ~same data movement
- amortized cost for compactions
- predictable perf.

Compaction **Granularity**

data moved per compaction



sorted runs in a level

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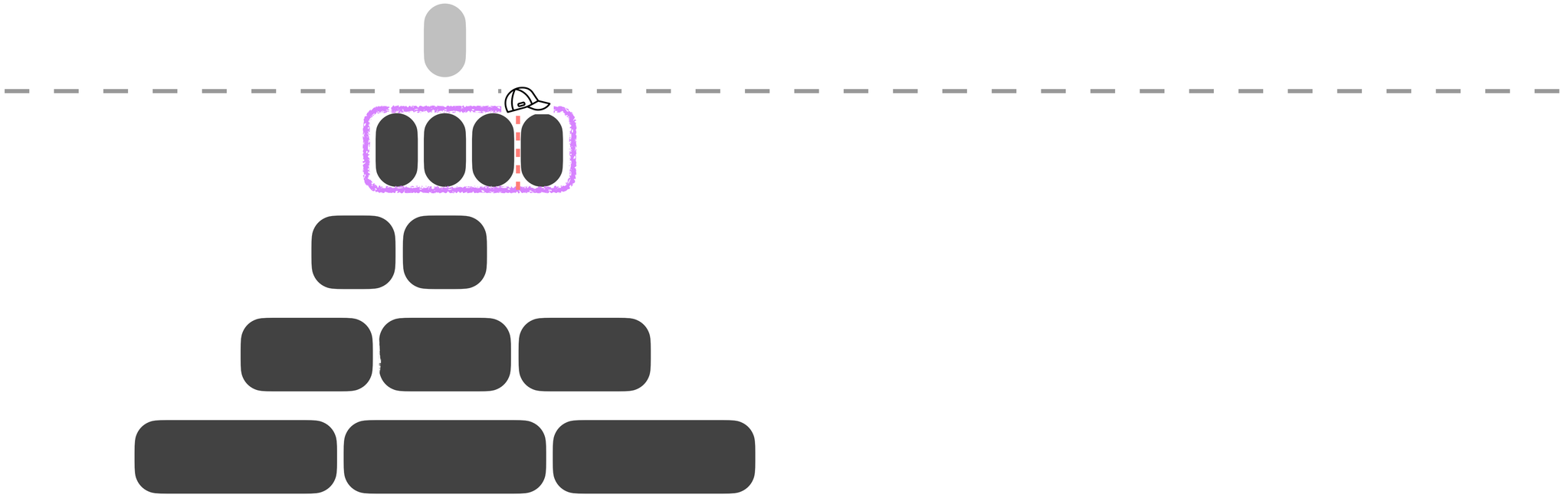
Compaction **Granularity**

data moved per compaction



sorted runs in a level

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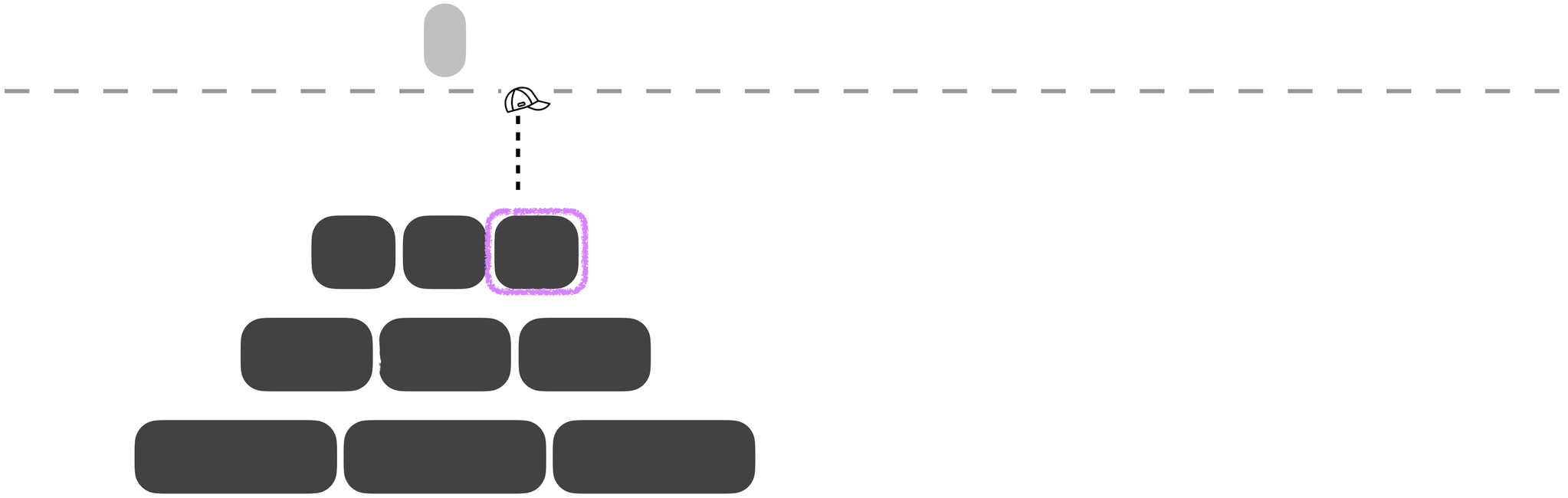
Compaction **Granularity**

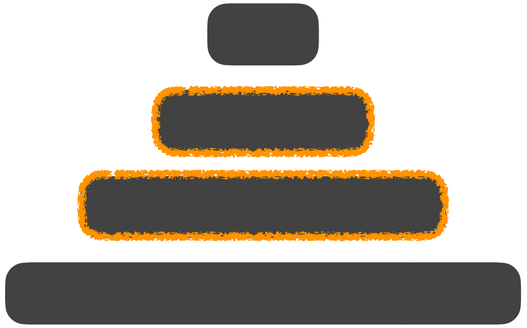
data moved per compaction



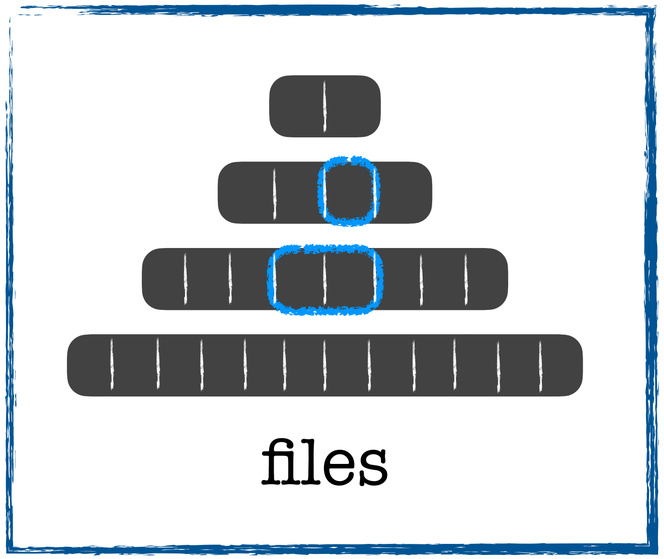
sorted runs in a level

Compaction **Granularity**

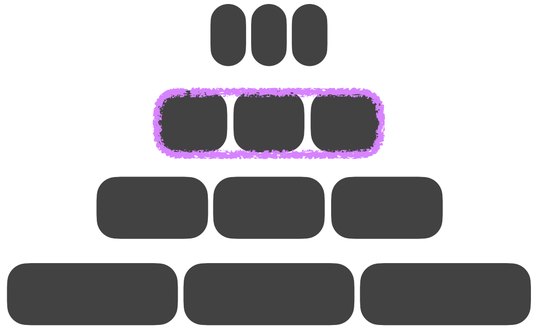
data moved per compaction



levels



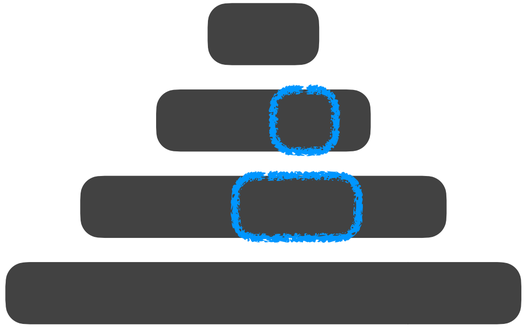
files



sorted runs in a level

Data Movement Policy

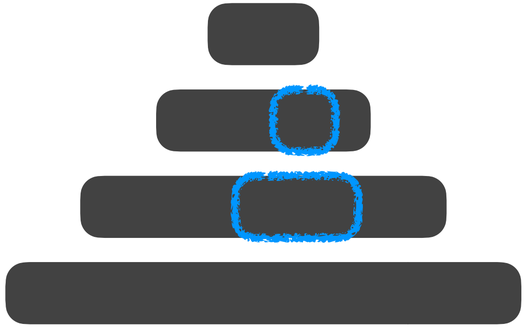
which data to compact



files

Data Movement Policy

which data to compact



files

round-robin !

minimum **overlap with parent** level WA

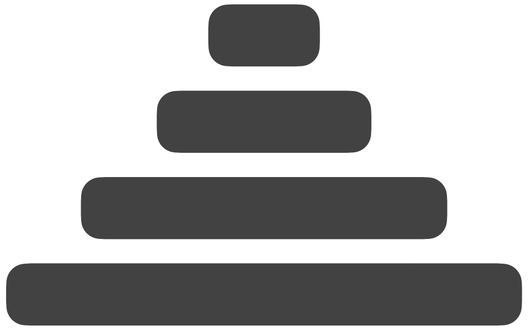
file with most **tombstones** SA

coldest file PQ

Compaction **Trigger**

invoking the compaction routine

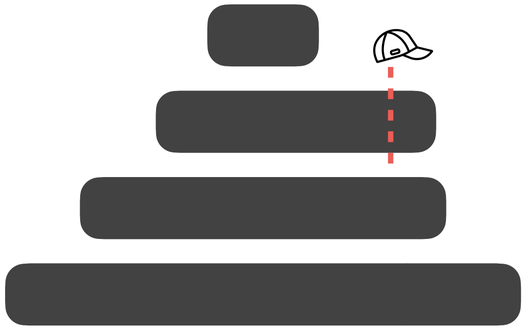
level **saturation**



Compaction **Trigger**

invoking the compaction routine

level **saturation**



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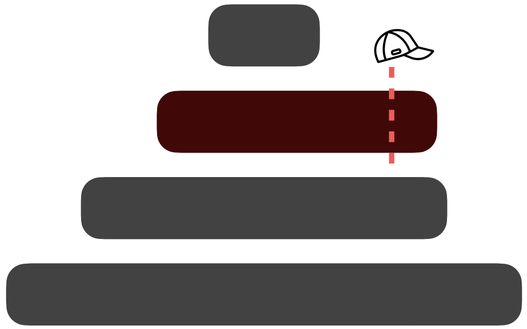
Compaction **Trigger**

invoking the compaction routine

level **saturation**



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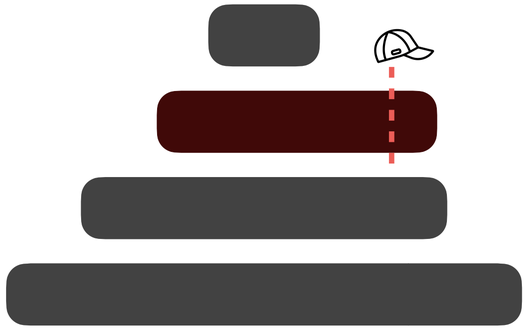
Compaction **Trigger**

invoking the compaction routine



level **saturation**

number of **sorted runs**

space amplification

SA

age of a file

De

Data Layout

Compaction Granularity

Data Movement Policy

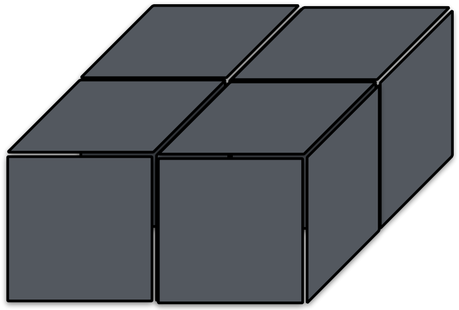
Compaction Trigger

Data Layout

Compaction Granularity

Data Movement Policy

Compaction Trigger



***Any* Compaction Algorithm**

Database	Data layout	Compaction Trigger					Compaction Granularity				Data Movement Policy							
		Level saturation	#Sorted runs	File staleness	Space amp.	Tombstone-TTL	Level	Sorted run	File (single)	File (multiple)	Round-robin	Least overlap (+1)	Least overlap (+2)	Coldest file	Oldest file	Tombstone density	Expired TS-TTL	N/A (entire level)
RocksDB [30], Monkey [22]	Leveling / 1-Leveling	✓		✓					✓	✓		✓		✓	✓	✓		
	Tiering		✓		✓	✓		✓										✓
LevelDB [32], Monkey (J.) [21]	Leveling	✓							✓		✓	✓	✓					
SlimDB [47]	Tiering	✓							✓	✓								✓
Dostoevsky [23]	*L*-leveling	$✓^L$	$✓^T$				$✓^L$	$✓^T$				$✓^L$						$✓^T$
LSM-Bush [24]	Hybrid leveling	$✓^L$	$✓^T$				$✓^L$	$✓^T$				$✓^L$						$✓^T$
Lethe [51]	Leveling	✓				✓			✓	✓		✓					✓	
Silk [11], Silk+ [12]	Leveling	✓							✓	✓	✓							
HyperLevelDB [35]	Leveling	✓							✓		✓	✓	✓					
PebblesDB [46]	Hybrid leveling	✓							✓	✓								✓
Cassandra [8]	Tiering		✓	✓		✓		✓										✓
	Leveling	✓				✓			✓	✓		✓				✓	✓	
WiredTiger [62]	Leveling	✓					✓											✓
X-Engine [34], Leaper [63]	Hybrid leveling	✓							✓	✓		✓				✓		
HBase [7]	Tiering		✓					✓										✓
AsterixDB [3]	Leveling	✓					✓											✓
	Tiering		✓					✓										✓

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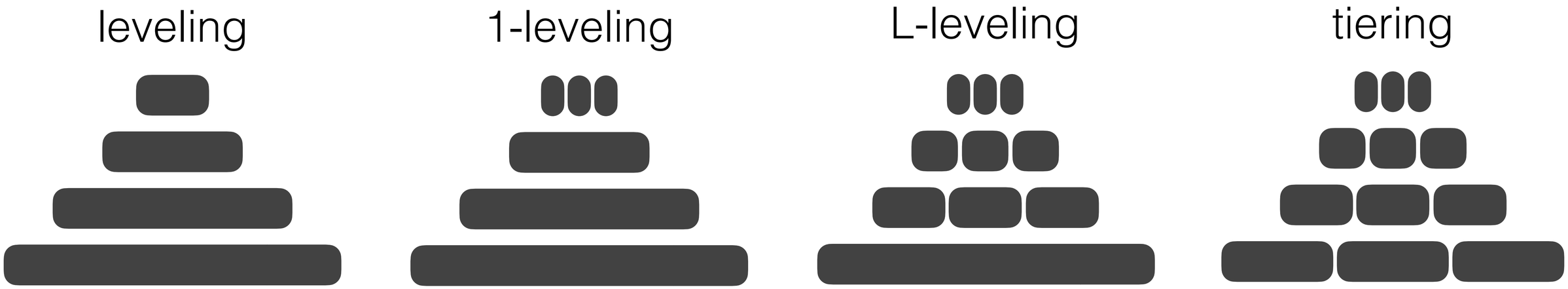
Database	Data layout	Compaction Trigger					Compaction Granularity				Data Movement Policy							
		Level saturation	#Sorted runs	File staleness	Space amp.	Tombstone-TTL	Level	Sorted run	File (single)	File (multiple)	Round-robin	Least overlap (+1)	Least overlap (+2)	Coldest file	Oldest file	Tombstone density	Expired TS-TTL	N/A (entire level)
RocksDB [30], Monkey [22]	Leveling / 1-Leveling	✓		✓					✓	✓		✓		✓	✓	✓		
	Tiering		✓		✓	✓		✓										✓
LevelDB [32], Monkey (J.) [21]	Leveling	✓							✓		✓	✓	✓					
SlimDB [47]	Tiering	✓							✓	✓								✓
Dostoevsky [23]	*L*-leveling	$✓^{L}$	$✓^{T}$				$✓^{L}$	$✓^{T}$				$✓^{L}$						$✓^{T}$
LSM-Bush [24]	Hybrid leveling	$✓^{L}$	$✓^{T}$				$✓^{L}$	$✓^{T}$				$✓^{L}$						$✓^{T}$
Lethe [51]	Leveling	✓				✓			✓	✓		✓					✓	
Silk [11], Silk+ [12]	Leveling	✓							✓	✓	✓							
HyperLevelDB [35]	Leveling	✓							✓		✓	✓	✓					
PebblesDB [46]	Hybrid leveling	✓							✓	✓								✓
Cassandra [8]	Tiering		✓	✓		✓		✓										✓
	Leveling	✓				✓			✓	✓		✓				✓	✓	
WiredTiger [62]	Leveling	✓					✓											✓
X-Engine [34], Leaper [63]	Hybrid leveling	✓							✓	✓		✓				✓		
HBase [7]	Tiering		✓					✓										✓
AsterixDB [3]	Leveling	✓					✓											✓
	Tiering		✓					✓										✓

Database	Data layout	Compaction Trigger					Compaction Granularity				Data Movement Policy							
		Level saturation	#Sorted runs	File staleness	Space amp.	Tombstone-TTL	Level	Sorted run	File (single)	File (multiple)	Round-robin	Least overlap (+1)	Least overlap (+2)	Coldest file	Oldest file	Tombstone density	Expired TS-TTL	N/A (entire level)
RocksDB [30], Monkey [22]	Leveling / 1-Leveling	✓		✓					✓	✓		✓		✓	✓	✓		
	Tiering		✓		✓	✓		✓										✓
LevelDB [32], Monkey (J.) [21]	Leveling	✓							✓		✓	✓	✓					
SlimDB [47]	Tiering	✓							✓	✓								✓
Dostoevsky [23]	*L*-leveling	$✓^{L}$	$✓^{T}$				$✓^{L}$	$✓^{T}$				$✓^{L}$						$✓^{T}$
LSM-Bush [24]	Hybrid leveling	$✓^{L}$	$✓^{T}$				$✓^{L}$	$✓^{T}$				$✓^{L}$						$✓^{T}$
Lethe [51]	Leveling	✓				✓			✓	✓		✓					✓	
Silk [11], Silk+ [12]	Leveling	✓							✓	✓	✓							
HyperLevelDB [35]	Leveling	✓							✓		✓	✓	✓					
PebblesDB [46]	Hybrid leveling	✓							✓	✓								✓
Cassandra [8]	Tiering		✓	✓		✓		✓										✓
	Leveling	✓				✓			✓	✓		✓				✓	✓	
WiredTiger [62]	Leveling	✓					✓											✓
X-Engine [34], Leaper [63]	Hybrid leveling	✓							✓	✓		✓				✓		
HBase [7]	Tiering		✓					✓										✓
AsterixDB [3]	Leveling	✓					✓											✓
	Tiering		✓					✓										✓

Storage Layer **Design Continuum**

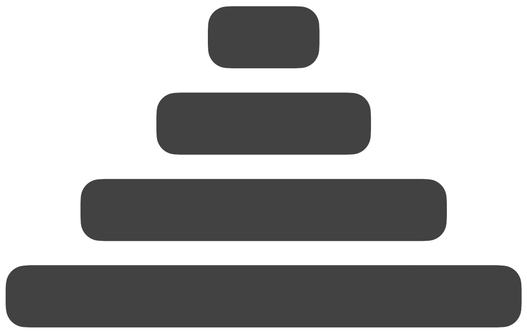


Any design can be defined by the tuple-set: $(\mathtt{T}, \mathtt{i})$

Storage Layer **Design Continuum**

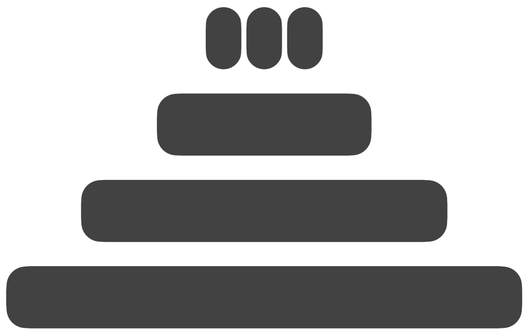
leveling

(T, 0)



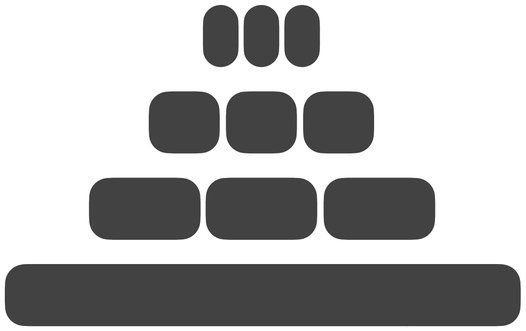
1-leveling

(T, 1)



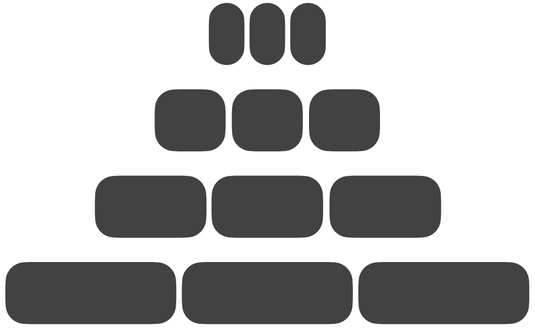
L-leveling

(T, L)



tiering

(T, L+1)



Any design can be defined by the tuple-set: (T, i)

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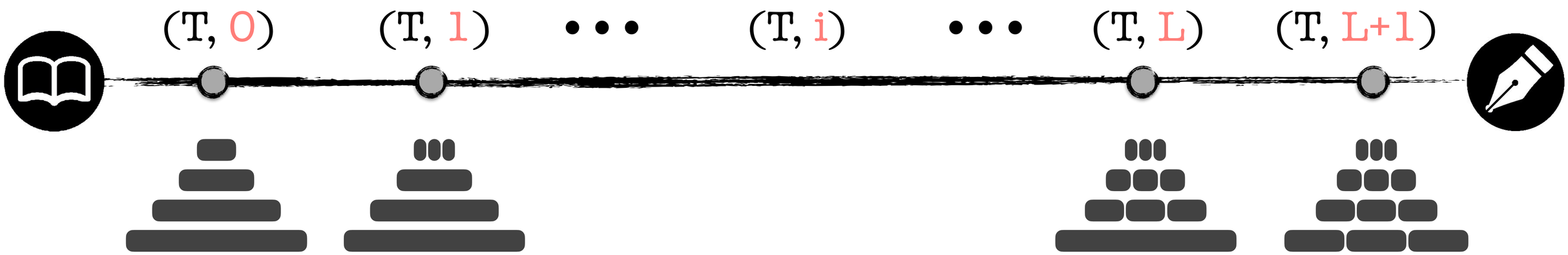
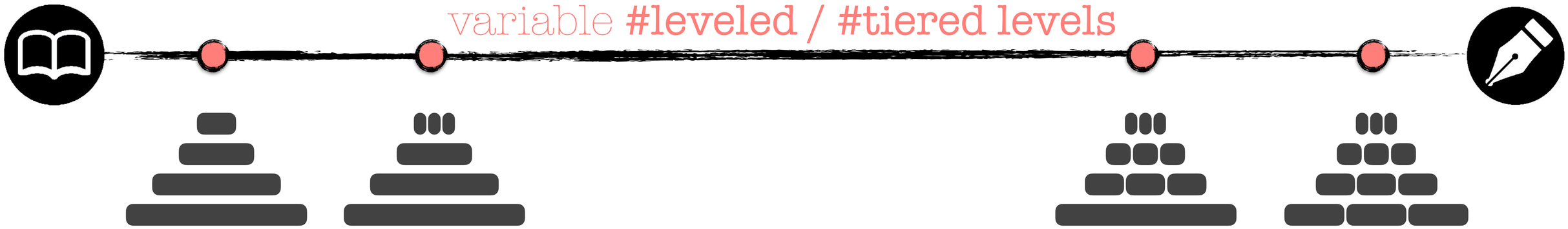
SarkarVLDB21

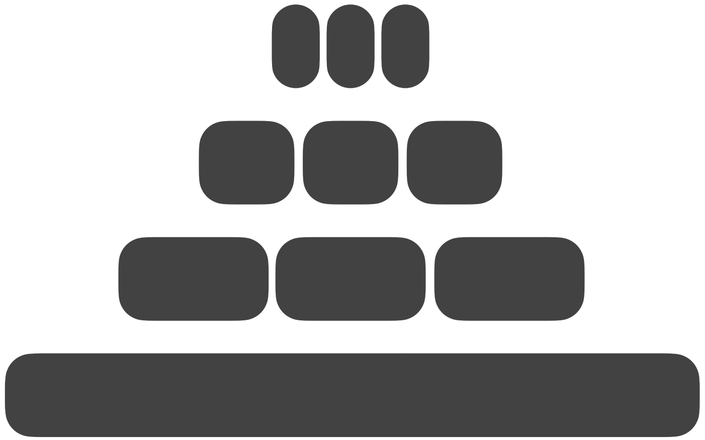
Storage Layer **Design Continuum**



Storage Layer **Design Continuum**



Storage Layer **Design Continuum**



size ratio

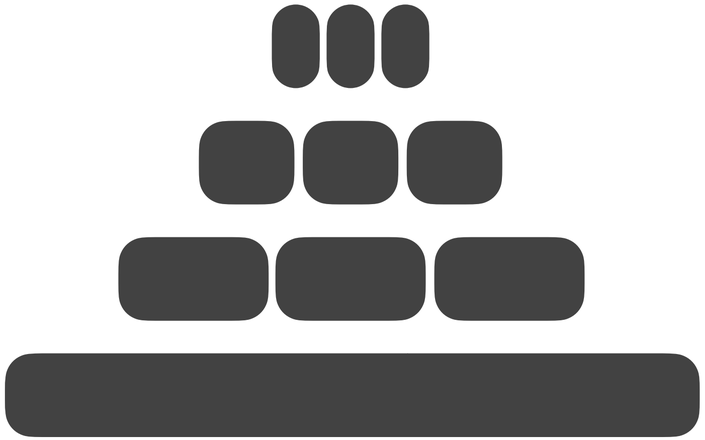
T

T

T

T

Storage Layer **Design Continuum**



size ratio

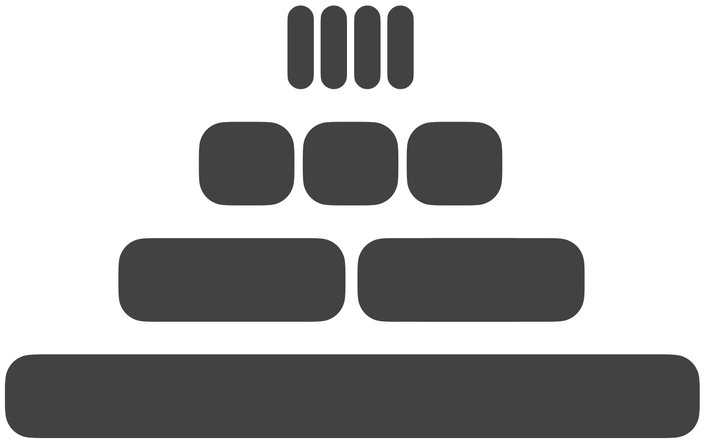
T

T

T

T

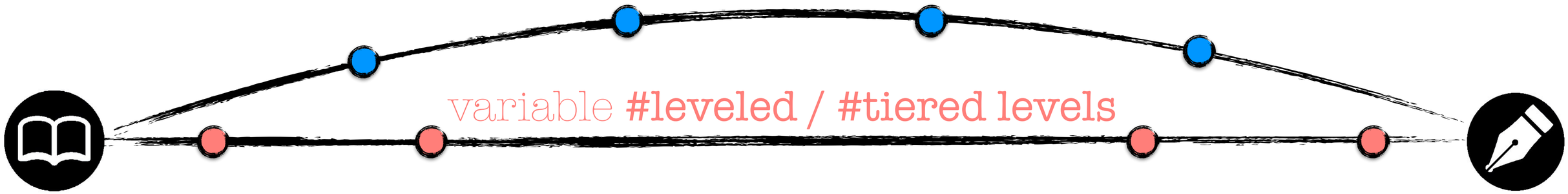
Storage Layer **Design Continuum**



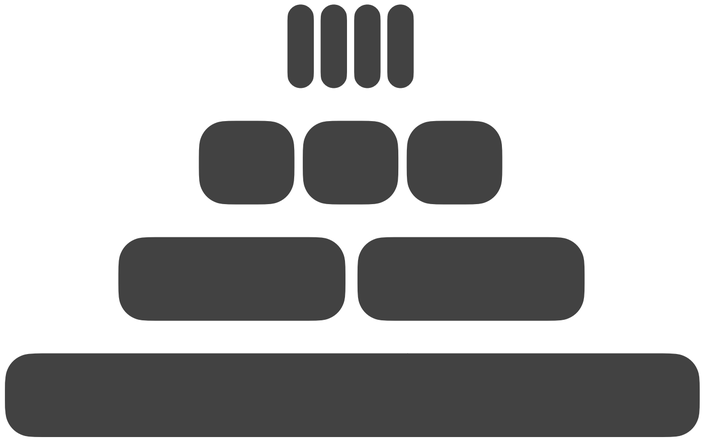
size ratio	#runs
T	4
T	3
T	2
T	1

Storage Layer **Design Continuum**

variable **#runs/level**



variable **#leveled / #tiered levels**



size ratio	#runs
T	4
T	3
T	2
T	1

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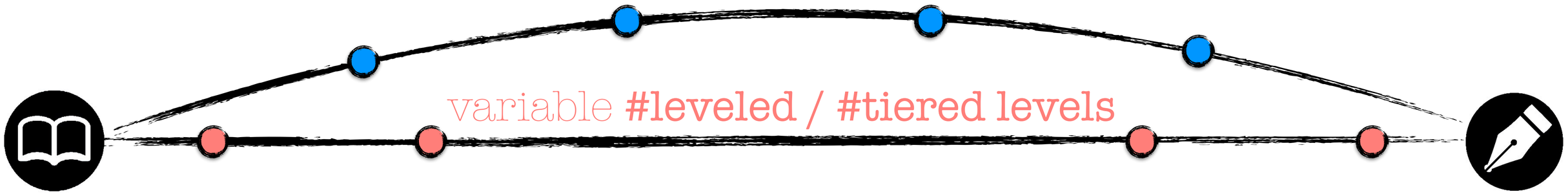
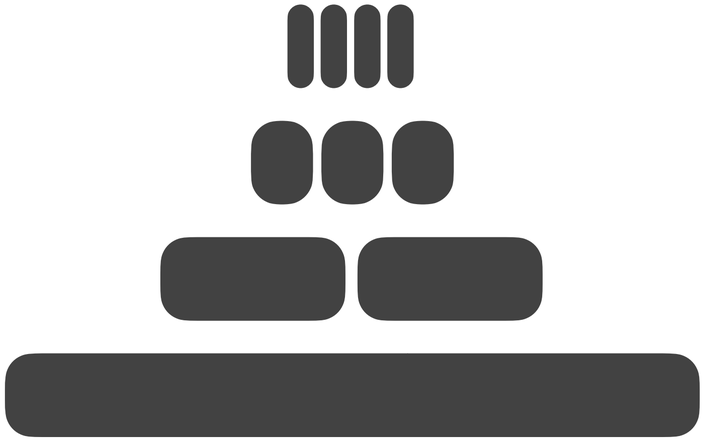
DayanSIGMOD18

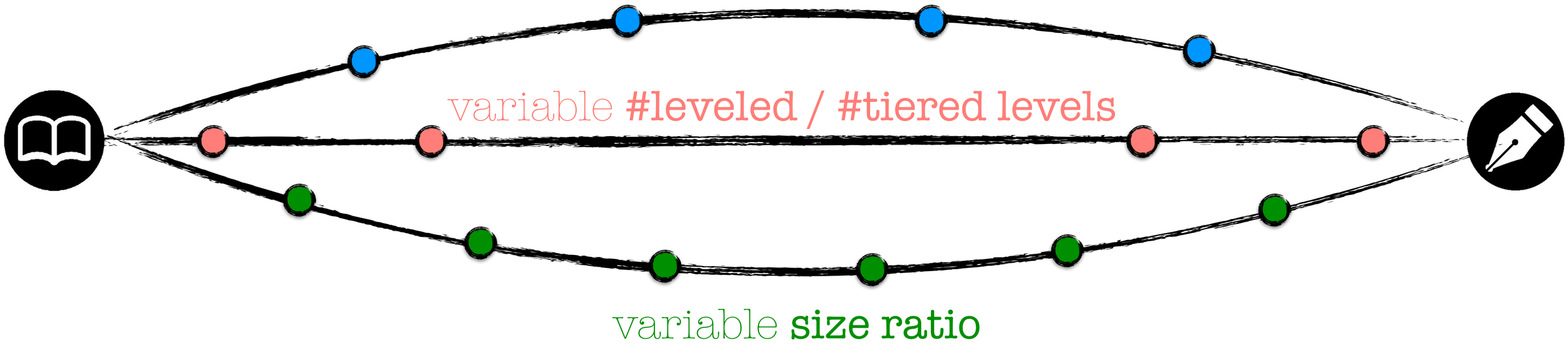
Storage Layer **Design Continuum**



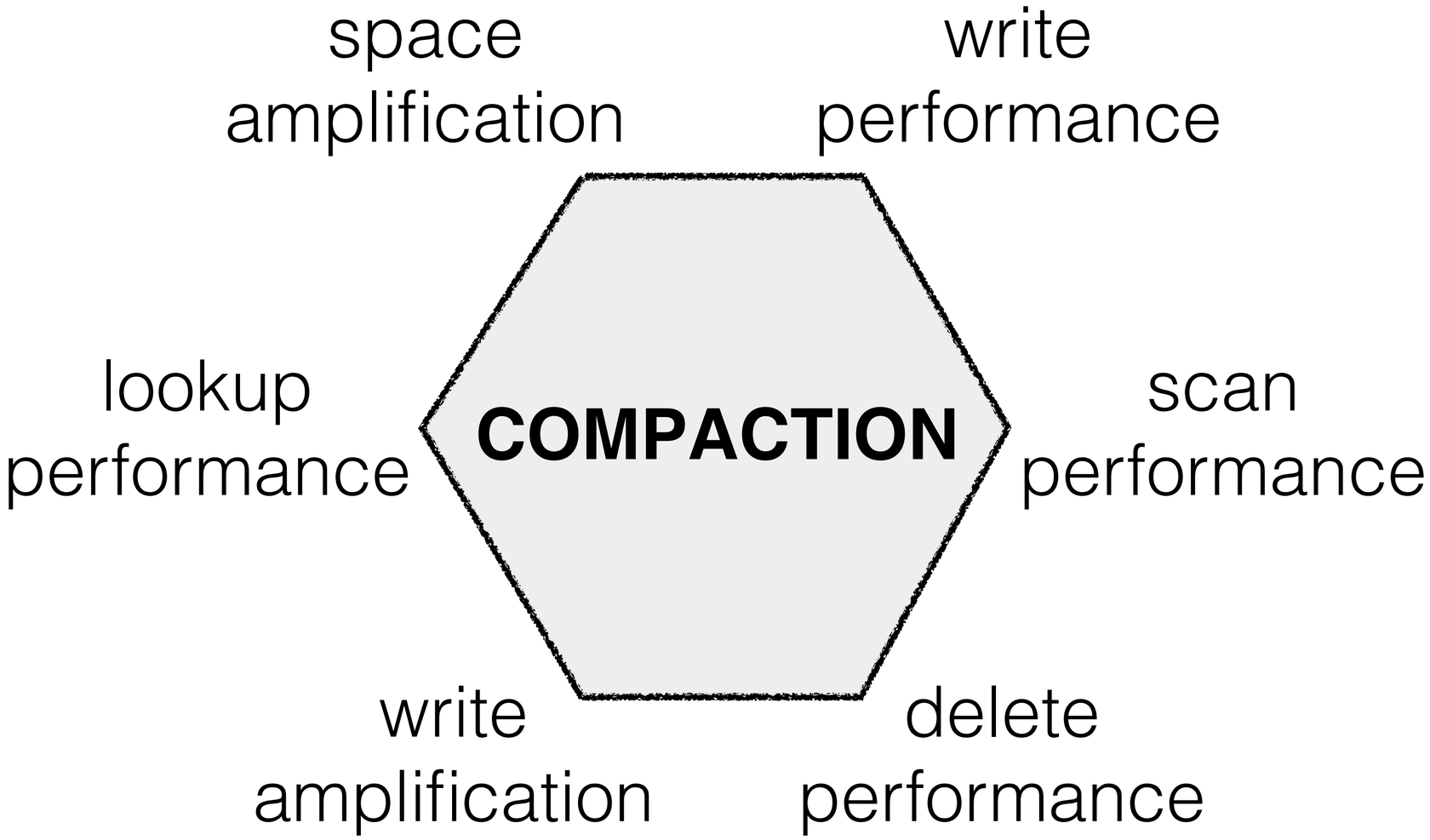


size ratio	#runs
2	4
2.5	3
3	2
4	1

Storage Layer **Design Continuum**



The LSM storage layer design continuum


space
amplification
write
performance
lookup
performance
COMPACTION
scan
performance
write
amplification
delete
performance

Optimizing **Compactions**

Background Compactions

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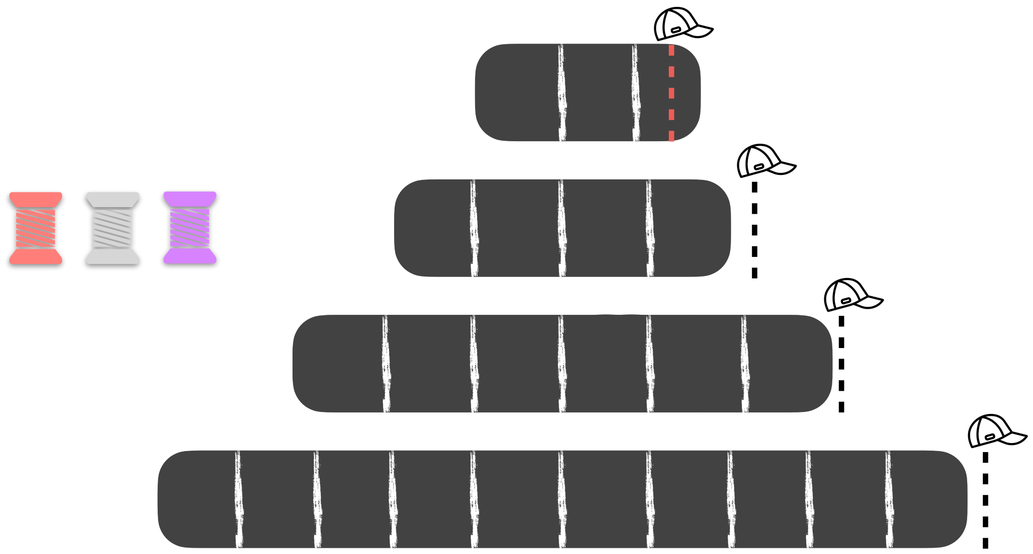
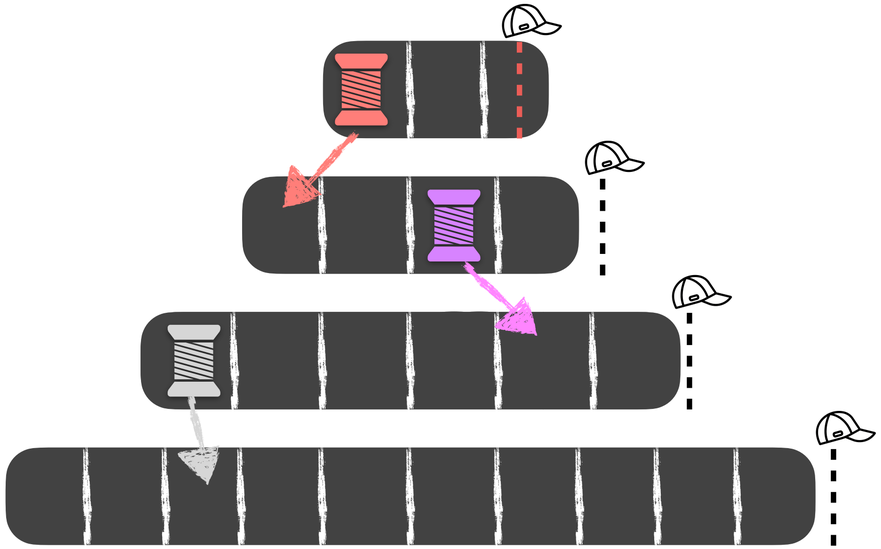
Optimizing **Compactions**

Background Compactions



Optimizing **Compactions**

Background Compactions



- non-blocking reads/writes
- improves write throughput

Optimizing **Compactions**

Background Compactions

Compaction Priority

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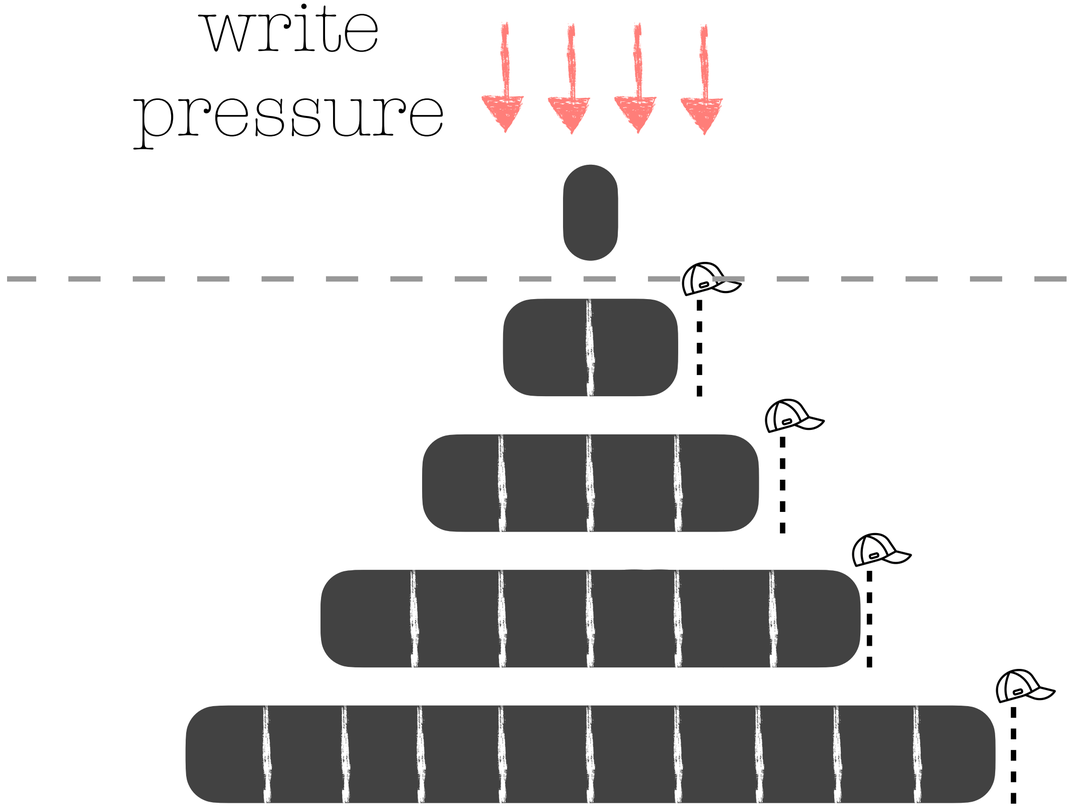
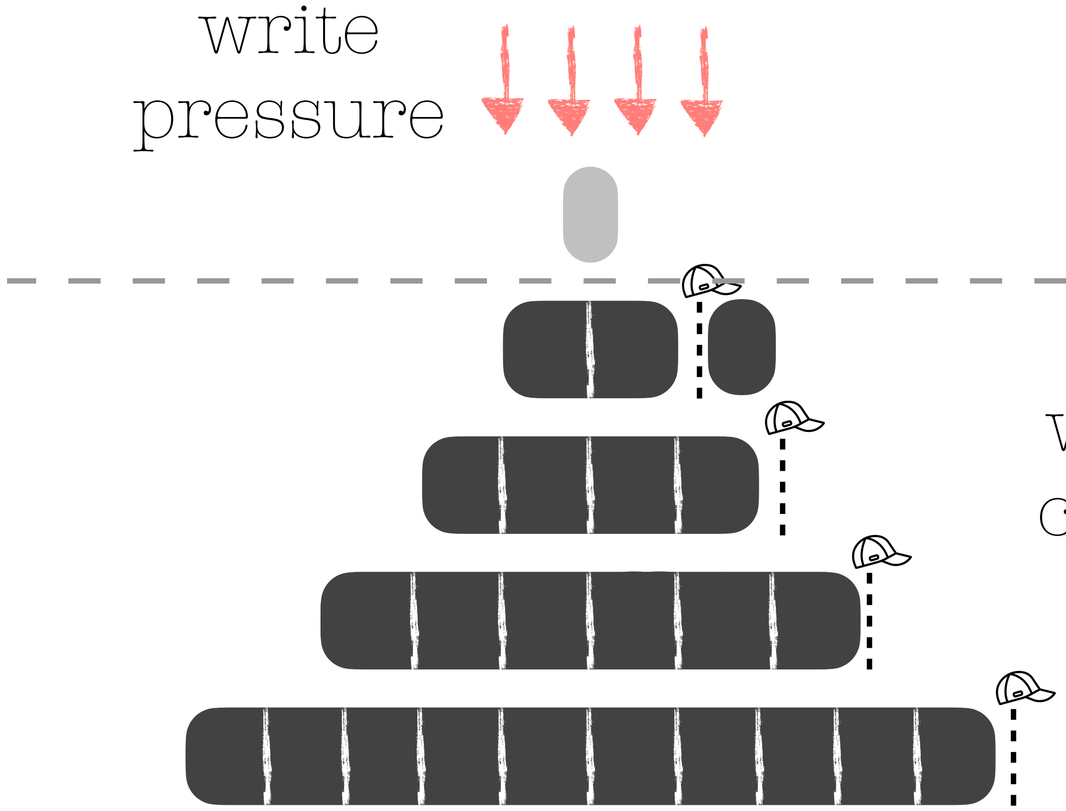
Optimizing **Compactions**



Background Compactions

Compaction Priority

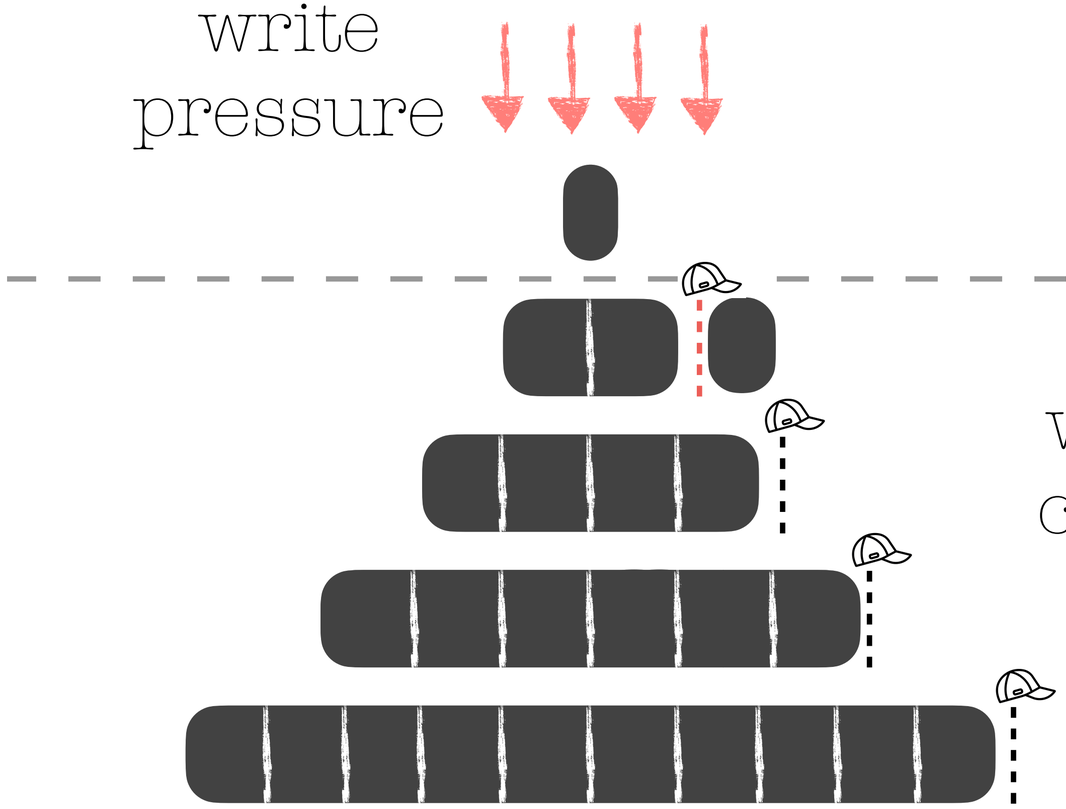
Optimizing **Compactions**



Background Compactions

Compaction Priority

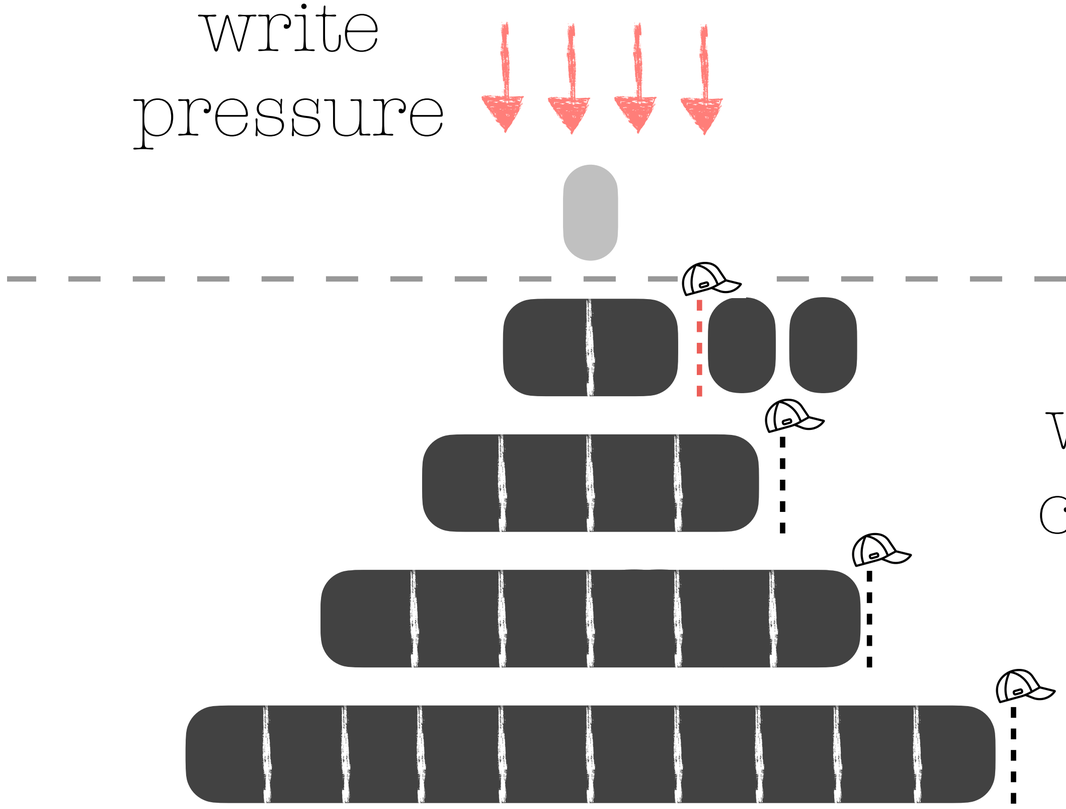
Optimizing **Compactions**



Background Compactions

Compaction Priority

Optimizing **Compactions**

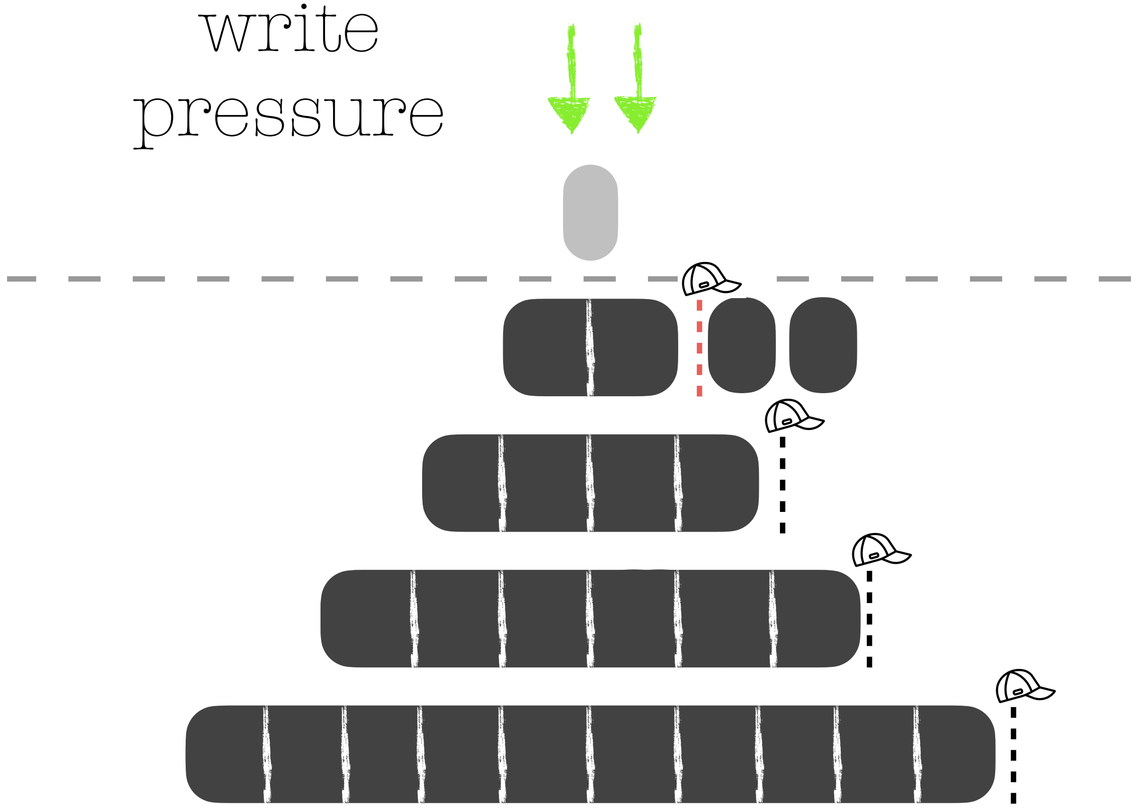


prioritize
writes over
compaction

Background
Compactions

Compaction
Priority

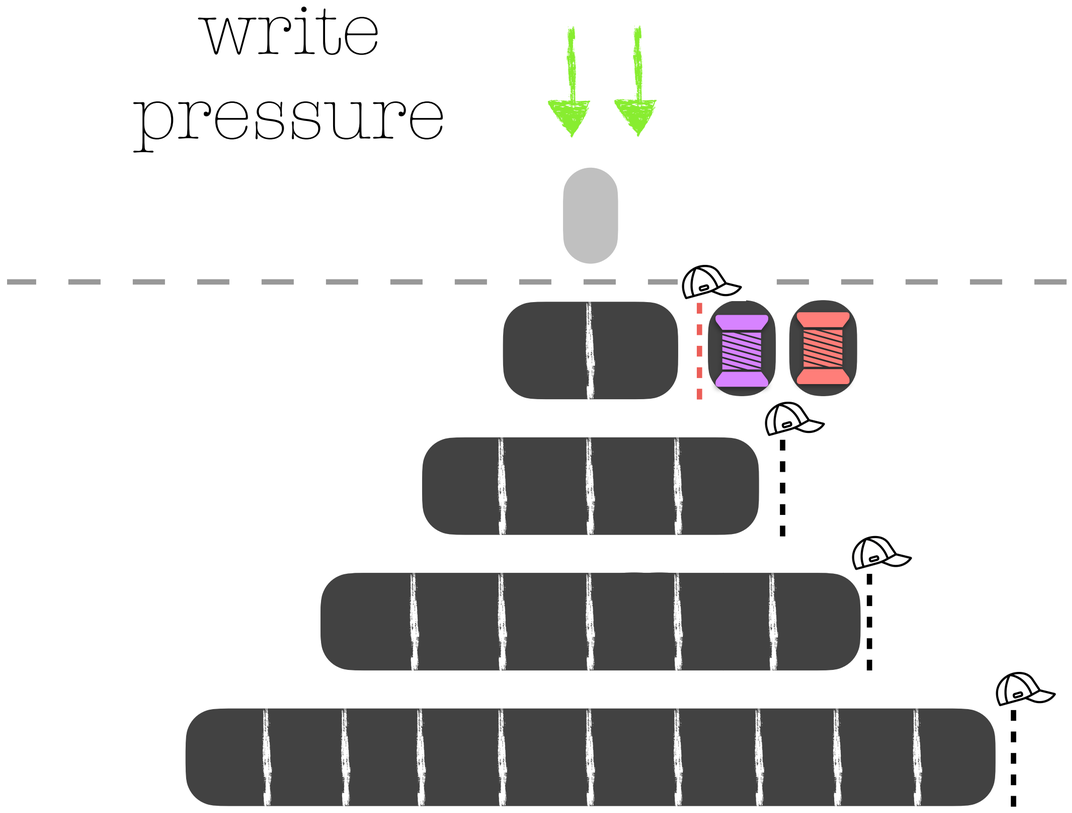
Optimizing **Compactions**



Background Compactions

Compaction Priority

Optimizing **Compactions**

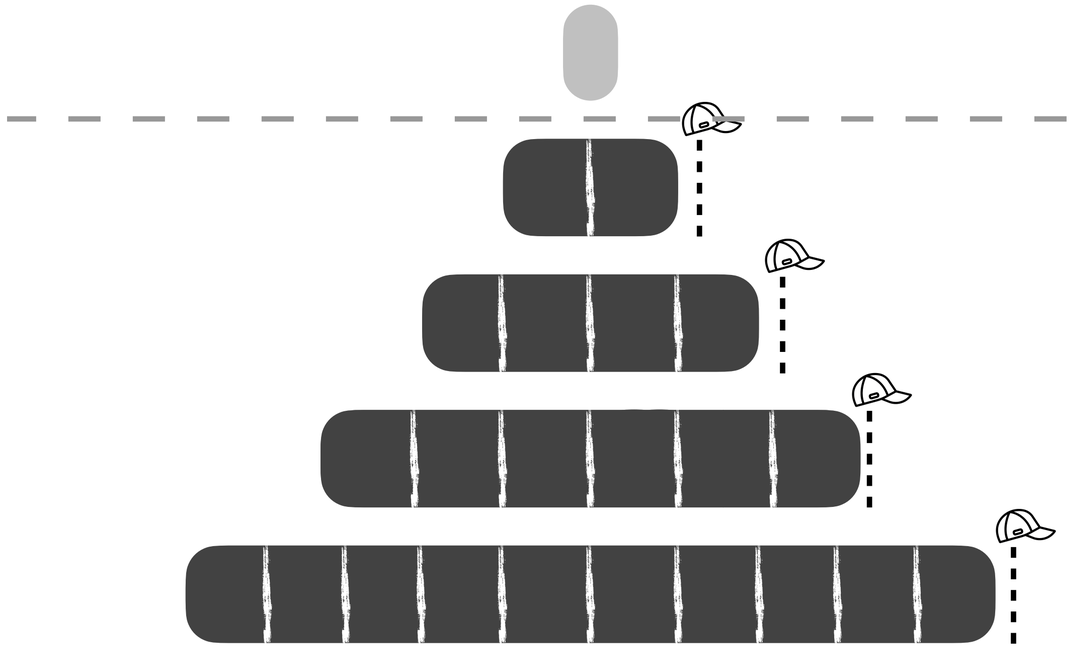


Background Compactions

Compaction Priority

- sustain heavy write bursts
- tree becomes out of shape

Optimizing **Compactions**

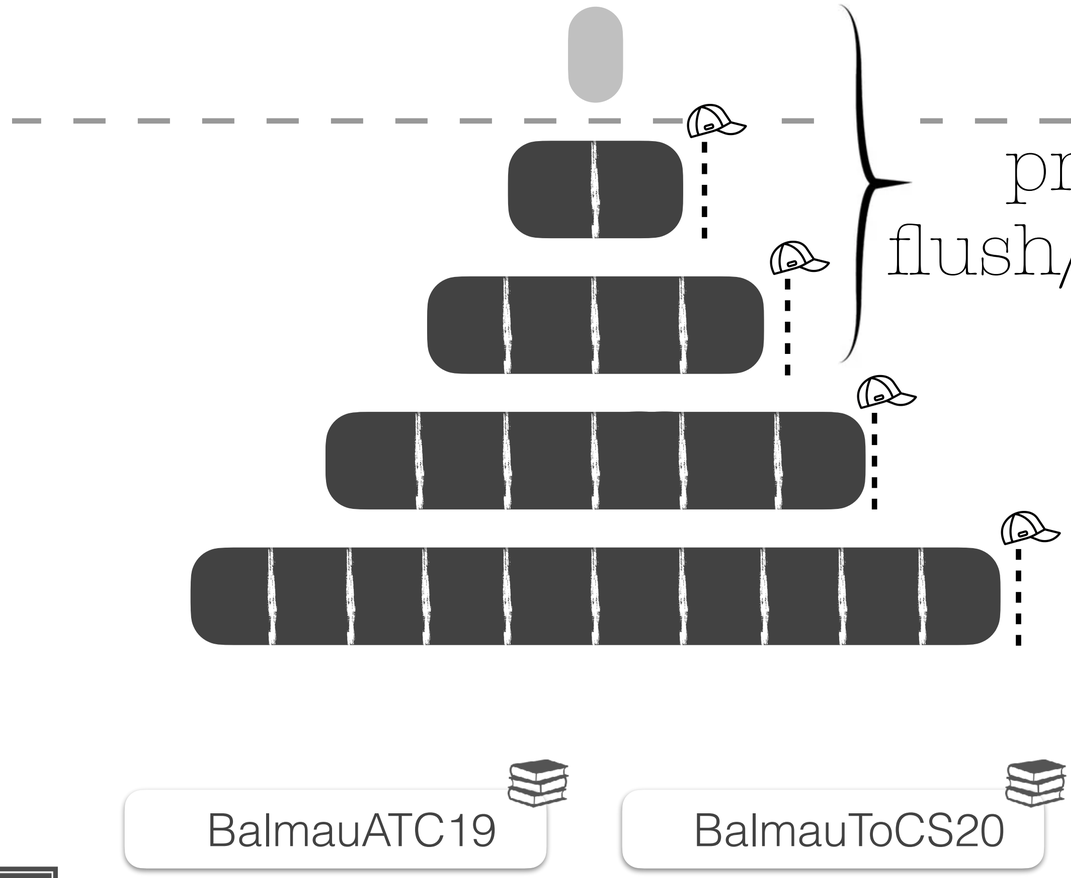


Background Compactions

Compaction Priority

I/O Scheduler

Optimizing **Compactions**



Background Compactions

Compaction Priority

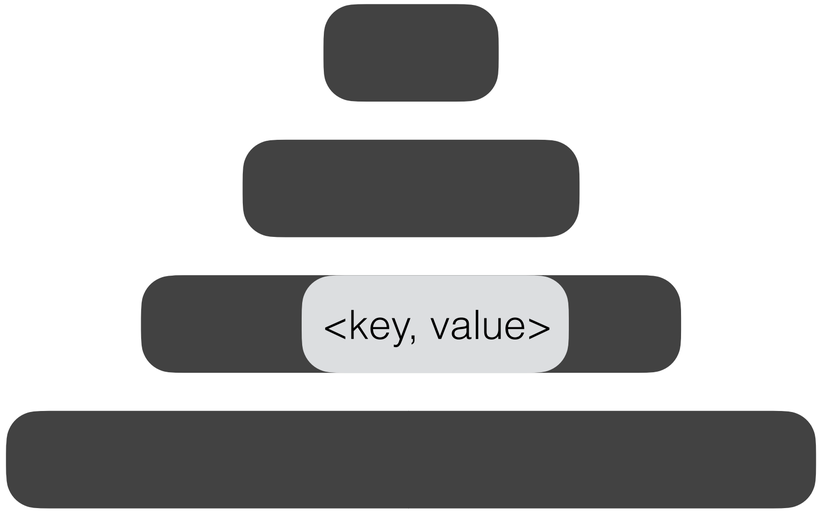
I/O Scheduler

- eliminates write stalls
- no unnecessary high-priority compactions in lower levels

BalmauATC19

BalmauToCS20

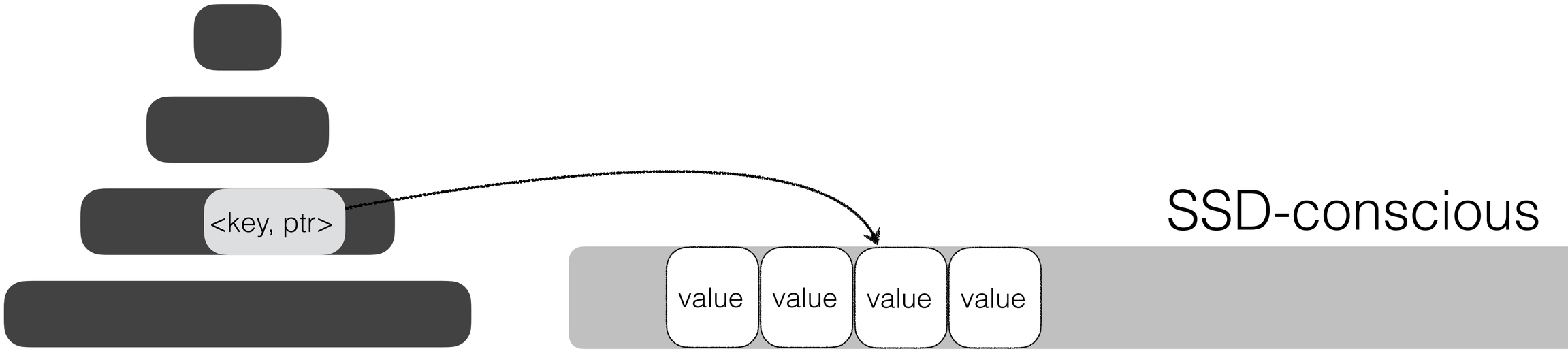
Data Placement Variations



key-value separation

LuFAST16

Data Placement Variations



key-value separation

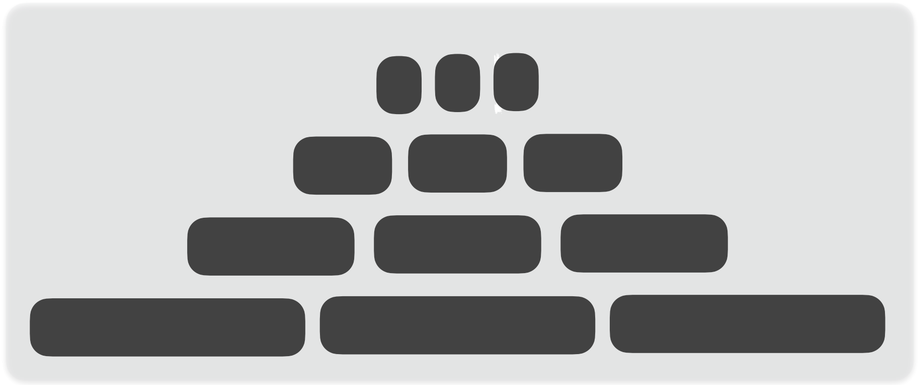
LuFAST16

- reduced write amplification
- better read performance

Data Placement Variations

partitioning / sharding

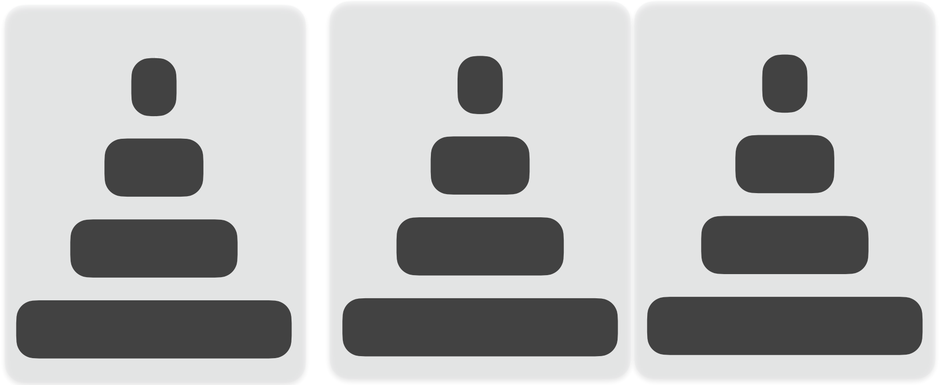
Data Placement Variations



storage

partitioning

RajuSOSP17



storage-1 storage-2 storage-3

sharding

HuangSIGMOD21

- improved ingestion throughput
- reduced write amplification

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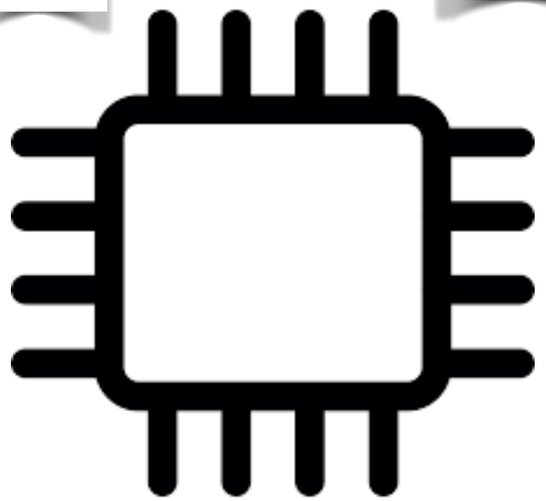
Summary: **Ingestion Optimization**

data structure

size

flush strategy



main memory design elements

compaction design space

tuning compactions

data layout on storage

key-value separation

data partitioning

data sharding

hardware-conscious designs

CS 561: ***Data Systems Architecture***

Class 7

Compaction in LSM Trees

Tarikul Islam Papon

BOSTON UNIVERSITY

Slide Courtesy: Dr. Subhadeep Sarkar

https://bu-disc.github.io/CS561/

DiSC lab