COSI 167A
Advanced Data Systems

Class 18

Indexing + Modern Hardware Trends

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Brandeis University

https://ssd-brandeis.github.io/COSI-167A/

lab

Class **logistics**

and administrivia

The **mid-semester project report** is due **today** (**11:59 PM**).

5 weeks remaining until the end of semester. **Use your time wisely**!

Final project report has **2 parts**.

- **Preliminary project report** due on **Dec 3**.
- Followed by **project presentation** (plan for a **15-min presentation**).
- **Final project report** due on **Dec 10**.

Today in COSI 167A

What's on the cards?

summarizing **indexing** techniques

modern **hardware trends**

What is an **index**?

The oracle of DBMSs!

Index

auxiliary data structure that helps find target data **quickly**

typically, **light-weight**, small enough to **fit in memory**

special form of < **key**, **value** >

indexed attribute

position/location/rowID/primary key/…

What are the possible **index designs**?

From B-trees to cracking

index	data organization	remark
B+-tree	Sorted & partitioned	Partition **k-ways** recursively
LSM-tree	Partially sorted	Optimize **inserts**
Radix tree	Radix-based	Partition using **key radix**
Hash index	Hash buckets	Partition by **hashing the key**
Bitmap index	None	Succinct **membership** represention
Zonemap	None	Use **metadata** to skip access
Cracking	Cracked & eventually sorted	**Query-driven** partitioning

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B+-tree					
LSM-tree					
Radix tree					
Hash index					
Bitmap index					
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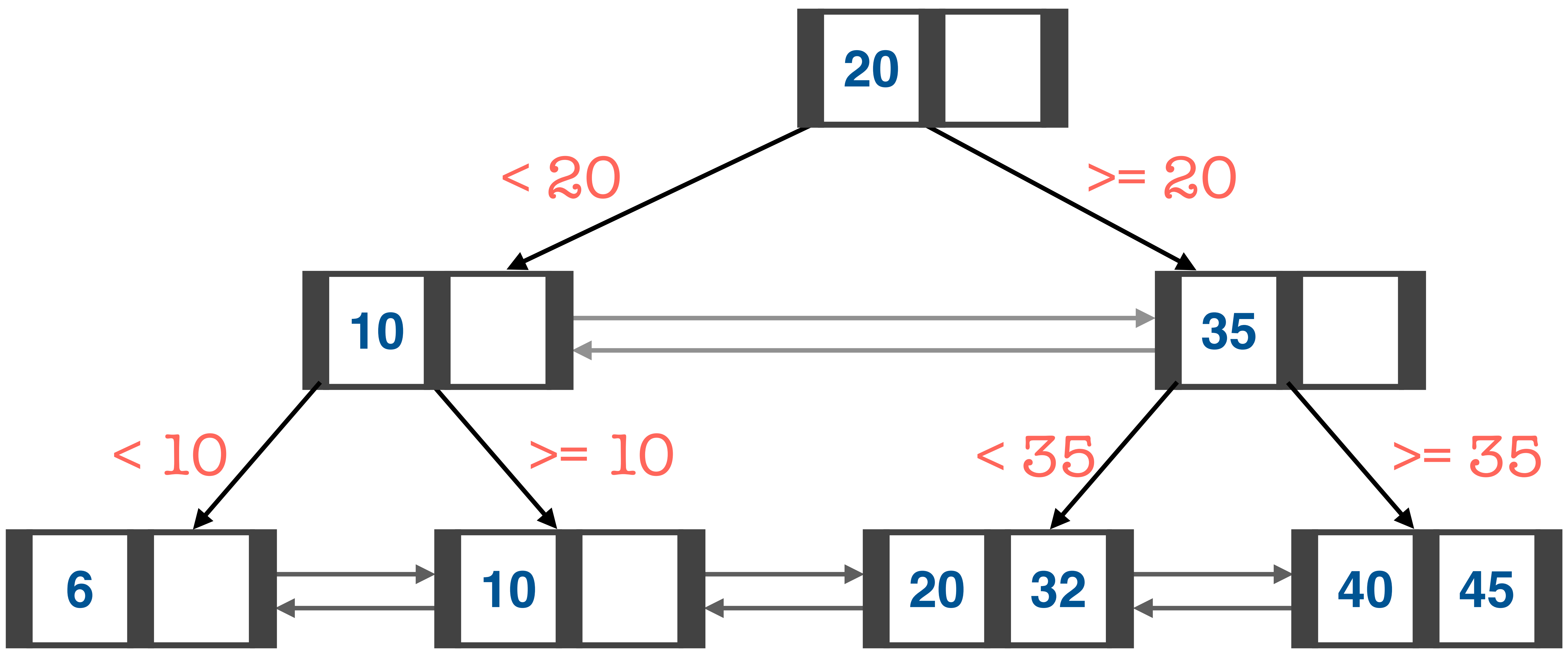
Cracking					

B⁺-tree

The most popular index data structure



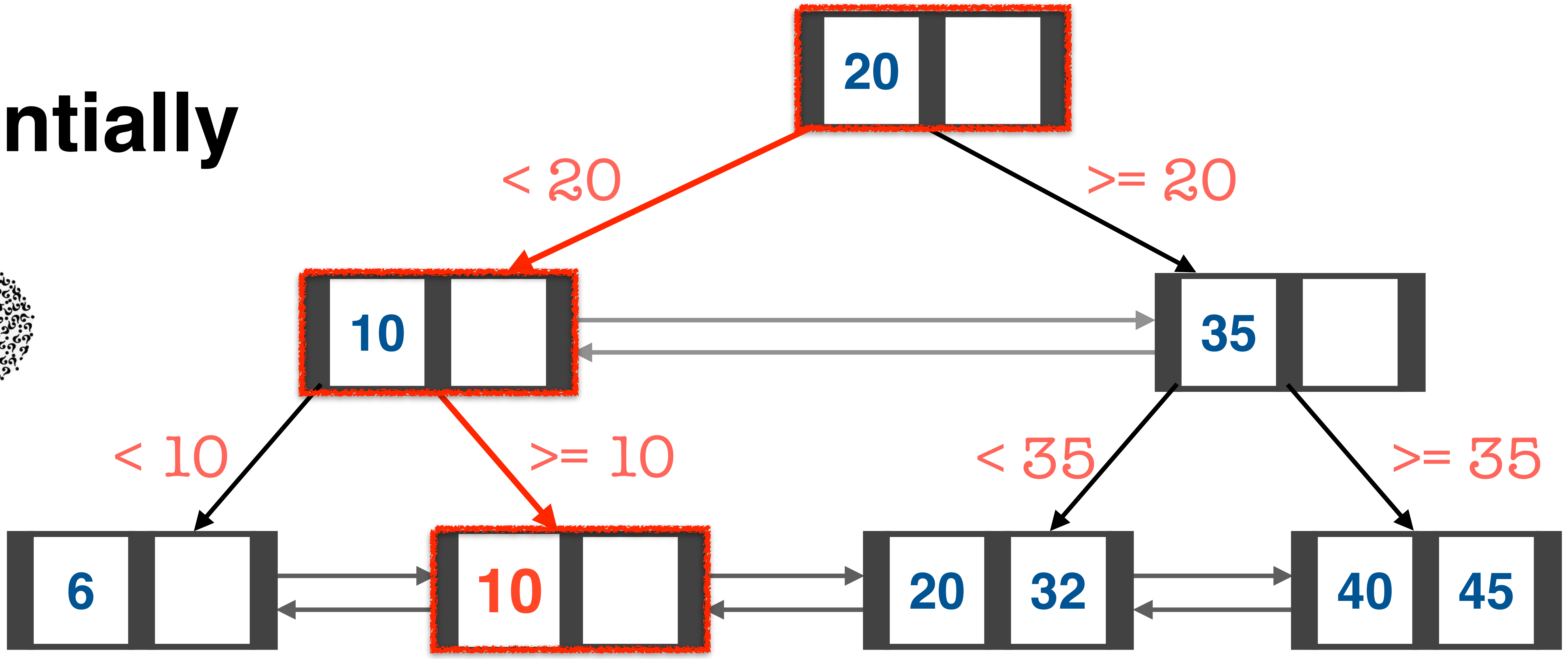
B^+-tree

The most popular index data structure

Search begins at root, and key comparisons **direct it to a leaf**

Point lookups are super-**efficient**

Range lookups can scan **sequentially**



Thought Experiment 1

What about **skewed data**?

It does well!

What are the possible **index designs**?

From B-trees to cracking

index	**point** queries	**short range** queries	**long range** queries	data **skew**	**updates**
B^+-tree	✓	✓	✓	✓	−
LSM-tree					
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Hash index					
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Cracking					

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LSM-tree	✓	✗	–	✓	✓
Radix tree					
Hash index					
Bitmap index					
Zonemap					
Cracking					

Thought Experiment 2

What about **growing data size**?

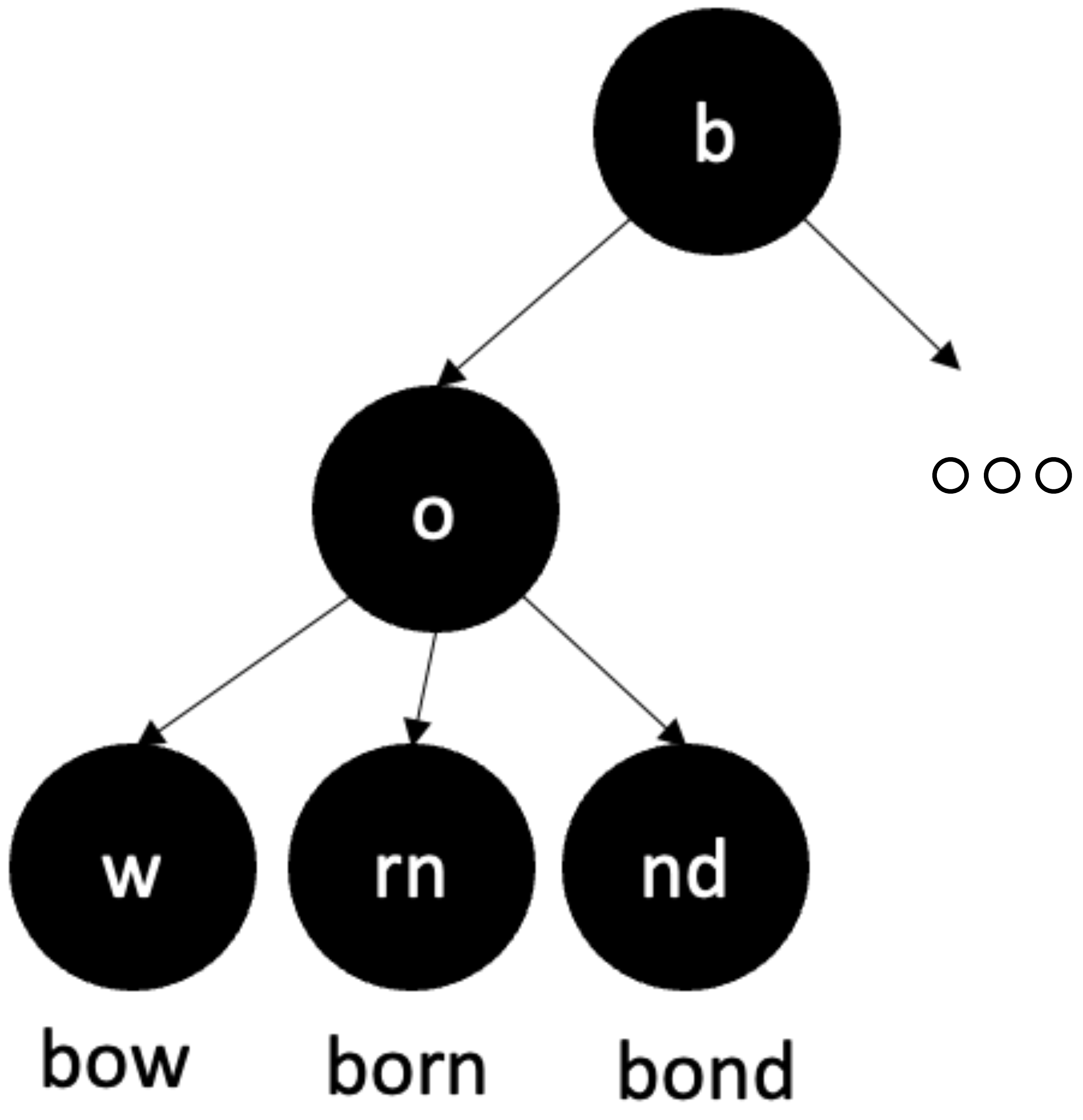
tree grows & so do costs!

Radix trees

A special case of tries and prefix B-trees

Idea: use **common prefixes** for internal nodes to **reduce size/height**!

max. tree hieght = **length of the longest key**



what about **integer keys**?

Radix trees

A special case of tries and prefix B-trees

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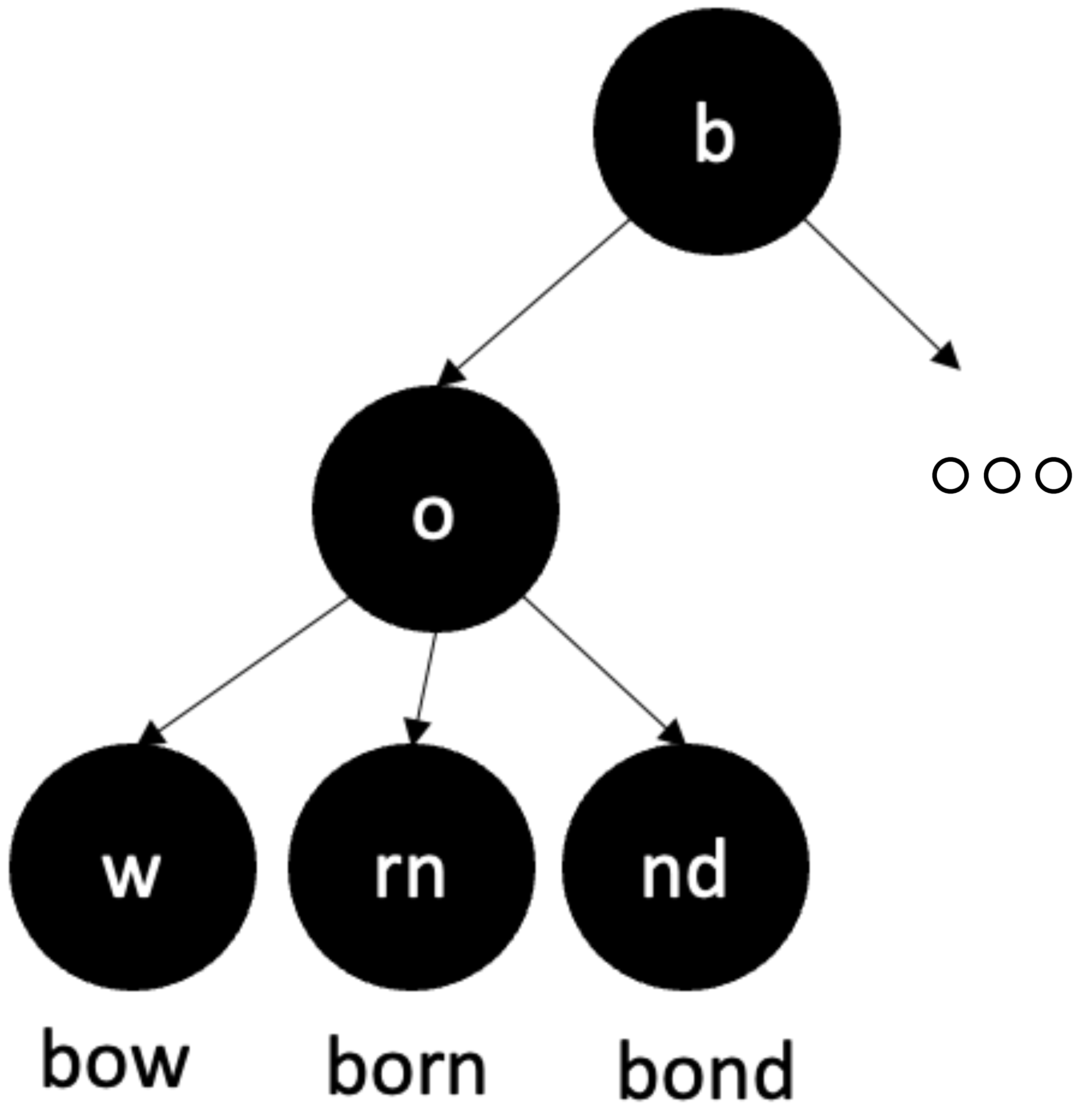

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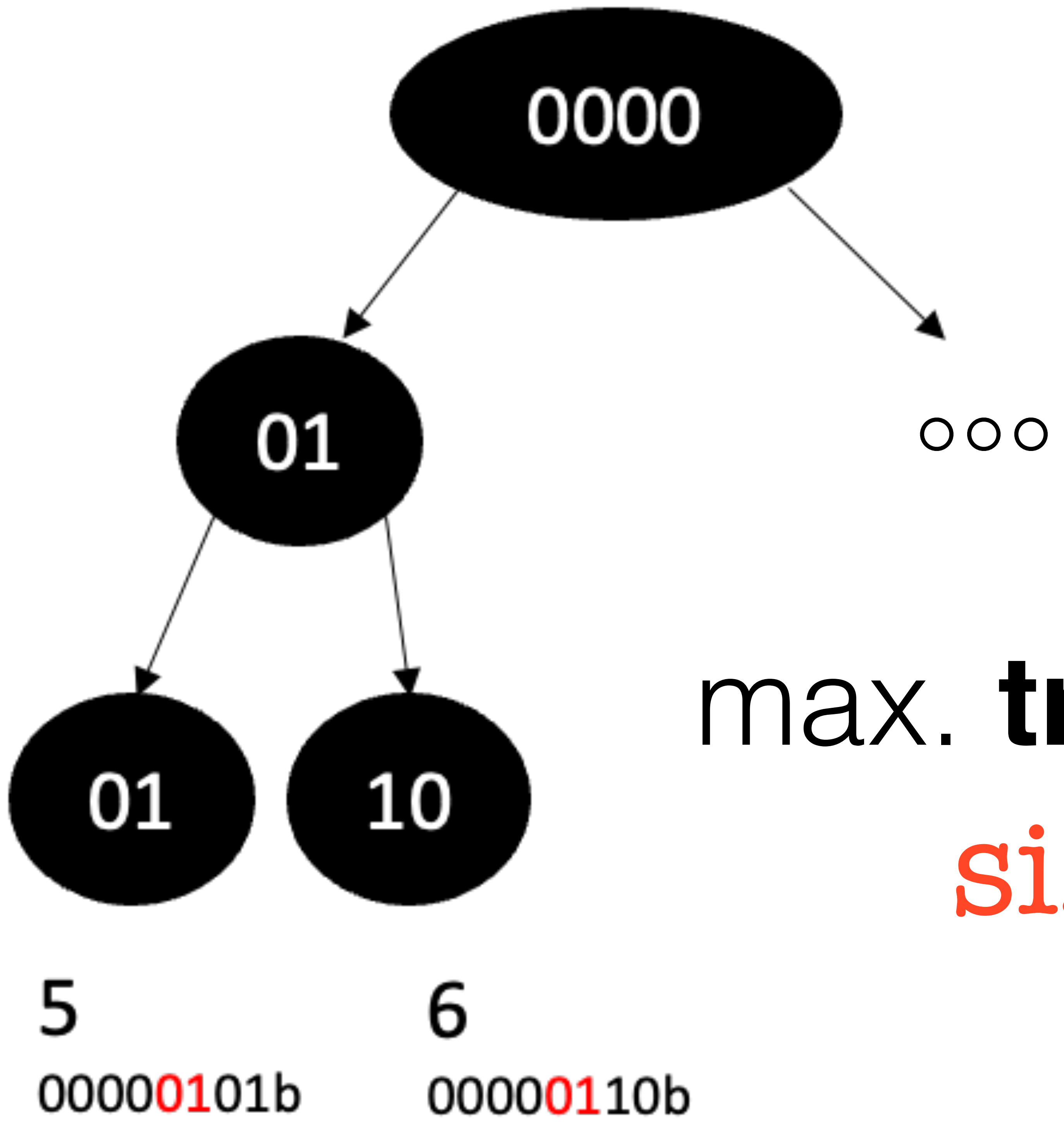

max. **tree hieght**?

size of integer

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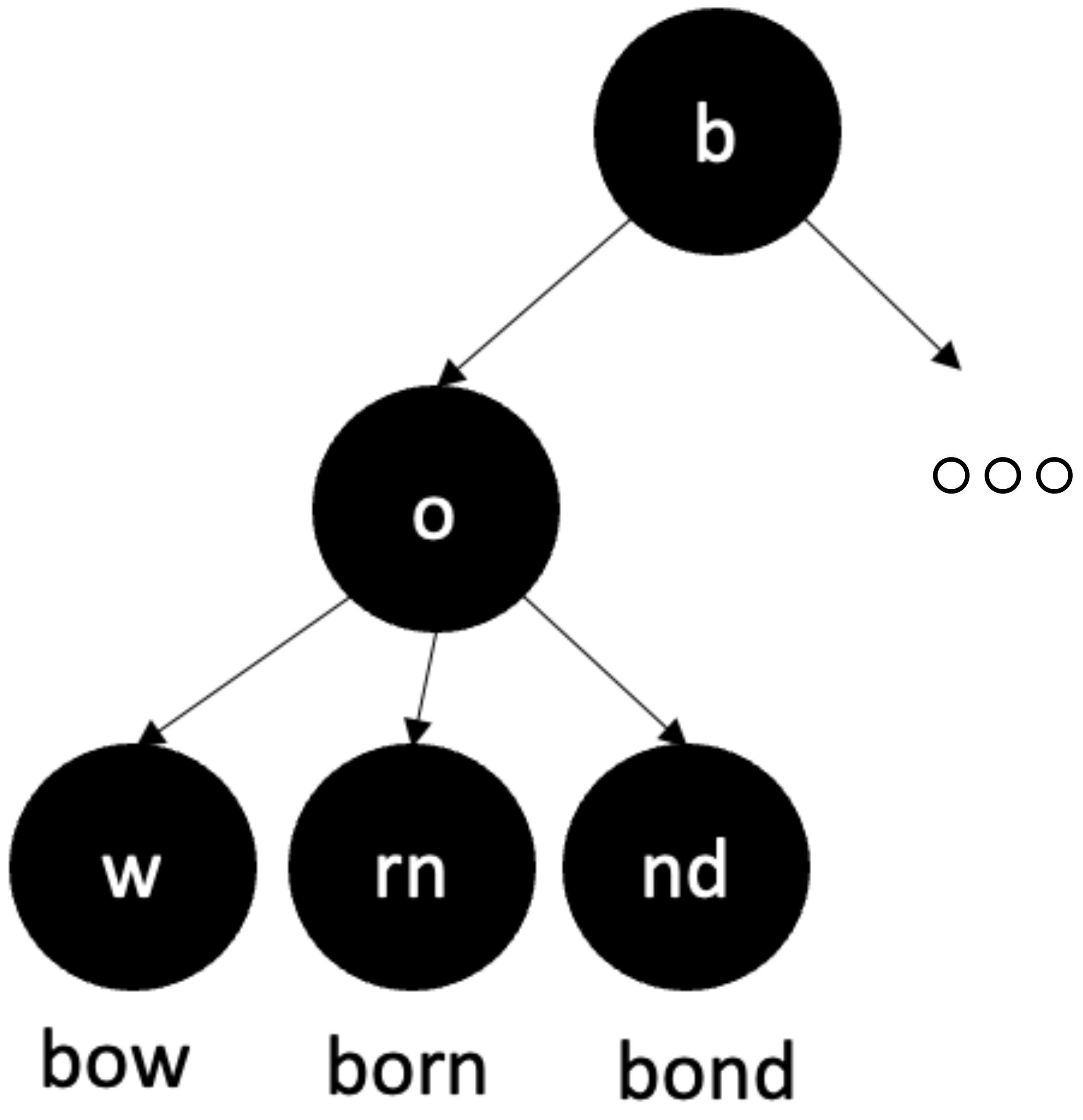

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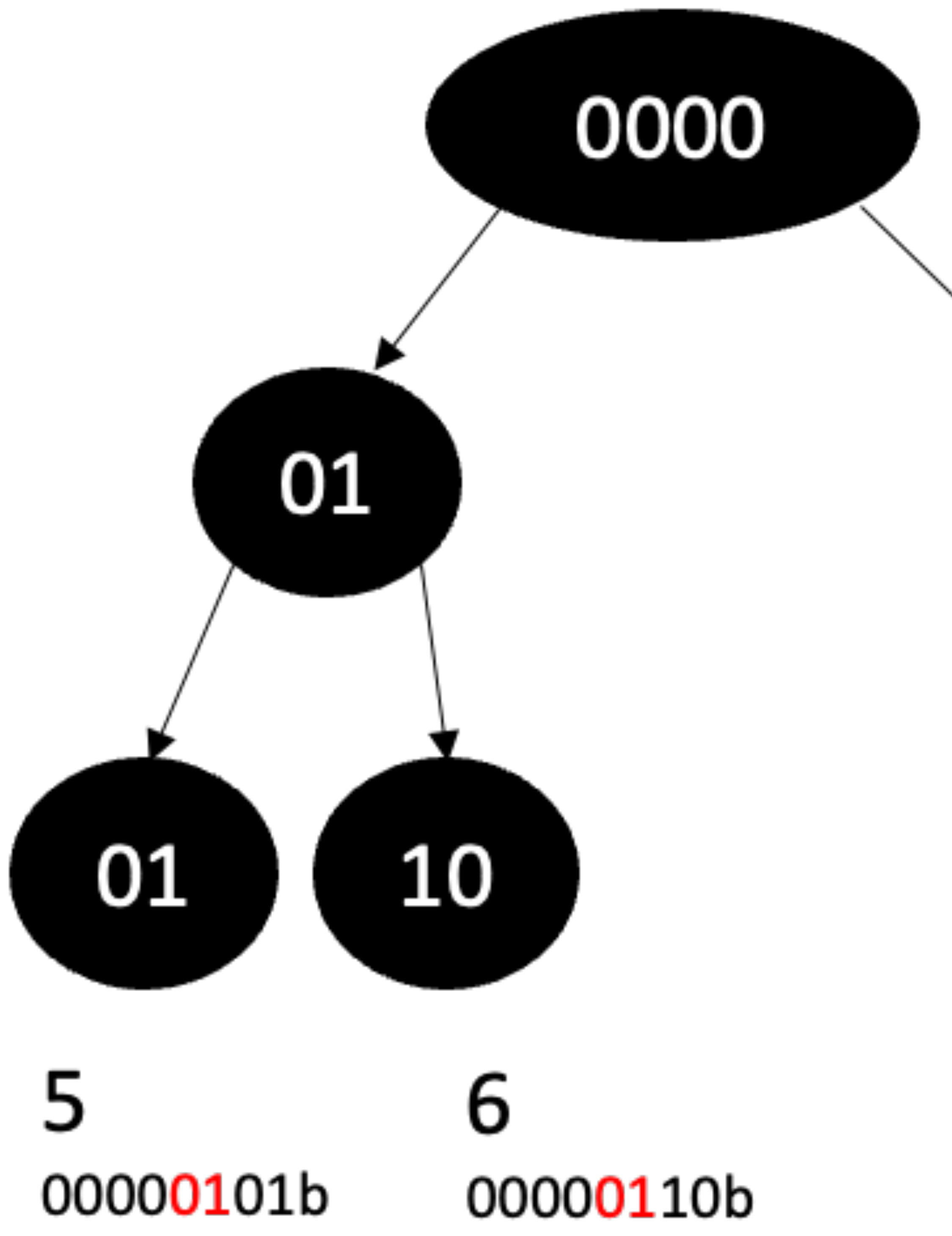

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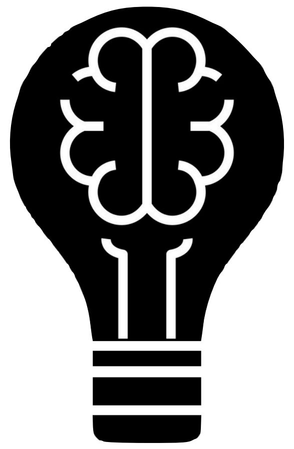

Thought Experiment 3

What about **data skew**?

radix trees perform poorly!

What are the possible **index designs**?

From B-trees to cracking

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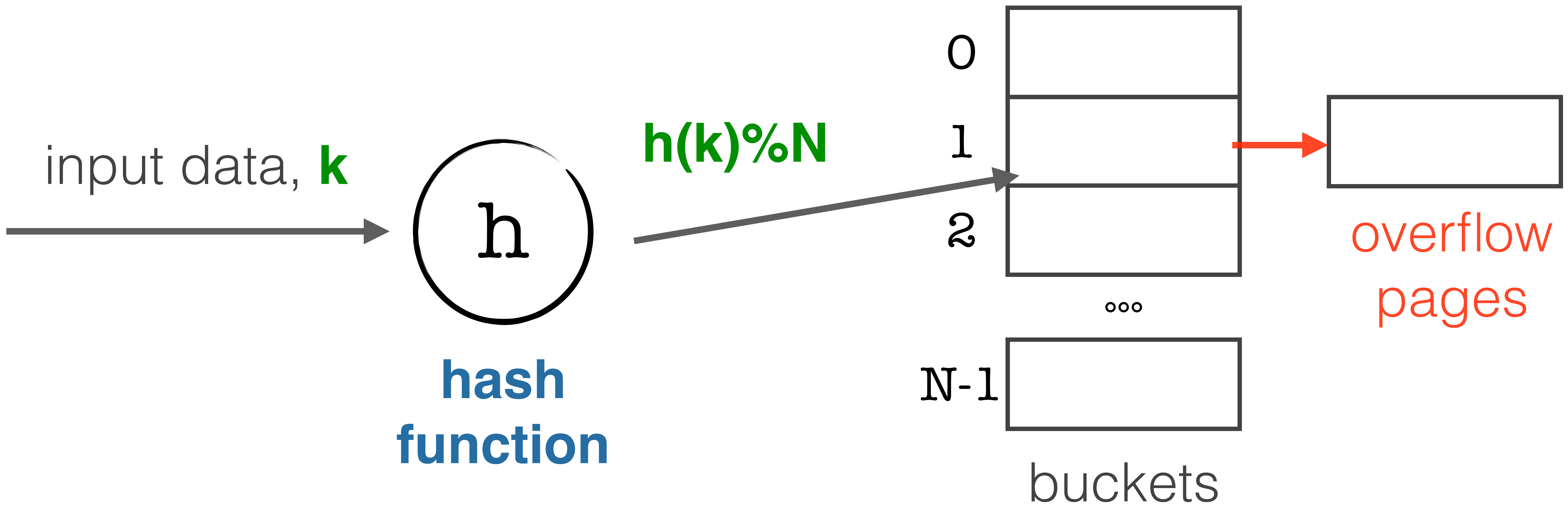
Radix tree	✓	✓	✓	✗	–
Hash index					
Bitmap index					
Zonemap					
Cracking					

Hash indexes

Using fast CPU cycles to our advantage

Idea: a function to map **a larger (infinite) space to a smaller finite space**

an **ideal** hash function would **distribute keys uniformly**



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Bitmap index					
Zonemap					
Cracking					

Bitmap index

Fast, light-weight but with limited applicability

Use case: **few distinct values repeating severally**

Column A
30
20
30
10
20
10
30
20

Bitmap index

Fast, light-weight but with limited applicability

Use case: **few distinct values repeating severally**

Column A	A=10	A=20	A=30
30	0	0	1
20	0	1	0
30	0	0	0
10	1	0	0
20	0	1	0
10	1	0	0
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Bitmap index

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Use case: **few distinct values** **repeating severally**

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Advantages:

Bitmap index

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Advantages:

speed & size

- **compact representation** of query result
- query result is **readily available**

bitvectors

- fast **Boolean operators** (AND/OR/NOT)
- bitwise ops faster than looping over metadata

Limitations:

Bitmap index

Fast, light-weight but with limited applicability

Use case: **few distinct values repeating severally**

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Limitations:

index size — **space-inefficient** for domains with **large cardinality**

imagine column A has **100M** entries

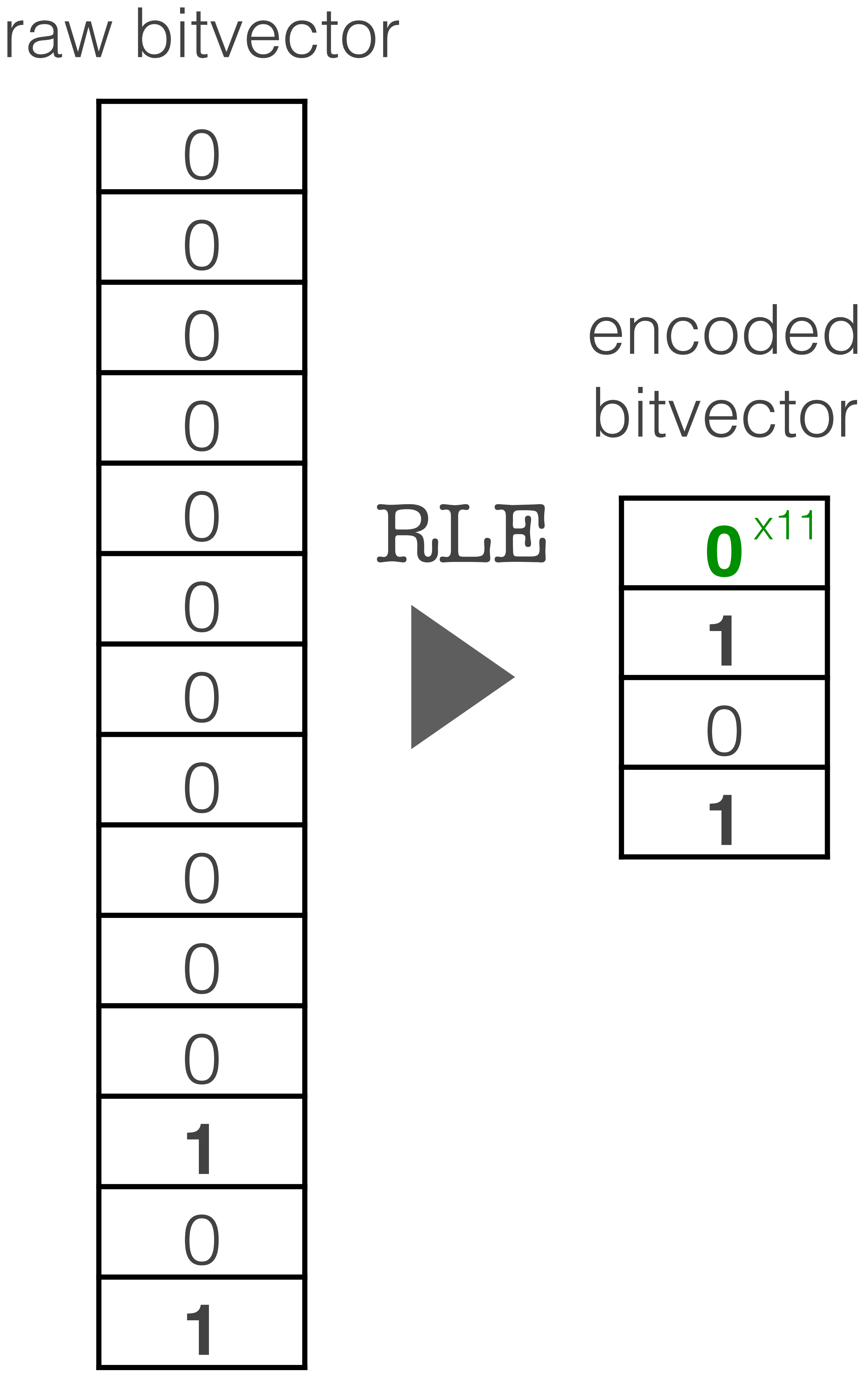
index size = **12.5 MB per distinct value**

solution?

run length encoding

Bitmap index

Fast, light-weight but with limited applicability



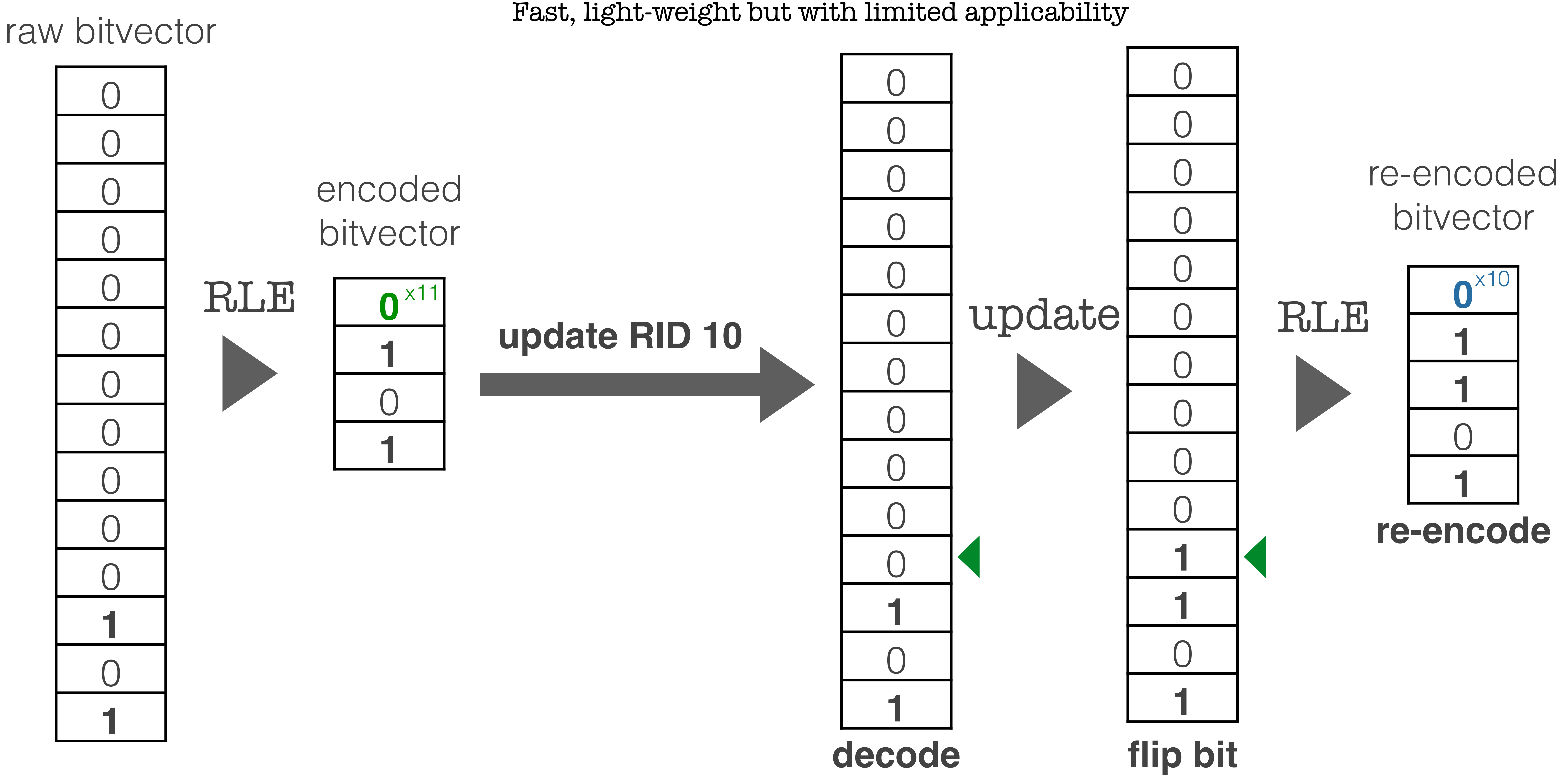
Thought Experiment 4

What about **updates**?

decompressing and re-compressing

Bitmap index

Fast, light-weight but with limited applicability



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Zonemap					
Cracking					

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Bitmap index	✓	–	–	–	✗
Zonemap	–	–	✓	✓	–
Cracking					

Cracking

Indexing on the fly

Idea: take **hints from queries** to **create partitions**

gradually moving toward a **sorted layout**

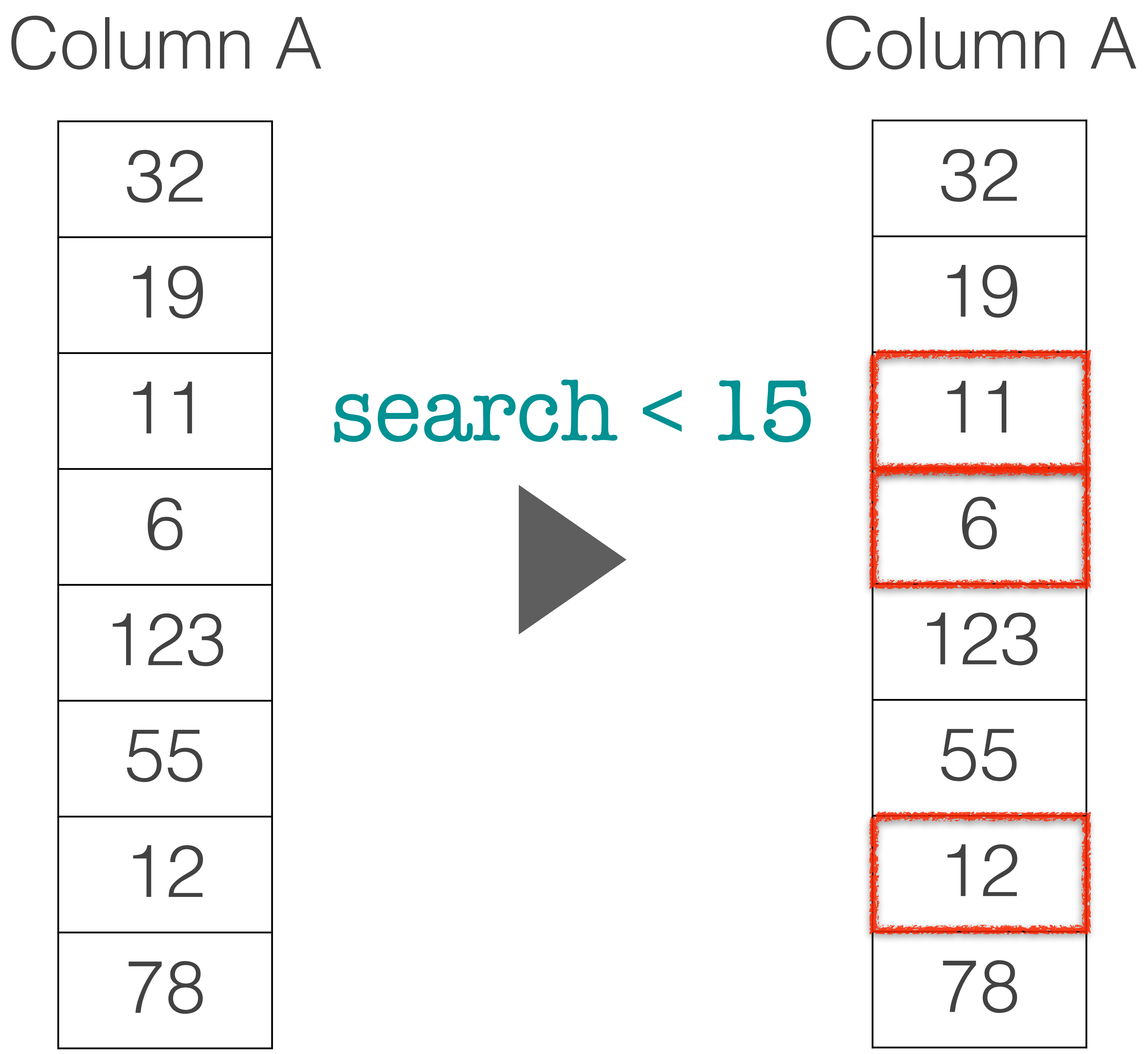
Column A

32
19
11
6
123
55
12
78

Cracking

Indexing on the fly

Idea: take **hints from queries** to **create partitions**
gradually moving toward a **sorted layout**



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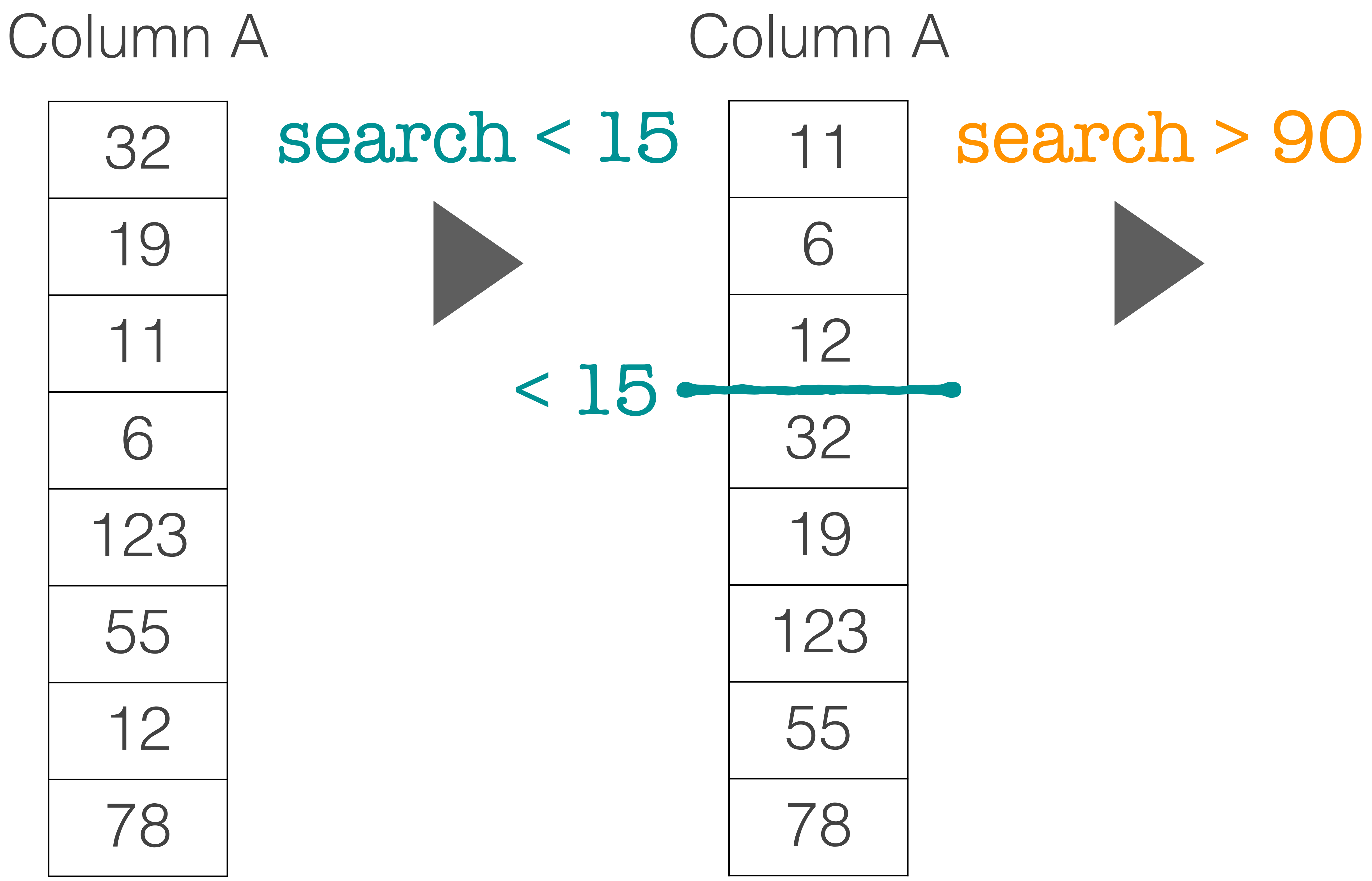

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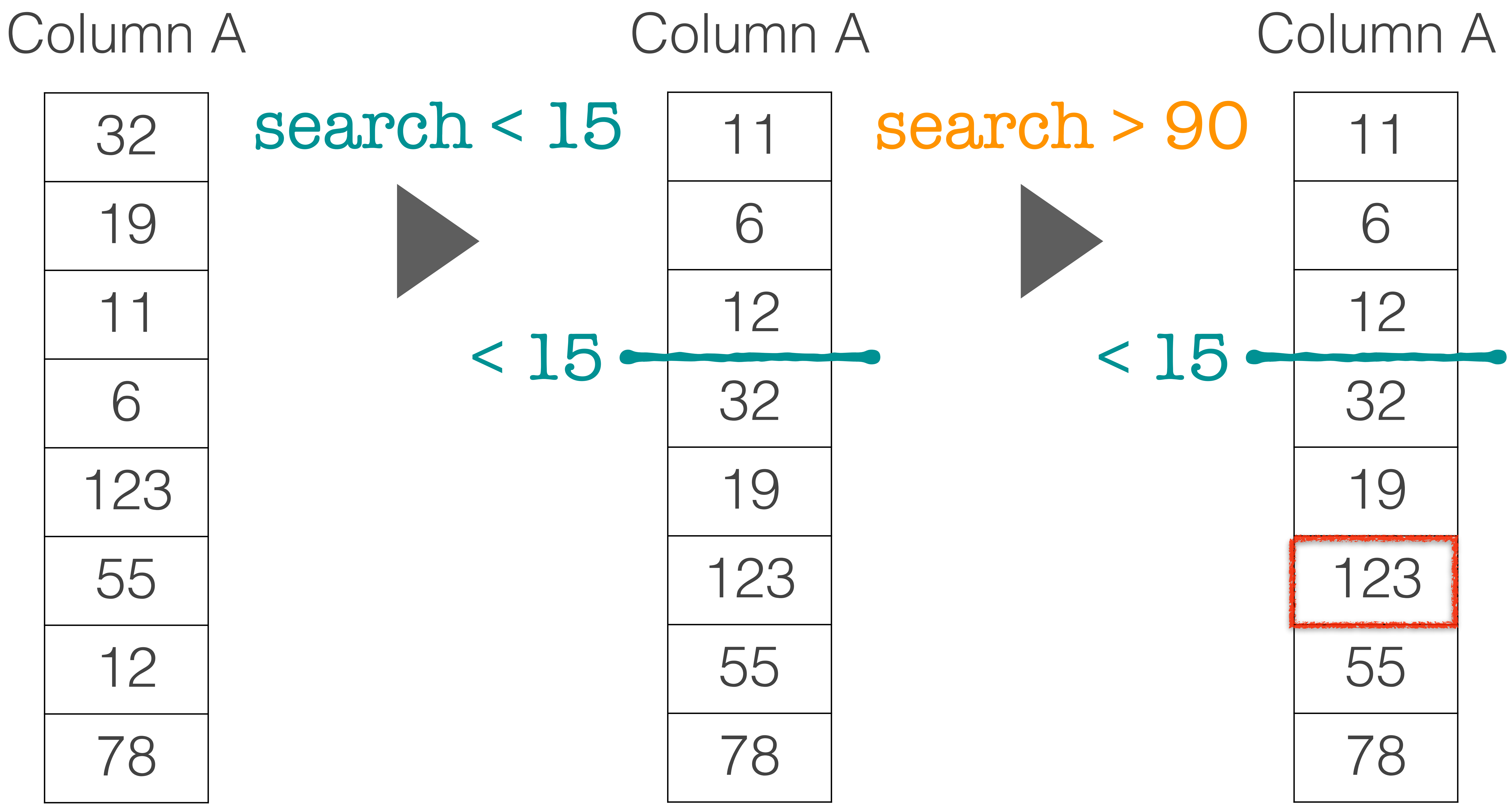

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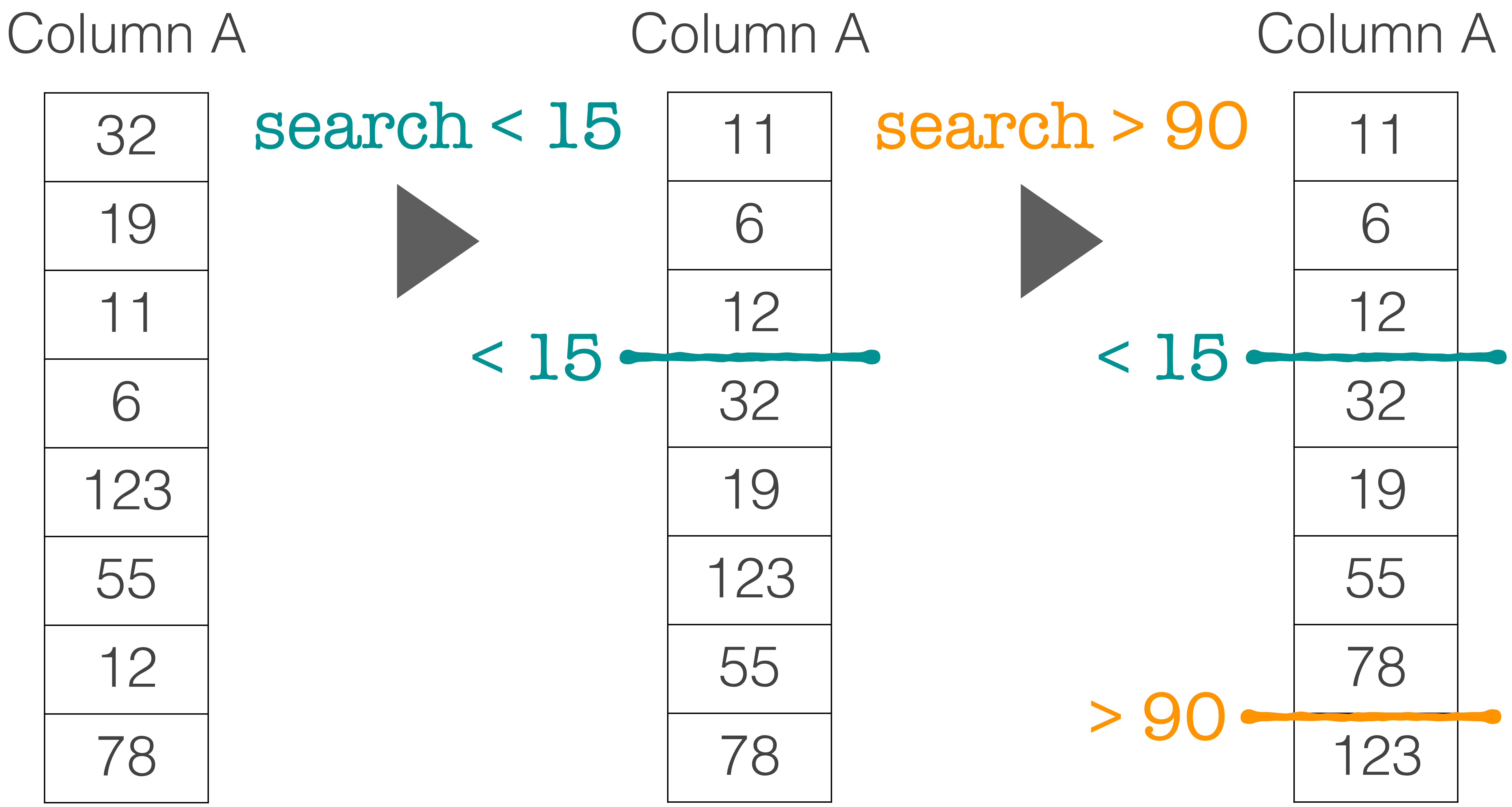

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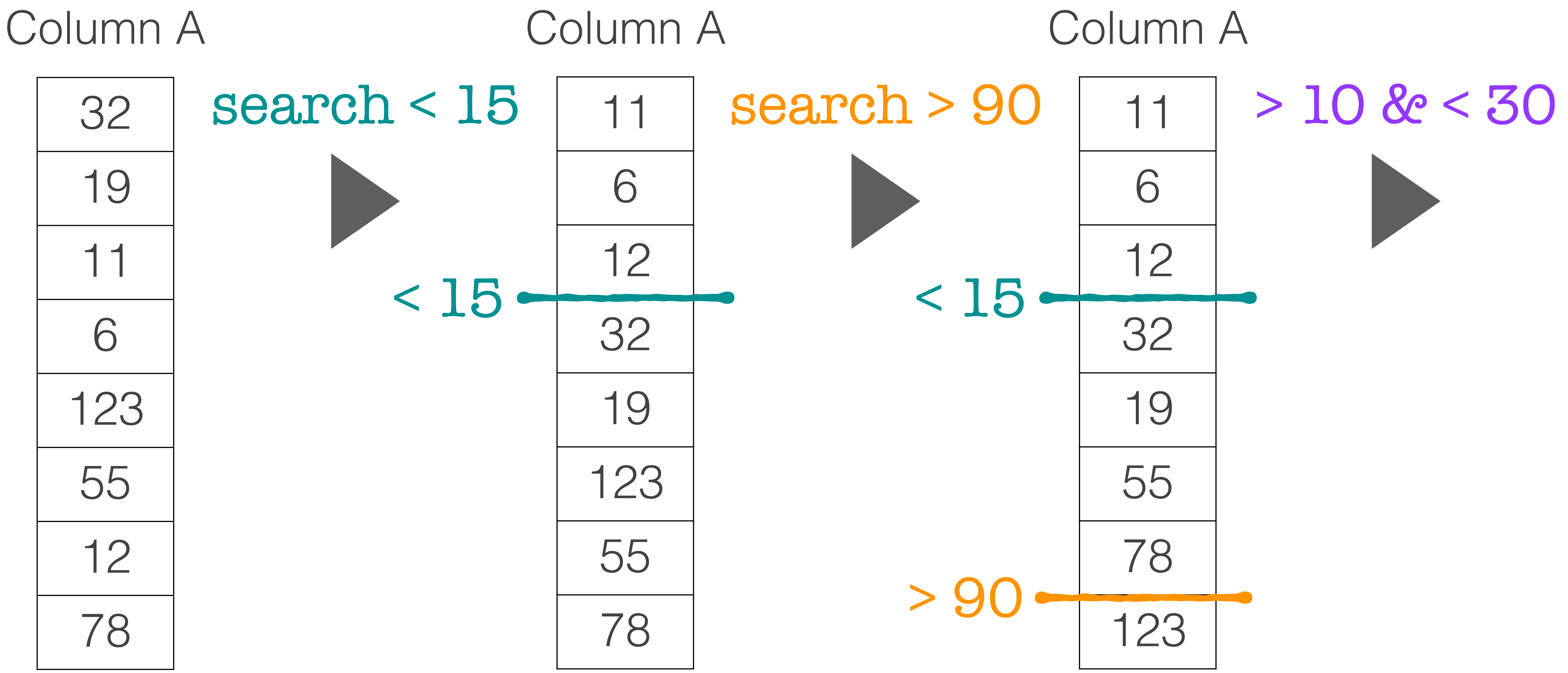

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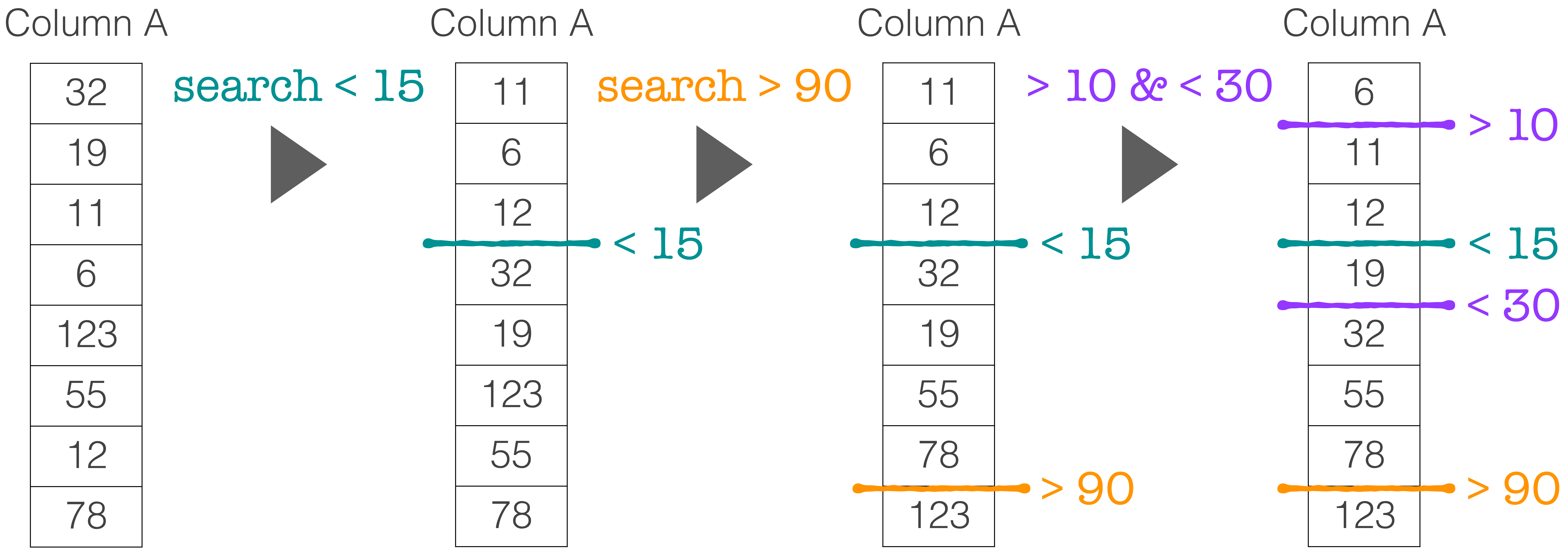

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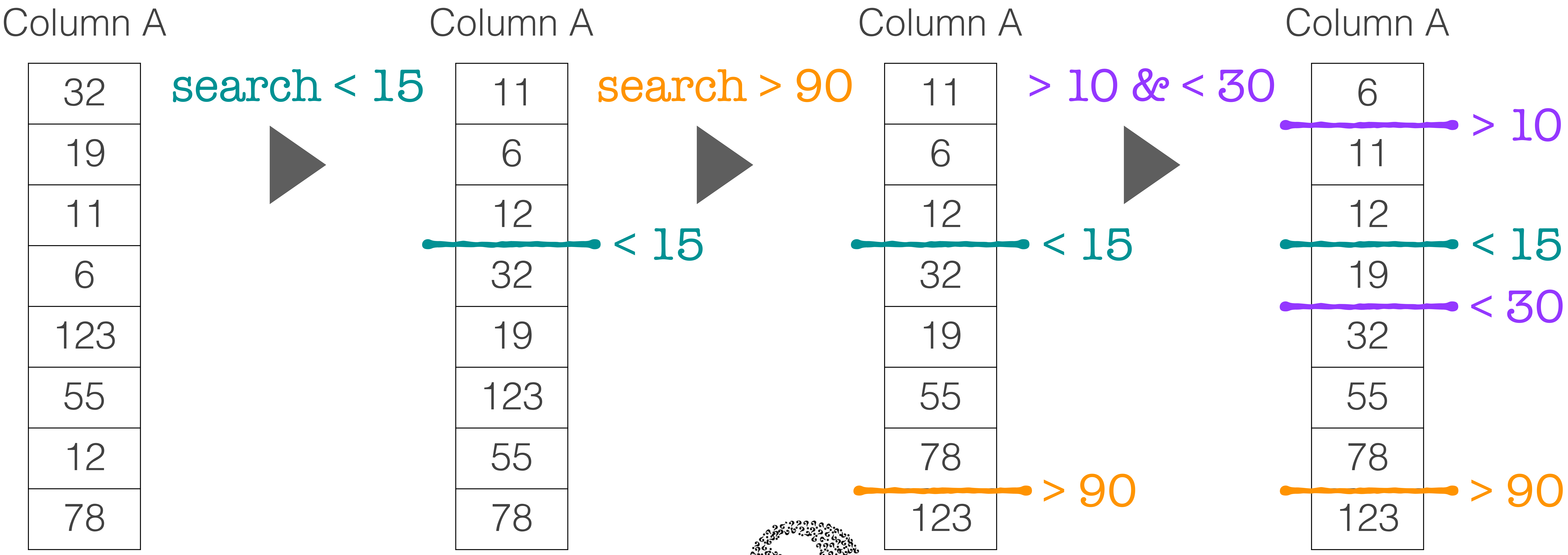

Thought Experiment 5

What about **updates**?

Lazy merging

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Bitmap index	✓	–	–	–	✗
Zonemap	–	–	✓	✓	–

How to decide which index to use?

How to decide **which index to use**?

The million dollar question

Break it down to
design primitives!

Index design primitives

Asking the fundamental design questions

How to **physically organize** the data?

How to **search** through the data?

Can we **accelerate** search **using metadata**?

How to **update** or **add** new **data**?

Index design primitives

Asking the fundamental design questions

Global data organization
- sorted
- unsorted
- logging

How to **search** through the data?

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Global data organization { sorted / unsorted / logging

Global search algorithm { scan / tight-loop search / direct addressing

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Index design primitives

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Global search algorithm
- scan
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Indexing technique
- zonemaps/imprints
- trees (radix/B+)
- Hash-based

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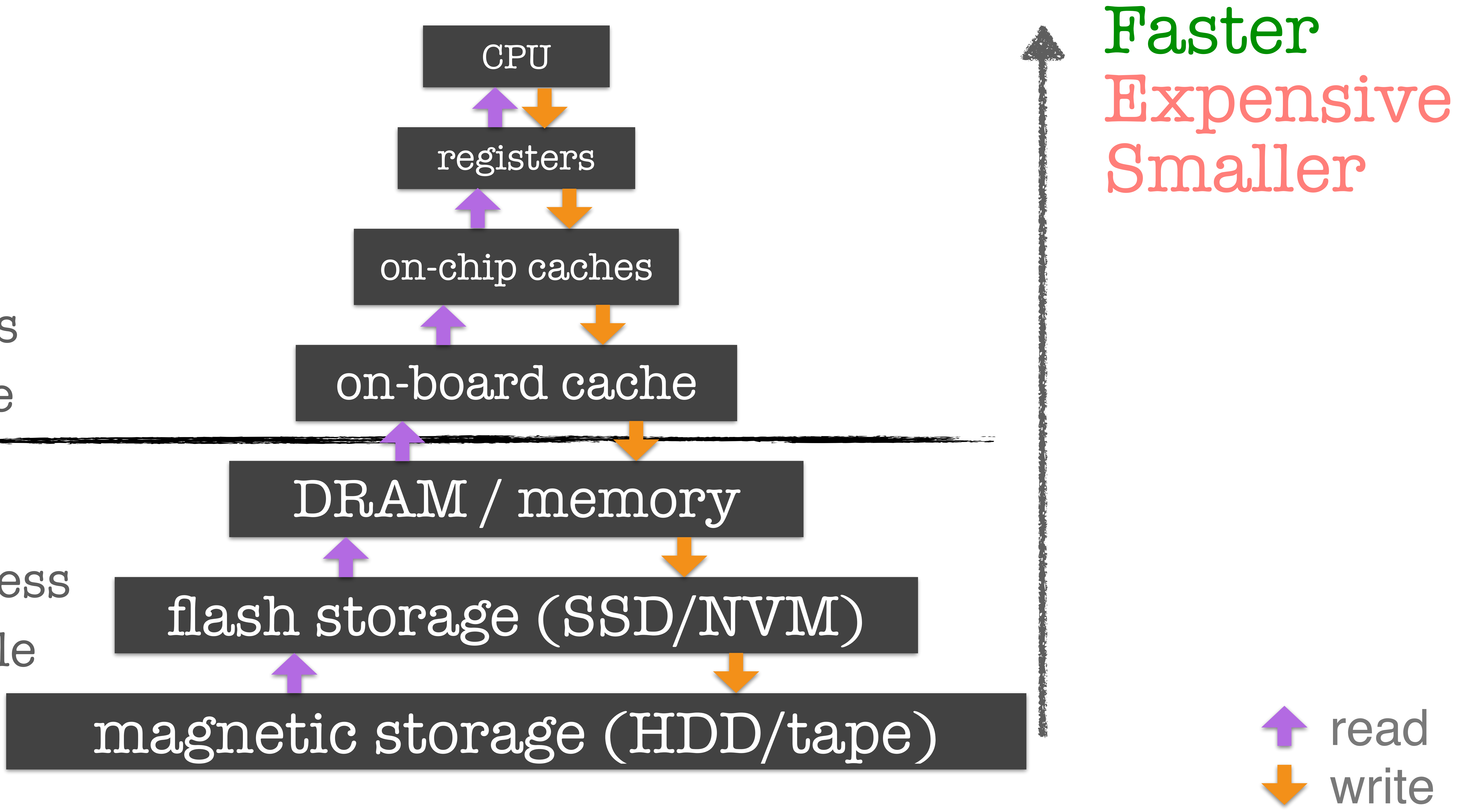
Data modification policy
- in-place
- out-of-place
- deffered in-place

Modern Hardware

Recap: **Storage hierarchy**

How data moves!



Volatile

Random access

Byte accessible

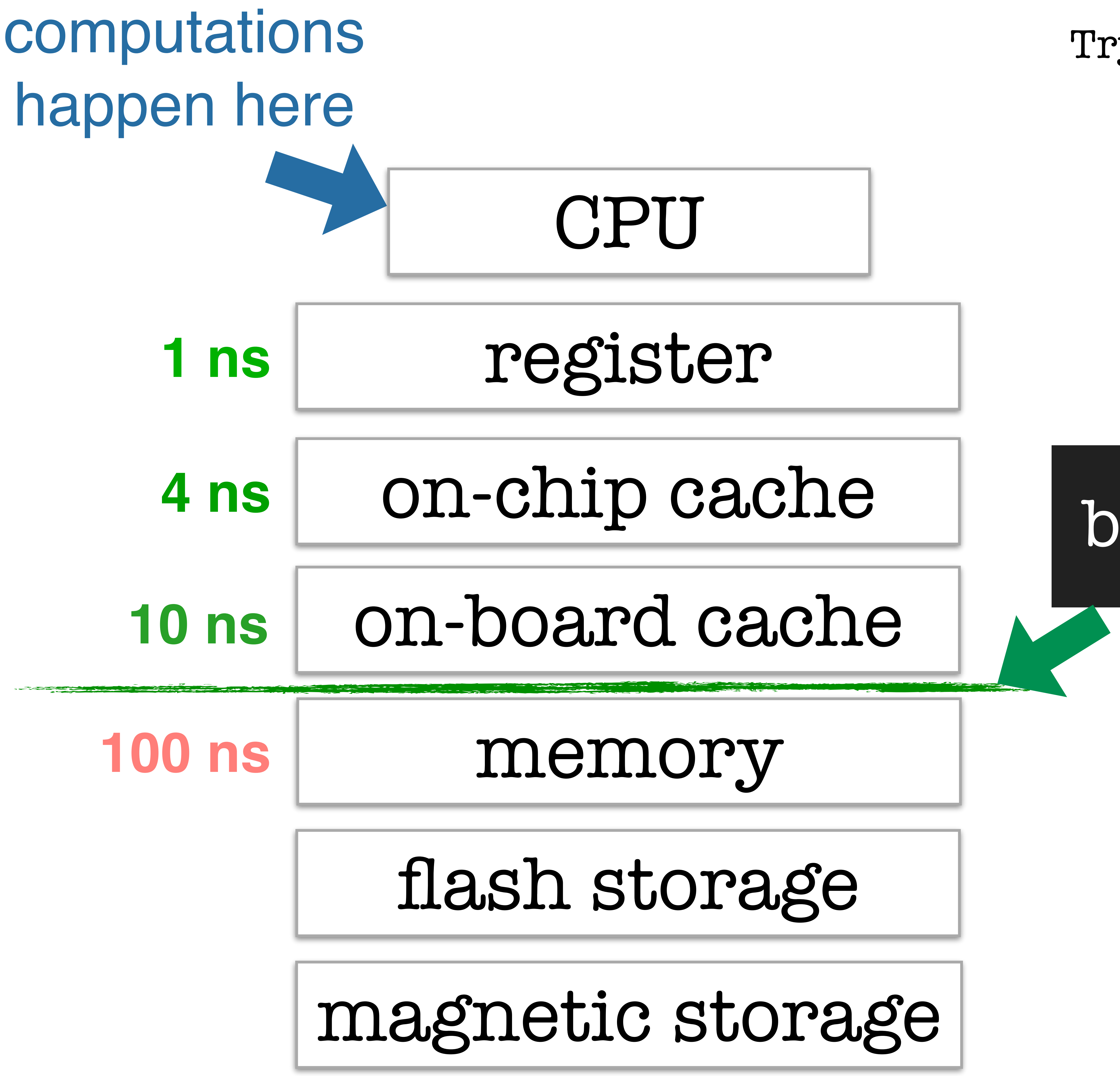
Non-volatile

Sequential access

Block accessible

Memory wall

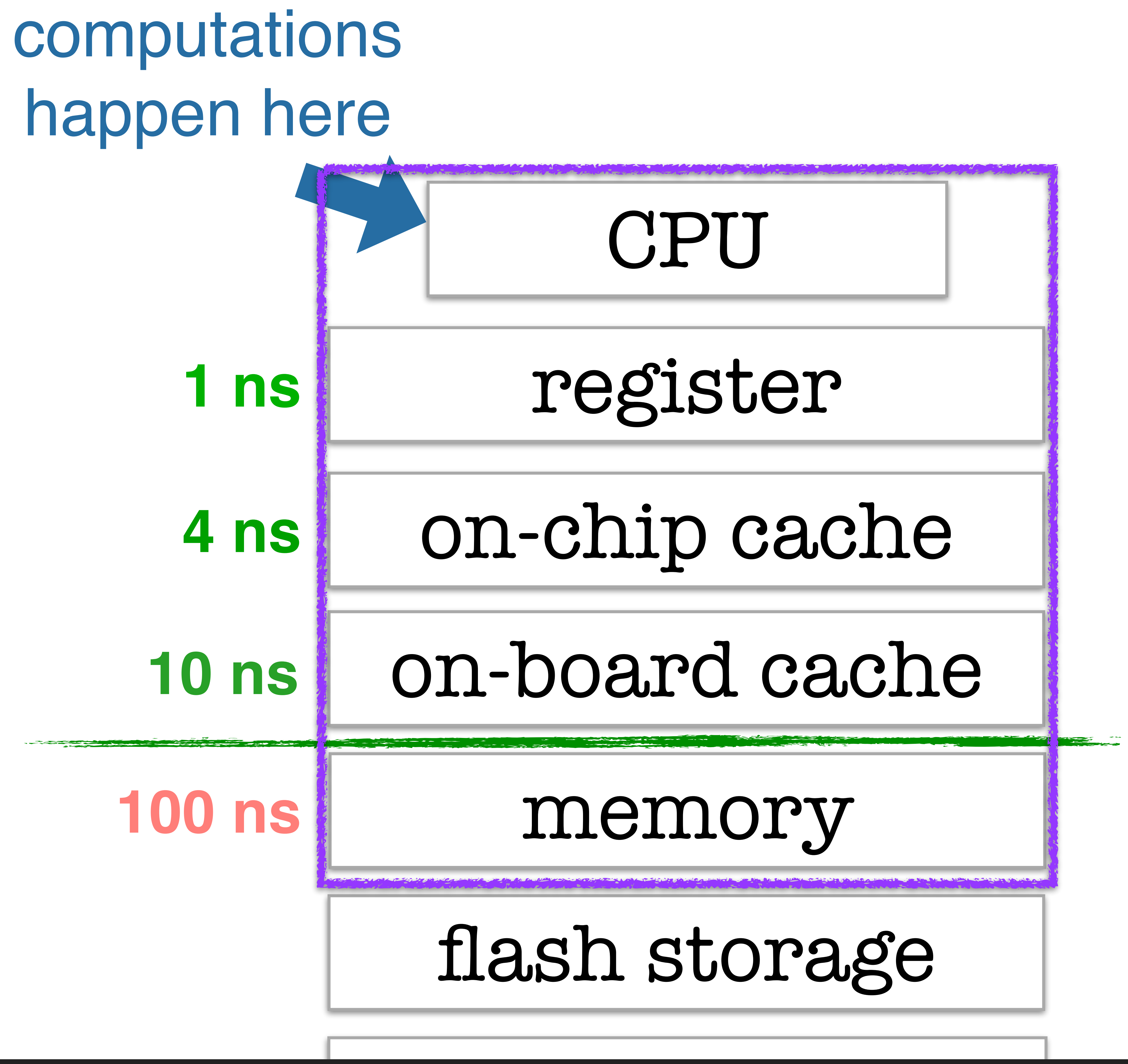
Try not to jump the wall



be careful when you go below the green line

Memory wall

Try not to jump the wall



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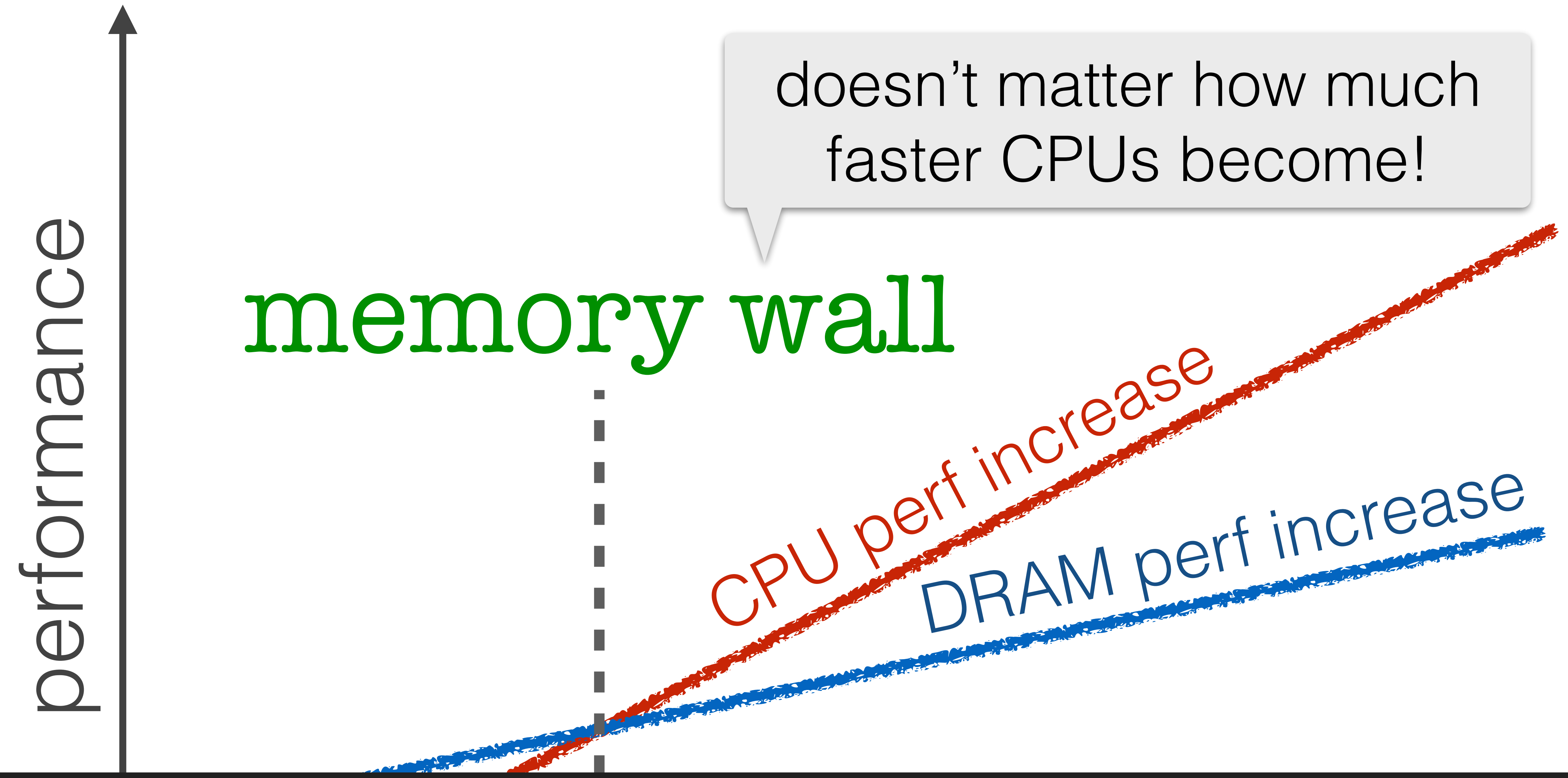


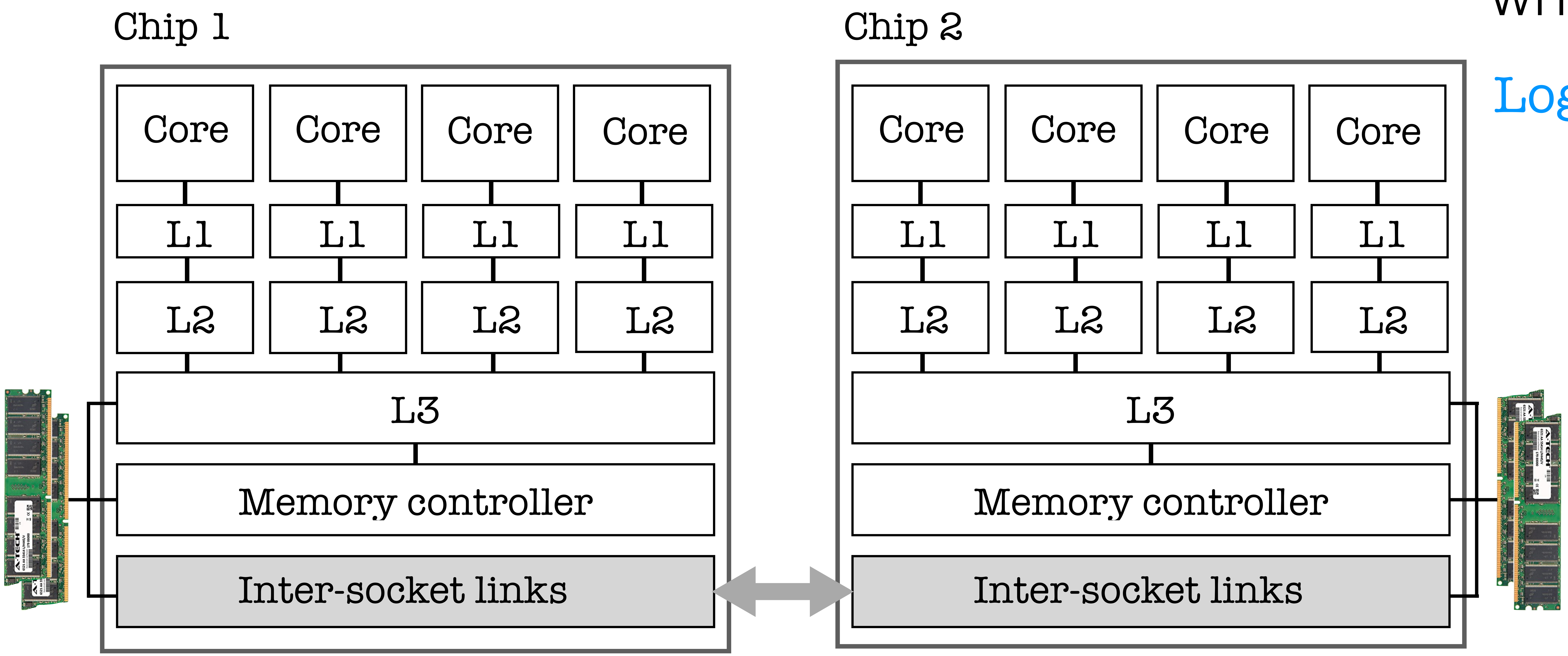
Can we optimize futher if **data fit in memory**?

Cache hierarchy

Optimizing data access

what is a **chip**?
what is a **socket**?
what is a **core**?

Logical vs. Physical core

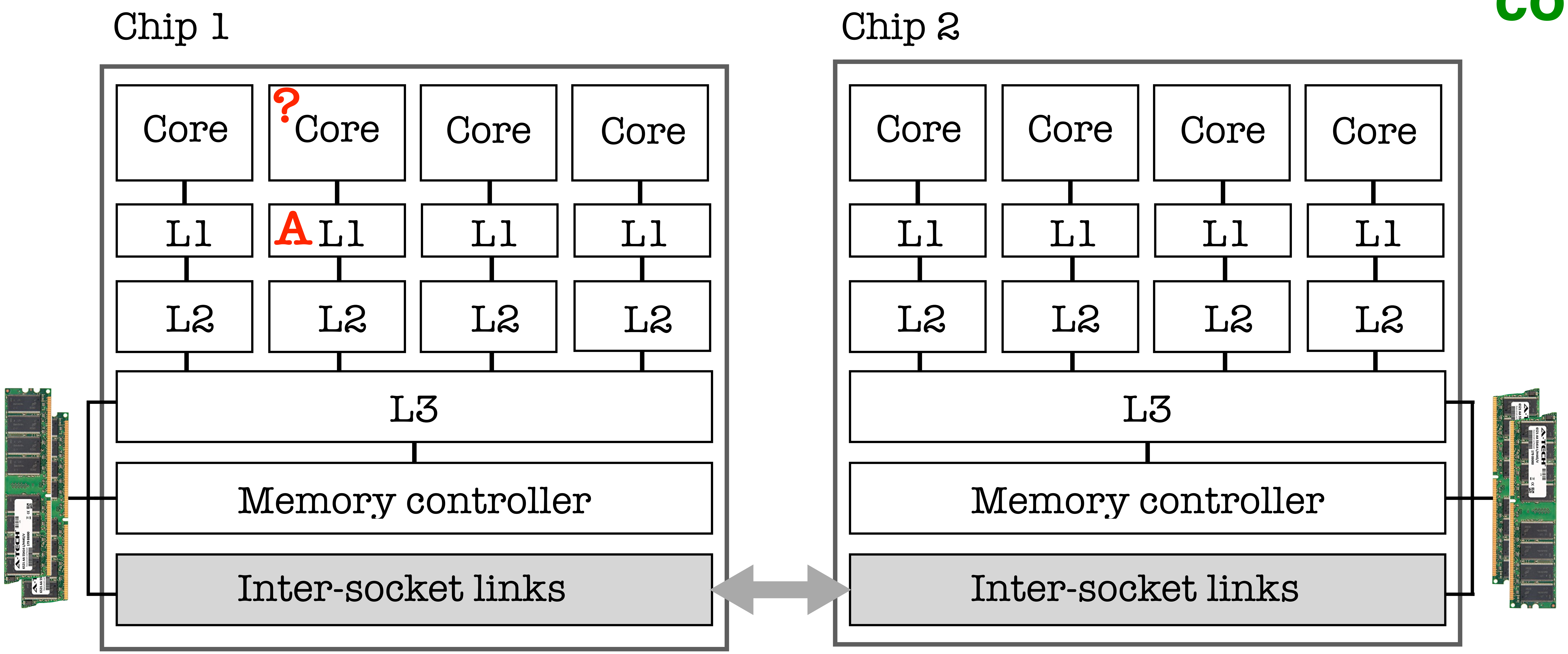


internals of a **multisocket multicore server**

Cache hierarchy

Optimizing data access

what if the target data is in the **core's private L1**?



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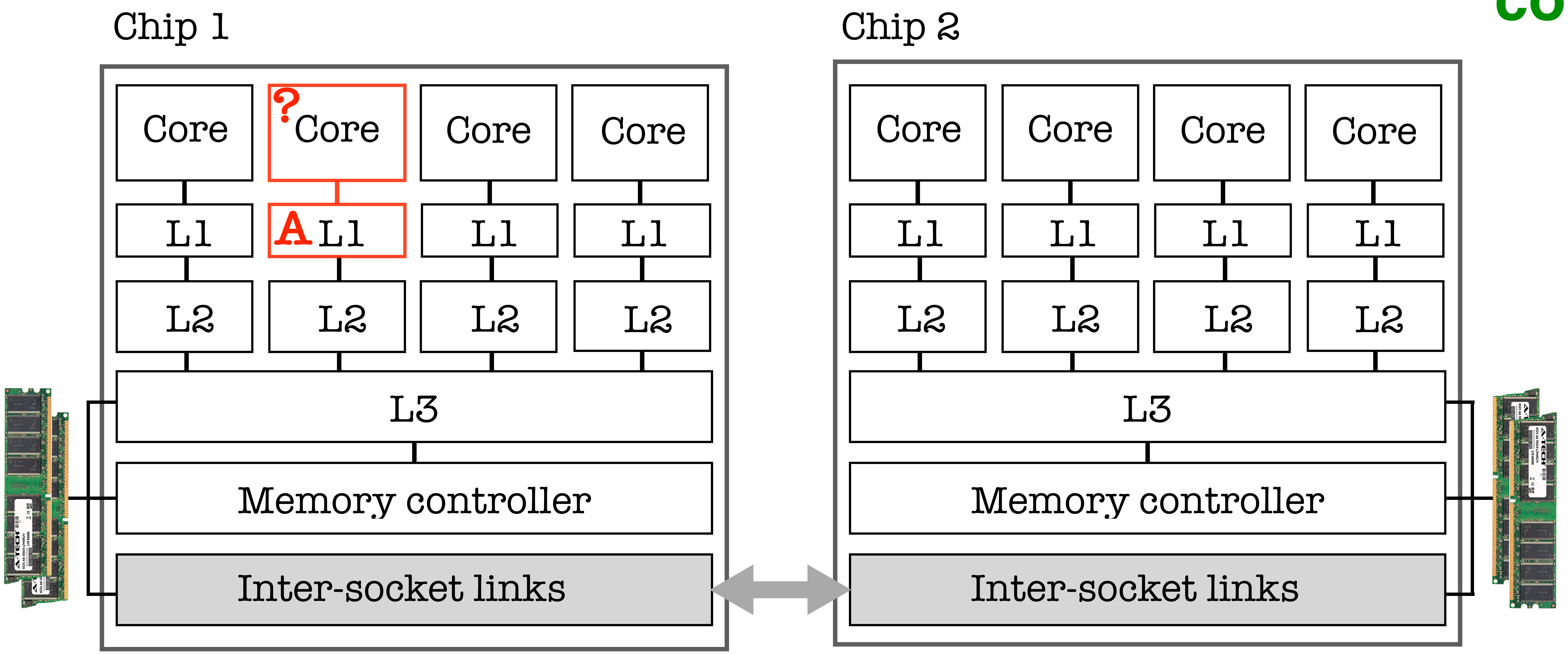
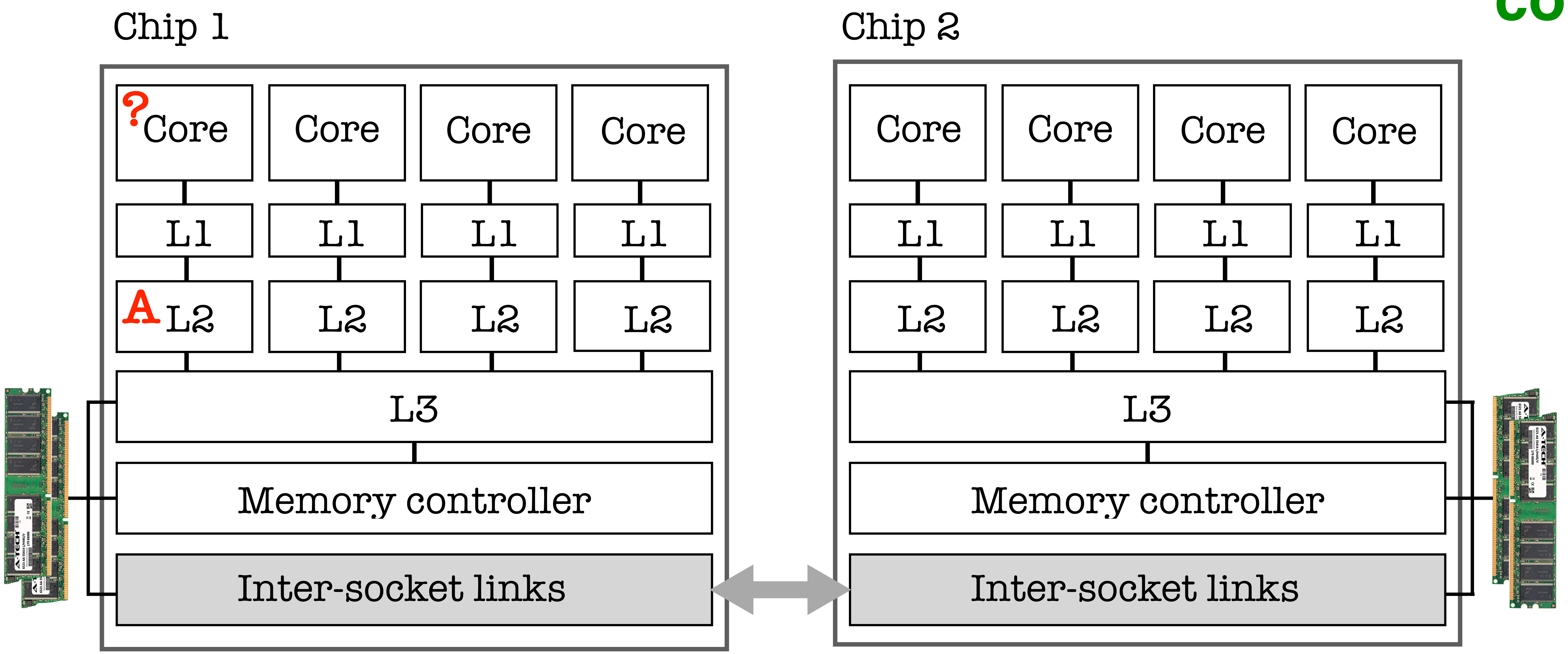


internals of a **multisocket multicore server**

Cache hierarchy

Optimizing data access

what if the target data is in the **core's private L2**?



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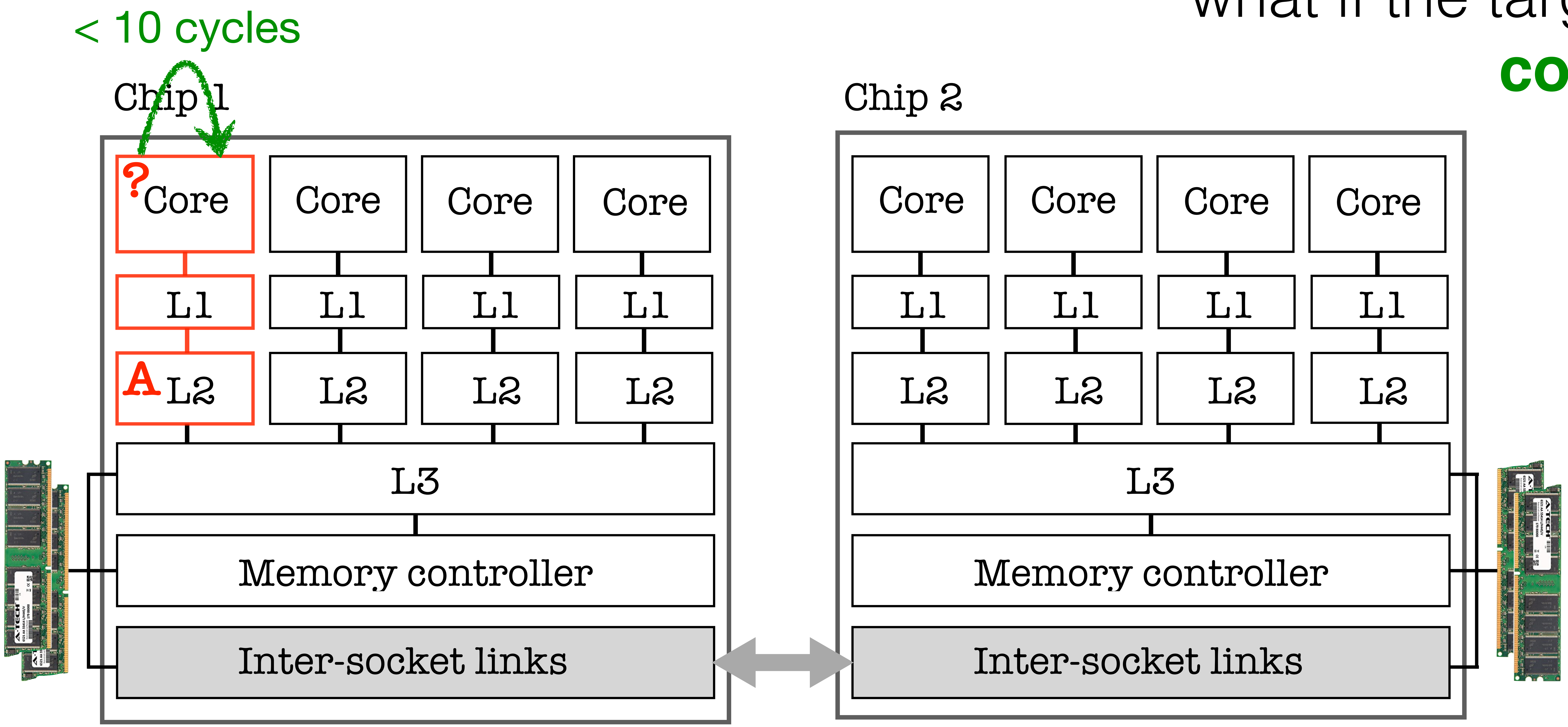

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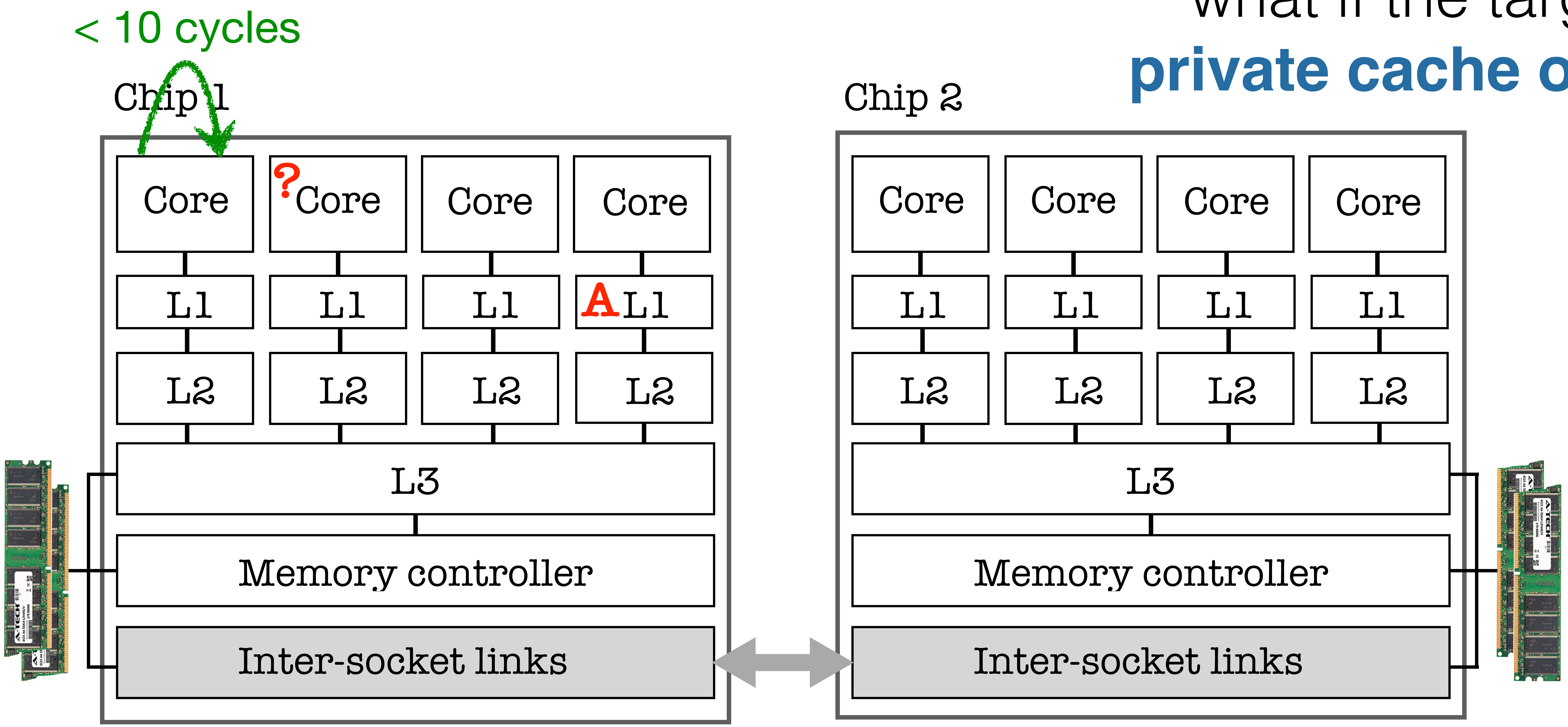

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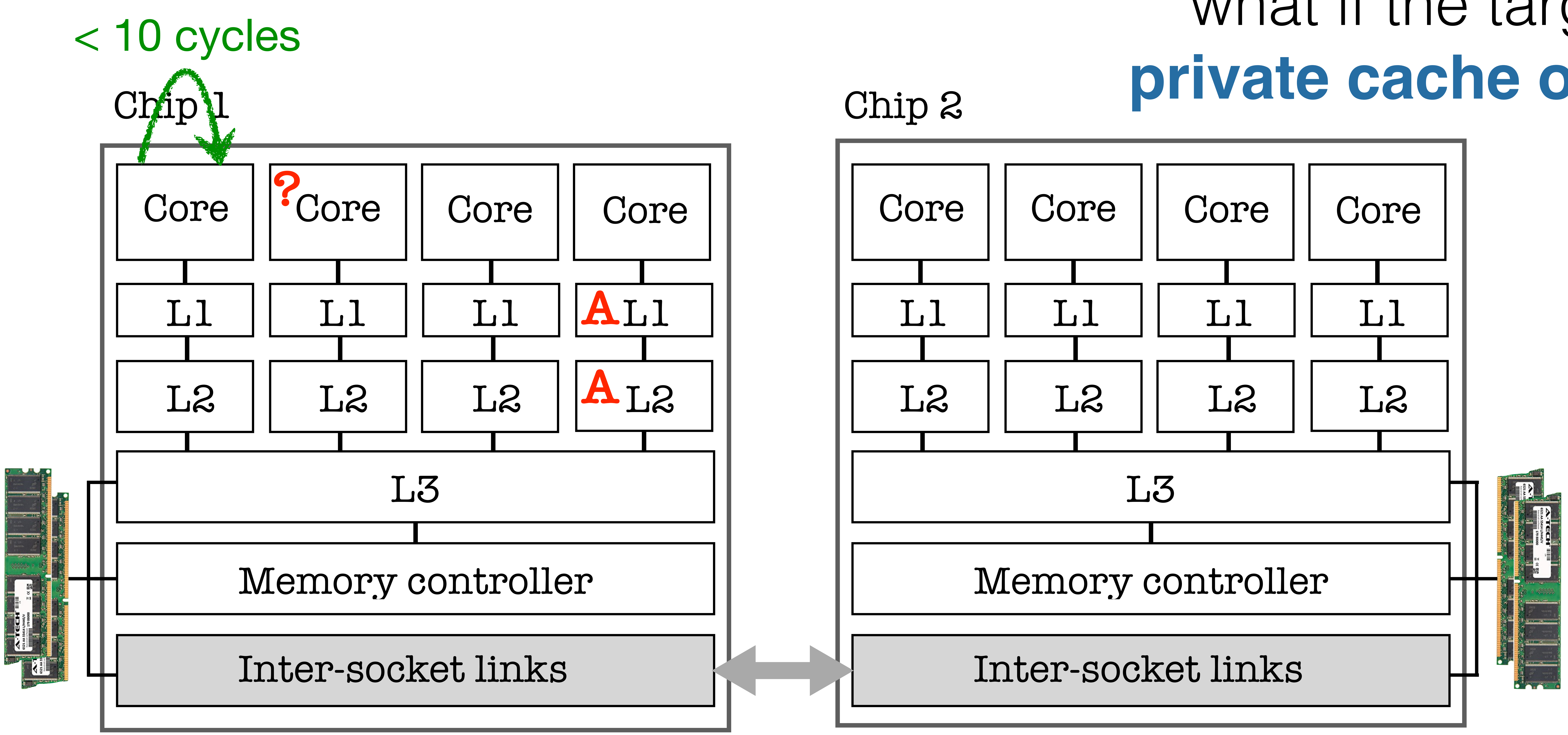

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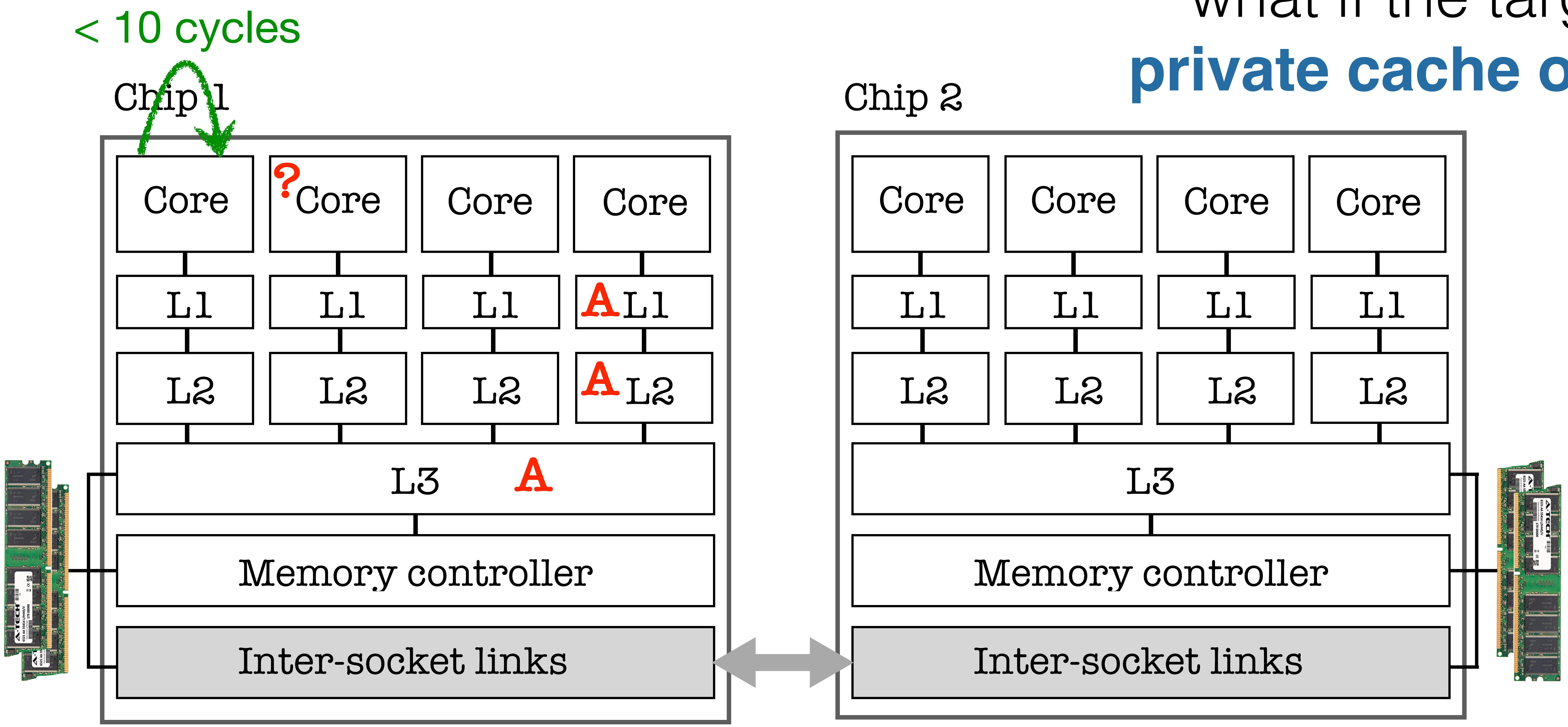

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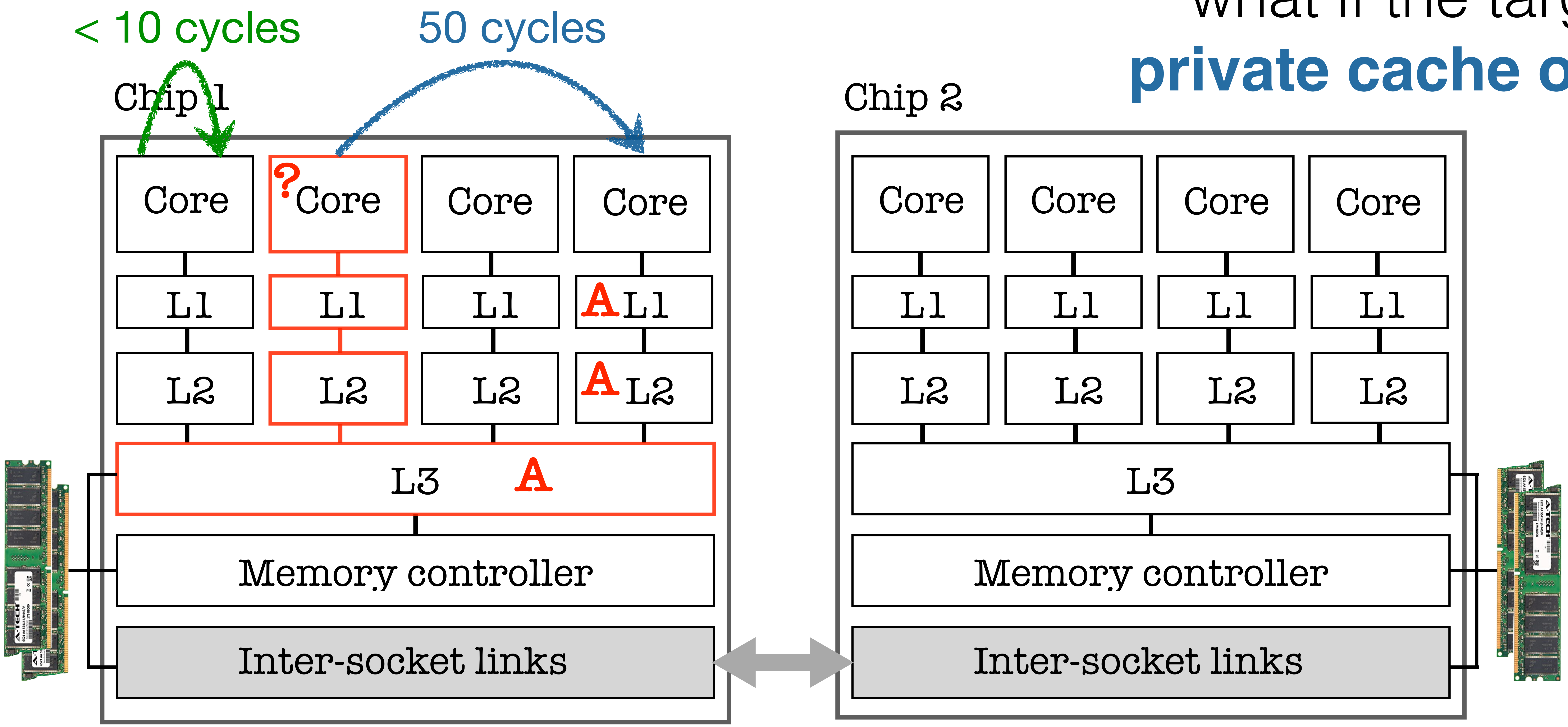
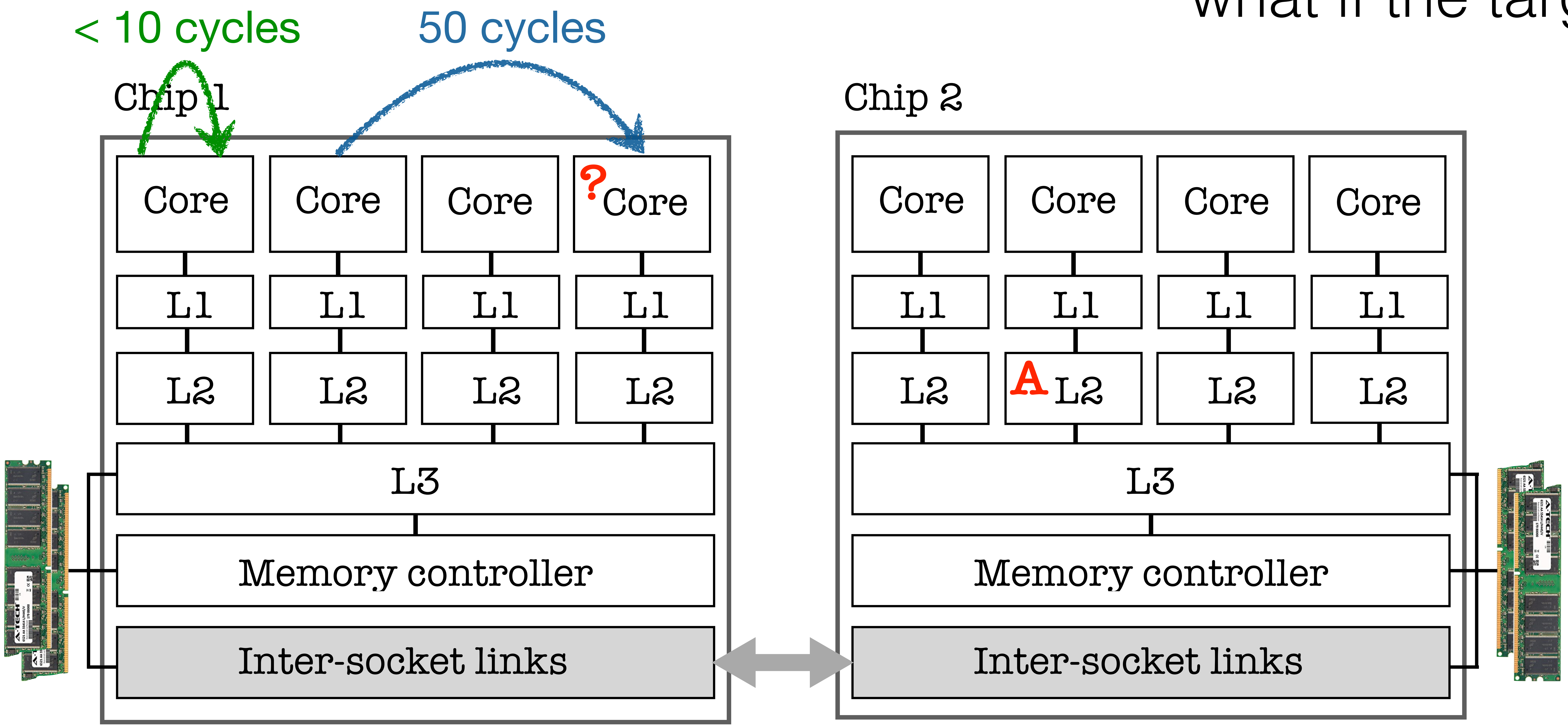


internals of a **multisocket multicore server**

Cache hierarchy

Optimizing data access

what if the target data is in the **another chip**?

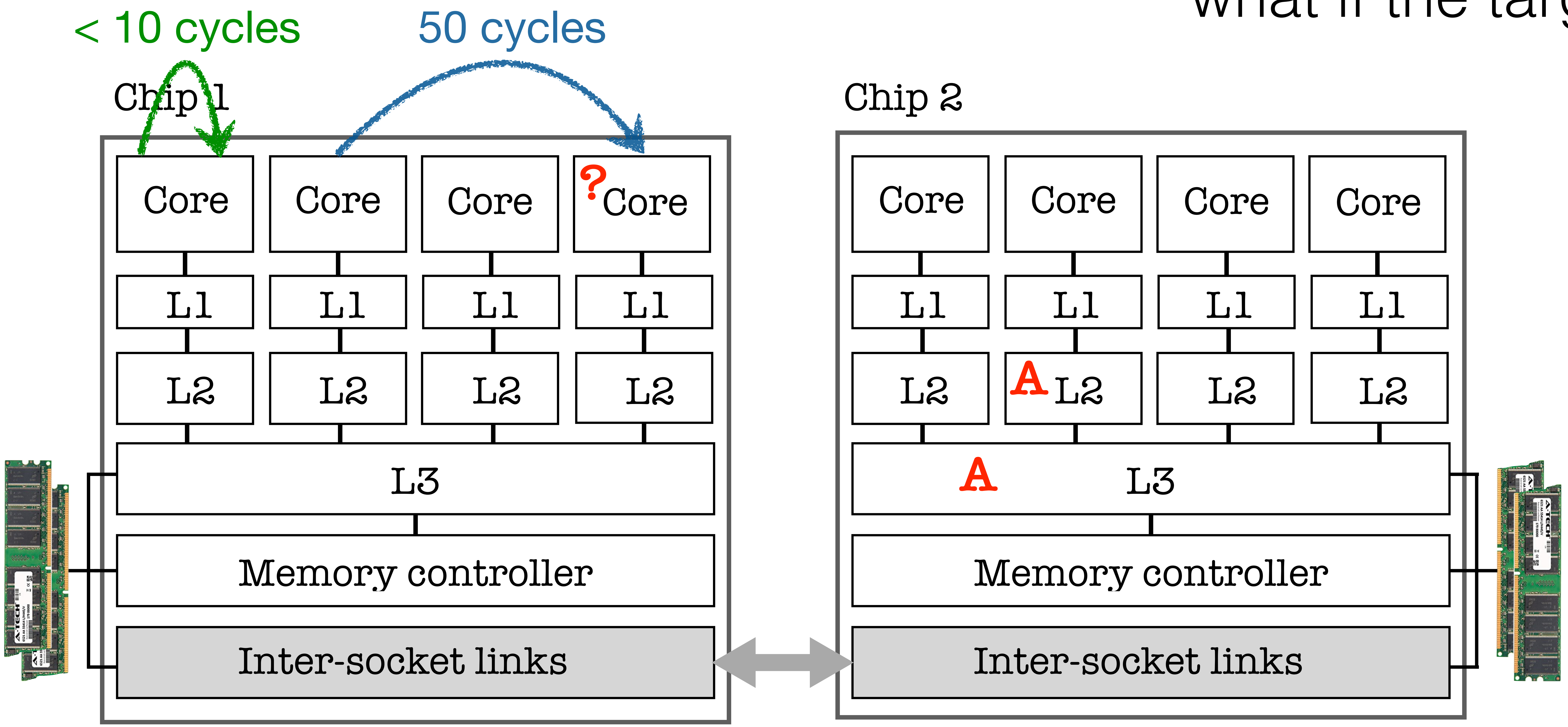


internals of a **multisocket multicore server**

Cache hierarchy

Optimizing data access

what if the target data is in the **another chip**?



internals of a **multisocket multicore server**

Cache hierarchy

Optimizing data access

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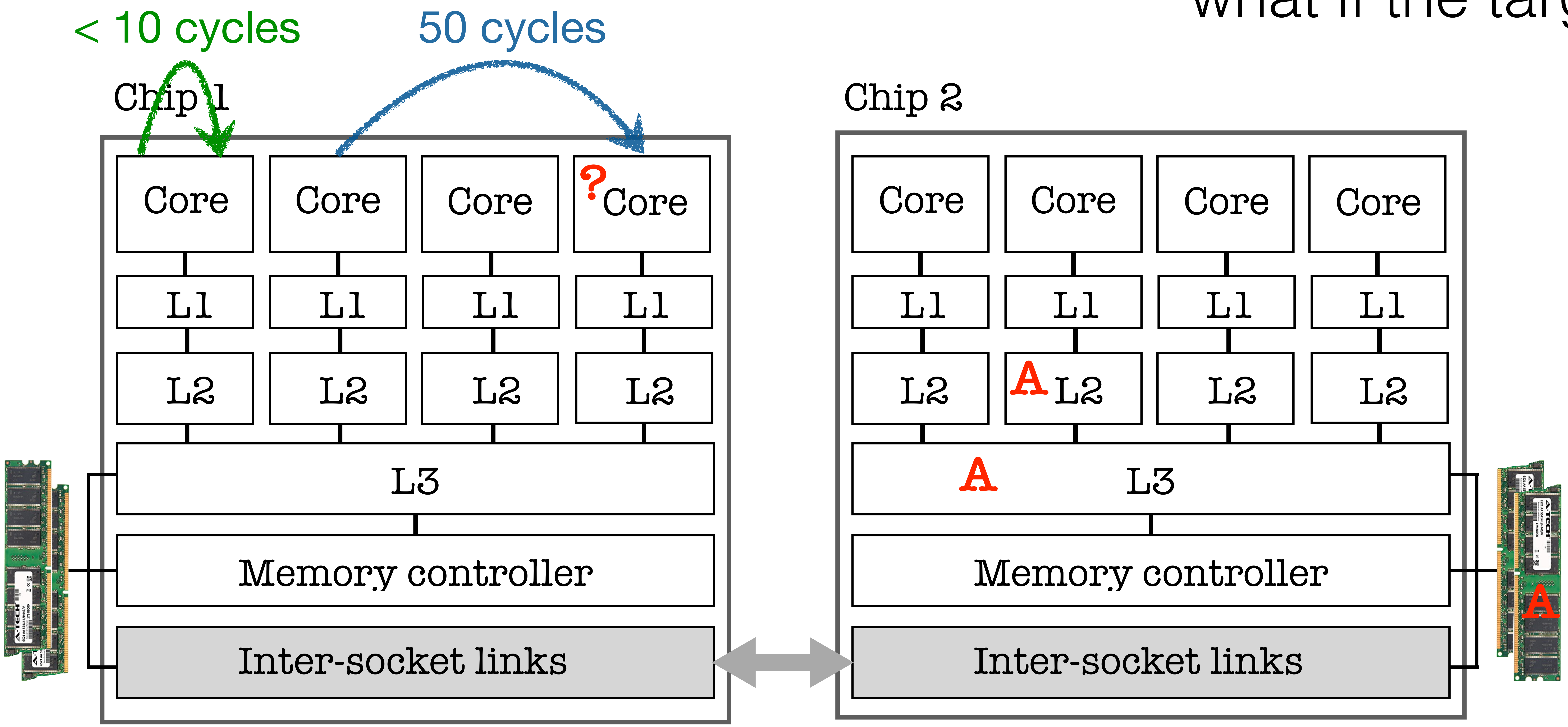
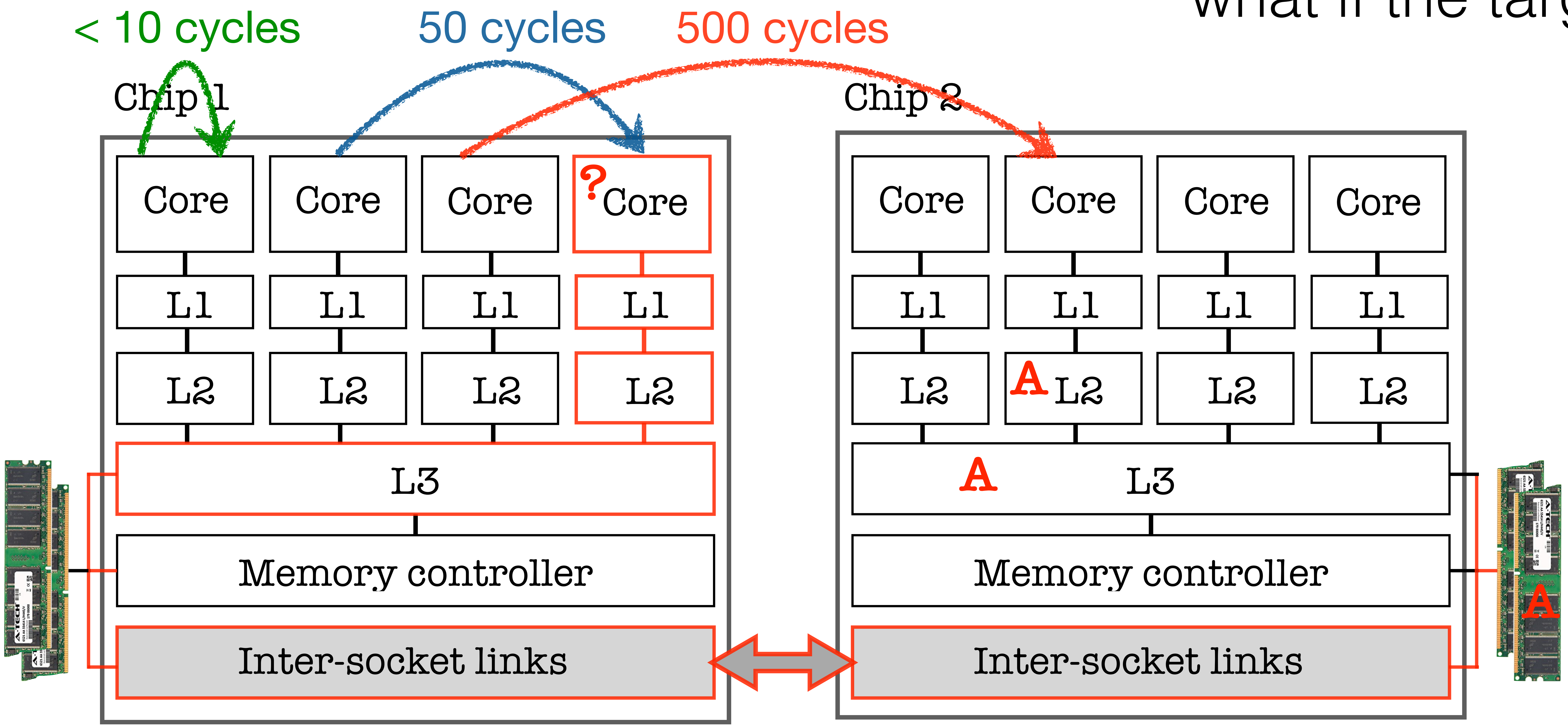


internals of a **multisocket multicore server**

Cache hierarchy

Optimizing data access

what if the target data is in the **another chip**?



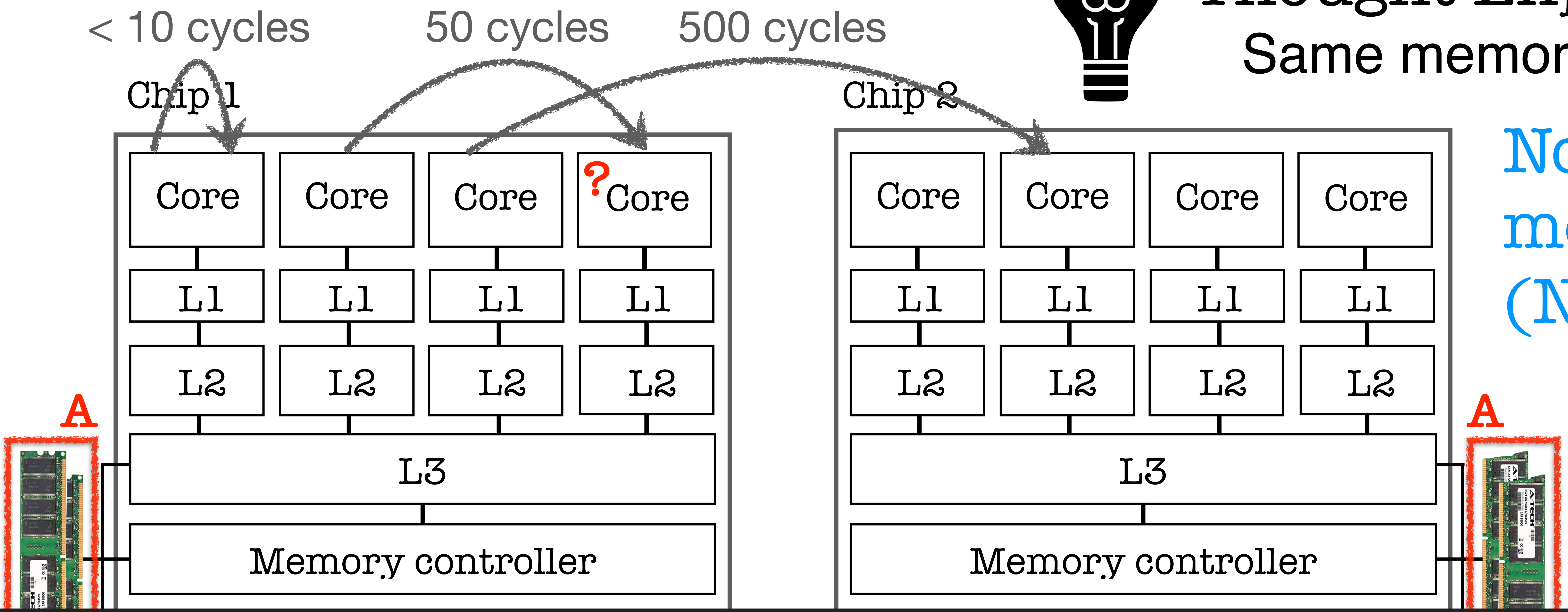
internals of a **multisocket multicore server**

Cache hierarchy

Optimizing data access

Thought Experiment 6

Same memory access time?



Non-uniform memory access (NUMA)

We data is placed in cache matters!

Disks

What are they really?

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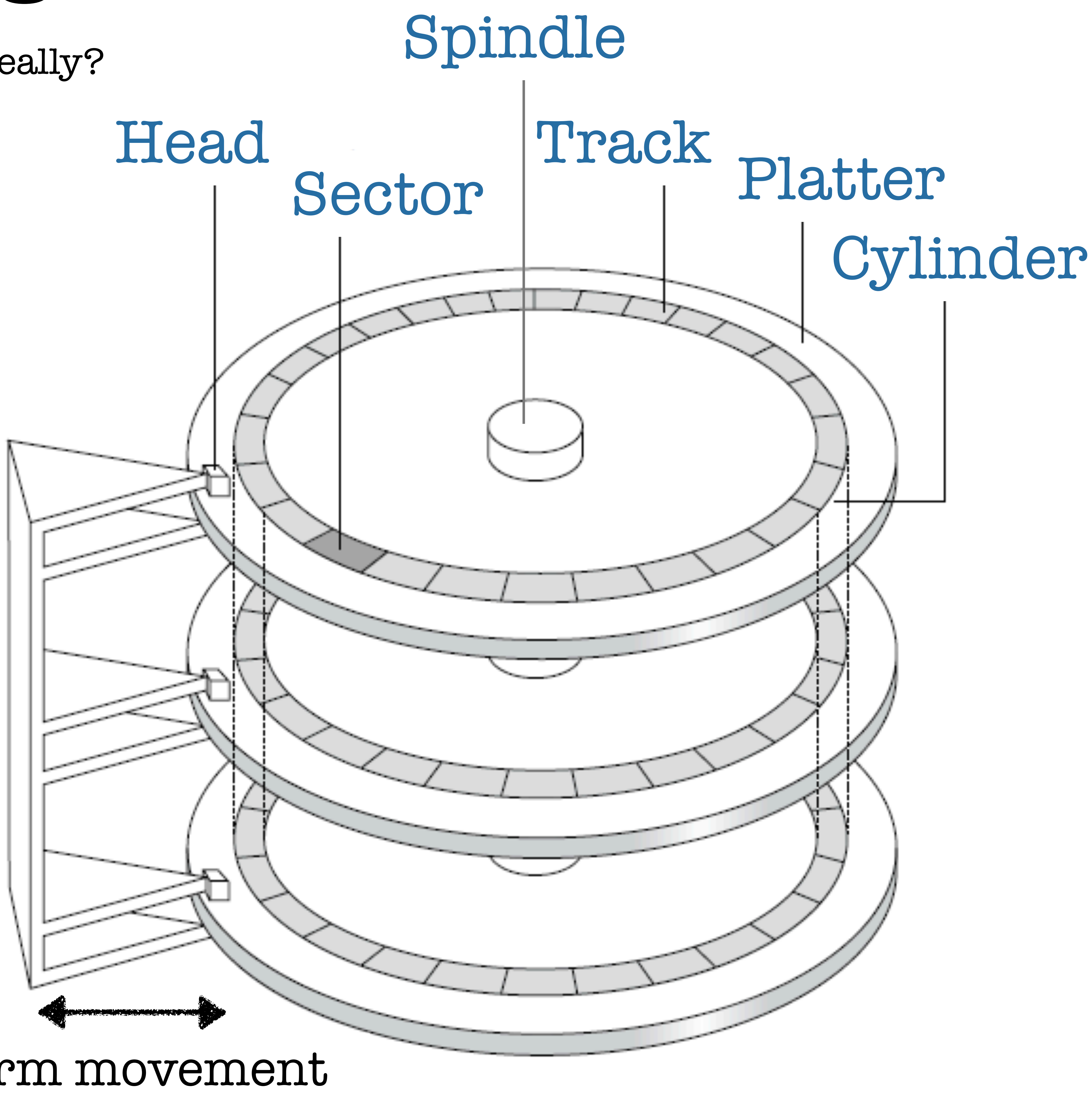
Disks

What are they really?

Arm assembly moves in and out to point to the correct **track**

Platters move around the spindle to get the desired **sector**

One head reads/writes at a time



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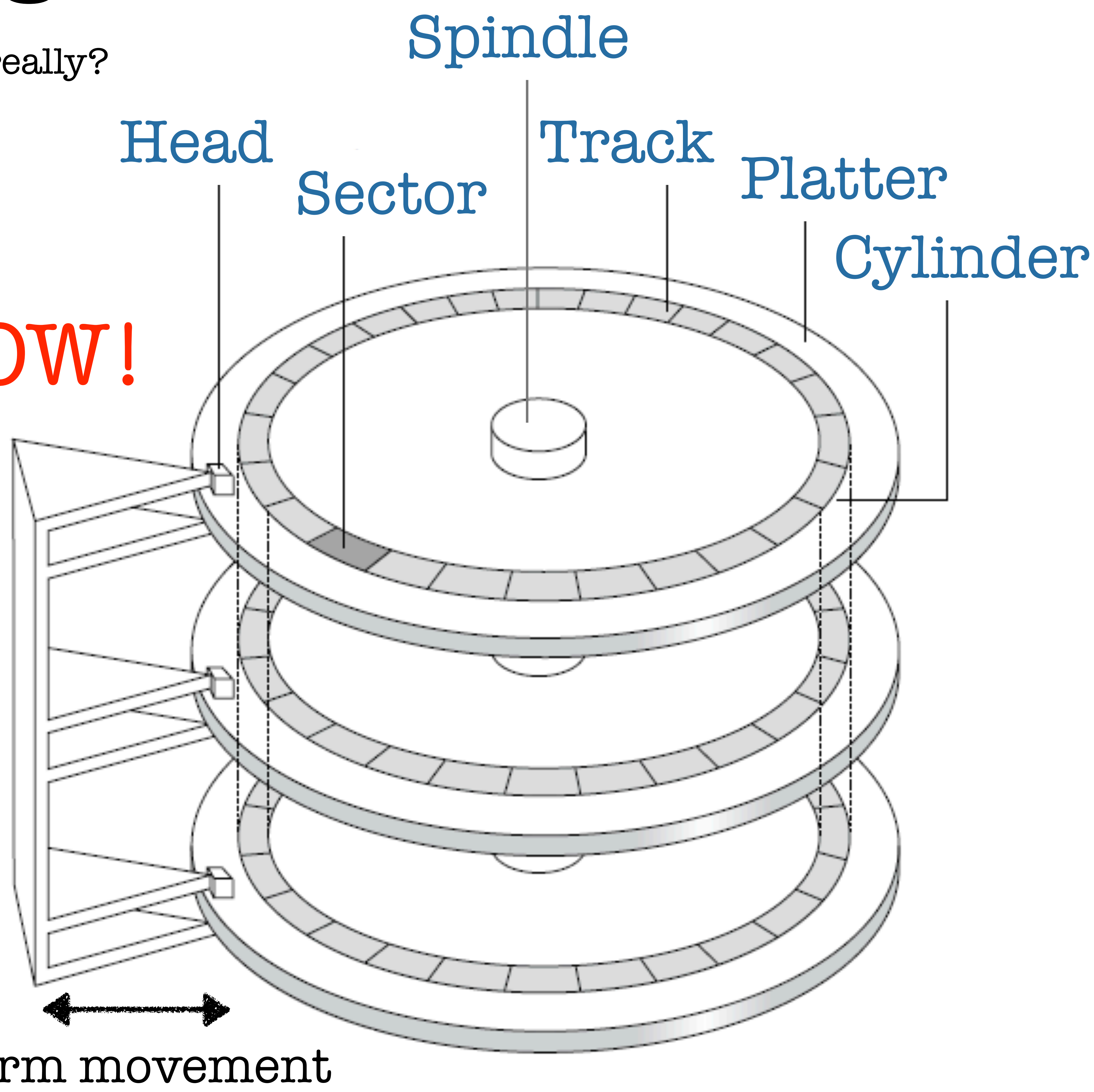
Disks

What are they really?

Time to access a **page of data**:

1. Find the **track** (move arm to track)
   seek latency
2. Find the **sector** (rotate the platters)
   rotational latency
3. Read/Write **page** (head does this)
   transfer latency

SLOW!



Flash disks

Around for >30 years, now!

Writes, **reads**, and **deletes** happen **electronically**!

no mechanical component

Data is still stored in **pages** (typically **4KB**)

Random reads are almost **as fast as sequential reads**

the 10%-20% difference in speed owes to **prefetching**

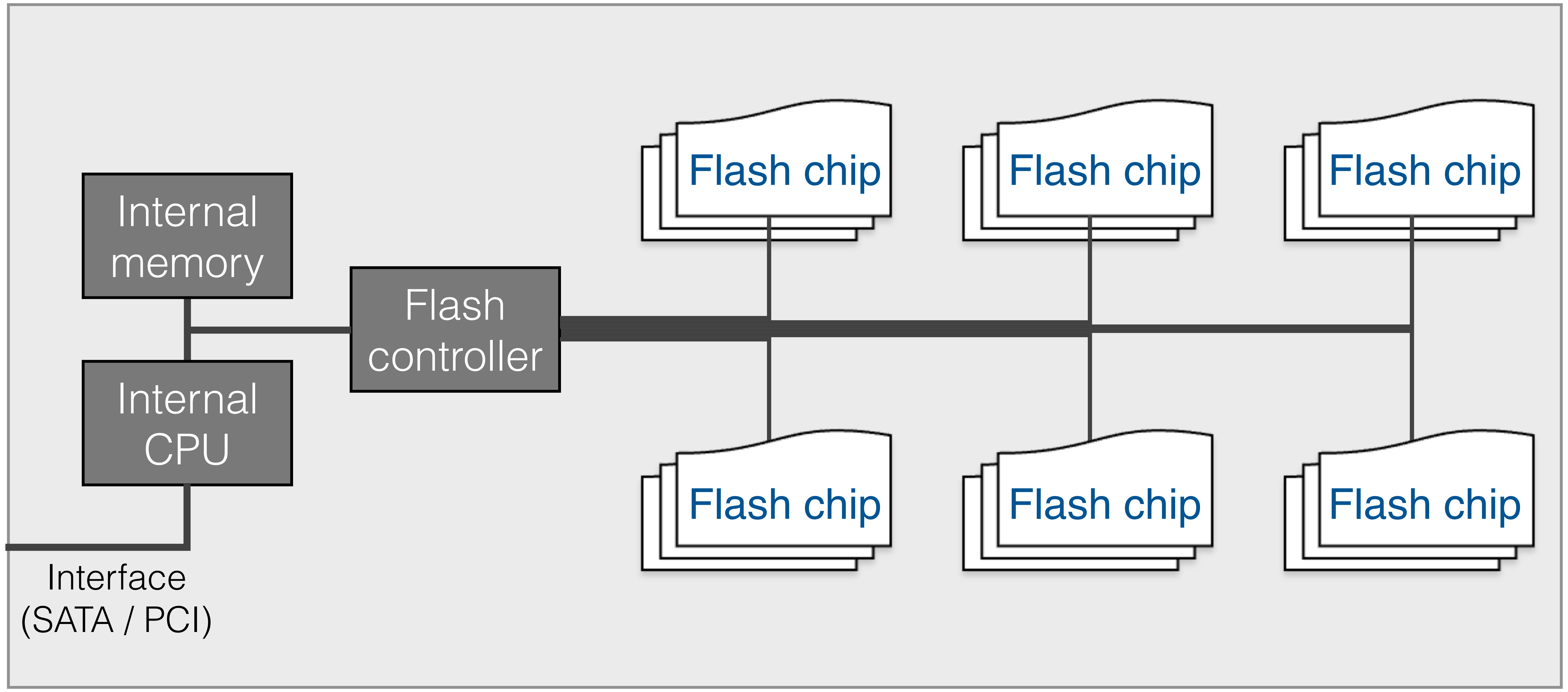
But, **random writes** are **slower than random reads**

an **asymmetry** exists **between reads and writes** on SSDs

Internals of **flash** disks

Let's have a sneak peak

SSD

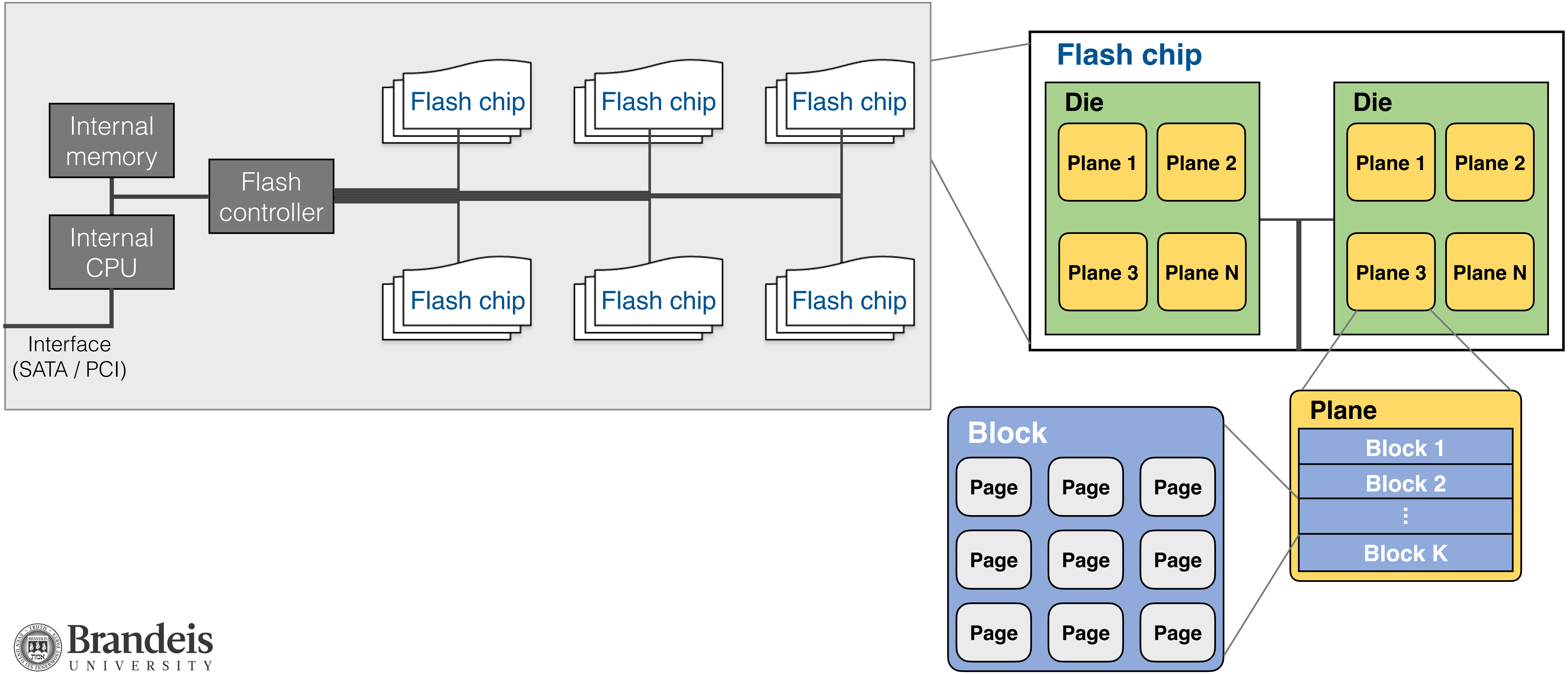


Reads/Writes can happen parallely in multiple flash chips

Internals of **flash** disks

SSD

Let's have a sneak peak



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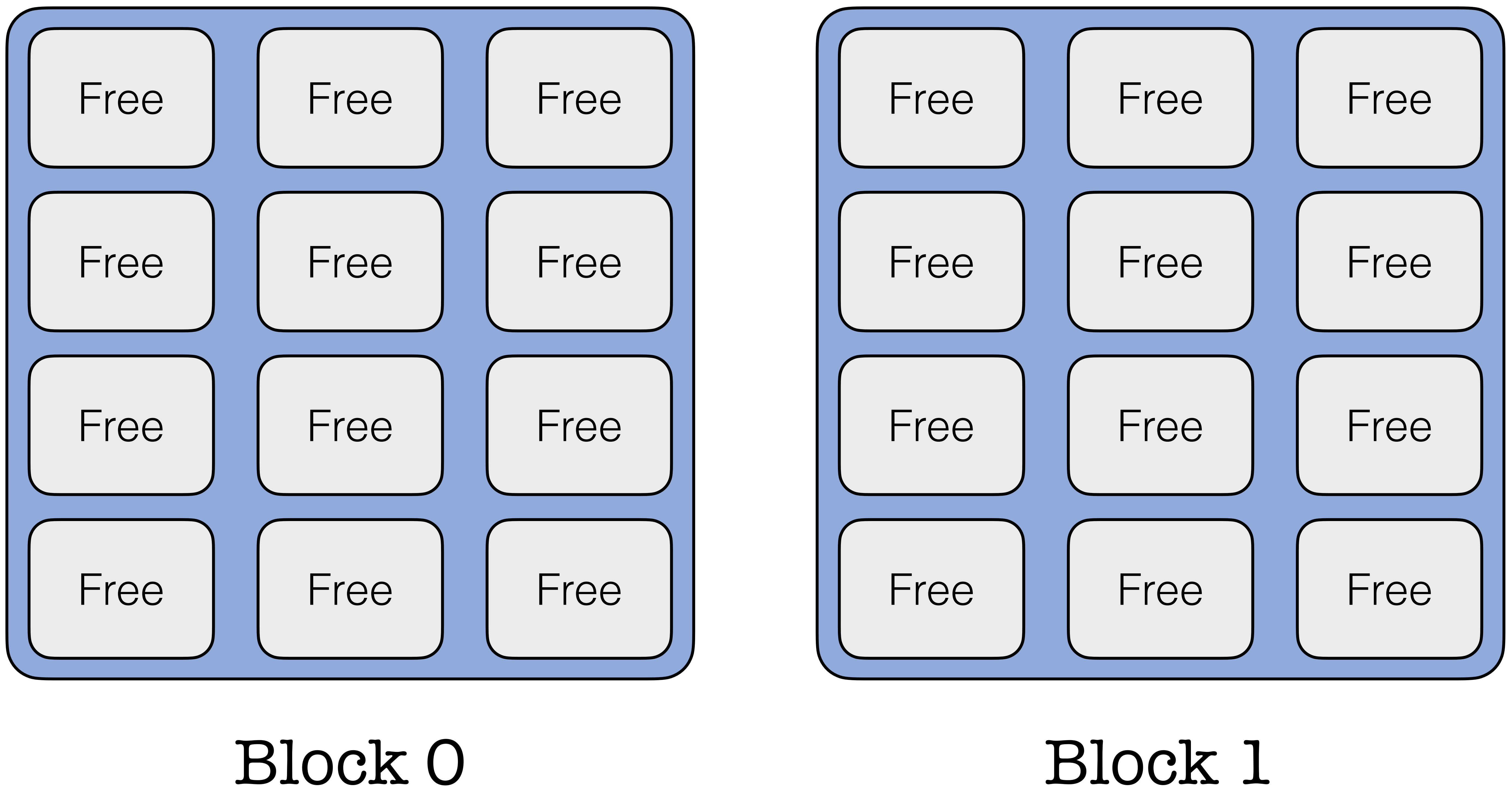
Writes in **SSDs**

Writes are out of place

Insert
A, B, C, D, E, F, G, H



Writes in SSDs

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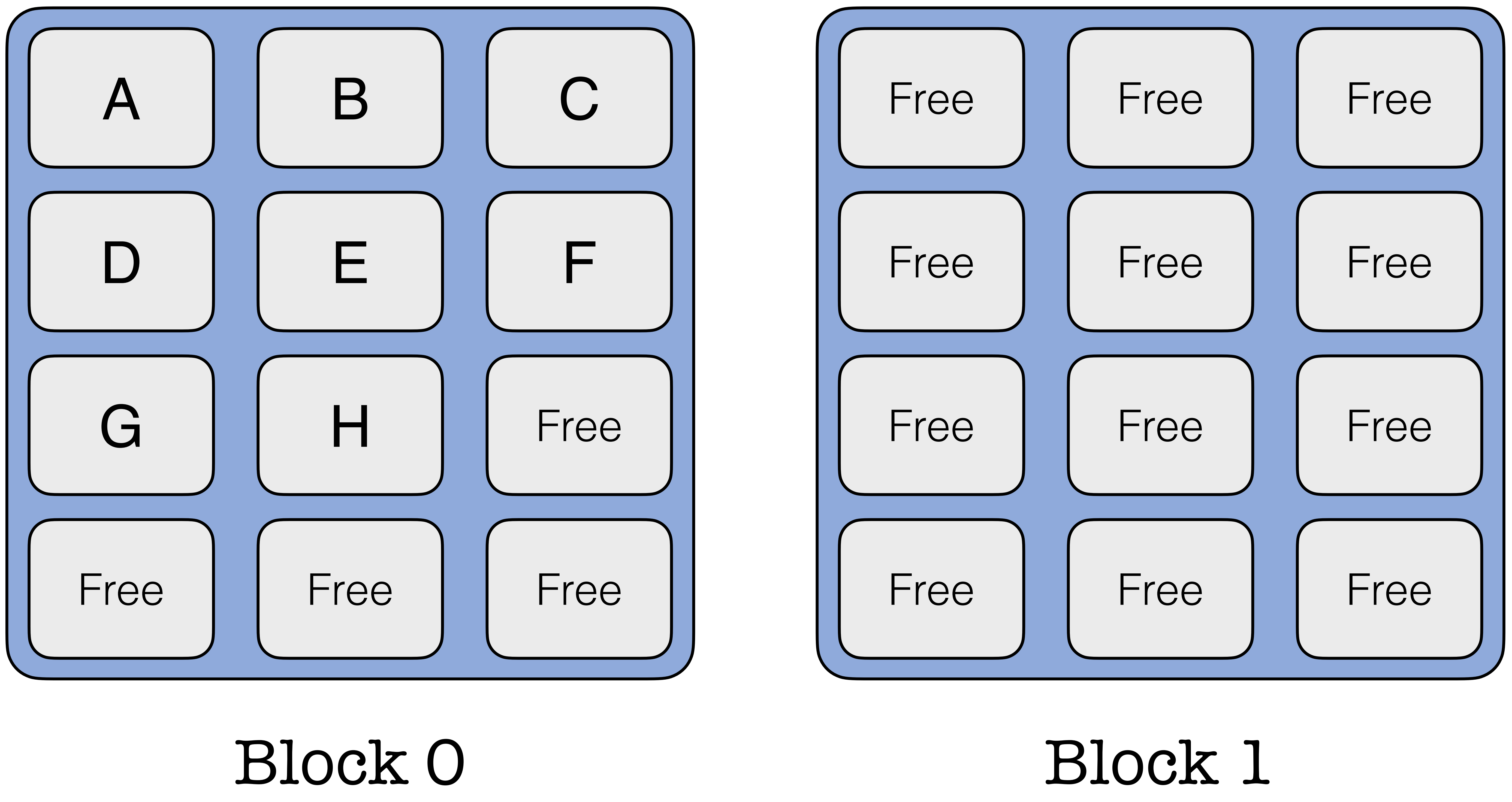
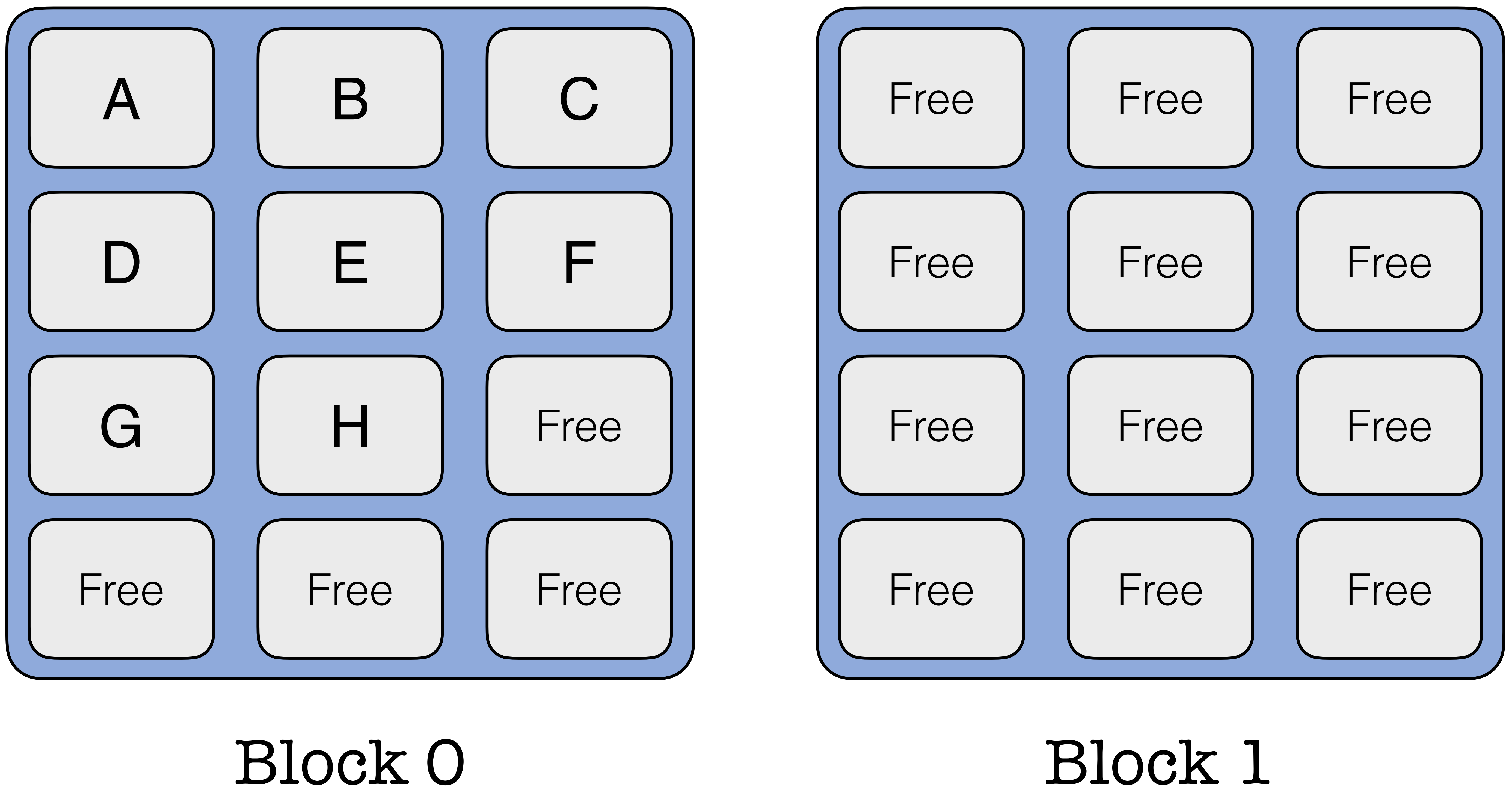


Writes in **SSDs**

Writes are out of place

Insert
A, B, C, D, E, F, G, H

Update
A, B, C, D



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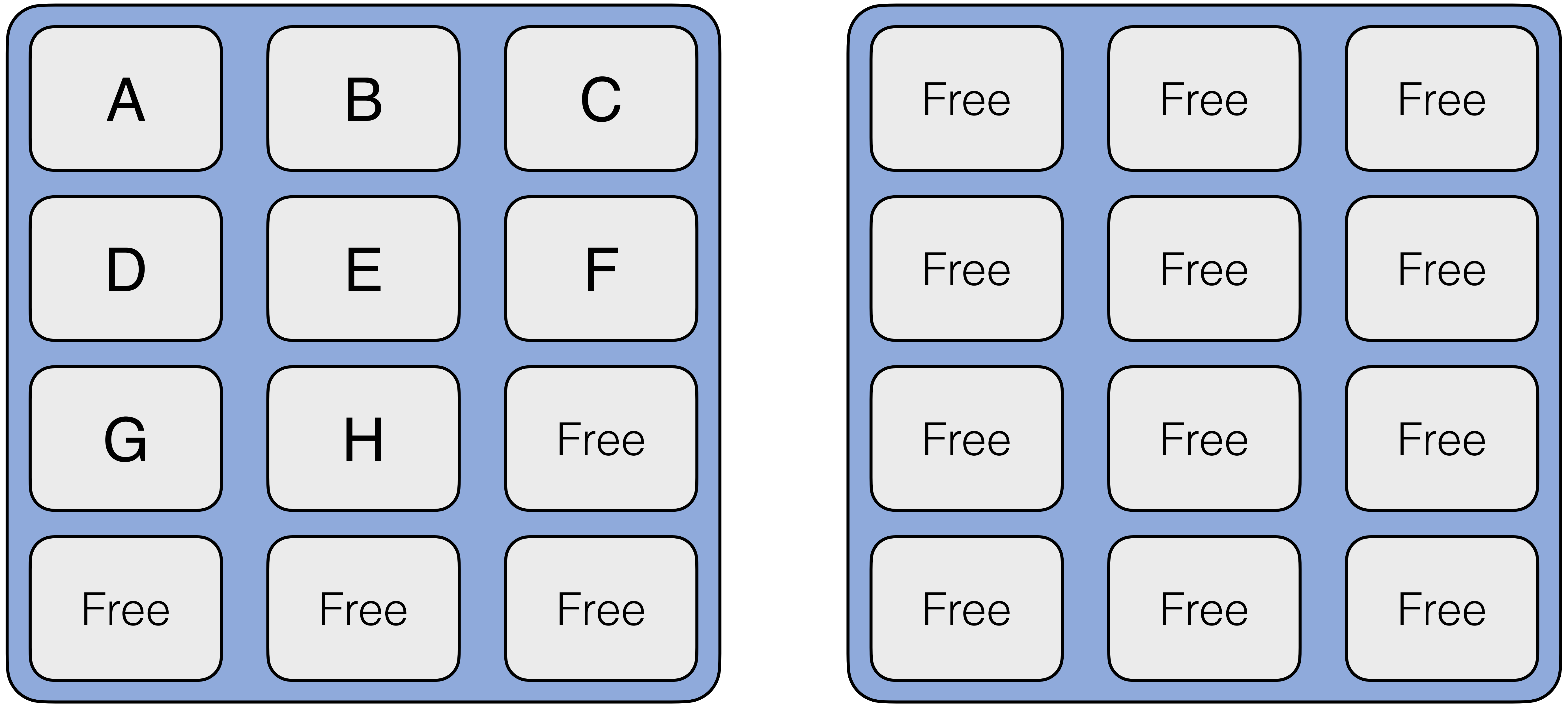

Block 0 Block 1

Writes in SSDs

Writes are out of place

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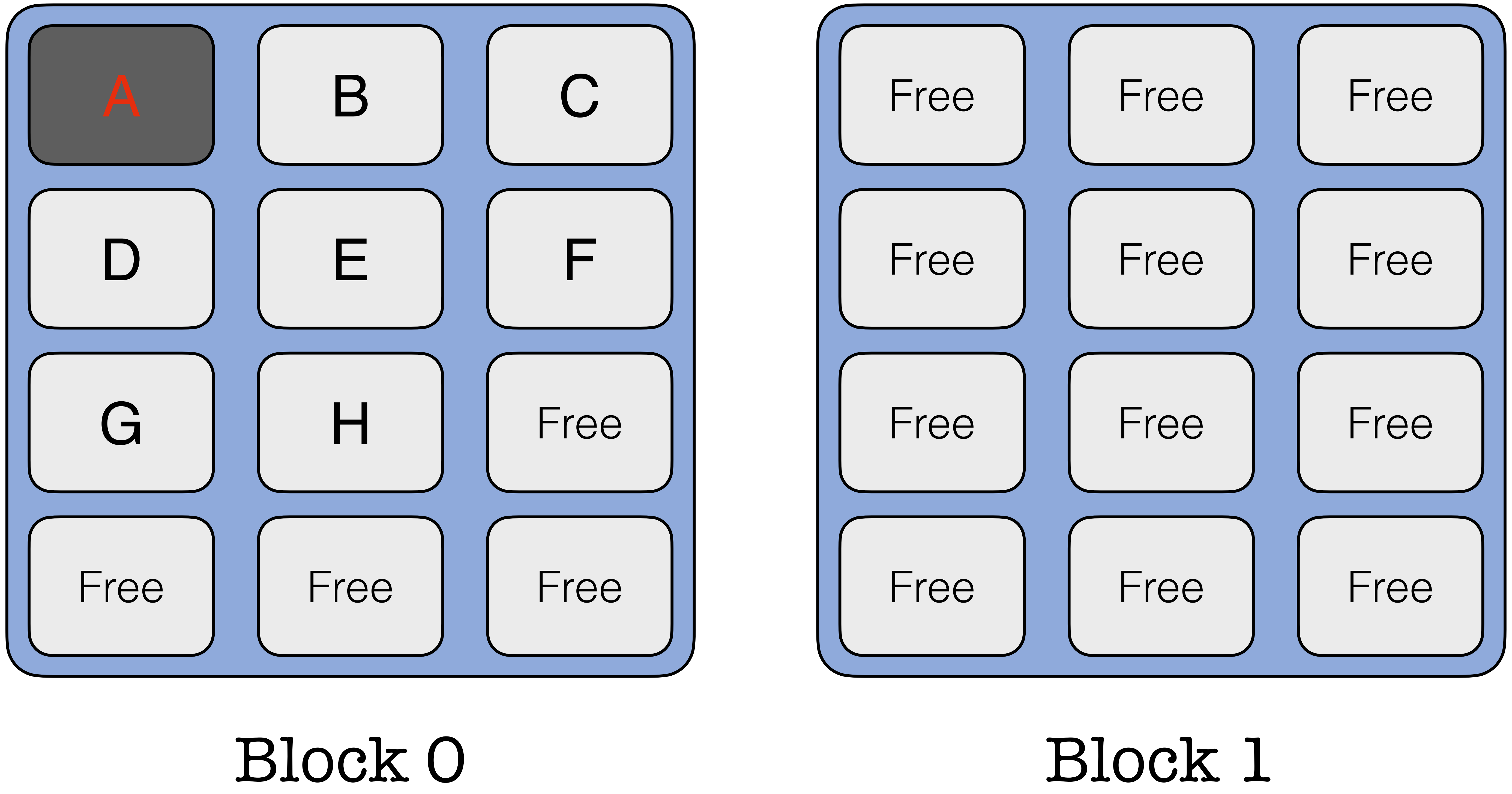
Update
A, B, C, D



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Writes in **SSDs**

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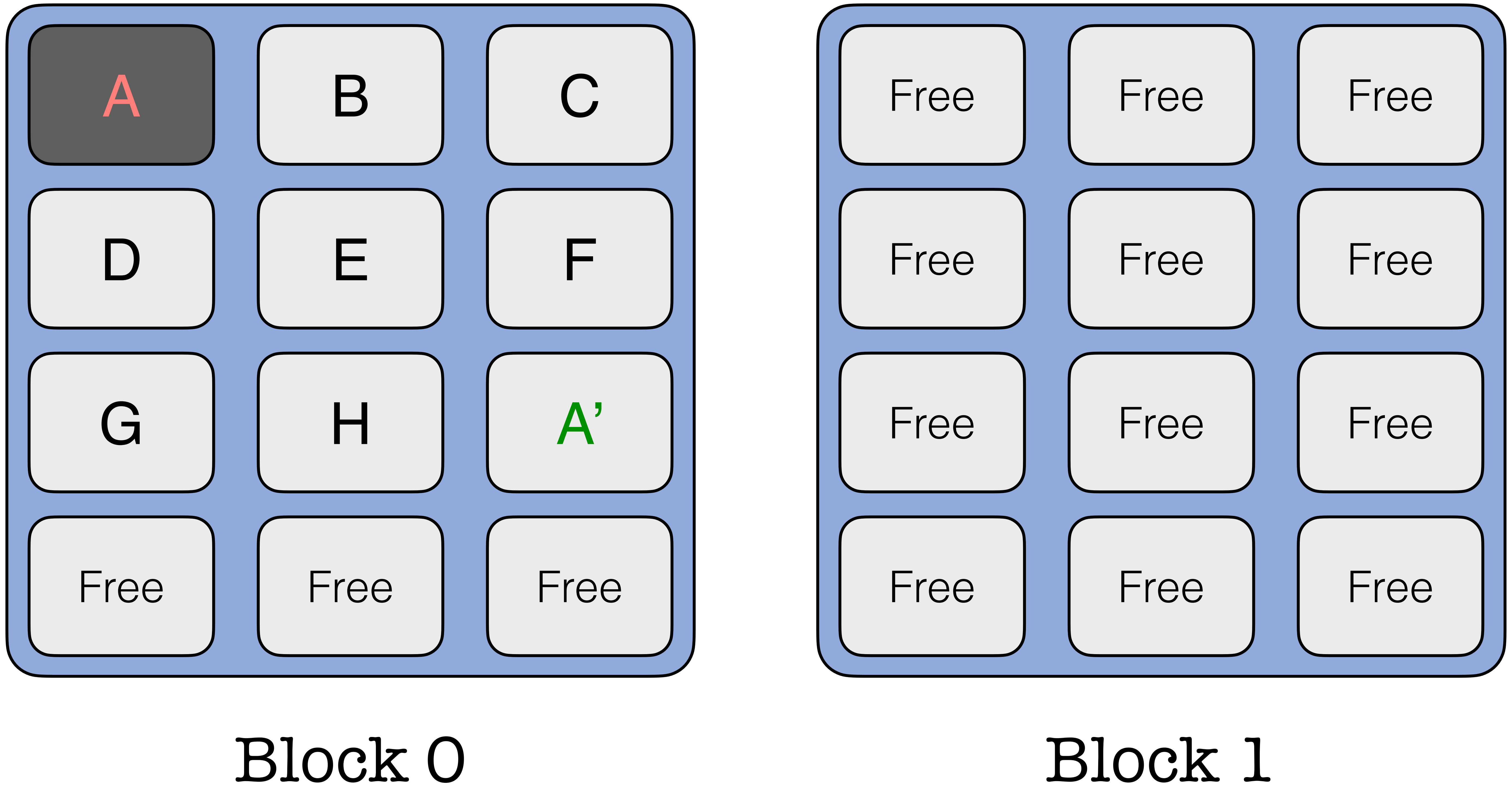

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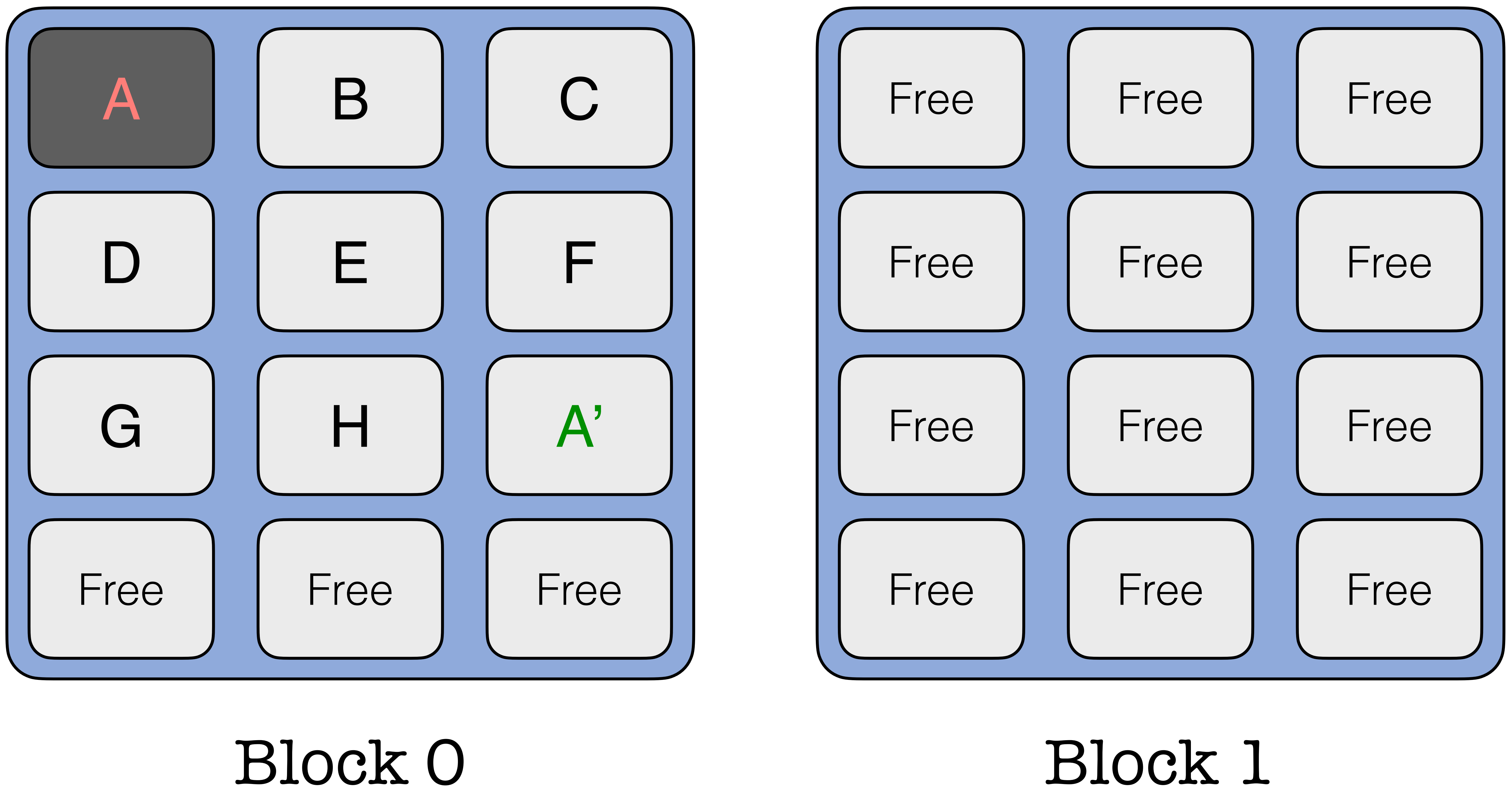

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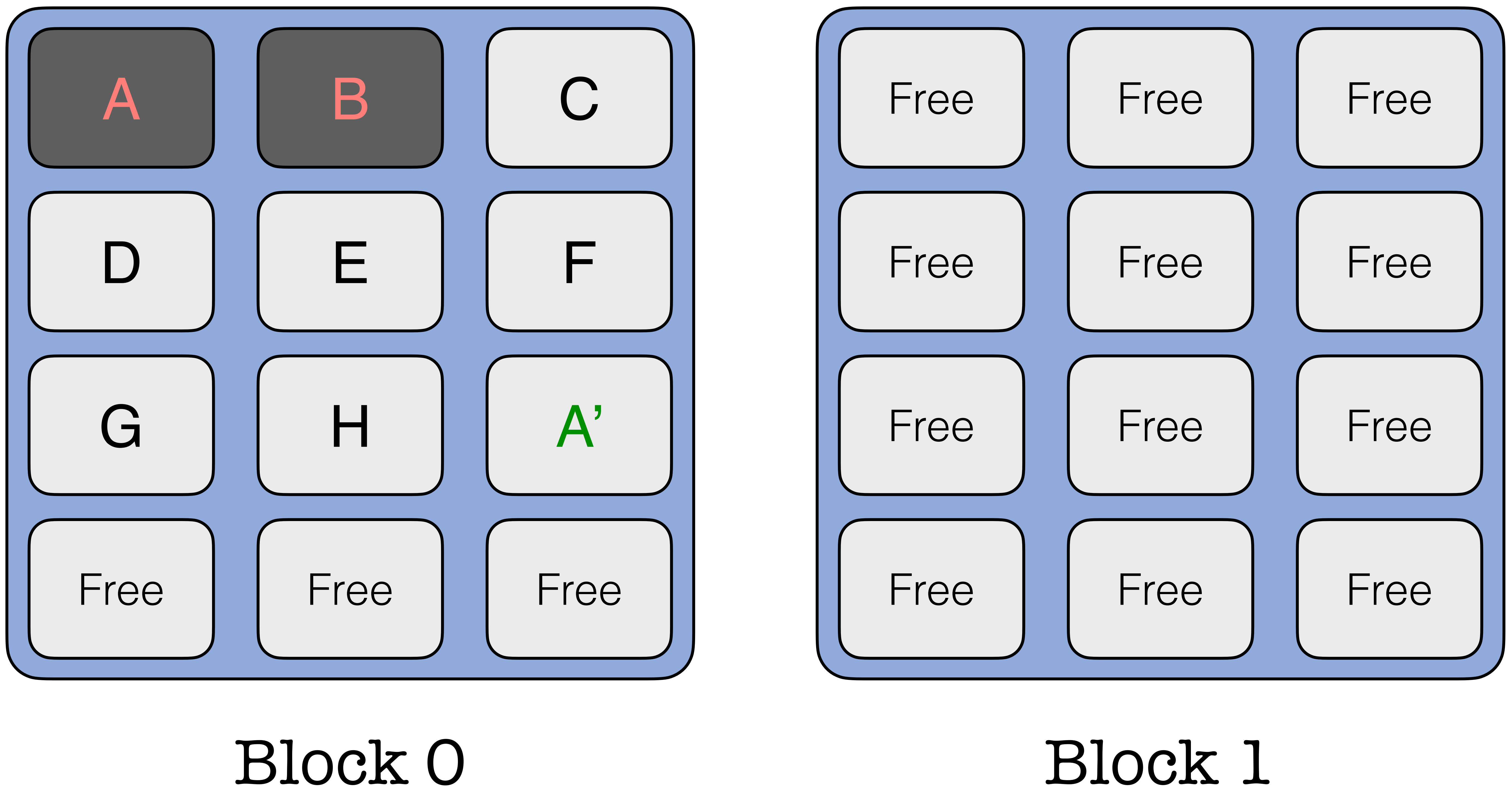

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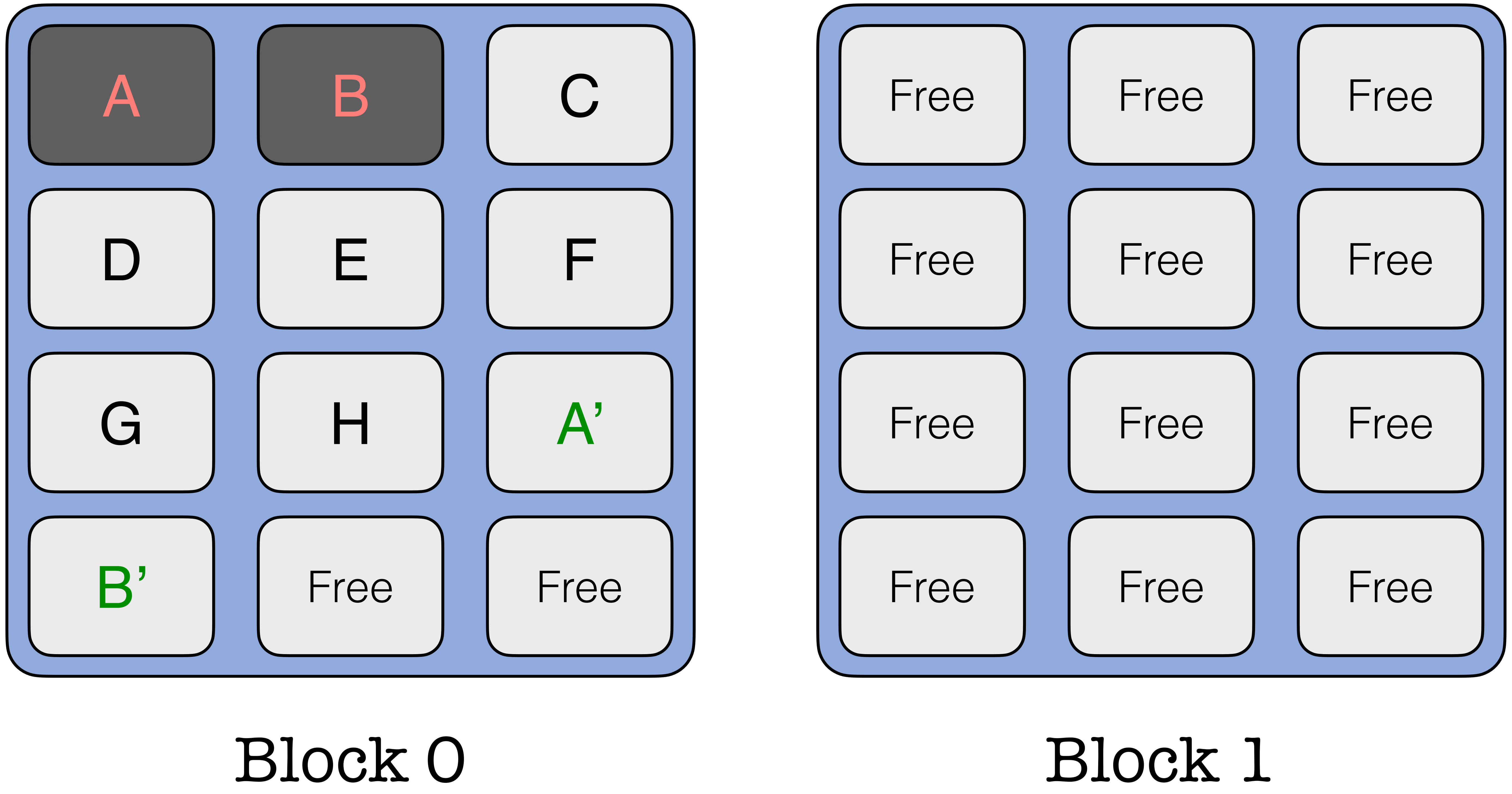

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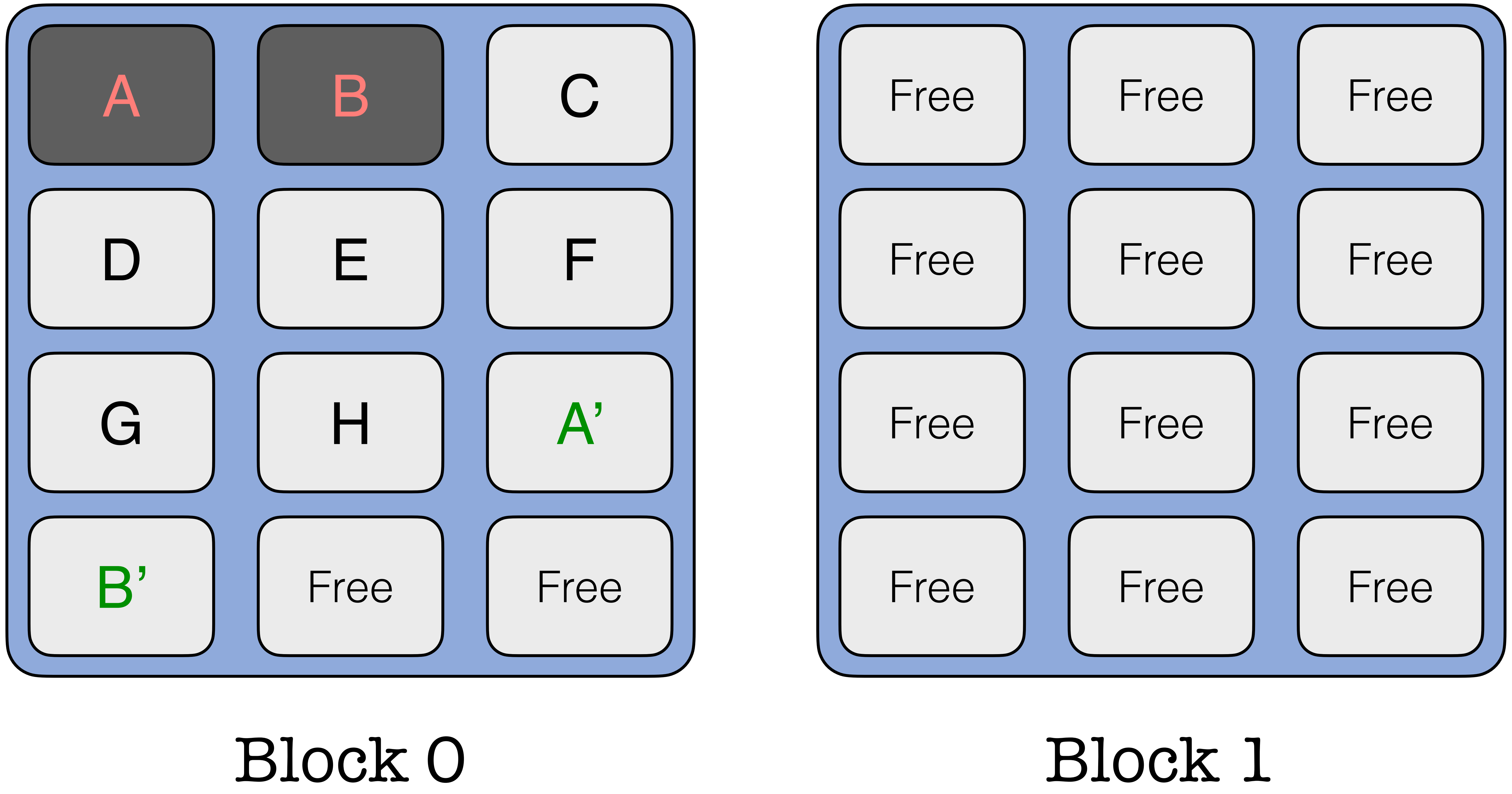

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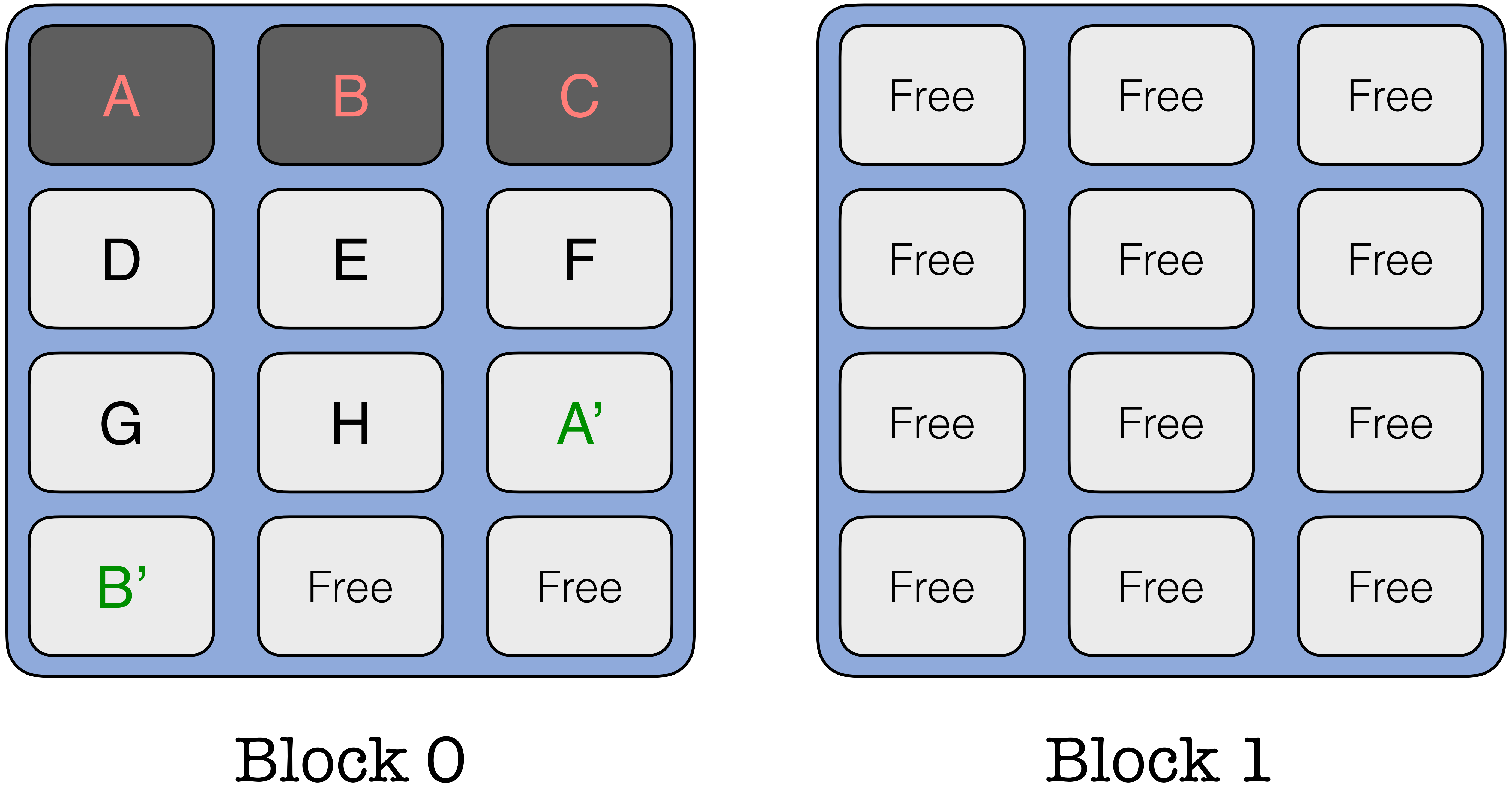

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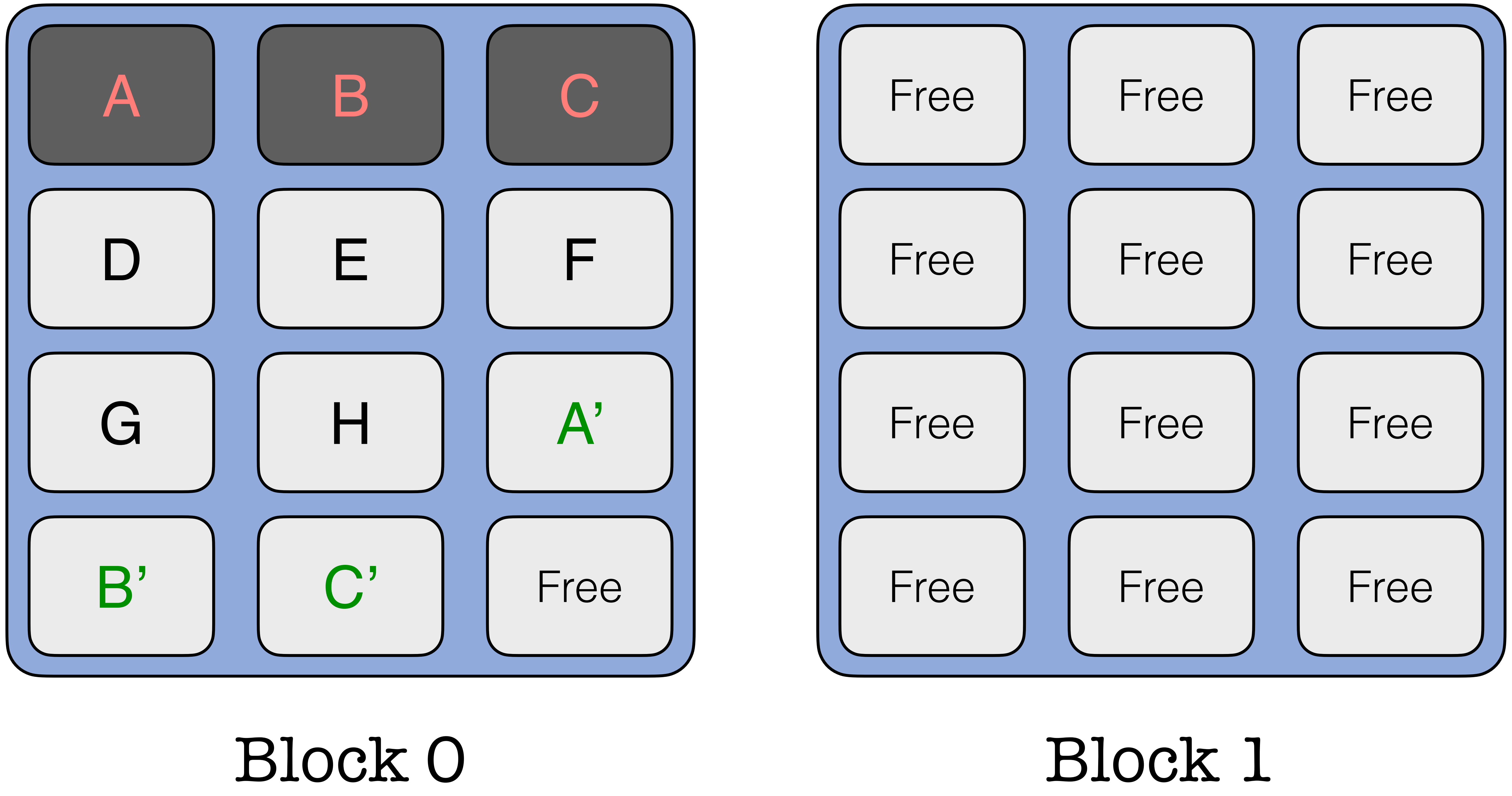

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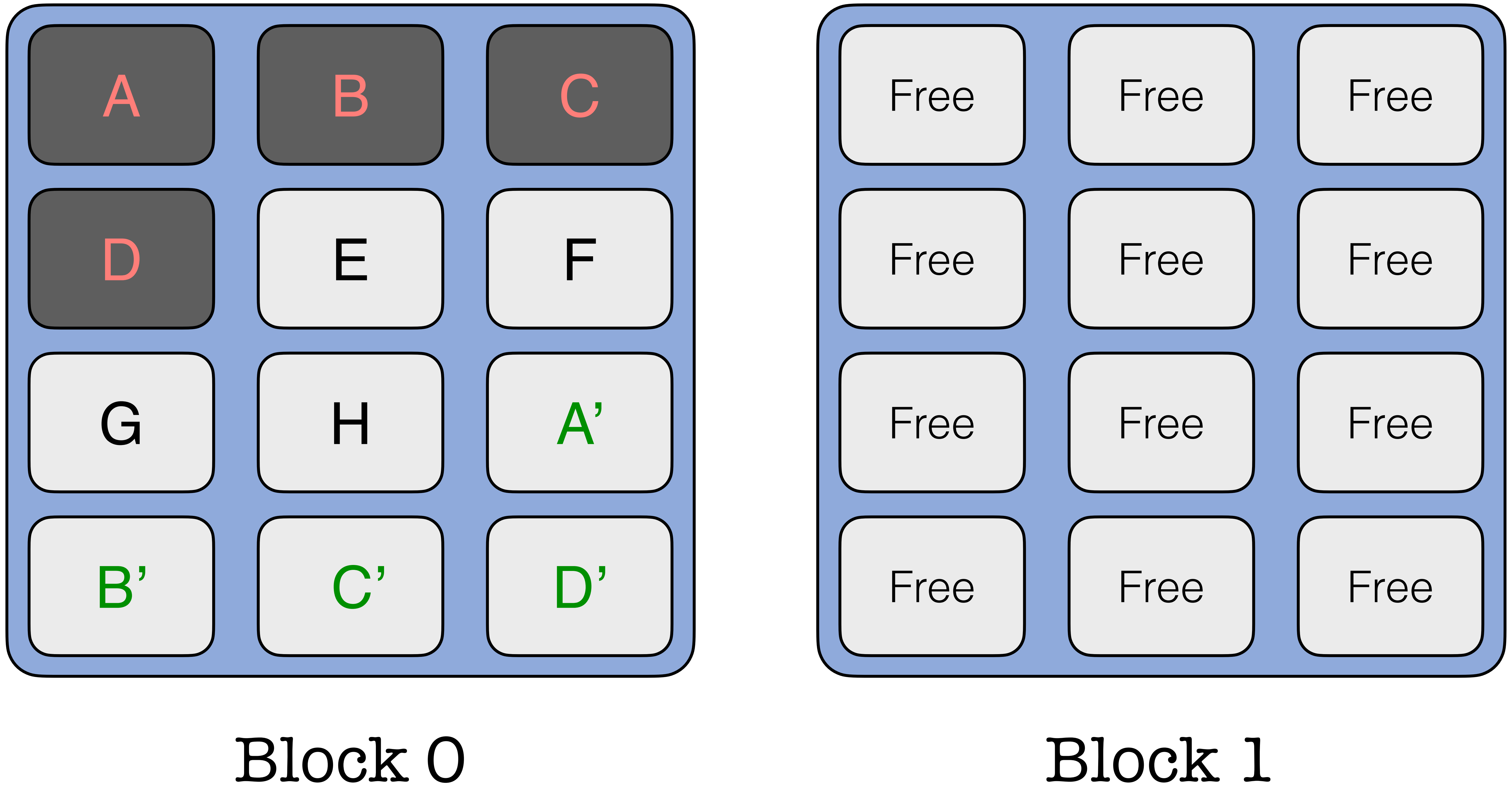

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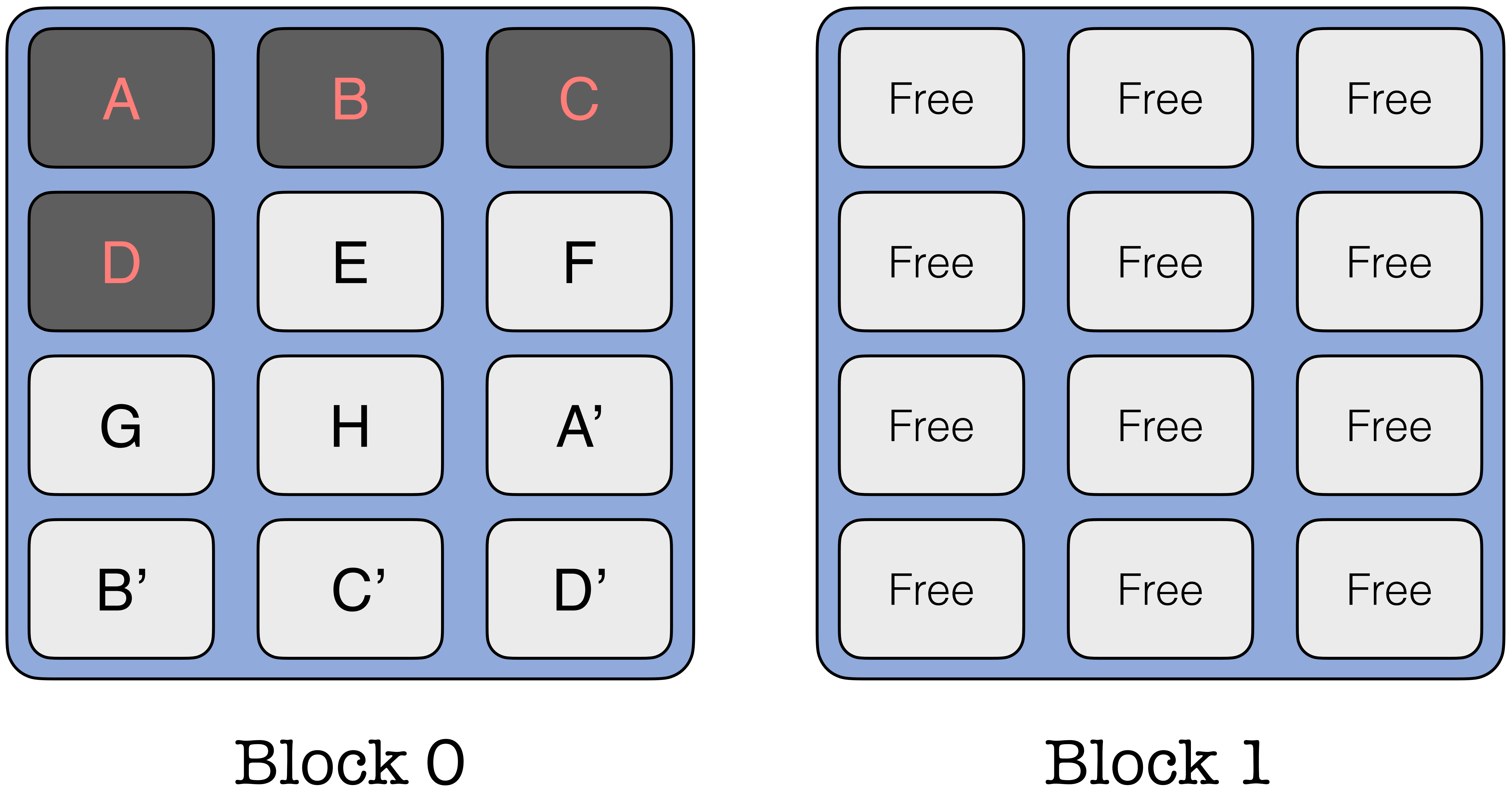
Writes in SSDs

Writes are out of place

Insert
A, B, C, D, E, F, G, H

Update
A, B, C, D

Insert
M, N, O, P, Q, R



Writes in **SSDs**

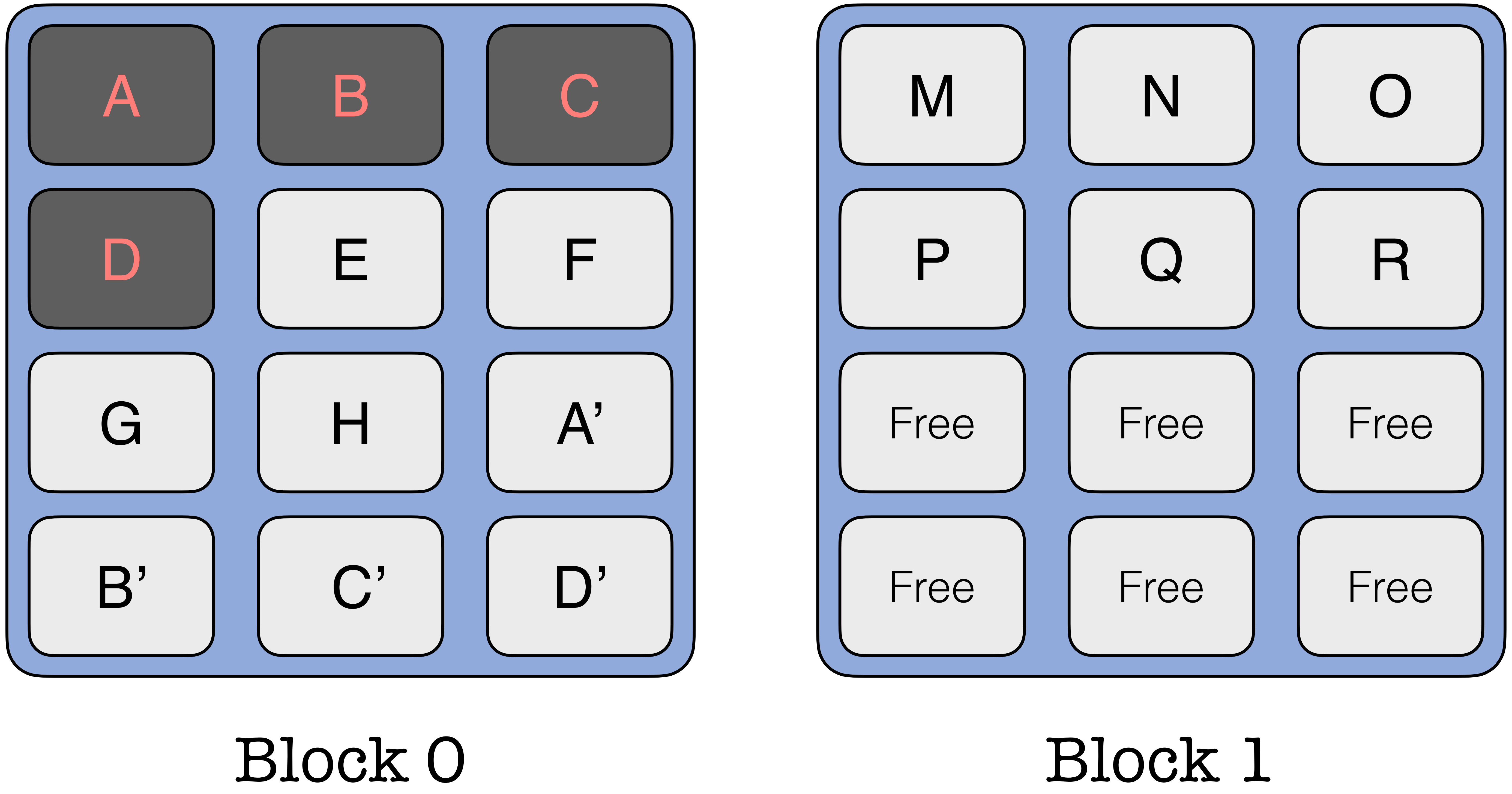
Writes are out of place

Insert
A, B, C, D, E, F, G, H

Update
A, B, C, D

Insert
M, N, O, P, Q, R

Update
M, N, O, P, Q, R



Writes in **SSDs**

Writes are out of place

Insert
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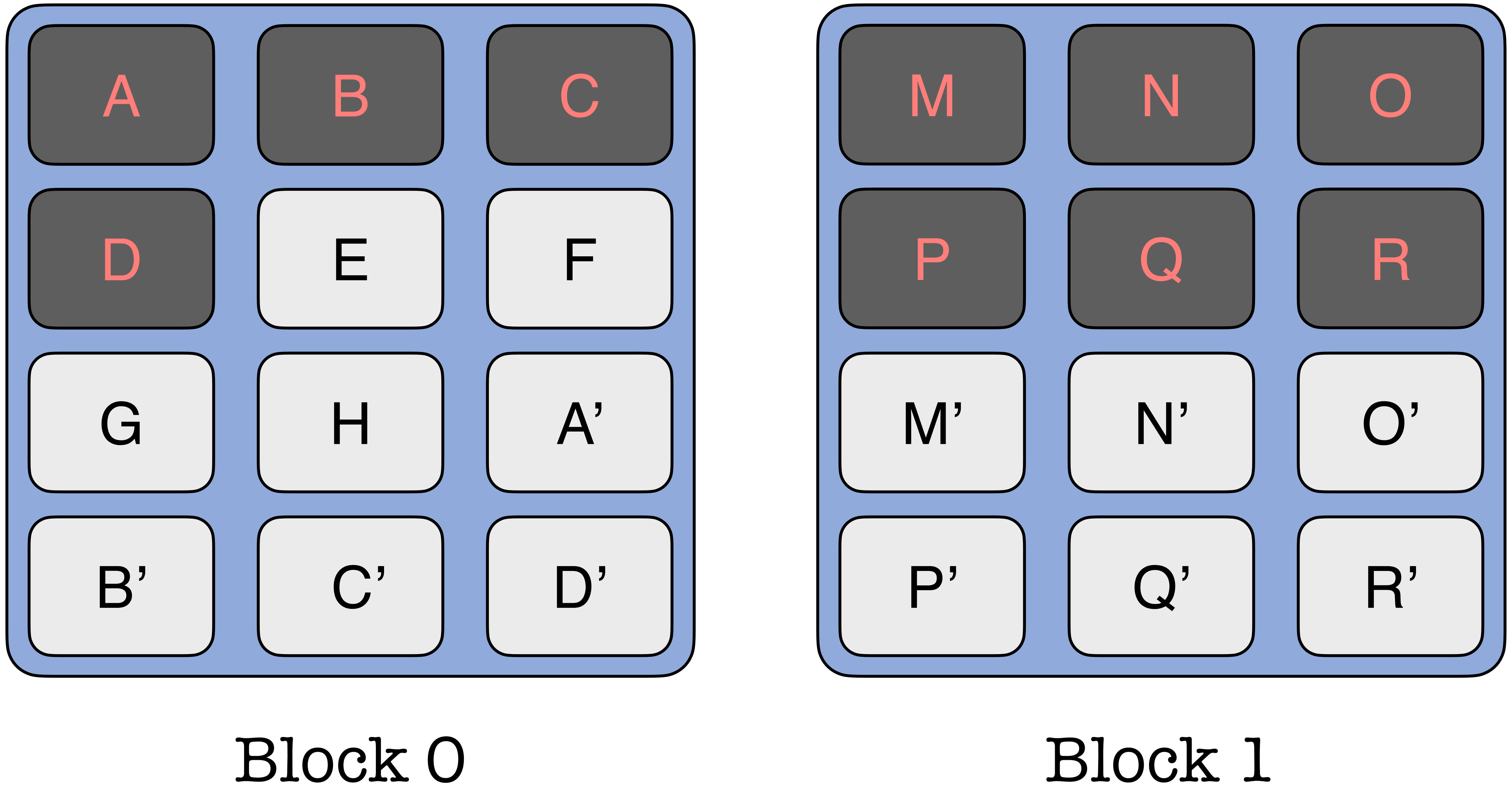
Update
A, B, C, D

Insert
M, N, O, P, Q, R

Update
M, N, O, P, Q, R



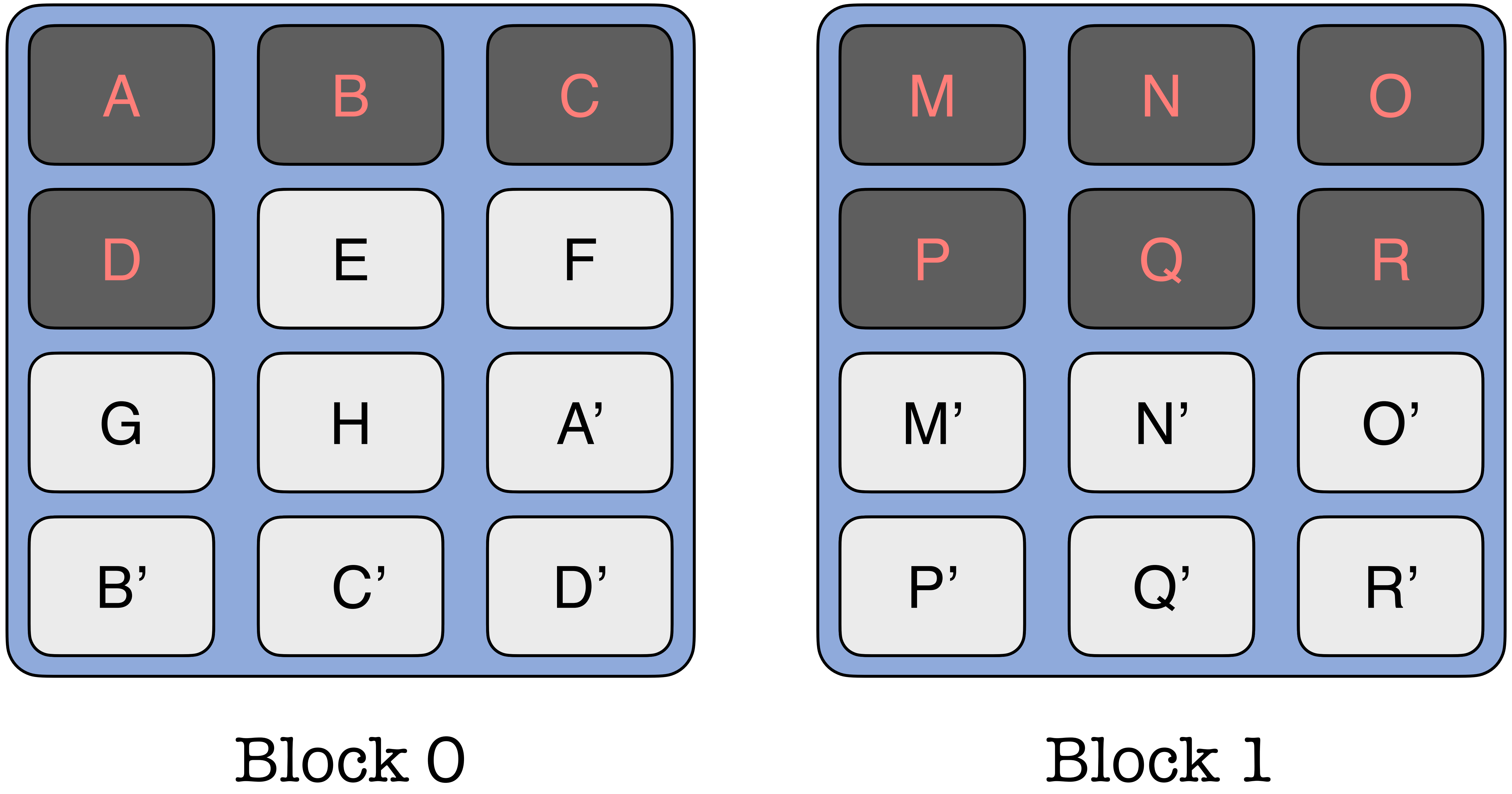
Writes in SSDs

Writes are out of place

What if all blocks are full?

Garbage Collection

1 **keep track** of valid pages



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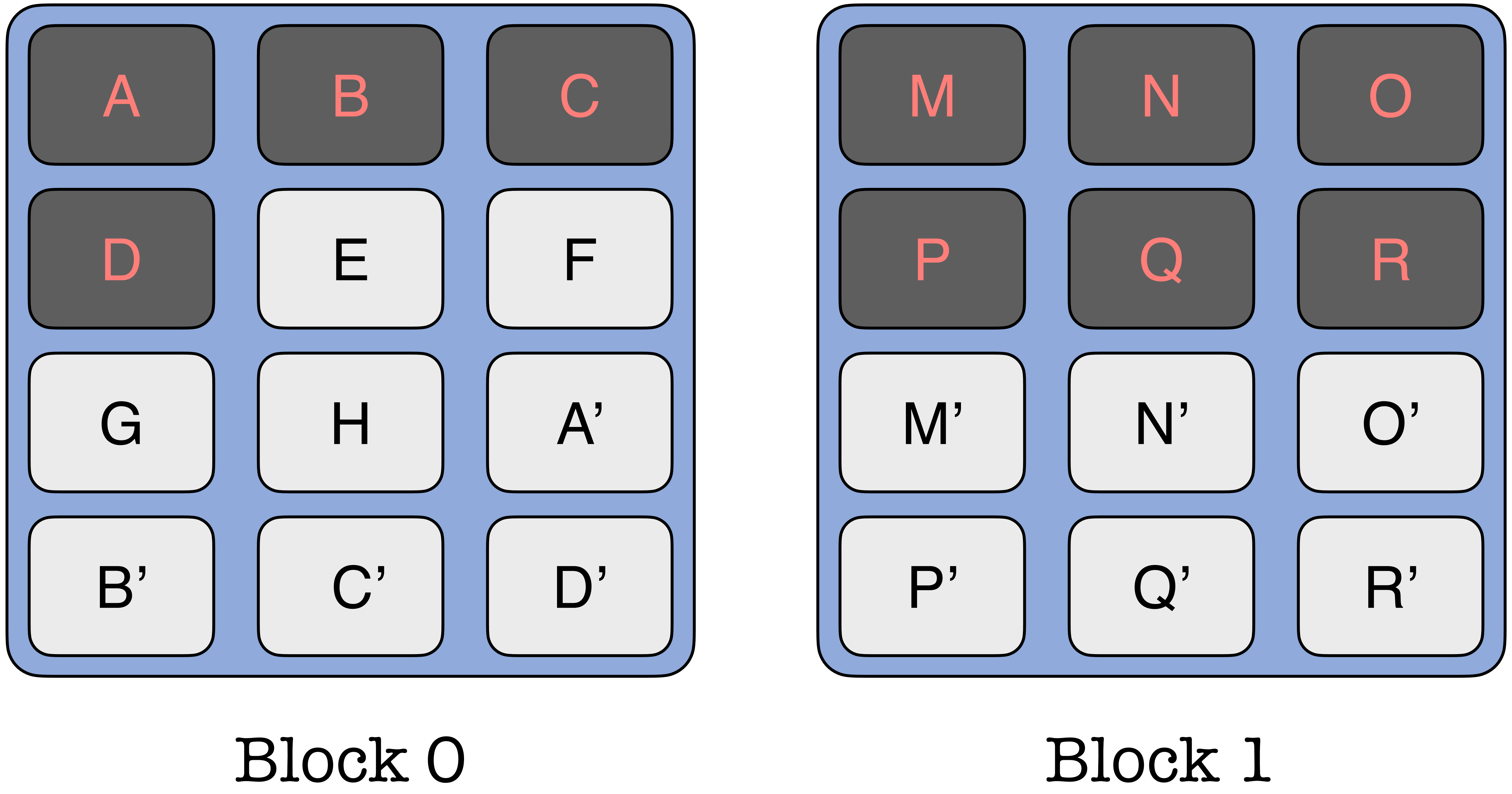
Writes in **SSDs**

Writes are out of place

What if all blocks are full

Garbage Collection

1. **keep track** of valid pages
2. **erase** all pages



valid pages | E | F | G | H | A’ | B’ | C’ | D’ | M’ | N’ | O’ | P’ | Q’ | R’ |

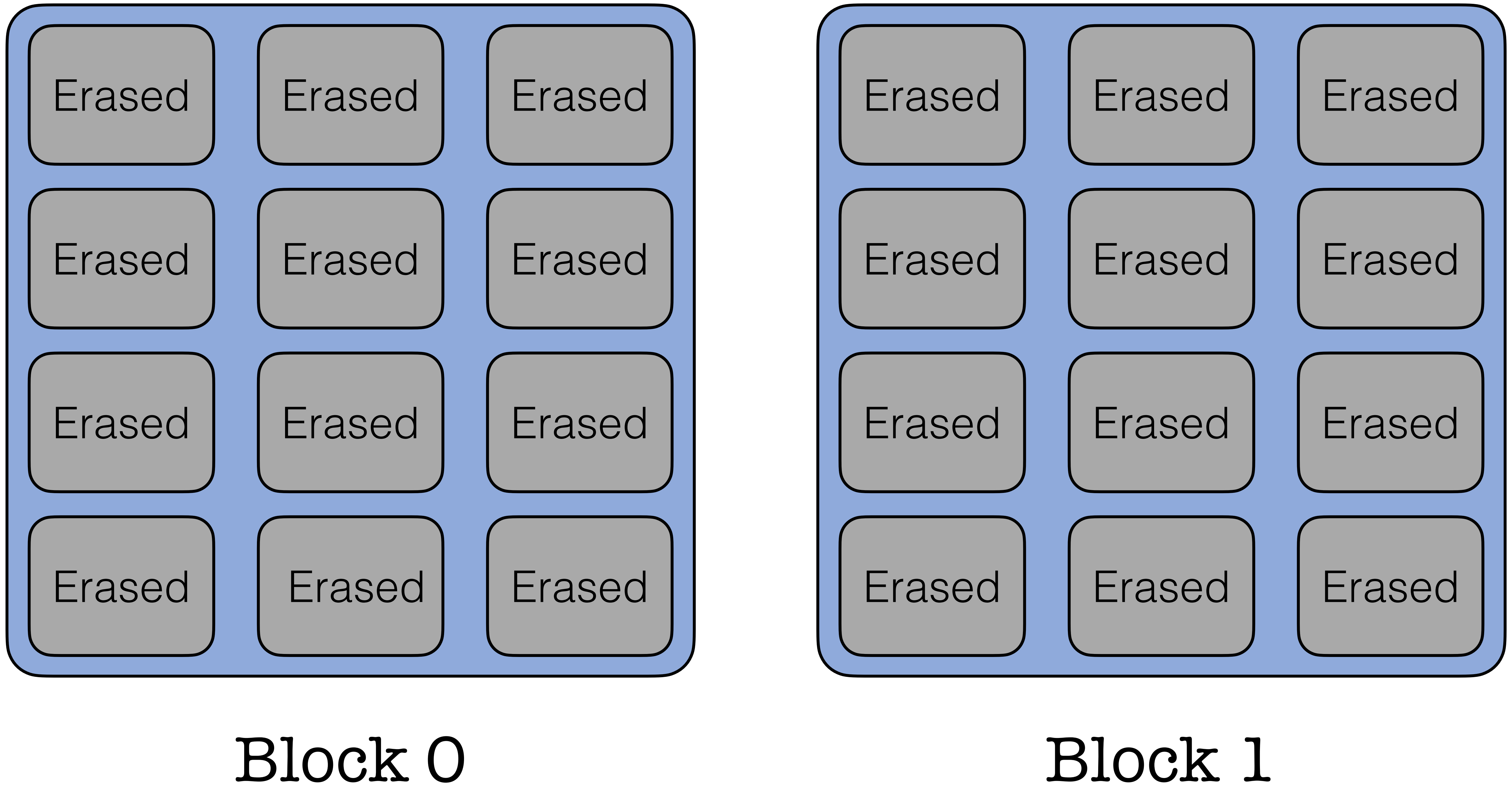
Writes in **SSDs**

Writes are out of place

What if all blocks are full?

Garbage Collection

1. **keep track** of valid pages
2. **erase** all pages



valid pages | E | F | G | H | A' | B' | C' | D' | M' | N' | O' | P' | Q' | R'

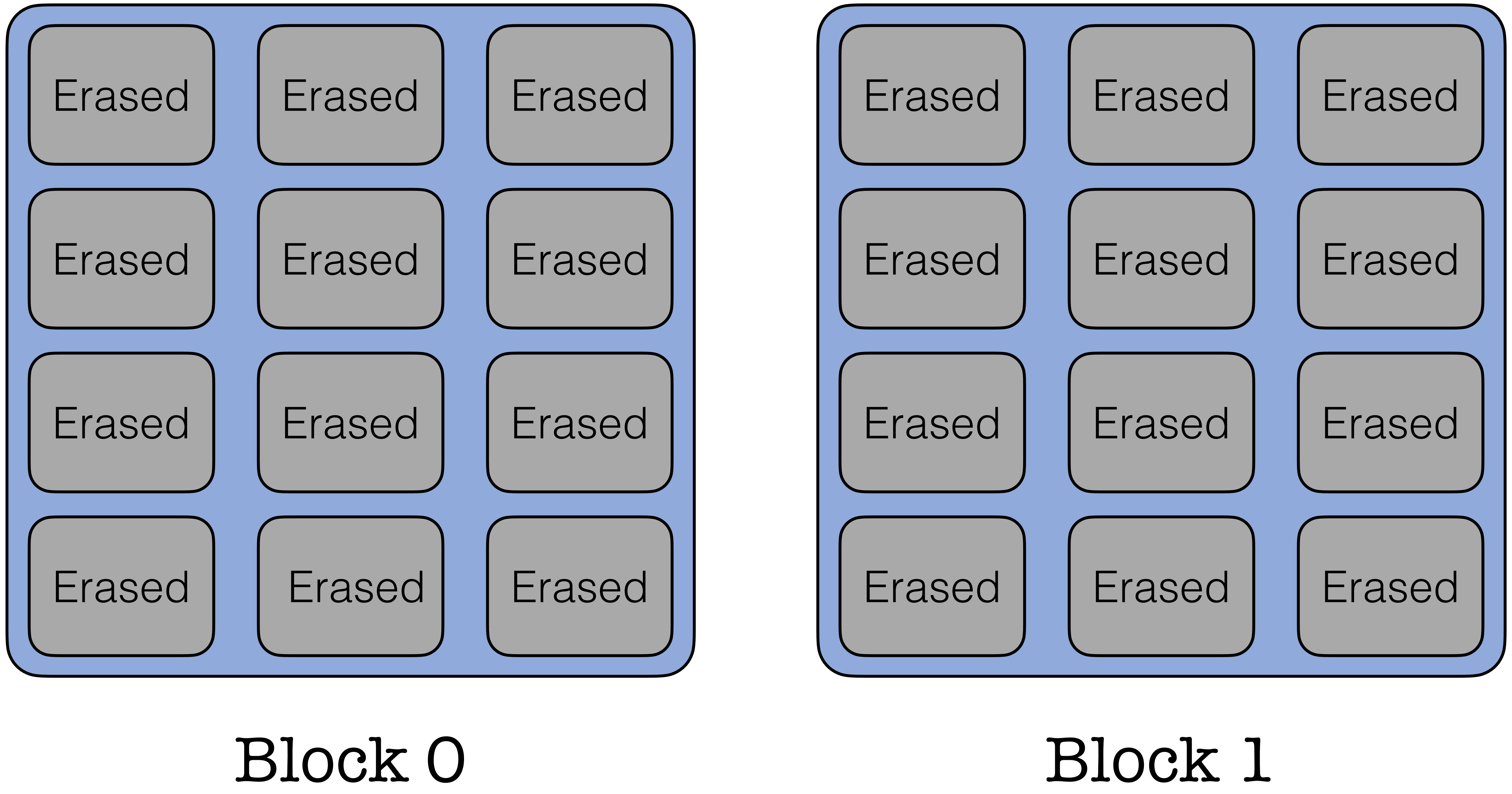
Writes in **SSDs**

Writes are out of place

What if all blocks are full?

Garbage Collection

1. **keep track** of valid pages
2. **erase** all pages
3. **write back** valid pages



valid pages | E | F | G | H | A' | B' | C' | D' | M' | N' | O' | P' | Q' | R' |

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Writes in **SSDs**

Writes are out of place

What if all blocks are full

Garbage Collection

1. **keep track** of valid pages
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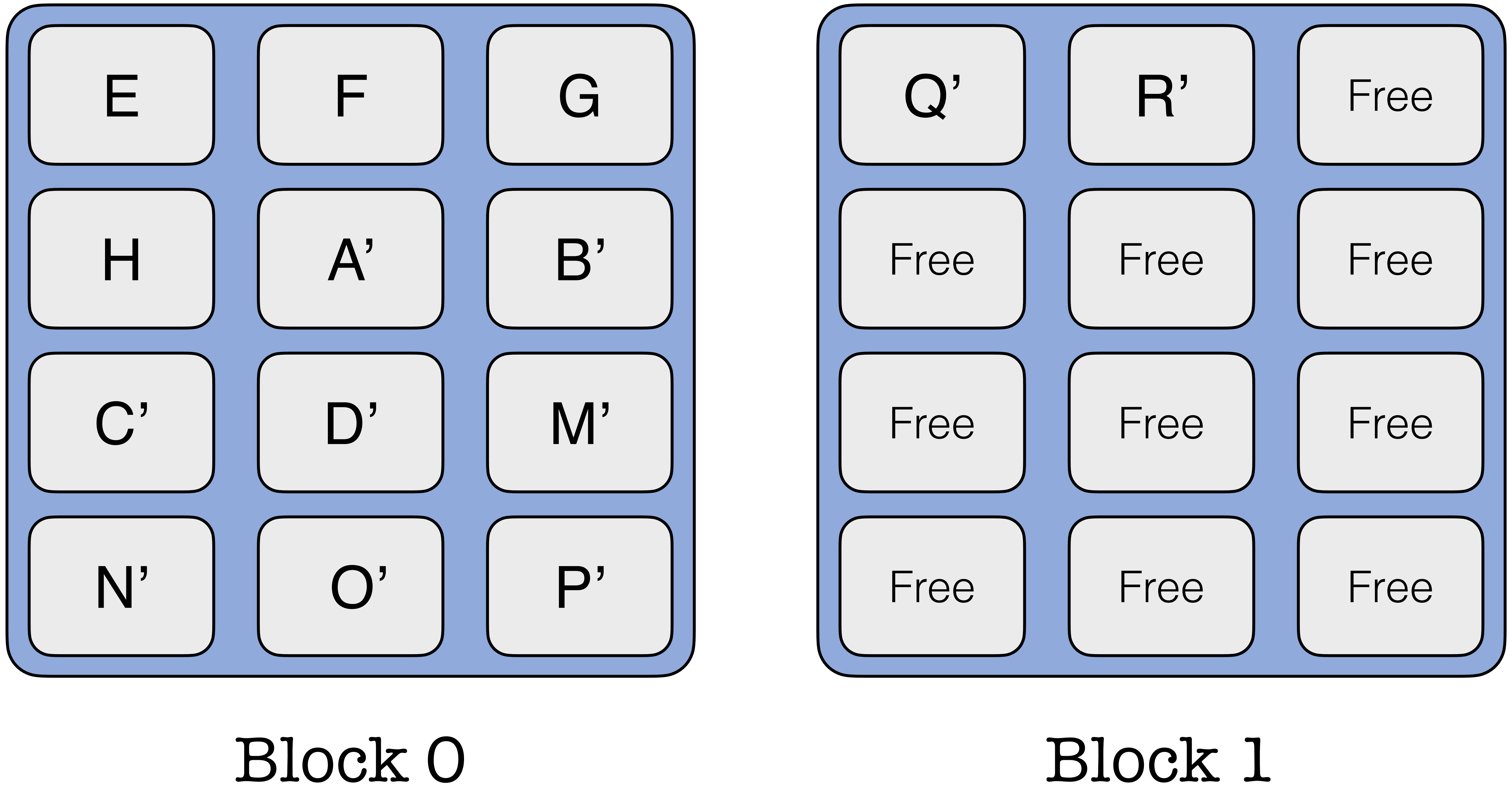
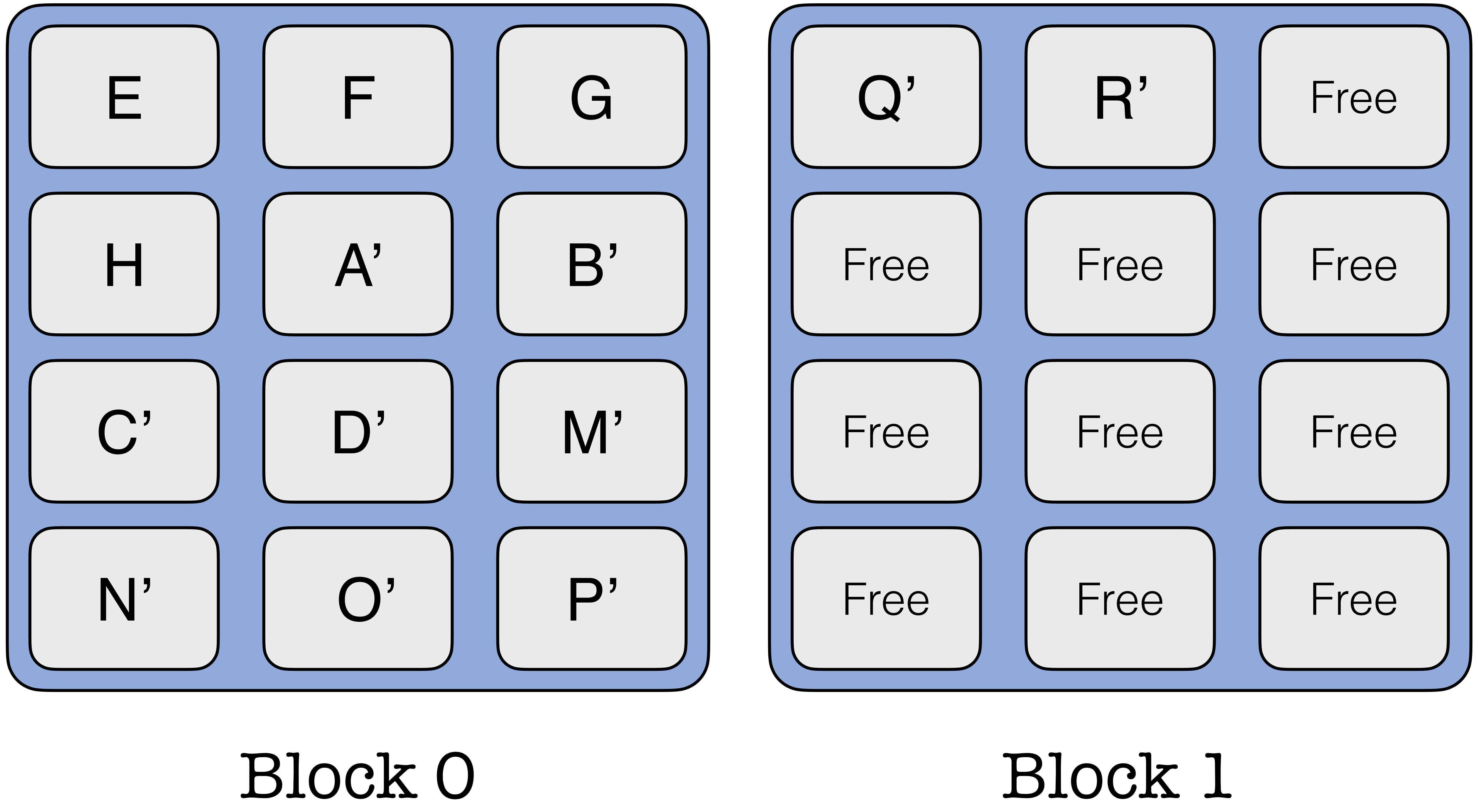
3. **write back** valid pages



Writes in SSDs

Writes are out of place



Thought Experiment 7

Any **limitations**?

1. high **write amplification**
2. limited **device lifetime**

Now, think of

LSM on SSDs!

Summary

The key takeaways

Data placement is critical!

be it on **storage**, **memory** or **cache**!

Flash operates **electronically** and is **fast**!

updates are **out of place**; suffers from **high write amplification**

Understanding the **underlying hardware** is critical for performance

hardware-aware indexes, **caching**, and **access methods**

Next time in COSI 167A

Row stores vs. Column stores

ACEing the Bufferpool Management Paradigm for Modern Storage Devices

Cosine: A Cloud-Cost Optimized Self-Designing Key-Value Storage Engine

COSI 167A
Advanced Data Systems

Class 18

Indexing + Modern Hardware Trends

Prof. Subhadeep Sarkar

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https://ssd-brandeis.github.io/COSI-167A/