Adaptive Filters

How to learn from your mistakes

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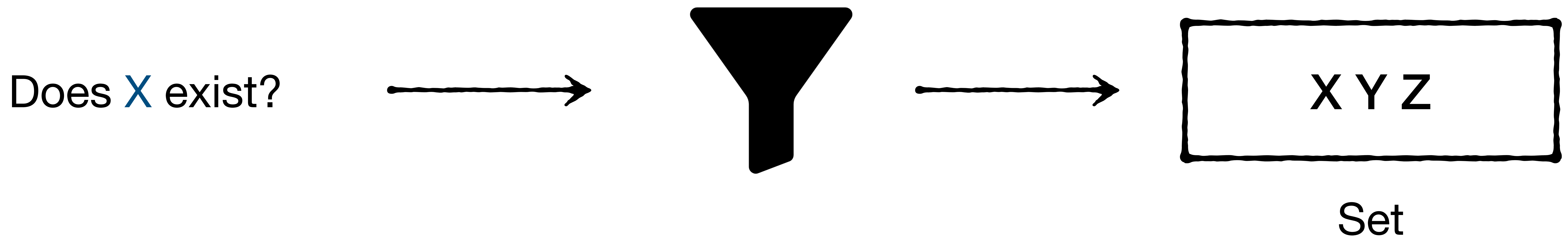
https://prashantpandey.github.io/

What is a filter data structure?



A filter compactly represents a set by trading off accuracy for space efficiency

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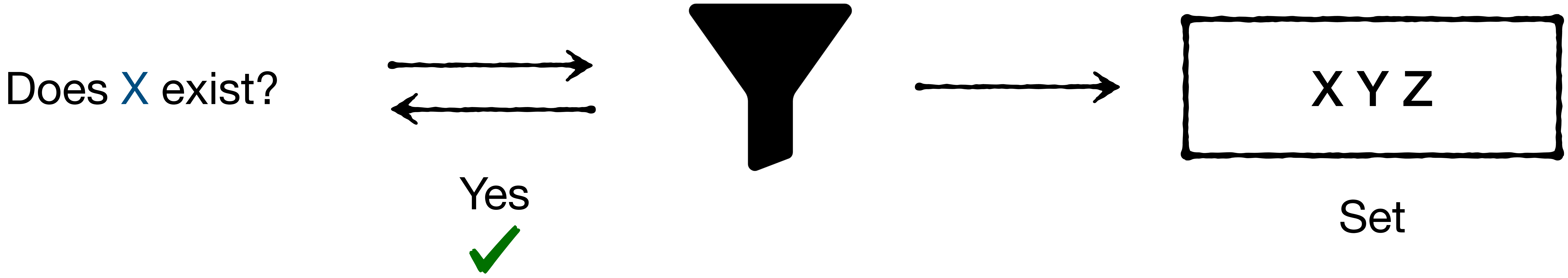

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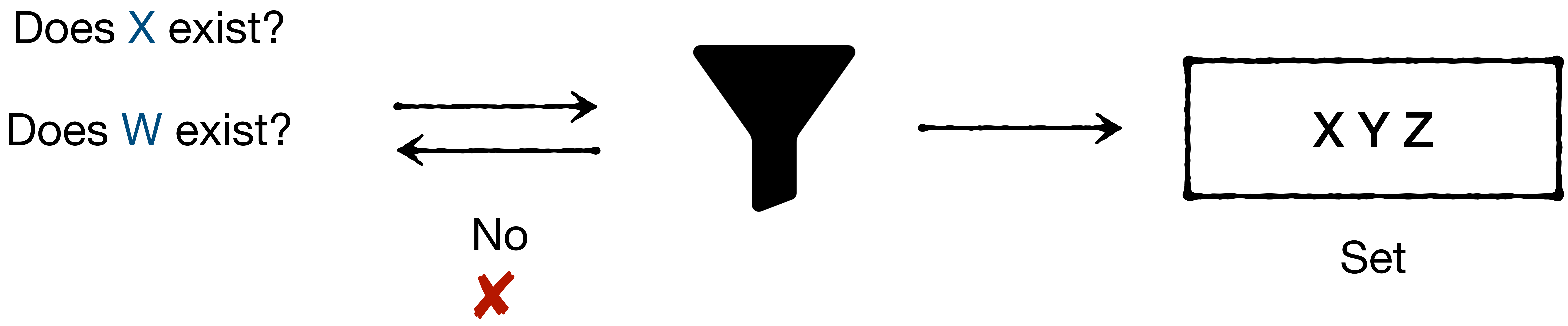

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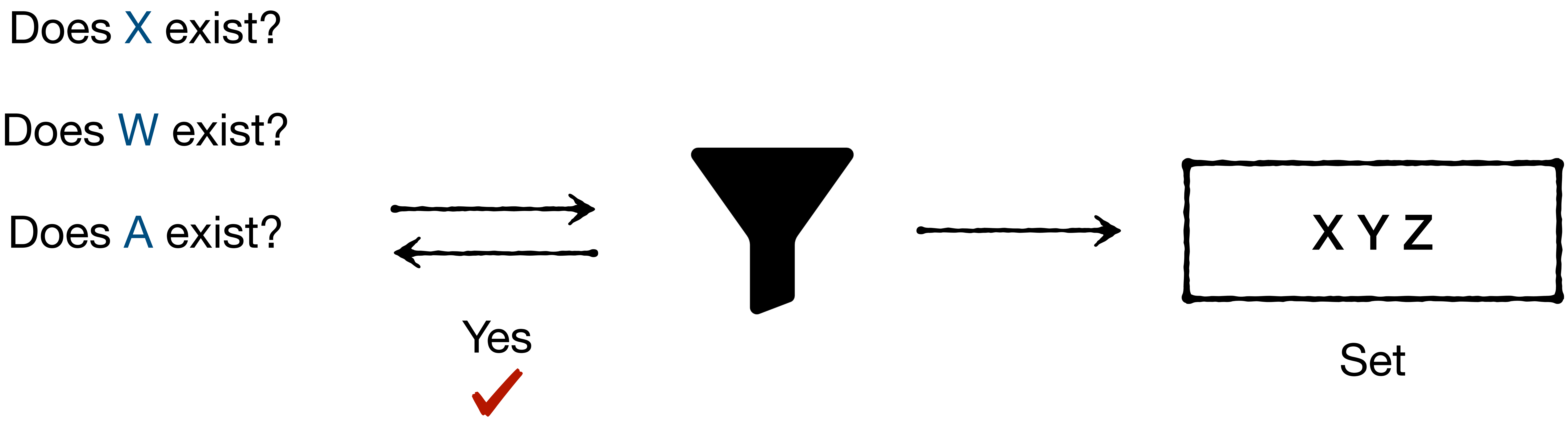


A filter compactly represents a set by trading off accuracy for space efficiency

A filter guarantees a false-positive rate ϵ

$q =$ **query item** $S =$ **set of items**

if q ∈ S, return	**True** with probability 1	true positive
if q ∉ S, return	**False** with probability $> 1 - \epsilon$	true negative
	True with probability $\leq \epsilon$	false positive

One-sided errors

False positives with tunable probability

False-positives enable filters to be compact

$n =$ **number of items** $U =$ **universe of items**

space $\geq n \log(1/\epsilon)$

Small

space $= \Omega(n \log(|U|))$

Large

Filter

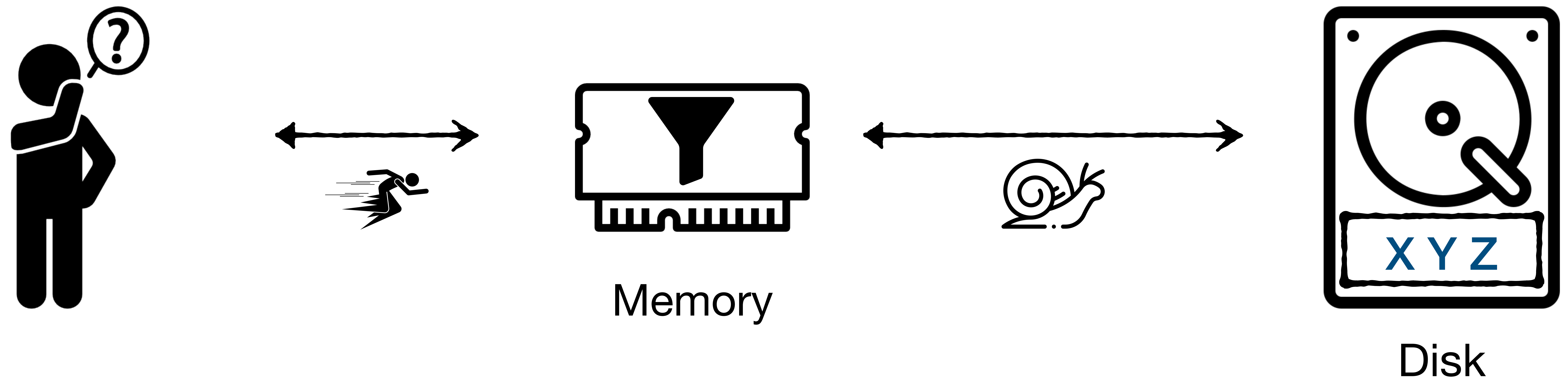
Hash table/Tree

For $\epsilon = 2\,\%$, filters require ~1 Byte/item. Hash table/Tree can take >8-16 Byte/item.

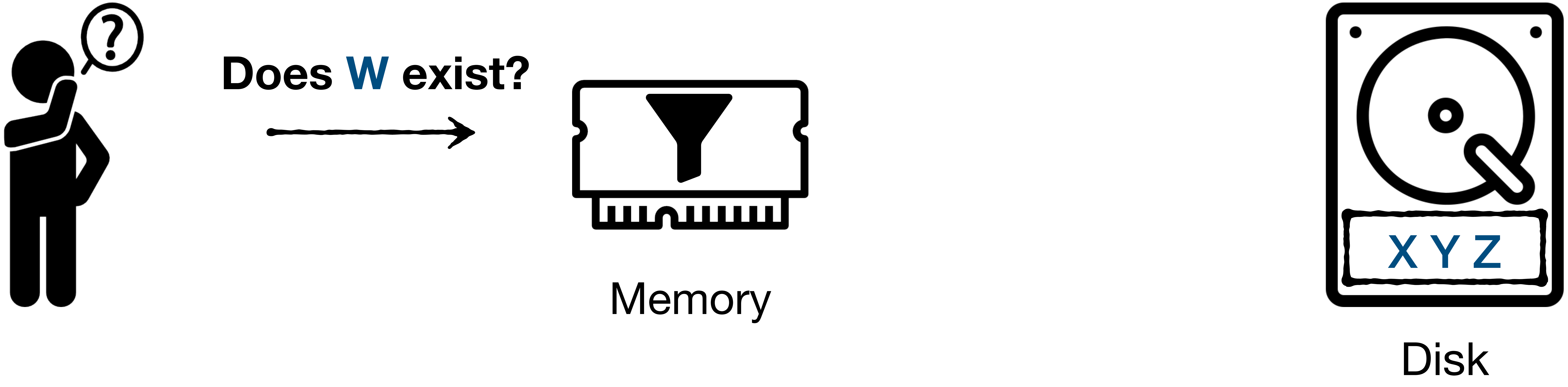
Filters offer weak guarantees

The maximum false positive rate is only guaranteed for a single query and not an arbitrary sequence of queries

Skewed workloads can make filters obsolete



Skewed workloads can make filters obsolete



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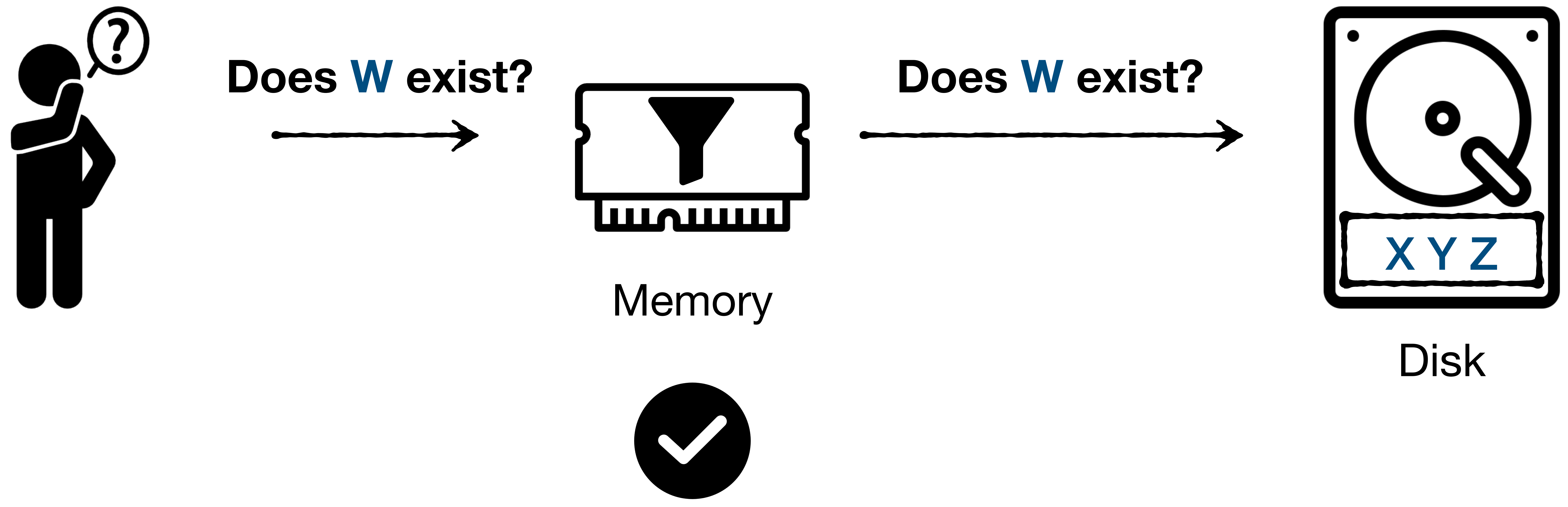

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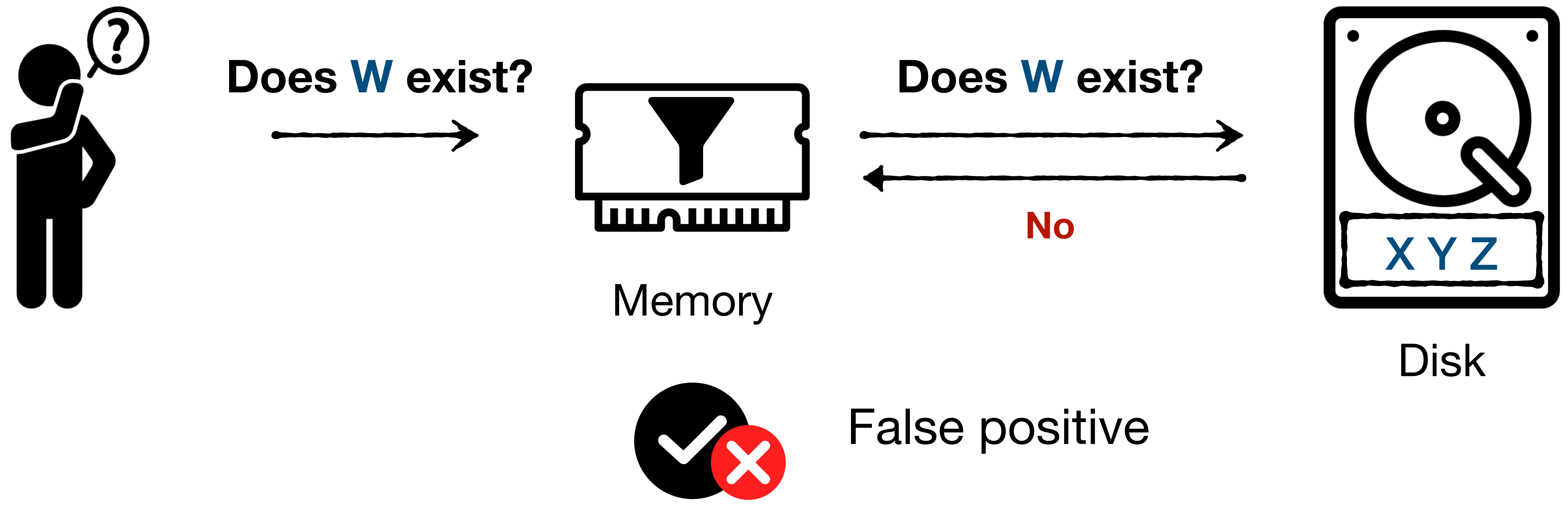

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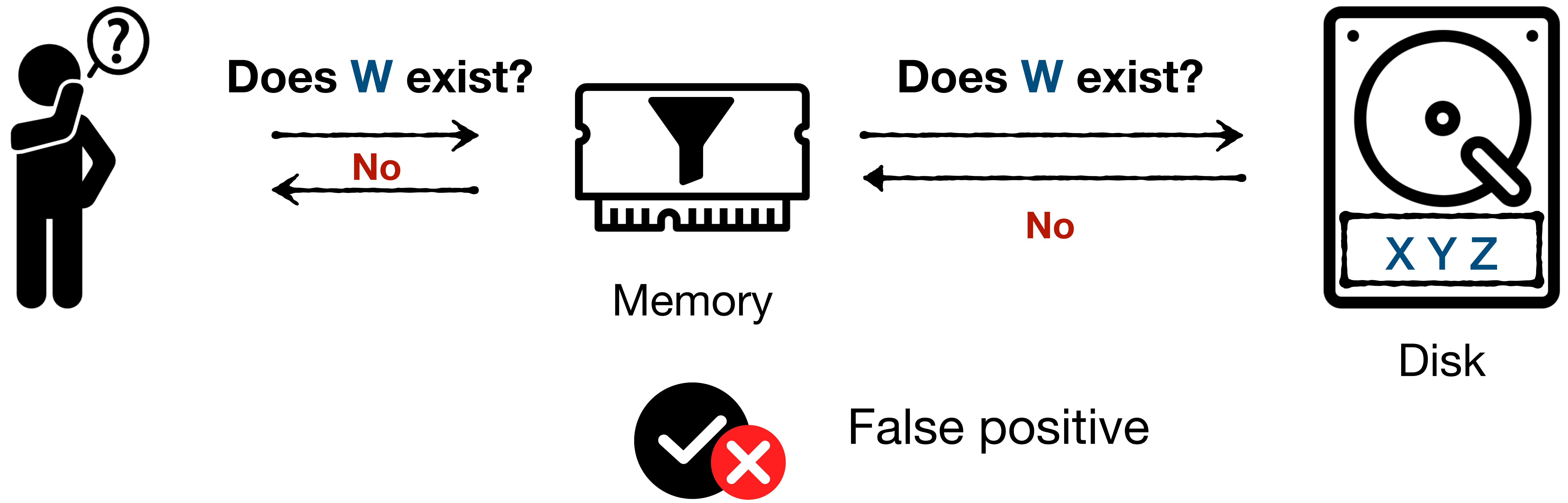

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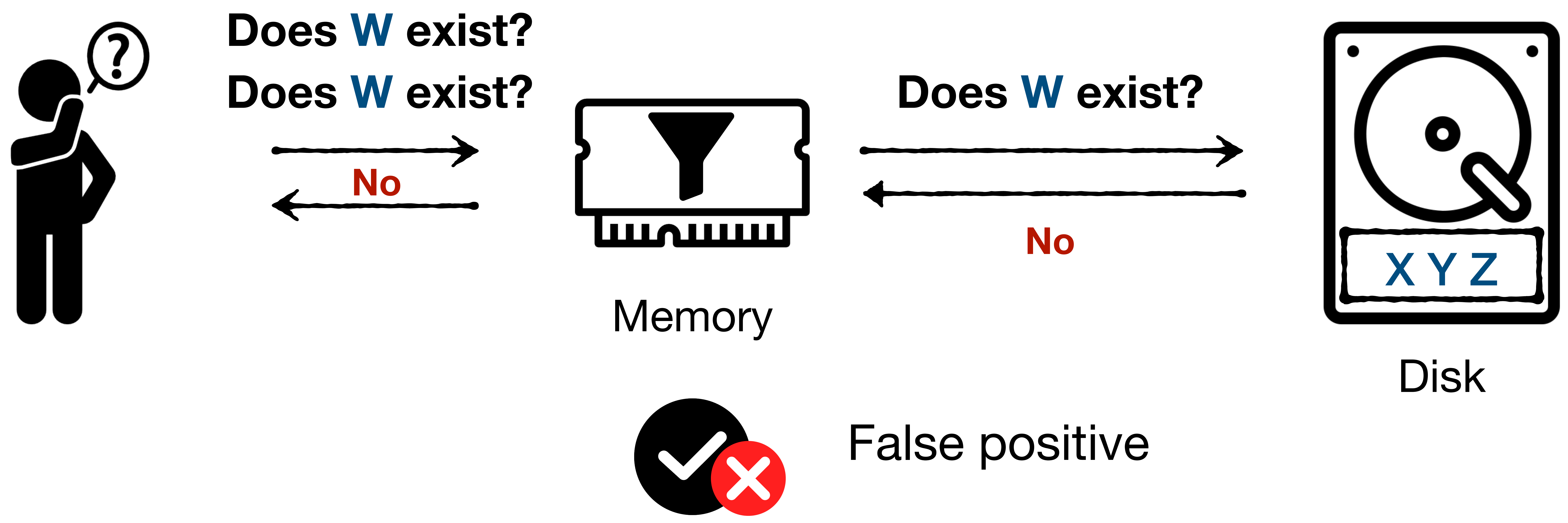

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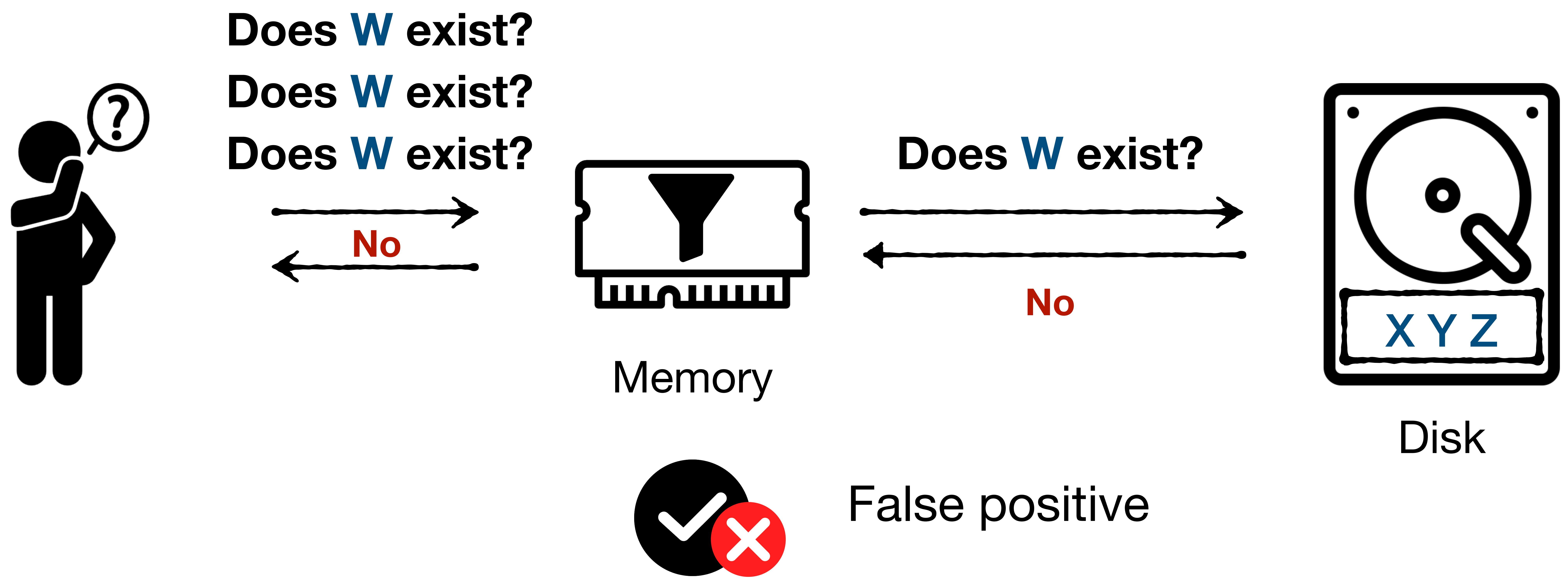

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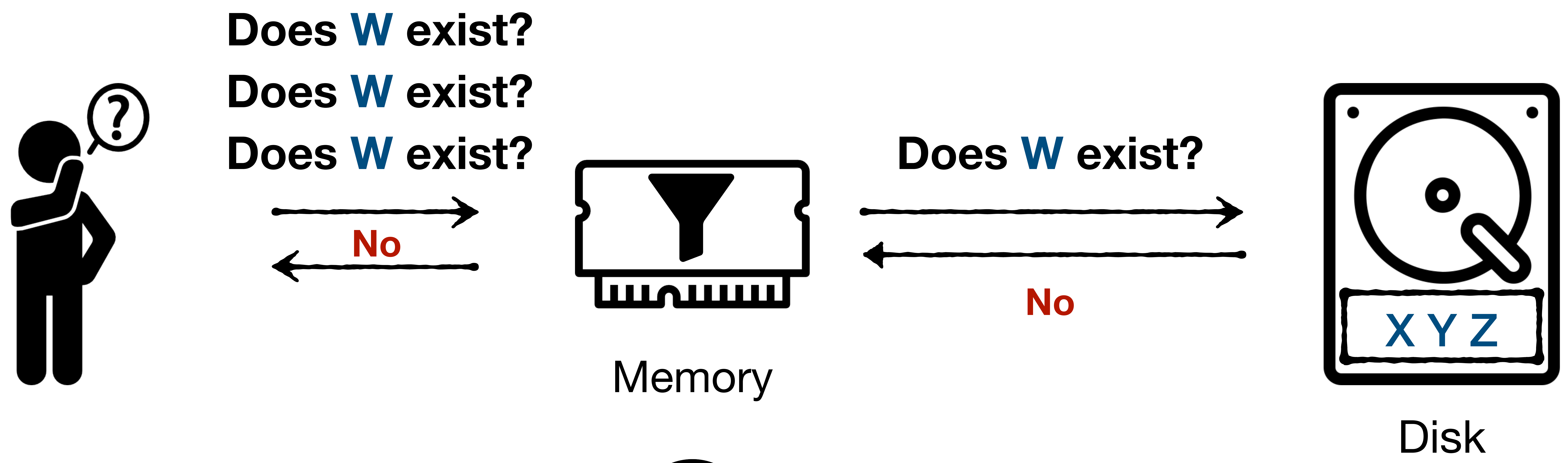
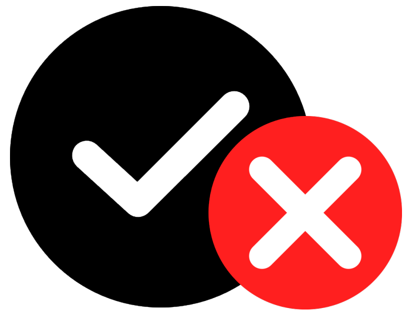


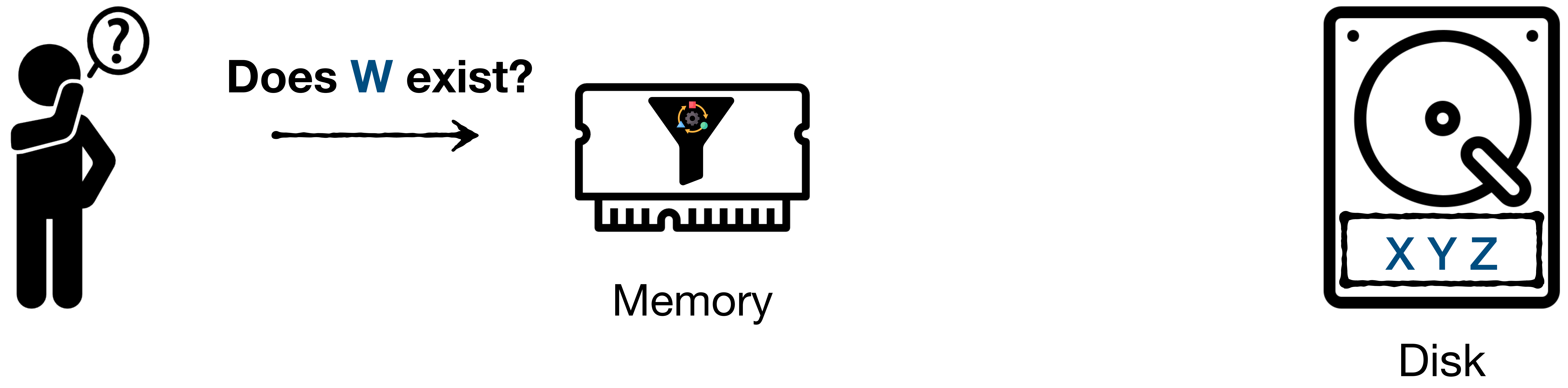


False positive

False-positive rate $\leq \epsilon$, only for a single query

Can we learn from the feedback?

Adaptive filters change their state upon feedback



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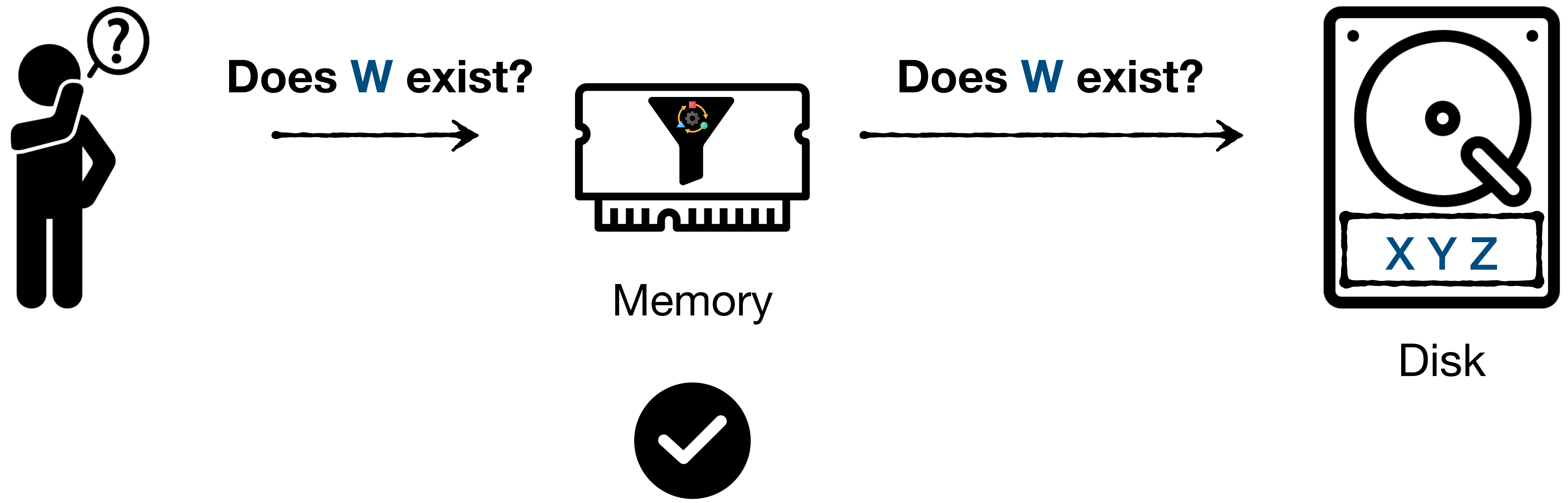

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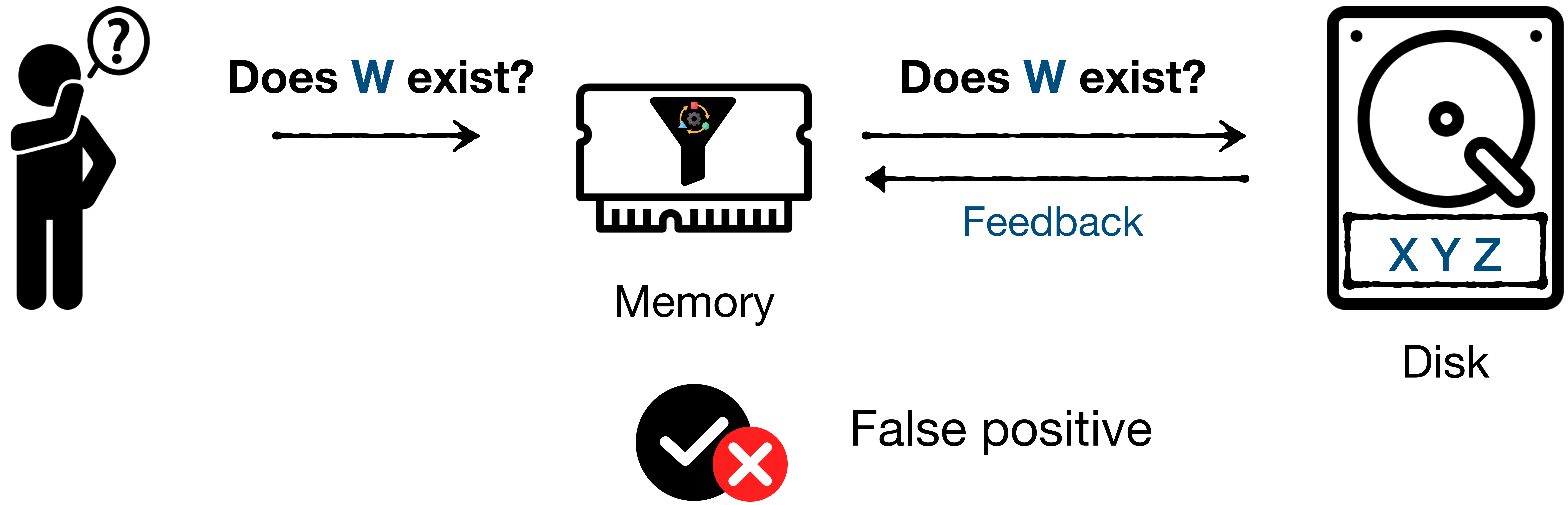

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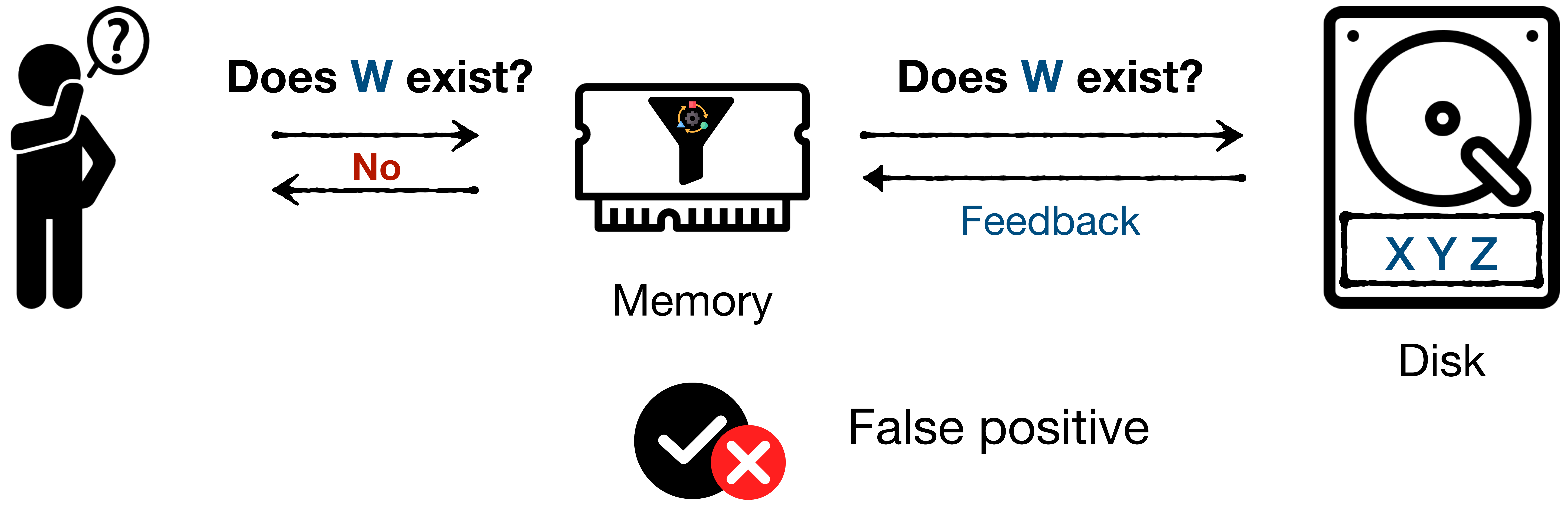

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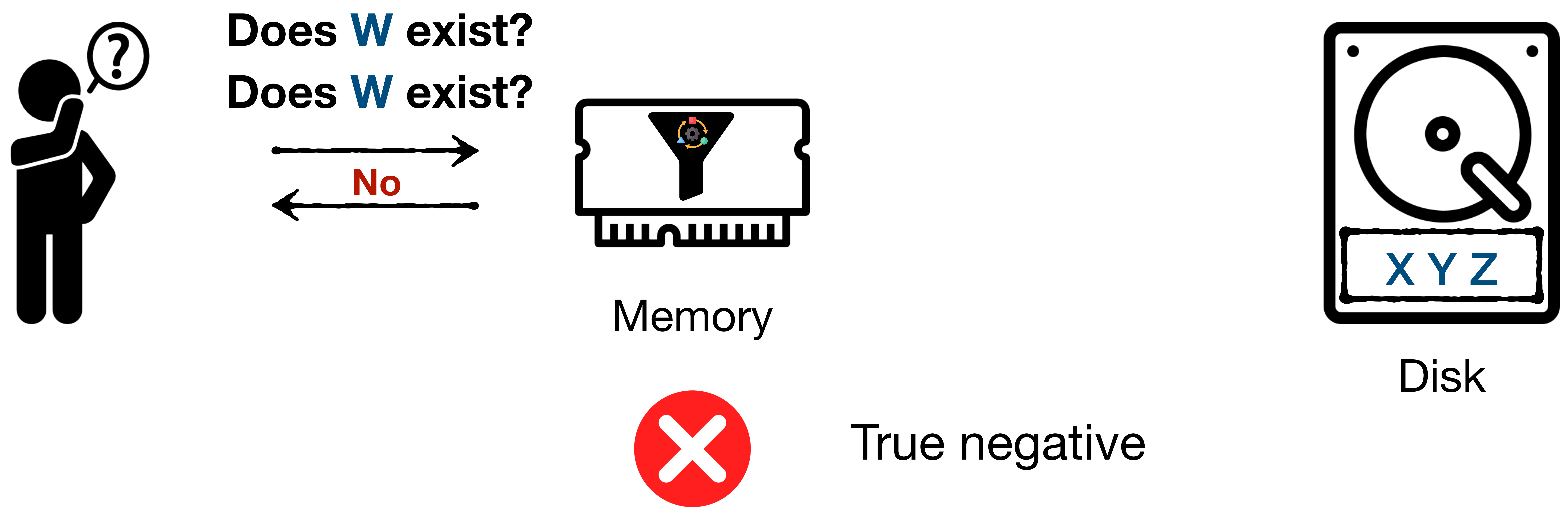

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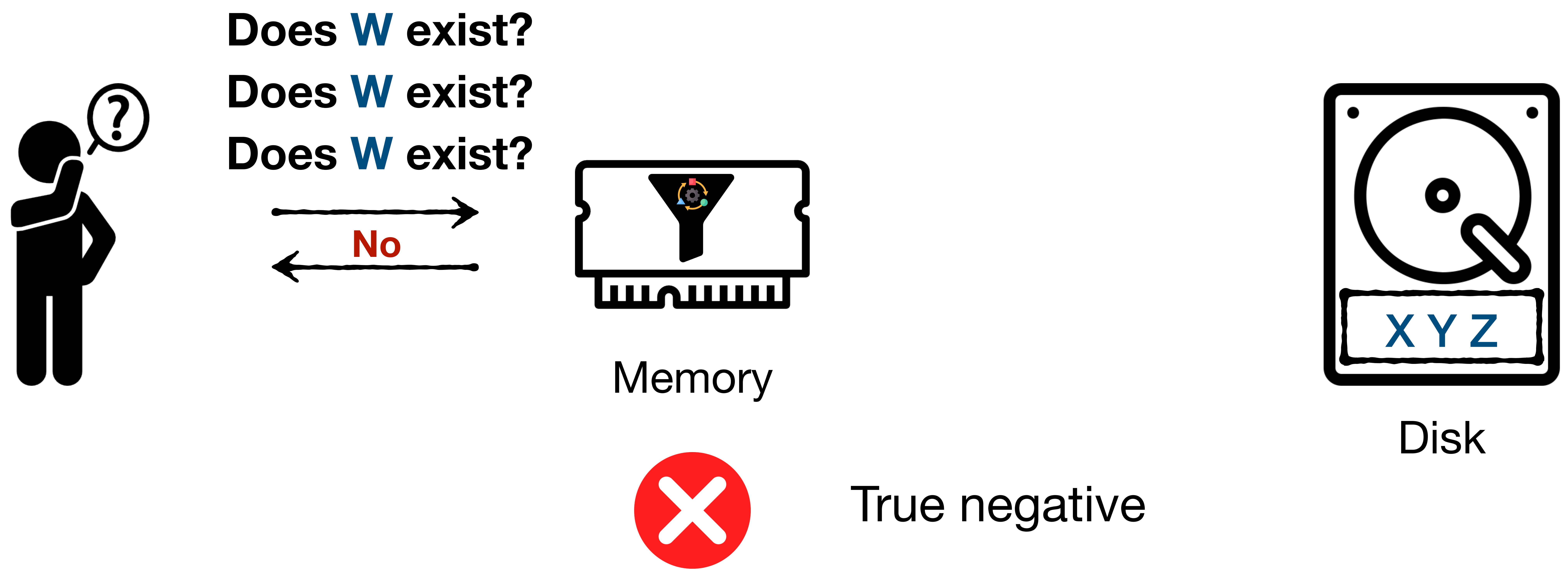
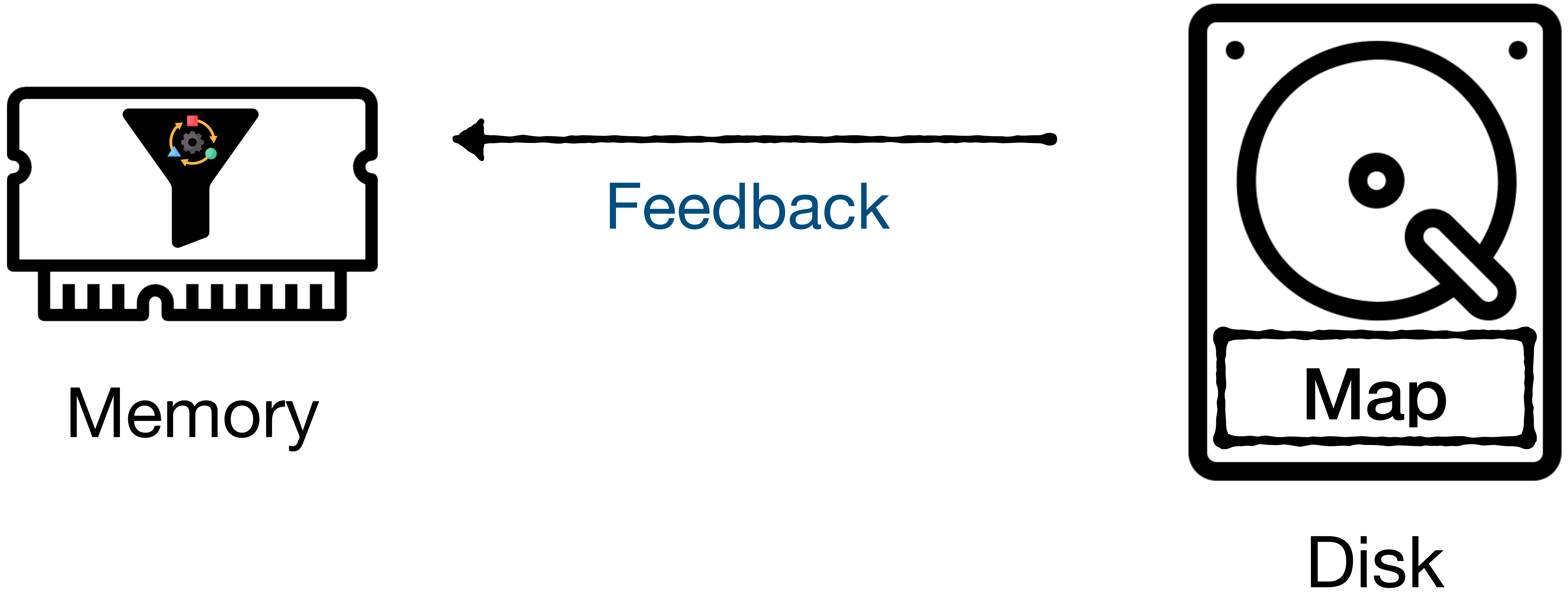


Adaptive filters [BFG+ 2018]

An adaptive filter modifies its state upon feedback and produces close to $O(\epsilon n)$ false positives for any sequence of n queries

False-positive rate $\leq \epsilon$, independent of the query distribution

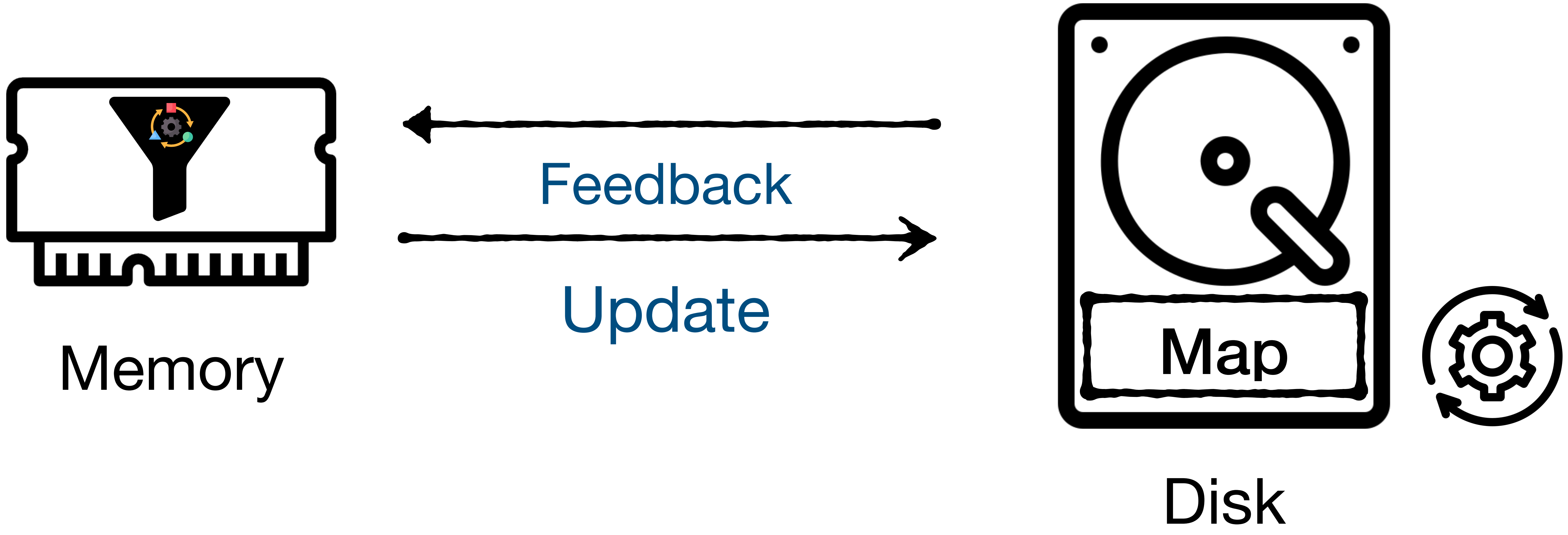
Adaptive filter design has two parts [BFG+ 2018]



Small in-memory filter
accessed on every query

Large disk-resident map
accessed during adaptations

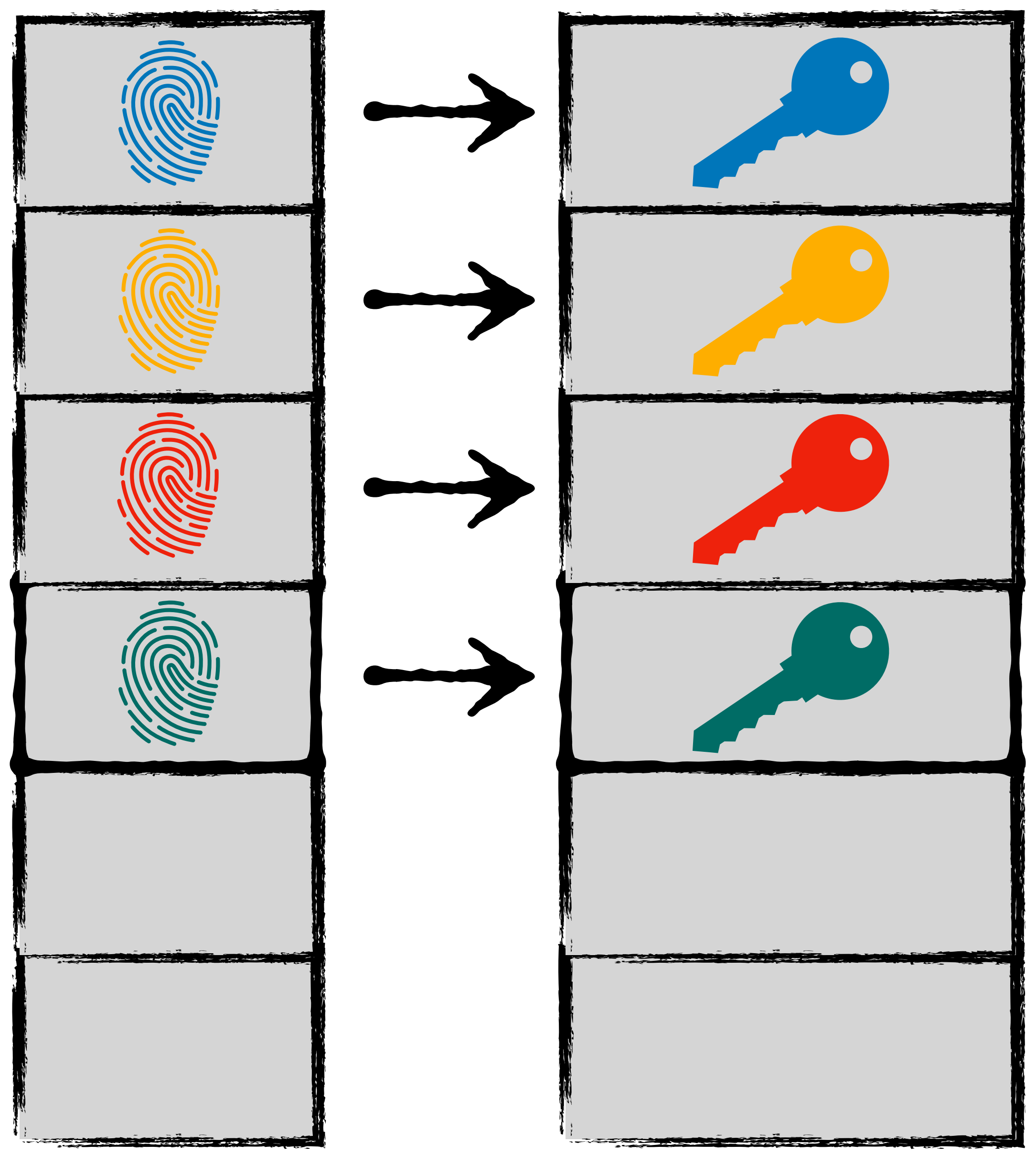
Adaptive filter design has two parts [BFG+ 2018]



On-disk map enables adaptations and is updated to fix fingerprint collisions

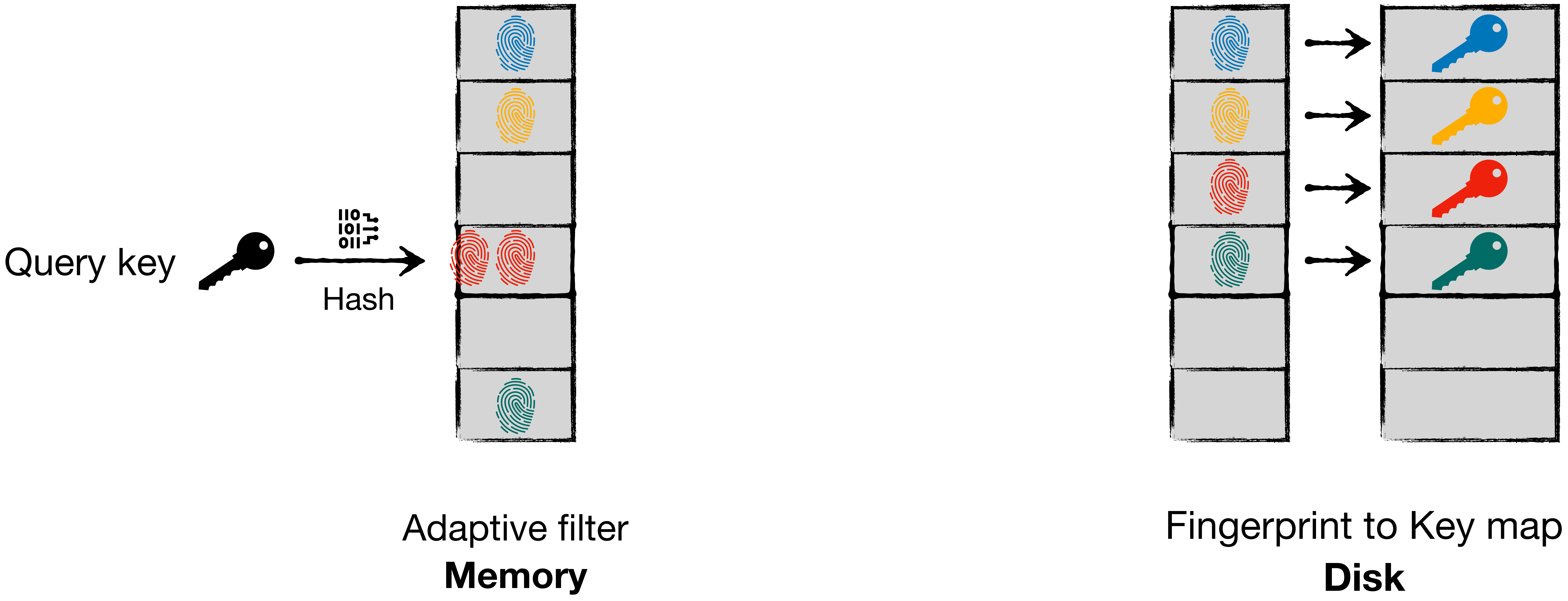
Adaptive filters employ variable-length fingerprints

Adaptive filter
Memory



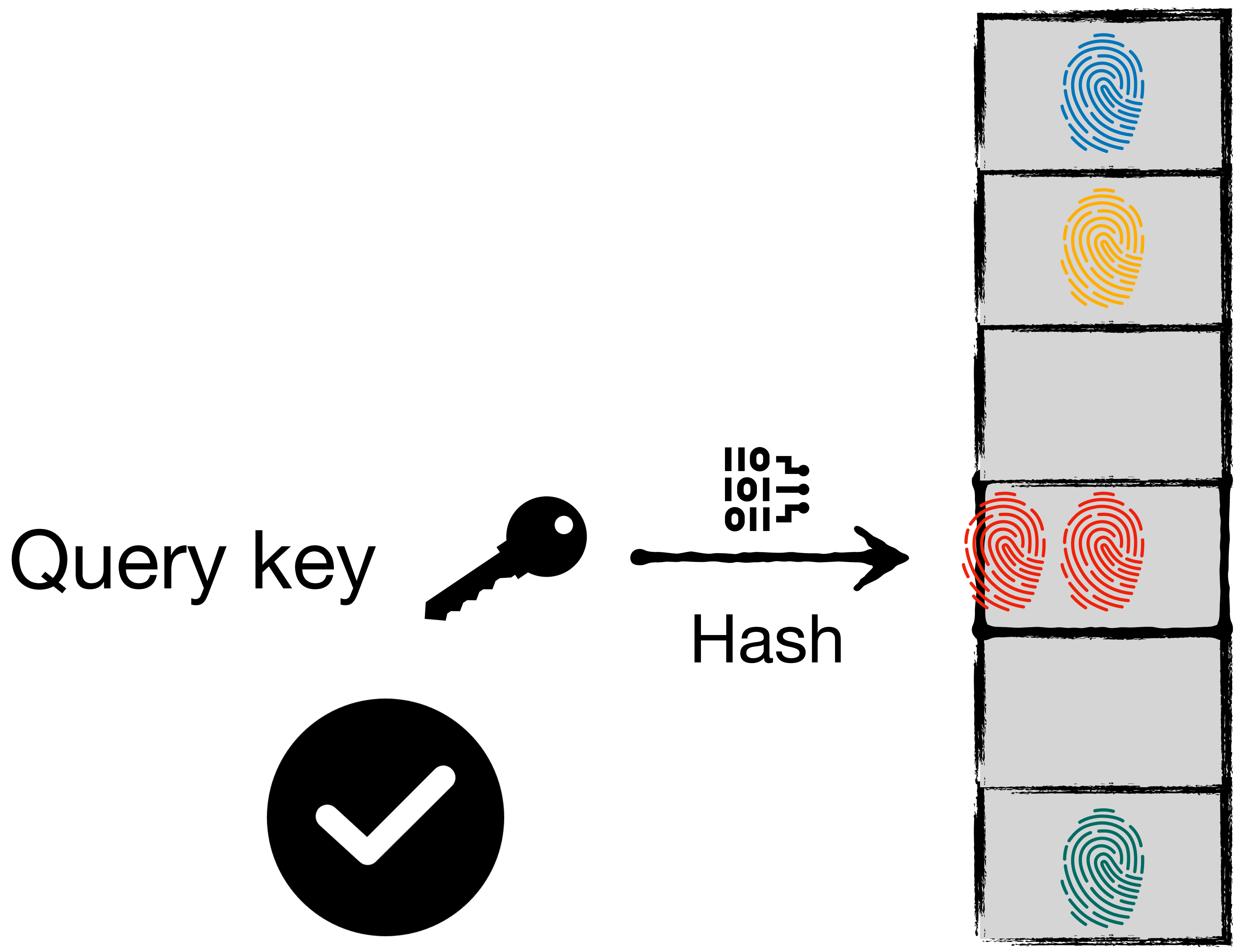
Fingerprint to Key map
Disk

Adaptive filters employ variable-length fingerprints

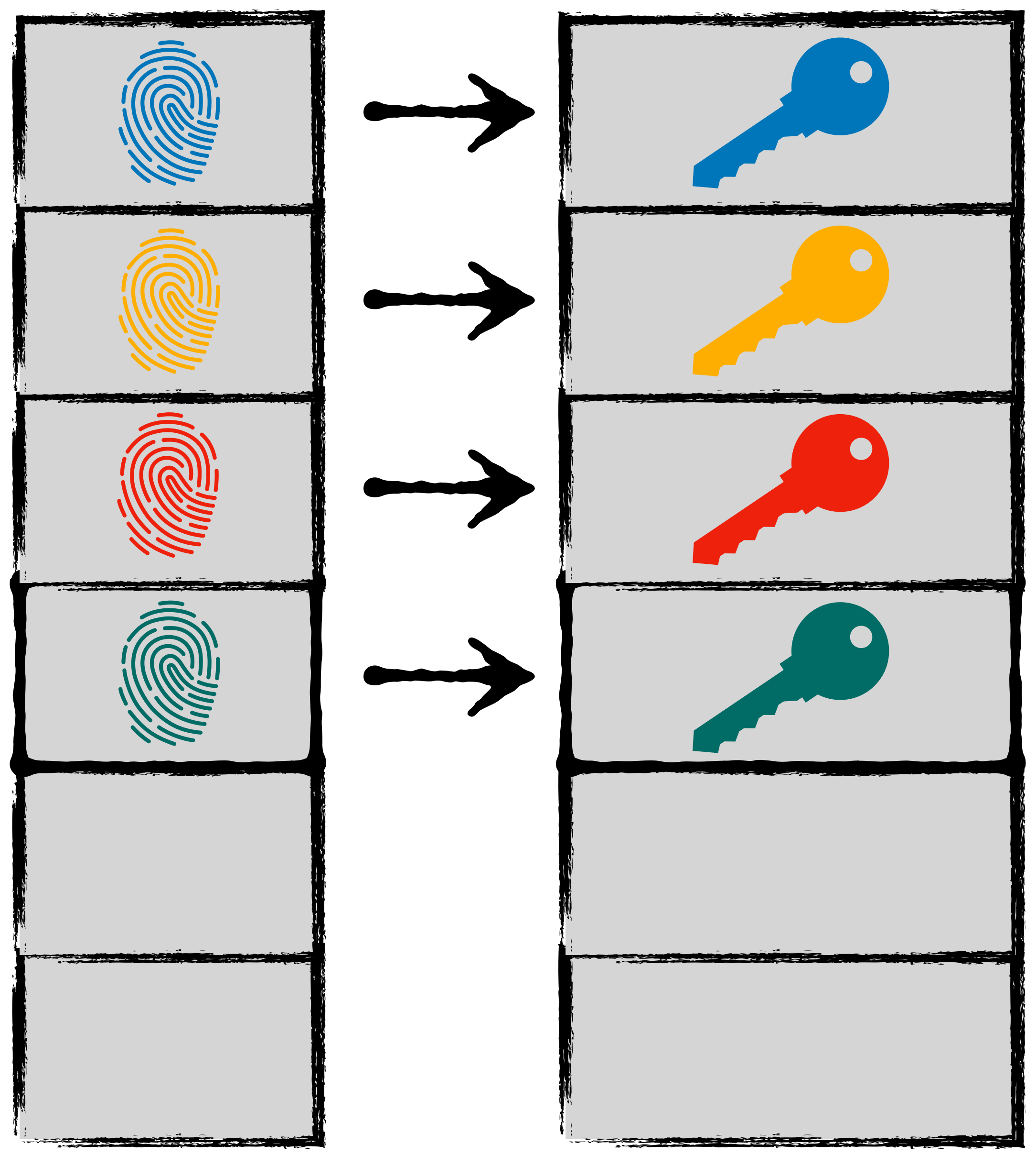


Fingerprint collisions can cause false positives

Adaptive filters employ variable-length fingerprints



Adaptive filter
Memory



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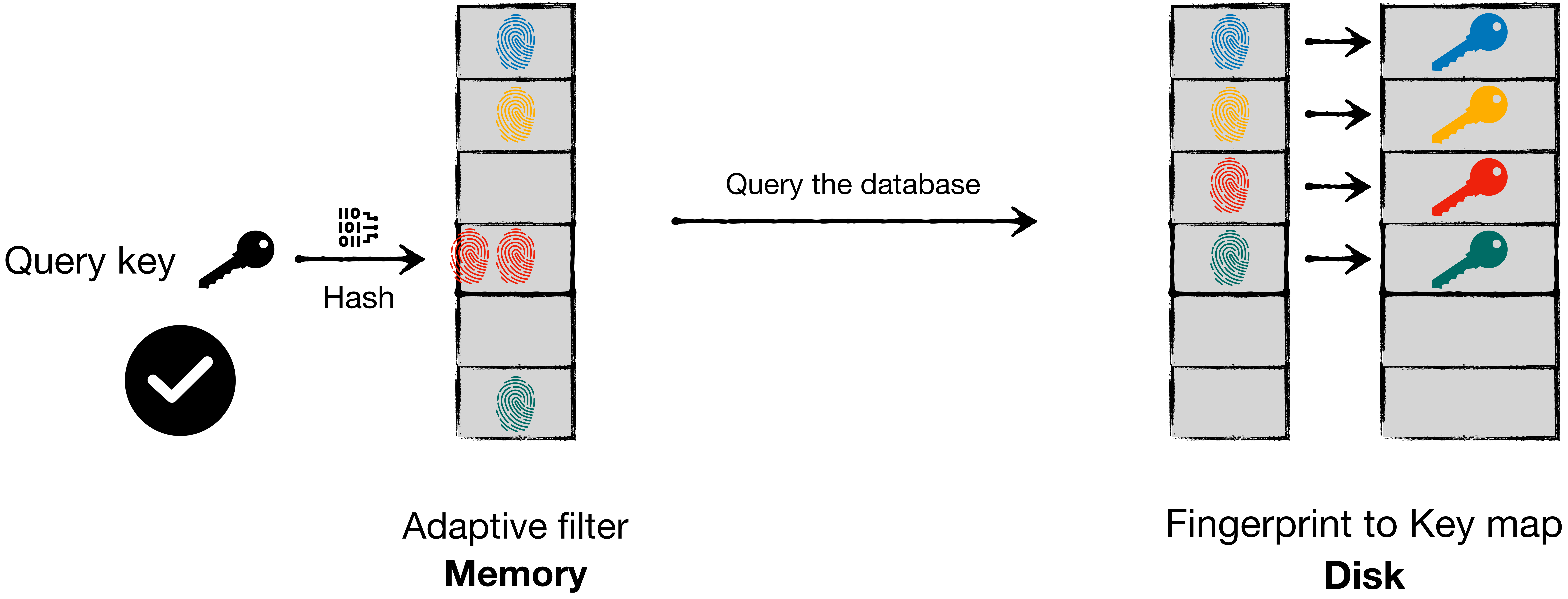

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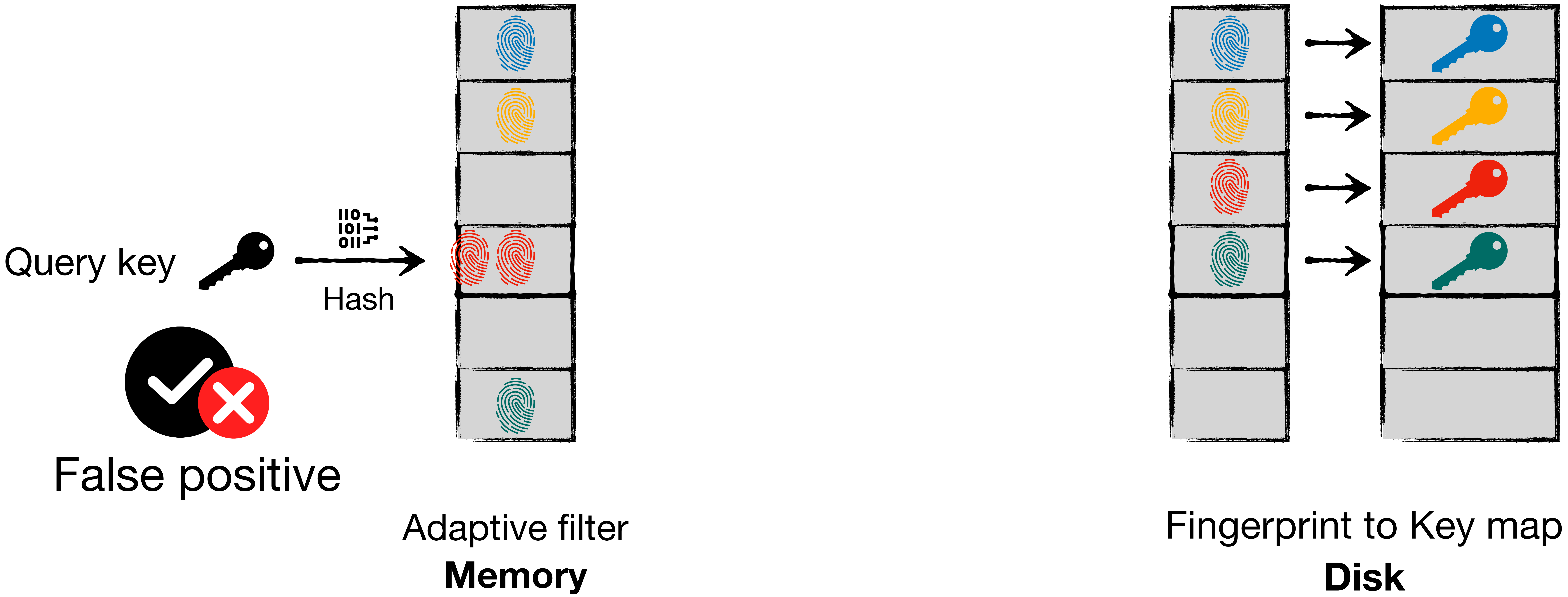

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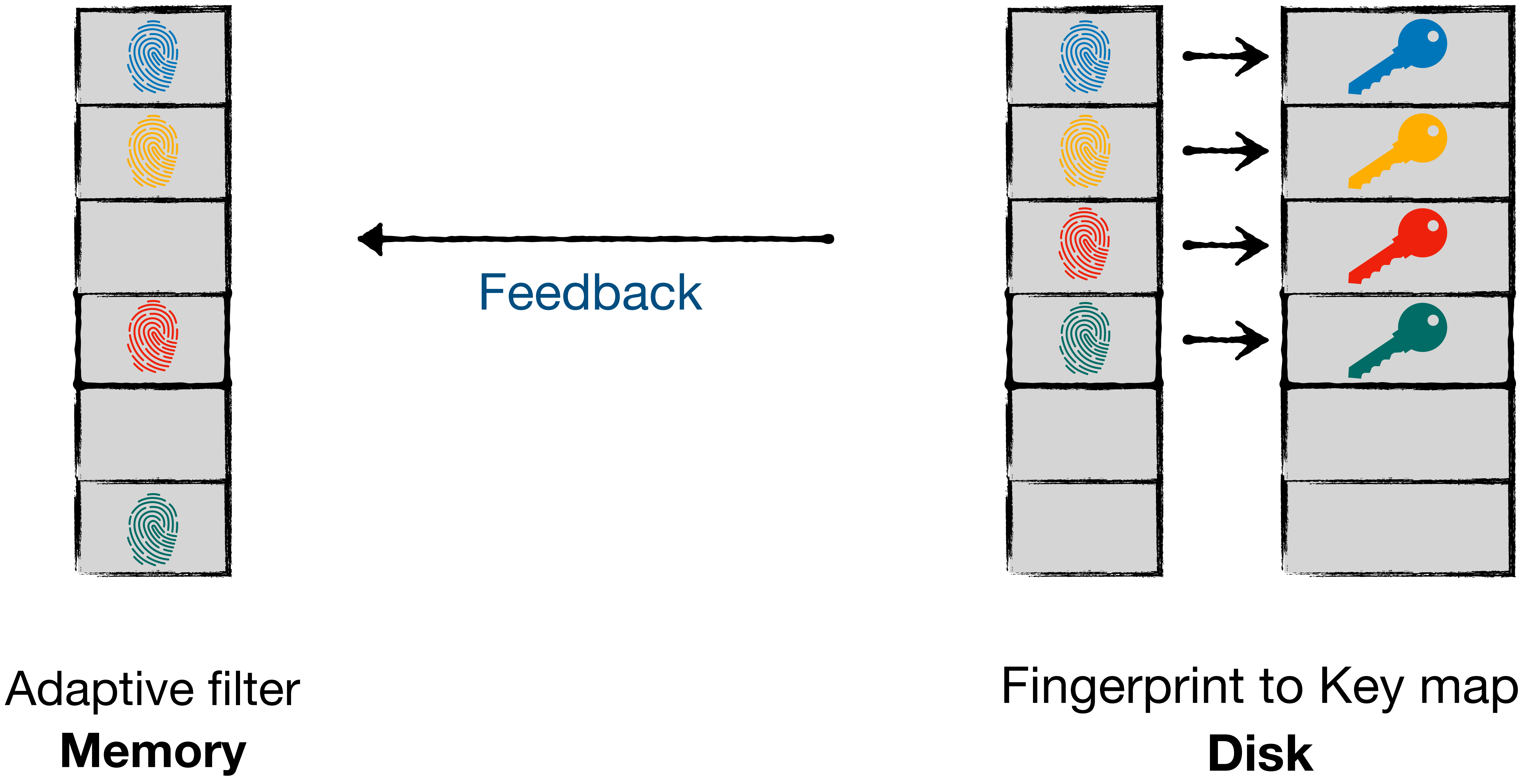
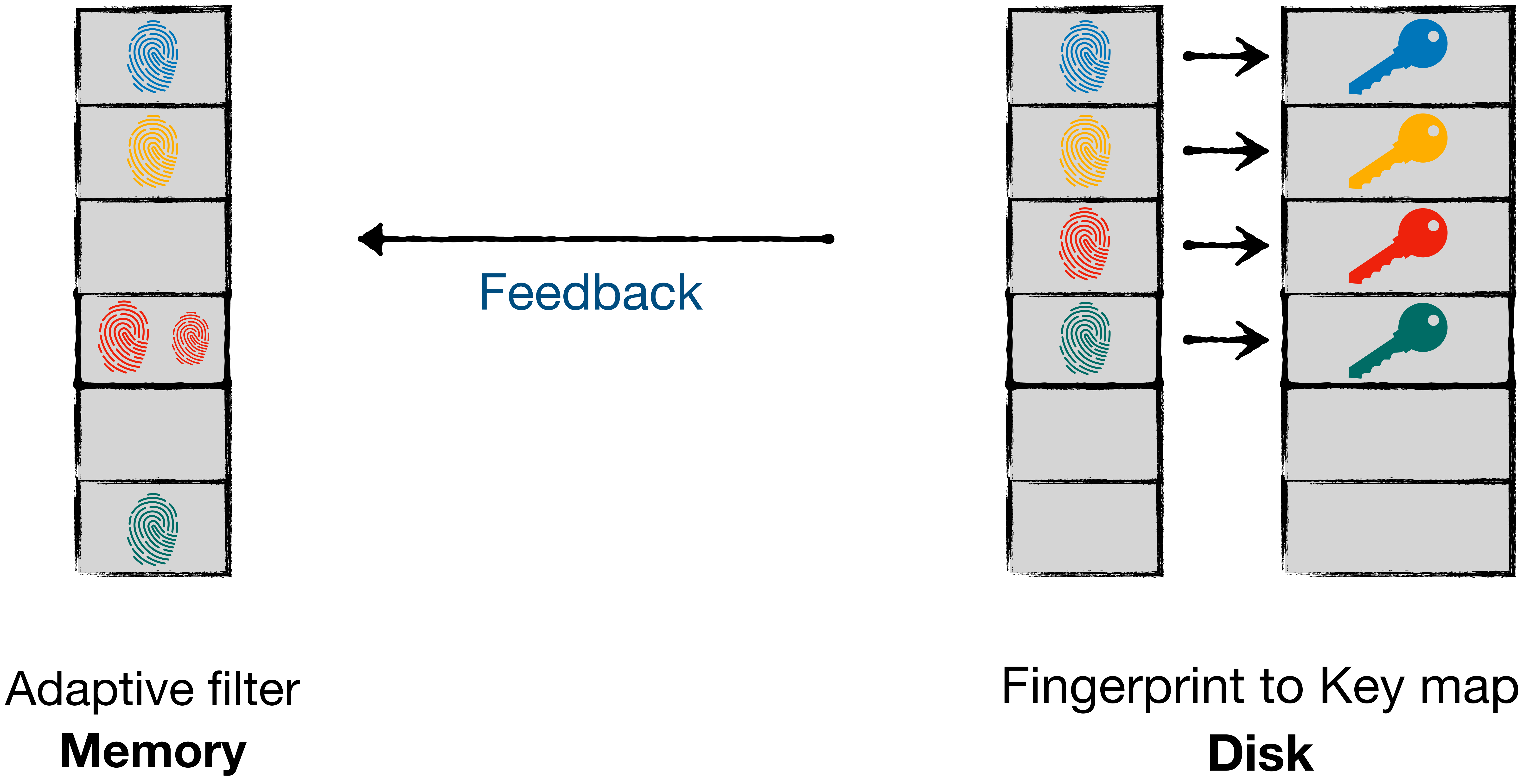


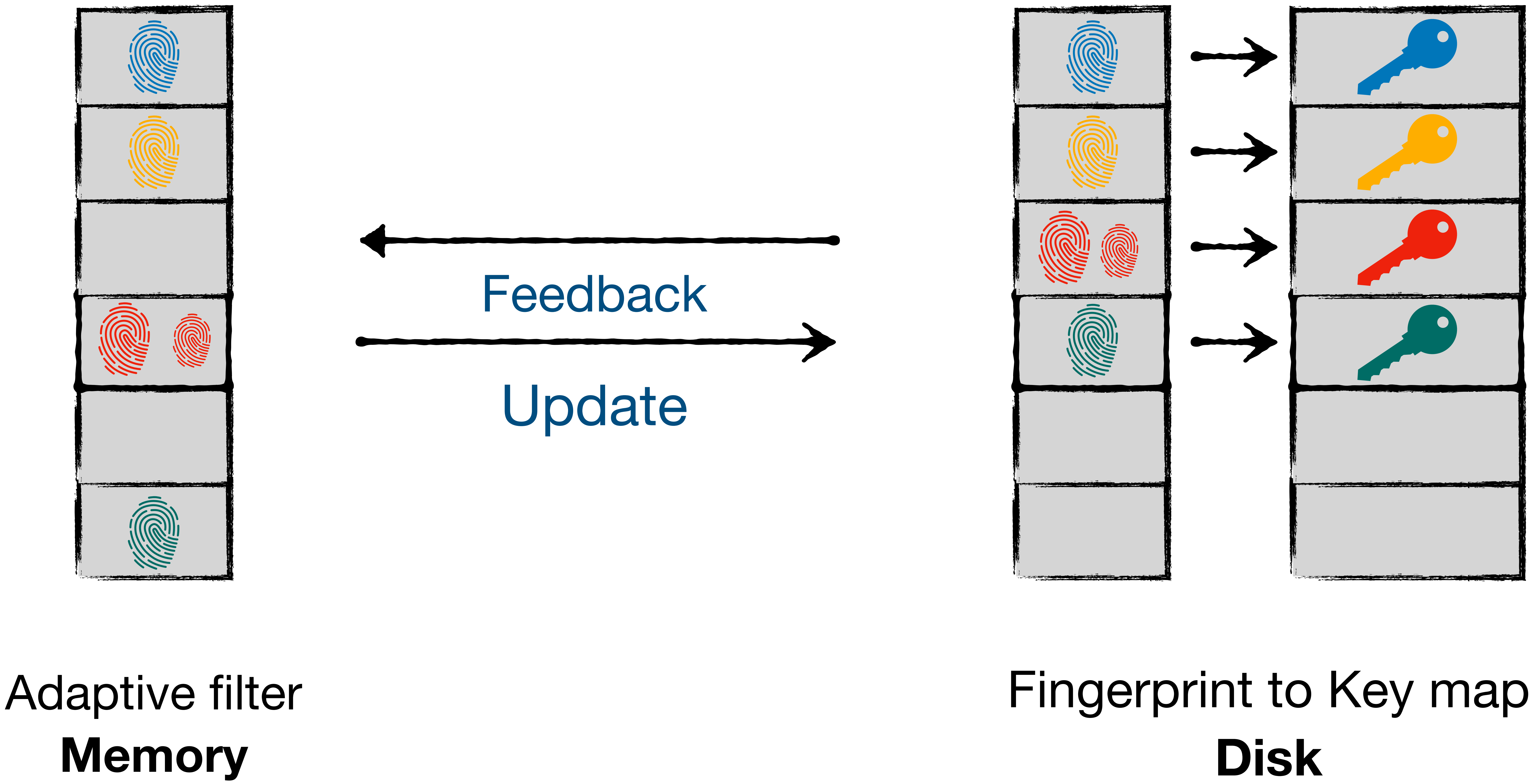
Feedback from the map can help fix the false positive

Adaptive filters employ variable-length fingerprints



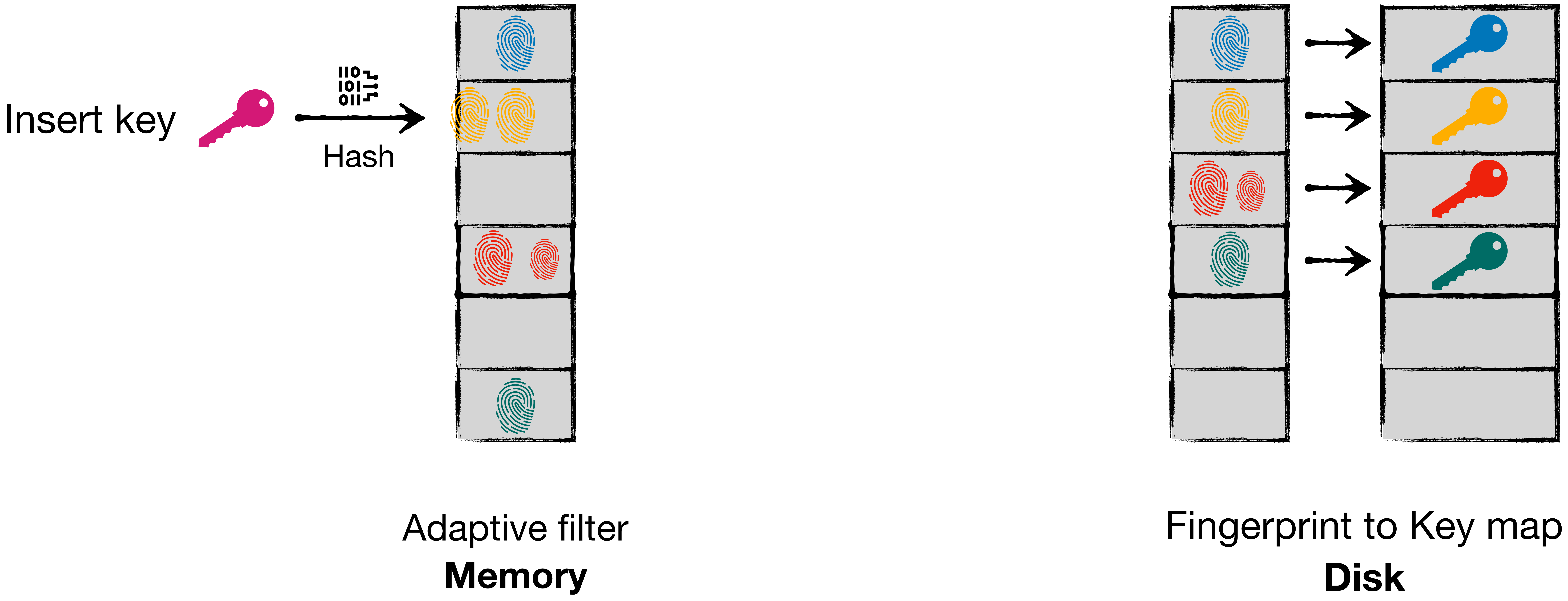
Extending the fingerprint of the existing key can avoid future false positives

Adaptive filters employ variable-length fingerprints



Fingerprint map is updated accordingly

Adaptive filters employ variable-length fingerprints



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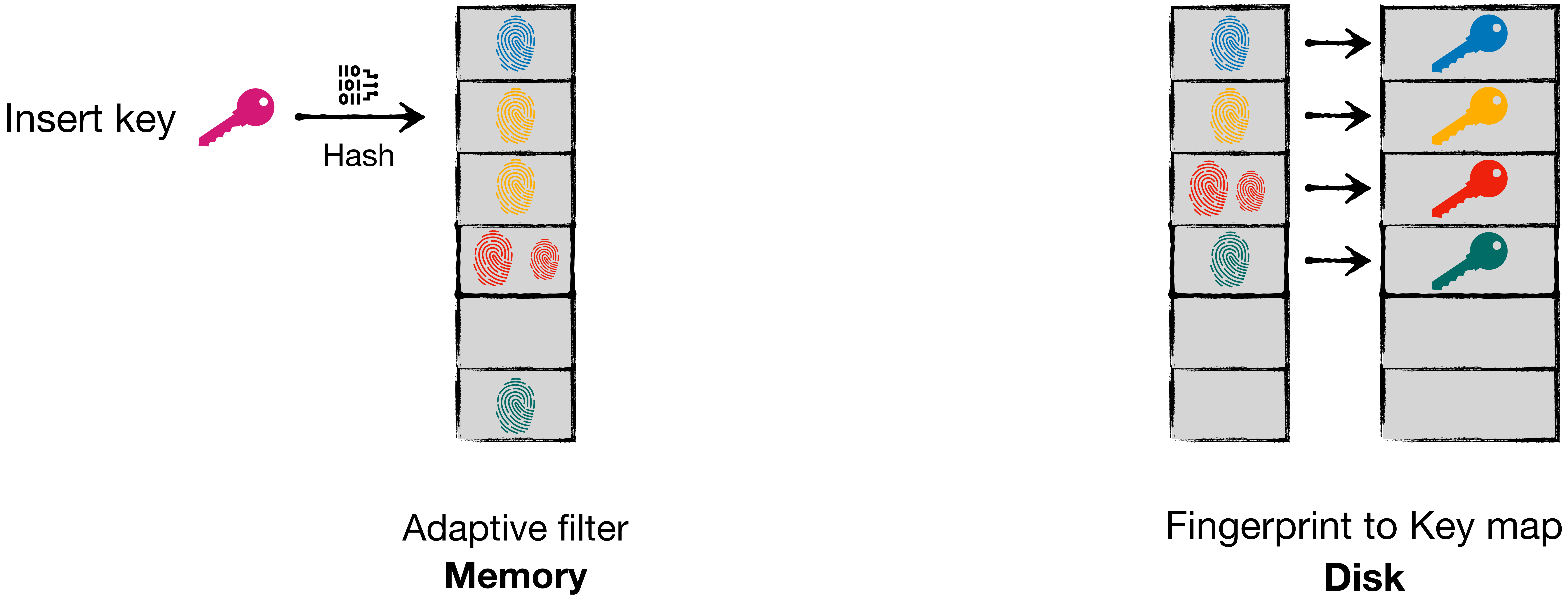

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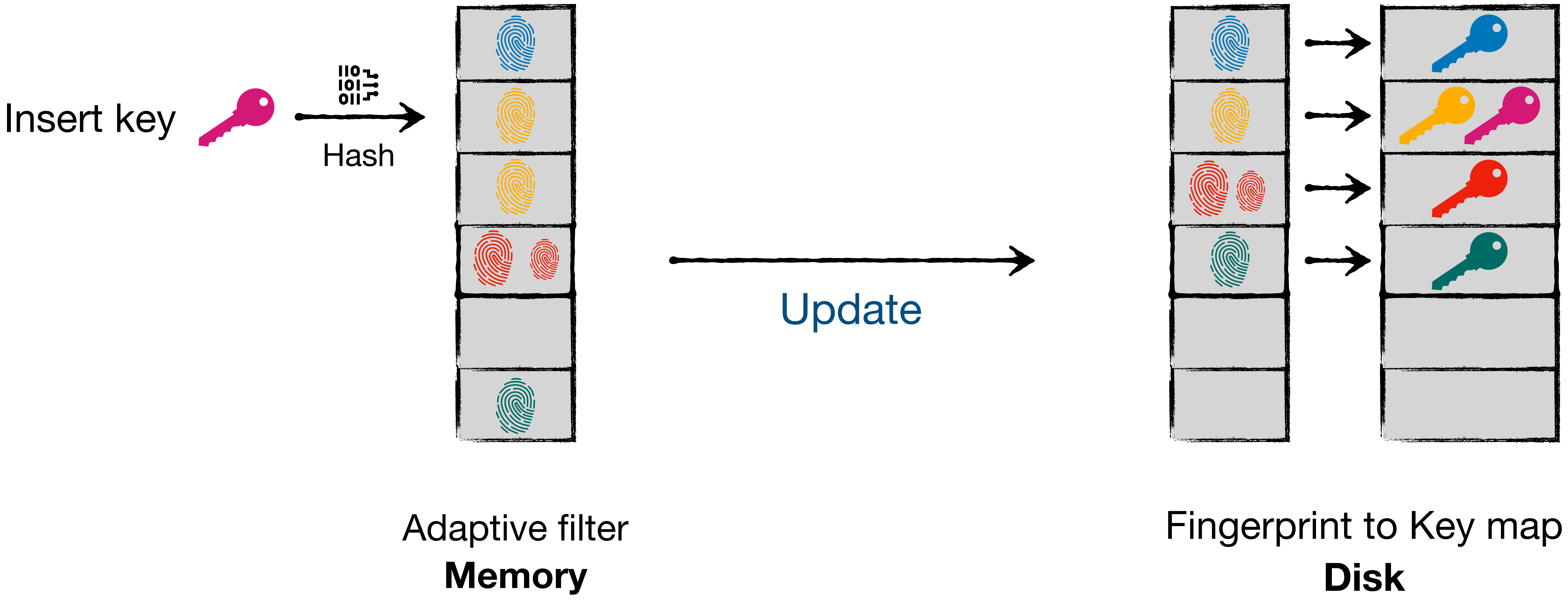
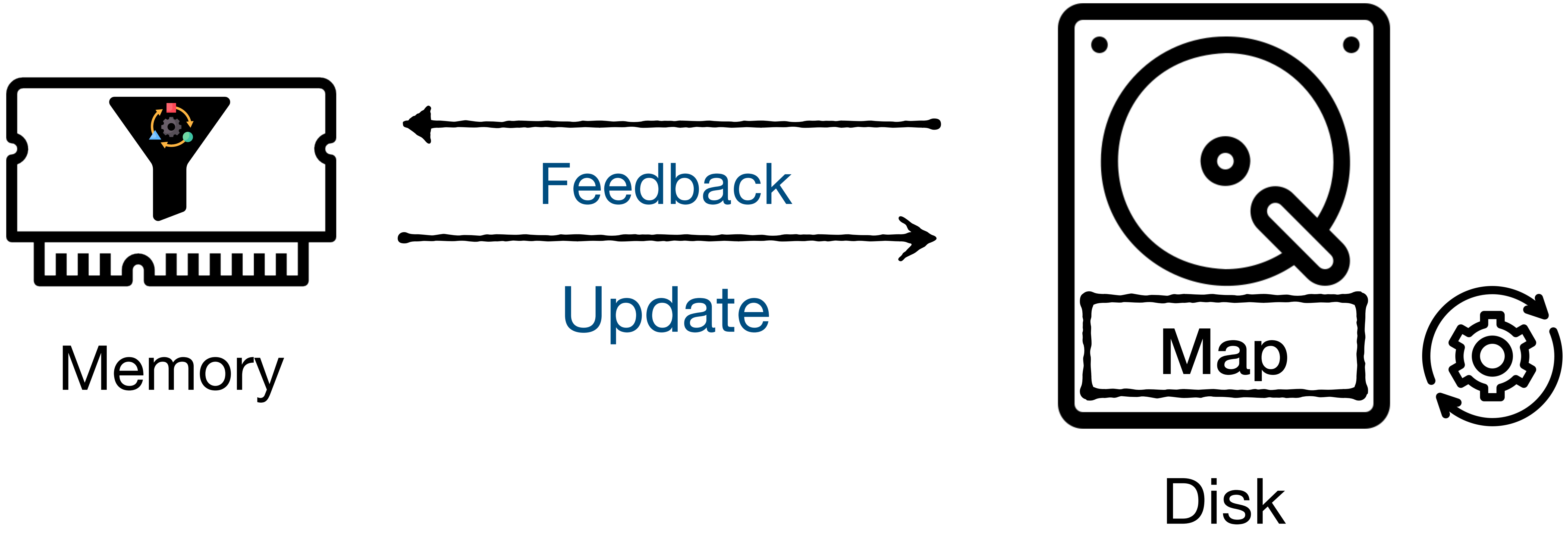


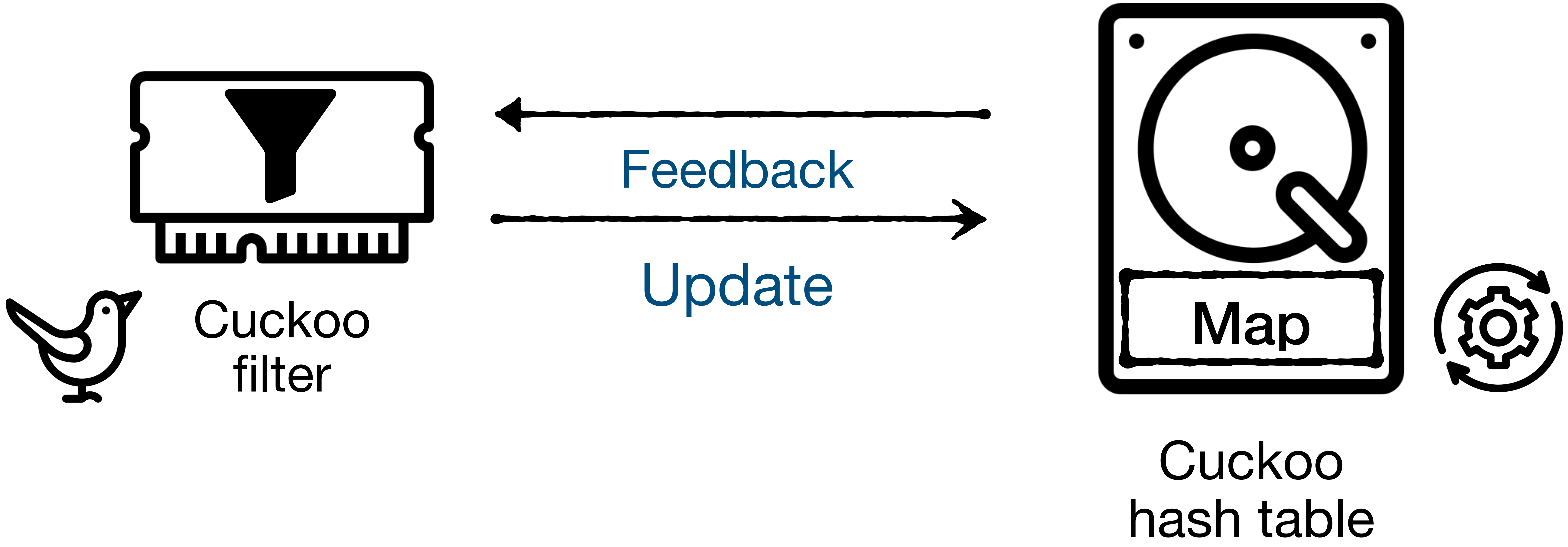
Fingerprint map is updated accordingly

Fingerprint map updates dominate the performance



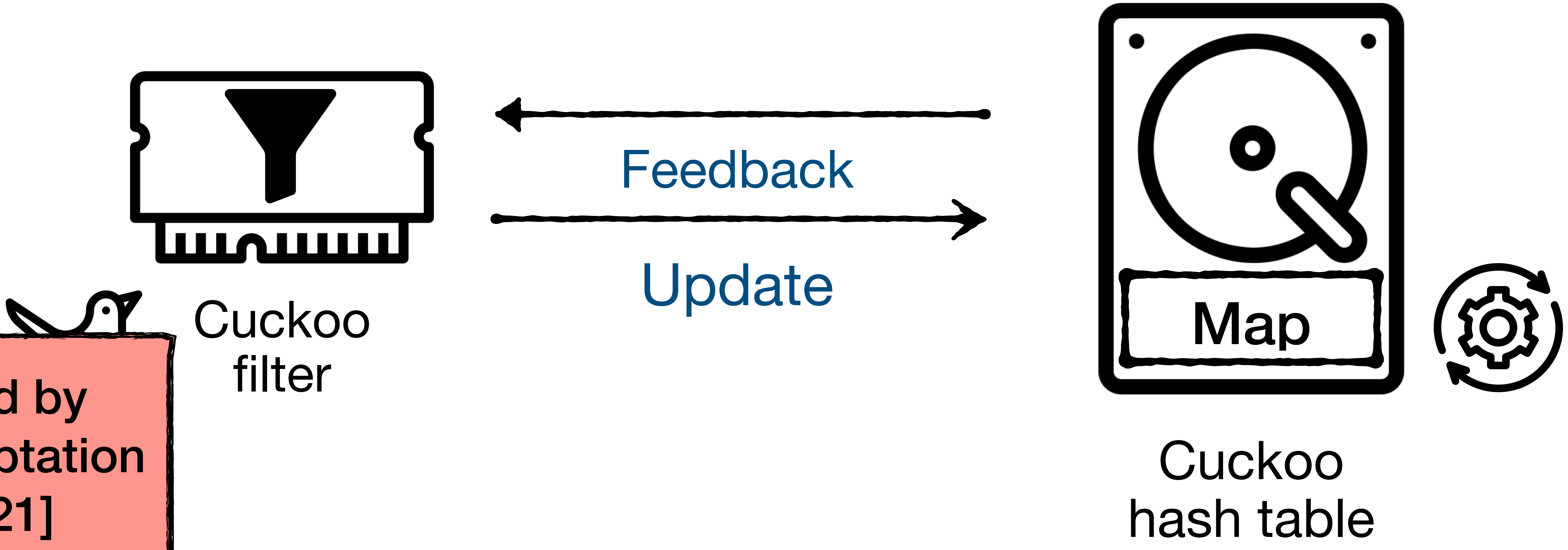
Minimizing the work in the map is crucial for the performance

Adaptive cuckoo filters [MPR+ 2020]



Adaptivity by moving fingerprints around

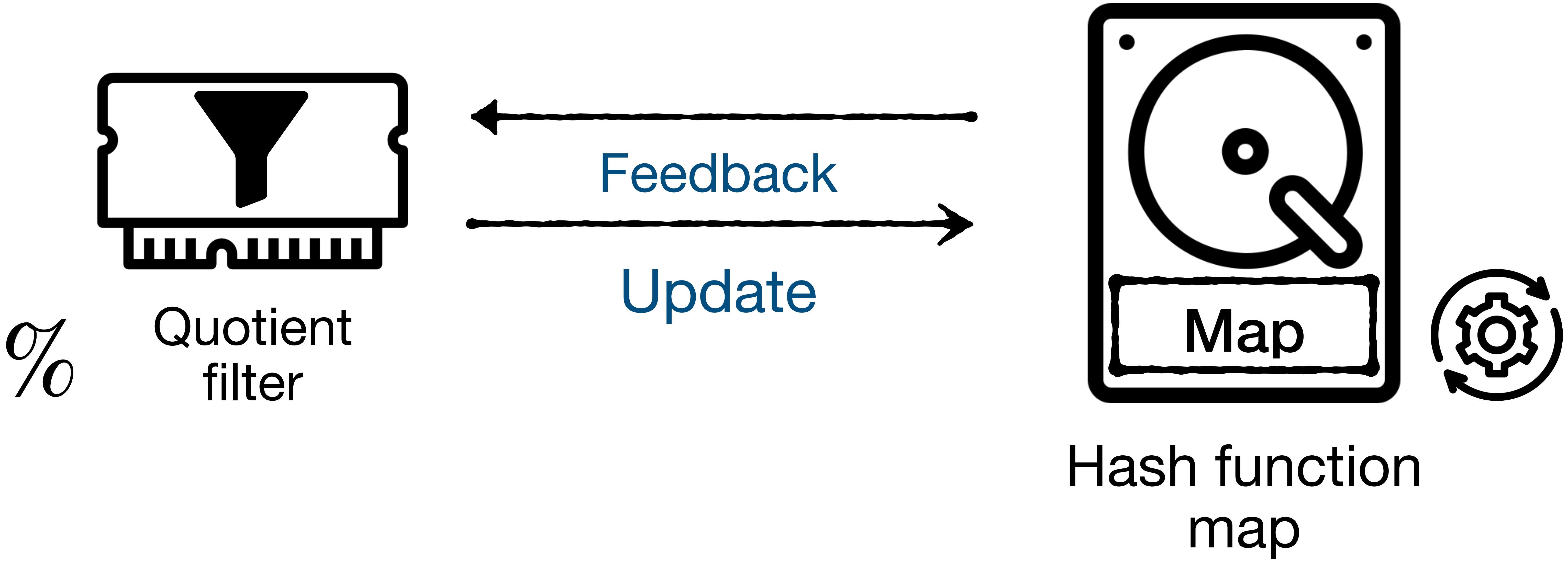
Adaptive cuckoo filters offer weak adaptivity



Can be attacked by identifying an adaptation loop [KMP 2021]

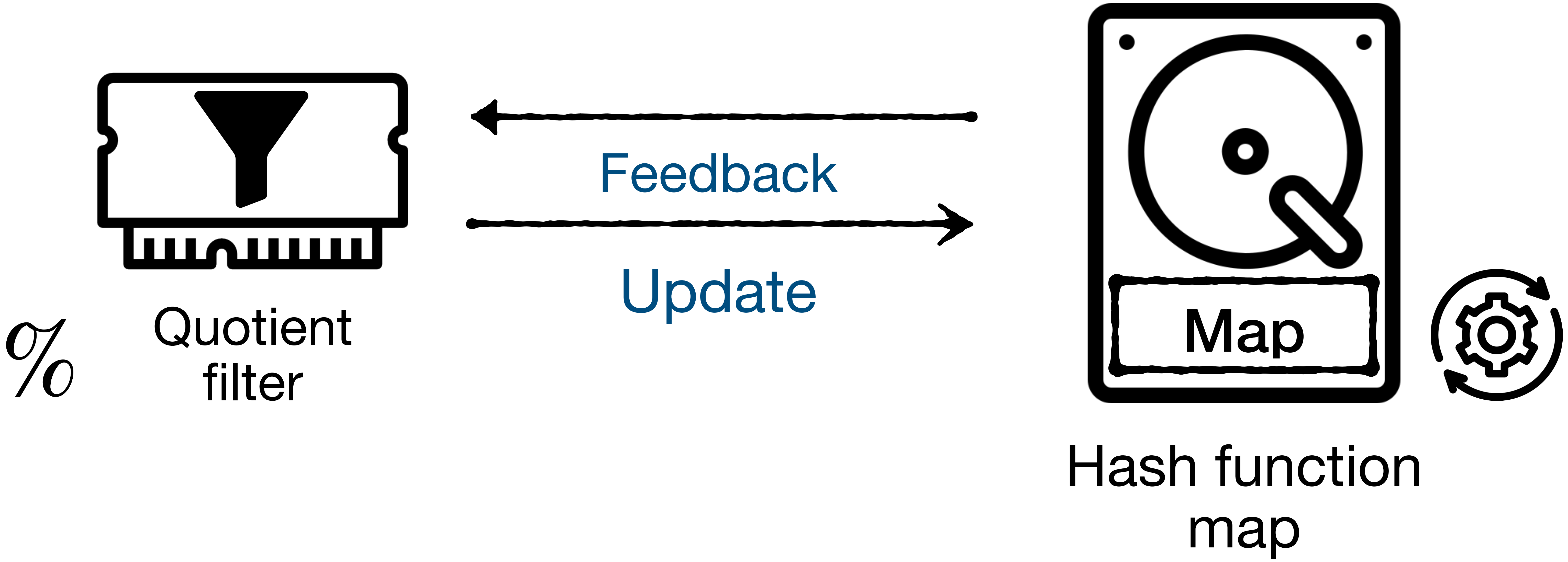
- Adaptivity by moving fingerprints around during insertions/queries
- Can forget previous false positives while adapting for new ones

Telescoping filters [LMS+ 2021]



Adaptivity by changing hash function during insertions/queries

Telescoping filters offer strong adaptivity



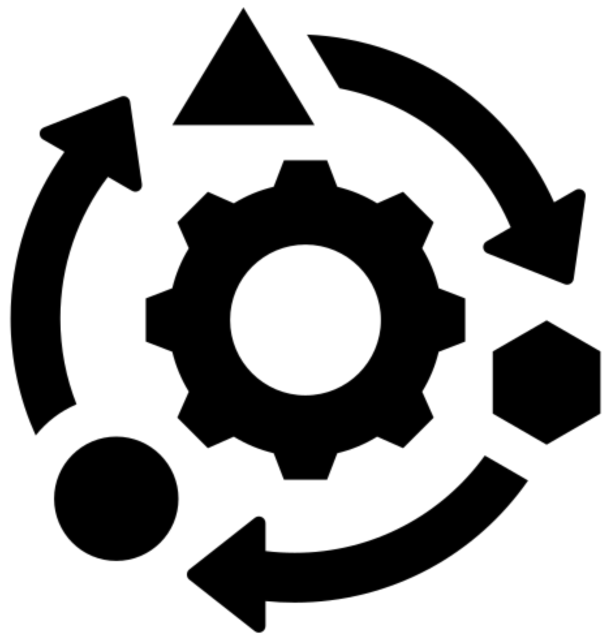
Adaptivity by changing hash function during insertions/queries

Hash map grows during adaptations (variable-length fingerprints)

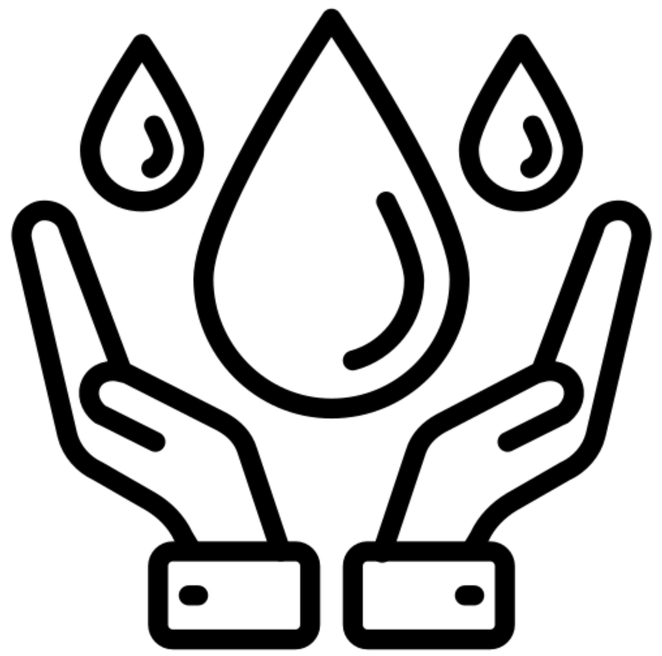
Does not forget previously learned fingerprints

Adaptive quotient filter [WMT+ SIGMOD 2025]

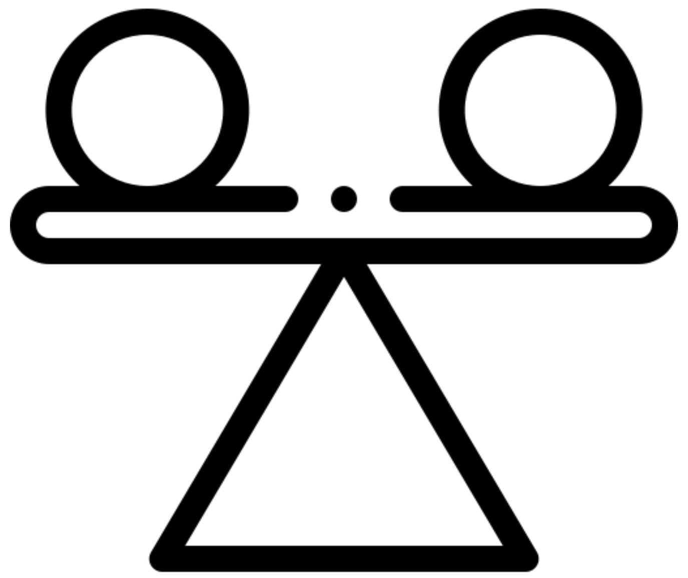
- Adaptivity by using variable-length fingerprints to avoid collisions
- Based on the counting quotient filter (CQF) [PBJ+ 2017]
- Matches the space lower-bound to lower-order terms
- 10X—30X faster than other adaptive filters (ACF, TF) for disk-based database benchmarks
- Up to 6X faster performance than traditional filters (QF, CF) for disk-based database benchmarks



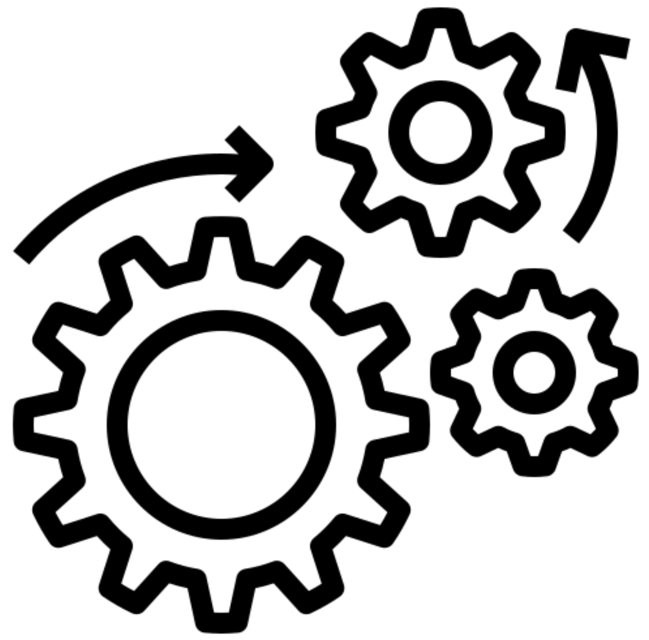
Adaptive quotient filter design



Preserves CQF
performance and features

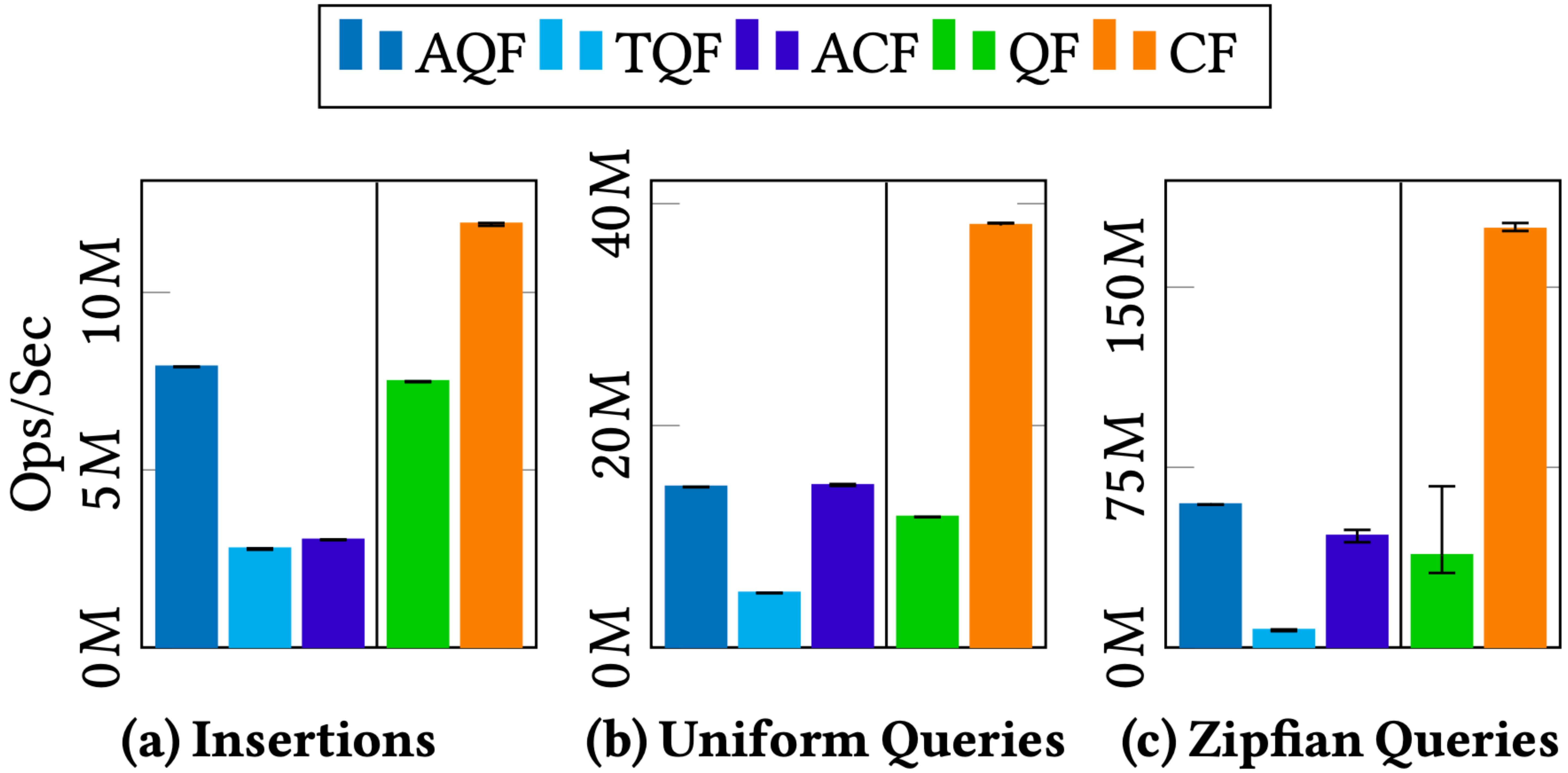


Stable reverse map
during insertions



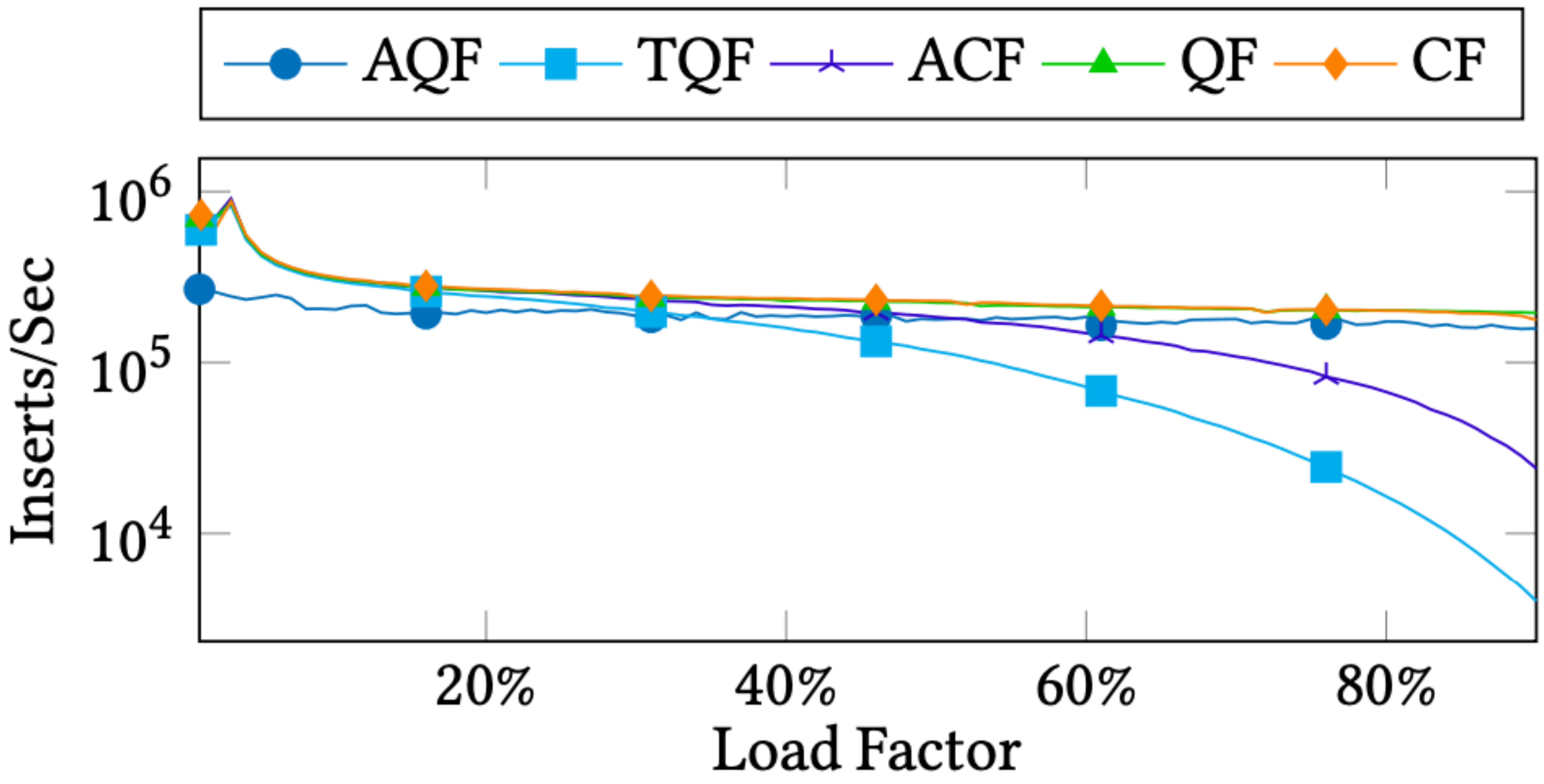
Supports dynamic
operations

Micro-benchmark performance



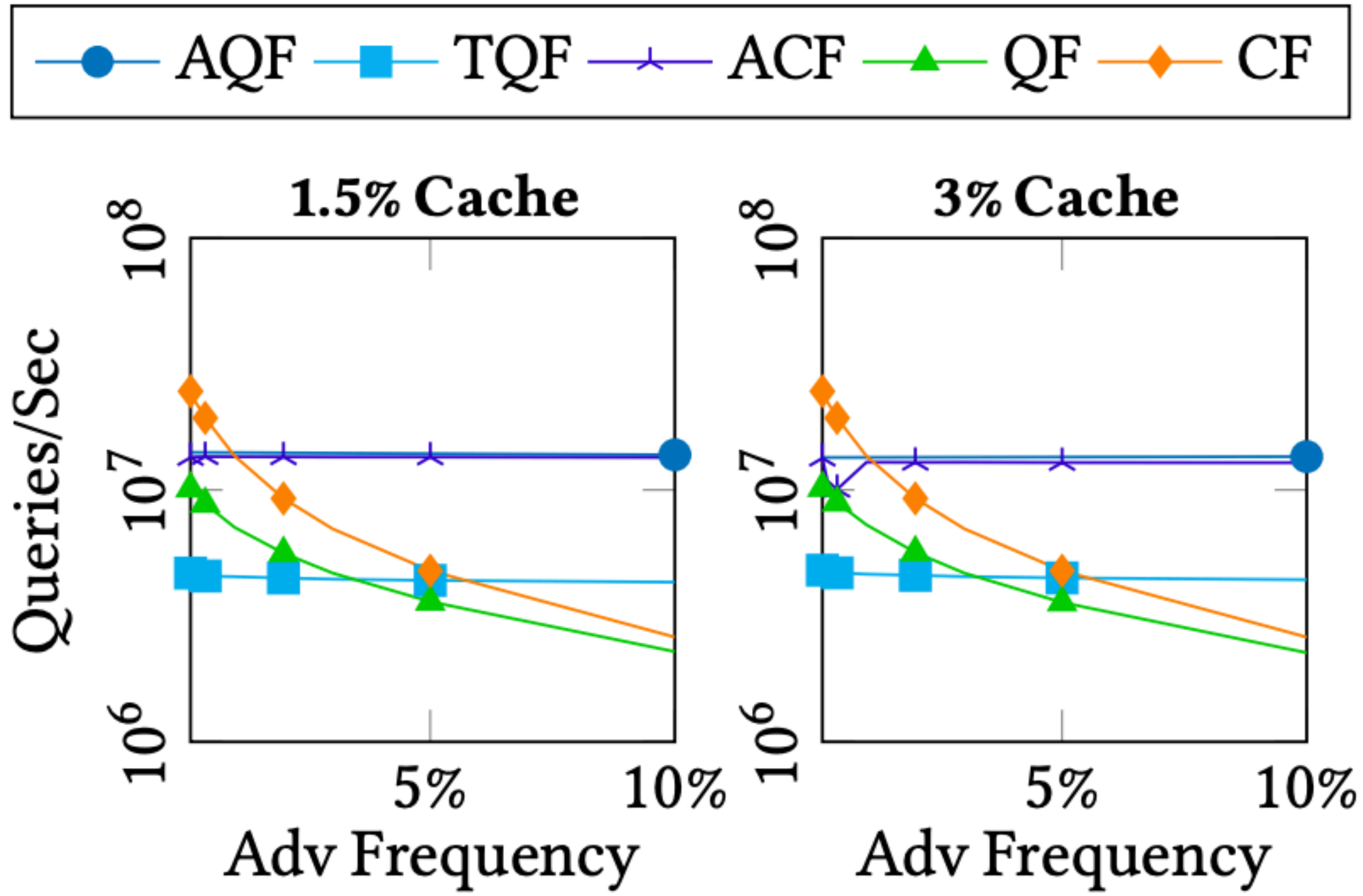
AQF has no overhead compared to the traditional CQF

Database insertion performance



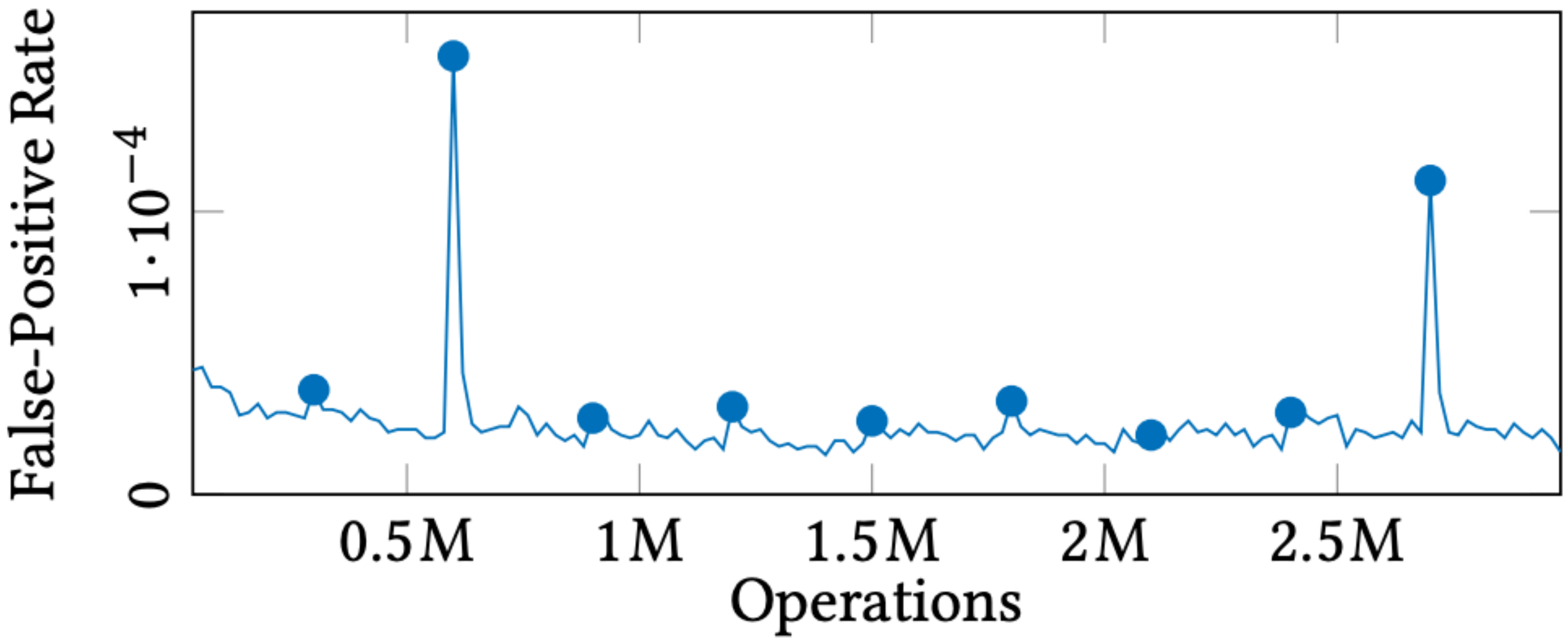
AQF performs similarly to QF/CF for database insertions
10X—30X faster than other adaptive filters

Database query performance



AQF up to 6X faster compared to QF/CF for database queries

Adaptivity rate on a churn workload



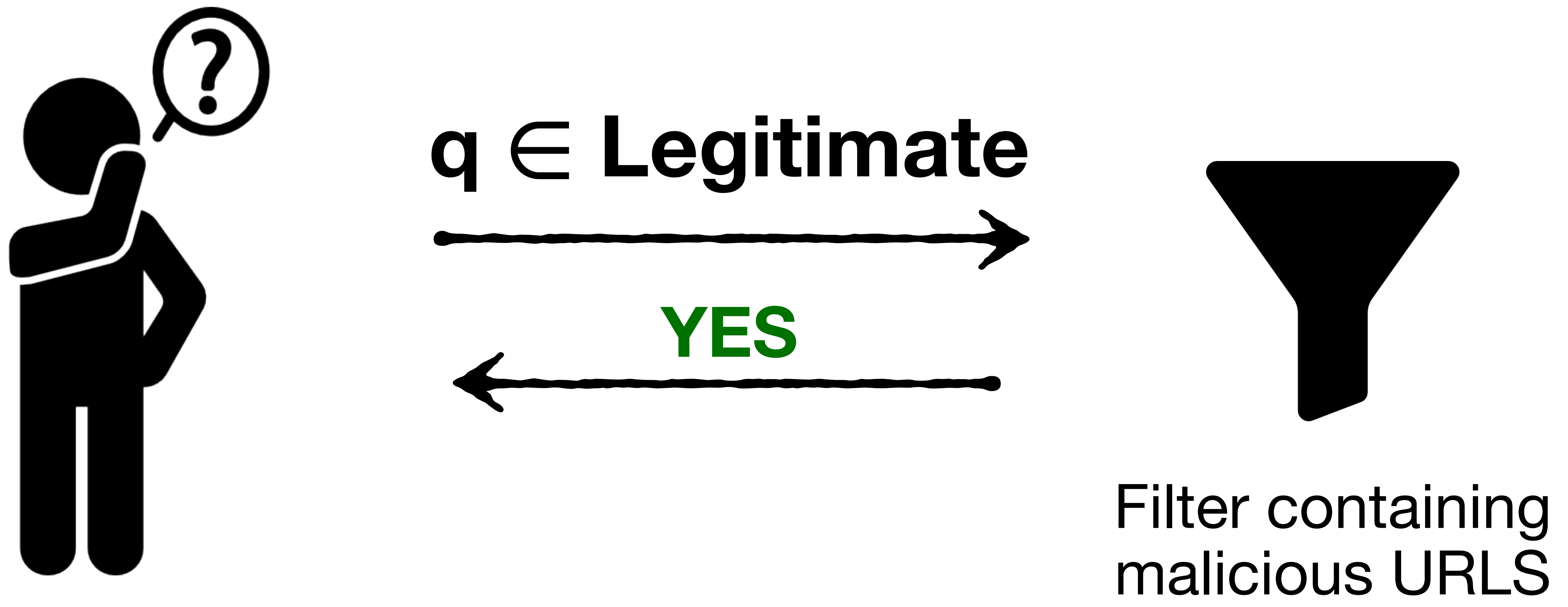
AQF adapts to new false positives almost immediately for churn workloads

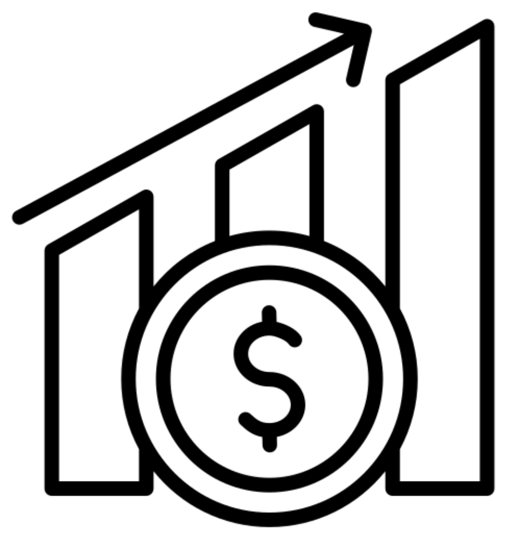
AQF offers even stronger guarantees compared to the broom filter [BFG+ 2018]

False positives can be really expensive

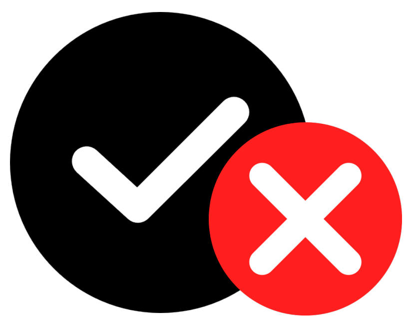
Malicious URLs

Legitimate URLs





A false positive can block critical URLs such as a voter registration webpage or emergency weather info



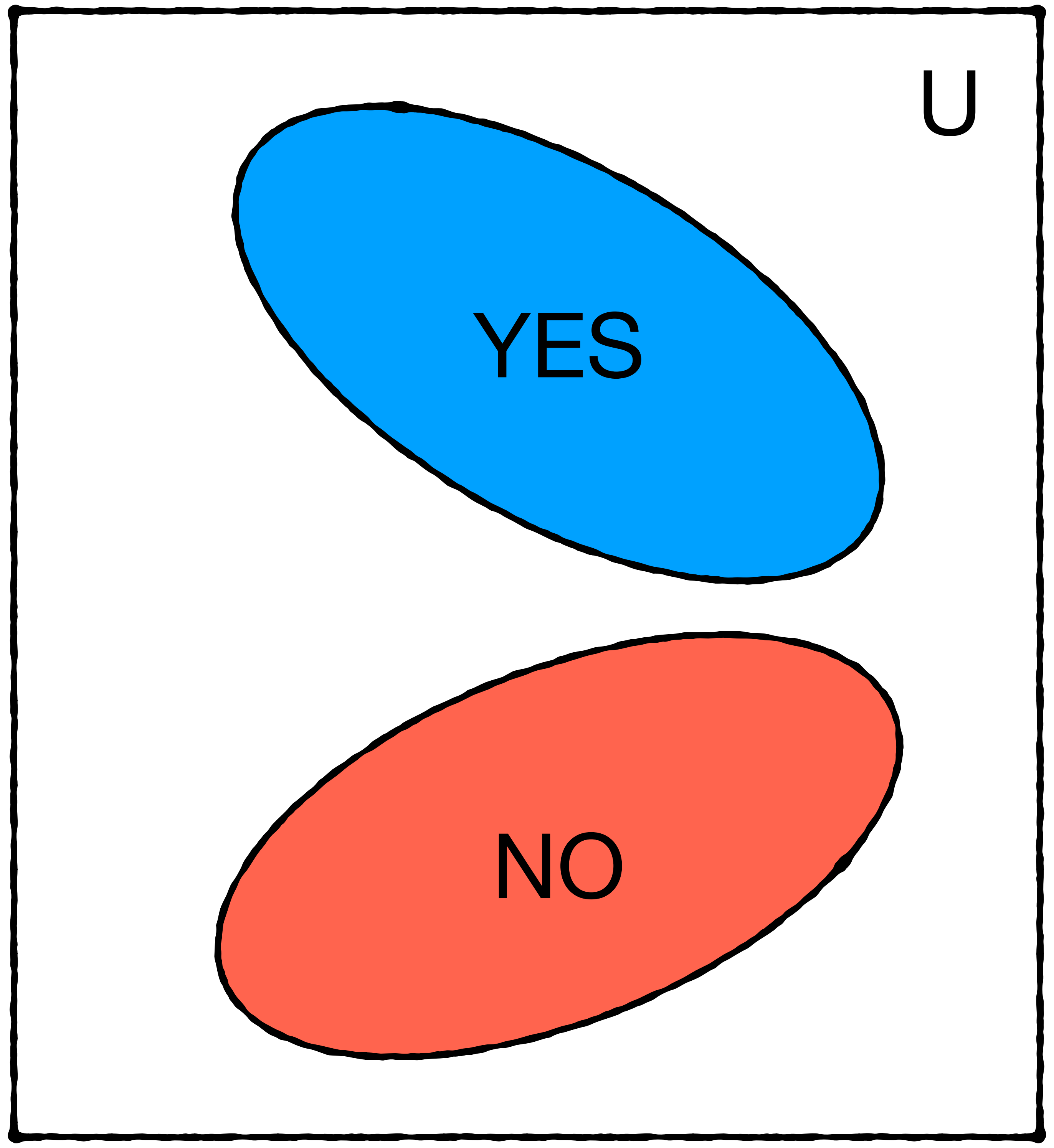
False positive

YES/NO list problem

if q ∈ YES, return **True** with probability 1

if q ∈ NO, return **False** with probability 1

Otherwise **False** with probability $> 1 - \epsilon$



Applications:

- Detecting malicious URL
- Certificate revocation lists
- De Bruijn graph traversal

Monotonicity is critical to support YES/O List problem!

Prior work considered each problem separately

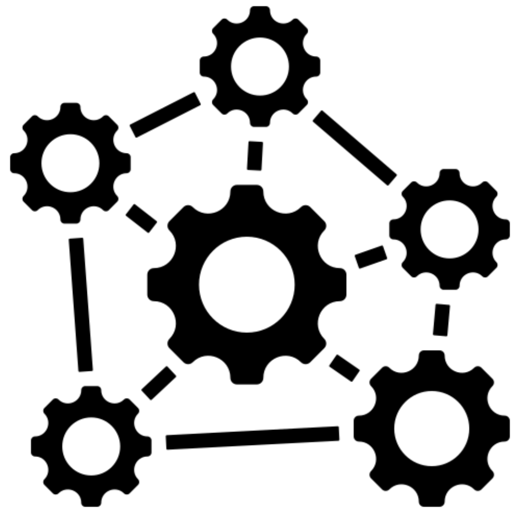
Purpose-built solutions

Bloomier filter [CKR+ 2004]

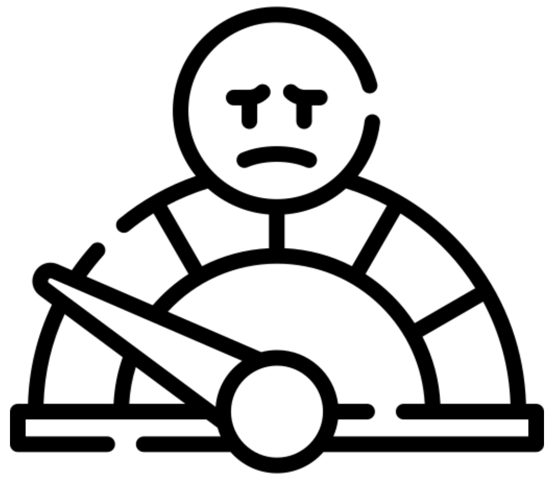
Cascading Bloom filter [TC 2009]

Static XOR filter [RSW+ 2021]

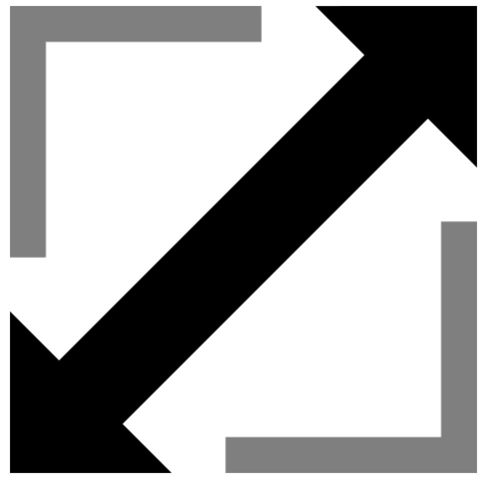
Seesaw counting filter [LCD+ 2022]



Complex design



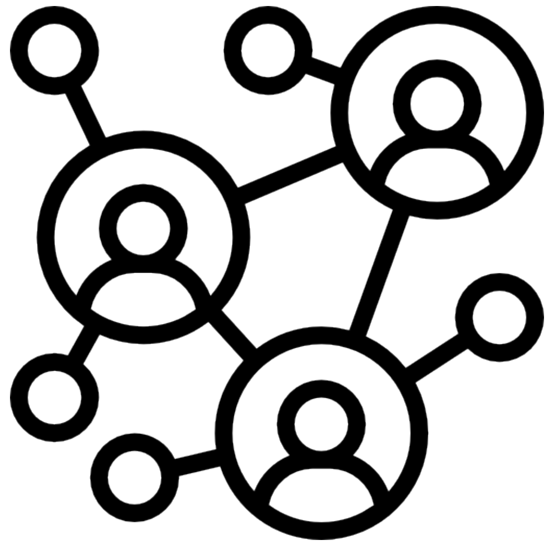
Low performance



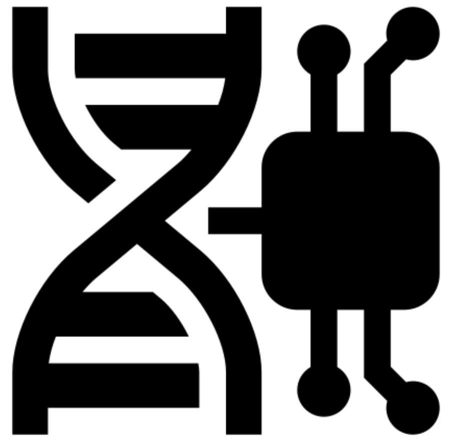
High space

Monotonically adaptive filters solve many problems

- Security; avoiding DOS attacks
  - Static YES/NO list
  - Dynamic YES/NO list

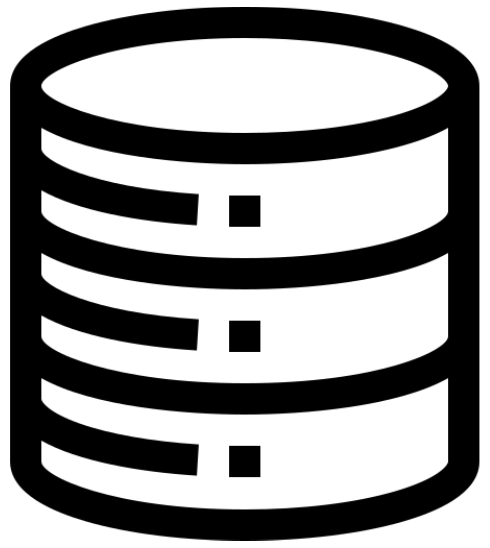


Networking



Computational biology

- Robust performance guarantees
  - Skewed query distributions
  - Adversarial queries



Databases

Takeaways

- Adaptability is a critical to achieve robust performance in the context of skewed/adversarial workloads
- Monotonically adaptive filters can help address challenges across applications
- We need to redesign traditional applications in the context of newer guarantees and API offered by adaptive filters

Acknowledgment: All icons in the talk are taken from https://www.flaticon.com/