BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows

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Executive Summary

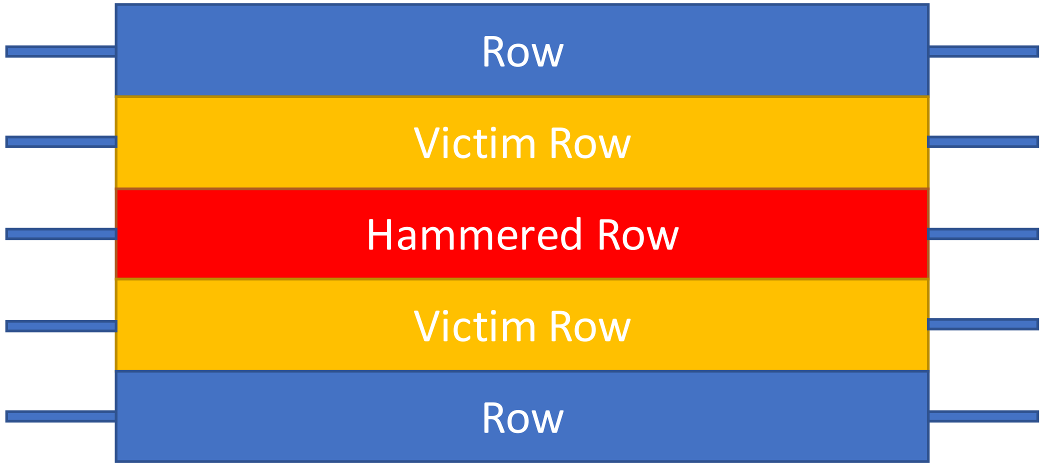
- Background: RowHammer is a serious security issue
- Problem: Mitigation mechanisms have limited support for current/future chips
  - **Compatibility** with commodity DRAM chips
  - **Scalability** with worsening RowHammer effects
- Goal: Efficient and scalable method to prevent RowHammer bit-flips without knowledge of or modifications to DRAM internals
- Key Mechanism:
  - Selectively **limit memory accesses** that may cause RowHammer bit-flips
  - **Identifying** and **throttling** potential attacker
- Key Results:
  - Scalable complexity
  - Highly efficient solution in terms of energy consumption (<0.6%) and performance (71% under an attack)

Outline

- Recab: RowHammer
- Requirements for the solution
- Possible Solutions
- BlockHammer
  - General
  - RowBlocker
  - AttackThrottler
- Evaluation
- Conclusion
- Strengths and Weaknesses
- Discussion

RowHammer

- We are seeing here a DRAM bank



Requirements

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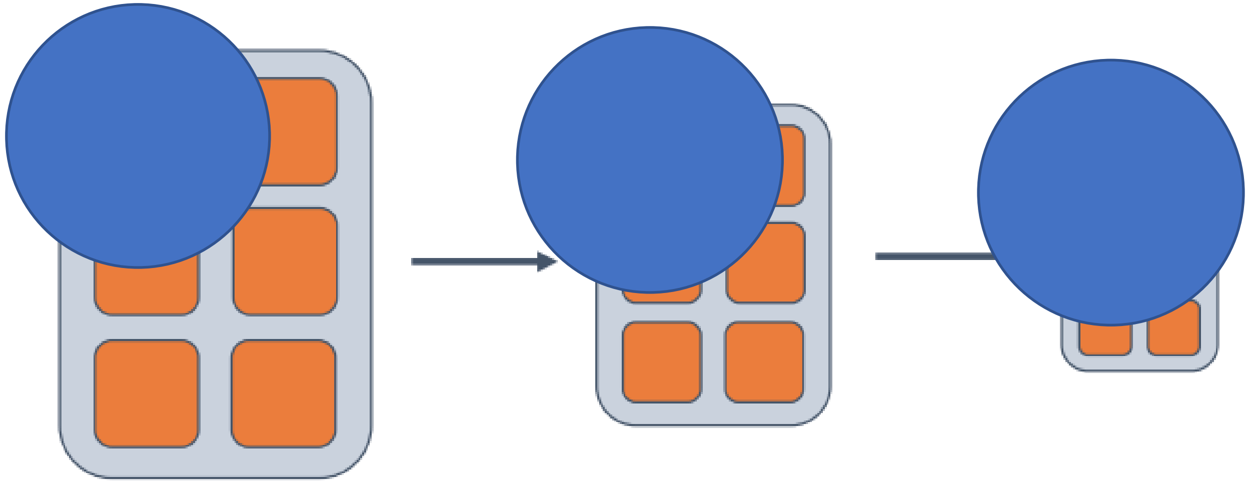
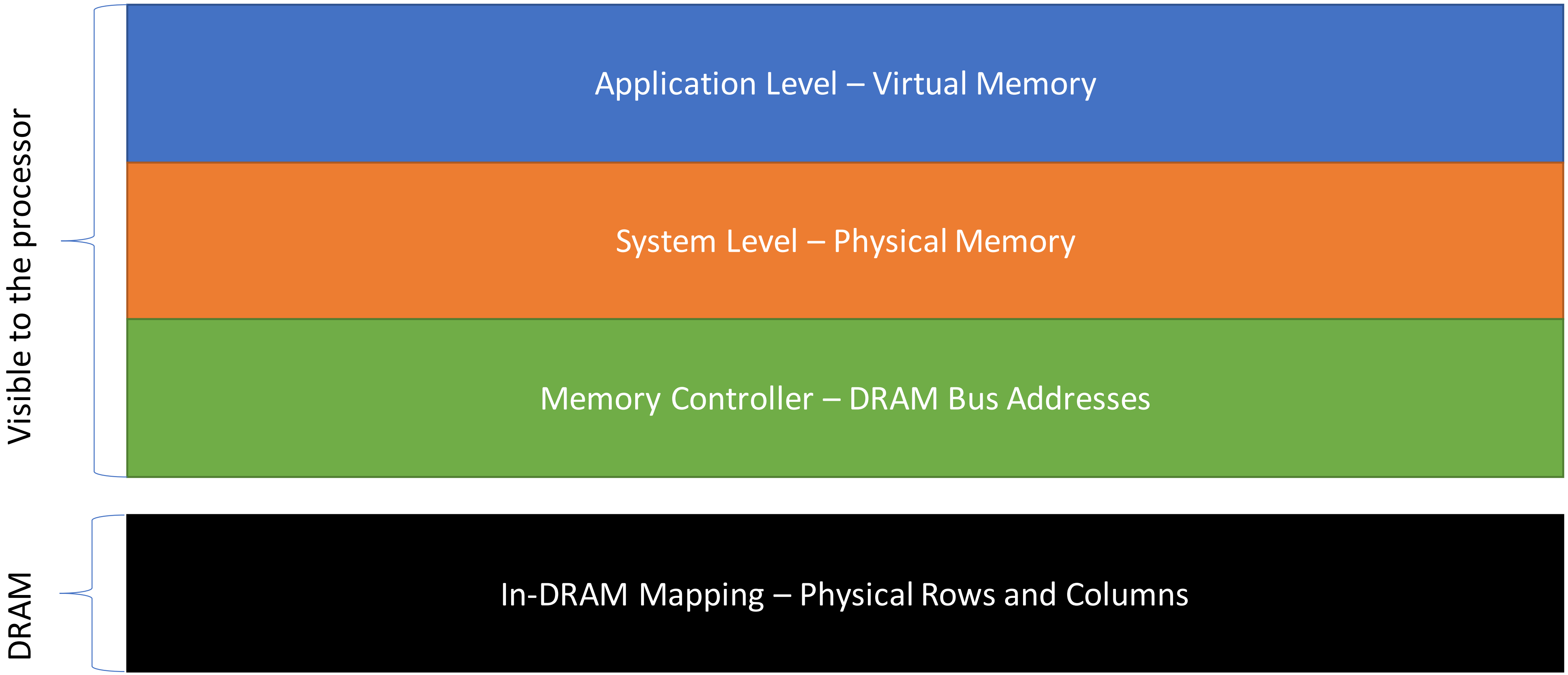
Scalability

- DRAM chips are more vulnerable to RowHammer today
- The density of DRAM chips increases
- A RowHammer bit-flip occurs with a lower amount of accesses
- Blast radius is increasing



Compatibility



In-DRAM Mapping

- **Design Optimizations**: Provides better density, power and performance by simplifying DRAM circuitry
- **Yield Improvements**: Internal mapping from faulty rows to working rows

- In-DRAM mapping is not published to the outer world

Our solution should not require knowledge of DRAM internals!

Possible Solutions

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Solution 1: Increase Refresh Rate

- Process: Increase the refresh rate of all DRAM rows to prevent RowHammer bit-flips
- Drawbacks:
  - Higher power consumption
  - Performance loss

Available for: OS X Mountain Lion v10.8.5, OS X Mavericks v10.9.5

Impact: A malicious application may induce memory corruption to escalate privileges

Description: A disturbance error, also known as Rowhammer, exists with some DDR3 RAM that could have led to memory corruption. This issue was mitigated by increasing memory refresh rates.

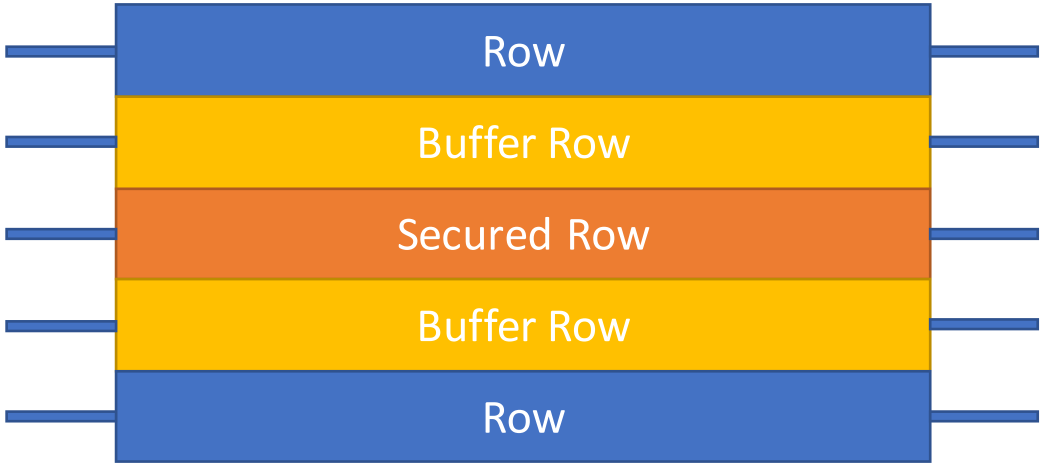
CVE-ID

CVE-2015-3693 : Mark Seaborn and Thomas Dullien of Google, working from original research by Yoongu Kim et al (2014)

Compatible but not scalable

Solution 2: Physical Isolation

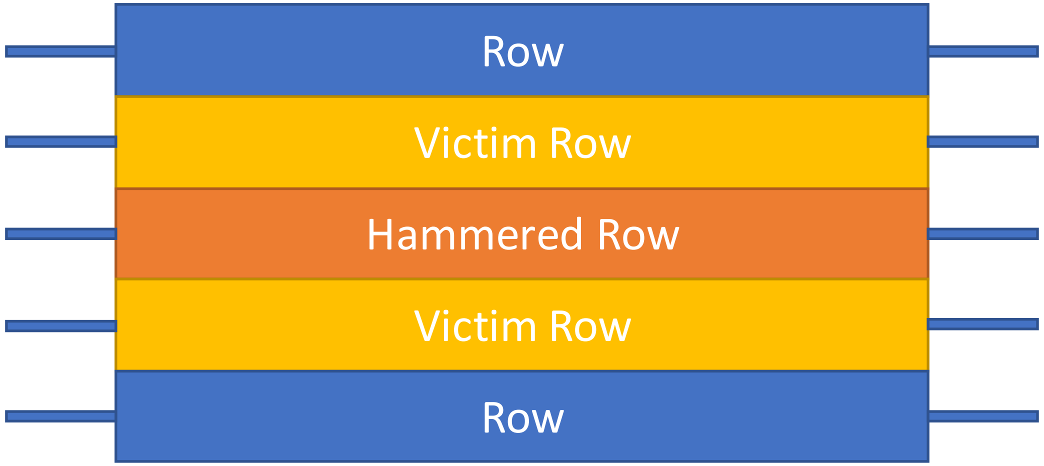
- Process: Separate physically sensitive data
- Drawbacks:
  - Requires a lot memory
  - Because RowHammer is getting worse, the fraction of cells we can protect decreases
  - Requires knowledge on DRAM internals



Not compatible and not scalable

Solution 3: Reactive Refresh

- Process: Observes activations and refreshes potential victim rows
- Used in PARA, Graphene, TwiCe
- Drawback
  - Requires knowledge on DRAM internals



Not compatible but scalable

Solution 4: Proactive throttling

- Process: Limit repeated access to the same row
- Drawback
  - Decreases performance of benign applications

Compatible and scalable but not efficient

Solution

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Goal

Prevent RowHammer bit-flips **efficiently** and **scalably** without any knowledge of or modifications to DRAM

Idea

Selectively **throttle memory accesses** that may cause RowHammer bit-flips

Idea in Detail

- An attacker **hammers** a row
- BlockHammer **detects** a RowHammer attack
- BlockHammer **selectively** throttles accesses from within the memory controller
- Access **limitations** make it impossible for bit-flips to occur
- BlockHammer informs the system software about a potential attack

BlockHammer Overview

- **RowBlocker**
  - Tracks row activations rates
  - Blacklists rows
  - Throttles activations targeting a blacklisted row

  => Limits the row activation rate

- **AttackThrottler**
  - Identifies threads that perform RowHammer attacks
  - Reduces memory bandwidth usage of identified potential threads

  => Reduces performance degradation during an attack

RowBlocker

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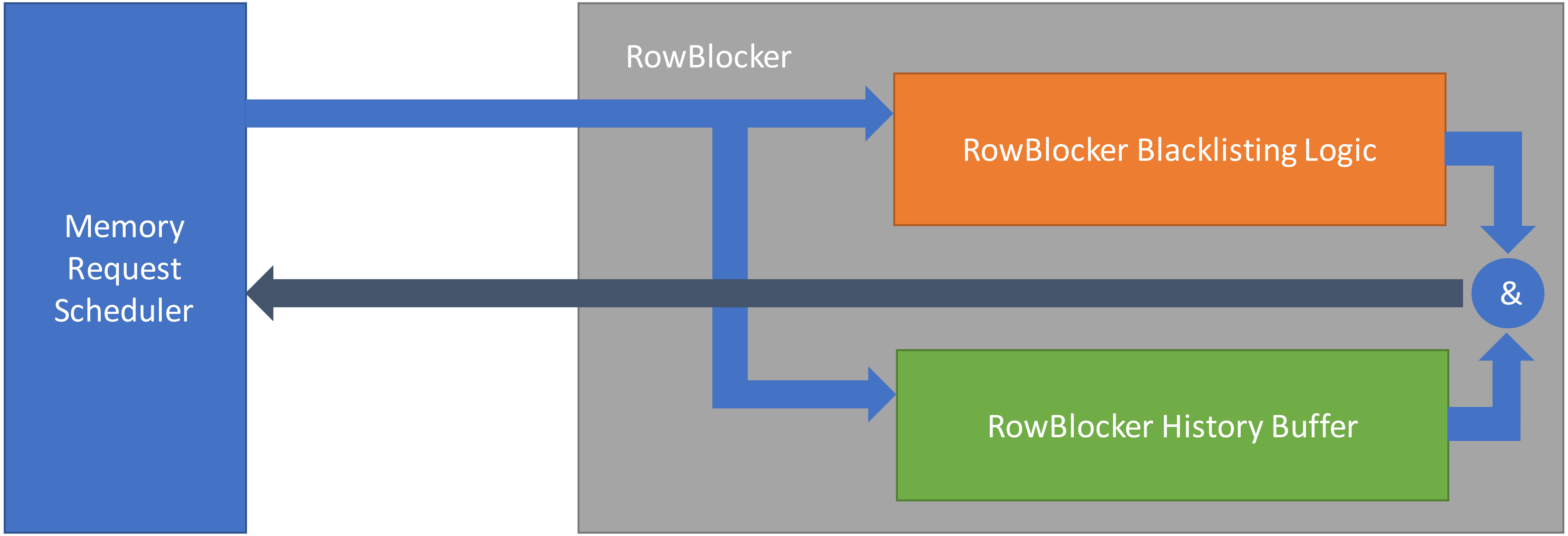
RowBlocker - Overview

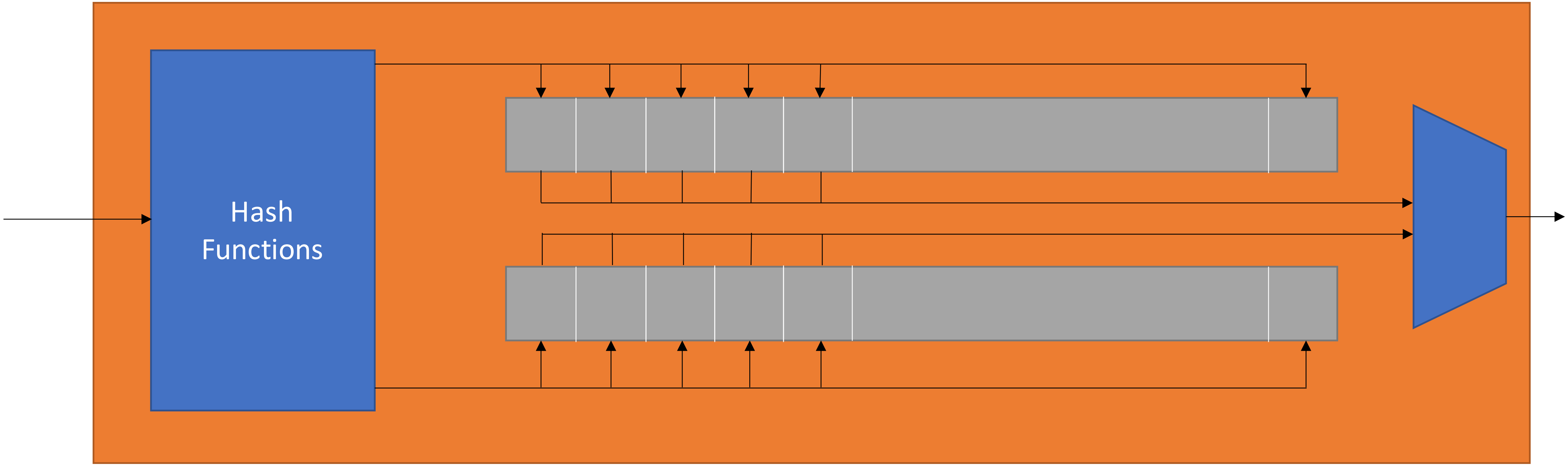
- Throttles row activations
- Blacklists rows and delays activations of blacklisted rows



RowBlocker - Blacklisting Logic

- **Blacklists** a row when the row‘s activation count in a time window exceeds a threshold
- Uses two efficient **Bloom filter** to track the recent accesses
- Accesses are stored in **both filters**
- Only **one** filter is active at a given time

RowBlocker – Blacklisting Logic



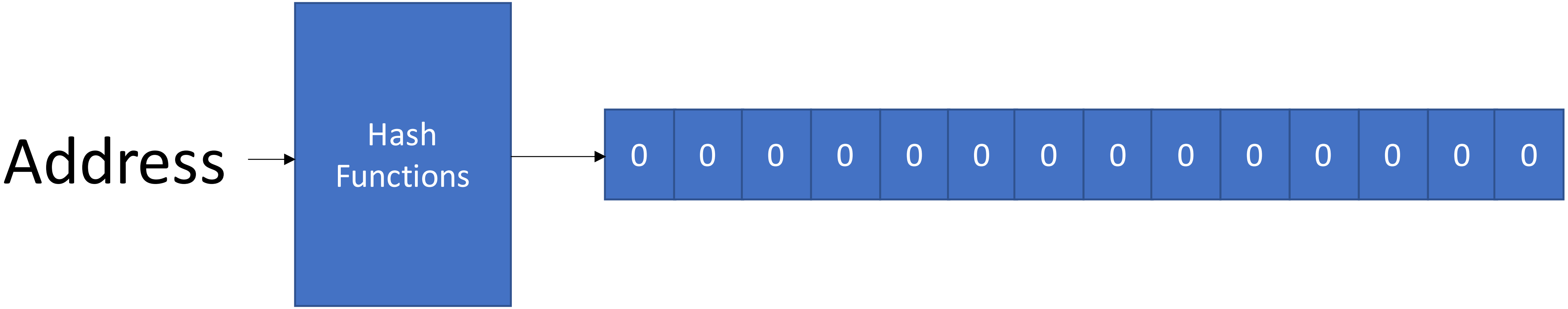
Bloom filter

- We want an efficient method to check whether a row has been recently accessed!
- We do not want false negatives

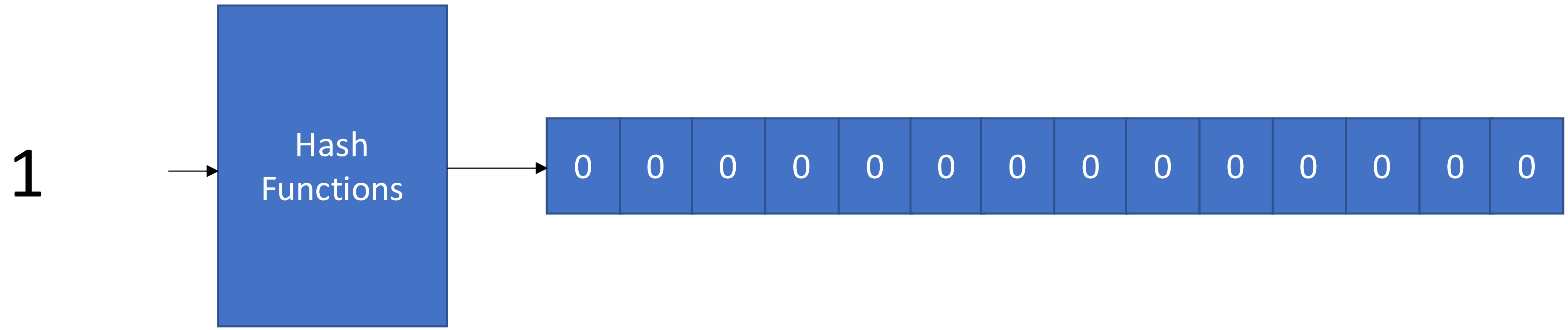
		Actual	
		Positive	Negative
Predicted	Positive	True Positive	False Positive
	Negative	False Negative	True Negative

We can use a Bloom filter

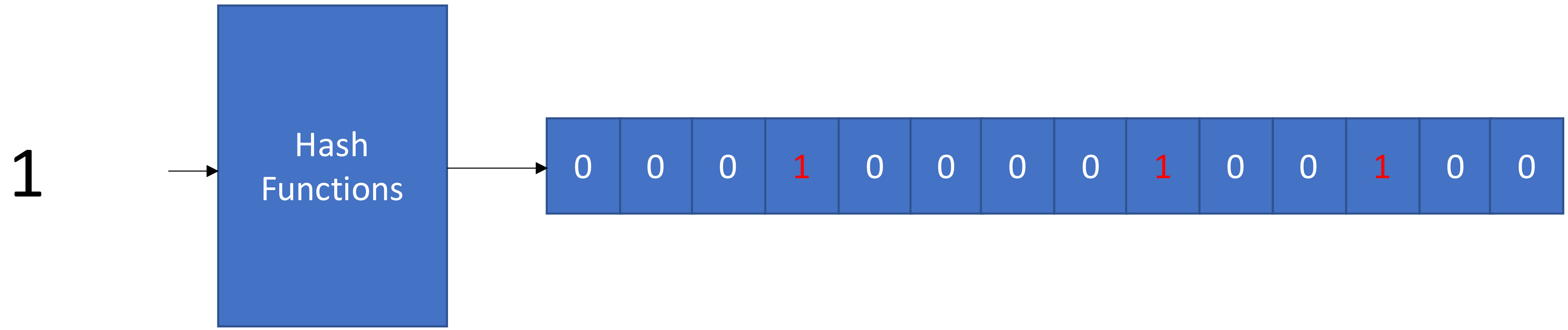
Bloom filter



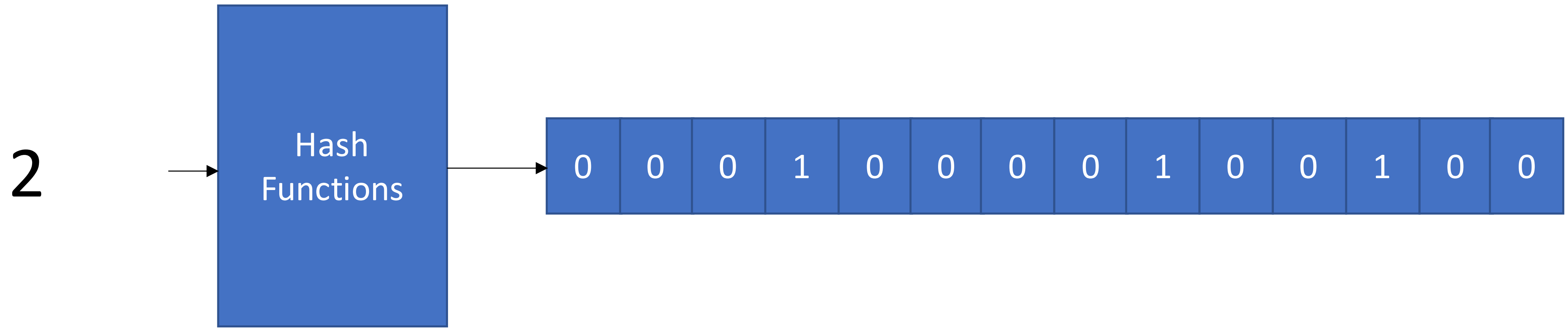
Bloom filter



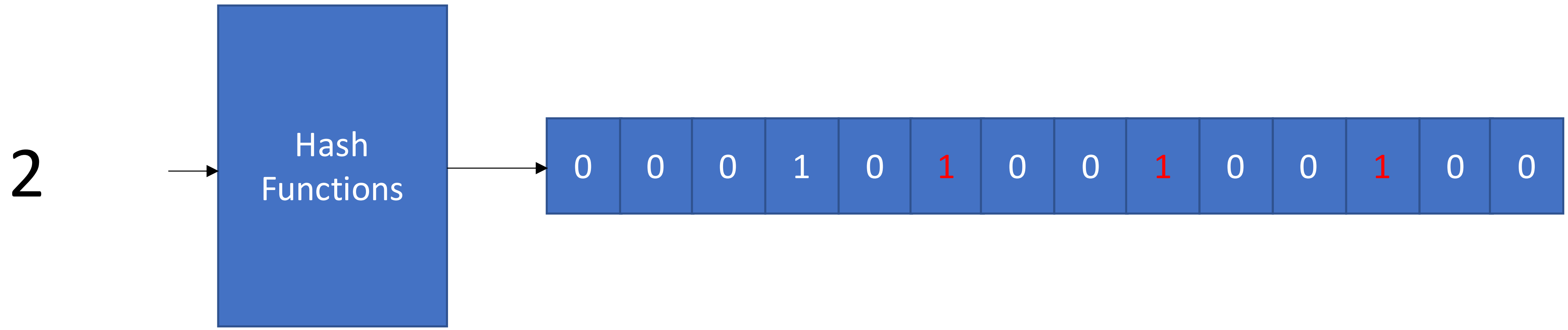
Bloom filter



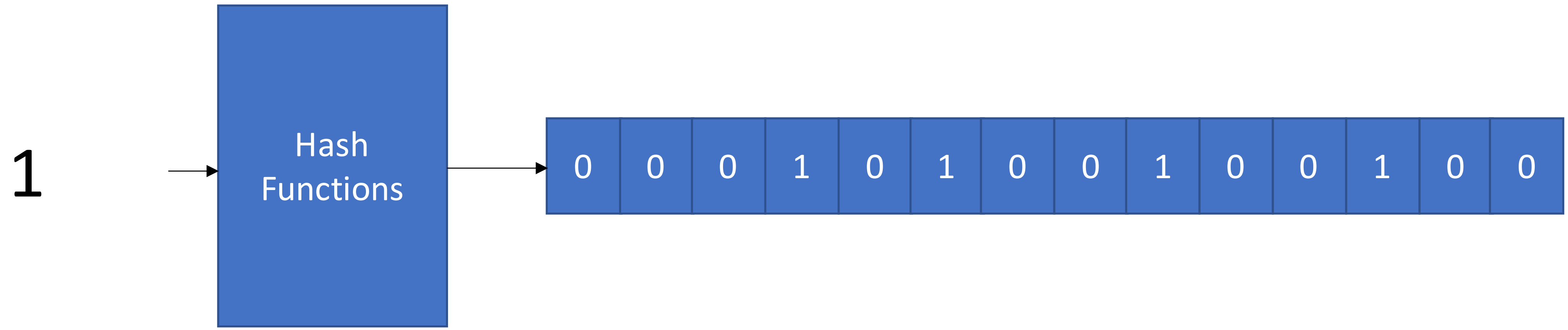
Bloom filter



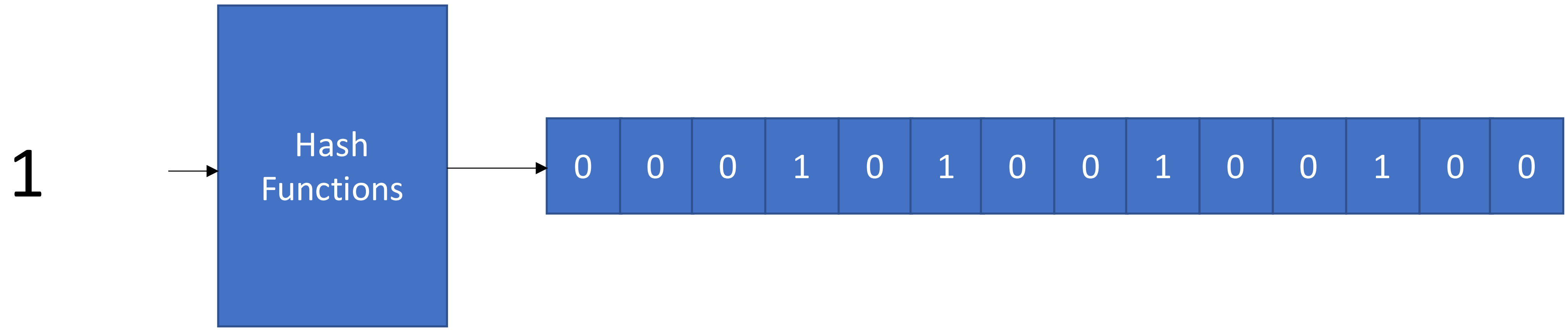
Bloom filter



Bloom filter

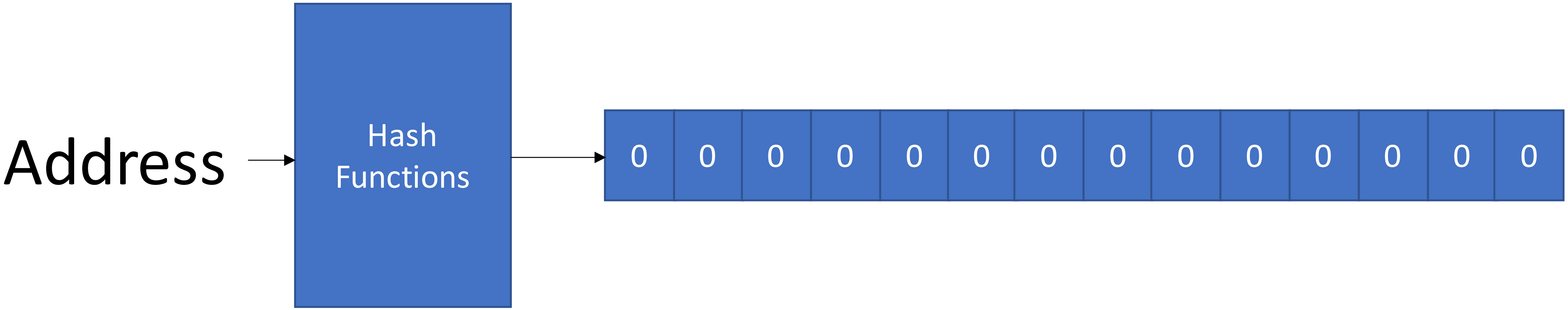


Bloom filter

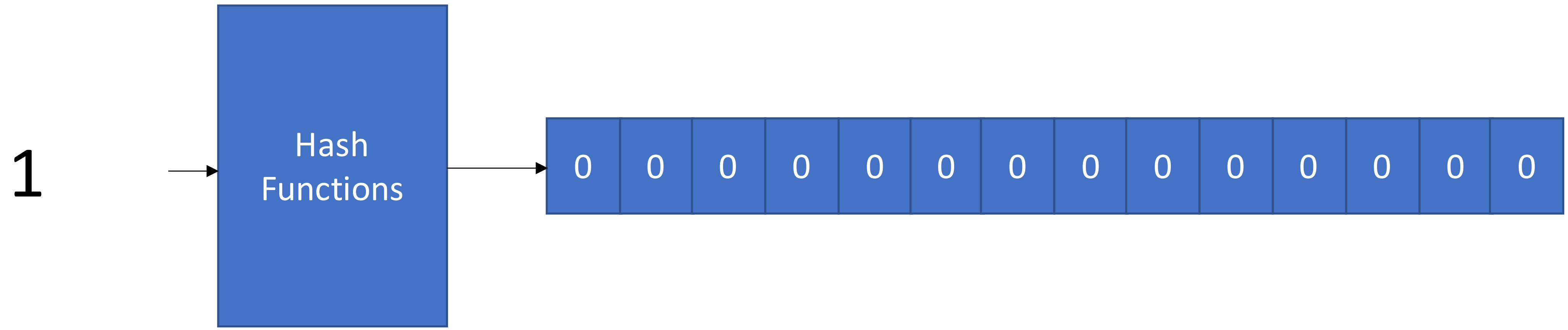


Now, we know if a row has been accessed! But how often have we accessed a row?

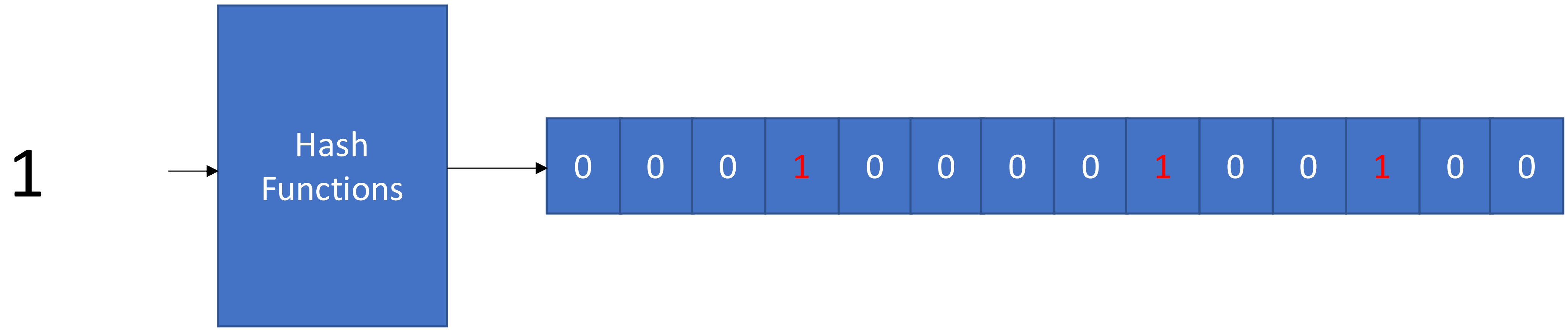
Counting Bloom filter



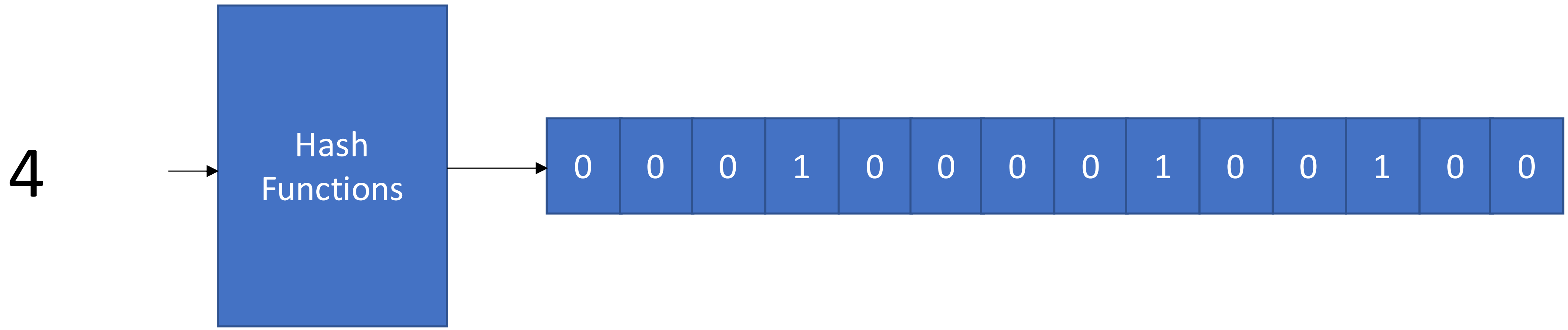
Counting Bloom filter



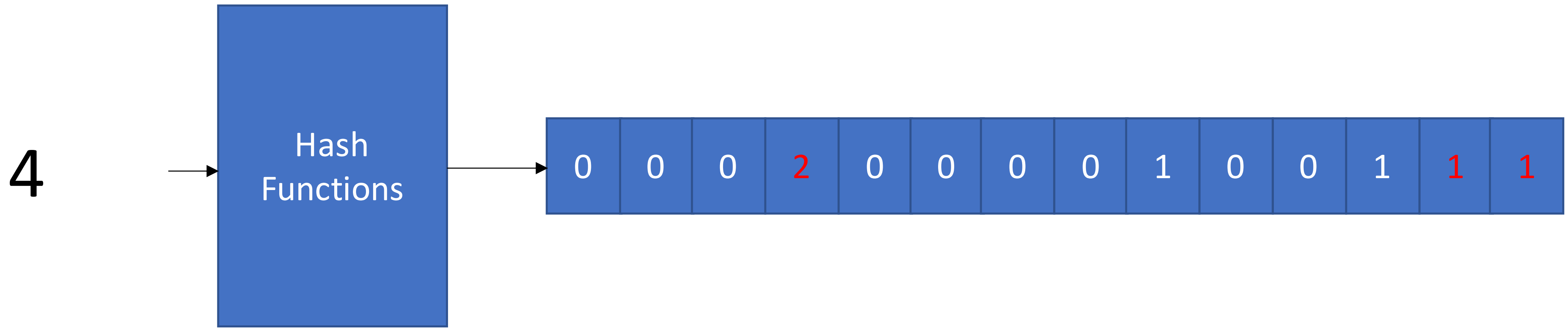
Counting Bloom filter



Counting Bloom filter

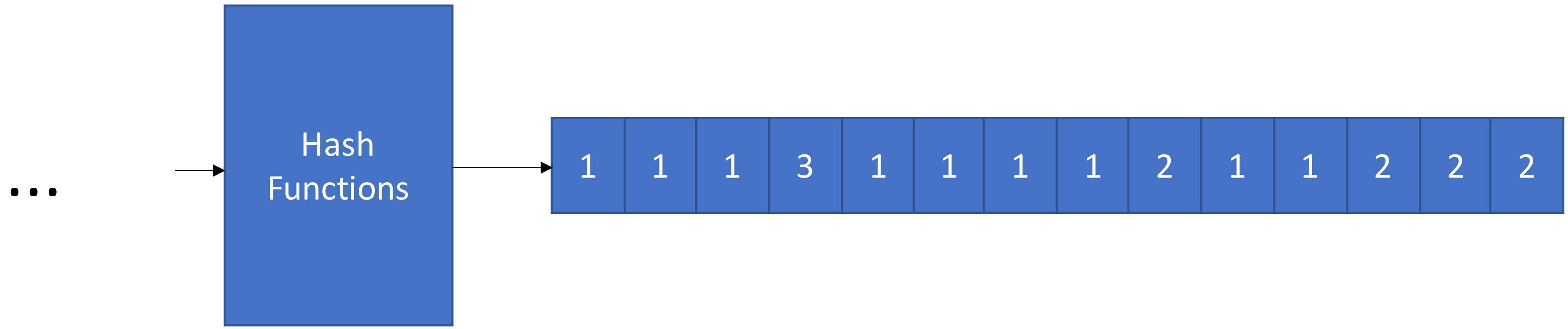


Counting Bloom filter

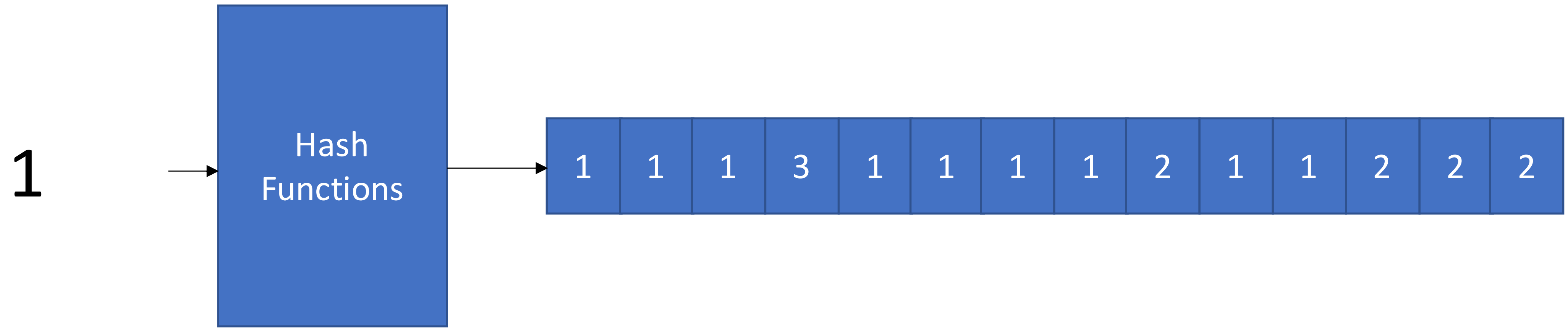


Counting Bloom filter

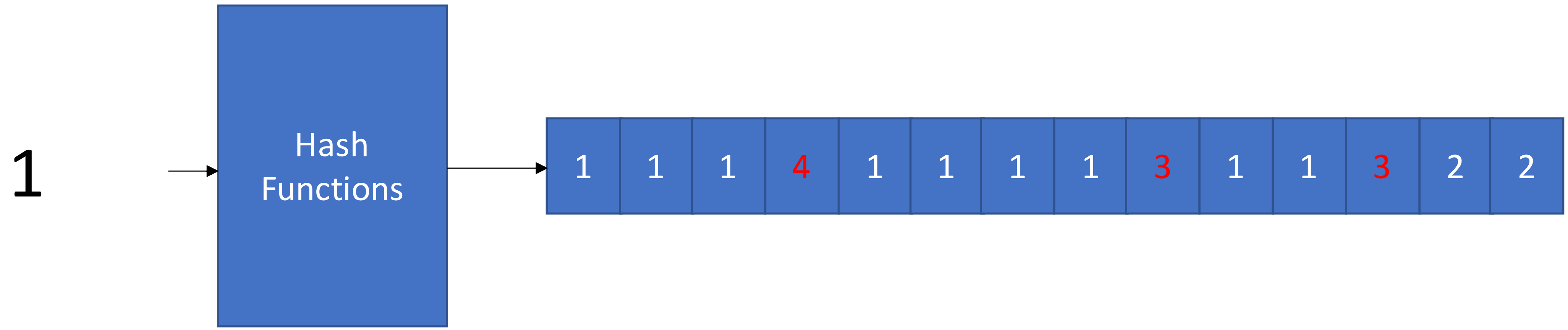
- We continue adding elements...



Counting Bloom filter

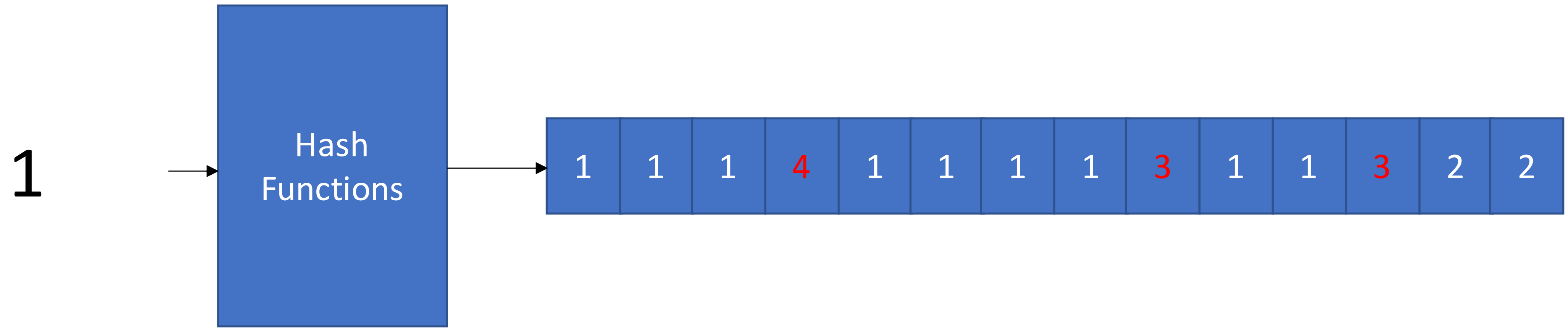


Counting Bloom filter



Counting Bloom filter

- How often have we accessed Row 1 at most?



Now, we have an upper bound!
We want to track the accesses in a specific interval. How can we clear the filter without losing all data?

Why are we using two Bloom filter?

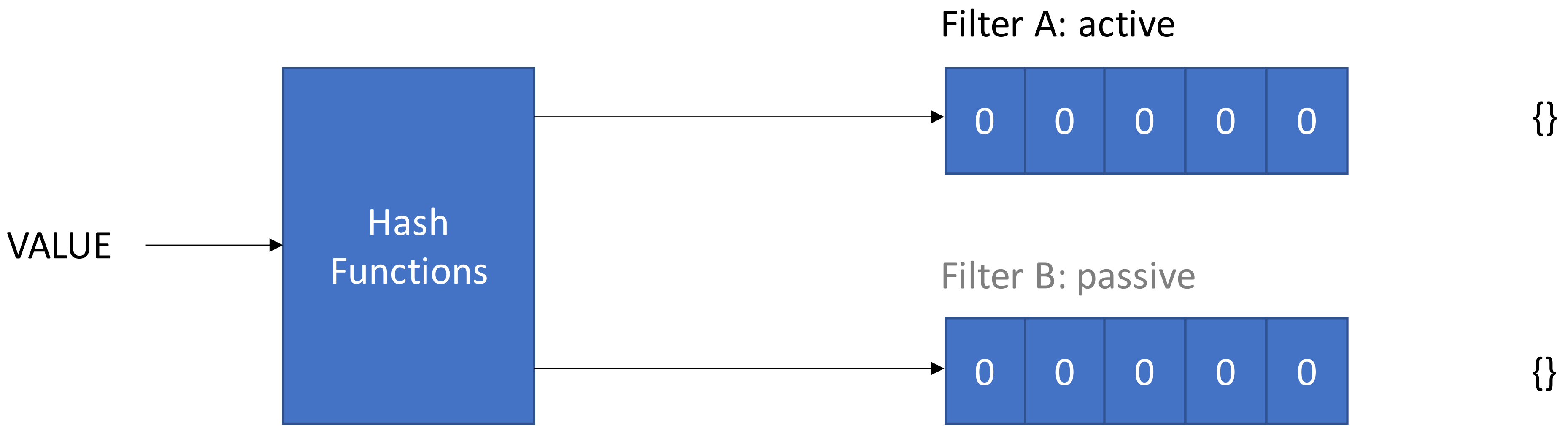
- We want to clear the filter in regular intervals to see the number of accesses in a specific interval.
- How do we achieve this?

Unified Bloom filter

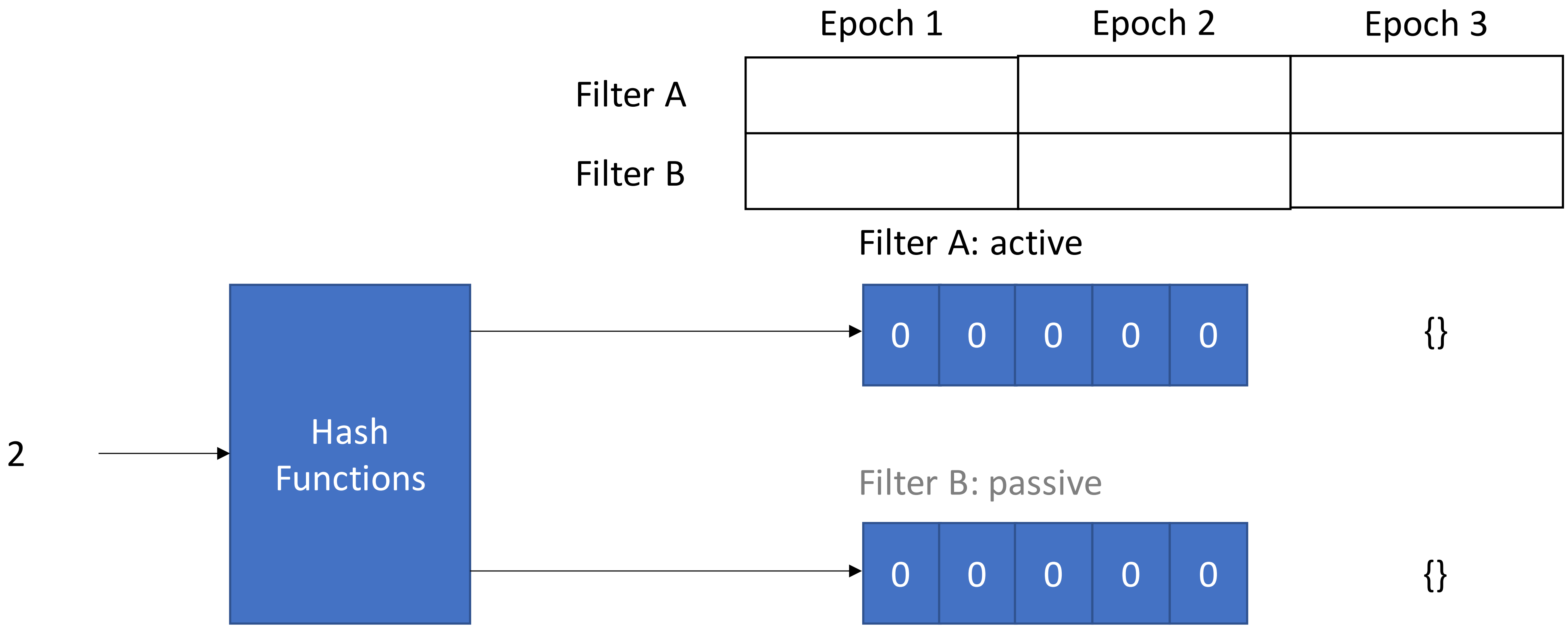
- All elements are inserted **into both** filter
- **Only one** filter is **active** and responses to queries
- Active filter clears array at the end of a specified time interval
- **Switches roles** after an interval

Unified Bloom filter

	Epoch 1	Epoch 2	Epoch 3
Filter A			
Filter B			

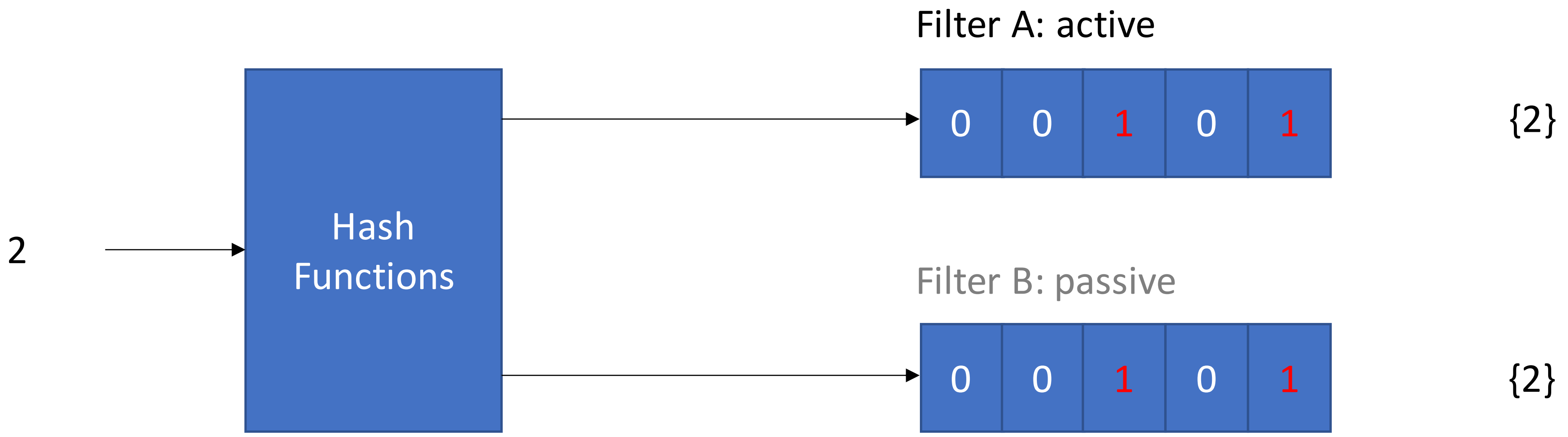


Unified Bloom filter

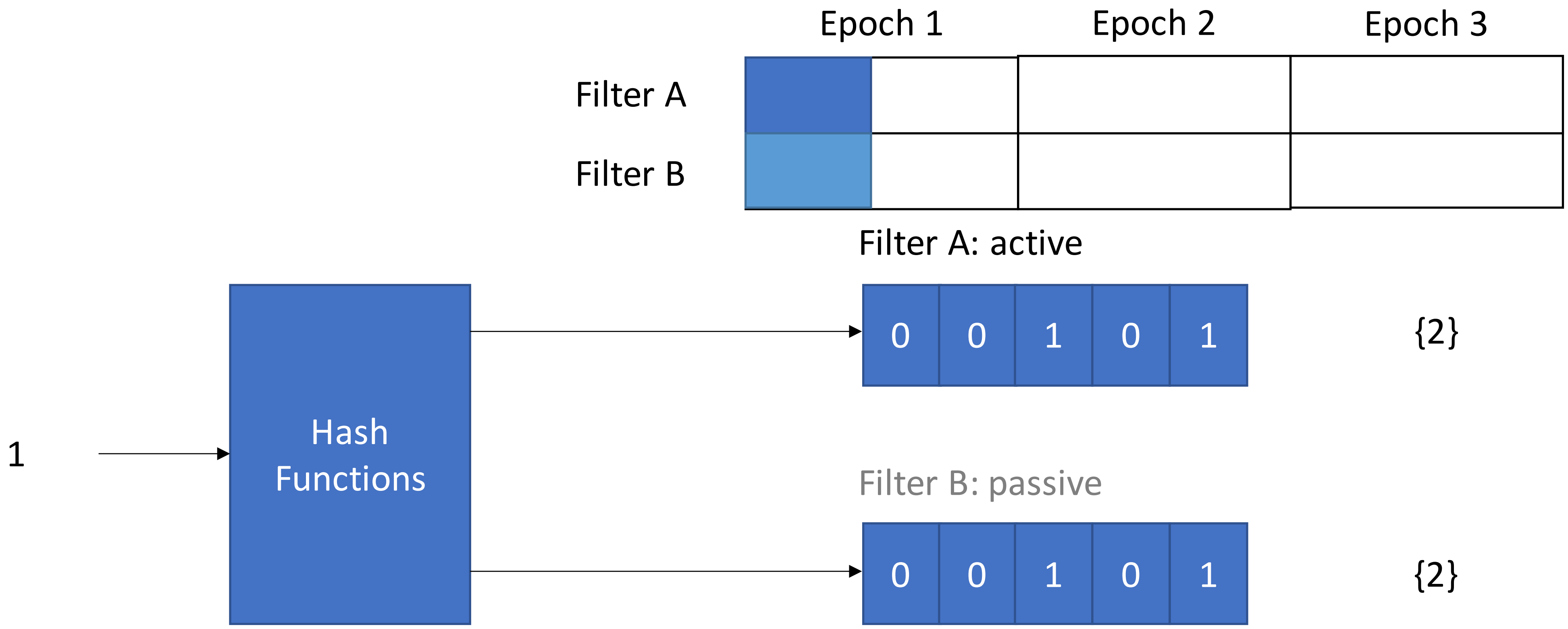


Unified Bloom filter

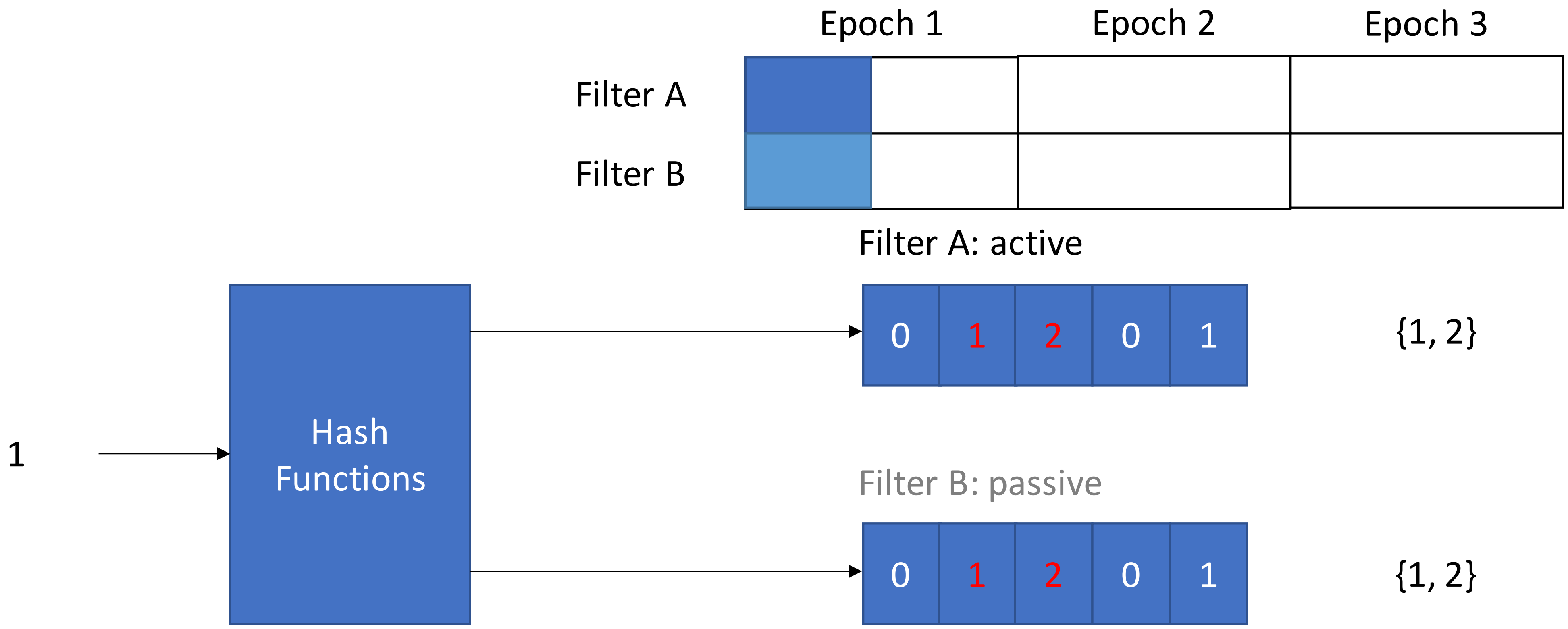
	Epoch 1	Epoch 2	Epoch 3
Filter A			
Filter B			



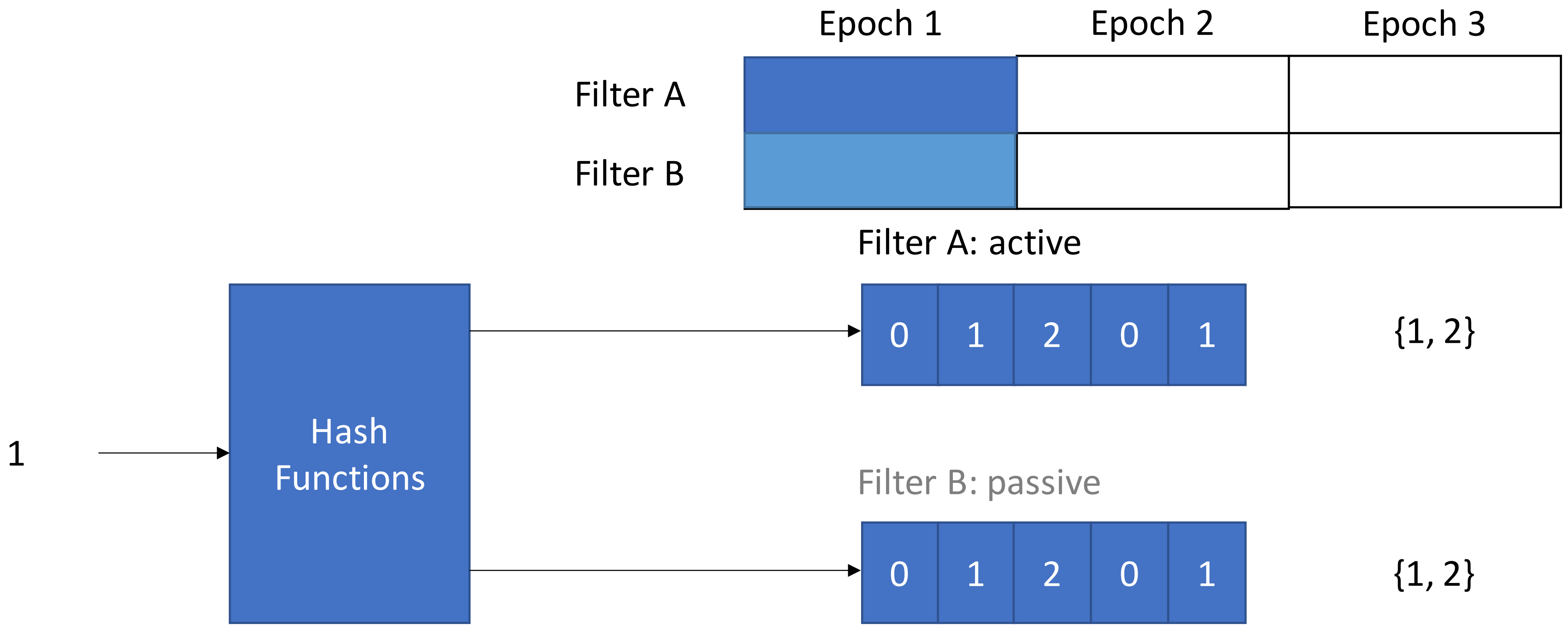
Unified Bloom filter



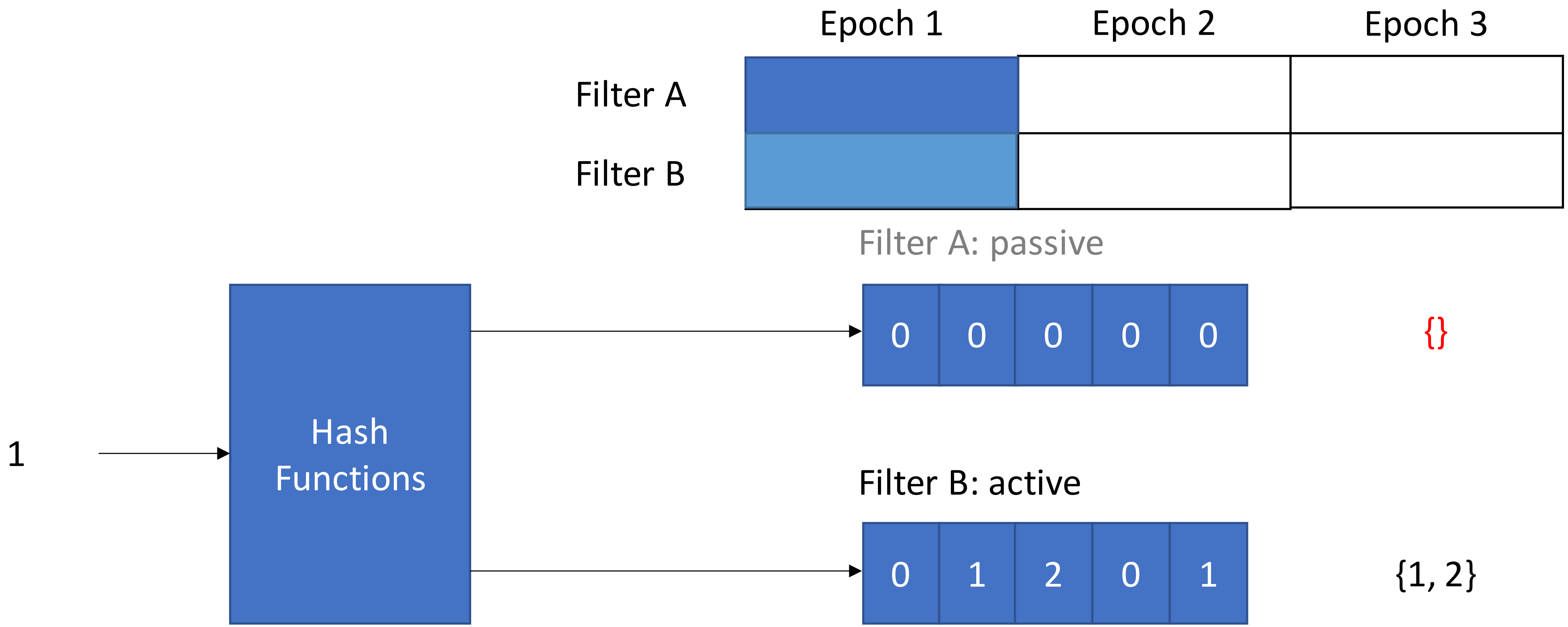
Unified Bloom filter



Unified Bloom filter



Unified Bloom filter



An unified Bloom filter gives us an upper bound of the last n accesses! How can we increase security to make the filter unpredictable?

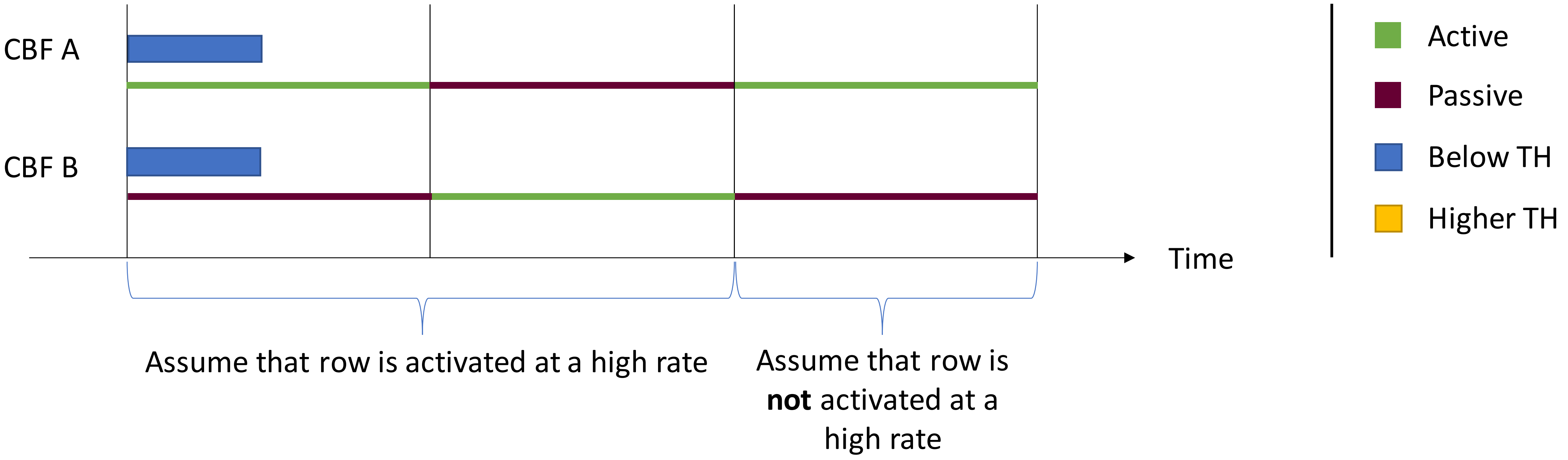
Dual counting Bloom filter

- Both filters use **different hash functions**
- Hash functions of the active filter are **altered** at the **end of each epoch**

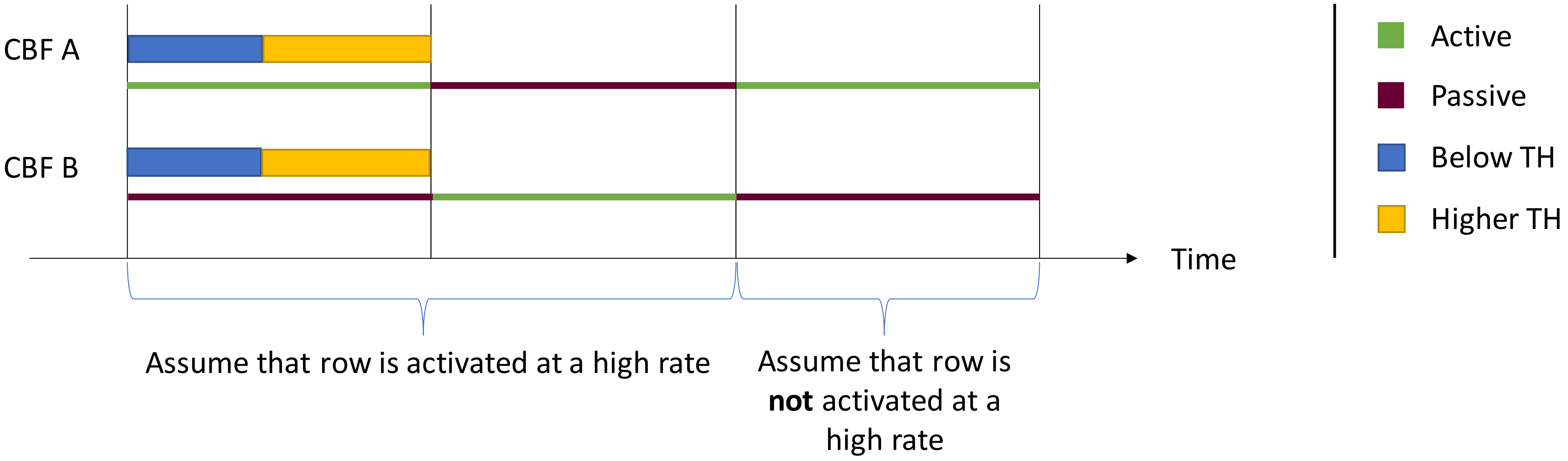
Bloom filter

- With a Bloom filter we can get **false positives**
- With a Bloom filter we cannot get **false negatives**
- A **counting Bloom filter** gives us an **upper bound** of accesses
- Additionally, by using a **unified Bloom filter**, we can track the last n insertions
- A **dual counting Bloom filter** increases security and makes the filter harder to attack

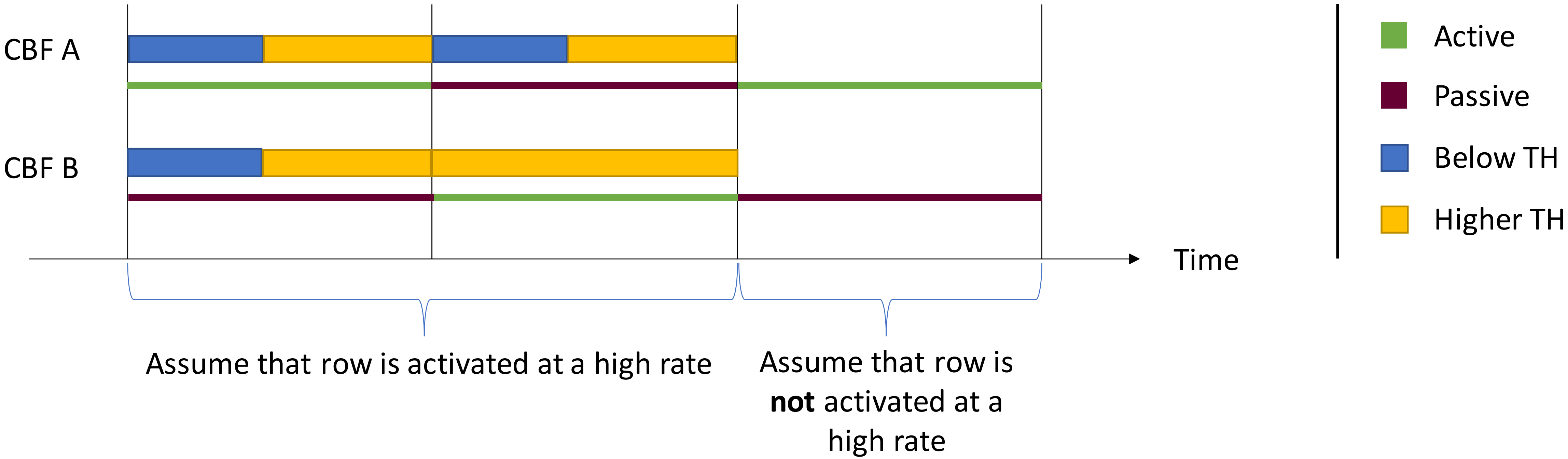
Blacklisting Logic



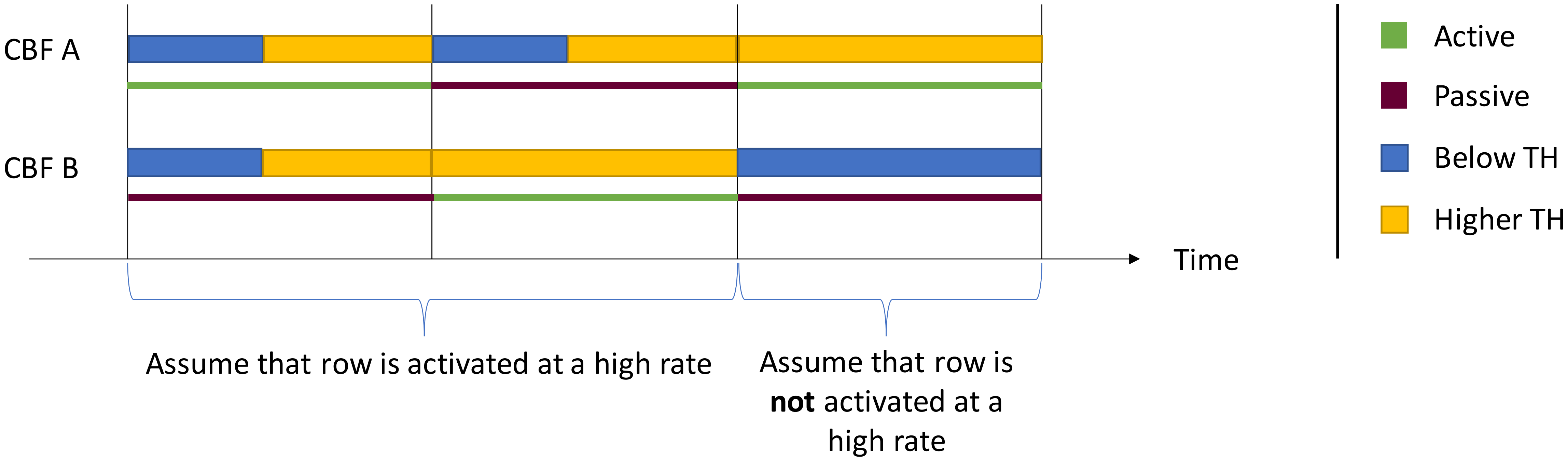
Blacklisting Logic



Blacklisting Logic

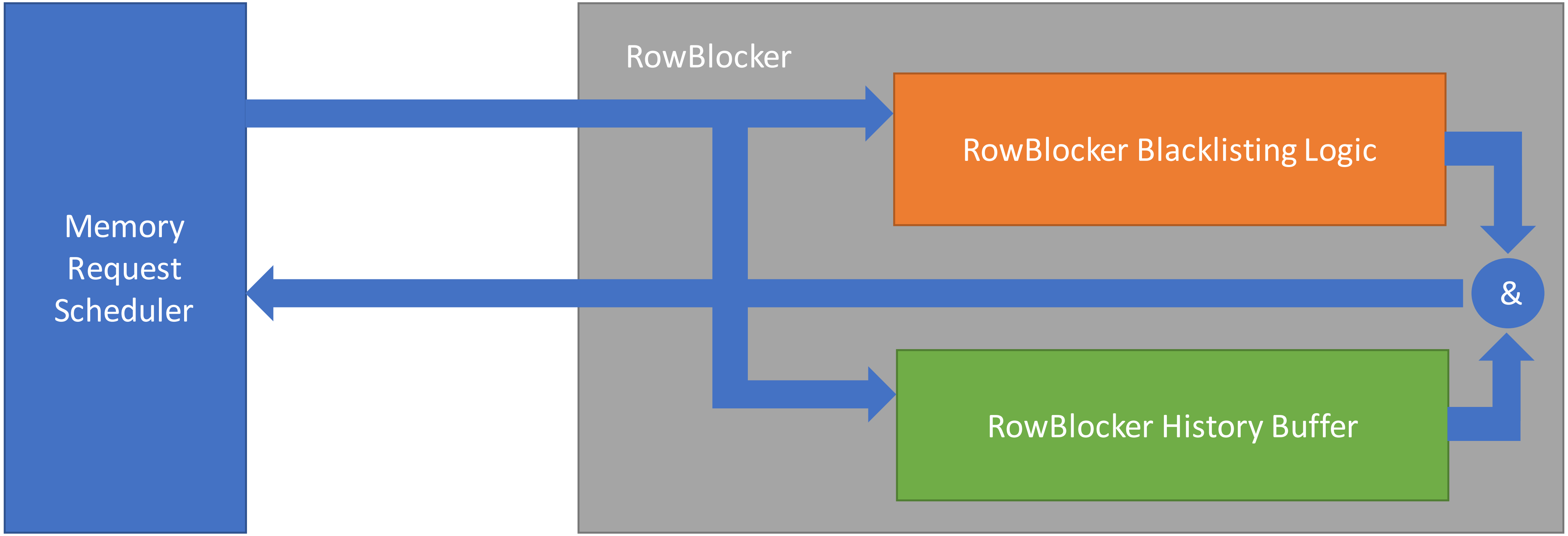


Blacklisting Logic



RowBlocker - Overview

- Throttles row activations
- Blacklists rows and delays activations of blacklisted rows



RowBlocker – History Buffer

- In order to induce a bit-flip, the aggressor row must be activated with a minimum frequency. If we keep a certain amount of time between each activation, we can guarantee RowHammer safety
- History Buffer writes most recently accesses in a (FIFO) queue
- Queue stores
  - Row ID: A rank-unique ID for all rows
  - Timestamp
  - Valid bit

Conclusion for RowBlocker

- Not possible to activate a row often enough to induce a bit-flip
- A row access is delayed when the row is blacklisted and was accessed in the last time window

AttackThrottler

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AttackThrottler

- Reduces the performance degradation and energy wastage during a RowHammer attack
- A RowHammer attack keeps activating blacklisted rows

RowHammer Likelihood Index (RHLI)

- The RHLI defines the possibility of a RowHammer attack
- A benign application has index 0
- A malicious software has index 1

⇒RHLI is larger when a thread‘s access pattern is more similar to a RowHammer attack

$$\Rightarrow \text{RHLI} = \frac{\text{\#blacklisted row activations a thread performed to a DRAM bank}}{\text{maximum \# times a blacklisted row can be activated in a protected system}}$$

AttackThrottler

- If the RHLI is large, then we limit the thread‘s bandwidth

f(x) = 1/x

Identifying attacker threads

- We use an active and a passive counter to track the accesses for every <thread, bank> pair
- Active counter is used for calculating the RHLI
- RHLI could be used by an antivirus to find malicious software

Evaluation with other techniques

- We compare the techniques in the following categories:
  - Hardware complexity analysis (scalable and low cost)
  - Efficiency in terms of performance and energy usage

Other techniques - Overview

- 3 probabilistic mechanisms
  - PARA 2014 (Yoongu Kim)
  - ProHIT 2017 (Mungyu Son)
  - MRLoc 2019 (Jung Min You)
- 3 deterministic mechanisms
  - CBT 2018 (Seyed Mohammed Seydzadeh)
  - TWiCe (Eojin Lee) 2019
  - Graphene (Yeonhong Park) 2020

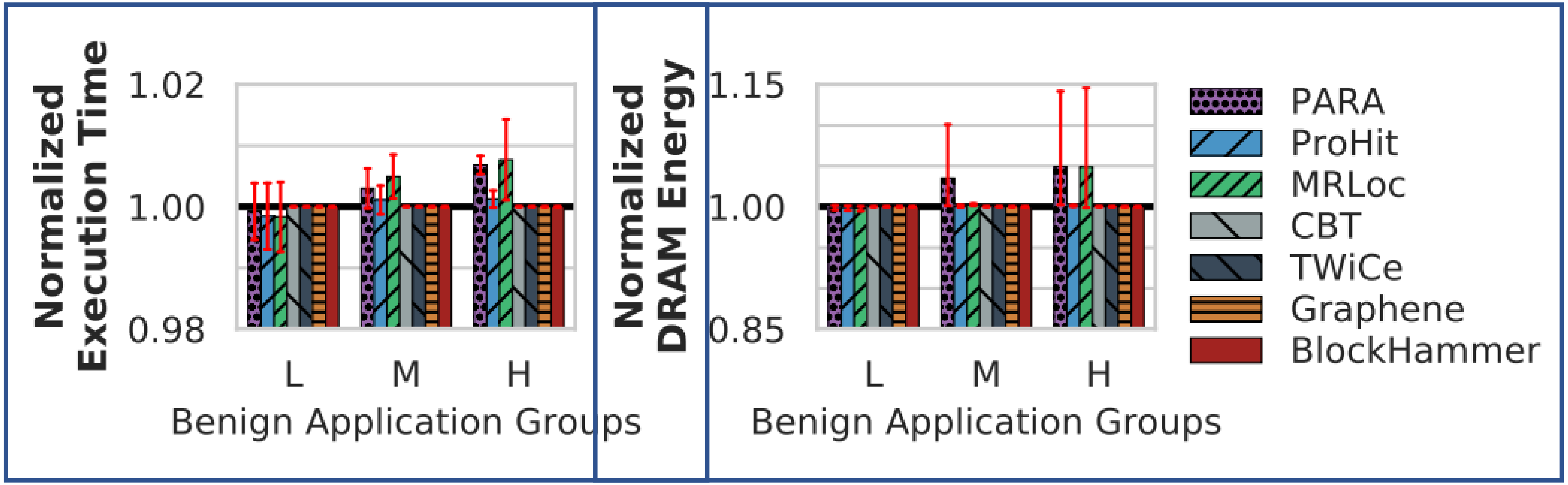
Hardware complexity

Mitigation Mechanism	N_{RH}=32K*						N_{RH}=1K					
	SRAM KB	*CAM* KB	*Area* mm^2	*Area* % CPU	Access Energy (pJ)	Static Power (mW)	*SRAM* KB	*CAM* KB	*Area* mm^2	*Area* % CPU	Access Energy (pJ)	Static Power (mW)
BlockHammer	**51.48**	**1.73**	**0.14**	**0.06**	**20.30**	**22.27**	**441.33**	**55.58**	**1.57**	**0.64**	**99.64**	**220.99**
Dual counting Bloom filters	48.00	-	0.11	0.04	18.11	19.81	384.00	-	0.74	0.30	86.29	158.46
H3 hash functions	-	-	< 0.01	< 0.01	-	-	-	-	< 0.01	< 0.01	-	-
Row activation history buffer	1.73	1.73	0.03	0.01	1.83	2.05	55.58	55.58	0.83	0.34	12.99	62.12
AttackThrottler counters	1.75	-	< 0.01	< 0.01	0.36	0.41	1.75	-	< 0.01	< 0.01	0.36	0.41
PARA [73]	**-**	**-**	**< 0.01**	**-**	**-**	**-**	**-**	**-**	**< 0.01**	**-**	**-**	**-**
ProHIT [137]*	**-**	**0.22**	**< 0.01**	**<0.01**	**3.67**	**0.14**	×	×	×	×	×	×
MrLoc [161]*	**-**	**0.47**	**< 0.01**	**<0.01**	**4.44**	**0.21**	×	×	×	×	×	×
CBT [132]	**16.00**	**8.50**	**0.20**	**0.08**	**9.13**	**35.55**	**512.00**	**272.00**	**3.95**	**1.60**	**127.93**	**535.50**
TWiCE [84]	**23.10**	**14.02**	**0.15**	**0.06**	**7.99**	**21.28**	**738.32**	**448.27**	**5.17**	**2.10**	**124.79**	**631.98**
Graphene [113]	**-**	**5.22**	**0.04**	**0.02**	**40.67**	**3.11**	**-**	**166.03**	**1.14**	**0.46**	**917.55**	**93.96**

* PRoHIT [137] and MRLoc [161] do *not* provide a concrete discussion on how to adjust their empirically-determined parameters for different N_{RH} values. Therefore, we (1) report their values for a fixed design point that each paper provides for N_{RH}=2K and (2) mark values we cannot estimate using an ×.

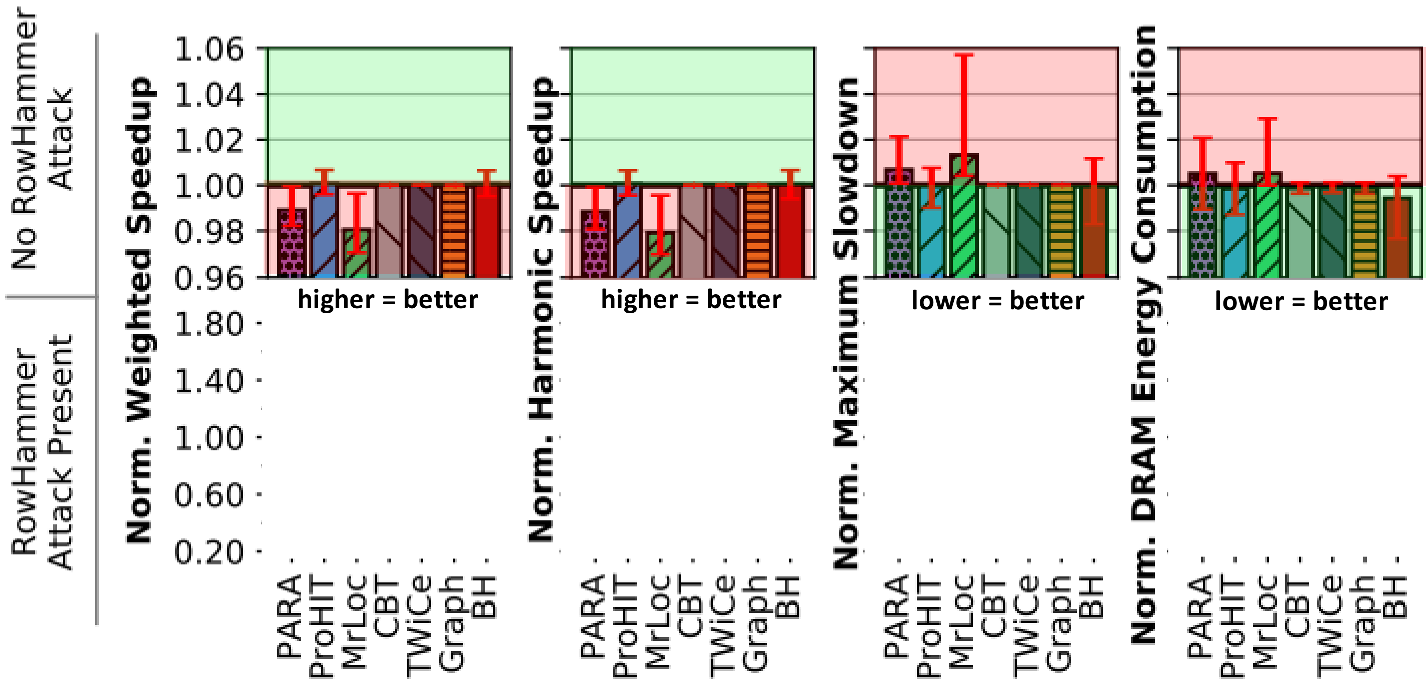
- PARA, PRoHIT, MRLoc -> probabilistic methods and are therefore very area-efficient
- If we reduce the threshold, then BlockHammer scales better than the other techniques

Evaluation – Single-Core



Deterministic approaches do not have a high overhead because benign applications do not reach the threshold!

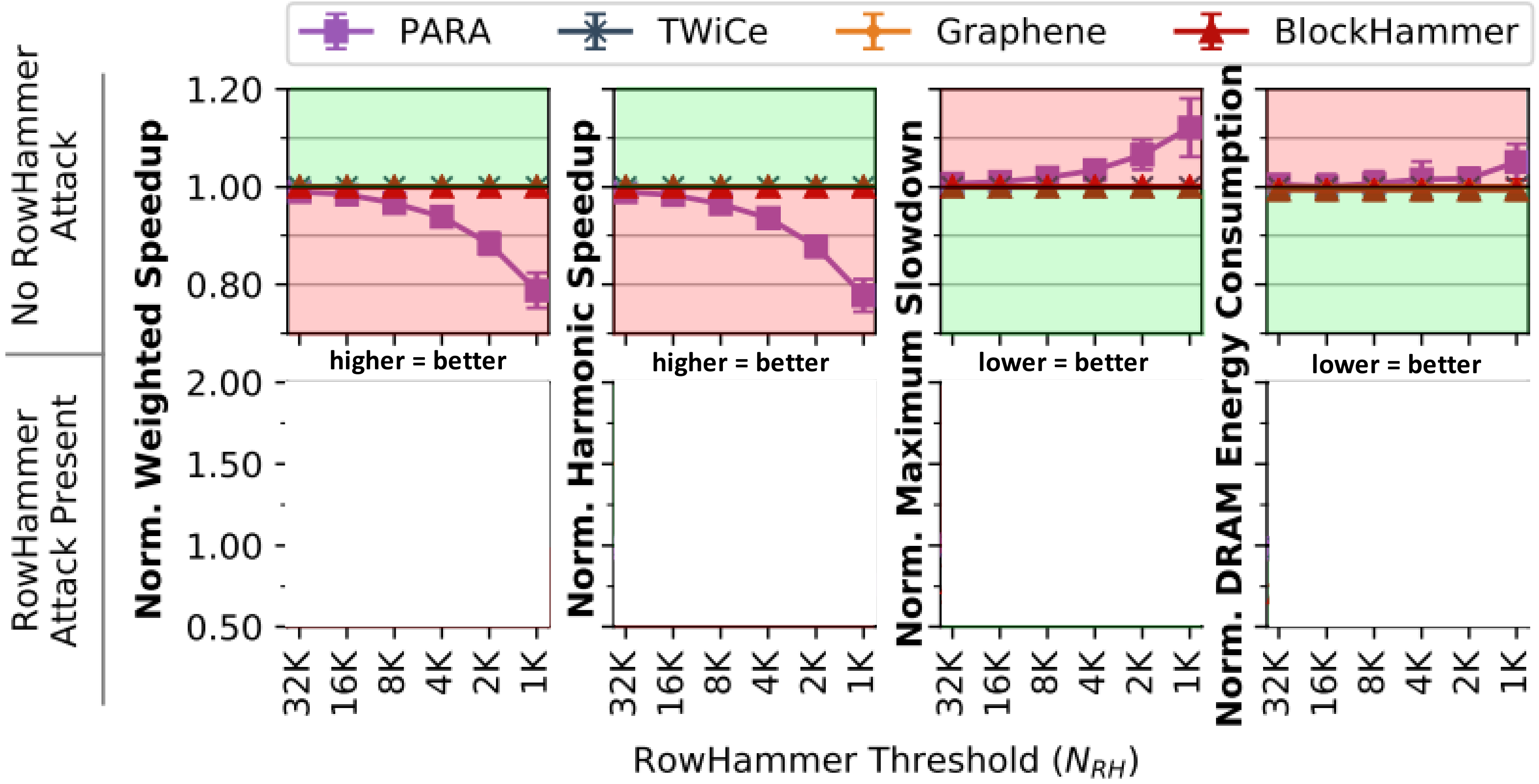
Evaluation – Multi-Core



BlockHammer has competitive performance and energy usage when no attack is present

Under an attack, BlockHammer has much higher performance and much lower DRAM energy consumption!

Evaluation – Energy consumption



BlockHammer has negligible performance and energy overheads, even if chips become more vulnerable to RowHammer!

BlockHammer has significantly better performance and lower energy consumption as RH worsens

Conclusion

- Most mechanisms to prevent RowHammer bit-flips **do not work perfectly** and do **not scale** accordingly
- Many solutions often require **knowledge** of or modification to DRAM **internals**
- Finds a scalable and efficient mechanism that works without any knowledge of or modification to DRAM internals
- BlockHammer consists of two parts
  - **RowBlocker**: Tracks all row activations and limits potentially unsafe accesses
  - **AttackThrottler**: Calculates RHLI and limits potential attacker's bandwidth
- When there is no attack, then **BlockHammer** is competitive with other mechanisms
- If there it an attack, then BlockHammer **outperforms** the other mechanisms

Strengths

- BlockHammer has high **potential** in the future, as it **scales well** with upcoming DRAM chips
- Keeps high **efficiency** when running benign and attacking threads
- BlockHammer is **compatible** with all DRAM chips
- Creates an interface for other applications
  - I.e., gives an antivirus access to the RHLI

Weaknesses

- Is implemented in memory controller -> Cannot be implemented in **already manufactured** chips
- Potentially opens a door for other attacks. An attacker could use the **false positive rate** to decrease performance
- What is the impact on virtual machines? AttackThrottler would start limiting bandwidth
  - => Open door for potential denial of service attacks

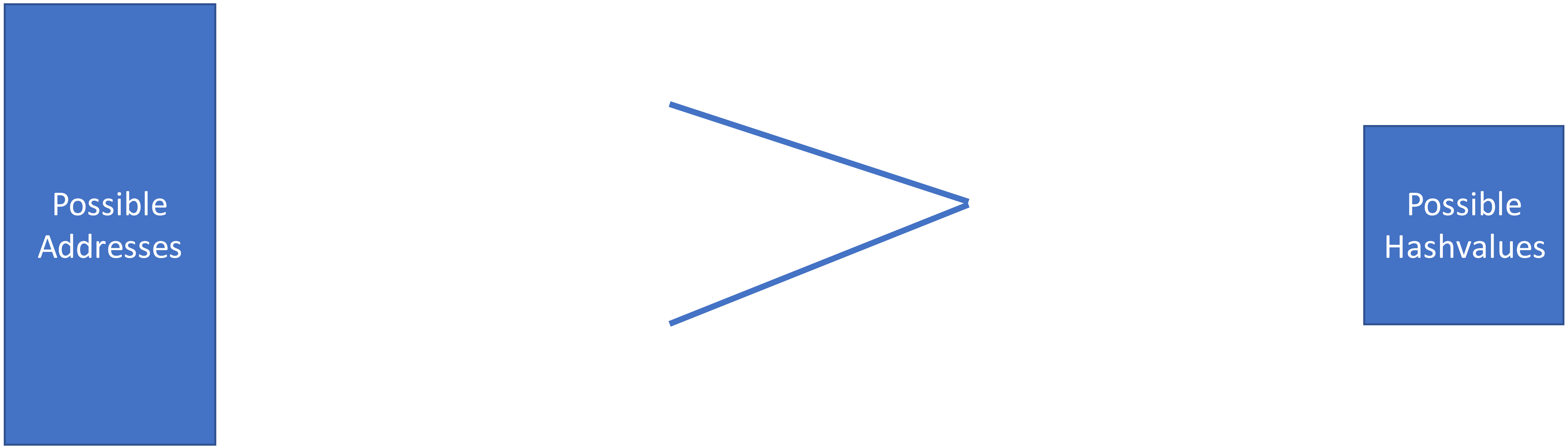
Discussion

Discussion

- Do you see any potential attacks that can be made possible by using BlockHammer? Do you see any solution to prevent the presented attacks?

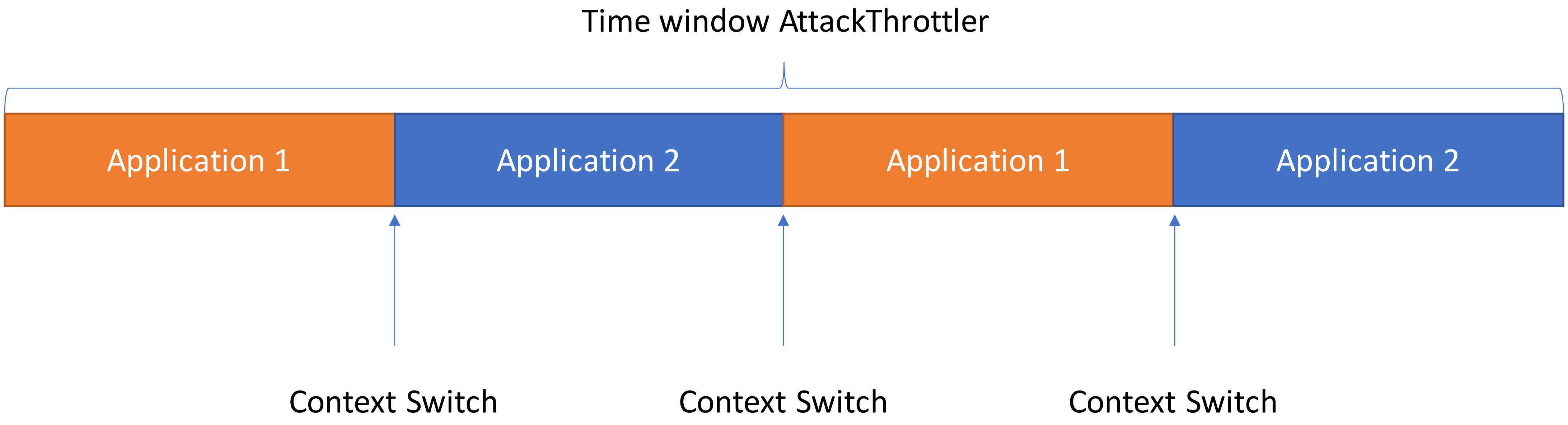
Discussion – Possible Attack

- Blacklist specific rows



Discussion – Possible Attack

- We attack a system using AttackThrottler



Application 1 is hammering a row
Application 2 is a benign application

Discussion

- Do you see any potential attacks that can be made possible by using BlockHammer? Do you see any solution to prevent these attacks?

Discussion

- We have seen many potential solutions against RowHammer. Do you have an idea how we can improve BlockHammer even further?
- Should we find a solution in software? What are the main differences between a solution in software versus hardware?
- Should we implement BlockHammer in DRAM?

Discussion

- We could give the operating system access to the RHLI
- What can we do with this value?
  - For example: Improve database for antivirus
  - Optimize caching

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