Microarchitectural Attacks and Defenses in JavaScript

Michael Schwarz, Daniel Gruss, Moritz Lipp

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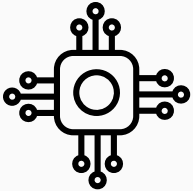
www.iaik.tugraz.at

Microarchitecture



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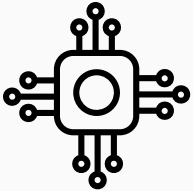

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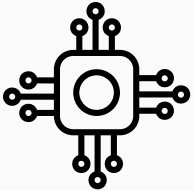

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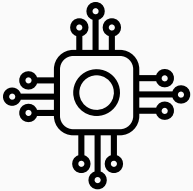

Microarchitecture...

- is not defined on the architectural state
- should not be visible to software
- is hardware specific and not fully documented
- changes to some extend with new processor generations

Microarchitectural Attacks

Microarchitectural states can be used for attacks

- Cache state $\Rightarrow$ data access

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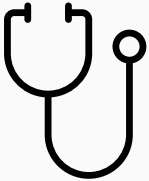
- Branch predictors ⇒ program flow
- Timings ⇒ data values

Side-Channel Attacks



Side-channel attacks exploit side effects of operations

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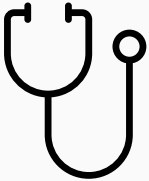

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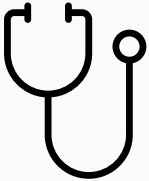

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- Sensors $\Rightarrow$ user activity
- Timings $\Rightarrow$ data values, activity

One Important Component

- A core component of many such attacks: Timers

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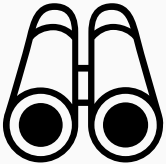
- A core component of many such attacks: Timers
- Side-channel attacks often require high-resolution timers
- Differences to measure are often in the range of nanoseconds or microseconds
- Microarchitectural attacks usually require highest precision

Attacks in JavaScript

First Side-Channel Attack



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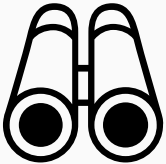

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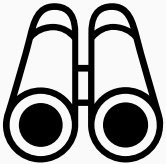

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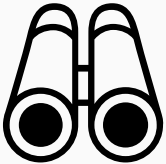

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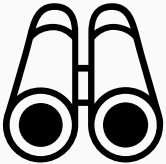
- Stone et al. (2013): Pixel perfect timing attacks with HTML5
- Timing of various redraw events (e.g., visited state of links)
- SVG filter timing to extract individual pixels (already 2011)
- High-resolution timer was available in browser

First Microarchitectural Attack



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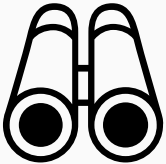

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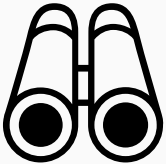

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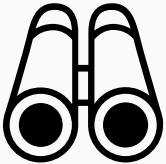

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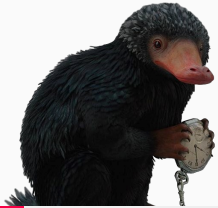
- Oren et al. (2015): The Spy in the Sandbox
- Timing of memory accesses
- Allows to determine whether data is cached or uncached
- Possibility to infer info about other programs from browser

FANTASTIC TIMERS AND WHERE TO FIND THEM

HIGH-RESOLUTION MICROARCHITECTURAL ATTACKS IN JAVASCRIPT



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performance.now()

[...] represent times as floating-point numbers with up to microsecond precision.

— Mozilla Developer Network

...up to microsecond precision?

Firefox ≤ 36	$1 \cdot 10^{-3}$

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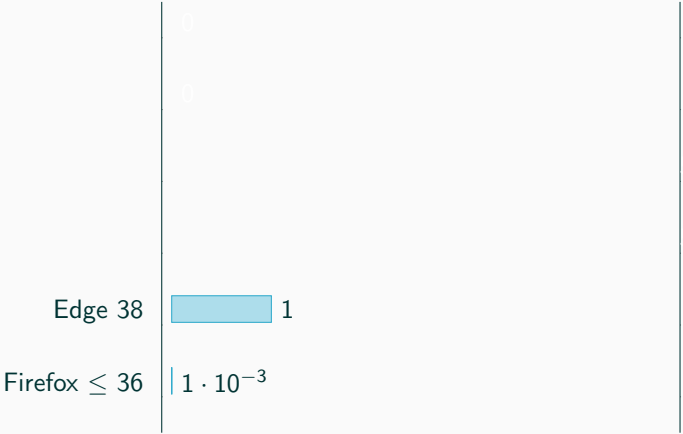

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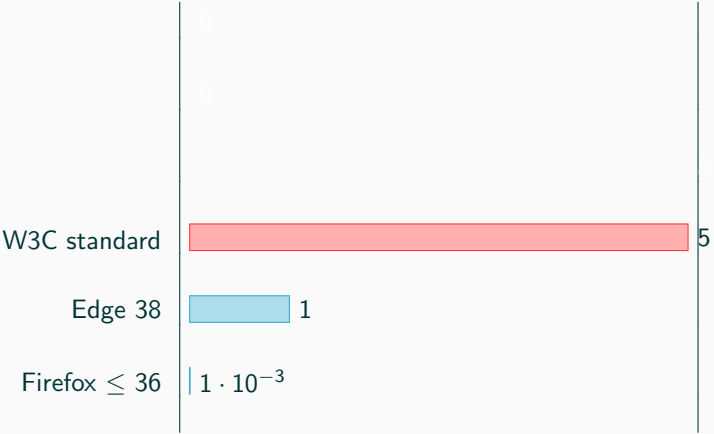

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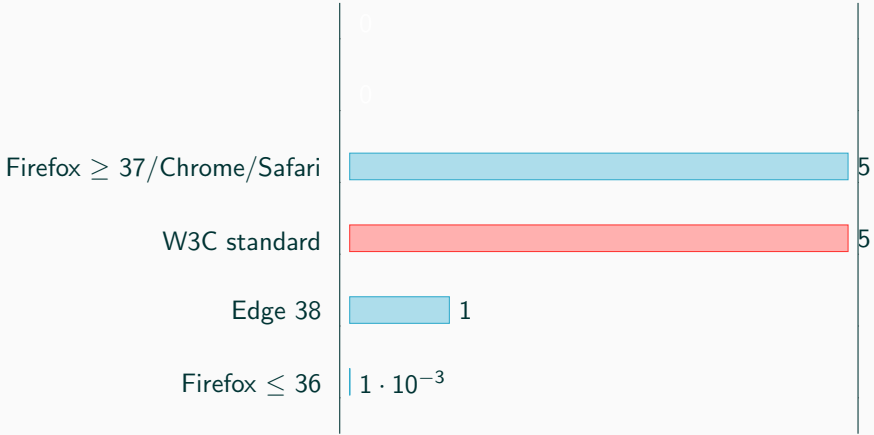

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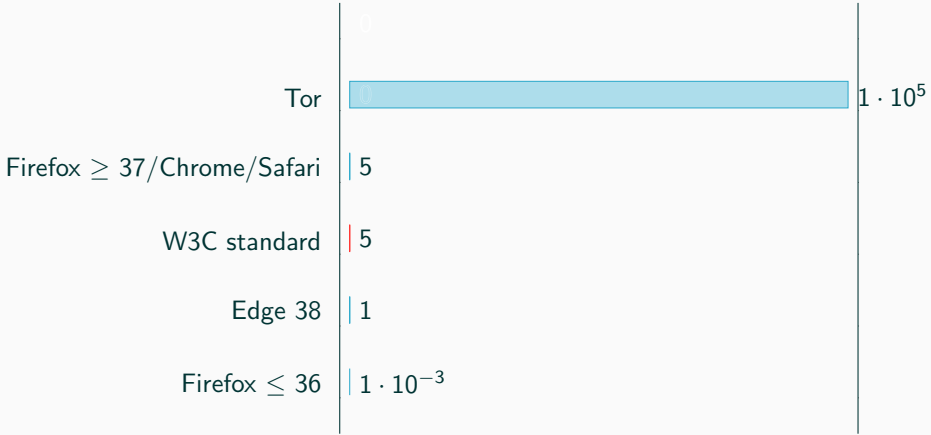

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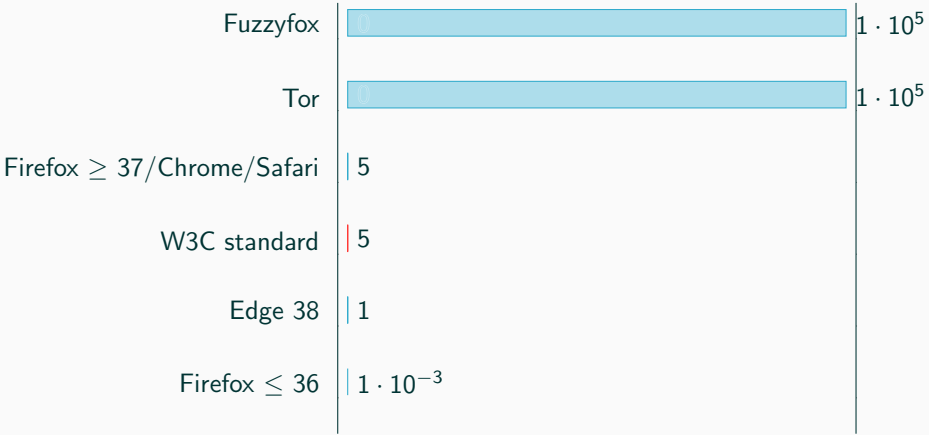

New timer

We require a higher resolution

- Current precision is not sufficient to measure cycle differences

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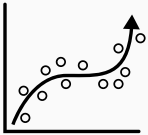
- Build our own high-resolution timer

Recovering resolution - Clock interpolation



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- Measure how often we can increment a variable between two timer ticks
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- To measure with high resolution:
  - Start measurement at clock edge
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- Highly accurate: 500 ns (Firefox/Chrome), 15 µs (Tor)

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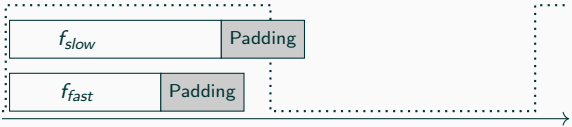

- Edge thresholding: apply padding such that the slow function crosses one more clock edge than the fast function.

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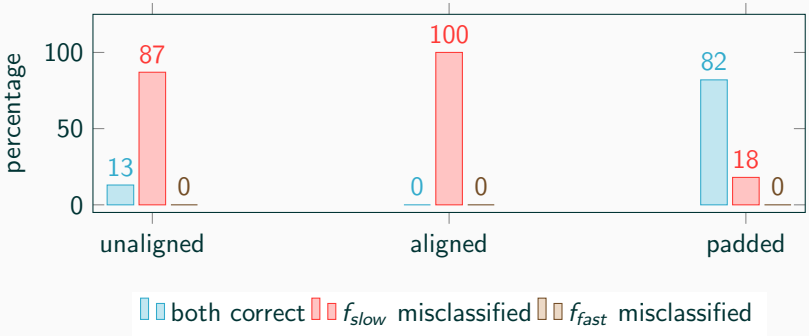

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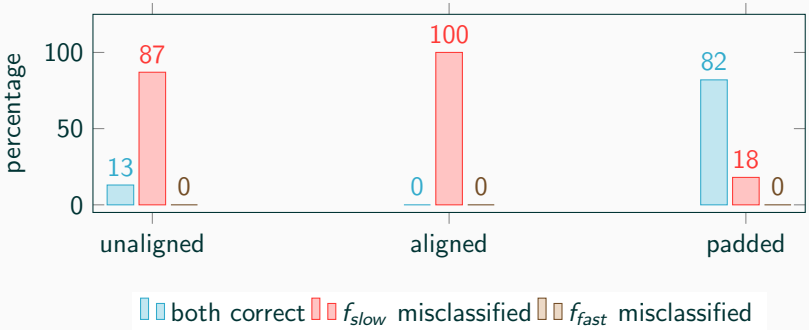

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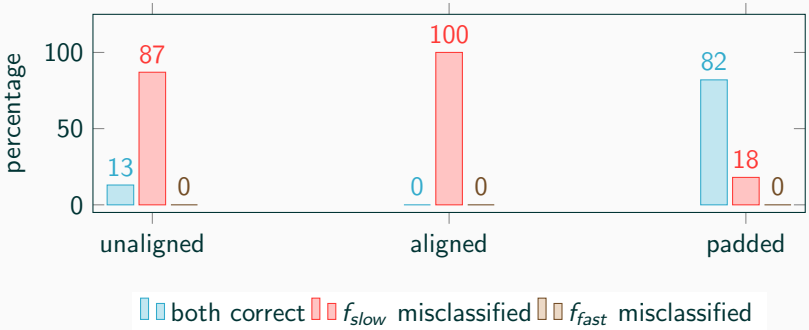
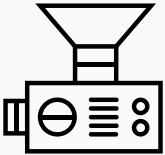


- Yields nanosecond resolution
- Firefox/Tor (2 ns), Edge (10 ns), Chrome (15 ns)

Building a timer



- Goal: counter that does not block main thread

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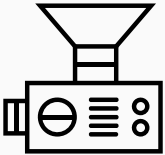

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- Baseline setTimeout: 4 ms (except Edge: 2 ms)

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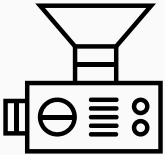

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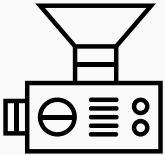

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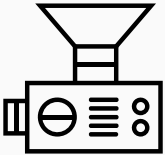

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- CSS animation: increase width of element as fast as possible
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- However, animation is limited to 60 fps $\rightarrow$ 16 ms

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- JavaScript can spawn new threads called web worker
- Web worker communicate using message passing
- Let worker count and request timestamp in main thread
- Multiple possibilities: `postMessage`, `MessageChannel` or `BroadcastChannel`
- Yields microsecond resolution (even on Tor and Fuzzyfox)

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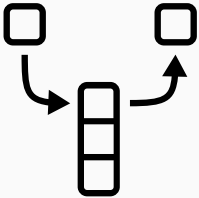

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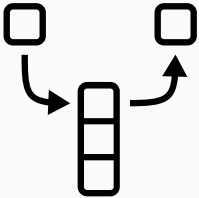

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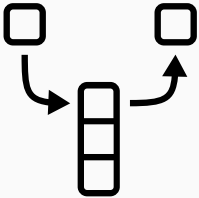

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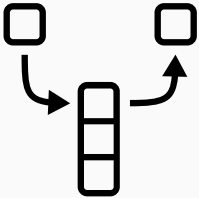

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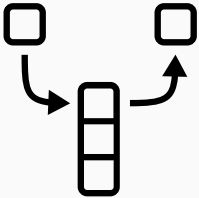

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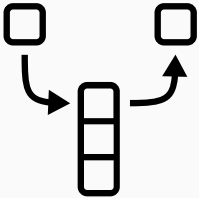

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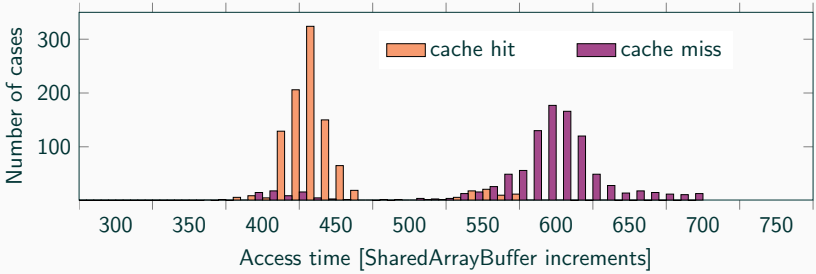
- Firefox/Fuzzyfox: 2 ns, Chrome: 15 ns
- Sufficient for microarchitectural attacks

Timer evaluation



Attack Requirements

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- Timers can (always) be built
- Some attacks do not require timers at all
- Important to understand requirements before designing countermeasures

JavaScript zero

REAL JavaScript AND ZERO SIDE-CHANNEL ATTACKS

Identify requirements

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  - Memory addresses
  - Accurate timing
  - Multithreading
  - Shared data
  - Sensor API

Identify requirements

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- Analyse requirements for every attack
- Results in 5 categories
  - Memory addresses
  - Accurate timing
  - Multithreading
  - Shared data
  - Sensor API
- Every attack is in at least one category

Attacks and Categories

	Memory addresses	Accurate timing	Multithreading	Shared data	Sensor API
Rowhammer.js	●	●	○	○	○
Practical Memory Deduplication Attacks in Sandboxed Javascript	◐	●	○	○	○
Fantastic Timers and Where to Find Them	●	●†	◐	◐	○
ASLR on the Line	●	●†	◐	◐	○
The spy in the sandbox	◐	●	○	○	○
Loophole	○	◐	●	○	○
Pixel perfect timing attacks with HTML5	○	●†	◐	◐	○
The clock is still ticking	○	●	◐	○	○
Practical Keystroke Timing Attacks in Sandboxed JavaScript	○	◐†	●	◐	○
TouchSignatures	○	○	○	○	●
Stealing sensitive browser data with the W3C Ambient Light Sensor API	○	○	○	○	●

† If accurate timing is not available, it can be approximated using a combination of multithreading and shared data.

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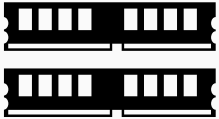

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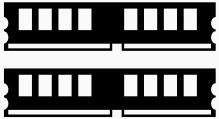

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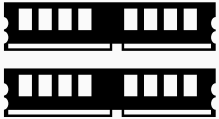

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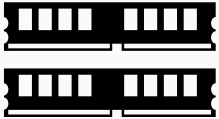

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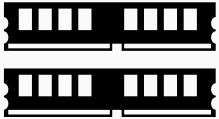

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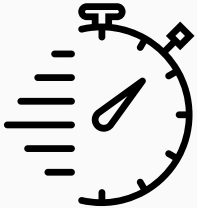
- If not page aligned: detect page faults through timing

Accurate Timing



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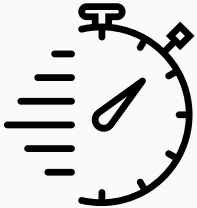

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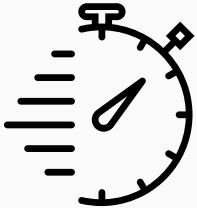

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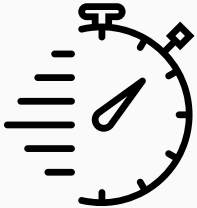

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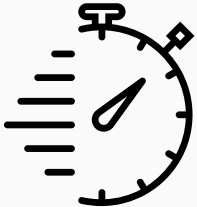

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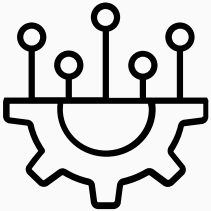
- If attack is repeatable, less accurate timing can be sufficient

Multithreading



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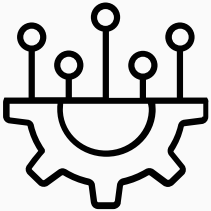

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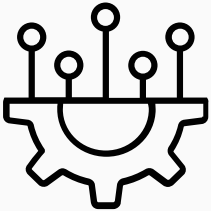

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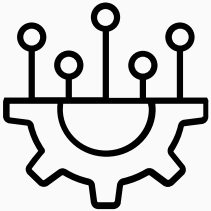

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Defenses

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- Implementation is on the "microarchitectural" level of JavaScript
- If no category is usable for attacks anymore, future attacks are hard

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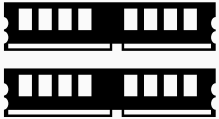

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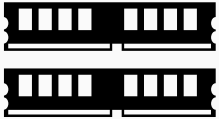

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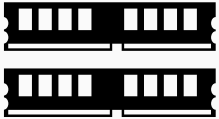

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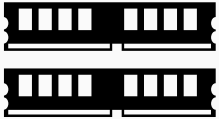

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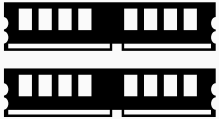

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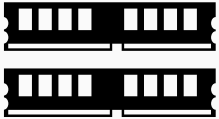

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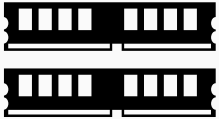

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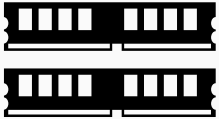

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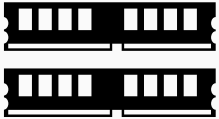

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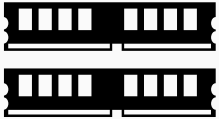

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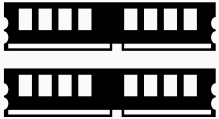

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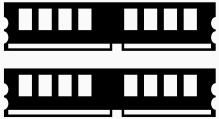

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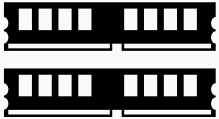

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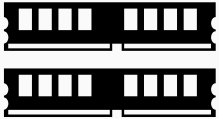

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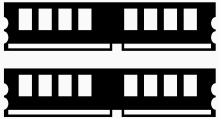

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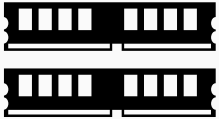

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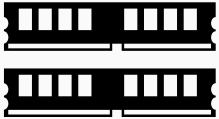

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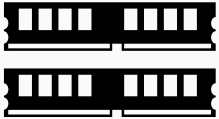

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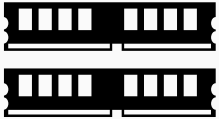

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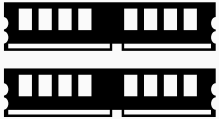

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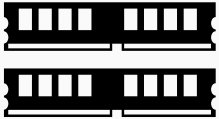

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- Side effect: make exploits harder where addresses are required

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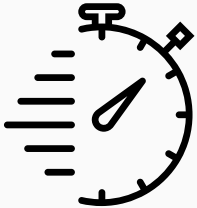

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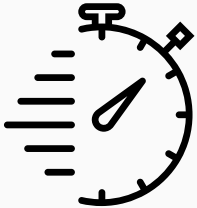

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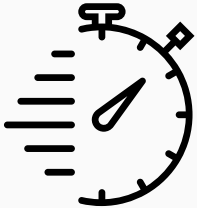

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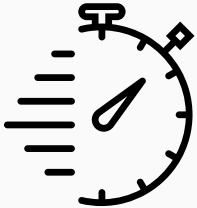

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- Timestamps are still monotonic, but clock edges are randomized

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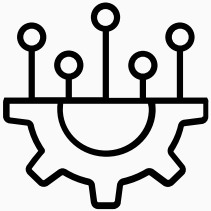

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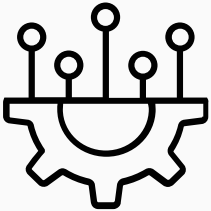

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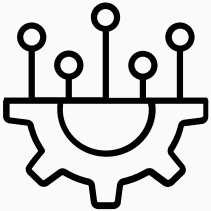

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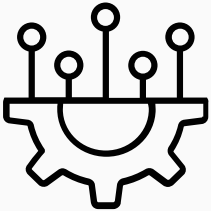

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- Prevents certain timing primitives and attacks on the event-queue latency

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Sensor API

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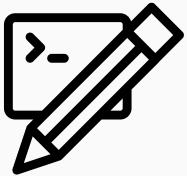
- To not break existing applications, sensors return constant value

Implementation

Designing the Countermeasure



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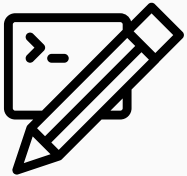
Designing the Countermeasure



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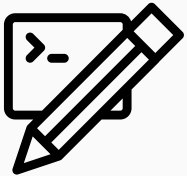

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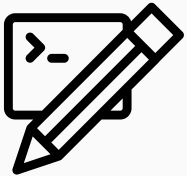

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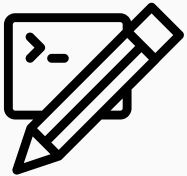

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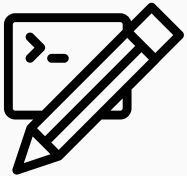

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- Proof-of-concept is implemented as browser extension

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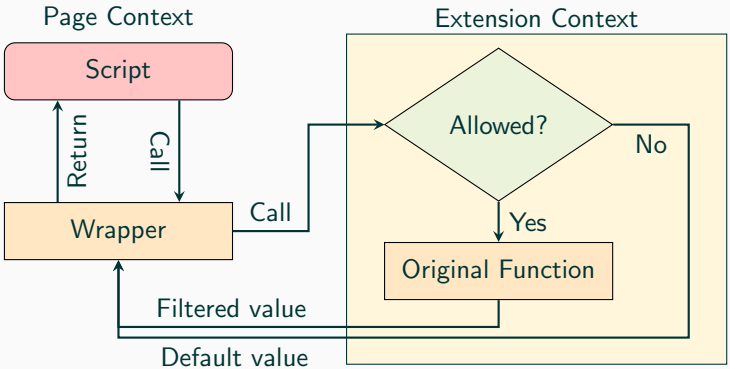
Virtual Machine Layering

- Functions and properties are replaced by wrappers



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- Properties can be replaced by accessor properties

Virtual Machine Layering for Objects

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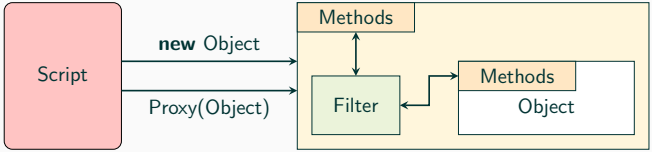

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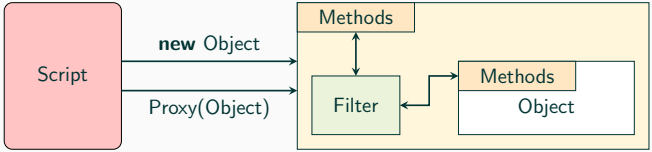

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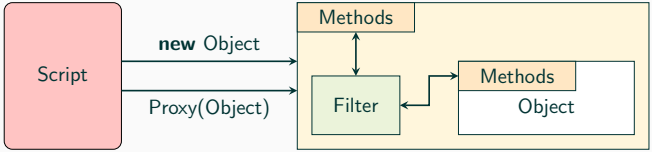

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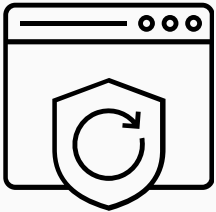
Self Protection

- Attacker tries to circumvent JavaScript Zero



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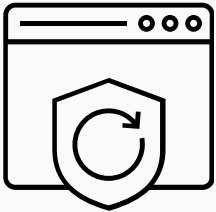

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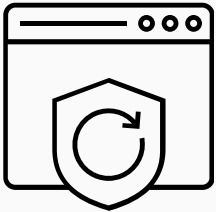

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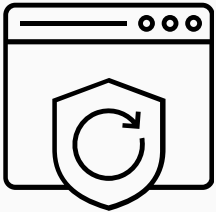

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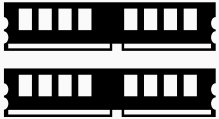
- Prevent objects from being modified: `Object.freeze`

Evaluation

Page Border Detection



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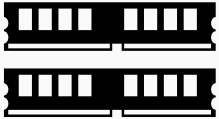

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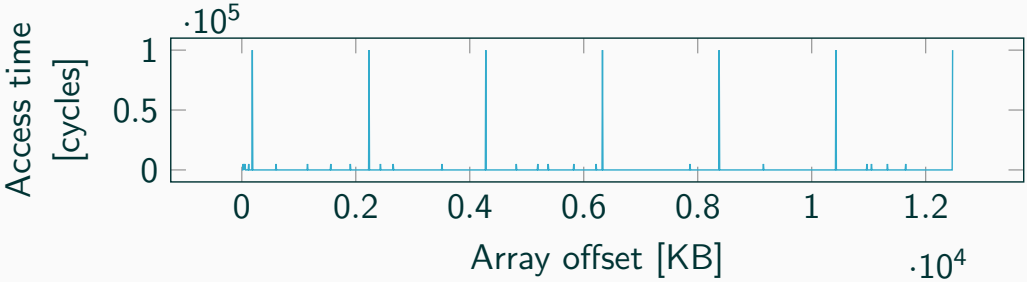
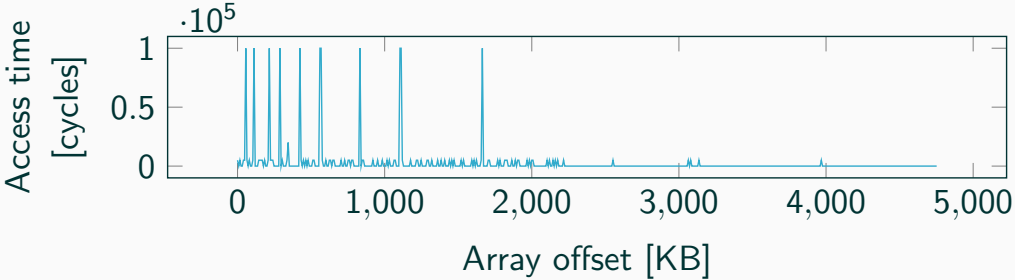
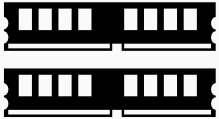


Page Border Detection with Random Access



Prime+Probe

- Find addresses (= array indices) that fall into same cache set



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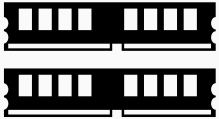

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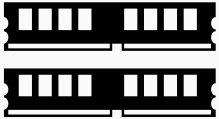

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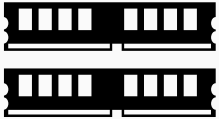

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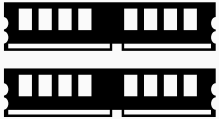

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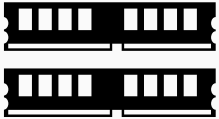

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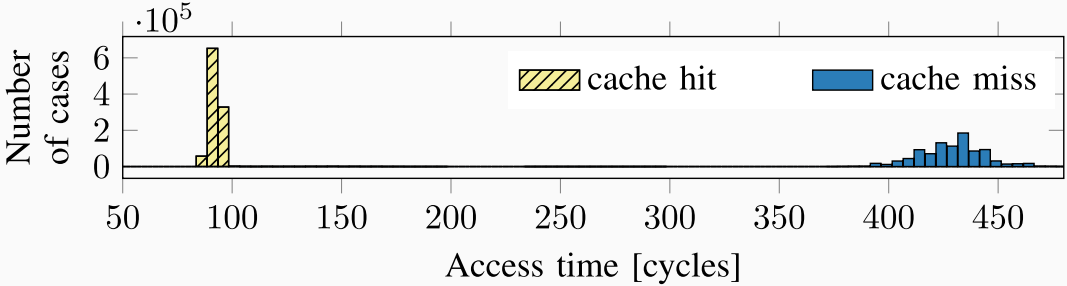
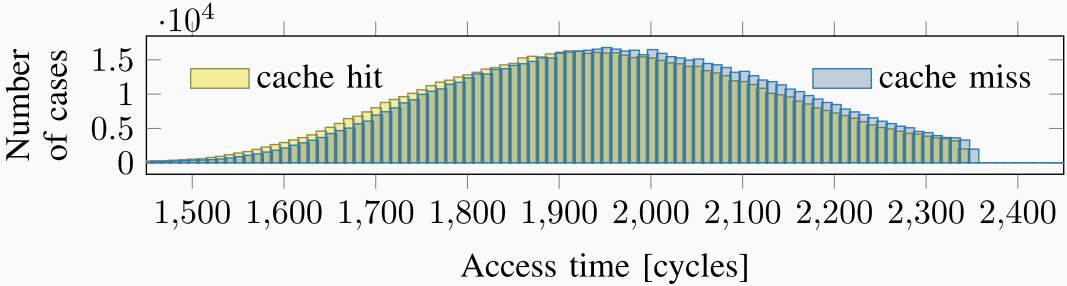
- If it is slow, someone used this cache set and evicted our addresses

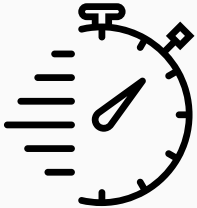
Prime+Probe


$\cdot 10^5$
Number of cases
6
4
2
0
cache hit
cache miss
50
100
150
200
250
300
350
400
450
Access time [cycles]

Prime+Probe with Random Access



Interrupt Detection



- Multithreading allows to detect interrupts

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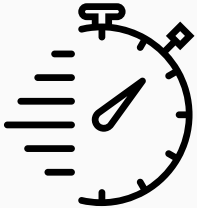

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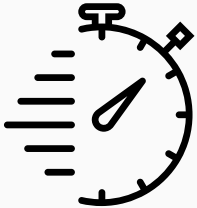

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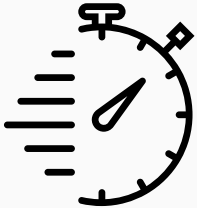

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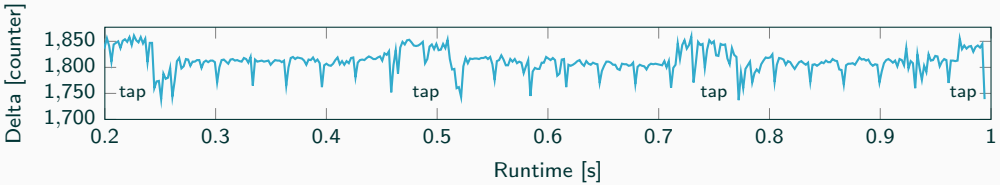
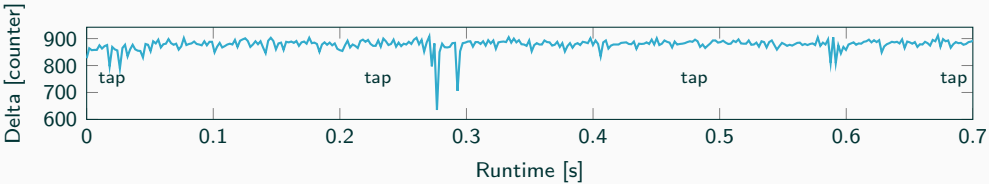
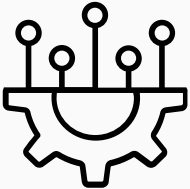


Interrupt Detection with Fuzzy Time



Event Queue Spying



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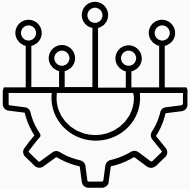

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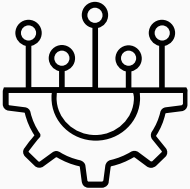

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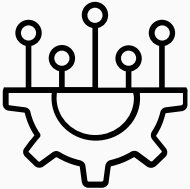

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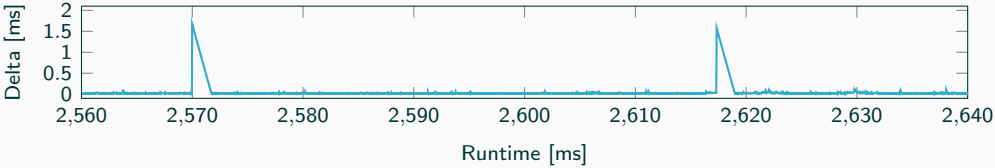
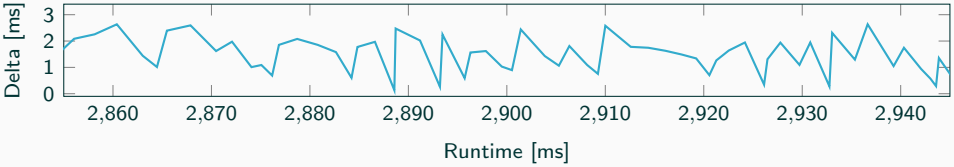


Event Queue Spying with Message Delay



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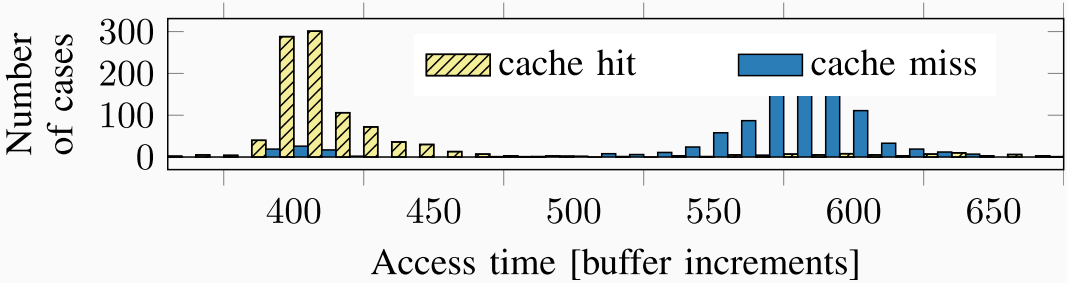
- Adding random delay to access degrades resolution

SharedArrayBuffer



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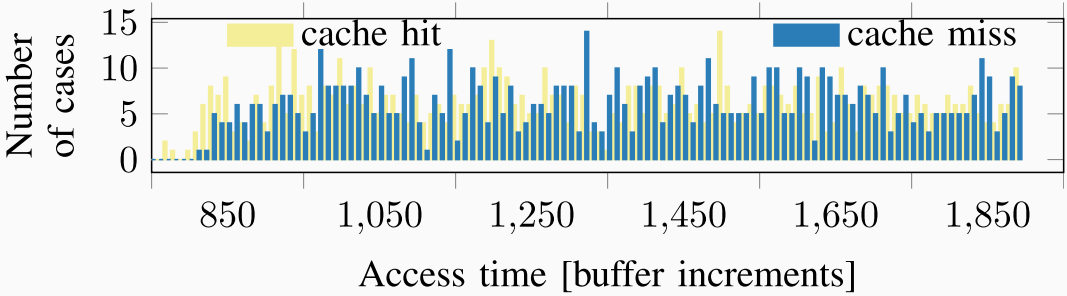
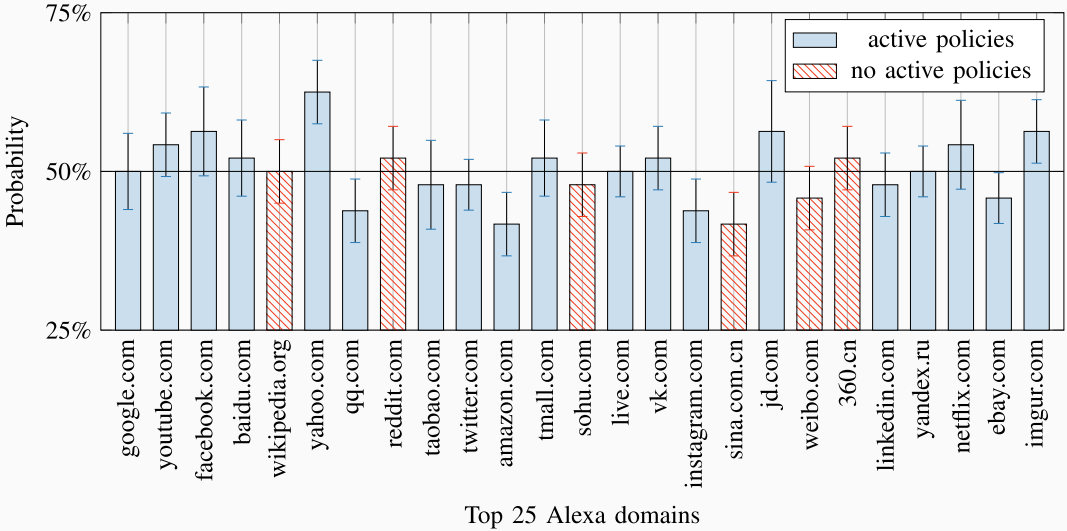


Defense \ Prevents	Rowhammer.js	Page Deduplication	DRAM Covert Channel	Anti-ASLR	Cache Eviction	Keystroke Timing	Browser
Buffer ASLR	○	◐	○	●	●	○	○
Array preloading	●	○	●	○	○	○	○
Non-deterministic array	●	◐	◐	●	●	○	○
Array index randomization	○	●	○	●	○	○	○
Low-resolution timestamp	○	◐	○	○	○	◐	◐
Fuzzy time	○	◐*	○	○*	○	●*	●*
`WebWorker` polyfill	○	○	●	●	●	●	○
Message delay	○	○	○	○	○	◐	◐
Slow `SharedArrayBuffer`	○	○	●	◐	●	○	○
No `SharedArrayBuffer`	○	○*	●	●*	●	○*	○*
Summary	●	●	●	●	●	●	●

Symbols indicate whether a policy fully prevents an attack, (●), partly prevents and attack by making it more difficult (◐), or does not prevent an attack (○).
A star (*) indicates that all policies marked with a star must be combined to prevent an attack.

User Experience



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