Microarchitectural Attacks and Defenses in JavaScript

Michael Schwarz, Daniel Gruss, Moritz Lipp

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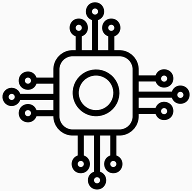
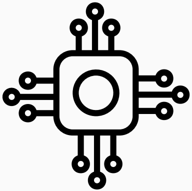
www.iaik.tugraz.at



Microarchitecture...

- is not defined on the architectural state

Microarchitecture



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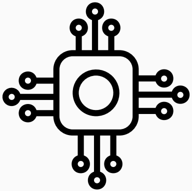

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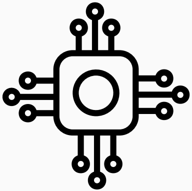
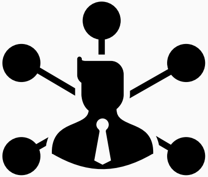


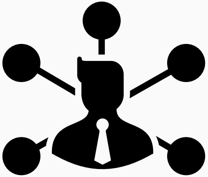
Microarchitecture...

- 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 states can be used for attacks

- Cache state $\Rightarrow$ data access



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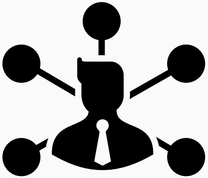
- DRAM buffers ⇒ data access

Microarchitectural Attacks



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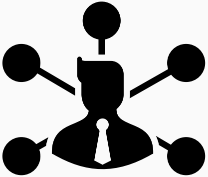
Microarchitectural Attacks



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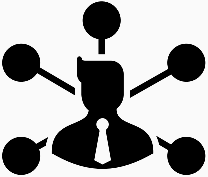
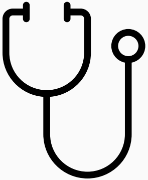


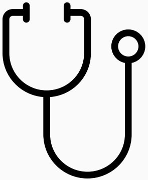
Microarchitectural states can be used for attacks

- Cache state ⇒ data access
- DRAM buffers ⇒ data access
- Interrupts ⇒ keystrokes
- Branch predictors ⇒ program flow
- Timings ⇒ data values



Side-channel attacks exploit side effects of operations

- Microarchitectural attacks are usually side-channel attacks



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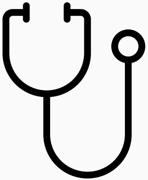
- Sensors ⇒ user activity



Side-channel attacks exploit side effects of operations

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

- A core component of many such attacks: Timers

One Important Component

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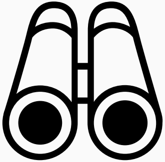
- A core component of many such attacks: Timers
- Side-channel attacks often require high-resolution timers
- Differences to measure are often in the range of nanoseconds or microseconds
- Microarchitectural attacks usually require highest precision

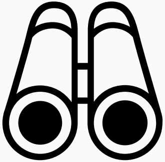
Attacks in JavaScript

First Side-Channel Attack



First side-channel attack in JavaScript

- Stone et al. (2013): Pixel perfect timing attacks with HTML5



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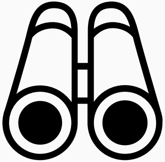

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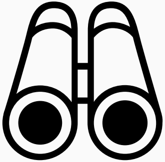
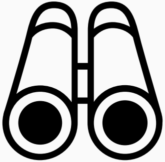


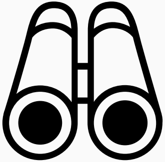
First side-channel attack in JavaScript

- 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 in JavaScript

- Oren et al. (2015): The Spy in the Sandbox



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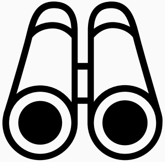

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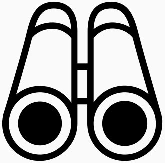
- Allows to determine whether data is cached or uncached



First microarchitectural attack in JavaScript

- 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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Timers in JavaScript

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- JavaScript: `performance.now()` has the highest resolution

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performance.now()

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

— Mozilla Developer Network

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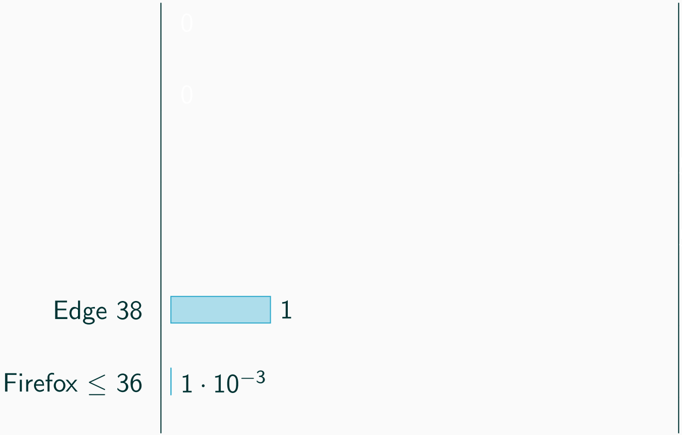
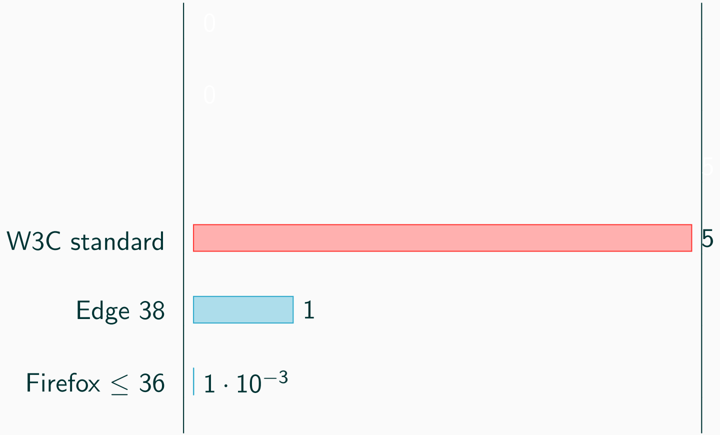
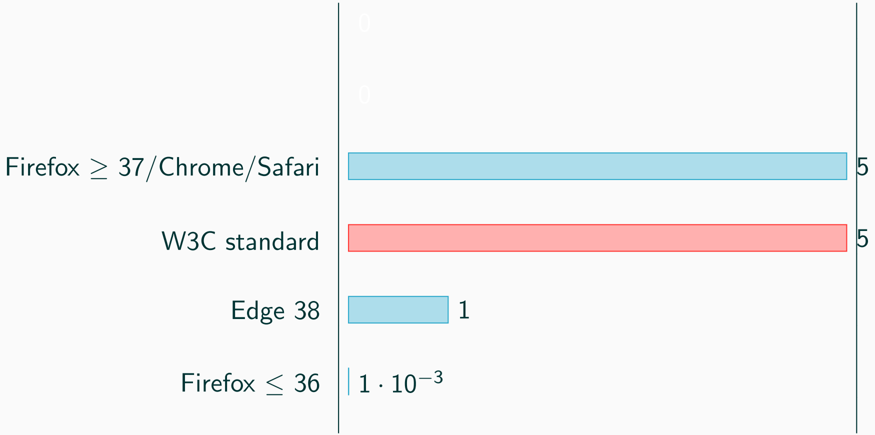



W3C standard
5
Edge 38
1
Firefox ≤ 36
$1 \cdot 10^{-3}$


Firefox ≥ 37/Chrome/Safari
5
W3C standard
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Edge 38
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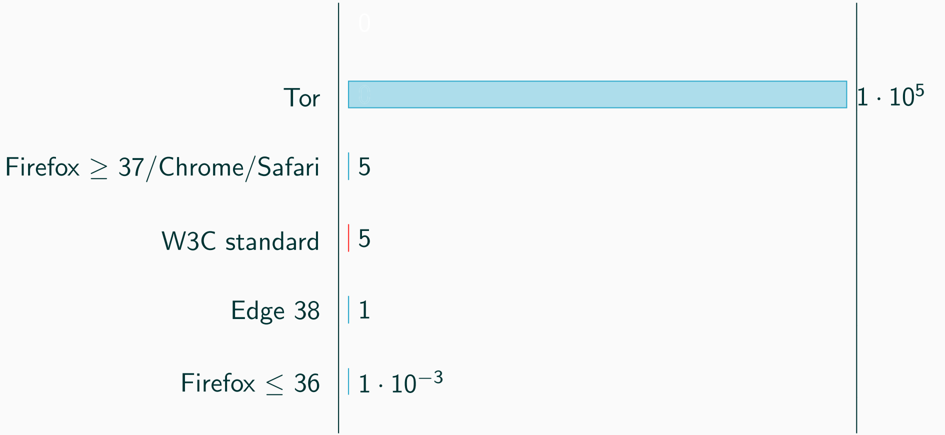
...up to microsecond precision?



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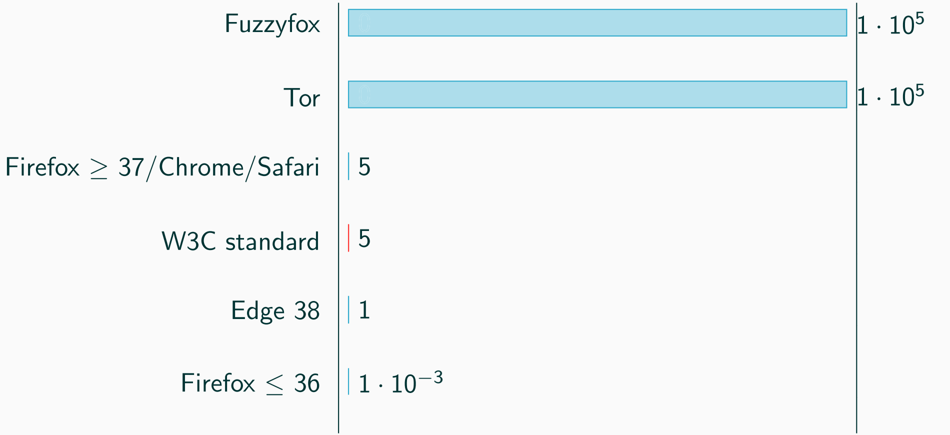
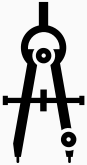
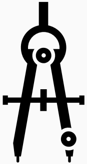


New timer

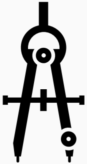


- Current precision is not sufficient to measure cycle differences



- Current precision is not sufficient to measure cycle differences
- We have two possibilities

We require a higher resolution



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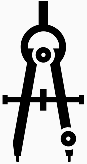
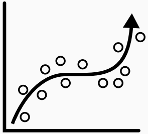
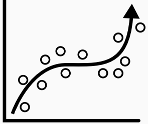


- Current precision is not sufficient to measure cycle differences
- We have two possibilities
- Recover a higher resolution from the available timer
- Build our own high-resolution timer

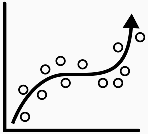


- Measure how often we can increment a variable between two timer ticks



- Measure how often we can increment a variable between two timer ticks
- Average number of increments is the interpolation step

Recovering resolution - Clock interpolation



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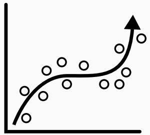

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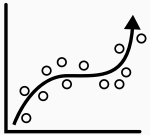

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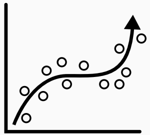

- Measure how often we can increment a variable between two timer ticks
- Average number of increments is the interpolation step
- To measure with high resolution:
  - Start measurement at clock edge
  - Increment a variable until next clock edge
- Highly accurate: 500 ns (Firefox/Chrome), 15 µs (Tor)

Recovering resolution - Edge thresholding

- We can get a higher resolution for a classifier only

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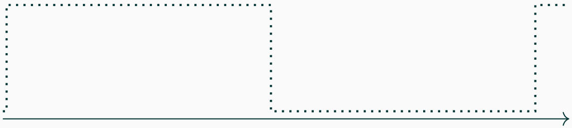

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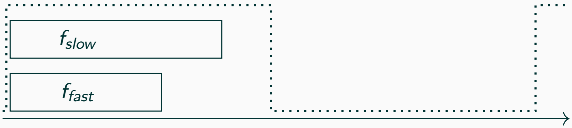

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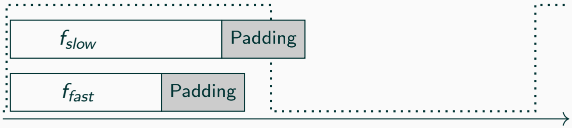
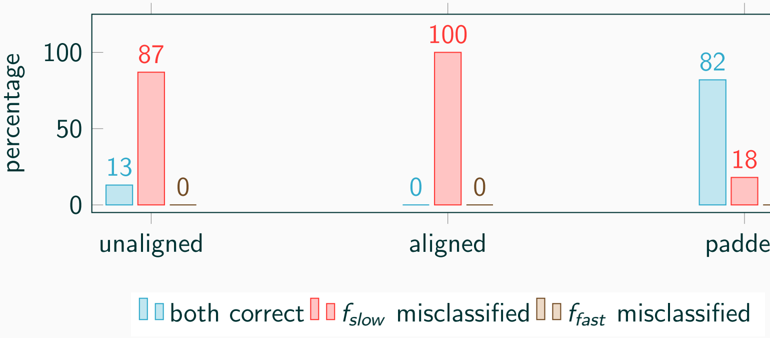
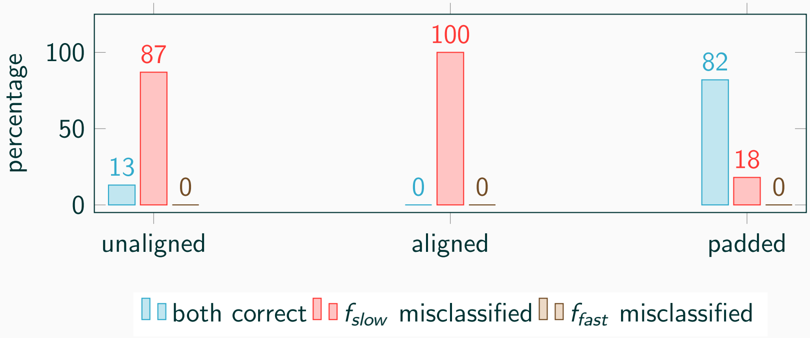


- Edge thresholding: apply padding such that the slow function crosses one more clock edge than the fast function.

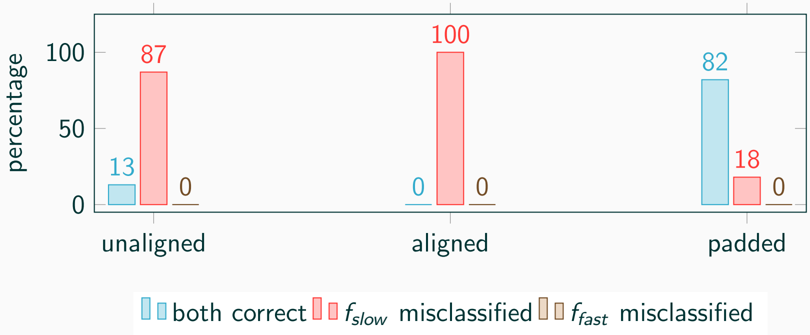


percentage
100
50
0
87
13
0
100
0
0
82
18
0
unaligned
aligned
padded
both correct
f_{slow} misclassified
f_{fast} misclassified

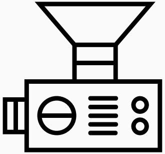
Recovering resolution - Edge thresholding



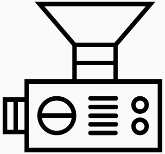
- Yields nanosecond resolution



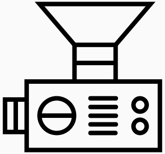
- Yields nanosecond resolution
- Firefox/Tor (2 ns), Edge (10 ns), Chrome (15 ns)



- Goal: counter that does not block main thread



- Goal: counter that does not block main thread
- Baseline setTimeout: 4 ms (except Edge: 2 ms)



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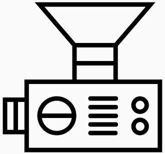
- CSS animation: increase width of element as fast as possible

Building a timer



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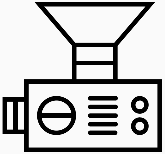
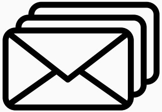
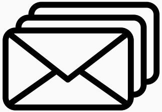


- Goal: counter that does not block main thread
- Baseline setTimeout: 4 ms (except Edge: 2 ms)
- CSS animation: increase width of element as fast as possible
- Width of element is timestamp
- However, animation is limited to 60 fps → 16 ms

- JavaScript can spawn new threads called web worker





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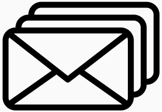

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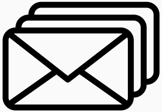

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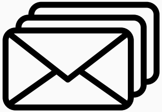
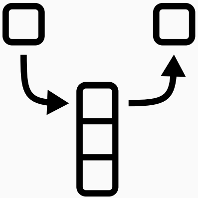
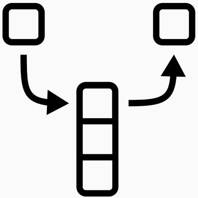


- JavaScript can spawn new threads called web worker
- Web worker communicate using message passing
- Let worker count and request timestamp in main thread
- Multiple possibilities: `postMessage`, `MessageChannel` or `BroadcastChannel`
- Yields microsecond resolution (even on Tor and Fuzzyfox)



- Experimental feature to share data: `SharedArrayBuffer`



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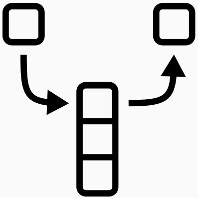
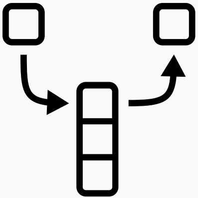


- Experimental feature to share data: `SharedArrayBuffer`
- Web worker can simultaneously read/write data
- No message passing overhead



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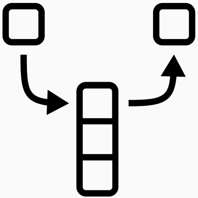
Building a timer - Web worker



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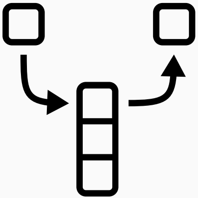

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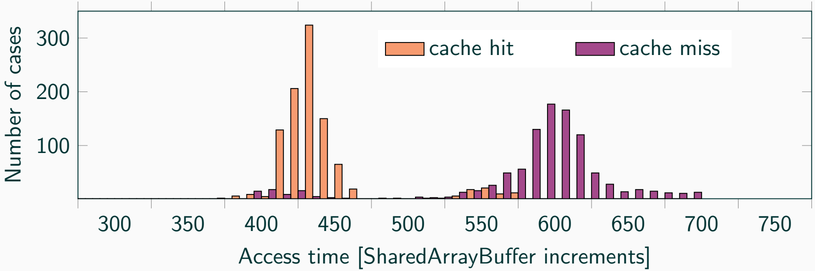
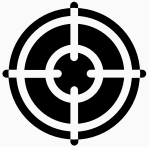
- Sufficient for microarchitectural attacks

Timer evaluation



Attack Requirements

Attack requirements



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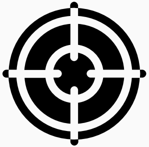

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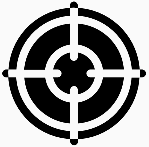

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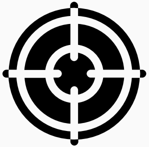

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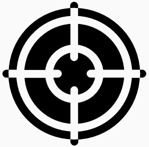

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- Timers can (always) be built
- Some attacks do not require timers at all
- Important to understand requirements before designing countermeasures

JavaScript zero

REAL JavaScript AND ZERO SIDE-CHANNEL ATTACKS

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    - Memory addresses
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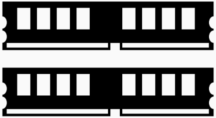
    - Shared data
    - Sensor API
- Every attack is in at least one category

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.

Memory Addresses



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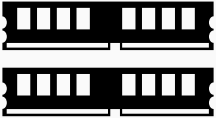

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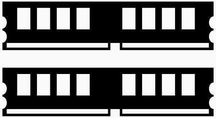

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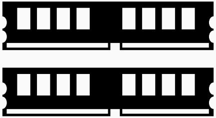

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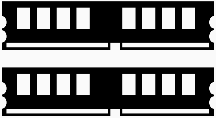

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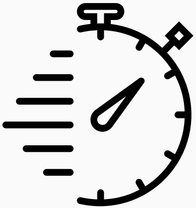
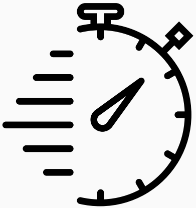
- If not page aligned: detect page faults through timing

Accurate Timing



- Nearly all attacks require accurate timing



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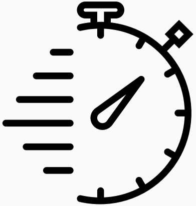

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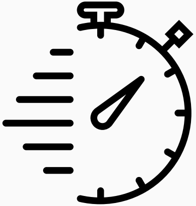

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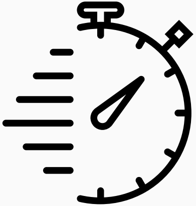

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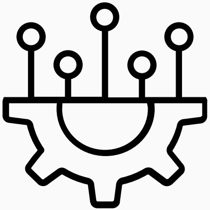
- If attack is repeatable, less accurate timing can be sufficient



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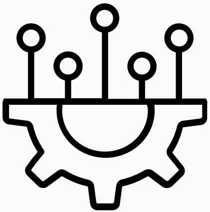

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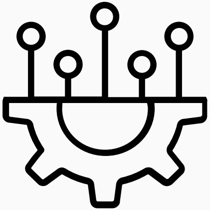

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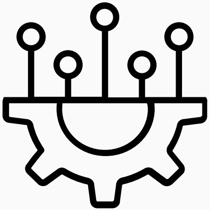
Multithreading



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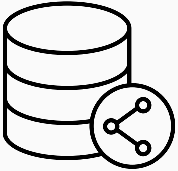
Shared Data



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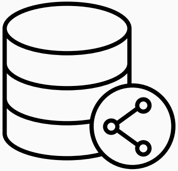

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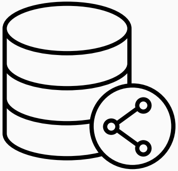

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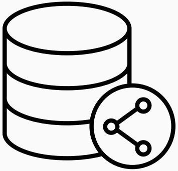

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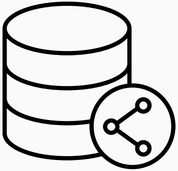

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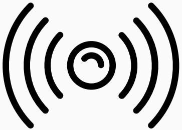

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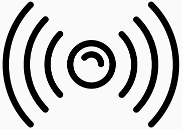

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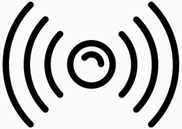
Sensor API



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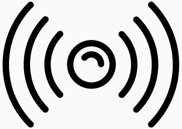

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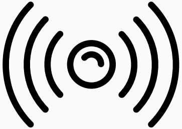

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Defenses

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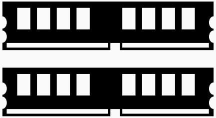
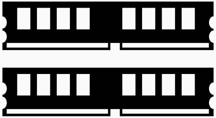
- If no category is usable for attacks anymore, future attacks are hard



#1: Buffer ASLR



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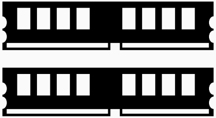

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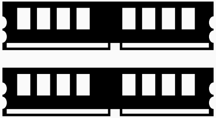

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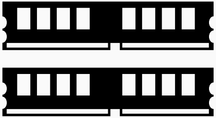

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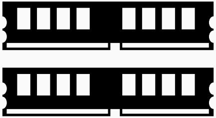
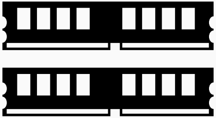


#2: Preloading

- Instead of lazy initialization for arrays, ensure that they are always memory backed



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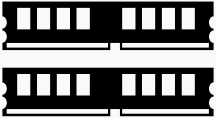

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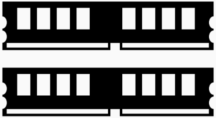

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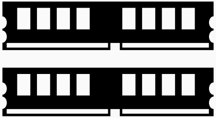
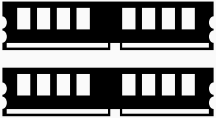


#3: Non-determinism

- For every array access, add another random access



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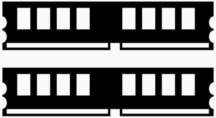

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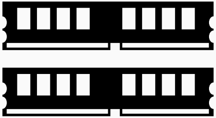

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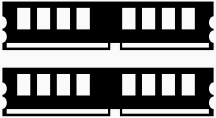

#4: Array Index Randomization

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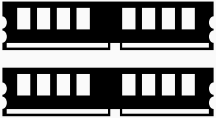

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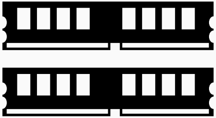

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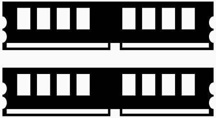

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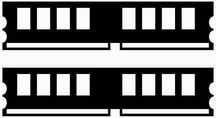
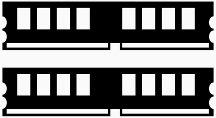


- The four defenses prevent attackers from getting virtual and physical addresses

Memory Addresses



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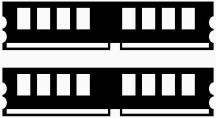

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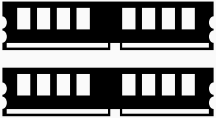

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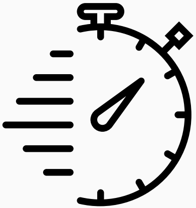
- Prevents many microarchitectural attacks
- Have to be combined for maximum security
- Side effect: make exploits harder where addresses are required

Accurate Timing



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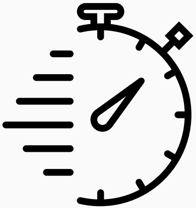
Accurate Timing



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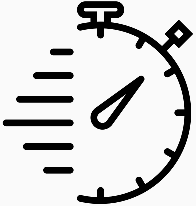

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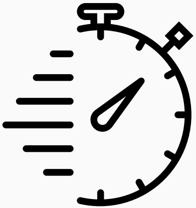

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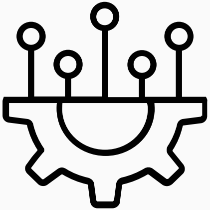

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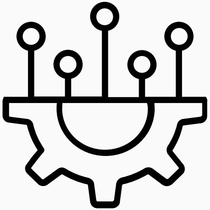
Multithreading



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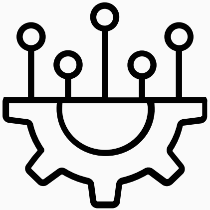

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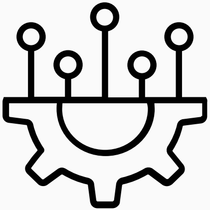
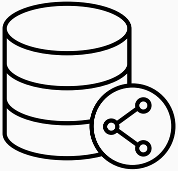
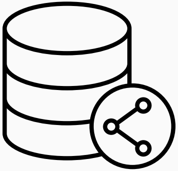


- Only real solution is to prevent multithreading
- We used a polyfill to not completely break websites
- Some attacks can be prevented by adding random delays to `postMessage`
- Prevents certain timing primitives and attacks on the event-queue latency



- Best countermeasures: do not allow shared data



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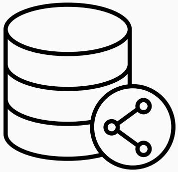

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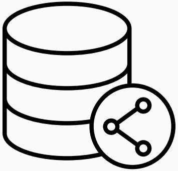
Shared Data



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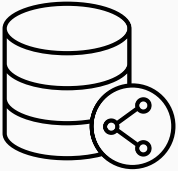

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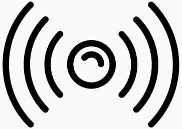
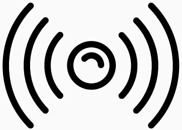
- Degrades resolution of timing primitive to microseconds



- Reduce resolution and update frequency of sensors



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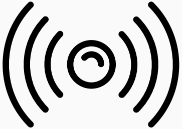

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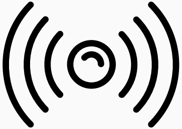
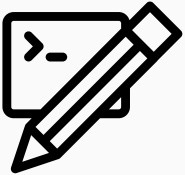
Sensor API



- Reduce resolution and update frequency of sensors
- Sensor APIs should always ask user for permission
- Every sensor is usable for attacks, even ambient light sensor
- To not break existing applications, sensors return constant value

Implementation



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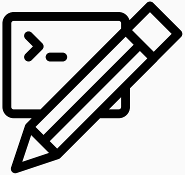

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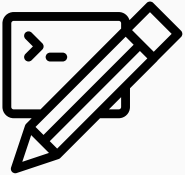

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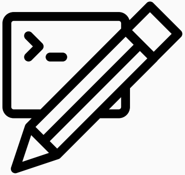

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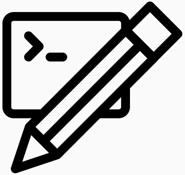
Designing the Countermeasure



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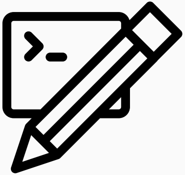

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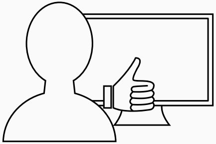
- Proof-of-concept is implemented as browser extension

User Experience



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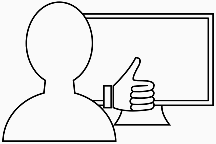

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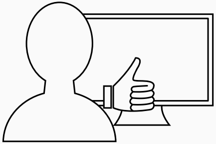

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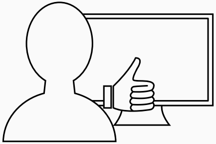

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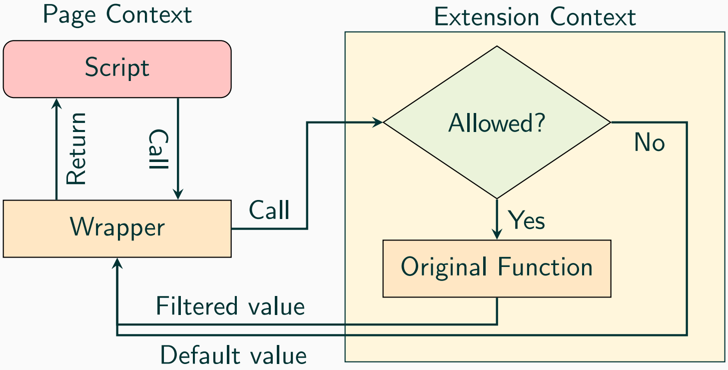
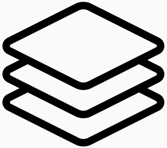
- The user can choose one of several pre-defined protection levels
- Protection levels apply different combinations of defenses
- Each defense can either be disabled, enabled, or require user permission

- Functions and properties are replaced by wrappers





- Functions can be re-defined in JavaScript

```
var original_reference = window.performance.now;
window.performance.now = function() { return 0; };
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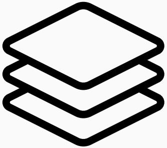

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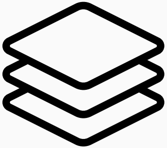

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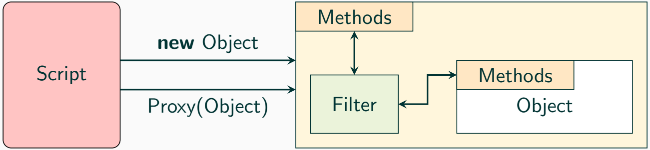
- Properties can be replaced by accessor properties

Virtual Machine Layering for Objects

- Objects are proxied



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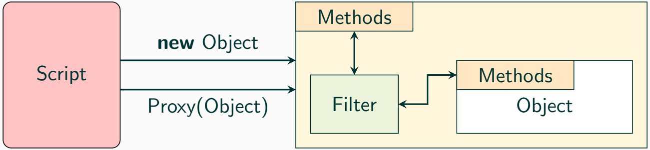

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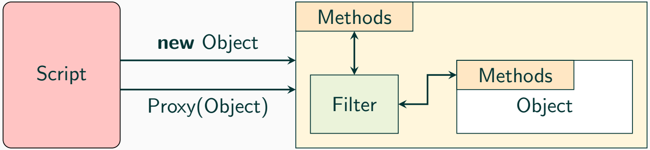
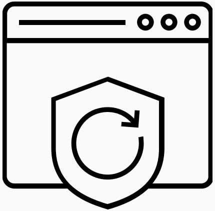
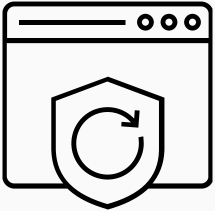


- All properties and functions are handled by the original object
- Functions and properties can be overwritten in the proxy object

- Attacker tries to circumvent JavaScript Zero



Self Protection



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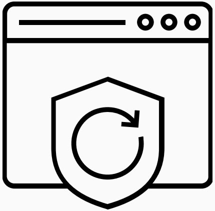

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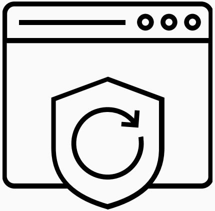

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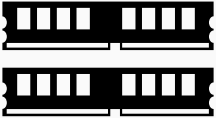
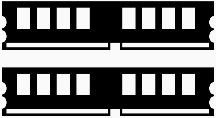
- Prevent objects from being modified: `Object.freeze`

Evaluation



- Border of pages leak 12 or 21 bits (depending on page size)



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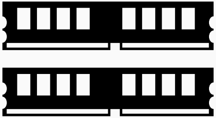

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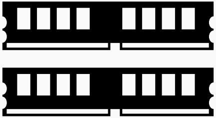
Page Border Detection



- Border of pages leak 12 or 21 bits (depending on page size)
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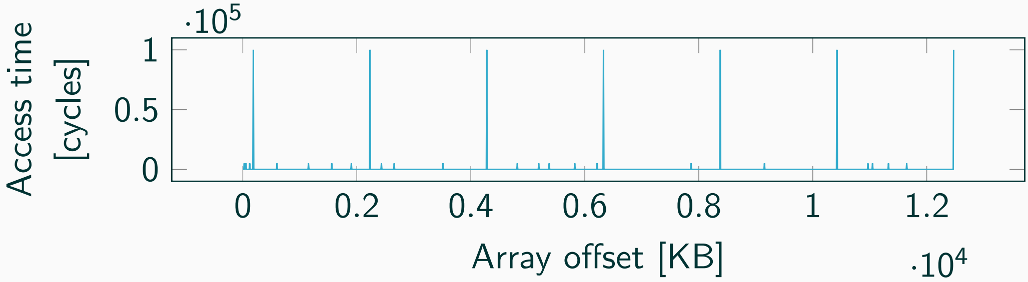
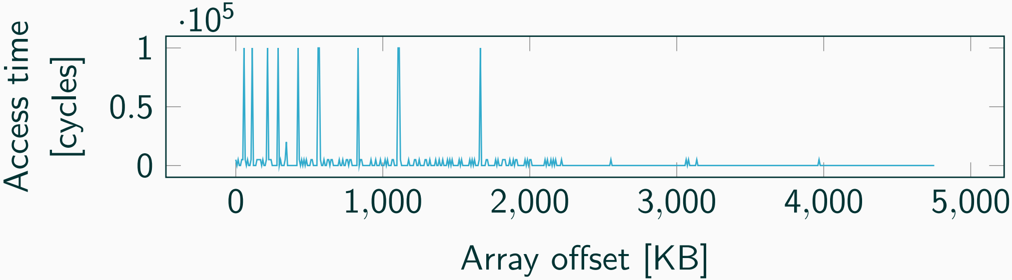
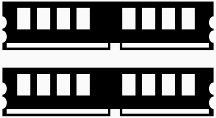
- Iterate over array, measure access time
- Page border raise pagefault, taking significantly longer to access

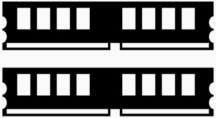

·10^5
1
0.5
0
Access time [cycles]
0
0.2
0.4
0.6
0.8
1
1.2
Array offset [KB]
·10^4

Page Border Detection with Random Access





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



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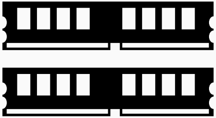

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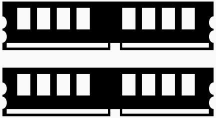

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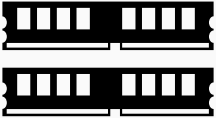
Prime+Probe



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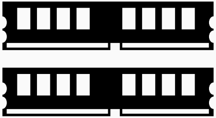

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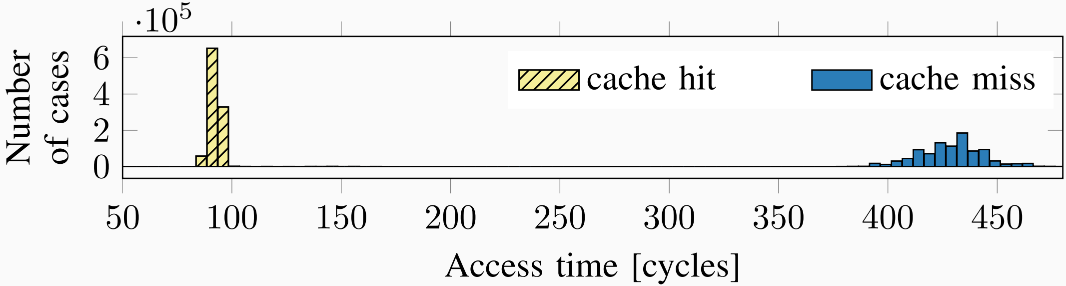
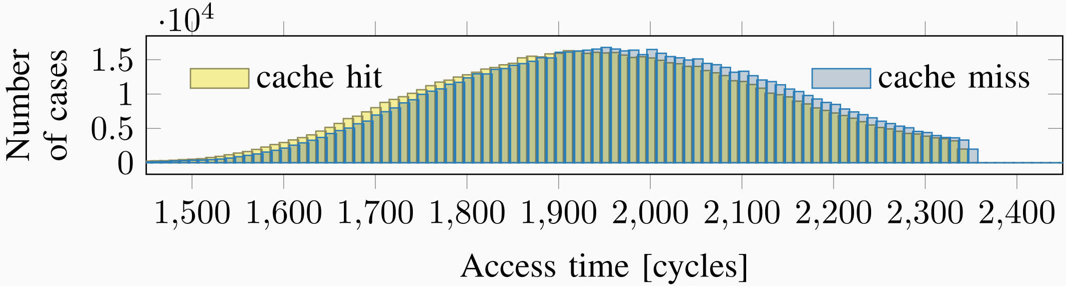
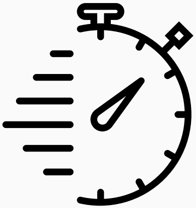
- If it is slow, someone used this cache set and evicted our addresses

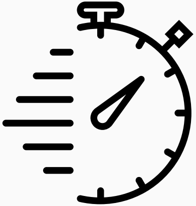

·10^5
Number of cases
6
4
2
0
cache hit
cache miss
50
100
150
200
250
300
350
400
450
Access time [cycles]


$\cdot 10^4$
Number of cases
1.5
1
0.5
0
cache hit
cache miss
1,500
1,600
1,700
1,800
1,900
2,000
2,100
2,200
2,300
2,400
Access time [cycles]

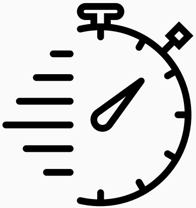


- Multithreading allows to detect interrupts

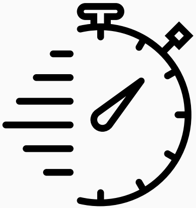
Interrupt Detection



- Multithreading allows to detect interrupts
- Endless loop which counts number of increments in time window

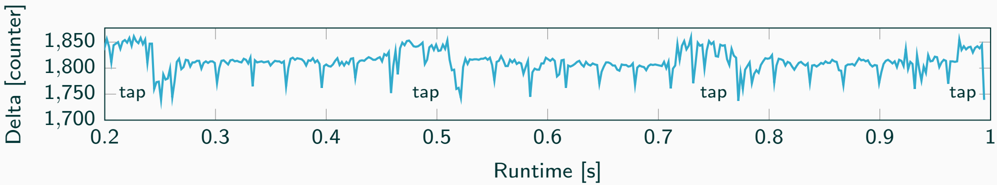


- Multithreading allows to detect interrupts
- Endless loop which counts number of increments in time window
- Different number of increments indicate interrupt

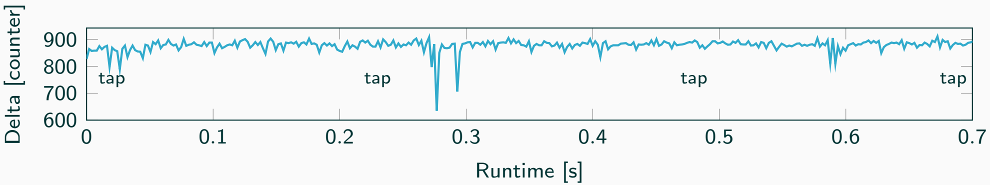


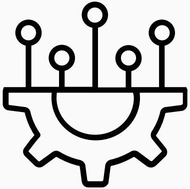
- Multithreading allows to detect interrupts
- Endless loop which counts number of increments in time window
- Different number of increments indicate interrupt
- Fuzzy time prevents deterministic equally-sized time window

Interrupt Detection



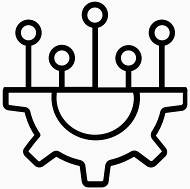
Interrupt Detection with Fuzzy Time





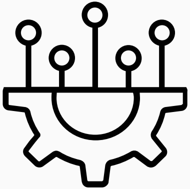
- Messages between web workers are handled in the event queue

Event Queue Spying



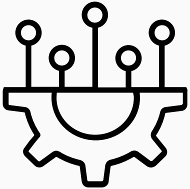
- Messages between web workers are handled in the event queue
- User activity is also handled in the event queue

Event Queue Spying

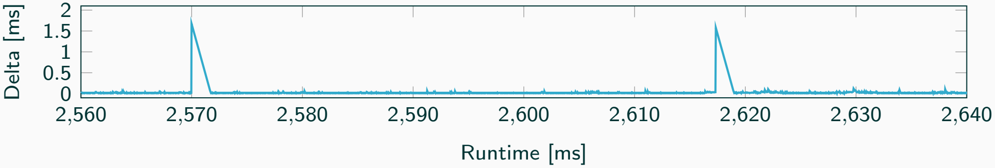


- Messages between web workers are handled in the event queue
- User activity is also handled in the event queue
- Posting many messages allows to measure latency

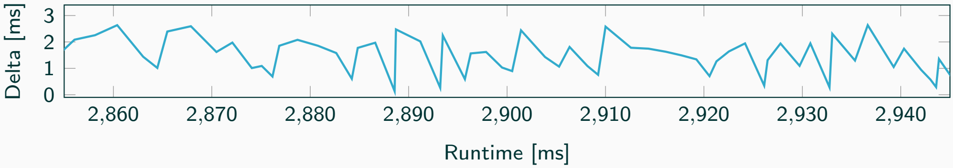
Event Queue Spying

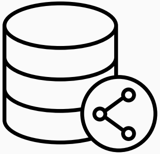


- Messages between web workers are handled in the event queue
- User activity is also handled in the event queue
- Posting many messages allows to measure latency
- Latency indicates user input


Delta [ms]
2
1.5
1
0.5
0
2,560
2,570
2,580
2,590
2,600
2,610
2,620
2,630
2,640
Runtime [ms]

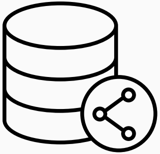
Event Queue Spying with Message Delay





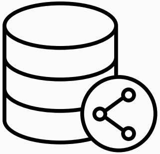
- SharedArrayBuffer allows to build a timing primitive with the highest resolution

`SharedArrayBuffer` Timing Primitive



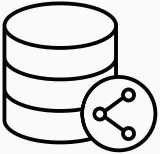
- `SharedArrayBuffer` allows to build a timing primitive with the highest resolution
- One web worker continuously increments variable in the shared array

`SharedArrayBuffer` Timing Primitive

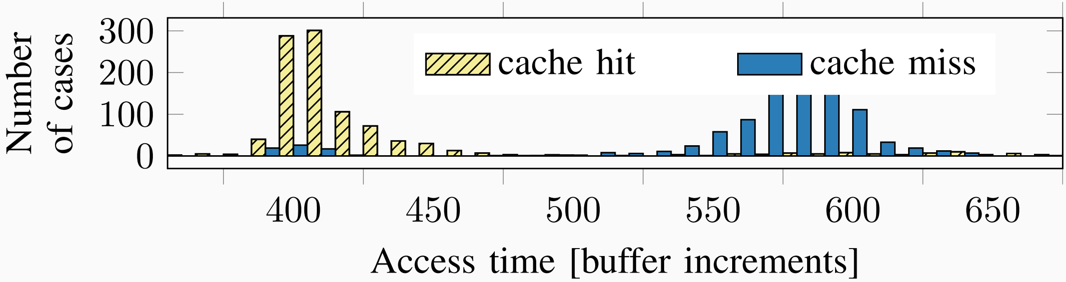


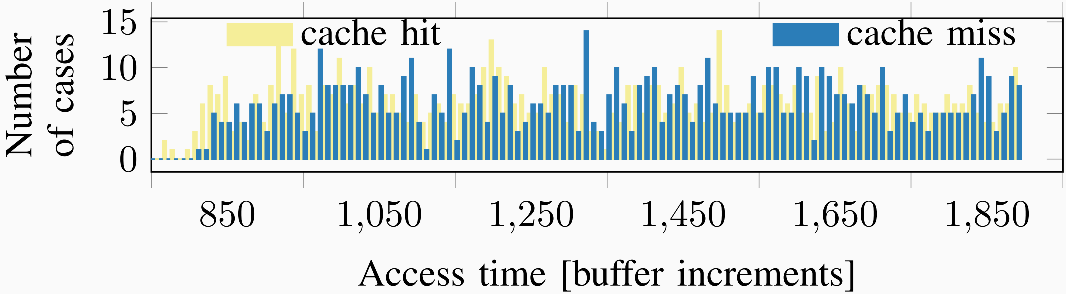
- `SharedArrayBuffer` allows to build a timing primitive with the highest resolution
- One web worker continuously increments variable in the shared array
- Other worker uses this as a timestamp

`SharedArrayBuffer` Timing Primitive



- `SharedArrayBuffer` allows to build a timing primitive with the highest resolution
- One web worker continuously increments variable in the shared array
- Other worker uses this as a timestamp
- Adding random delay to access degrades resolution

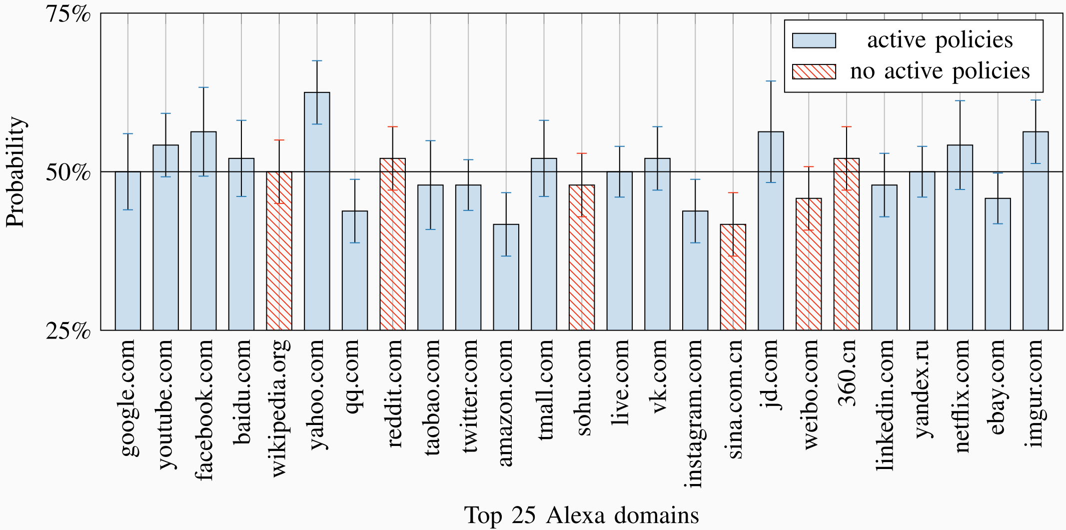

Number of cases
300
200
100
0
cache hit
cache miss
400
450
500
550
600
650
Access time [buffer increments]


cache hit
cache miss
15
10
5
0
Number of cases
850
1,050
1,250
1,450
1,650
1,850
Access time [buffer increments]

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	●	●	●	●	●	●	●

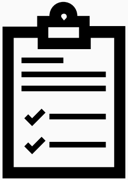
Symbols indicate whether a policy fully prevents an attack, (●), partly prevents and attack by making it more difficult (◐), or does not prevent an attack (○).

A star (*) indicates that all policies marked with a star must be combined to prevent an attack.


75%
50%
25%
Probability
active policies
no active policies
google.com
youtube.com
facebook.com
baidu.com
wikipedia.org
yahoo.com
qq.com
reddit.com
taobao.com
twitter.com
amazon.com
tmall.com
sohu.com
live.com
vk.com
instagram.com
sina.com.cn
jd.com
weibo.com
360.cn
linkedin.com
yandex.ru
netflix.com
ebay.com
imgur.com
Top 25 Alexa domains

Conclusion

- Just rounding timers is not sufficient



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- Multithreading and shared data allow to build new timers
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- Efficient countermeasures can be implemented in browsers
- More microarchitectural attacks in JavaScript will appear