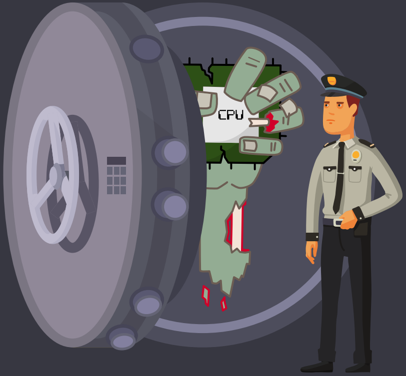
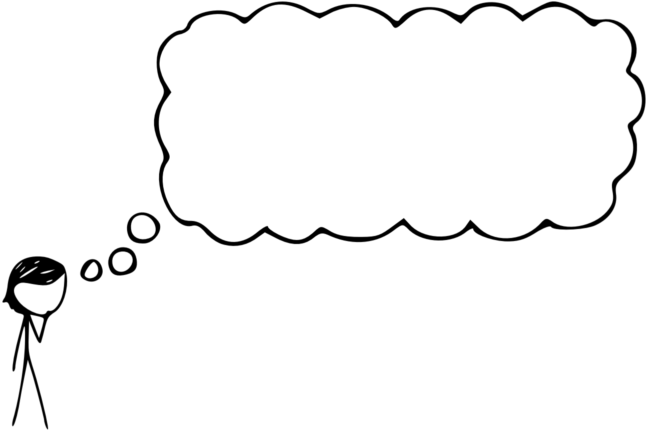
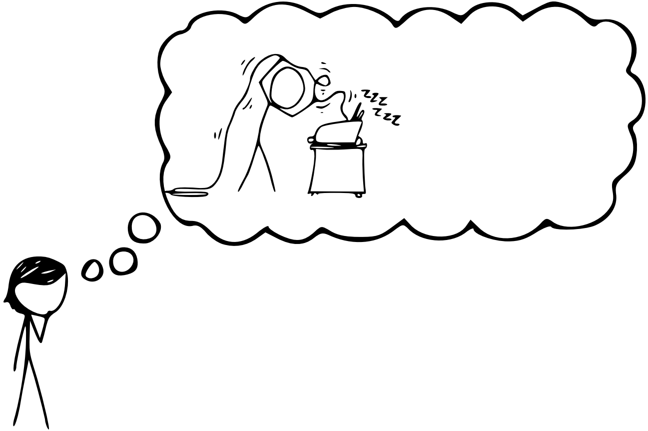
Software-based Side-Channel Attacks and Defenses in Restricted Environments

Heinz Zemanek Preis Hearing 2020

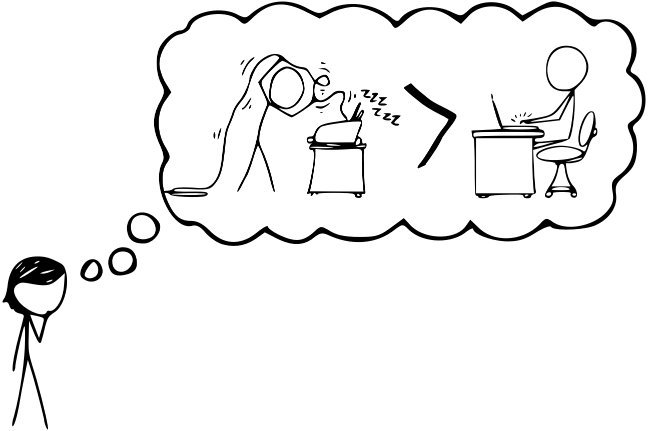


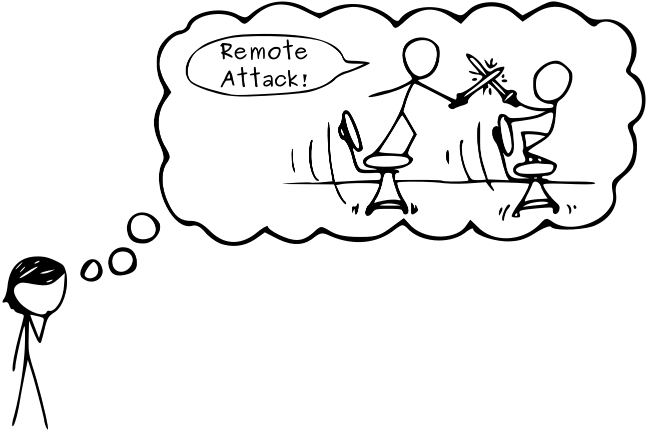
Michael Schwarz
IAIK, Graz University of Technology
May 28, 2020




zzz
zzz

Motivation





Research Question

How far can we reduce requirements?

24
(**13** tier 1)

9
(**4** tier 1)

34

9

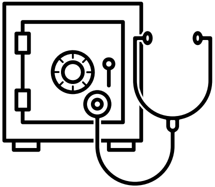
2975
(**513** first author)

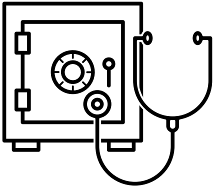
10
(**3** co-authors)


Side Channels

$$M \equiv C^d \pmod{n}$$

Description



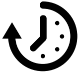


$$M \equiv C^d \pmod{n}$$

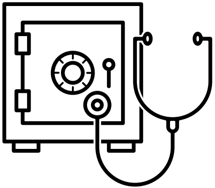
Description

$$C^n = \begin{cases} (C^2)^{\frac{n}{2}} & \text{if } n \equiv 0 \mod 2 \\ C \cdot (C^2)^{\frac{n-1}{2}} & \text{if } n \equiv 1 \mod 2 \end{cases}$$

Software



Execution time



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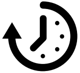
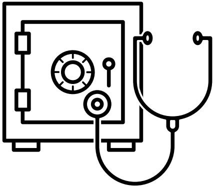
Software

Hardware



Execution time

Power consumption



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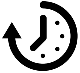
Software

Hardware



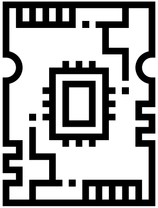
Execution time

Power consumption

CPU caches

μ-arch

- Specific implementation of a CPU



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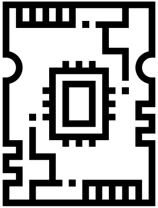
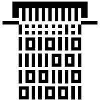
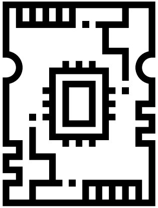


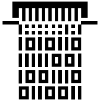


Decoder

Microarchitectural Elements

- Specific implementation of a CPU

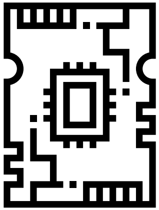


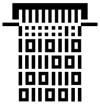


Decoder

Predictor

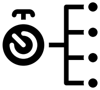
- Specific implementation of a CPU





Decoder

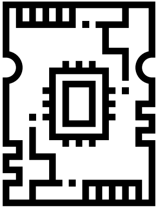
Predictor

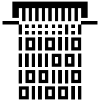


Scheduler

Microarchitectural Elements

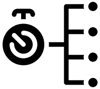
- Specific implementation of a CPU



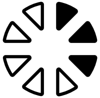


Decoder

Predictor

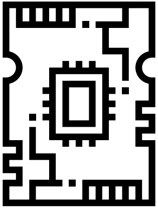


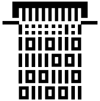
Scheduler



Buffer

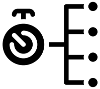
- Specific implementation of a CPU





Decoder

Predictor



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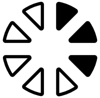
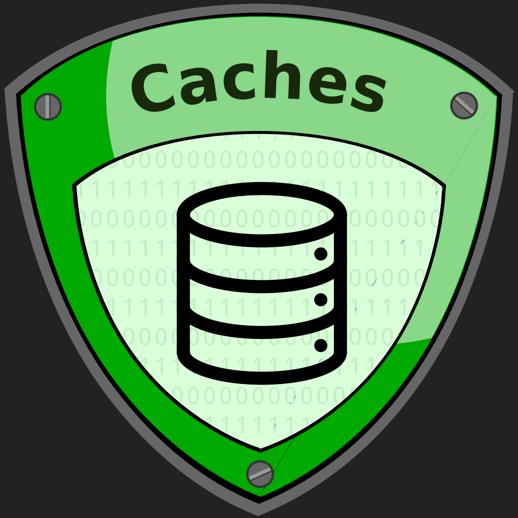


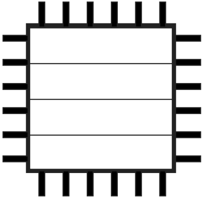
Buffer

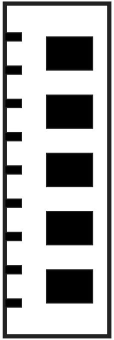
Caches

•••


Caches

```
printf("%d", i);
printf("%d", i);
```





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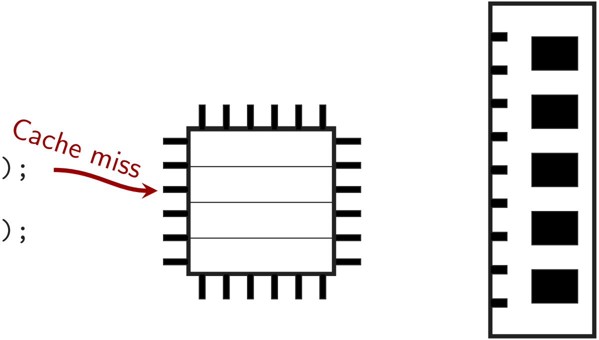

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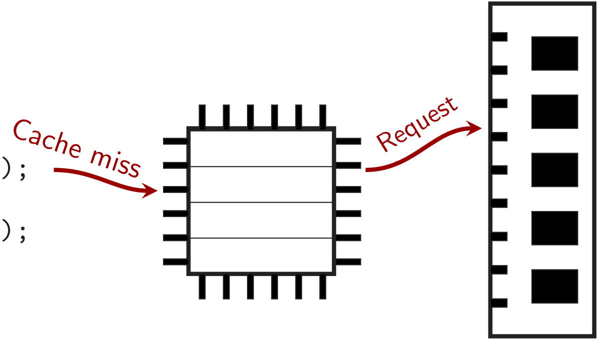

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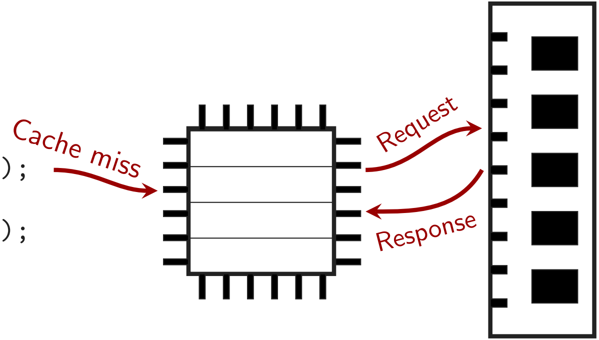

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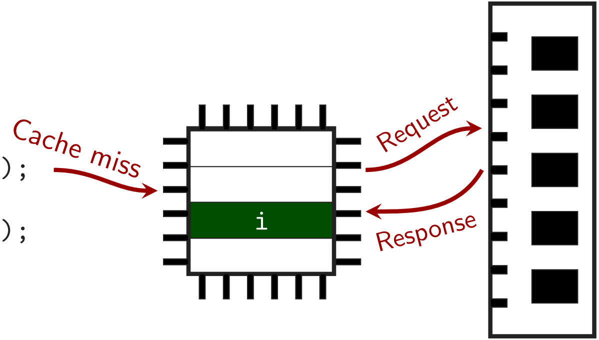
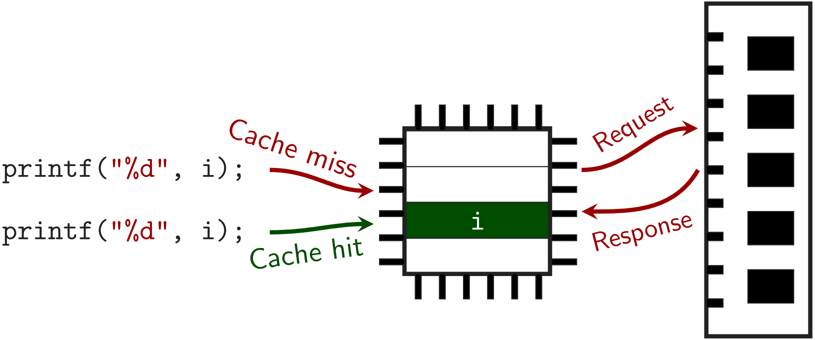
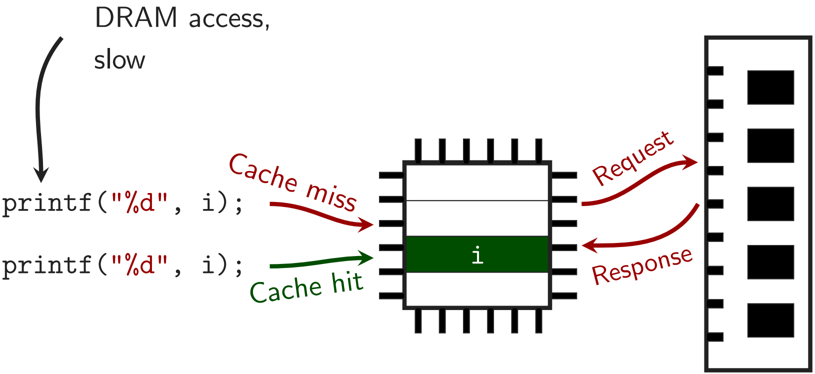
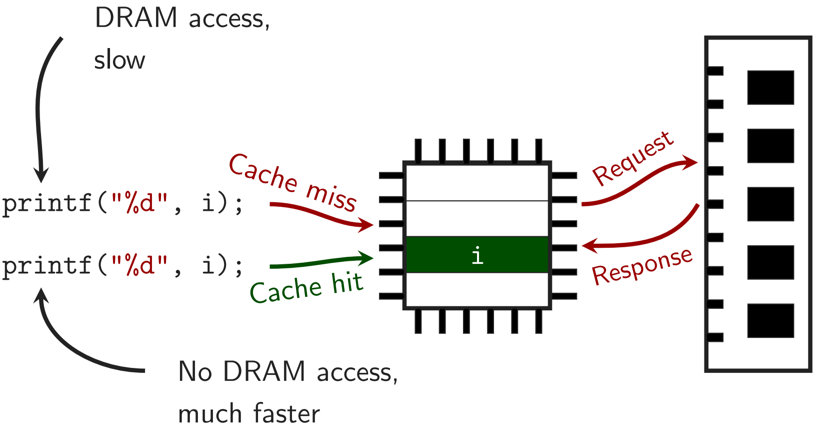
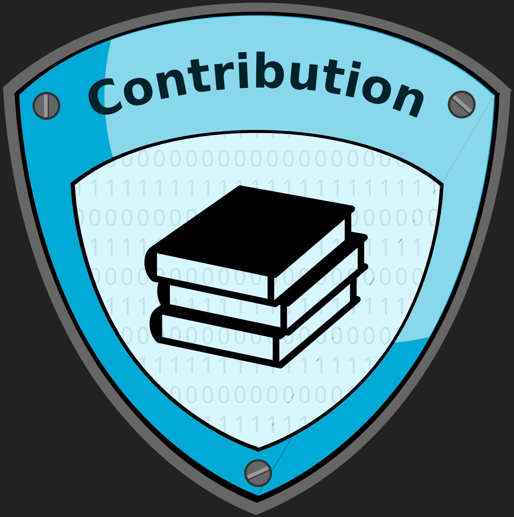


CPU Cache




DRAM access,
slow
printf("%d", i);
printf("%d", i);
Cache miss
Cache hit
i
Request
Response


DRAM access,
slow
printf("%d", i);
printf("%d", i);
Cache miss
Cache hit
i
Request
Response
No DRAM access,
much faster


Contribution

Publications

FANTASTIC TIMERS AND WHERE TO FIND THEM

HIGH-RESOLUTION MICROARCHITECTURAL ATTACKS IN JAVASCRIPT

malware inside

SGX

KeyDrown

JavaScript zero

REAL JavaScript AND ZERO SIDE-CHANNEL ATTACKS

DECAF

JS

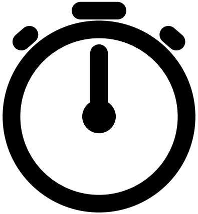
Template Attacks

ZOMBIELOAD

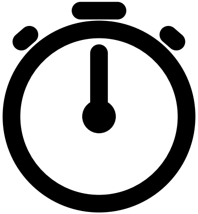
FANTASTIC TIMERS
AND WHERE TO FIND THEM

HIGH-RESOLUTION MICROARCHITECTURAL ATTACKS IN JAVASCRIPT

FC'17



- High-resolution timer to measure microarchitectural effects



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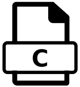
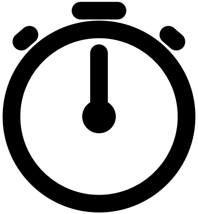


rdtsc

Timers in JavaScript



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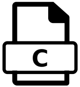
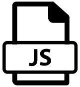
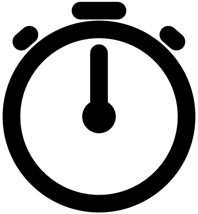


`rdtsc`



`performance.now()`



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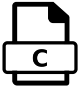

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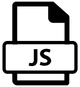
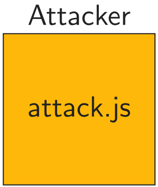


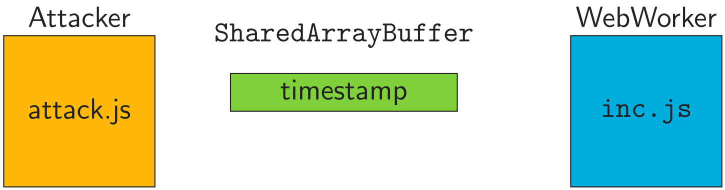
`performance.now()`

performance.now()

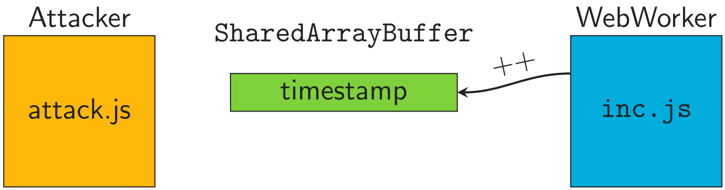
> [...] represent times as floating-point numbers with up to microsecond precision.
>
> — Mozilla Developer Network

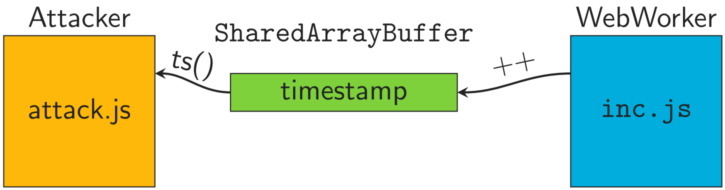

Attacker
attack.js

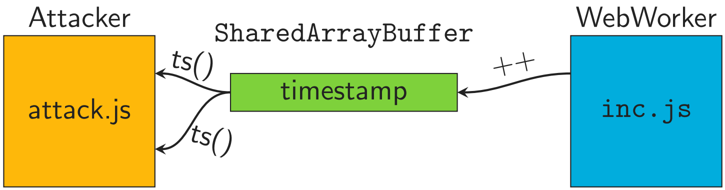

Attacker
attack.js
WebWorker
inc.js


Attacker
attack.js
SharedArrayBuffer
timestamp
WebWorker
inc.js

Building a timer - Web worker




Attacker
attack.js
ts()
SharedArrayBuffer
timestamp
++
WebWorker
inc.js


Attacker
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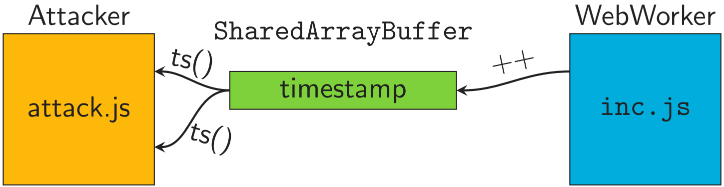
Building a timer - Web worker



2 ns

15 ns

Summary

- Rounding timers is not a solution

FC'17

Michael Schwarz, Clémentine Maurice, Daniel Gruss and Stefan Mangard.
Fantastic Timers and Where to Find Them: High-Resolution Microarchitectural Attacks in JavaScript.

Summary

- Rounding timers is not a solution
- State of the art for timers in JavaScript

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Summary

- Rounding timers is not a solution
- State of the art for timers in JavaScript
- Microarchitectural attacks in the browser are possible again

FC'17

Michael Schwarz, Clémentine Maurice, Daniel Gruss and Stefan Mangard.
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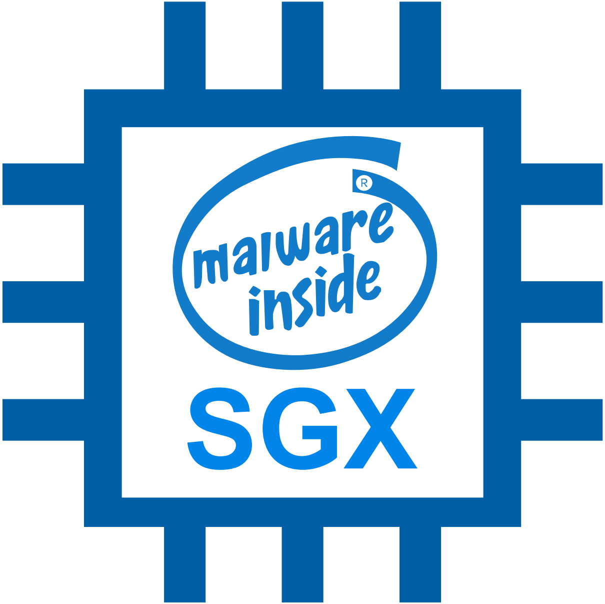
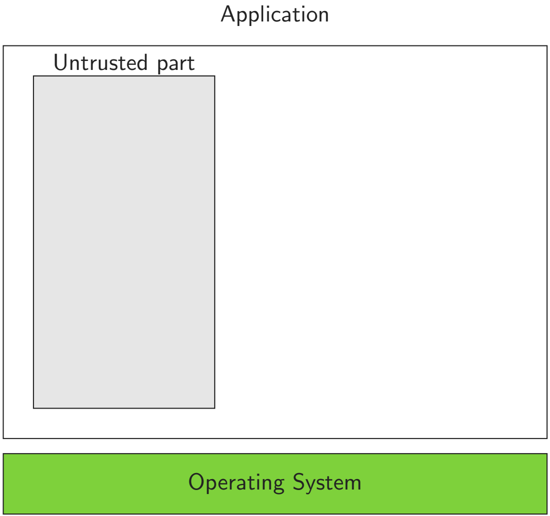
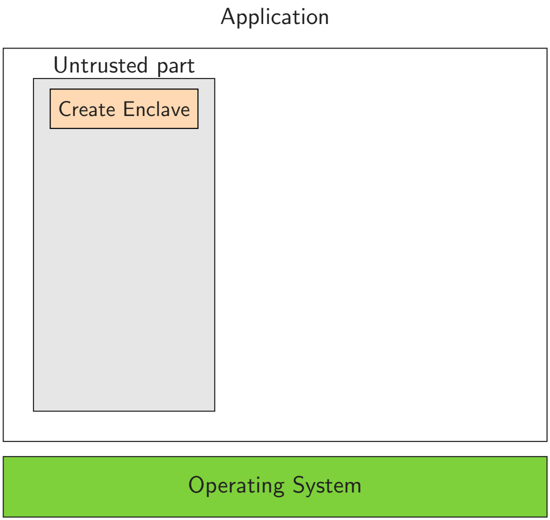
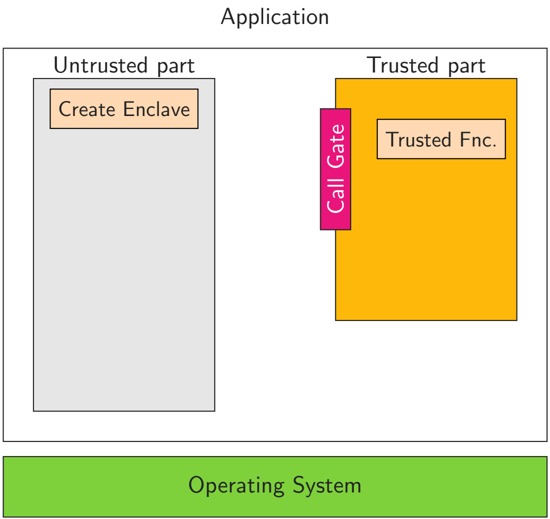
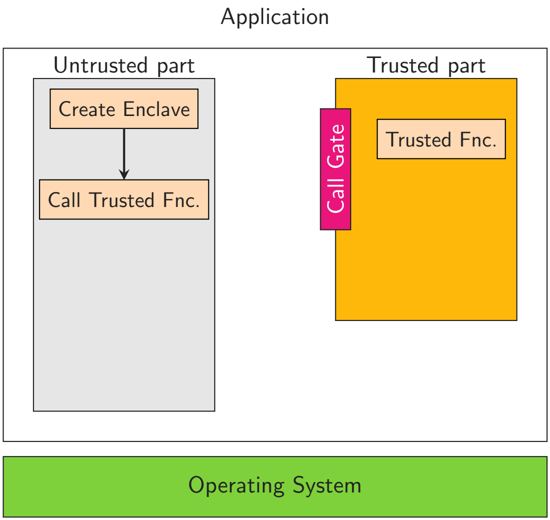


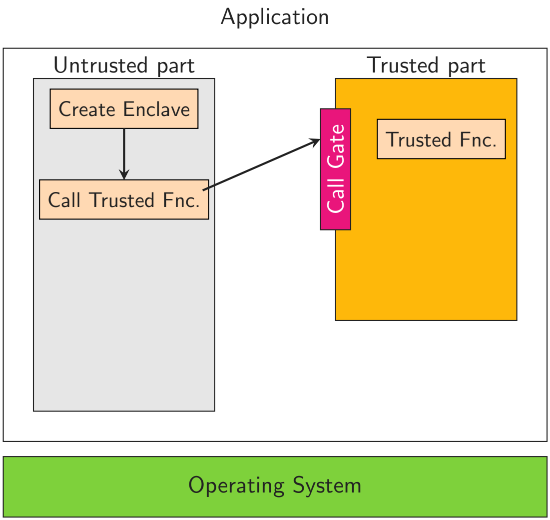
DIMVA'17


Application
Untrusted part
Operating System


Application
Untrusted part
Create Enclave
Operating System


Application
Untrusted part
Create Enclave
Trusted part
Call Gate
Trusted Fnc.
Operating System


Application
Untrusted part
Create Enclave
Call Trusted Fnc.
Trusted part
Call Gate
Trusted Fnc.
Operating System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Call Trusted Fnc.
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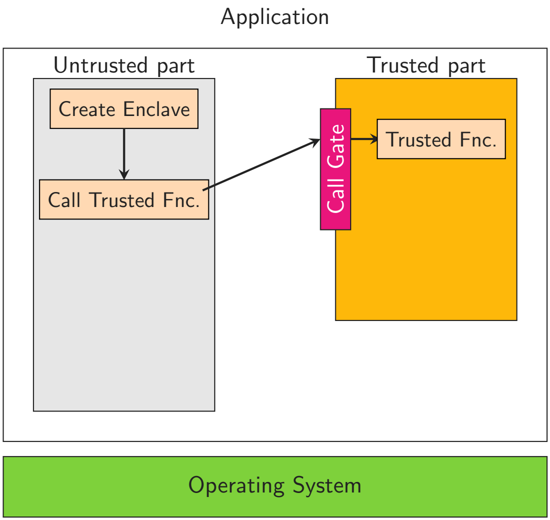
Operating System


Application
Untrusted part
Trusted part
Create Enclave
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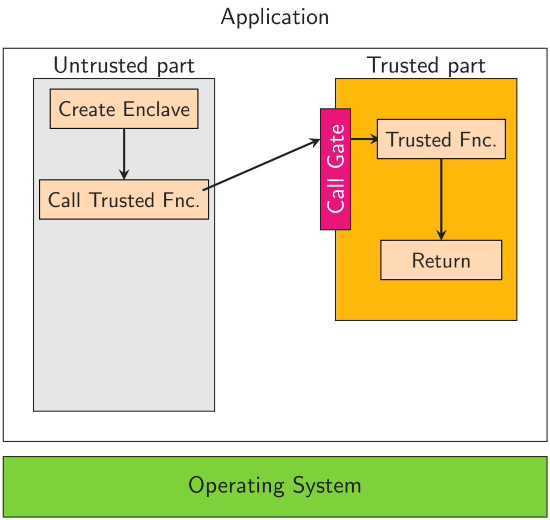
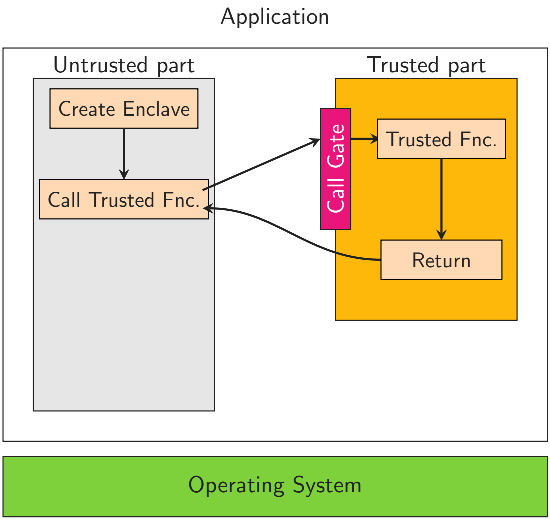
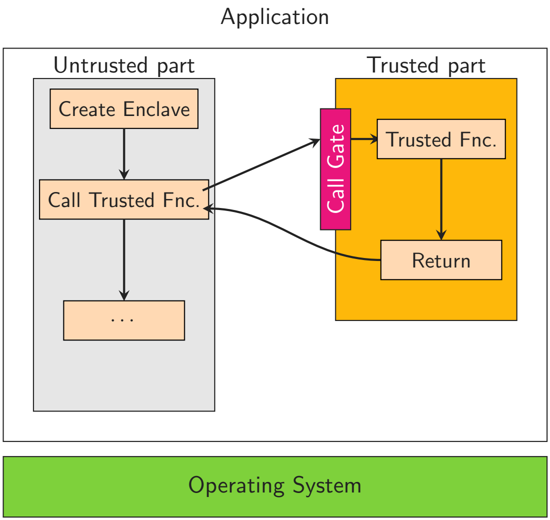
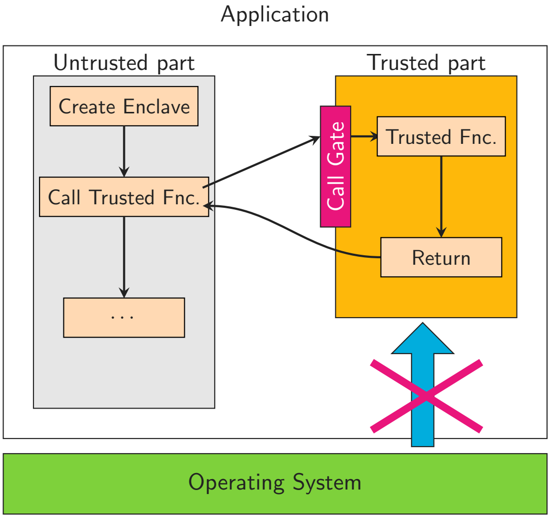
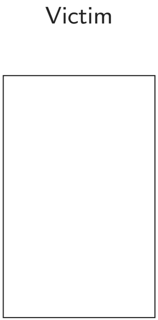
Operating System


Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Fnc.
Call Gate
Trusted Fnc.
Return
Operating System

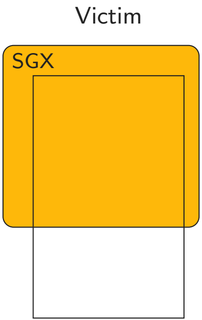

Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Fnc.
Call Gate
Trusted Fnc.
Return
Operating System


Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Fnc.
...
Call Gate
Trusted Fnc.
Return
Operating System

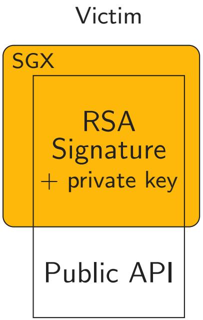

Application
Untrusted part
Trusted part
Create Enclave
Call Trusted Fnc.
. . .
Call Gate
Trusted Fnc.
Return
Operating System


Victim

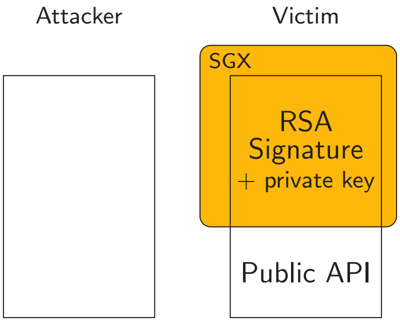
Attack Settings

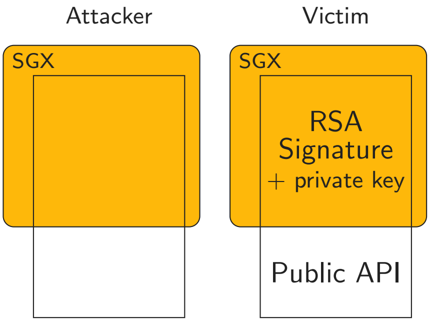


Attack Settings

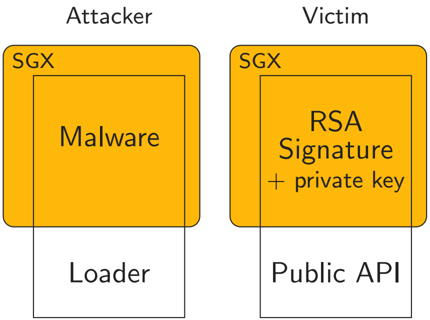


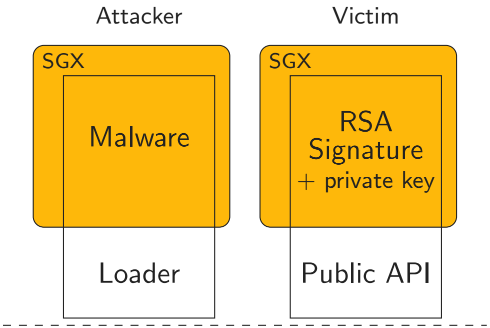
Attack Settings



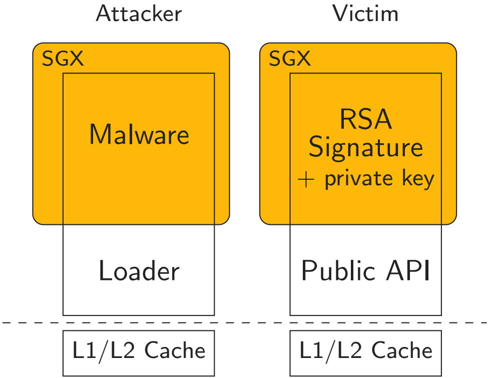

Attacker
Victim
SGX
SGX
RSA
Signature
+ private key
Public API

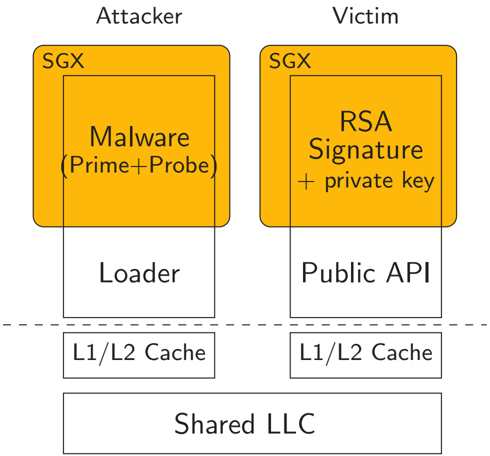
Attack Settings




Attacker
Victim
SGX
Malware
Loader
SGX
RSA
Signature
+ private key
Public API

Attack Settings



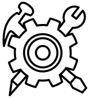

Attacker
Victim
SGX
Malware
(Prime+Probe)
Loader
SGX
RSA
Signature
+ private key
Public API
L1/L2 Cache
L1/L2 Cache
Shared LLC

SGX Limitations

No privileges

SGX Limitations

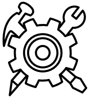
No privileges



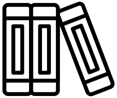
No syscall

SGX Limitations

No privileges

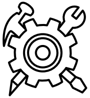


No syscall

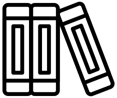


No shared memory

No privileges



No syscall

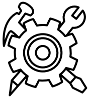


No shared memory

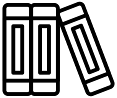
No rdtsc

SGX Limitations

No privileges



No syscall



No shared memory

No rdtsc

No physical addresses

SGX Limitations

No privileges

No syscall

No shared memory

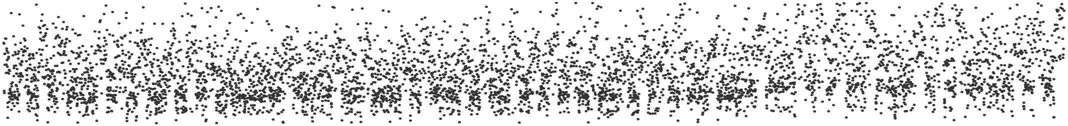
No rdtsc

No physical addresses

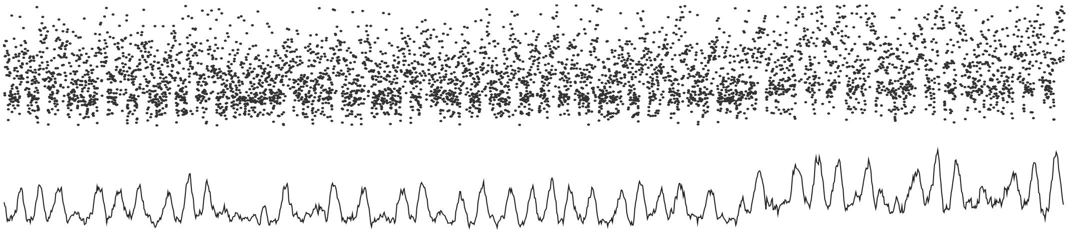
No 2 MB pages

Measured Trace

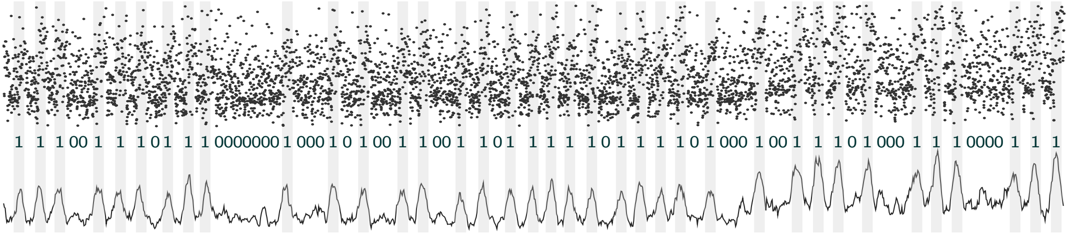
Raw Prime+Probe trace...



...processed with a simple moving average...



...allows to clearly see the bits of the exponent



- Attacks from within SGX possible

DIMVA'17

Michael Schwarz, Samuel Weiser, Daniel Gruss, Clémentine Maurice, Stefan Mangard.
Malware Guard Extension: Using SGX to Conceal Cache Attacks.

Summary

- Attacks from within SGX possible
- New state-of-the-art high-resolution timer

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- Leaked 4096-bit RSA key (11 traces)

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- Attacks from within SGX possible
- New state-of-the-art high-resolution timer
- Leaked 4096-bit RSA key (11 traces)
- SGX allows hiding an attack

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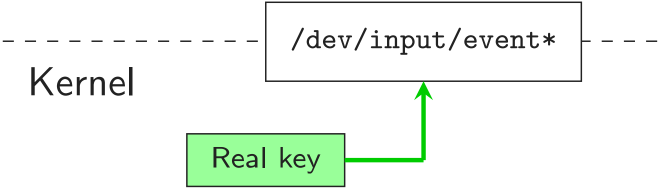
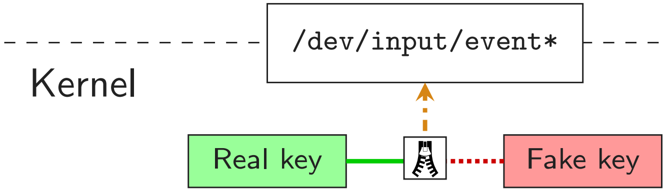
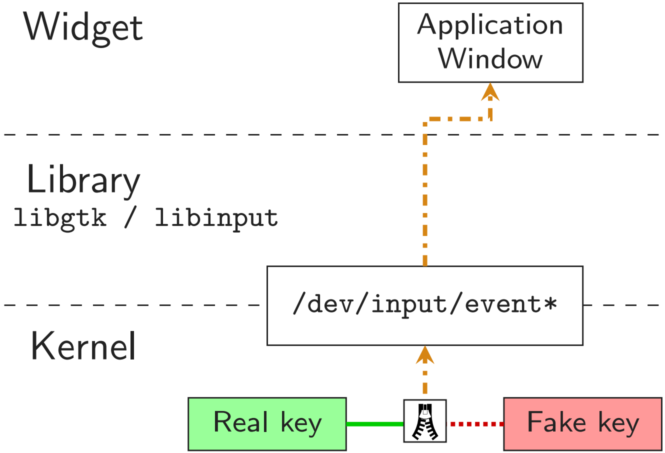
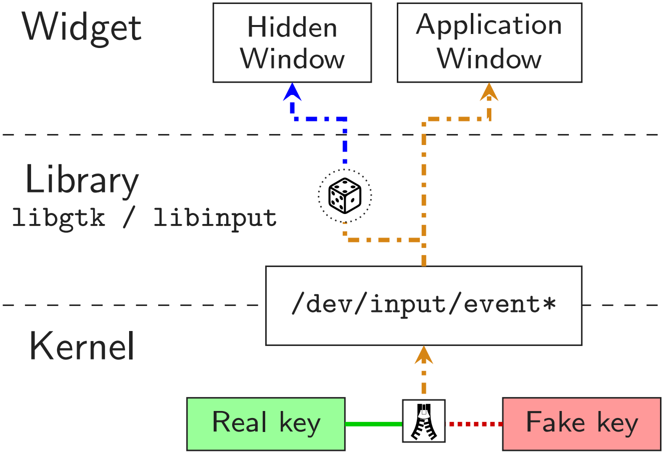
KeyDrown

NDSS'18

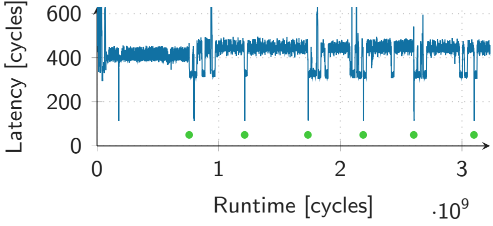

/dev/input/event*
Kernel
Real key


/dev/input/event*
Kernel
Real key
Fake key

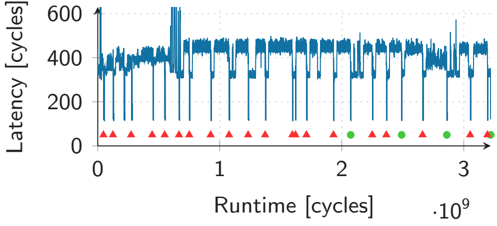

Widget
Application Window
Library
libgtk / libinput
/dev/input/event*
Kernel
Real key
Fake key


Widget
Hidden Window
Application Window
Library
libgtk / libinput
/dev/input/event*
Kernel
Real key
Fake key

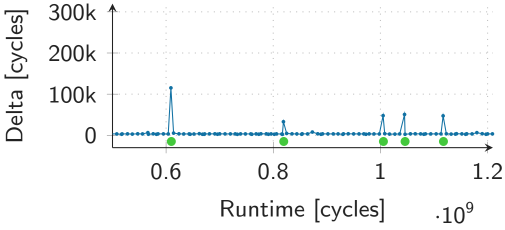
Flush+Reload on `libgdk-3.so`



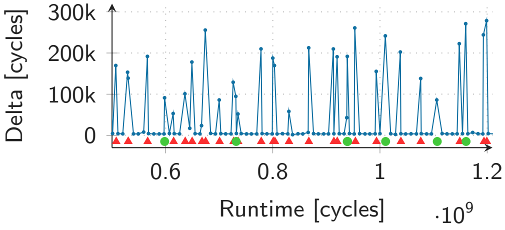
Without Keydrown, F-Score 0.99



With Keydrown, F-Score 0.09



Without Keydrown, F-Score 0.94



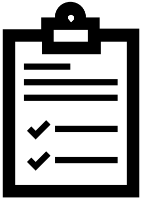
With Keydrown, F-Score 0.14

Summary

- Keystroke-timing attack only with high-resolution timer

NDSS'18

Michael Schwarz, Moritz Lipp, Daniel Gruss, Samuel Weiser, Clémentine Maurice, Raphael Spreitzer, Stefan Mangard.
KeyDrown: Eliminating Software-Based Keystroke Timing Side-Channel Attacks.



- Keystroke-timing attack only with high-resolution timer
- First accurate Prime+Probe attack on kernel

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Summary

- Keystroke-timing attack only with high-resolution timer
- First accurate Prime+Probe attack on kernel
- First generic countermeasure against keystroke-timing attack
- PoC for Linux and Android

NDSS'18

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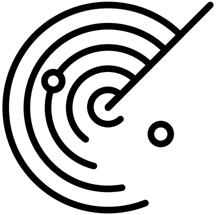
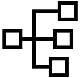
JavaScript zero

REAL JavaScript AND ZERO SIDE-CHANNEL ATTACKS

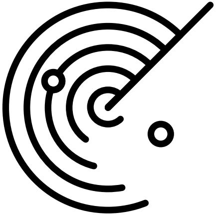
NDSS'18



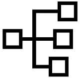
11 known attacks



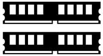
5 identified categories



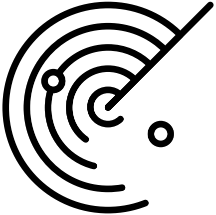
11 known attacks



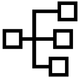
5 identified categories



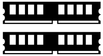
Memory addresses



11 known attacks



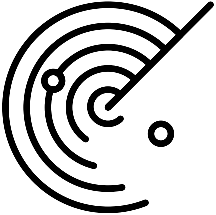
5 identified categories



Memory addresses

Accurate timing

Landscape of Microarchitectural Attacks



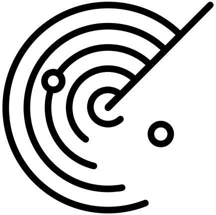
11 known attacks

5 identified categories

Memory addresses

Accurate timing

Multithreading



11 known attacks

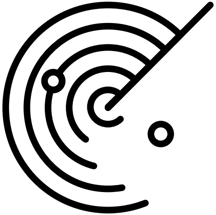
5 identified categories

Memory addresses

Accurate timing

Multithreading

Shared data



11 known attacks

5 identified categories

Memory addresses

Accurate timing

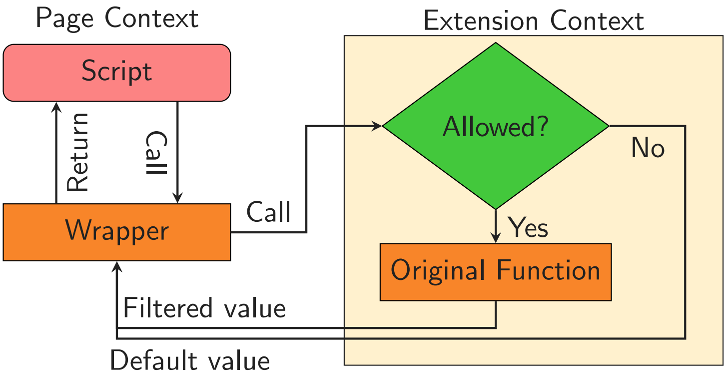
Multithreading

Shared data

Sensor API

Virtual Machine Layering

- Functions and properties are replaced by wrappers



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	●	●	●	●	●	●	●

Fully prevented (●), partly prevented (◐), not prevented (○). Policies must be combined (*).

- First systematic analysis of the attack surface

NDSS'18

Michael Schwarz, Moritz Lipp, Daniel Gruss.
JavaScript Zero: Real JavaScript and Zero Side-Channel Attacks.

Summary

- First systematic analysis of the attack surface
- Microarchitectural attacks in the browser are still possible

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- First efficient countermeasures in browsers

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Summary

- First systematic analysis of the attack surface
- Microarchitectural attacks in the browser are still possible
- First efficient countermeasures in browsers
- More microarchitectural attacks in JavaScript will appear

NDSS'18

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JavaScript Zero: Real JavaScript and Zero Side-Channel Attacks.

DECAF

AsiaCCS'18

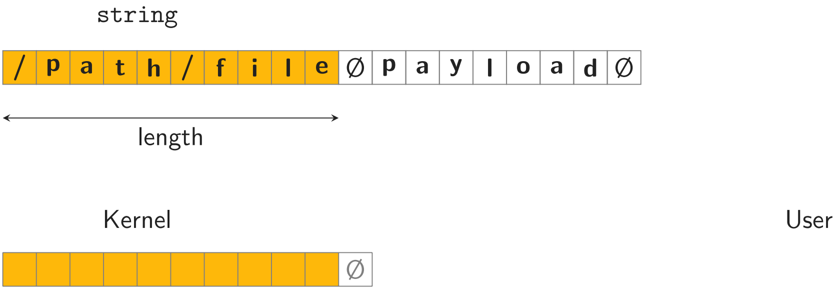
`string`

/	p	a	t	h	/	f	i	l	e	∅	p	a	y	l	o	a	d	∅

length

Kernel

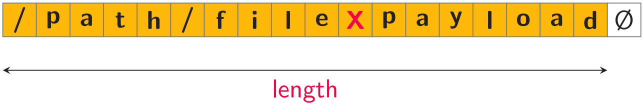
User



string
/ p a t h / f i l e ∅ p a y l o a d ∅
length
Kernel
User
∅

A Double Fetch

`string`

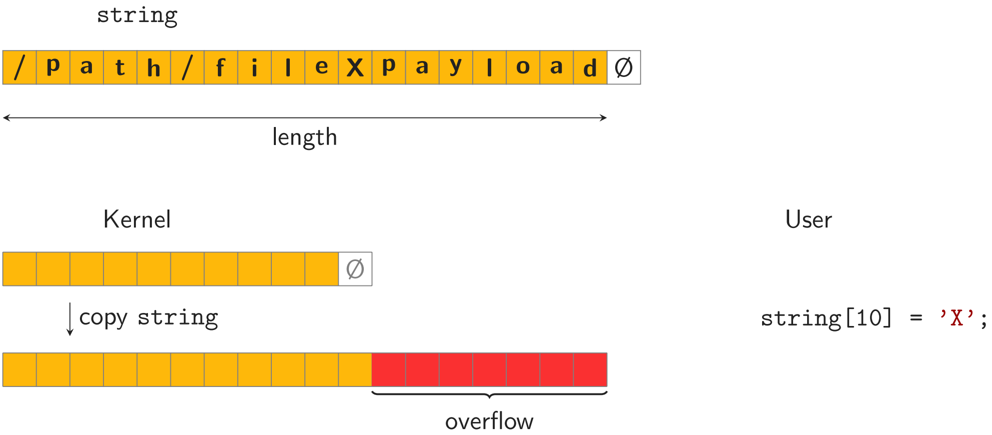


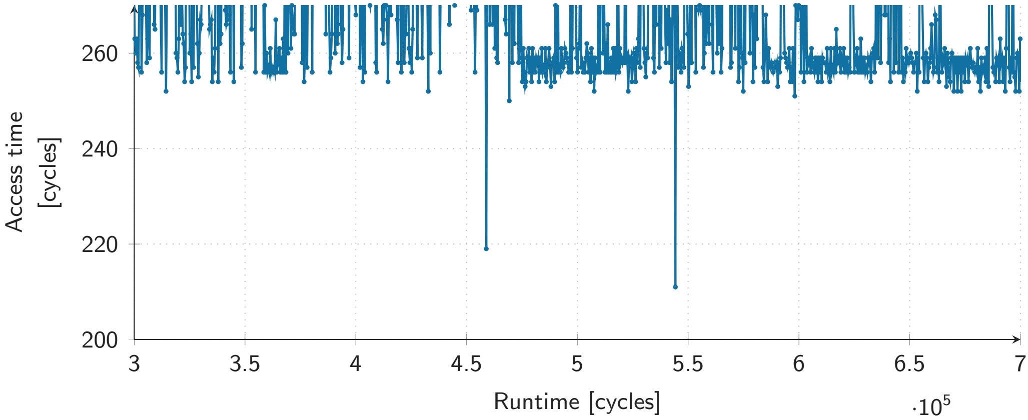
Kernel

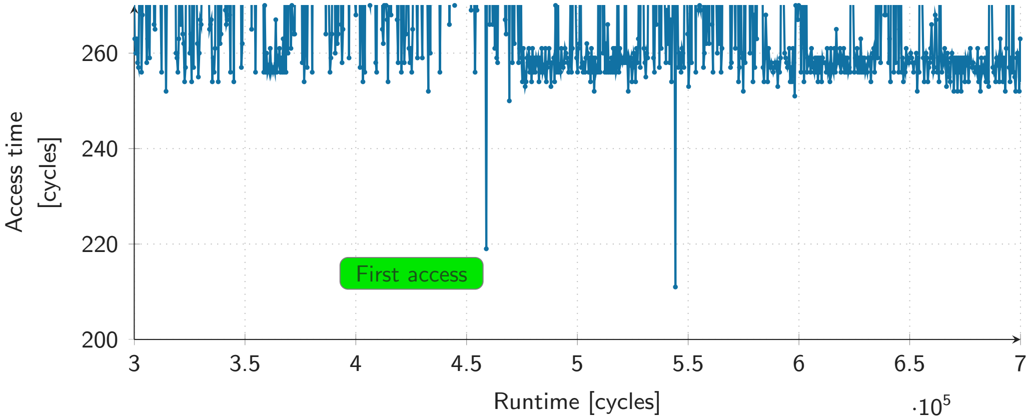
User

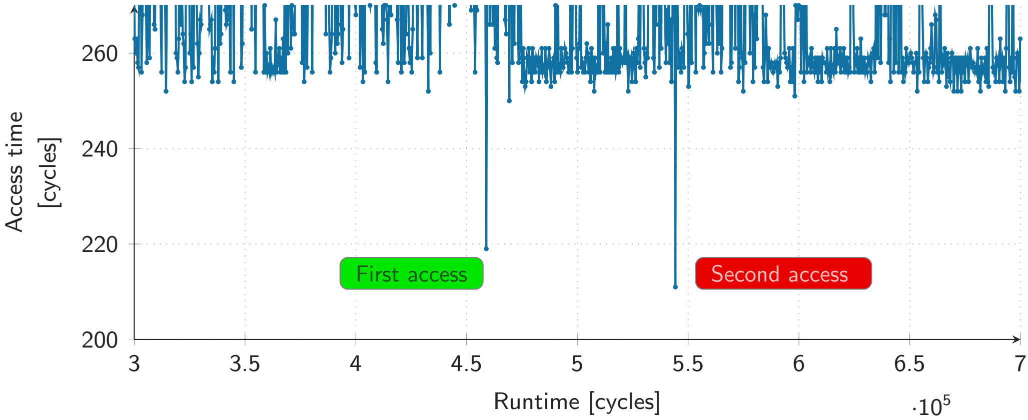
```
string[10] = 'X';
```

A Double Fetch

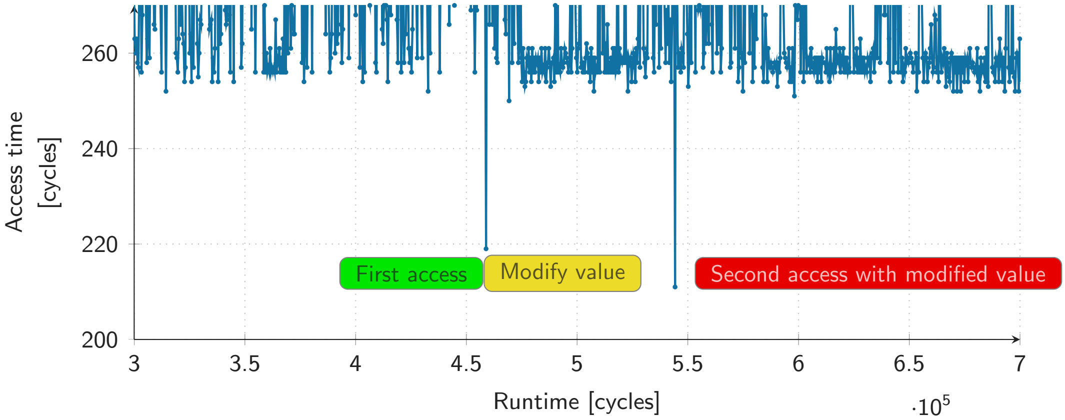



Access time [cycles]
260
240
220
200
3
3.5
4
4.5
5
5.5
6
6.5
7
Runtime [cycles]
$\cdot 10^5$


Access time [cycles]
260
240
220
200
First access
3
3.5
4
4.5
5
5.5
6
6.5
7
Runtime [cycles]
$\cdot 10^5$



Access time [cycles]
260
240
220
200
First access
Second access
3
3.5
4
4.5
5
5.5
6
6.5
7
$\cdot 10^5$
Runtime [cycles]


260
240
220
200
Access time [cycles]
3
3.5
4
4.5
5
5.5
6
6.5
7
$\cdot 10^5$
Runtime [cycles]
First access
Modify value
Second access with modified value

Summary

- Fuzzing + cache attacks → double-fetch bugs

AsiaCCS'18

Michael Schwarz, Daniel Gruss, Moritz Lipp, Clémentine Maurice, Thomas Schuster, Anders Fogh, Stefan Mangard.
Automated Detection, Exploitation, and Elimination of Double-Fetch Bugs using Modern CPU Features.

Summary

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- Cache as trigger outperforms state of the art

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Summary

- Fuzzing + cache attacks → double-fetch bugs
- Cache as trigger outperforms state of the art
- Hardware transactional memory prevents exploitation

AsiaCCS'18

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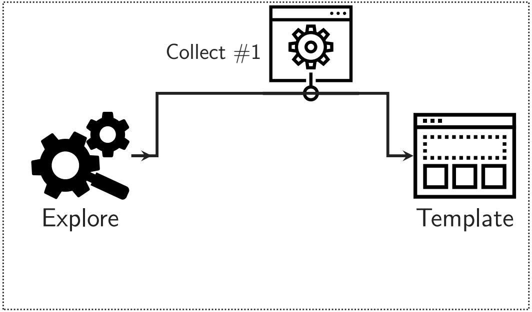
JS
Template Attacks

NDSS'19

- Template attack on JavaScript properties

Profiling Phase

- Template attack on JavaScript properties



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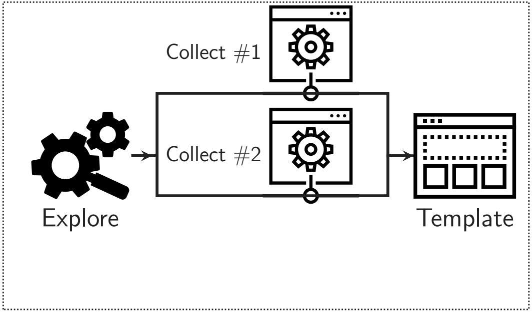

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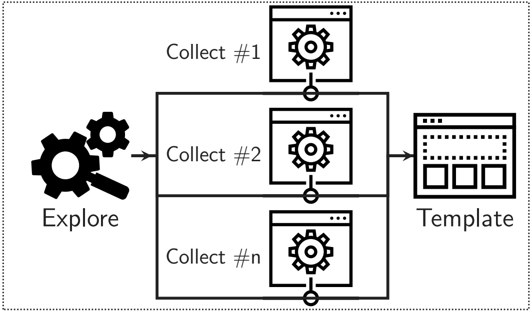

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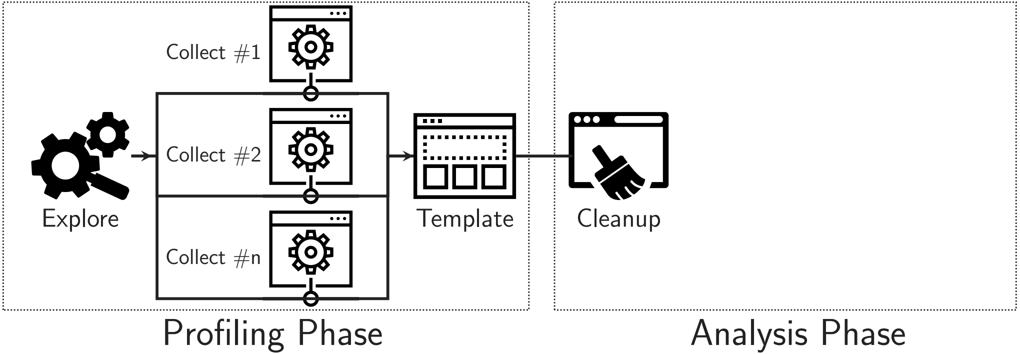

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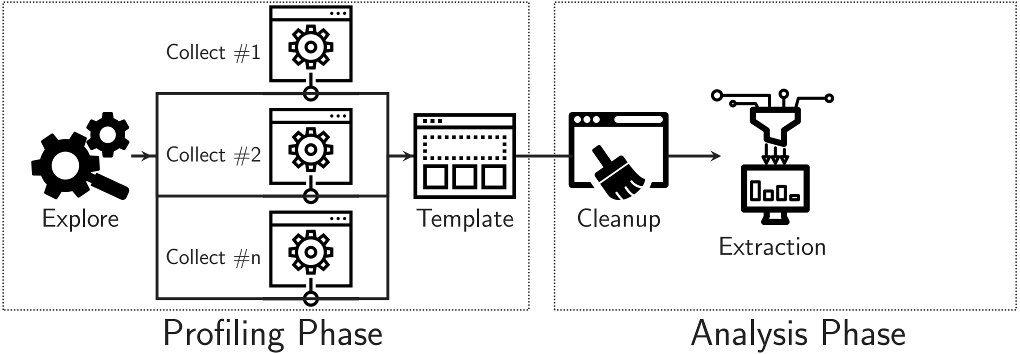

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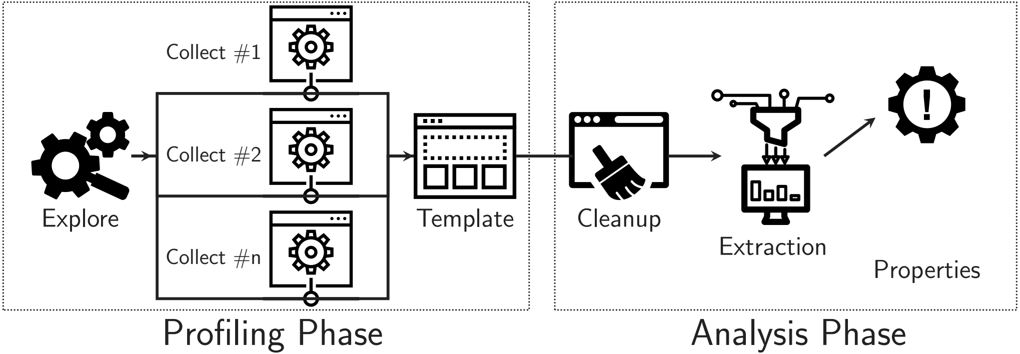

JavaScript Template Attacks

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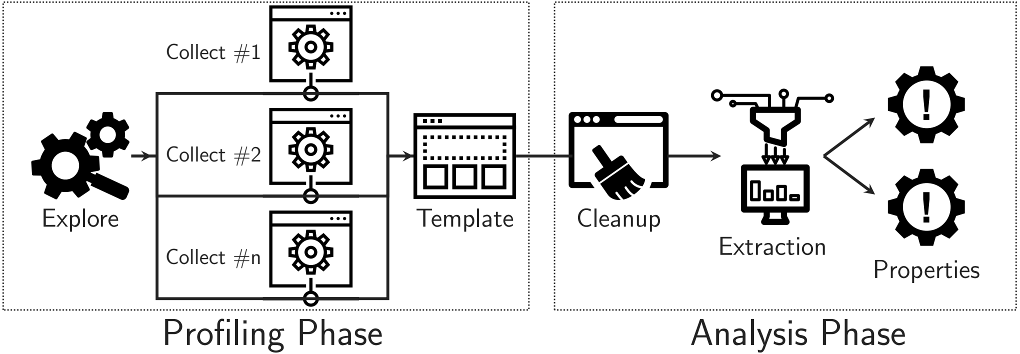
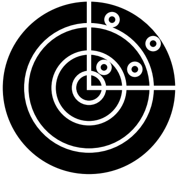


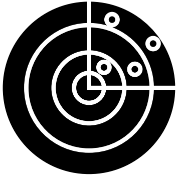


Browser + version

Detection

Browser + version

Privacy extensions



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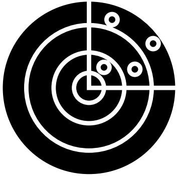
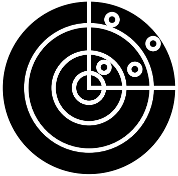
Private mode



- Browser + version
- Privacy extensions
- Private mode
- Operating system



Browser + version

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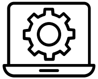
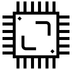


Operating system



CPU vendor

Detection

- Browser + version
- Privacy extensions
- Private mode
- Operating system
- CPU vendor
- Virtual machine

- JavaScript Template attacks detect environment properties

NDSS'19

Michael Schwarz, Florian Lackner, Daniel Gruss.
JavaScript Template Attacks: Automatically Inferring Host Information for Targeted Exploits.

Summary

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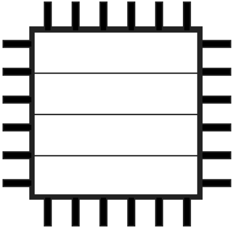
ZombieLoad

CCS'19

User Memory

	A	B
C	D	E
F	G	H
I	J	K
L	M	N
O	P	Q
R	S	T
U	V	W
X	Y	Z

```
char value = faulting[0]
```



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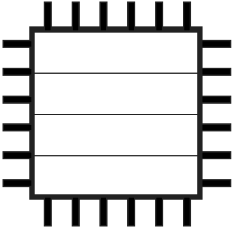
Fault



Fill-buffer Leakage

User Memory

	A	B
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R	S	T
U	V	W
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```
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```
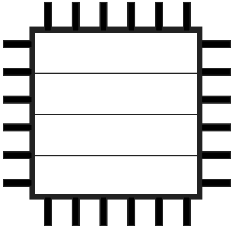
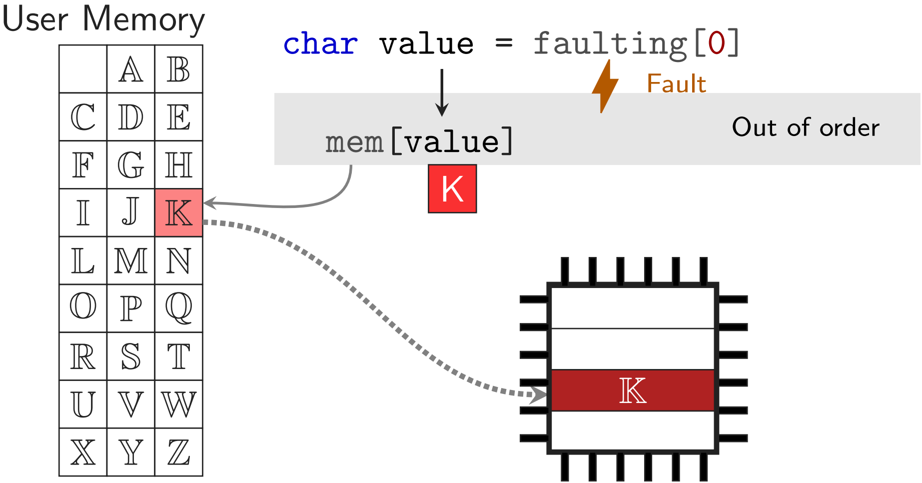

Fault

```
mem[value]
```

Out of order

K

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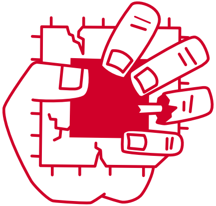
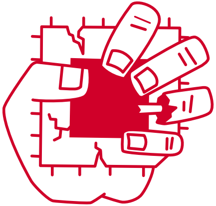
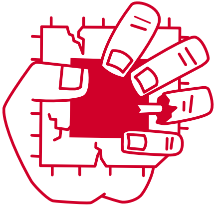


AES-NI key



AES-NI key

SGX sealing key



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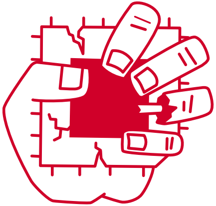
Cross-VM covert channel



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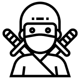
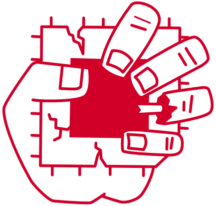


Cross-VM covert channel

Keyword matching

Results



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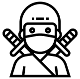

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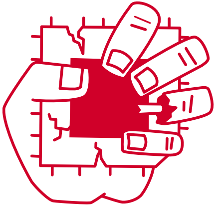
URL recovery



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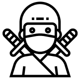

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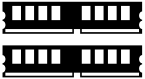

Targeted leakage

- Meltdown on the line-fill buffer

CCS'19

Michael Schwarz, Moritz Lipp, Daniel Moghimi, Jo Van Bulck, Julian Stecklina, Thomas Prescher, Daniel Gruss.
ZombieLoad: Cross-Privilege-Boundary Data Sampling.

- Meltdown on the line-fill buffer
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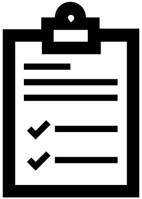

- Meltdown on the line-fill buffer
- Data sampling attacks are powerful
- Basis for Load Value Injection (LVI)

CCS'19

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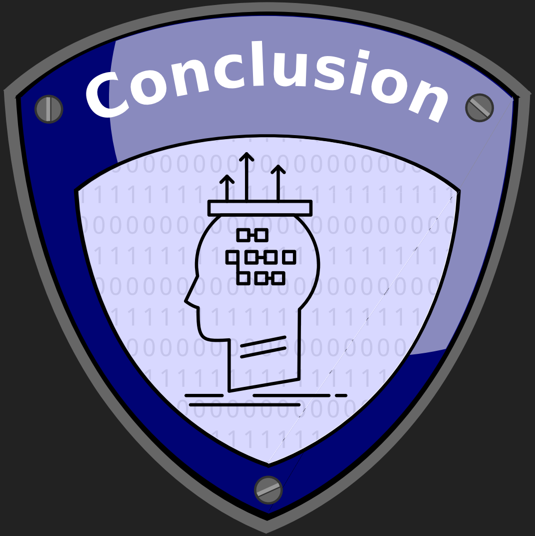
Conclusion

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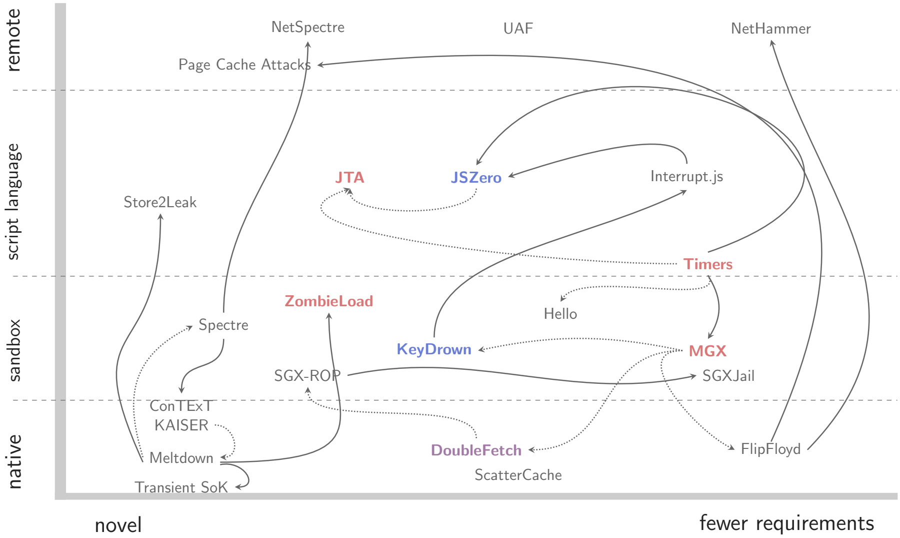
{...}

- Attack research is necessary for effective defenses
- Data-dependent optimizations often lead to side channel
- Trade-off between performance and security
- Created new field of transient-execution attacks

Paper Connections



Software-based Side-Channel Attacks and Defenses in Restricted Environments

Heinz Zemanek Preis Hearing 2020

Michael Schwarz
IAIK, Graz University of Technology
May 28, 2020