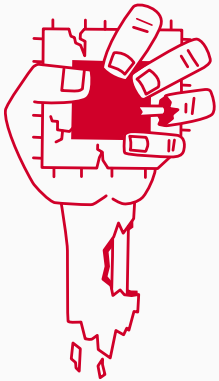
ZombieLoad

Cross-Privilege-Boundary Data Sampling

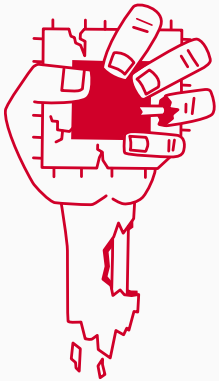
Michael Schwarz[1], **Moritz Lipp**[1], **Daniel Moghimi**[2], **Jo Van Bulck**[3], **Julian Stecklina**[4], **Thomas Prescher**[4], **Daniel Gruss**[1]

November 11, 2019

[1] Graz University of Technology, [2] Worcester Polytechnic Institute, [3] imec-DistriNet, KU Leuven, [4] Cyberus Technology



- A new Meltdown-type transient-execution attack



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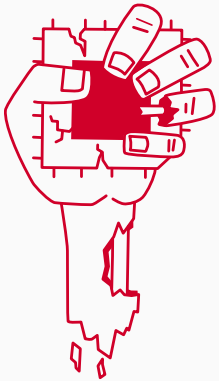

- A new Meltdown-type transient-execution attack
- Leaks data on Intel CPUs
- Really new? Published in May 2019...

BBC

Intel Zombieload bug fix to slow data centre computers

THE VERGE

ZombieLoad attack lets hackers steal data from Intel chips

FORTUNE

'Zombieload' Flaw Lets Hackers Crack Almost Every Intel Chip Back to 2011. Why's It Being Downplayed?

How-To Geek

Only New CPUs Can Truly Fix ZombieLoad and Spectre

ZombieLoad

- CVE-2018-12130
- CVE-2019-11091

ZombieLoad

- CVE-2018-12130
- CVE-2019-11091

RIDL

- CVE-2018-12127
- CVE-2018-12130
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RIDL

- CVE-2018-12127
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Fallout

- CVE-2018-12126

ZombieLoad

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- CVE-2019-11091
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RIDL

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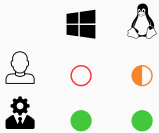
Fallout

- CVE-2018-12126

Variant 1

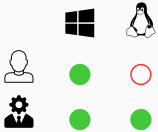
Kernel Mapping



Variant 3

Microcode-Assisted

Page-Table Walk



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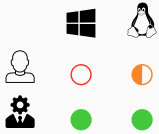
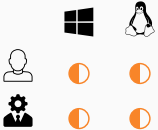


Variant 2

Transactional Asynchronous Abort



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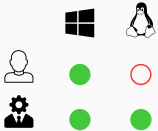

Embargo

- Variant 2 embargoed until November 12, 2019

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- Only variant without hardware mitigations

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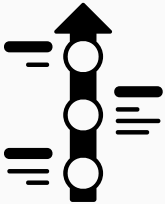
→ Works on MDS-resistant Cascade Lake CPUs

March 28, 2018 We report Meltdown on fill buffer (CVE-2019-11091)



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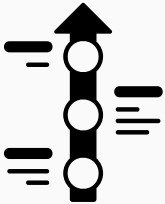

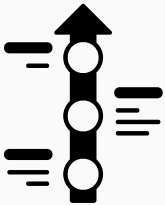

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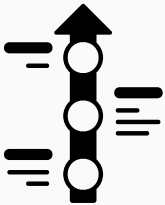

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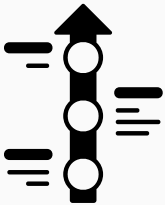

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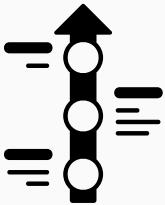

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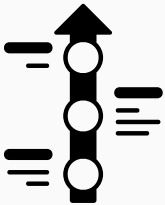

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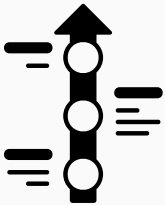

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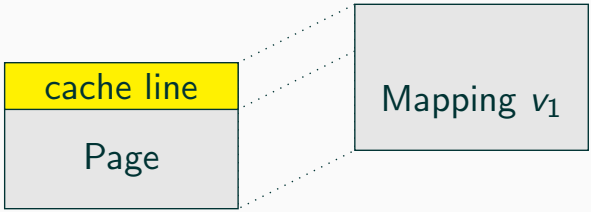
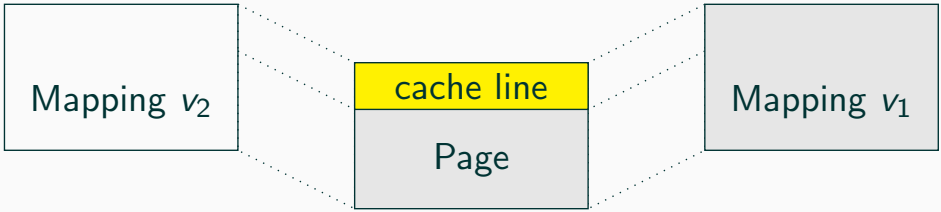
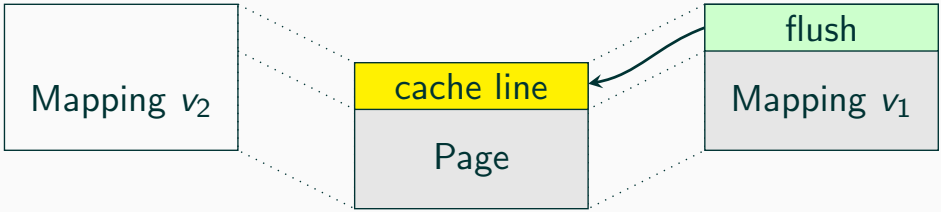
→ Additional embargo until November 12, 2019 (TAA)

	Fill Buffer, Load Ports, ?	Fill Buffer, Load Ports	Store Buffer
	All loads & stores	Uncached loads & stores	Stores
	✓	✗	✗
	✓	✗ (before Cascade Lake)	✗ (before Cascade Lake)

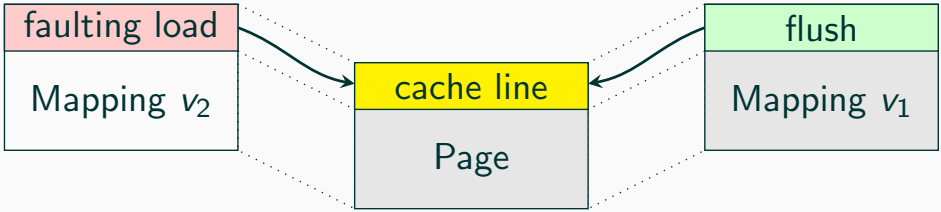
ZombieLoad works **despite** software **mitigations** and even on **MDS-resistant** CPUs (e.g., Cascade Lake)


cache line
Page
Mapping v_1


Mapping v_2
cache line
Page
Mapping v_1


Mapping v_2
cache line
Page
flush
Mapping v_1

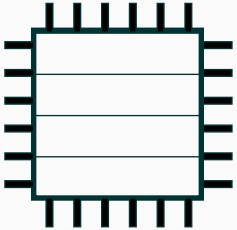
ZombieLoad Cache-line Conflicts



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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ℂ	𝔻	𝔼
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𝕃	𝕄	ℕ
𝕆	ℙ	ℚ
ℝ	𝕊	𝕋
𝕌	𝕍	𝕎
𝕏	𝕐	ℤ

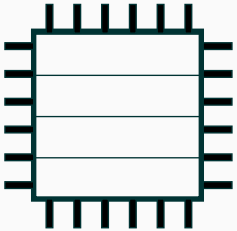
```
char value = faulting[0]
```

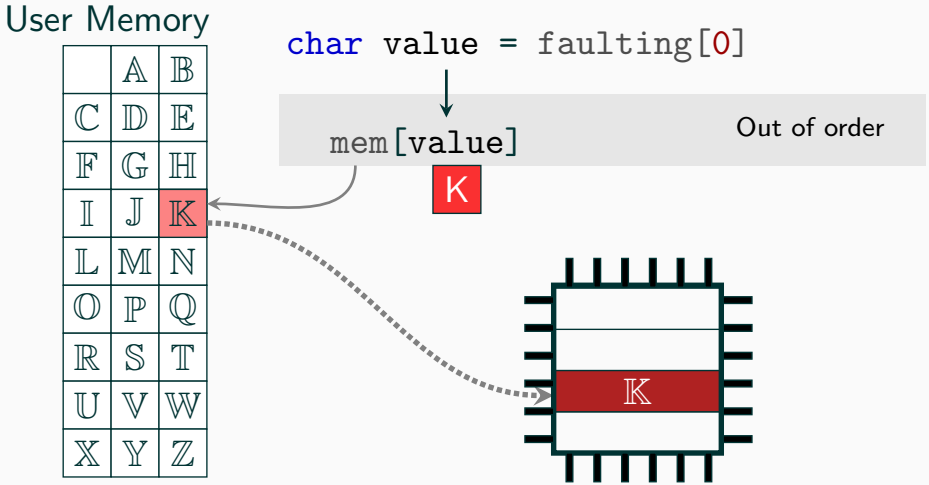
↓

```
mem[value]
```

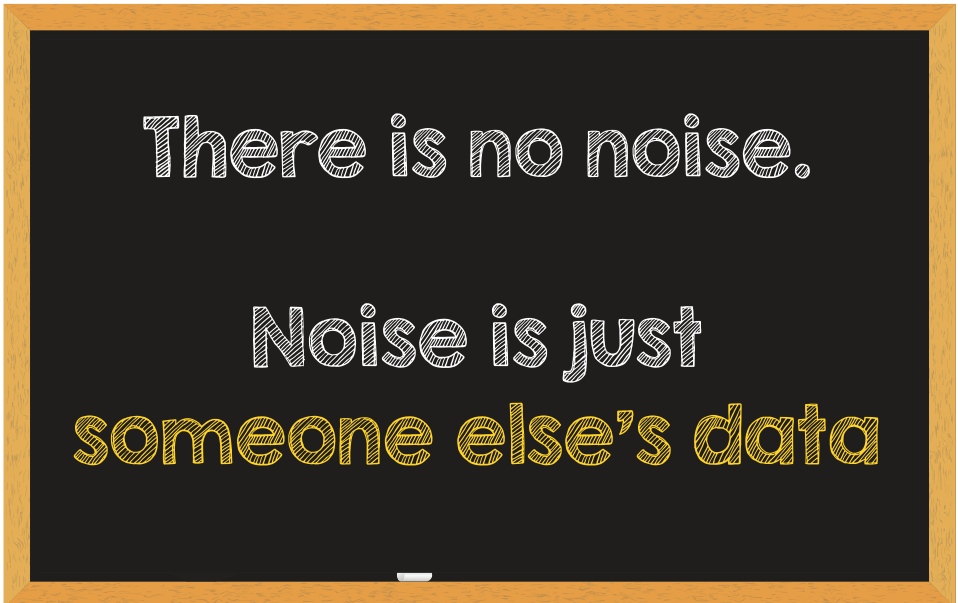
Out of order

K

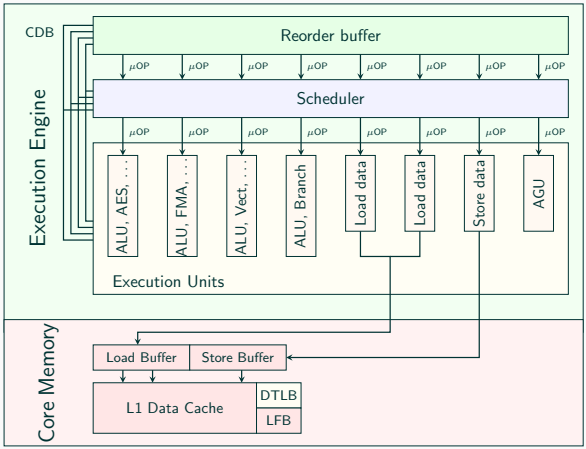



User Memory
A B
C D E
F G H
I J K
L M N
O P Q
R S T
U V W
X Y Z
char value = faulting[0]
mem[value]
Out of order
K
K


NOISE


There is no noise.
Noise is just
someone else's data

Complex Load Situations



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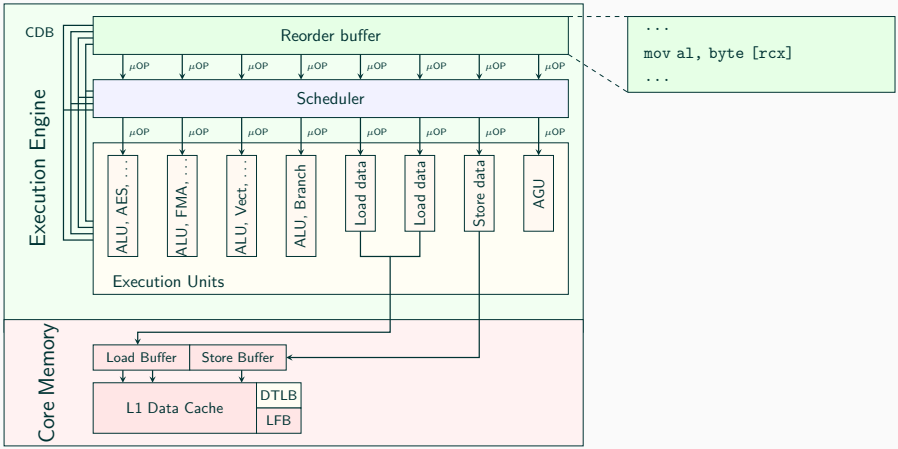

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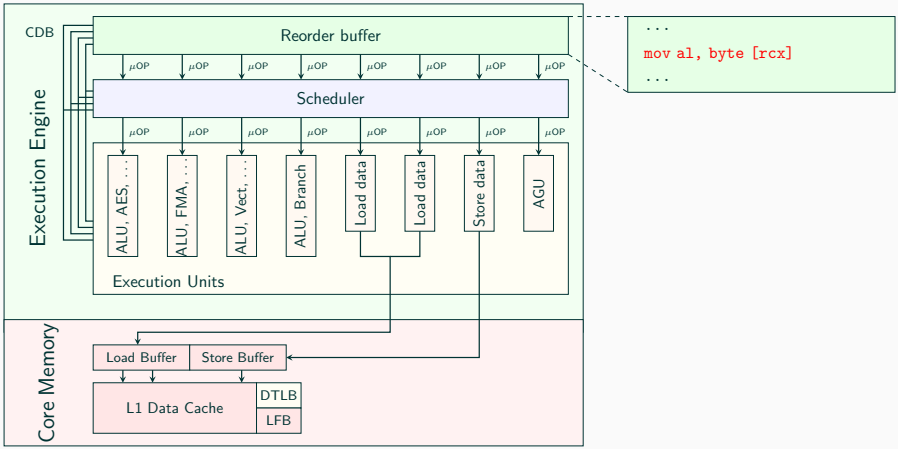

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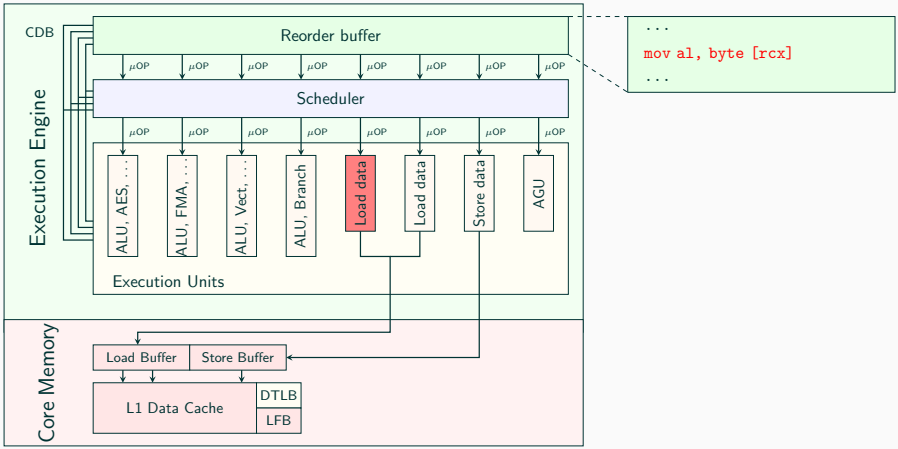

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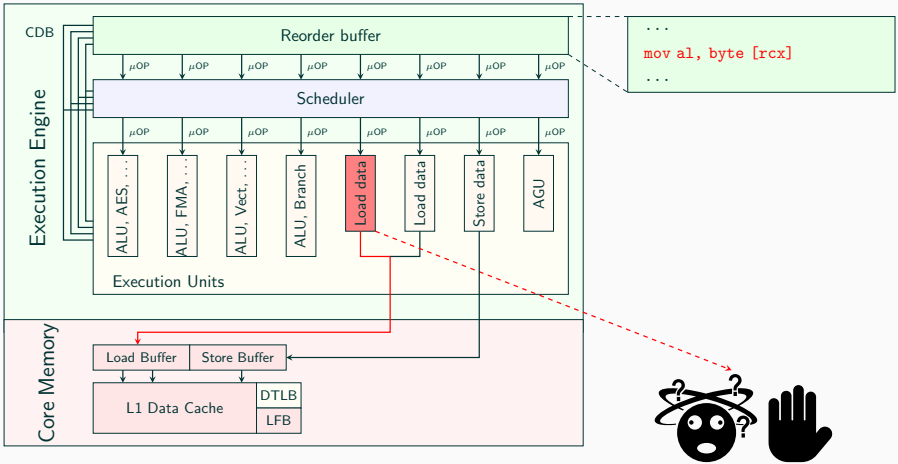

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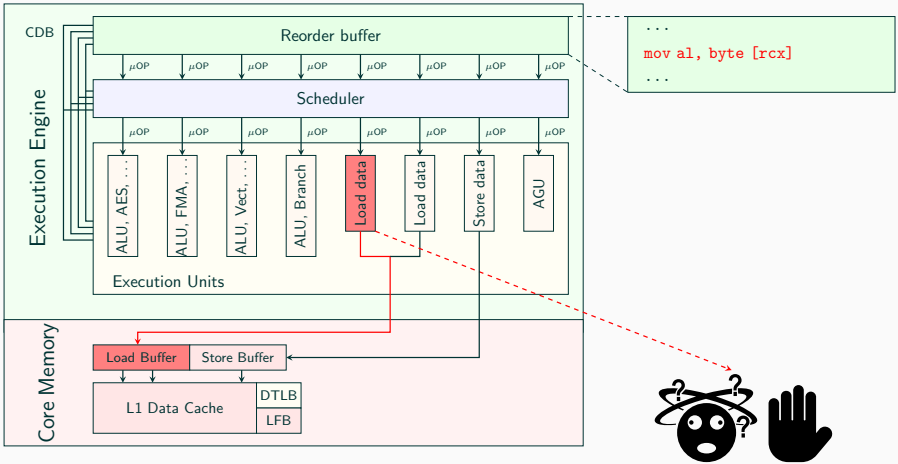

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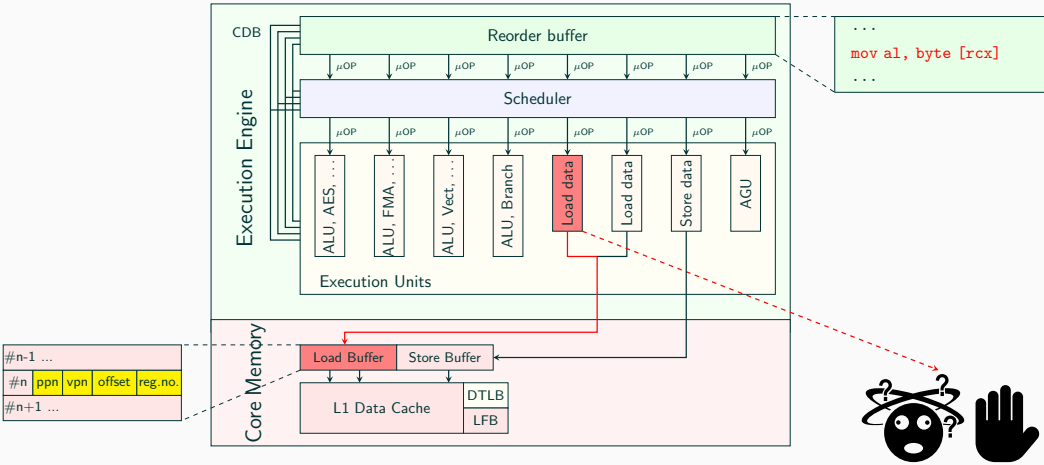

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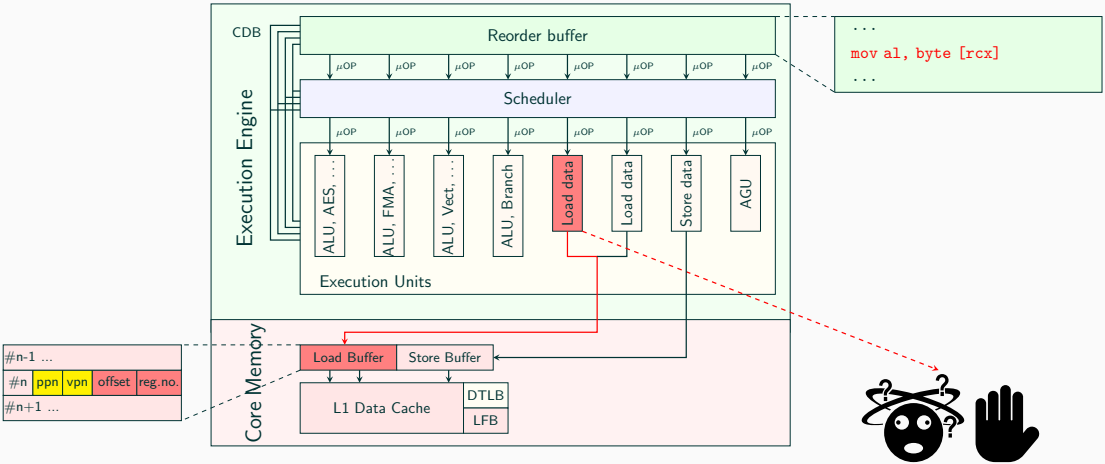

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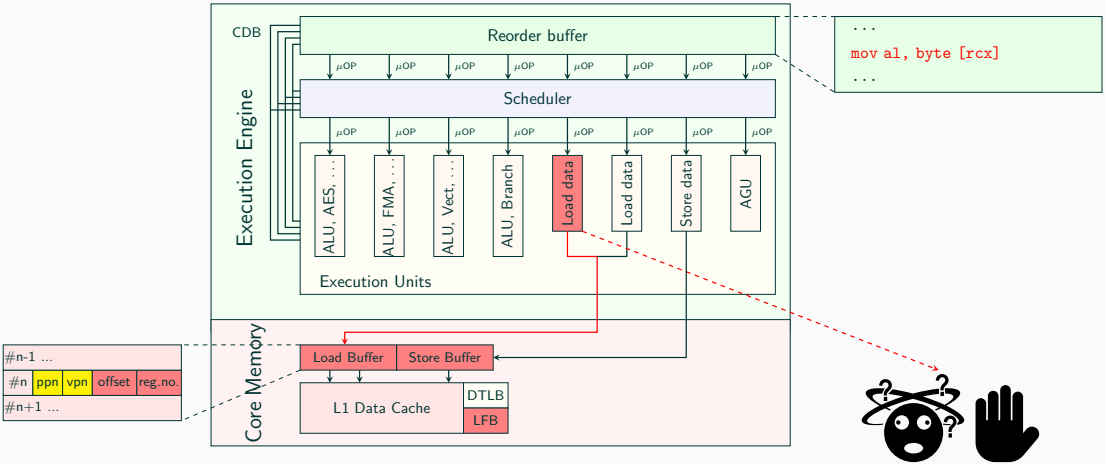

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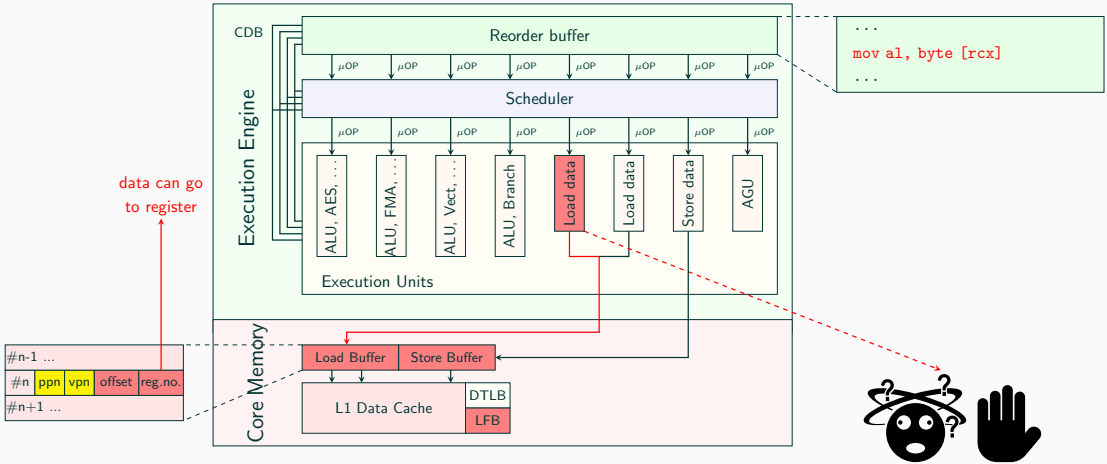

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  - ...
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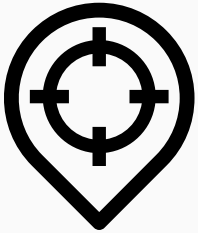
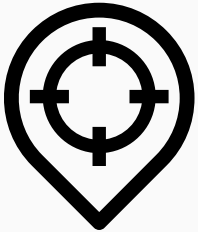
- Meltdown effects due to "microarchitectural fault"
- No architectural fault handling required

Attack Targets



- Leak data on same and sibling hyperthread

Attack Targets



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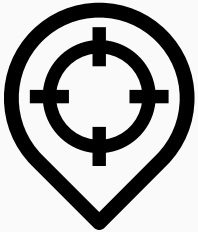
Applications

Attack Targets



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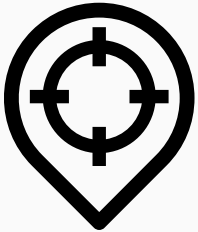
Applications

Operating System

Attack Targets



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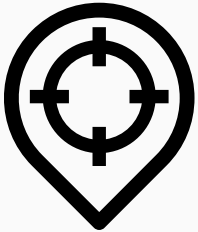
Applications

Operating System

SGX Enclave

Attack Targets



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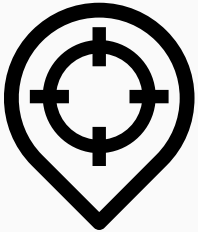
Applications

Operating System

SGX Enclave

Virtual Machine

Attack Targets



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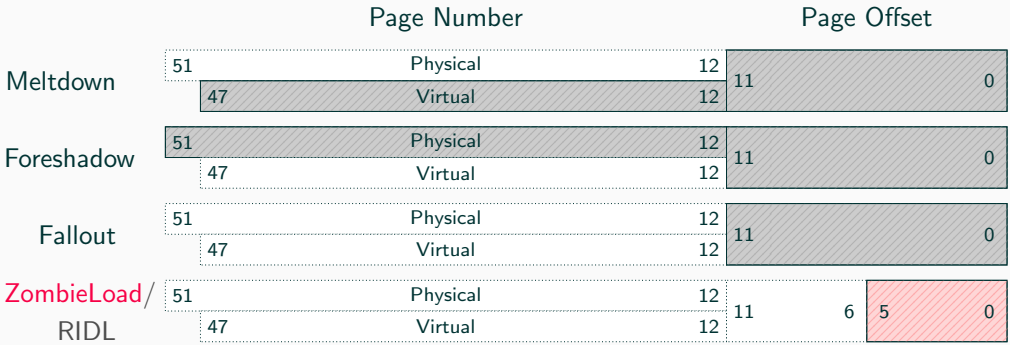
Applications

Operating System

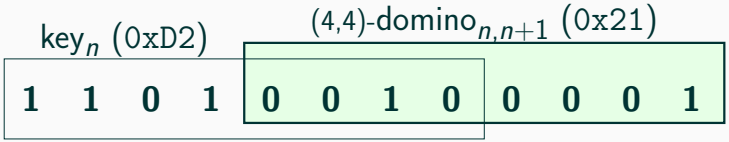
SGX Enclave

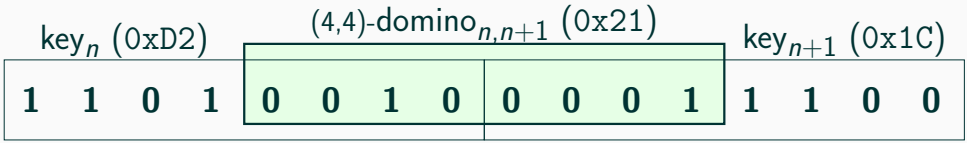
Virtual Machine

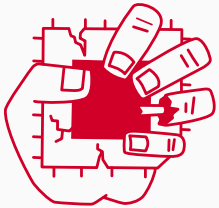
Hypervisor


Page Number
Page Offset
Meltdown
51
Physical
12
11
0
47
Virtual
12
Foreshadow
51
Physical
12
11
0
47
Virtual
12
Fallout
51
Physical
12
11
0
47
Virtual
12
ZombieLoad / RIDL
51
Physical
12
11
6
5
0
47
Virtual
12


key$_n$ (0xD2)
1 1 0 1 0 0 1 0

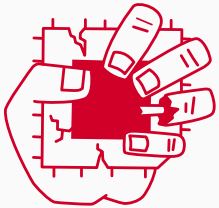

key$_n$ (0xD2)
(4,4)-domino$_{n,n+1}$ (0x21)
1 1 0 1 0 0 1 0 0 0 0 1


key$_n$ (0xD2)
(4,4)-domino$_{n,n+1}$ (0x21)
key$_{n+1}$ (0x1C)
1 1 0 1 0 0 1 0 0 0 0 1 1 1 0 0



AES-NI key

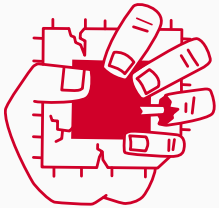
Results



AES-NI key

SGX sealing key

Results

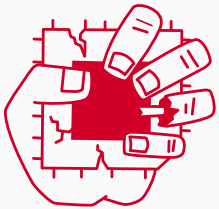


AES-NI key

SGX sealing key

Cross-VM covert channel

Results



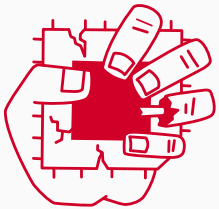
AES-NI key

SGX sealing key

Cross-VM covert channel

Keyword matching

Results



AES-NI key

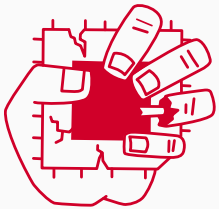
SGX sealing key

Cross-VM covert channel

Keyword matching

URL recovery

Results



AES-NI key

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Keyword matching

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Targeted leakage

Variant 1

Kernel Mapping

5.30 kB/s

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5.30 kB/s

Variant 2

Transactional
Asynchronous Abort

39.66 kB/s

Performance

Variant 1

Kernel Mapping

5.30 kB/s

Variant 2

Transactional Asynchronous Abort

39.66 kB/s

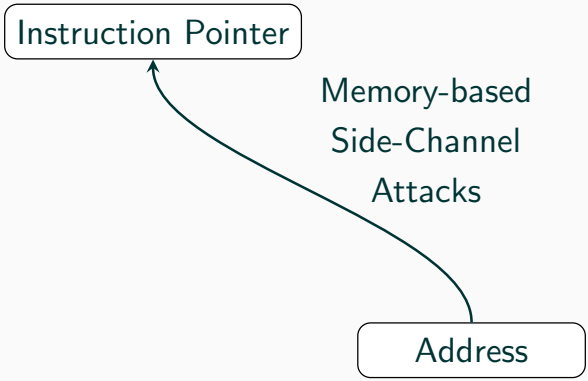
Variant 3

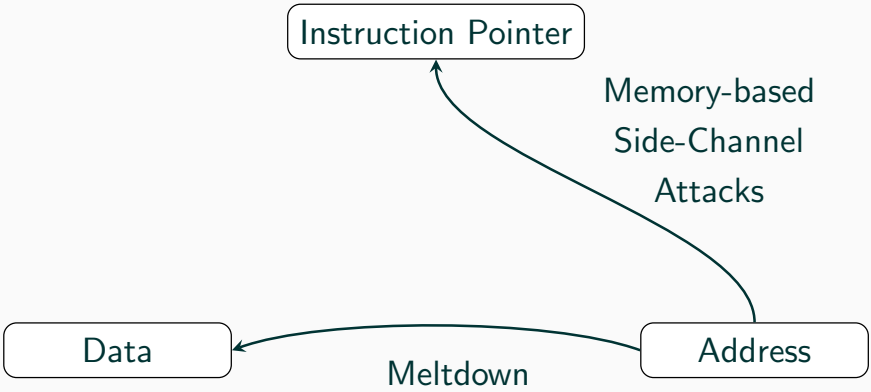
Microcode-Assisted Page-Table Walk

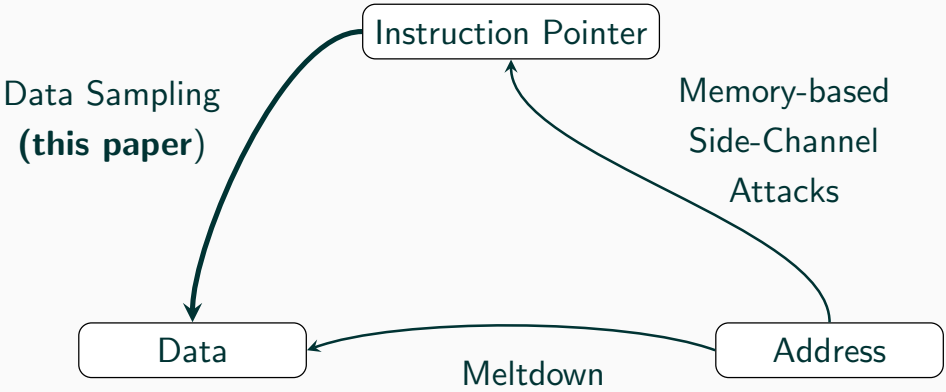
7.73 kB/s


zombieload : zsh — Konsole <2>
File Edit View Bookmarks Settings Help
michael@hp /tmp/zombieload %
zombieload : zsh

Address


Instruction Pointer
Memory-based
Side-Channel
Attacks
Address


Instruction Pointer
Memory-based
Side-Channel
Attacks
Data
Address
Meltdown


Instruction Pointer
Data Sampling
(this paper)
Memory-based
Side-Channel
Attacks
Data
Address
Meltdown

- Disable hyperthreading or group scheduling

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- Overwrite microarchitectural buffers

Intel Mitigations

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  - `VERW` instruction (microcode update)

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CPU	Meltdown	Foreshadow	RIDL	Fallout	MLPDS	MDSUM
8th/9th gen. Intel Core Coffee Lake	✗	✗	✗	✗	✗	✗
Intel Xeon Cascade Lake	✗	✗	✗	✗	✗	✗

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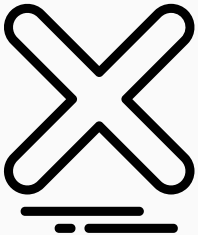
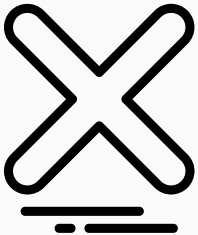
CPU	Meltdown	Foreshadow	RIDL	Fallout	MLPDS	MDSUM	ZombieLoad
8th/9th gen. Intel Core Coffee Lake	✗	✗	✗	✗	✗	✗	???
Intel Xeon Cascade Lake	✗	✗	✗	✗	✗	✗	???

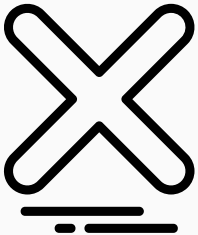


- Variant 2 works on all CPUs



- Variant 2 works on all CPUs

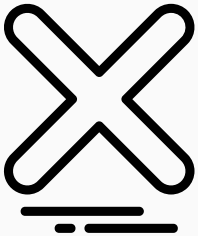
→ Embargoed until November 12, 2019



- Variant 2 works on all CPUs

→ Embargoed until November 12, 2019

- Microcode and software sequences do not prevent ZombieLoad



- Variant 2 works on all CPUs

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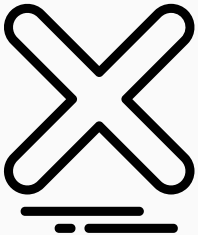
→ Reported on May 16, 2019



- Variant 2 works on all CPUs

→ Embargoed until November 12, 2019

- Microcode and software sequences do not prevent ZombieLoad

→ Reported on May 16, 2019

- ZombieLoad might not only leak from fill buffer

- Disable hyperthreading

ZombieLoad Mitigations

- Disable hyperthreading
- Flush all buffers on privilege-level change

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ZombieLoad Mitigations

- Disable hyperthreading
- Flush all buffers on privilege-level change
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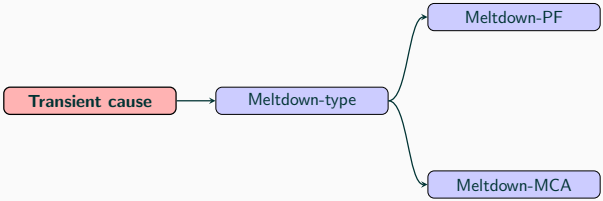
- Disable Intel TSX (`MSR_TSX_FORCE_ABORT`)

Transient Execution Attack Tree

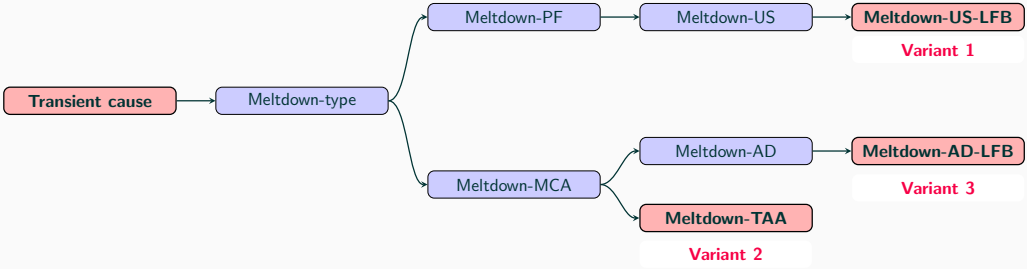
Transient cause

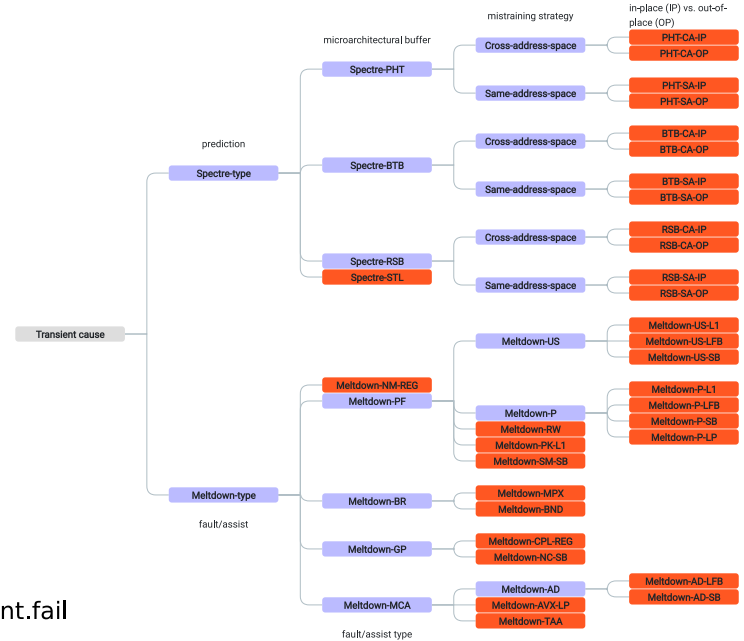
Transient Execution Attack Tree

Transient Execution Attack Tree



Transient Execution Attack Tree





https://transient.fail

You can find our proof-of-concept implementation on:

- `https://github.com/IAIK/ZombieLoad`

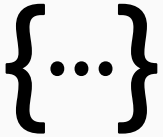
{...}

- Transient-execution attacks: the gift that keeps on giving

{...}

- Transient-execution attacks: the gift that keeps on giving
- Class of Meltdown attacks is larger than expected

Conclusion



- Transient-execution attacks: the gift that keeps on giving
- Class of Meltdown attacks is larger than expected
- CPUs are deterministic - there is no noise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MICHAEL SCHWARZ
DANIEL MOGHIMI
JO VAN BULCK
ZOMBIELOAD
GRAZ UNIVERSITY OF TECHNOLOGY PRESENTS IN COLLABORATION WITH
WORCESTER POLYTECHNIC INSTITUTE, KU LEUVEN, AND CYBERUS TECHNOLOGY
AN ACM CCS 2019 PAPER "ZOMBIELOAD: CROSS-PRIVILEGE-BOUNDARY DATA SAMPLING"
WRITTEN BY MICHAEL SCHWARZ, MORITZ LIPP, DANIEL MOGHIMI, JO VAN BULCK, JULIAN STECKLINA, THOMAS PRESCHER, DANIEL GRUSS

ZombieLoad

Cross-Privilege-Boundary Data Sampling

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November 11, 2019

Graz University of Technology